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Review

Future Circular Collider Feasibility Study Report

Volume 3 Civil Engineering, Implementation and Sustainability

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S. Beuvier and M. Klein are deceased.

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F. Zimmermann is the Deputy Study Leader.

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Y. Chae[4], F. Chagnet[152], I. Chaikovska[9,10,11], M. Chalhoub[86], M. Chamizo-Llatas[6], M. Champagne[153],
H. Chanal[9,154,155], G. Chapelier[108], P. Charitos[1], C. Charles[105], T.K. Charles[156], C. Charlot[9,81,82],
S. Chatterjee[4], A. Chaudhuri[157], R. Chehab[9,10,11], S.V. Chekanov[158], H. Chen[6], T. Chesne[105],
F. Chiapponi[25,26], G. Chiarello[159,160], M. Chiesa[127], P. Chiggiato[1], P. Chomaz[3], M. Chorowski[161], J.P. Chou[162],
M. Chrzaszcz[107], W. Chung[163], S. Ciarlantini[68,164], A. Ciarma[48], D. Cieri[131], A.K. Ciftci[165], R. Ciftci[166],
R. Cimino[48], F. Cirotto[35,36], M. Ciuchini[110], M. Cobal[167,168], A. Coccaro[140], R. Coelho Lopes De Sa[169],
J.A. Coleman-Smith[1], F. Collamati[170], C. Colldelram[171], P. Collier[1], P. Collins[1], J. Collot[9,172,173],
M. Colmenero[1], L. Colnot[149], G. Coloretti[73], D. Contardo[9,56,57], E. Conte[9,42,43], F.A. Conventi[35,174], A. Cook[1],
L. Cooley[175,176], A.S. Cornell[177], C. Cornella[1], G. Cornette[105], I. Corredoira[178], P. Costa Pinto[1], F. Couderc[3],
J. Coupard[1], S. Coussy[86], G. Crawford[179], R. Crescenzi[180], I. Crespo Garrido[1,181], T. Critchley[1,101],
A. Crivellin[73], T. Croci[63], C. Cudré[105], G. Cummings[37], F. Cuna[12], R. Cunningham[1], B. Curé[1], E. Curtis[182],
M. D'Alfonso[183], L. D'Aloia Schwartzentruber[184], G. D'Amen[6], B. D'Anzi[12,13], A. D'Avanzo[35,36], D. d'Enterria[1],
A. D'Onofrio[35], M. D'Onofrio[185], M. Da Col[149], M. Da Rocha Rolo[60], C. Dachauer[186], B. Dağli[24], A. Dainese[68],
B. Dalena[3], W. Dallapiazza[187], M. Dam[188], H. Damerau[1], V. Dao[62], A. Das[189], M.S. Daugaard[1], S. Dauphin[108],
A. David[1], T. Davídek[190], G.J. Davies[182], J. Davighi[1], S. Dawson[6], J. de Blas[191], A. de Cosa[150],
S. De Curtis[192], N. De Filippis[12,50], E. De Lucia[48], R. De Maria[1], E. De Matteis[44], A. De Roeck[1],
A. De Santis[48], A. De Vita[1,68,164], A. Deandrea[9,56,57], C.J. Debono[193], M. Deeb[100], M.M. Defranchis[1],
J. Degens[185], S. Deghaye[1], V. Del Duca[48], C.L. Del Pio[6], A. Del Vecchio[90], D. Delikaris[1], A. Dell'Acqua[1],
M. Della Pietra[35,36], M. Delmastro[9,16,17], L. Delprat[1], E. Delugas[149], Z. Demiragli[194], L. Deniau[1], D. Denisov[6],
H. Denizli[195], A. Denner[196], A. Denot[108], G. Deptuch[6], A. Desai[197], H. Deveci[1], A. Di Canto[6],
A. Di Ciaccio[20,21], L. Di Ciaccio[9,16,17], D. Di Croce[1,114], C. Di Fraia[35,36], B. Di Micco[29,110], R. Di Nardo[29,110],
T.B. Dingley[8], F. Djama[9,75,76], F. Djurabekova[198], D. Dockery[37], S. Doebert[1], D. Domange[1,199], M. Donegà[150],
U. Dosselli[68], H.A. Dostmann[1,200], J.A. Dragovich[37], I. Drebot[44], M. Drewes[201], T.A. du Pree[202], Z. Duan[203],
C. Duarte-Galvan[204], O. Duboc[205], I. Dubovyk[206], M. Duda[2], P. Duda[161], H. Duran Yildiz[58], H. Durand[105],
P. Durand[105], G. Durieux[201], Y. Dutheil[1], I. Dutta[37], J.S. Dutta[207], S. Dutta[208], F. Duval[1], F. Eder[1],
M. Eisterer[98], Z. El Bitar[9,42,43], A. El Saied[209], M. Elisei[44], J. Ellis[1,210], W. Elmetenawee[12], J. Elmsheuser[6],
V. Daniel Elvira[37], S.C. Eno[211], Y. Enomoto[212], B.A. Erdelyi[68,164], O.E. Eruteya[101,213], M. Escobar[214],
O. Etisken[215], I. Eymard[144], J. Eysermans[183], D. Falchieri[25], C. Falkenberg[205], F. Fallavollita[1,131],
A. Afalou[1,9,10], J. Faltova[190], J. Fanini[1], L. Fanò[63,64], K. Fanti[105], R. Farinelli[25], M. Farino[163], S. Farinon[140],
H. Fatehi[38], J. Fatterbert[105], A. Faure[216], A. Faus-Golfe[9,10,11], G. Favia[1], L. Favilla[35,118], W.J. Fawcett[32],
A. Federowicz[37], L. Feligioni[9,75,76], L. Felsberger[1], Y. Feng[23], A. Fernández Téllez[217], R. Ferrari[127], L. Ferreira[1],
F. Ferro[140], M. Fiascaris[1], C. Fiorio[45], S.A. Fleury[1], L. Florez[187], M. Florio[45,149], A. Fondacci[63],
B. Fontimpe[214], K. Foraz[1], R. Fortunati[2], M. Fouaidy[9,10,11], A. Foussat[1], A. Fowler[1], J.D. Fox[218],
M. Francesconi[35], B. Francois[1], R. Franqueira Ximenes[1], F. Fransesini[48], A. Frasca[1,185], A. Freitas[219],
J.A. Frost[8], K. Furukawa[212], A. Gabrielli[25,26], A. Gaddi[1], F. Gaede[4], A. Gallén[130], R. Galler[220,221],
E. Gallice[105], E. Gallo[4,115], H. Gamper[1], G. Ganis[1], S. Ganjour[3], S. Gao[6], A. Garand[148], C. Garaus[205],
D. Garcia[1], R. García Alía[1], R. García Gil[222], C.M. Garcia Jaimes[1,114], H. Garcia Rodrigues[2,223], C. Garion[1],
M. Garlaschè[1], D. Garnier[152], M.V. Garzelli[115], S. Gascon-Shotkin[9,56,57], M. Gasior[1], G. Gaudino[35,118],
G. Gaudio[127], V. Gaur[224], K. Gautam[73,116], V. Gawas[1], T. Gehrmann[73], A. Gehrmann-De Ridder[73,150],
K. Geiger[1], M. Genco[149], F. Gerigk[1], H. Gerwig[1], A. Ghribi[1,9,225], P. Giacomelli[25], S. Giagu[90,170],
E. Gianfelice[37], S. Giappichini[132], D. Gibellieri[1,226], F. Giffoni[149], G. Gil da Silveira[227], S.S. Gilardoni[1],
M. Giovannetti[48], T. Girardet[105], S. Girod[1,105], P. Giubellino[60], P. Giubilato[68,164], F. Giuli[20,21], M. Giuliani[102],
E.L. Gkougkousis[1,73], S. Glukhov[228], J. Gluza[206], B. Goddard[1], C. Goffing[1,132], D. Goldsworthy[1], T. Golling[101],
R. Gonçalo[51,229], V.P. Gonçalves[47,230], T. Gonçalves Da Silva[214], J. Gonski[7], R. Gonzalez Suarez[130],
S. Gorgi Zadeh[1], S. Gori[231], E. Gorini[159,232], L. Gouskos[233], M. Gouzevitch[9,56,57], E. Granados[1],
F. Grancagnolo[159], S. Grancagnolo[159,232], A. Grassellino[37], A. Grau[132], E. Graverini[40,77,114], F.G. Gravili[159,232],
H.M. Gray[141,234], M. Grazzini[73], Mario Greco[29,110], Michela Greco[60,235], A. Greljo[49], J.-L. Grenard[1],
A.V. Gritsan[236], R. Gröber[68,164], A. Grudiev[1], E. Gschwendtner[1], J. Gu[237], D. Guadagnoli[17,137,238],
G. Guerrieri[1], A. Guiavarch[209], G. Guillermo Canton[1,239], M. Guinchard[1], Y.O. Günaydin[240], K. Gurcel[92],
L.X. Gutierrez Guerrero[241,242], D. Gutiérrez Rueda[1], A. Gutiérrez-Rodríguez[243], V. Guzey[198,244], C. Haber[141],
T. Hacheney[245], B. Hacışahinoğlu[33], K. Hahn[122], J. Hajer[129], T. Hakulinen[1], J.C. Hammersley[246], M. Hance[231],
J.B. Hansen[188], B. Härer[132], E. Hauzinger[220], M. Haviernik[190], B. Hegner[1], C. Helsens[114], Ana Henriques[1],
C. Hernalsteens[1], H. Hernández-Arellano[217], R.J. Hernández-Pinto[204], M.A. Hernández-Ruíz[243],
J. Hernández-Sánchez[217], J.W. Heron[1], L.M. Herrmann[1], R. Hirosky[247], J.F. Hirschauer[37], J.D. Hobbs[62],
K. Hock[6], S. Höche[37], M. Hofer[1], G. Hoffstaetter[6,248], W. Höfle[1], M. Hohlmann[249], F. Holdener[250], B. Holzer[1],
C.G. Honorato[217], H. Hoorani[251], A. Houver[105], E. Howling[1,8,136], X. Huang[7], F. Hug[252], B. Humann[1],
P. Hunchak[120], Y. Husein[1], A. Hussain[1,253], G. Iadarola[1], G. Iakovidis[6], G. Iaselli[12,50], P. Iengo[35], A. Ilg[73],
M. Iodice[110], A.O.M. Iorio[35,36], V. Ippolito[170], U. Iriso[171], J. Isaacson[37], G. Isidori[73], R. Islam[254],
A. Istepanyan[105], S. Izquierdo Bermudez[1], V. Izzo[35], P.D. Jackson[197], R. Jafari[1,38], S.S. Jagabathuni[1,101],
S. Jana[255,256], C. Järmyr Eriksson[1], P. Jausserand[152], M. Jensen[257], J.M. Jimenez[1], F.R. Joaquim[129],

O.R. Jones[1], J. Joos[108], E. Jourd'huy[9,258], E. Jourdan[214], J.M. Jowett[1,259], A. Jueid[260], A.W. Jung[207],
M. Kagan[7], I. Kahraman[58], V. Kain[1], J. Kalinowski[261], J.F. Kamenik[262,263], A. Kanso[264], T. Kar[265],
S.O. Kara[266], H. Karadeniz[267], B. Karmakar[206], S.R. Karmarkar[207], V. Karpati[268], I. Karpov[1], M. Karppinen[1],
P. Karst[9,75,76], S. Kartal[33], V.V. Kashikhin[37], U. Kaya[58], A. Kehagias[1,269], J. Keintzel[1], M. Kennouche[1],
M. Kenzie[32], M. Kerréveur-Lavaud[46], R. Kersevan[1,270], V. Keus[198,271], H. Khanpour[14,272,273], V.V. Khoze[274],
V.A. Khoze[274], P. Kicsiny[1], R. Kieffer[1], C. Kiel[114], J. Kieseler[132], A. Kilic[275], B. Kilminster[73], S. Kim[276],
Z. Kırca[275], M. Klein[185], A. Klimentov[6], M. Klute[132], V. Klyukhin[119,277], M. Knecht[137,278,279], B. Kniehl[115],
P. Ko[280], S. Ko[1], F. Kocak[275], T. Koffas[281], C. Kokkinos[282,283], K. Kołodziej[206], K. Kong[284], P. Kontaxakis[101],
I.A. Koop[119], P. Kopciewicz[1], P. Koppenburg[202], M. Koratzinos[1,2], K. Kordas[285], A. Korsun[9,10,11],
O. Kortner[131], S. Kortner[131], B. Korzh[101], T. Koseki[212], J. Kosse[2], P. Kostka[1,185], S. Kostoglou[1], A.V. Kotwal[80],
G. Kozlov[1,277], I. Kozsar[1], T. Kramer[1], P. Krkotić[1], H. Kroha[131], K. Kröninger[245], S. Kuday[1,58],
G. Kuhlmann[286], O. Kuhlmann[1,287], M. Kuhn[288], A. Kulesza[289], M. Kumar[290], F. Kurian[6], A. Kurtulus[1,150],
T.H. Kwok[73], S. La Mendola[1], M. Lackner[98,291], T. Ładziński[1], D. Lafarge[1], P. Laïdouni[1], G. Lamanna[9,16,17],
N. Lamas[19], G. Landsberg[233], C. Lange[2], D.J. Lange[163], A. Langner[1], A.J. Lankford[292], L. Lari[6],
M.S. Larson[293], K. Lasocha[1], A. Latina[1], S. Lauciani[48], M. Laufenberg[105], G. Lavezzari[1], L. Lavezzi[60],
L. Lavezzo[1], M. Le Garrec[1,9,16], A. Le Jeune[102], P. Lebrun[1,294], Y. Léchevin[1], A. Lechner[1], E. Lecointe[105],
J.S.H. Lee[295], S.W. Lee[296], S.J. Lee[280,297], T. Lefevre[1], C. Leggett[141], T. Lehtinen[298], S. Leone[40],
C. Leonidopoulos[299], S. Leontsinis[73], G. Leprince-Maillère[300], G. Lerner[1], O. Leroy[9,75,76], T. Lesiak[107],
P. Levai[78], A. Leveratto[91], R. Levi[152], A. Li[6], S. Li[301,302], D. Liberati[303], G.L. Lichtenstein[47], M. Liepe[248],
Z. Ligeti[141], H. Lin[304], S. Linda[144], E. Lipeles[305], Z. Liu[306], S.M. Liuzzo[307], T. Loeliger[288],
A. Loeschcke Centeno[308], A. Lorenzetti[73], C. Lorin[3], R. Losito[1], M. Louka[12,309], M.L. Loureiro García[181],
I. Low[122,158], K. Lubonis[152], M.T. Lucchini[30,31], V. Lukashenko[73], G. Luminati[48], A.J.G. Lunt[1,310],
A. Lusiani[40,311], M. Luzum[312], H. Ma[6], A. Maas[313], E. Macchia[1,90,170], A. Macchiolo[73], G.E. Machinet[264],
R. Madar[9,154,155], T. Madlener[4], C. Madrid[23], A. Magalotti[29], M. Maggiora[60,235], A.-M. Magnan[182],
M.A. Mahmoud[314], Y. Mahmoud[315,316], F. Mahmoudi[1,9,56], H. Mainaud Durand[1], J. Maitre[108],
Y. Makhloufi[101], B. Malaescu[9,117,317], A. Malagoli[91], C.H. Malan[108], M. Malekhosseini[38], A. Maloizel[1,96,97],
S. Malvezzi[30], A. Malzac[148], G. Manco[127], L.S. Mandacarú Guerra[163], P. Manfrinetti[91,318], E. Manoni[63],
J. Mans[306], L. Mantani[319], S. Manzoni[1], L. Marafatto[167], C. Marcel[1], T. Marcel[109], R. Marchevski[114],
G. Marchiori[9,96,97], F. Mariani[44,90], V. Mariani[63,64], S. Marin[1], C. Marinas[319], V. Marinozzi[37], S. Mariotto[44,45],
C. Marquis[105], J. Martelain[320], G. Martelli[63,64], A. Martens[9,10,11], I. Martin-Melero[1],
V.I. Martinez Outschoorn[169], F. Martinez[217], C.M. Jardim[27], L. Marzola[321,322], S. Masciocchi[259,265],
A. Mashal[14], A. Masi[1], I. Masina[146,147], P. Mastrapasqua[201], V. Mateu[323], S. Mattiazzo[68,164], M. Maugis[102],
V. Maura[210], D. Mauree[144], G.H.I. Maury-Cuna[324], A. Mayoux[1], E. Mazzeo[1], S. Mazzoni[1], M. McCullough[1],
M. Meena[9,42,43], E. Meftah[101], Andrew Mehta[185], Ankita Mehta[1], B. Mele[170], R. Mena-Andrade[1], M. Mentink[1],
D. Mergelkuhl[1], V. Mertinger[268], L. Mether[1], S. Meylan[105], T. Michel[102], T. Michlmayr[2], M. Migliorati[90,170],
A. Milanese[1], C. Milardi[48], G. Milhano[51], M. Minty[6], C. Mirabelli[325], T. Miralles[9,154,155], L. Miralles Verge[1],
D. Mirarchi[1], K. Mirbaghestan[73], N. Mirian[4,326], V.A. Mitsou[319], D.S. Mitzel[245], M. Mlynarikova[1], S. Möbius[89],
M. Mohammadi Najafabadi[1,14], G.B. Mohanty[327], R.N. Mohapatra[211], S. Moneta[63], P.F. Monni[1],
E. Monnier[9,75,76], S. Monteil[9,154,155], I. León Monzón[204], F. Moortgat[1,328], N. Morange[9,10,11], M. Moretti[146,147],
S. Moretti[71], T. Mori[1,212], I. Morozov[119], A. Morozzi[63], M. Morrone[1], A. Moscariello[101], F. Moscatelli[63,329],
I. Moulin[216], N. Mounet[1], A. Mueller[330], A.-S. Müller[132], B.O. Müller[286], J. Mundet[222], E. Musa[1,4],
V. Musat[1,8], R. Musenich[140], E. Musumeci[319], M. Mylona[1], V.V. Mytrochenko[9,10,133], B. Nachman[141],
S. Nagaitsev[6], T. Nakamoto[212], M. Napsuciale[324], M. Nardecchia[90,170], G. Nardini[331], G. Narváez-Arango[332],
S. Naseem[61], A. Natochii[6], A. Navascues Cornago[1], B. Naydenov[1], G. Nergiz[1], A.V. Nesterenko[277],
C. Neubüser[333], H.B. Newman[334], F. Niccoli[1,335], O. Nicrosini[127], U. Niedermayer[228], G. Niehues[132], J. Nielsen[1],
G. Nigrelli[1,90,170], S. Nikitin[119], I.B. Nikolaev[119], A. Nisati[170], N. Nitika[167,168], J.M. No[336], M. Nonis[1],
Y. Nosochkov[7], A. Novokhatski[1,7], J.M. O'Callaghan[337], S.A. Ochoa-Oregon[204], K. Ohmi[203,212], K. Oide[1,101,212],
V.A. Okorokov[119], C. Oleari[30,31], D. Oliveira Damazio[1,6], Y. Onel[112], A. Onofre[338,339,340], P. Osland[341],
Y.M. Oviedo-Torres[342,343,344], A. Ozansoy[58], F. Ozaydin[87,345], K. Ozdemir[346], A. Ozturk[1],
M.A. Pérez de León[204], S. Pacetti[63,64], H. Pacey[8], J. Paciello[108], C.E. Pagliarone[347,348], A. Paillex[105],
H.F. Pais da Silva[1], F. Palla[40], A. Pampaloni[140], C. Pancotti[149], M. Pandurović[349], O. Panella[63],
G. Panizzo[167,168], C. Pantouvakis[68,164], L. Panwar[9,117,317], P. Paolucci[35], Y. Papa[105], A. Papaefstathiou[350],
Y. Papaphilippou[1], A. Paramonov[158], A. Pareti[127,351], B. Parker[6], V. Parma[1], F. Parodi[140,318], M. Parodi[1],
B. Paroli[44,45], J.A. Parsons[352], D. Passarelli[37], D. Passeri[63,64], B. Pattnaik[319], A. Patwa[353], C. Paus[183],
F. Pauss[150], F. Peauger[1], I. Pedraza[217], R. Pedro[51], J. Pekkanen[1], G. Peon[1], A. Perez[109], E. Perez[1], F. Pérez[171],
J.C. Perez[1], J.M. Pérez[27], R. Perez-Ramos[137,138,354], G. Pérez Segurana[1], A. Perillo Marcone[1], S. Perna[35,36],
K. Peters[4], S. Petracca[35,355], A.R. Petri[44], F. Petriello[122], A. Petrovic[1], L. Pezzotti[25], G. Piacquadio[62],
G. Piazza[180], A. Piccini[1], F. Piccinini[127], A. Pich[319], T. Pieloni[114], J. Pierlot[1], A.D. Pilkington[52], M. Pillet[325],
M. Pinamonti[167,168], N. Pinto[236], L. Pintucci[167,168], F. Pinzauti[1], K. Piotrzkowski[272], C. Pira[48], M. Pitt[1],
R. Pittau[191], S. Pittet[1], P. Placidi[63,64], W. Płaczek[356], S. Plätzer[313,357], M.-A. Pleier[6], E. Ploerer[73,116],

H. Podlech[358,359], F. Poirier[9,16,17], G. Polesello[127], M. Poli Lener[48], J. Polinski[161], Z. Polonsky[73], N. Pompeo[29], M. Pont[171], G. Alexandru-Popeneciu[360], W. Porod[196], L. Porta[1], L. Portales[3], T. Portaluri[308], M.A.C. Potenza[45], C. Prasse[286], E. Premat[184], M. Presilla[132], S. Prestemon[141], A. Price[356], M. Primavera[159], R. Principe[1], M. Prioli[44], F.M. Procacci[12], E. Proserpio[44,134], A. Provino[91,318], C. Pueyo[1], T. Puig[19], N. Pukhaeva[277], S. Pulawski[206], G. Punzi[40,77], A. Pyarelal[361], J. Qian[304], H. Quack[362], F.S. Queiroz[47], G. Quintas-Neves[300], H. Rafique[71], J.-Y. Raguin[2], J. Raidal[321], M. Raidal[321], P. Raimondi[37], A. Rajabi[4], S. Ramírez-Uribe[204], S. Randles[185], T. Rao[6], C.Ø. Rasmussen[6], A. Ratkus[363], P.N. Ratoff[53,364], P. Razis[365,366], P. Rebello Teles[1,367], M.N. Rebelo[129], M. Reboud[9,10,11], S. Redaelli[1], C. Regazzoni[105], L. Reichenbach[1,368], M. Reissig[132], E. Renou[105], A. Rentería-Olivo[319], J. Reuter[4], S. Rey[105], A. Ribon[1], D. Ricci[1], W. Riegler[1], M. Rignanese[68,164], S. Rimjaem[369], R.A. Rimmer[370], R. Rinaldesi[1], L. Rinolfi[1,294], O. Rios[1], G. Ripellino[130], B. Rivas[371], A. Rivetti[60], T. Robens[372], F. Robert[184], E. Robutti[140], C. Roderick[1], G. Rodrigo[319], M. Rodríguez-Cahuantzi[217], L. Röhrig[154,155,245], M. Roig[373], F. Rojat[108], J. Rojo[202,374], J. Roloff[233], P. Roloff[1], A. Romanenko[37], A. Romero Francia[1], H. Romeyer[375], N. Rompotis[185], N. Rongieras[102], G. Rosaz[1], K. Roslon[376], M. Rossetti Conti[44], A. Rossi[63,64], E. Rossi[35,36], L. Rossi[44,45], A.N. Rossia[68,164], S. Rostami[38], G. Roy[1], B. Rubik[37], I. Ruehl[1], A. Ruiz-Jimeno[377], R. Ruprecht[132], J.P. Rutherfoord[361], L. Rygaard[4], M.S. Ryu[296], L. Sabato[1,114], G. Sadowski[9,42,43], D. Saez de Jauregui[132,378], M. Sahin[379], A. Sailer[1], M. Saito[380], P. Saiz[1], G.P. Salam[381,382], R. Salerno[9,81,82], T. Salmi[298], B. Salvachua[1], J.P.T. Salvesen[1,8,136], B. Salvi[300], D. Sampsonidis[285], Y. Villamizar[137,138,139], C. Sandoval[332], S. Sanfilippo[2], E. Santopinto[140], R. Santoro[44,134], X. Sarasola[114], L. Sarperi[288], I.H. Sarpün[383], S. Sasikumar[1], M. Sauvain[384], A. Savoy-Navarro[3,9], R. Sawada[380], G. Sborlini[385], J. Scamardella[35,36], M. Schaer[2], M. Schaumann[1,4], M. Schenk[1], C. Scheuerlein[1], C. Schiavi[140,318], A. Schloegelhofer[1], D. Schoerling[1], A. Schöning[265], S. Schramm[101], D. Schulte[1], P. Schwaller[252,386], A. Schwartzman[7], P. Schwemling[3], R. Schwienhorst[387], A. Sciandra[6], L. Scibile[1], I. Scimemi[388], E. Scomparin[60], C. Sebastiani[1], B. Seeber[389], J.T. Seeman[7], F. Sefkow[4], M. Seidel[2,114], S. Seidel[74], J. Seixas[340,390,391], N. Selimović[68], M. Selvaggi[1], C. Senatore[101], A. Senol[195], N. Serra[73], A. Seryi[370], A. Sfyrla[101], Pramond Sharma[392], Punit Sharma[6], C.J. Sharp[1], L. Shchutska[114], V. Shiltsev[393], M. Siano[44,45], R. Sierra[1], E. Silva[29], R.C. Silva[47,344], L. Silvestrini[170], F. Simon[132], G. Simonetti[1], R. Simoniello[1], B.K. Singh[394], S. Singh[6], B. Singhal[79], A. Siodmok[1,356], Y. Sirois[9,81,82], E. Sirtori[149], B. Sitar[395], D. Sittard[1], E. Sitti[150], T. Sjöstrand[59], P. Skands[396], L. Skinnari[293], K. Skoufaris[1], K. Skovpen[328], M. Skrzypek[107], P. Slavich[137,138,139], V. Slokenbergs[23], V. Smaluk[6], J. Smiesko[1,397], S.S. Snyder[6], E. Solano[171], P. Sollander[1], O.V. Solovyanov[1,9,154], M. Son[398], F. Sonnemann[1], R. Soos[1,9,10], F. Sopkova[190], T. Sorais[399], M. Sorbi[44,45], S. Sorti[44,45], R. Soualah[400], M. Souayah[1], L. Spallino[48], S. Spanier[401], P. Spiller[259], M. Spira[2], D. Stagnara[102], M. Stallmann[187], D. Standen[1], J.L. Stanyard[1], B. Stapf[1], G.H. Stark[231], M. Statera[44], C. Staudinger[1,205], B.A. Stefanek[402], G. Streicher[403], N.P. Strohmaier[2], R. Stroynowski[106], S. Stucci[6], G. Stupakov[7], S. Su[361], A. Sublet[1], K. Sugita[259], M.K. Sullivan[7], S. Sultansoy[24], D. Sutherland[179], I. Syratchev[1], R. Szafron[6], A. Sznajder[404], W. Tachon[405], N.D. Tagdulang[37,171,337], N.A. Tahir[259], Y. Takahashi[123], J. Tamazirt[9,10,11], S. Tang[6], Y. Tanimoto[212], I. Tapan[275], G.F. Tassielli[12,406], A.M. Teixeira[9,154,155], V.I. Telnov[119], H.H.J. Ten Kate[1,407], V. Teotia[6], J. ter Hoeve[299], A. Thabuis[1], G.T. Telles[19], A. Tishelman-Charny[6], S. Tissandier[108], S. Tizchang[14,408], J.-P. Tock[1], B. Todd[1], L. Toffolin[1,167,409], A. Tolosa-Delgado[1], R. Tomás García[1], T. Tomasini[410], G. Tonelli[40,77], T. Tong[411], F. Toral[27], T. Torims[1,363], L. Torino[171], K. Torokhtii[29], R. Torre[140], E. Torrence[412], R. Torres[53,185], T. Mitsuhashi[212], A. Tracogna[149], O. Traver[171], D. Treille[1], A. Tricoli[6], P. Trubacova[1], E. Tsesmelis[1], G. Tsipolitis[269], V. Tsulaia[141], B. Tuchming[3], C.G. Tully[163], I. Turk Cakir[58], C. Turrioni[63], J. Tynan[105], F.P. Ucci[127,351], S. Udongwo[413], C.S. Ün[275], A. Unnervik[1], A. Upegui[99,100], J.P. Uribe-Ramírez[204], J. Uythoven[1], R. Vaglio[36,91], F. Valchkova-Georgieva[414], P. Valente[170], R.U. Valente[170], A.-M. Valente-Feliciano[370], G. Valentino[1,193], C.A. Valerio-Lizarraga[204,324], S. Valette[1], J.W.F. Valle[319], L. Valle[1], N. Valle[127], N. Vallis[1,2,114], G. Vallone[141], P. van Gemmeren[158], W. Van Goethem[1], P. van Hees[59], U. van Rienen[413], L. van Riesen-Haupt[1,114], P. Van Trappen[1], M. Vande Voorde[415,416], A.L. Vanel[1], E.W. Varnes[361], J.-L. Vay[141], F. Veit[286], I. Veliscek[6], R. Veness[1], A. Ventura[159,232], S. Verdú-Andrés[6], M. Verducci[40,77], C.B. Verhaaren[417], C. Vernieri[7], A.P. Verweij[1], J.-F. Vian[418], A. Vicini[44,45], N. Vignaroli[159,232], S. Vignetti[149], M.C. Villeneuve[220], I. Vivarelli[25,26], E. Voevodina[1,131], D.M. Vogt[419], B. Voirin[420], S. Voiriot[105], J. Voiron[144], P. Vojtyla[1], V. Völkl[1], L. von Freeden[1], Z. Vostrel[1,421], N. Voumard[1], E. Vryonidou[52], V. Vysotsky[119], R. Wallny[150], L.-T. Wang[422], Y. Wang[9,10,11], R. Wanzenberg[4], B.F.L. Ward[423], N. Wardle[182], Z. Wąs[107], L. Watrelot[1], A.T. Watson[424], M.F. Watson[424], M.S. Weber[89], C.P. Welsch[53,185], M. Wendt[1,6], J. Wenninger[1], B. Weyer[1], G. White[425], S. White[307], B. Wicki[1], M. Widorski[1], U.A. Wiedemann[1], A.R. Wiederhold[52], A. Wiedl[132], H.-U. Wienands[158], A. Wieser[150], C. Wiesner[1], H. Wilkens[1], D. Willi[426], P.H. Williams[53,427], S.L. Williams[32], A. Winter[424], R.B. Wittwer[73], D. Wollmann[1], Y. Wu[114], Z. Wu[9,16,17], J. Xiao[9,56,57], K. Xie[387], S. Xie[37,334], M. Yalvac[22], F. Yaman[427,428], W.-M. Yao[141], M. Yeresko[9,154,155], A. Yilmaz[195], H.D. Yoo[276], T. You[210], F. Yu[252,386], S.S. Yu[79], T.-T. Yu[412], S. Yue[1], A. Zaborowska[1], M. Zahnd[105], C. Zamantzas[1], G. Zanderighi[65,131], C. Zannini[1], R. Zanzottera[44,45], P. Zaro[102], R. Zennaro[2], M. Zerlauth[1], H. Zhang[203], J. Zhang[158], Y. Zhang[203], Z. Zhang[9,10,203], Y. Zhao[1], Y.-M. Zhong[429], B. Zhou[304], D. Zhou[212], J. Zhu[304], G. Zick[373], M.A. Zielinski[1], E. Zimmermann[105], A. Zingaretti[68,164], J. Zinn-Justin[3], A.V. Zlobin[37], M. Zobov[48], F. Zomer[9,10,11], S. Zorzetti[37], X. Zuo[132], J. Zurita[319], V.V. Zutshi[393], and M. Zykova[2]

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Abstract Volume 3 of the FCC Feasibility Report presents studies related to civil engineering, the development of a project implementation scenario, and environmental and sustainability aspects. The report details the iterative improvements made to the civil engineering concepts since 2018, taking into account subsurface conditions, accelerator and experiment requirements, and territorial considerations. It outlines a technically feasible and economically viable civil engineering configuration that serves as the baseline for detailed subsurface investigations, construction design, cost estimation, and project implementation planning. Additionally, the report highlights ongoing subsurface investigations in key areas to support the development of an improved 3D subsurface model of the region. The report describes the development of the project scenario based on the 'avoid-reduce-compensate' iterative optimisation approach. The reference scenario balances optimal physics performance with territorial compatibility, implementation risks, and costs. Environmental field investigations covering almost 600 hectares of terrain—including numerous urban, economic, social, and technical aspects—confirmed the project's technical feasibility and contributed to the preparation of essential input documents for the formal project authorisation phase. The summary also highlights the initiation of public dialogue as part of the authorisation process. The results of a comprehensive socio-economic impact assessment, which included significant environmental effects, are presented. Even under the most conservative and stringent conditions, a positive benefit-cost ratio for the FCC-ee is obtained. Finally, the report provides a summary of the studies conducted to document the current state of the environment.

Note from the Editors One of the recommendations of the 2020 update of the European Strategy for Particle Physics was that "Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

In June 2021, the CERN Council launched the FCC Feasibility Study to be completed by 2025, in time for the next update of the European Strategy for Particle Physics. The study results are made publicly available through this FCC Feasibility Study Report, as input to the European Particle Physics Strategy update process, initiated by the CERN Council in March 2024. The studies presented in this FCC Feasibility Study Report do not imply any commitment by the CERN Member or Associate Member States to build the Future Circular Collider.

This report and the assumptions contained in it do not prejudge further territorial feasibility analysis by the Host States, France and Switzerland, as well as the outcome of their respective public debate and concertation processes, and future decisions of their relevant authorities.

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Preface from CERN's Director-General In 2021, in response to the 2020 update of the European Strategy for Particle Physics, the CERN Council initiated the Future Circular Collider (FCC) Feasibility Study.

This report summarises an immense amount of work carried out by the international FCC collaboration over several years. It covers, inter alia, physics objectives and potential, geology, civil engineering, technical infrastructure, territorial implementation, environmental aspects, R&D needs for the accelerators and detectors, socio-economic benefits and cost. It constitutes important input for the ongoing update of the European Strategy for Particle Physics.

The Feasibility Study required engagement with a broad range of stakeholders. In particular, throughout the Study, CERN has been accompanied by its two Host States, France and Switzerland, and has been working with entities at local, regional and national level. I am very grateful to the Host State authorities and teams for their invaluable help. Furthermore, significant sections of the Study were supported by the European Union under the Horizon 2020 and Horizon Europe framework programmes. The Study also greatly benefited from contributions from accelerator laboratories and universities from across Europe, such as the Swiss Accelerator Research and Technology (CHART) initiative, and from the Americas, Asia, Africa and Australia.

The proposed FCC integrated programme consists of two possible stages: an electron–positron collider serving as a Higgs-boson, electroweak and top-quark factory running at different centre-of-mass energies, followed at a later stage by a proton–proton collider operating at an unprecedented collision energy of around 100 TeV. The complementary physics programmes of each stage match the physics priorities expressed in the 2020 update of the European Strategy for Particle Physics.

A major achievement of the Feasibility Study is the choice of placement of the collider ring and the entire infrastructure, including the surface sites and the access shafts, which was developed and optimised over several years following the principle 'avoid, reduce, compensate'. Sustainability studies have assessed energy efficiency, land use, water and resource management, and socio-economic impact, ensuring that the FCC is designed in accordance with the latest environmental and societal standards.

I would like to thank all contributors to this report for their hard work and commitment, which allowed the outstanding results presented here to be achieved.

Fabiola Gianotti
CERN, Director-General

Preface from the FCC Collaboration Board Chair Building on the earlier Future Circular Collider (FCC) Conceptual Design Study conducted between 2014 and 2018, the FCC Feasibility Study (2021–2025) has been undertaken by a robust international collaboration, now comprising over 160 institutes worldwide. The FCC 'integrated programme', developed in the framework of the Feasibility Study, consists of an initial electron-positron collider, the FCC-ee, which could be followed by a proton-proton collider, the FCC-hh. This staging takes into account the physics priorities as formulated in the updates of the European Strategy for Particle Physics of 2012 and 2020, as well as the relative technology readiness and costs of the FCC-ee and FCC-hh.

Over the years, I have closely followed the steady progress of the study, representing the FCC collaboration at the international steering committee and participating in annual FCC Week meetings, which include sessions of the International Collaboration Board. The commitment and enthusiasm of the members of the collaboration has always been impressive. The collective effort is clearly visible. Participation by students and early-career researchers is increasing. There is a shared determination and momentum to move forward.

The strong international collaboration around the FCC and its global network provides a solid foundation for the future of this project. The FCC community continues to grow, with increasing engagement from new institutes and partners worldwide. This broad support will be essential as the project enters its next phase.

The FCC Feasibility Study demonstrates not only the technical viability of the project, but also the strength of the international community that supports it. As we move towards the next step in the decision-making phase, this collective effort is key to showing a possible path forward. The FCC promises far-reaching scientific opportunities and long-term benefits for innovation, training, and global collaboration in science and technology.

Philippe Chomaz
CEA, Chair of the FCC International Collaboration Board

Contents

1 Civil engineering
  1.1 Introduction
  1.2 Underground structures
  1.3 Surface structures
  1.4 Staged approach
  1.5 Subsurface site investigations
  1.6 Management of excavated materials
2 Territorial implementation
  2.1 Introduction
  2.2 Methodology to develop a sustainable project
  2.3 Requirements and invariants
  2.4 Territorial constraints
  2.5 Initial variants
  2.6 Reference scenario
  2.7 Territorial infrastructure needs
3 Environment
  3.1 Context
  3.2 Environmental aspects
  3.3 Current state of the environment
  3.4 Conclusion
4 Sustainability
  4.1 Context
  4.2 Introduction
  4.3 Methodology
  4.4 Socio-economic sustainability enablers
  4.5 Comprehensive sustainability performance assessment based on Cost-Benefit Analysis
  4.6 Limitations
  4.7 Lifecycle analysis
  4.8 Socio-economic performance
  4.9 Returns to participating countries
  4.10 Requirements and constraints for a preparatory phase
  4.11 Recommendations for a preparatory phase project
References

Chapter 1

Civil engineering

1.1 Introduction

Since the completion of the FCC conceptual design in 2018, several significant modifications have been made to civil engineering. They derive from the improved maturity of requirements for the systems that interface with civil engineering, such as the accelerators, the detectors, and the technical infrastructure to be housed within the underground and surface structures. Furthermore, more precise localisation of the surface sites has facilitated a greater understanding of the geographical and environmental constraints to be accounted for in the development of the civil engineering infrastructure. The main improvements that have occurred since the conceptual design of the underground civil engineering required for the FCC-ee collider was completed are as follows:

- A reduction in the overall circumference of the accelerator tunnel from 97.8 km to 90.6 km.
- A reduction in the number of surface sites (and access points to the underground) from 12 to 8.
- A reduction in the number of permanent shafts needed for operation from 18 to 12.
- A reduction of the depth to the deepest shaft from 578 m to 400 m.
- Additional underground civil engineering for the RF systems at technical sites PH and PL.
- A simplification of the civil engineering needed for the beam absorber system.
- Simplification of the underground infrastructure required for the beam transfer lines, with the use of a single tunnel to house both clockwise and anti-clockwise transfer to the FCC.

In addition to the above, a more detailed—yet still evolving—understanding of the requirements for surface civil engineering has been built up. Initial spatial arrangements for all eight surface sites have been developed, with preliminary dimensioning of the necessary buildings, roads, and other surface infrastructure providing a framework for further refinement. For two of the eight sites, and under a collaboration with the U.S. Fermi National Accelerator Laboratory, preliminary design studies for buildings have been carried out. The results offer valuable insights into space requirements, user access needs and cost envelopes. They were mainly informed by the technical needs of the interfacing systems. The integration of the 'Avoid, Reduce, Compensate' approach to develop the surface sites is an iterative process, requiring continued efforts to understand the technical needs, the territorial requirements and constraints and the project cost and risk implications. Understanding the technical system requirements is an essential guiding element. The analysis of the current state of the environment also carried out in the frame of the feasibility study, is another aspect that will inform the subsequent activities.

A staged approach to civil engineering has been studied. Infrastructure essential for the operation of the FCC-ee collider and its associated experiments is included within the initial stage, along with any civil engineering needed for FCC-hh for which it would be impossible, impractical, or inefficient to construct during a second stage. This staged approach primarily concerns the surface infrastructure since it is relatively straightforward to construct additional buildings in a second stage.

The civil engineering for the FCC-ee, as defined in this document, builds on the studies completed for the conceptual design phase and carried out for the feasibility phase. The current design demonstrates the technical feasibility of FCC civil engineering. It is to be noted, however, that there are still areas where further work needs to be done in order to reduce technical risks, in particular taking into account the remaining data that will be provided upon completion of phase 1 of the sub-surface site investigations that commenced in October 2024 and is expected to be completed before the end of 2025.

The work carried out since the completion of the conceptual design has largely maintained similar spatial elements for the underground works (sizes of caverns, shafts, tunnels, etc.), and therefore, it has not been necessary to undertake additional calculations for the overall structural stability of these elements. Furthermore, the construction methodologies remain largely as identified during the conceptual design phase, although the sequence for undertaking the works has now been revised, in particular, to account for the reduced number of access points to the underground civil engineering.

A key input to the feasibility study has come from the early interaction between the FCC civil engineering team and potential future stakeholders from the industry. CERN has held a number of meetings and workshops with several major contractors specialising in underground civil engineering. The feedback received has proved invaluable in developing not only robust technical solutions but also a realistic and efficient schedule for the execution of civil engineering. Feedback from the industry has also helped shape CERN's initial thinking on potential contractual routes for the delivery of the design and construction of civil engineering. The civil engineering schedule developed as part of the feasibility study has been integrated with the subsequent infrastructure and machine installation activities. The resulting integrated schedule results in a gradual handover of the civil engineering for each of the eight sectors, thus allowing parallel and more efficient execution of installation activities in the main tunnel.

1.2 Underground structures

Several improvements have been made to the underground structures since the conceptual design report was completed. A thorough identification has been made of the underground structures necessary for the FCC-ee collider as well as those for the FCC-hh collider, which cannot be deferred. The latter will be constructed as part of the civil engineering necessary for the FCC-ee collider and associated experiments.

A Product Breakdown Structure (PBS) has been produced down to level 4, containing 205 uniquely identified structures. Table 1.1 lists the PBS and associated structures for the sector PA to PB. The PBS of other sectors follow a similar structure. In total, the underground civil works consist of twelve permanent shafts for operation, one temporary shaft required only during the civil engineering construction, twelve large caverns with spans exceeding

Table 1.1 PBS for sector PA to PB underground structures

PBS Level					PBS Description
0	1	2	3	4	
	2				**Civil engineering**
	2	**3**			**Underground structures**
	2	**3**	**1**		**Site PA**
	2	3	1	1	Experiment shaft
	2	3	1	2	Service shaft
	2	3	1	3	Experiment cavern
	2	3	1	4	Service cavern
	2	3	1	5	Alcoves
	2	3	1	6	Beam tunnel sector AB
	2	3	1	7	Bypass tunnel AL
	2	3	1	8	Bypass tunnel AB
	2	3	1	9	Connection tunnels and galleries
	2	3	1	10	Tunnel widenings

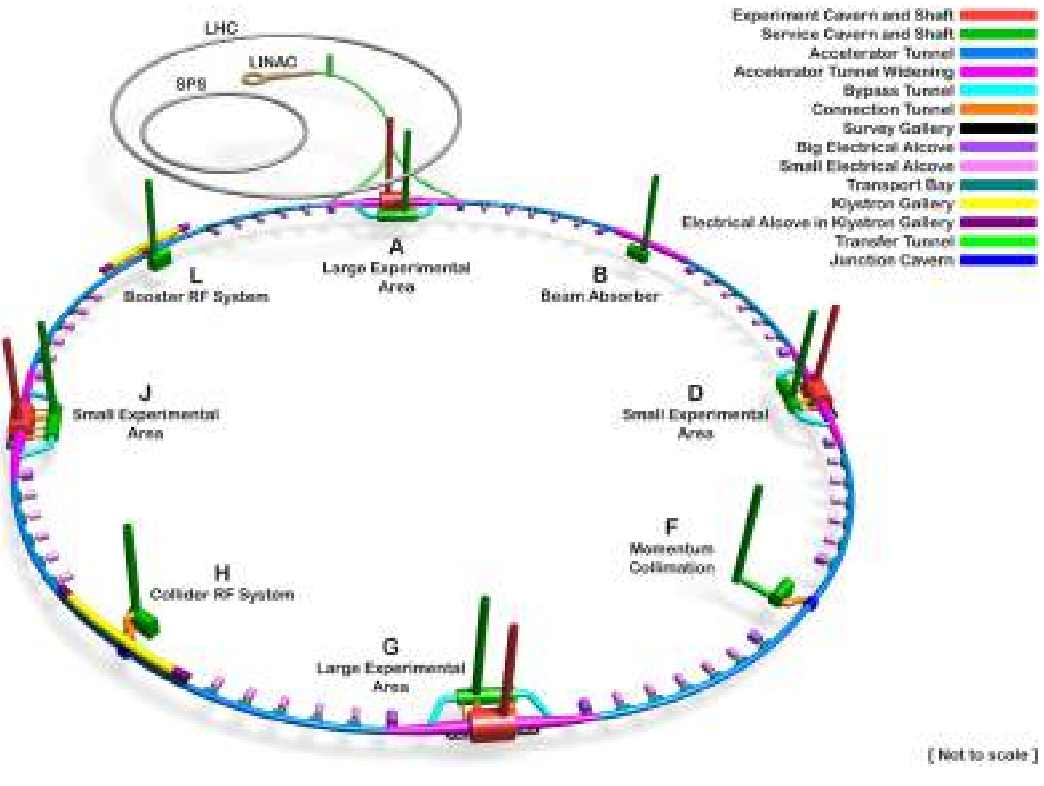


Fig. 1.1 Schematic layout of FCC-ee underground civil engineering

20 m as well as numerous smaller caverns, alcoves, connection and bypass tunnels that collectively make up the underground civil engineering. Figure 1.1 shows a schematic arrangement of underground civil engineering.

The overall circumference of the accelerator tunnel that will house the colliders is 90.6 km, a reduction of about 7% compared to the 97.8 km tunnel developed at the conceptual design phase. The accelerator tunnel, which will house the collider, has an internal nominal diameter of 5.5 m. On the basis of the pre-existing and recent site investigation data, the average elevation is 300 m above datum and the inclination of the tunnel plane has been maintained at 0.1% and 0.4% in the two axes. This results in a tunnel depth that varies between 30 m where the tunnel passes under the Rhône river and 560 m where the tunnel passes under the Borne plateau on the eastern side of the overall study site. The average depth of the tunnel is approximately 240 m below the ground surface.

Two sizes of experiment cavern complexes are envisaged; these are similar in layout and function. The first type includes a cavern to house the largest planned FCC-hh detector with a 35 m span (similar to that of the existing ATLAS detector cavern) and the second type includes a cavern to house the smaller FCC-hh detectors with a span of 25 m (similar to that of the existing CMS detector cavern).

A single transfer tunnel connecting the injection system to the FCC is envisaged. This tunnel starts close to the surface of the existing CERN Prévessin site where it will connect to the cut and cover tunnel that will house the high-energy LINAC. The tunnel will descend over a distance of about 5 km at which point it will bifurcate at a location close to PA to allow symmetrical clockwise and anticlockwise injection into the FCC. The injection will take place on either side of the experiment area located in PA.

Expectations regarding the geology to be encountered during the civil engineering of the underground structures are consistent with those established during the conceptual design phase of the FCC-ee study, providing a solid foundation for further refinement and risk mitigation in subsequent phases. The current expectation is that the majority of the tunnels and the cavern complexes will be located within the molasse rock, a low to medium-strength sedimentary rock made up of complex sequences of marls and sandstones. This material is well suited for tunnelling since it is typically watertight and can be supported through the implementation of a range of standard rock support measures such as rock bolts, shotcrete, reinforced concrete segments etc. Larger caverns can become more challenging and will require more complex methods for the excavation and support of the rock mass. This is further detailed in Sect. 1.2.5.

The accelerator tunnel will pass through approximately 4.4 km of limestone rock. Whilst it will certainly be possible to excavate the rock by either tunnel boring machine or traditional drill and blast methods, this rock mass may contain large interconnected voids (karsts) with water and silt, potentially under high pressure. Specific construction measures may be needed in this area, as presented in Sect. 1.2.1. Placement optimisation of the underground structures has ensured that the location of larger underground structures, such as caverns and shafts, avoids areas where limestone formations are likely to be encountered. This will require careful review at the conclusion of the ongoing site investigation campaign. The shafts will need to be excavated through varying depths of so-called moraine strata before the molasse rock is reached. This stratum is a mix of clays, sands, gravels and boulders. It is known to contain aquifers.

CERN has over 40 years of experience in managing projects that involve the construction of tunnels, shafts, and caverns in the molasse rock and, therefore, has the experience and knowledge to undertake the FCC civil engineering. Some aspects, as listed below, will be challenging but nonetheless well within the capabilities of many Member States civil engineering contractors.

- The average depth at which the underground structures will be constructed is about three times greater than the average depth of the LHC tunnel. This will present higher ground stresses that will need to be considered in the design of the underground structures and when selecting the construction methodologies to be used. Proven engineering solutions will be applied to effectively mitigate potential challenges, such as ground deformation, and ensure the smooth operation of the tunnel boring machine.
- The tunnel will need to pass through a zone of so-called ‘molasse charrié’ a geological formation with different characteristics compared to the molasse rock in which CERN’s existing underground structures were constructed. These factors will be carefully addressed in the design and construction methodology to ensure a safe and efficient excavation process.
- The tunnel will pass through several kilometres of limestone, which may contain water at high pressure. Similar conditions were encountered during the construction of the LEP tunnel, providing valuable insights into mitigation measures. Careful consideration will need to be given to the tunnel design, selection of tunnelling methods and the provision of ground treatment ahead of the tunnelling face in this zone of limestone rock. Modern engineering solutions, coupled with CERN’s experience, ensure that potential challenges are well understood and can be managed effectively.
- The tunnel will pass under Lac Léman. As far as possible, the tunnel horizon will be kept within the molasse rock. If this is not possible then alternative tunnelling techniques for traversing water-bearing sands/gravel/silts will need to be used, such as earth pressure balance tunnel boring machines or so-called slurry tunnel boring machines).
- It is likely that during the construction of some shafts, water-bearing moraine strata will need to be traversed before reaching the more favourable moraine rock. Again, this will require the use of specialised construction methodologies such as diaphragm walls or ground freezing.

Although some aspects of the civil engineering underground construction will be technically more challenging than previous CERN construction projects, it is considered that the underground civil engineering structures can be designed and constructed using existing, proven, conventional techniques, including CERN’s extensive experience in underground construction. This consideration is supported by the technical discussions that CERN has held with tunnelling contractors.

The constraints arising from the large-scale geological environment on underground civil engineering, as described in the conceptual design report, are still largely valid. It is to be noted, however, that the reduction in

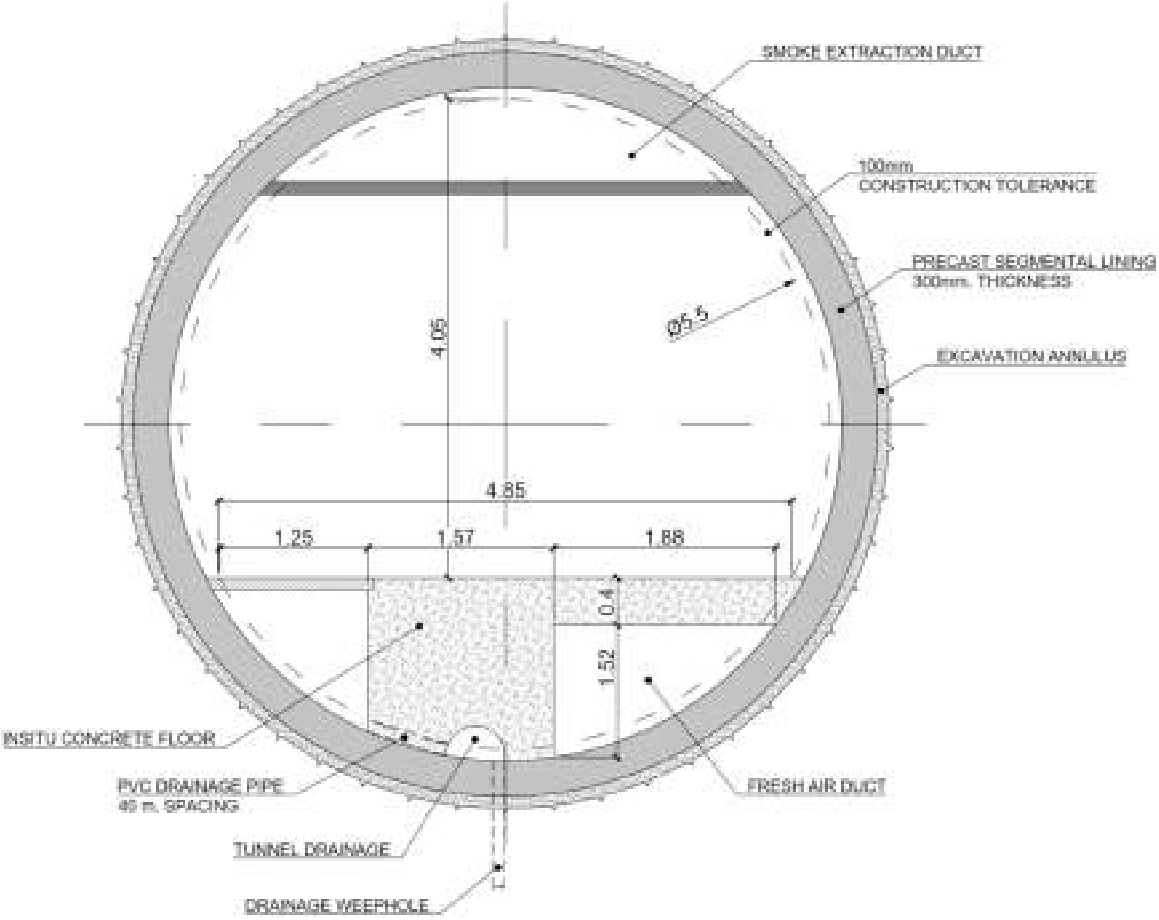


Fig. 1.2 Accelerator tunnel cross-section

the circumference of the collider and accelerator tunnel has resulted in a higher probability that the tunnel can be predominantly located in the favourable molasse rock due to the general displacement of the tunnel away from the limestone regions associated with the Jura, Vuache and Mandallaz outcrops. Again, this should be confirmed with the completion of the ongoing site investigations.

1.2.1 Accelerator tunnel

The majority of the 90.6 km circumference FCC tunnel alignment consists of a 5.5 m internal diameter tunnel, as illustrated in Fig. 1.2. There are eight sectors, each approximately 11.3 km in length. The majority of each sector consists of an arc of a radius of 14.5 km.

The accelerator tunnel houses the beam and service infrastructure, as well as a transport corridor. The current design of the tunnel assumes that where tunnel boring machines (TBMs) are used for excavation, a precast reinforced concrete segmental lining will be used to support the tunnel. In areas where TBMs will not be employed, primary support consisting of rock bolts and fibre-reinforced shotcrete will be used with a secondary cast in-situ concrete lining. The tunnel floor is to be cast in-situ concrete and installed over void formers for the tunnel drainage and the fresh air duct. Access chambers for the drainage network will be spaced every 100 metres along the tunnel. To ensure that the internal diameter is at least 5.5 m for the integration of technical infrastructure, the accelerator tunnel will be constructed with a tolerance envelope of 100 mm.

The installation of the precast segmental lining that supports the ground is carried out automatically from within the TBM. CERN has discussed with a European TBM manufacturer the potential machine requirements for the construction of FCC. They stated that either a double shield or single shield TBM (like that shown in Fig. 1.3) could be utilised.

A typical benefit of a double shield TBM over a single shield is the increased speed of construction, this is because the machine can simultaneously excavate the ground and install the segmental tunnel lining. Conversely,

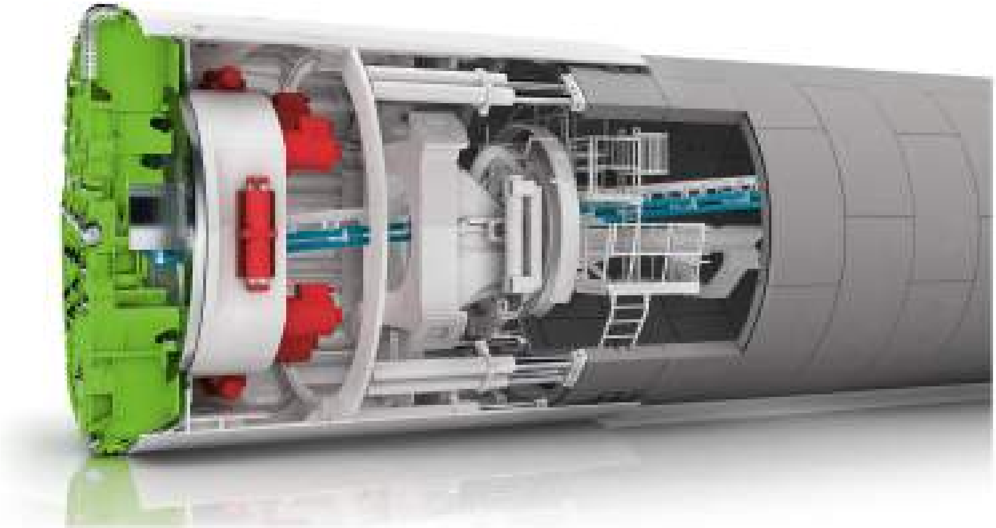


Fig. 1.3 Single shield TBM. Source: Herrenknecht

a single-shield machine requires these two phases to occur sequentially. A double-shield machine is also better suited and more adaptable to variable geology and unstable ground.

However, the increased complexity of the double shield machine TBM leads to greater capital cost, higher maintenance demand and increased risk of TBM breakdown, when compared to single shield TBM.

Feedback from civil engineering contractors specialised in tunnelling indicates that in the relatively stable molasse rock of the FCC a single shield TBM could be a more cost-effective solution. Furthermore, the increased speed of construction offered by a double shield machine may not actually be achieved, since the logistics of material delivery and spoil extraction at the shafts, and over the long tunnelling distances, would be more of a constraint to the TBM advance rate than the capability of the machine itself.

Whilst the majority of tunnel excavation will be within the molasse rock, which lends itself to TBM excavation, as detailed above, a specifically designed TBM may be used for the 4.4 km section of Mandallaz limestone likely to be encountered in the sector PG to PH. This TBM, which would be designed for soft and hard rock conditions, would also have the capability to probe ahead of the tunnel face and provide a real-time assessment of the ground conditions in front of the TBM. The machine would have the capability to inject cement-based grout ahead of the excavation to reduce the risk of ground collapse and water inflow. To take account of the potential difficulties that may be encountered in the limestone, the TBM advance rate has been reduced from an average of 16 m/day to 9 m/day in the construction schedule.

If not excavated by a TBM, this section of limestone would need to be excavated by drill and blast. This is a conventional tunnelling technique involving the use of explosives to excavate the rock face. Depending on the condition of the limestone in this area, additional ground treatment may be required ahead of the tunnel face to prevent water ingress during excavation. The ongoing site investigations will characterise the composition of the limestone along the FCC alignment and, therefore, provide greater certainty of the tunnelling conditions.

For the current feasibility study, it has been assumed that a single-pass precast lining will be the most efficient and effective ground support system, as this is the fastest and most cost-effective construction method. In the case that future site investigations reveal more challenging ground conditions than those that have been assumed, then a review of the tunnel support system will need to be carried out. Where necessary, a more appropriate ground support system, consisting of a drained, reinforced concrete in-situ lining, may be required.

Table 1.2 shows the excavation and lining parameters assumed for the feasibility study.

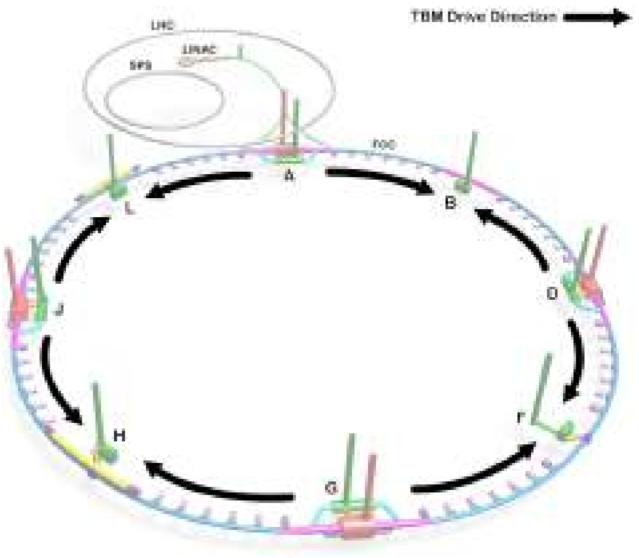
The current assumption for the start and finish sites for each of the TBMs is shown in Fig. 1.4. The main advantage of this arrangement is that it allows an earlier completion of the technical sites because these do not have TBM installation or deinstallation activities associated with them. This is a major benefit as it allows earlier installation of the infrastructure and accelerator components in the underground areas. Further benefits of this approach are:

- TBMs are large and heavy machines and as such cannot easily be manipulated in the confined spaces of an underground worksite. To install a TBM takes four to six months and requires a cavern large enough to allow the installation. At the four experiment sites, the two large caverns and the long, widened sections of the main beam tunnel can be used for the installation and commissioning of the TBMs.

Table 1.2 Proposed TBM excavation and lining parameters

Parameter	Properties
Minimum internal diameter (m)	5.5
Characteristic concrete compressive strength for pre-cast concrete, fck (MPa)	50
Pre-cast concrete thickness (m)	0.30
Reinforcement density for steel fibre reinforced pre-cast concrete (kg/m^3)	35
Reinforcement density for steel bar reinforced pre-cast concrete (kg/m^3)	80
Gasketed segments	yes
Total radial construction tolerance (m)	0.10
Excavation diameter	6.6

Fig. 1.4 Proposed arrangement of TBM drives



- The presence of a shaft located directly above the axis of the main beam tunnel gives a significant advantage for the installation of the TBM. It enables the TBM to be installed in relatively large pieces, thereby reducing installation time.
- Provision of two shafts, each capable of providing the necessary logistics and services to support a TBM (transport of people, spoil removal, material, power, water etc.), provides a level of redundancy since, if one shaft is out of action, work can continue via the second shaft.
- Two shafts provide better provision for the evacuation of people in case of an accident or an emergency when access to one shaft may not be possible.
- Concentrating the underground civil engineering at the four experiment sites will allow the four technical sites to have a reduced impact on the local community and the local environment (less dust, noise, traffic etc.).

CERN commissioned a study into the safety, ventilation, and logistics aspects of the FCC construction to address concerns that the 5.5 m internal diameter tunnel and 11 km TBM drives would present significant safety and logistical risks, particularly with only a single means of access and egress. It was demonstrated that using currently available technology, the tunnel could be constructed safely, and the assumed TBM advance rate could be achieved. Ventilation requirements were shown to be met over the full length of the tunnel, with ducting and fan specifications calculated to supply adequate fresh air to the excavation front. Finally, safety measures were outlined to ensure that construction activities would meet the required standards both nationally and internationally. An example of the tunnel cross-section during construction is shown in Fig. 1.5. An example of the safety refuge chambers specified in the study is shown in Fig. 1.6.

To accommodate the separation of the e^+ and e^- beams of the FCC-ee machine near the detector locations and the need to maintain space for the booster ring, the accelerator tunnel requires enlargement on each side of the experiment caverns at PA, PD, PG, and PJ. There are a total of 8 tunnel enlargement areas, which extend for 1.1 km on either side of the experiment caverns. To minimise construction costs and optimise efficiency, the enlargements will be created in a stepped design, as shown in Fig. 1.7.

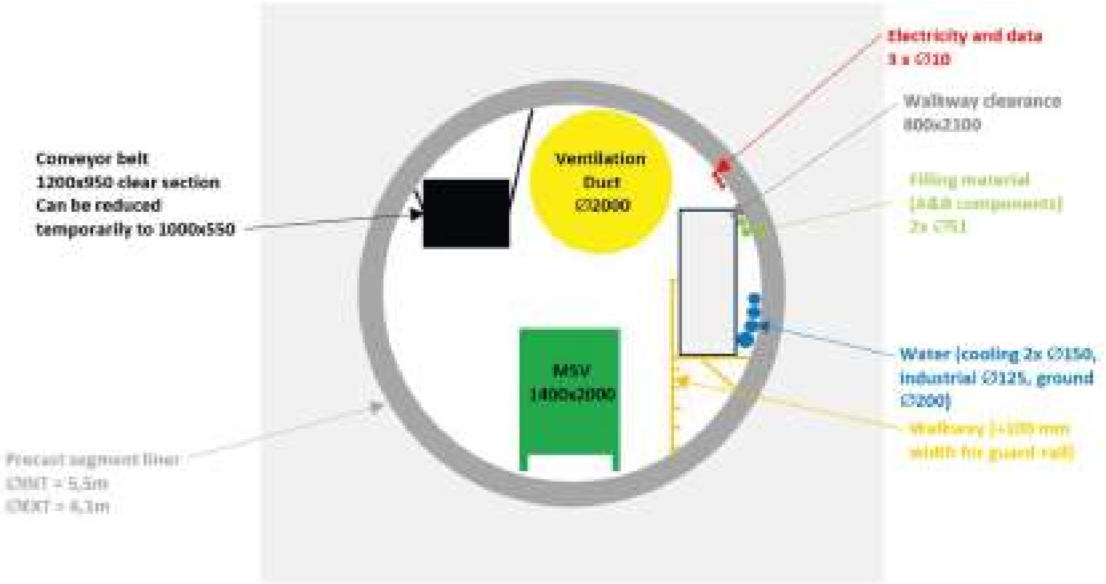


Fig. 1.5 Cross-section of the accelerator tunnel during construction. Credit: Amberg

Fig. 1.6 Example refuge chamber placed at the back of the TBM. Credit: mineARC

The widened tunnel sectors are split into 6 sections on either side of the experiment cavern, ranging from 18.6 m to 14.5 m in span and section lengths varying between 20 and 160 m. A seventh sector of widening tapers from 14.5 m span to the regular 5.5 m diameter of the accelerator tunnel. This seventh sector commences from the end of the long straight section through into the arc section for a length of 438.5 m. The beamstrahlung absorber will be located 500 m from the interaction point (IP) within Sect. 3 of the tunnel widening. A 20 m section of increased tunnel height may be required to provide space for a crane around the beamstrahlung absorber. This is not currently incorporated in the feasibility study baseline for civil engineering. If confirmed as necessary, this will be incorporated in the baseline during the next design phase.

The construction of the tunnel-widening sections is proposed to be undertaken using conventional excavation methods such as roadheader and/or hydraulic rock-breaker machines. A shotcrete final lining is proposed with the aim of reducing construction time, thereby enabling an earlier installation of the TBMs, which will be carried out within the tunnel widening sections on either side of each experiment cavern.

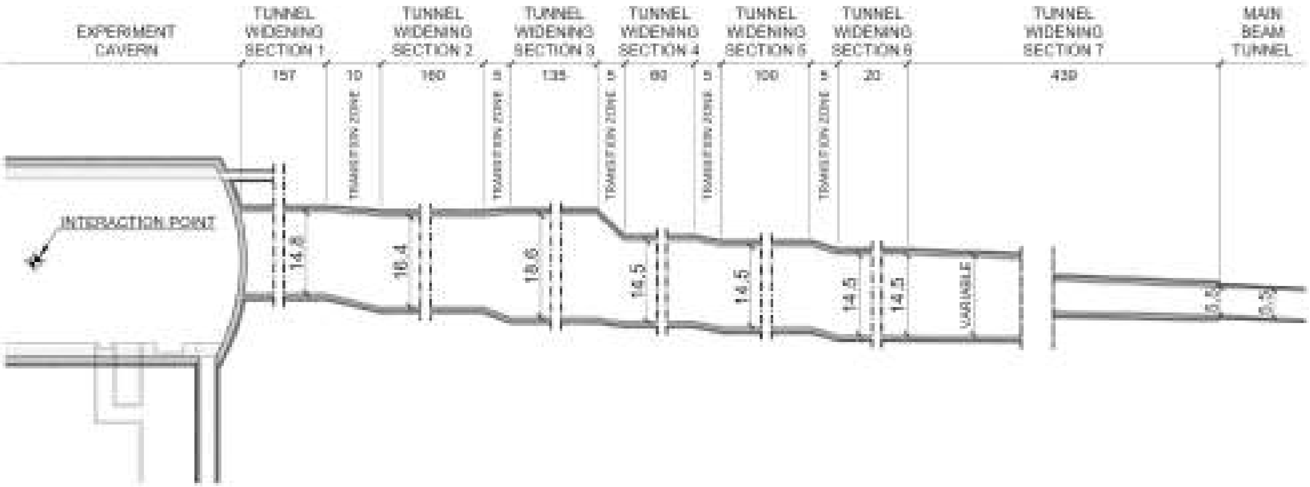


Fig. 1.7 Plan view of the typical tunnel widening at an experiment cavern

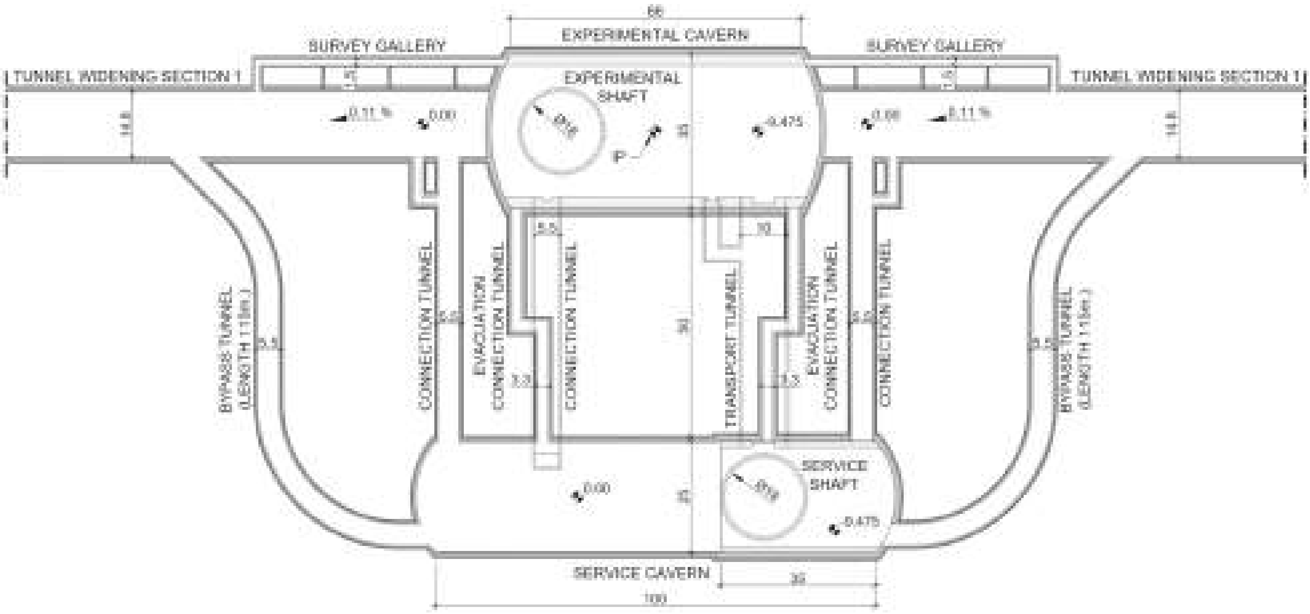


Fig. 1.8 Plan view of PA showing the layout of connection tunnels between the service cavern and experiment cavern

1.2.2 Bypass tunnels

Bypass tunnels are required at each of the four experiment areas to allow access for transport, personnel, and services directly from the service cavern to the accelerator tunnel, therefore bypassing the experiment cavern and detector areas. These tunnels will have an internal diameter of 5.5 m, similar to the cross-section of the accelerator tunnel. The length of the bypass tunnels varies between 110 and 115 m, depending on the experiment area. The 30 m radius bends allow transport vehicle movements as well as provide radiation protection between the accelerator tunnel and the service cavern. The bypass tunnels connect the service cavern to the accelerator tunnel within the first section of the tunnel widening, approximately 74 m from the experiment cavern. The junction between the accelerator tunnel and bypass tunnel is at an angle of 45 degrees, for the purpose of civil engineering constructibility. However, transport needs may require a shallower angle to be specified. In the next design phase, the details of the junctions between the two tunnels will be reassessed, and if required, a junction cavern or other more effective means of accommodating the connection will be implemented.

The bypass tunnels will be constructed using a roadheader machine and lined with in-situ concrete for the final lining. The construction of these tunnels will be completed in parallel with the works for the connection tunnels and tunnel-widening sections at each experiment point.

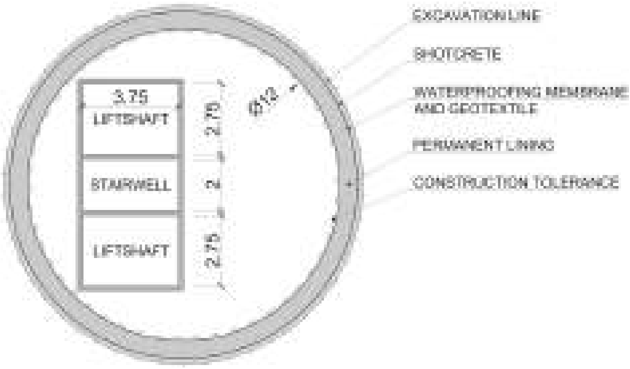


Fig. 1.9 Cross-section through the 12 m diameter service shaft, as proposed at the four technical areas

1.2.3 Connection tunnels

The connection tunnels between the service caverns and experiment caverns provide personnel access and materials/equipment transportation. These tunnels also house the service ducts, cables, and pipes linking the service caverns to the detectors and accelerator tunnels. Figure 1.8 shows a typical layout of connection and survey galleries at an experiment point. Two 5.5 m diameter connection tunnels link either end of the service cavern directly to the accelerator tunnel. These tunnels have an additional forked section of tunnel, of 2.8 m span, to allow personnel access whilst the radiation shielding doors remain closed across the full 5.5 m tunnel section. Two 3.3 m span evacuation tunnels provide a safe means of escape for personnel from the experiment cavern directly to the service cavern. These tunnels are designed with a chicane to provide radiation protection between the two caverns. At the lower level, a 5.5 m diameter connection tunnel is required for service connections and personnel access to the floor of the experiment cavern. The transport tunnel is 10 m in span to accommodate the movement of large equipment, and the connection tunnel has a span of 5.5 m for personnel access and the conveyance of services between the two caverns. At each of the 4 experiment points, a 10 m internal diameter connection tunnel between the bottom of the access shaft and the experiment cavern is required to transport large detector components to the areas inaccessible via the main shaft serving the experiment cavern.

1.2.4 Shafts

There are thirteen shafts proposed for accessing the underground structures:

- Four 12 m diameter shafts (like that shown in Fig. 1.9), one at each of the technical areas PB, PF, PH, and PL, for access and service requirements.
- Two 18 m diameter shafts, one at each of the experiment areas, PA, and PG, for access and installation of the detector components in the experiment cavern.
- Two 15 m diameter shafts, one at each of the experiment areas, PD, and PJ, for access and installation of the detector components in the experiment cavern. Note that these smaller experiment shafts are dimensioned to accommodate the smaller detectors planned for PD and PJ.
- Four 18 m diameter shafts, one at each of the service caverns at points PA, PD, PG, and PJ, for access, service requirements and to facilitate the lowering of the largest accelerator components.
- One 10 m diameter shaft on the CERN Prévessin site, to enable the construction of the transfer tunnel from the Injection Complex to the FCC. This shaft will only be used for construction, in particular, to allow the assembly of the TBM to drive the 5 km transfer tunnel length.

The service shafts at each of the eight points provide access to the service caverns. During the construction phase, these will be used for the installation and commissioning of the infrastructure and accelerator components. They will also be used during machine shutdowns for maintenance and upgrade of the accelerator and supporting infrastructure. They will be equipped with two lifts and a stairwell located within a pressurised inner shaft, which provides a safe escape route in case of fire. The shaft also contains a continuous vertical clear space for the crane to lower the equipment.

All four of the experiment caverns are served by either a 18 m or 15 m internal diameter shaft directly above the experiment cavern. These shafts primarily serve for the transportation of the detector components, which will be lowered down the shafts from the Surface hall(SX) for installation in the underground experiment caverns (UX). These shafts will also contain ventilation ducts and other services necessary to support the operation of the detector within the UX caverns. As PA and PG are the largest of the experiment areas, 18 m diameter shafts are required. Being the smaller experiment areas, PD and PJ only require a 15 m experiment shaft at each location.

Table 1.3 Shaft depths at each site

Site	PA	PB	PD	PF	PG	PH	PJ	PL	Transfer Tunnel
Moraine Depth [m]	54	30	25	<5	24	20	31	40	12
Molasse Depth [m]	147	171	156	400	202	215	222	210	17
Total Depth [m]	201	201	181	400	226	235	253	250	29

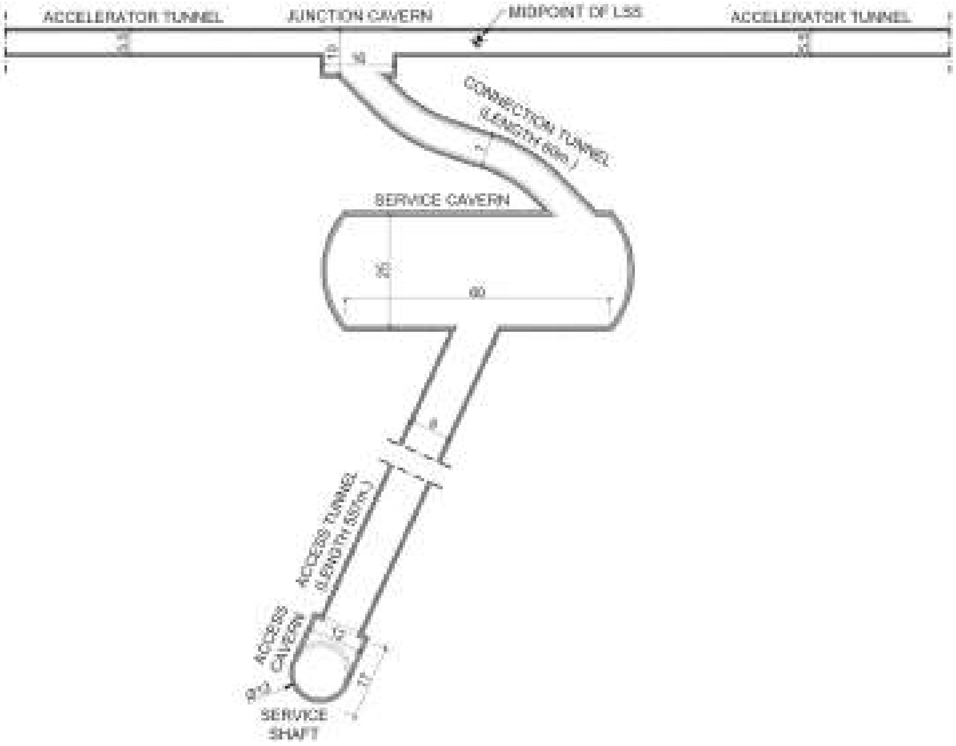


Fig. 1.10 Plan view of the sub-surface arrangement at PF, showing the offset service shaft and access tunnel arrangement

The construction shaft proposed for the TBM drives of the transfer tunnel may be used during the infrastructure installation phase to transfer equipment and/or components from the surface into the transfer tunnel.

The shafts have varying depths around the ring, ranging from 29 m to 400 m. Table 1.3 summarises the depths of the shafts at each site, including the depths of the moraine and molasse geological layers. Generally, the shafts are located directly above the corresponding cavern. However, at PF and PB, surface constraints require the shaft to be offset from the service cavern. At PF, this is achieved by constructing a 9 m internal diameter access tunnel 585 m in length, as shown in Fig. 1.10.

All the shafts will be excavated through the moraine strata. Historically, supporting methods such as diaphragm walls, secant piles, and ground freezing have all been used on CERN projects and, therefore, will be appropriate for the construction of FCC shafts.

The shaft depths below the moraine strata will be located in molasse rock. Shafts in molasse have historically been built most cost-effectively using conventional construction techniques (roadheader, hydraulic hammer) combined with shotcrete and rock bolts as primary support followed by a permanent cast in-situ reinforced concrete lining. Diaphragm wall construction consists of excavating a number of straight sections of wall to form a quasi-circular shape. The sides of these excavations are supported with a temporary bentonite slurry mix, which is replaced by reinforcement cages and concrete to form the primary lining, inside which the shaft excavation can proceed. Figure 1.11 shows an example of the cross-section of a typical 12 m diameter service shaft in the moraine using the diaphragm wall technique.

Once stable rock (i.e., the molasse) is reached, the excavation is supported temporarily by rock reinforcement such as rock bolts and shotcrete, before installing a waterproof membrane and the permanent cast in-situ reinforced concrete lining. The slip-forming technique can be used for the permanent lining, where the concrete is poured into a continuously climbing formwork.

The staircases and lift shafts required within the service shafts for personnel and material access are constructed from prefabricated elements that are stacked on top of each other from the top of the shaft. These are placed as

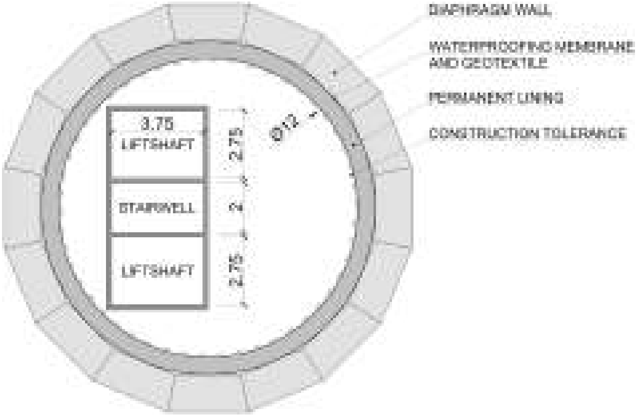


Fig. 1.11 Cross-section of the 12 m diameter service shaft with diaphragm wall construction

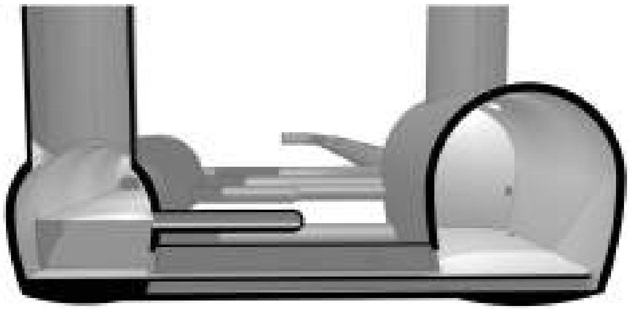


Fig. 1.12 Cross-section through the 3D model at PA, showing the service cavern (left) and experiment cavern (right)

one of the final construction activities once all major civil engineering works are completed below ground and before the civil engineering structures are handed over to CERN.

As the shafts for FCC are deeper than any previously constructed at CERN, a specialist shaft-sinking consultant provided an assessment of possible excavation techniques suitable for these greater depths. The study focused on the logistical considerations of the construction and the servicing of shafts to up to 400 m in depth (the deepest shaft at site PF). The assessment concluded that utilising current technologies and best working practices, the shafts as proposed are feasible to construct. They advised that with all shafts being constructed in parallel, procurement of sufficient specialised labour and equipment ahead of time would be key to ensuring that sufficient resources are available, thus minimising the risk of a delay to the construction schedule. The study also highlighted that there would be potential for equipment used during shaft sinking, also to be utilised during later cavern and tunnel excavation works. This could offer benefits to both the cost and the construction schedule. Furthermore, CERN was advised that advances in mechanisation and future shaft-sinking technologies could reduce construction durations as well as project risks, in particular through the recent development of a vertical shaft-sinking machine that does not require human intervention within the shaft itself.

1.2.5 Caverns

Large-span caverns are required at both experiments, PA and PG, to accommodate the FCC detectors and associated infrastructure. The proposed cavern dimensions are 66 m × 35 m × 35 m (L × W × H) and the caverns will be constructed at a depth of up to 226 m in the molasse rock. Although these will be the largest caverns ever constructed at CERN, they will not be significantly larger than the current ATLAS cavern of the LHC.

The construction sequence will consist of benched excavations using rock breaker and roadheader machines, with the primary support being provided by rock bolts, cable bolts and layers of steel-reinforced shotcrete. During the widening of the crown area of the experiment cavern, additional lattice girders and layers of steel-reinforced shotcrete will be installed. The lattice girders for the various excavation steps can be bolted together to ensure continuous rock support along the excavated area. The secondary lining will be constructed from cast in-situ concrete to provide additional strength and protection to the cavern walls. A waterproofing and drainage membrane will be installed between the primary and secondary linings to ensure that the cavern remains dry and that the structure is not subject to excessive water pressure arising from any groundwater that may be present.

Two smaller experiment caverns, 66 m × 25 m × 25 m (L × W × H), are required at PD and PJ. These caverns will be constructed at up to 253 m depth using the same techniques for excavation and support as the experiment caverns situated at PA and PG.

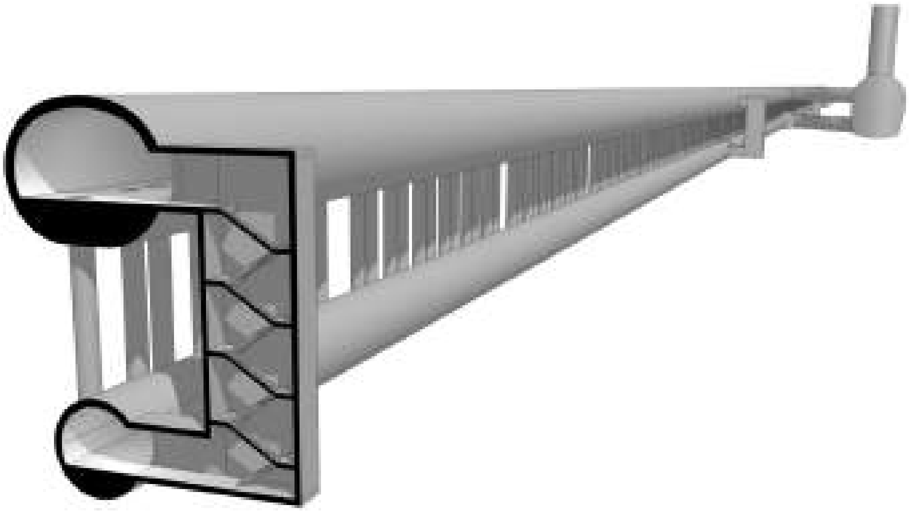


Fig. 1.13 3D model view of the klystron gallery arrangement at PH

A service cavern at the same elevation as the accelerator tunnel with dimensions of 100 m × 25 m (L × W) is required adjacent to each of the four experiment caverns. Figure 1.12 is a cross-section through the 3D model for PA showing the service and experiment caverns. Below the service shaft, the height of the service caverns is 22.4 m thereby providing direct access to the experiment cavern floor for large equipment and detector components. The remainder of the 100 m long service cavern has a height of 15 m. Shorter service caverns of 60 m length are necessary at the remaining four technical points. The service caverns will house infrastructure equipment such as electrical, cooling, ventilation and cryogenics. Furthermore, the caverns will provide a safe refuge in the event of an emergency, with a dedicated pressurised area at the bottom of the shaft. These caverns will be constructed in the same manner as the experiment caverns. At the experiment sites, the spacing between the two caverns is approximately 50 m, to mitigate electromagnetic effects from the detector on the nearby electrical components. This also improves the overall structural efficiency by providing a sufficiently large rock pillar between the experiment and service caverns, thus minimising the structural support needed and reducing the risk and complexity of construction.

The service caverns will contain three floor levels, with steel structures providing the frame for each level. This greatly increases the usable space for technical infrastructure and services. Steel structures will also be used to create the gallery levels around the detectors in the experiment caverns. These will be similar to the galleries currently in place within the LHC experiment caverns, such as ATLAS and CMS.

Where tunnels of similar cross-section dimensions connect, a junction cavern is required. PF, PH and PL each require a junction cavern where the 7 m diameter connection tunnel from the service cavern intersects with the 5.5 m accelerator tunnel. Each cavern is 16 m long and at a span of 10 m.

An additional cavern for the FCC-ee machine beam absorber will be located at PB, and this will accommodate two beam absorbers, one for each of the two beam lines. Further details of this structure are provided in Sect. 1.2.8.

Survey galleries are required at each of the four experiment caverns to survey the beam alignment on either side of the detectors. These consist of 1.5 m span tunnels of 60 m length, running parallel to the accelerator tunnel, with perpendicular connections made every 15 m into the tunnel widening Sect. 1. The possibility of incorporating these into the widened tunnel sections to reduce complexity and cost of construction will be studied in the next design phase.

1.2.6 Underground structures for Radio Frequency Infrastructure

The klystron galleries are an essential part of the FCC-ee civil engineering, as they will house the klystrons and other components of the Radio Frequency (RF) system. To accommodate the necessary infrastructure, two separate galleries will be constructed, one at PH and the other at PL. The klystron gallery at PH (Fig. 1.13) will be 2012 m long for the collider RF system, while the gallery at PL will be 1446 m long for the booster RF system. To allow access to the klystron galleries during the operation of the FCC-ee machine, sufficient radiation shielding needs to be provided. To achieve this, 10 m of rock will be maintained between the RF galleries and the accelerator tunnel. The internal dimensions of the galleries are 10 m in span and 5.5 m high to accommodate the transport and placement of the equipment within the galleries, as well as allowing access for maintenance and repair during the operation phase.

The galleries are sized with a 50 m extension in length at either end to incorporate the space for service equipment. This is proposed instead of constructing the large alcoves along the accelerator tunnel, thereby enabling a more efficient use of tunnel excavation and space.

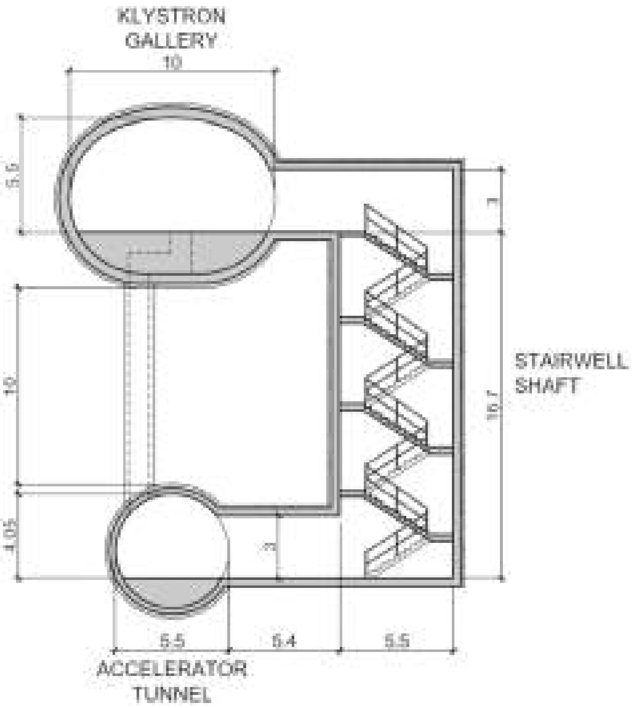


Fig. 1.14 Cross-section through the klystron gallery and accelerator tunnel, including wave-guide duct between

The galleries are connected directly to the accelerator tunnel via 1 m internal diameter wave-guide ducts, spaced every few metres along the gallery (see Fig. 1.14. There will be 428 individual wave-guide ducts at PH and 312 at PL.

The safety concept for FCC requires that for emergency egress, stairwell shafts are spaced at intervals of 341 m along the gallery to connect the galleries to the accelerator tunnel.

For access to the klystron galleries, a 7 m internal diameter connection tunnel links the upper level of the service cavern and the klystron gallery. This connection tunnel has a length of 62 m. The size of the connection tunnel is designed to accommodate personnel access and the transport of the RF equipment into the gallery.

The klystron galleries will be excavated using the same road header type machines that will be used for the excavation of the caverns and connection tunnels at points PH and PL. Roadheader excavation is efficient and accurate, allowing precise excavation of the galleries. The klystron gallery lining will consist of a shotcrete primary lining and a cast in-situ concrete secondary lining. It may be feasible to use shotcrete for the final lining of the gallery, as this would potentially offer faster construction and lower cost. This option will be studied during the next phase. The floor of the gallery will also be made of cast in-situ concrete and will include a drainage channel and the entry of the waveguide ducts up through the floor slab. The entry of the wave-guide ducts into the gallery will require the use of a chicane to provide radiation protection. This will likely be constructed with a precast concrete unit placed after the final installation of the cryogenic line (QRL) infrastructure through the duct.

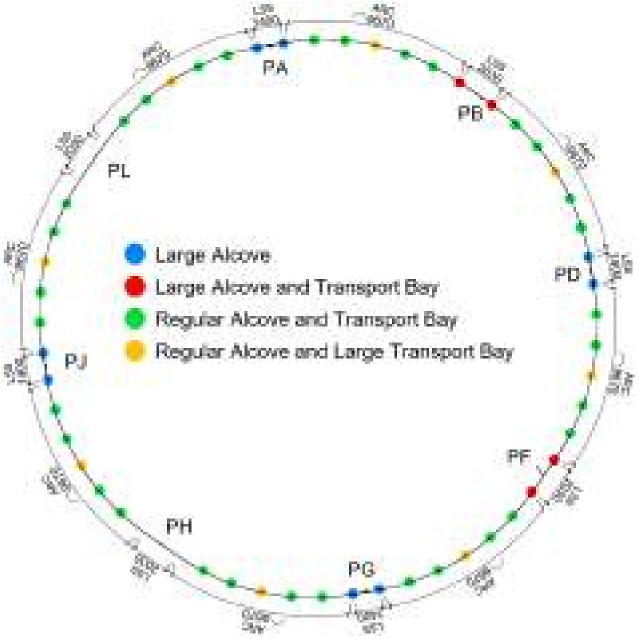
The wave-guide ducts, which will contain the wave-guides linking the klystrons to the RF cavities in the accelerator tunnel, will be excavated by raise boring. This process involves first drilling a pilot hole and then attaching a reamer head at the bottom, which is pulled up, excavating the duct from below in a vertical direction. This method of excavation is efficient and minimises disruption to the surrounding rock. A steel or concrete lining will be grouted into the rock to provide a suitable finished surface and final lining.

1.2.7 Alcoves

At 1.6 km centres around the circumference of the machine, equipment alcoves, as illustrated in Fig. 1.15, are required to accommodate electrical equipment, services and transport needs. The majority of these alcoves are considered ‘regular’, measuring 40 m in length, 10.6 m in width, and 4.6 m in height. Positioned on the inside of the ring, the alcoves are arranged perpendicular to the accelerator tunnel.

In addition to the regular alcoves, twelve ‘large’alcoves are needed on either side of each of the FCC access points to provide extra space for electrical equipment. These larger alcoves are 29 m in length, 18 m in width and 8.3 m in height. These large alcoves will be located at the end of the long straight sections on either side of the caverns. Two large alcoves are required at PA, PB, PD, PF, PG, and PJ, but not at PH or PL, because the additional size of the klystron galleries provides the necessary volume for the equipment. An example of a large alcove is shown in Fig. 1.16. In total, the project requires 40 regular alcoves and 12 large alcoves.

Fig. 1.15 Layout of alcoves around the FCC ring



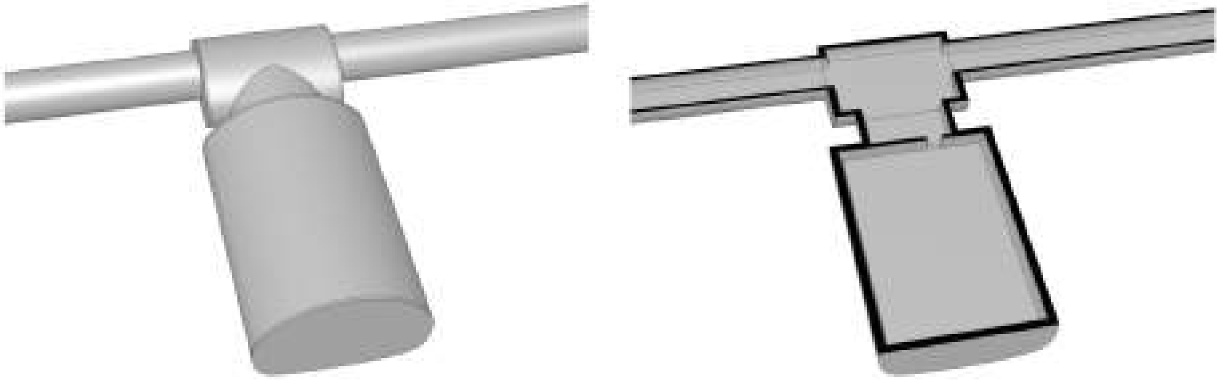


Fig. 1.16 Model view of a large alcove and transport passing bay

An access area to each alcove is provided to accommodate the radiation protection chicane walls. This section is 6 m long and has a 10.6 m span at the entrance to both large and regular alcove types.

A transport-passing bay is required at the entrance to each alcove. This will facilitate the passing of transport vehicles travelling in opposite directions through the tunnel. The passing bay also provides space for the parking of transport vehicles during installation and shutdowns, with additional space for servicing/repairing the vehicles if necessary. The majority of the passing bays are accommodated in a cavern along the accelerator tunnel alignment and measure 16 m in length and 11 m in width. Additional larger passing bays are required at the mid-section of each accelerator tunnel arc. There will, therefore, be a total of 8 larger passing bay caverns, measuring 30 m by 11 m. These facilitate the passing of the magnet delivery vehicles during the installation phase of the FCC-ee machine. An example of the large passing bay is shown in Fig. 1.17.

Unlike the caverns and tunnels in proximity to the FCC points, which can be at least partially excavated in parallel with the TBM drives, excavation of the alcoves and passing bays will need to be completed after the TBM drive is complete. This is because the full tunnel section is required to support the TBM (ventilation, conveyor for spoil removal, transport corridor for concrete segmented linings, corridor for personnel etc.). It will, therefore, be necessary to break out the concrete tunnel lining and excavate the passing bay cavern and alcoves using roadheader excavation. The inner lining works for the alcoves will then be carried out ahead of the relining of the accelerator tunnels. This will have to be coordinated with the installation of the tunnel floor. The overall construction sequence and structural design will be similar to the caverns, as detailed in Sect. 1.2.5.

The complexity of the alcove construction and the associated logistical challenges have a major impact on the construction schedule, since each alcove is potentially on the critical path for civil engineering. CERN has

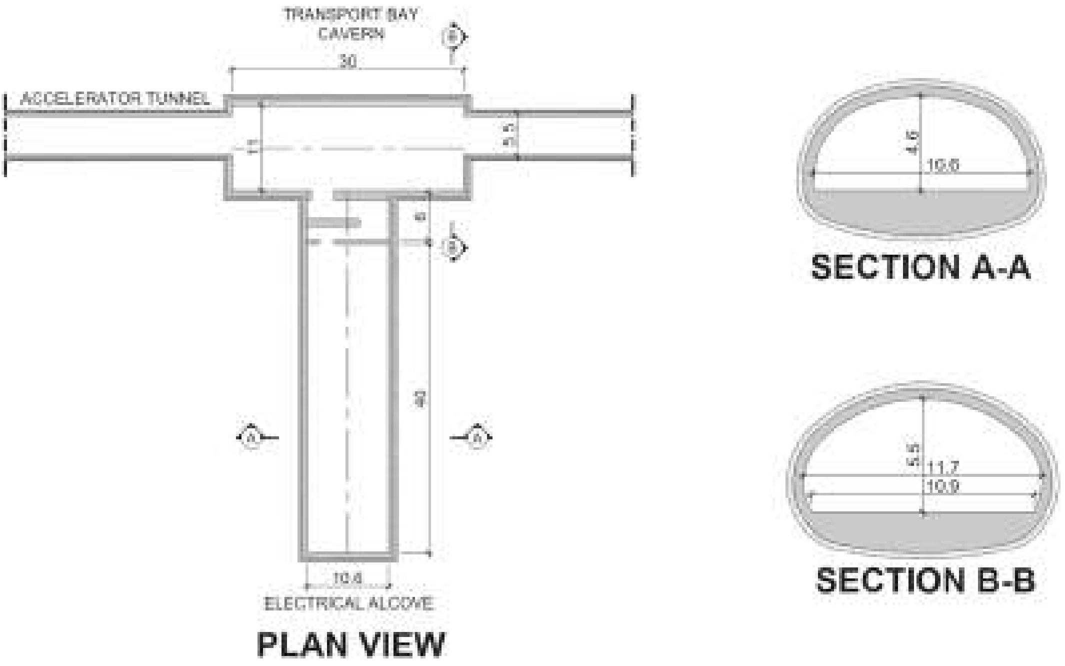


Fig. 1.17 Example of a regular alcove and large passing bay located at the centre of each arc sector

commissioned an additional study to investigate the optimal method of constructing the alcoves in order to minimise the impact on the overall construction schedule. As a result, the current assumption in the schedule remains that alcoves can be constructed in parallel to one another, maintaining sufficient access, safety and logistical standards. By adopting an overlapping sequence of construction activities, all alcoves of each sector can be constructed within a 12-month period, thereby achieving the targeted handover date of each sector for the subsequent infrastructure and accelerator installation.

1.2.8 Beam absorber cavern

The absorbers for the FCC-ee beams will be located at PB. The beam absorber cavern layout includes a 708 m long cavern with a span of 13.6 m, to house both the e^+ and e^- absorber infrastructure. The size of the cavern has been dictated by the beam extraction length and angle, which requires a separation from the accelerator line of at least 5.5 m and a septum/kicker angle of 10 mrad. The two beam extraction lines are arranged to cross at the centre of the cavern, adjacent to the centre of the PB long straight section. This ensures that the beam absorber cavern volume is optimised.

To accommodate the separation of the two FCC-ee beams on the approach to PB, a series of tunnel widening sections is required either side of the cavern. Three sections of tunnel widening, of lengths from 83 to 330 m will be constructed either side of the cavern to increase the span of the accelerator tunnel from 5.5 to 7.8 m.

The absorber cavern will be excavated in the same manner as other caverns, using roadheader and/or rock breaker machines to excavate from the roof level down using a series of ‘benches’. Due to the constraints at the surface, the service shaft and cavern will need to be offset from the centre point of the long straight section (LSS). The offset service shaft will, therefore, be positioned 350 m from the centre of the LSS and connect to the beam absorber cavern via a connection tunnel of 97 m length.

The absorber cavern will be constructed as mentioned in Sect. 1.2.5. There will be a shotcrete and rock bolt primary lining with an in-situ concrete secondary lining. However, the option to create the final lining from shotcrete will be considered in future design development to potentially reduce costs and reduce the construction time. It is yet to be confirmed whether a shielding wall/structure is required within the cavern to shield the accelerator from the beam absorber apparatus; however, this would be constructed with precast concrete blocks well after the civil engineering has been completed. A schematic view of PB including the beam absorber cavern is shown in Fig. 1.18.

1.2.9 Excavated material

To construct the subsurface structures, approximately 6.3 million m^3 (in-situ volume) of rock will be excavated. This material will be extracted via the eight FCC access points. The predominant rock type will be molasse,

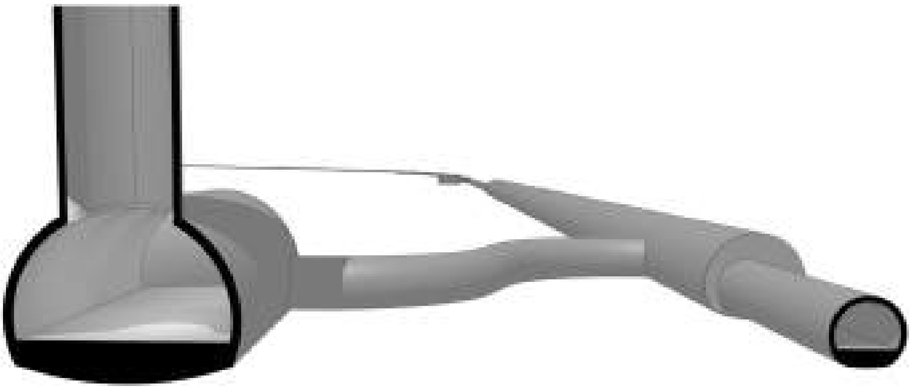


Fig. 1.18 Sub-surface structural layout at PB, service cavern (left) and beam absorber cavern (right)

Table 1.4 Excavation volumes for each FCC sector

	In-situ Vol., 10^3 m^3	Bulk Vol., 10^3 m^3	Compacted Vol., 10^3 m^3	% of Total
PA	1378	2205	1791	22%
PB	148	237	192	2%
PD	1274	2038	1656	20%
PF	165	264	215	3%
PG	1365	2184	1775	22%
PH	312	499	405	5%
PJ	1289	2062	1675	20%
PL	241	386	313	4%
Transfer Tunnel	122	195	159	2%

accounting for 96% of the total material. Moraine rock accounts for 1.5% of the excavated material, and limestone makes up the remaining 2.5%.

Figure 1.4 in Sect. 1.2.1 shows the baseline arrangement for the TBM drives. As mentioned, the accelerator tunnel sectors will be excavated using TBM. Shafts will be excavated by conventional mined excavation or vertical shaft-sinking machines. The use of diaphragm walls will be necessary to support the excavation of shafts through the initial moraine layer. All other excavations for subsurface structures will be constructed by hydraulic hammer (rock breaker) and roadheader machines. The physical characteristics of the excavated material will differ according to the excavation method utilised.

Table 1.4 provides a breakdown of the excavated material quantities extracted from each of the eight sites and the transfer line between Prévessin and the FCC tunnel. The volumes are expressed as the in-situ volume i.e., the volume prior to excavation, the bulked volume i.e., the volume after excavation and the compacted volume i.e., the volume after the material has been re-compacted for example in a spoil deposit zone.

Two TBM drives will commence at PA, one driven towards PB and the other driven towards PL. The resulting total material extracted from PA will be almost 1.4 million m^3, of which, 62,721 m^3 is expected to be moraine.

No TBM drives are planned from PB, the volume of excavated material, therefore, arises from the subsurface structures at PB, including the beam absorber cavern. Of the total quantity of, 147,852 m^3, 10,473 m^3 is expected to be moraine and the remainder is molasse.

Two TBM drives will commence at PD, one driven towards PB and the other towards PF. The resulting quantity of material to be extracted from PD is 1.3 million m^3 of which, 24,925 m^3 is expected to be moraine.

No TBM drives are planned from PF. As with PB, the excavated material at PF only arises from the subsurface structures directly located at PF and not the accelerator tunnels either side. Almost all the excavated material at PF will be molasse as there are little or no quaternary deposits.

Two TBMs will be driven from PG, one driving towards PF and the other towards PH. The total quantity of material excavated from PG is almost 1.4 million m^3. Moraine makes up 30,829 m^3 of the total excavated material at PG. However, due to the 4.4 km long sector of limestone along the accelerator tunnel between PG and PH, 141,175 m^3 of the total material will be limestone rock. The remaining 1.2 million m^3 of excavated material will be molasse.

No TBM drives are planned from PH, therefore all the excavated material comes directly from subsurface structures at PH, including the klystron gallery and associated structures. 7482 m^3 of the total excavated material at PH is expected to be moraine, and the remainder is molasse.

Two TBMs will be driven from PJ, one driven towards PH and the other towards PL. Therefore, the quantity of material extracted from PD is around 1.3 million m^3 of which, 29,910 m^3 is expected to be moraine.

No TBM drives are planned from PL, the volume of excavated material is therefore attributed to the subsurface structures at PL, including the klystron gallery and associated structures. Moraine rock is expected to make up 13,468 m^3 of the total excavated material at PL.

The Prévessin to SPS and SPS to FCC injection tunnels account for 122,329 m^3 of excavated material, the majority of this material will be extracted from the Prévessin site, by means of the proposed construction shaft. A small proportion of the excavated material will be moraine, from the initial excavation of the shaft, but the majority of the shaft and transfer tunnel excavation will be in molasse rock.

1.2.10 Tunnelling in the molasse rock

The large-scale geological environment within which the FCC underground infrastructure will be excavated is shown in Fig. 1.19, with most of the tunnel located within the Lower Freshwater Molasse (USM) and Lower Marine Molasse (UMM). The FCC will be excavated at depths of up to 560 m, with a total combined length of all excavations exceeding 100 km. Whilst the experience gained by CERN over the previous 50 years for the construction of the LEP, LHC and Hi-Luminosity LHC has given valuable insight into the likely characteristics and behaviour of the molasse rock, other projects excavated within the molasse rock have also been the subject of a desktop study in order to improve the understanding of the environment in which the FCC civil engineering will be constructed.

Most of the projects reviewed were transport tunnels (road and rail) from a few hundred metres to a few kilometres in length at shallow depths. Tunnels were excavated by means of conventional excavation, cut and cover, and TBM. One project in particular, the Moutier tunnel, was excavated by a single shield TBM in the Alsace tertiary molasse (a mix of marl, sandstone and limestone). Due to an unforeseen geological environment, the TBM became stuck 190 metres into the tunnel drive. As a result, the remainder of the tunnel was excavated using conventional methods. This project highlights the need for sufficient geotechnical investigations and appropriate analysis to be completed before construction begins. At the greater depth of FCC, the molasse is likely to be more consolidated and unlikely to have been altered due to weathering. However, appropriate geotechnical investigations and numerical analysis will be required to better predict the likely behaviour of rock and its influence on the performance of the tunnel boring machine.

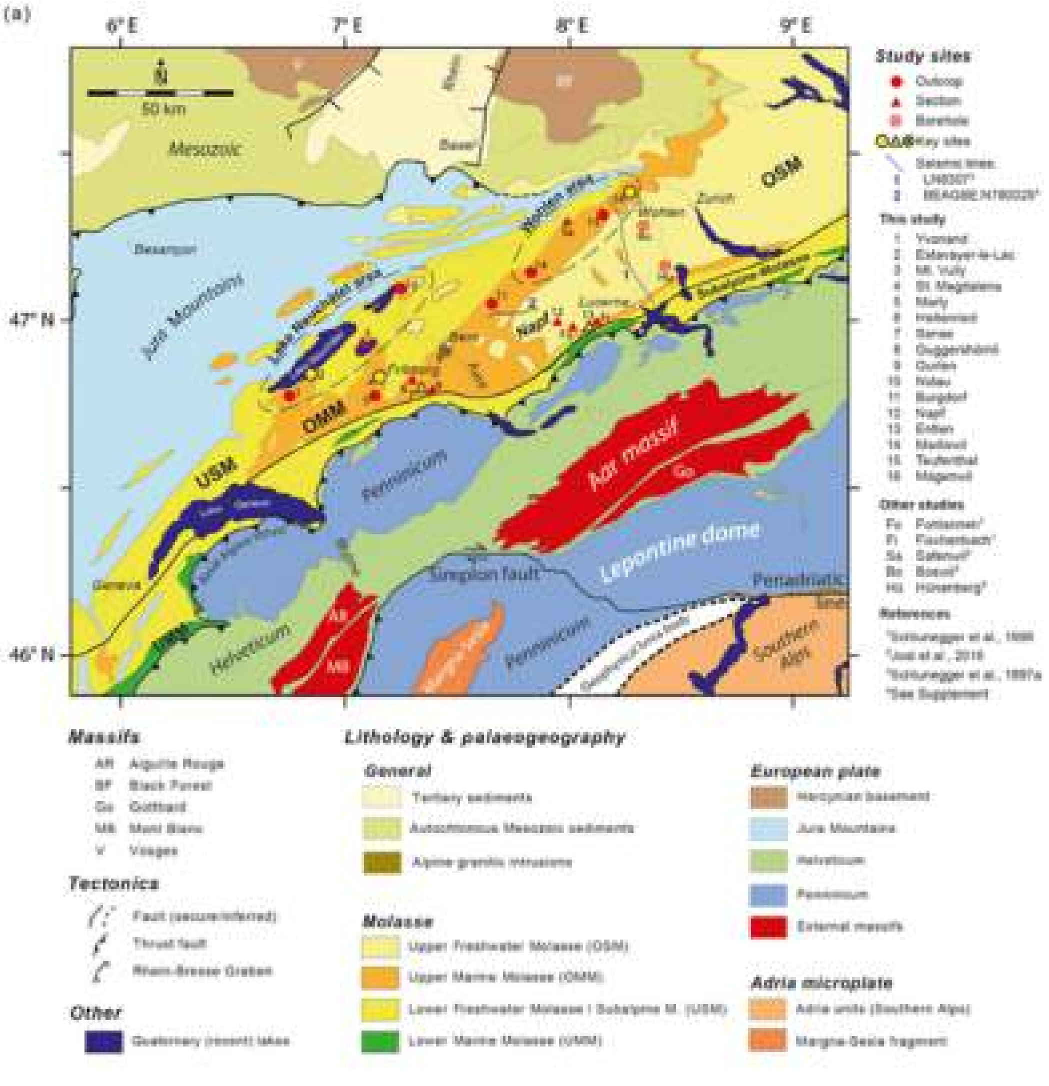
Generally, the review confirms that excavations in molasse rock have been extensively conducted in Switzerland using both TBM and conventional methods. However, the FCC will require a comprehensive geotechnical investigation to assess the characteristics of molasse as well as the in-situ stress regime. The investigation will address potential risks, including those arising from changes in pore water pressure, rock squeezing, and geological faults.

A tunnelling project has been identified in the UK with characteristics similar to those of the FCC. It is currently under construction as part of a new Halite mine development. A single TBM excavates a 37 km long tunnel with cross-sectional dimensions that are very similar to those of the FCC. Furthermore, the tunnel is being excavated at comparable depths and within sedimentary geology that is not dissimilar to that expected for the FCC. An average tunnelling excavation rate of 20 m/day have been achieved. CERN will assess this project for lessons learned in more detail during the next phase of the FCC.

In conclusion, it is considered that underground civil engineering for the FCC is feasible and within the current experience and capabilities of many of the major designers and contractors currently active within the CERN member states. Additional site investigations will be required to finalise the precise depth and inclination of the FCC tunnel and to determine the geotechnical properties of the rock mass, which are necessary for CERN to move forward to the detailed design and construction phases.

1.3 Surface structures

Since the completion of the conceptual design, there has been a rationalisation of the surface sites associated with the FCC-ee civil engineering, with the number of surface sites reduced from twelve to eight. The eight surface sites will comprise four areas suitable for siting experiments and four assigned as technical areas. The eight sites are spread evenly around the circumference of FCC-ee collider ring. The four experiment areas are symmetrically distributed such that each site is diametrically opposite another experiment site, as illustrated in Fig. 1.1. The experiment sites are at sites PA, PD, PG and PJ with the technical sites at the remaining sites PB, PF, PH and PL. The location of the four experiment surface sites is interdependent since the interaction points for each of the four sites define the location of the experiment and service shafts at each site as illustrated in Fig. 1.20



Map mod. after Froitzheim et al., 1996; Schmid et al., 2004; Handy et al., 2010 and Kissling and Schlunegger, 2018

Fig. 1.19 Geographical map of Switzerland. Credit: Philippos Garefalakis, F. S. (2019). Tectonic processes, variations in sediment flux, and eustatic sea level recorded by the 20 Myr old Burdigalian transgression in the Swiss Molasse basin

The experiment access shafts can only be in one of two locations with respect to the interaction point, and the machine access shafts should ideally be placed directly above the service cavern, which itself needs to be located approximately 50 m from the experiment cavern for structural stability of the two caverns and for electromagnetic shielding. Since each of the four interaction points associated with the experiment areas is located precisely with respect to each other, the locations of the shafts at each experiment point are also fixed with respect to the shafts at the other experiment points. This interdependency across the four experiment sites influences the layouts of the surface sites, since the two shafts are associated with specific building configurations.

The selection of surface site locations for the experiment areas requires careful coordination, as each site is interconnected with the location of the other three. For the technical sites, while proximity to the centre of the associated long straight section (LSS) is a key factor, some flexibility exists. The single machine access shaft can be linked to the accelerator tunnel via an access gallery, which, if required, can extend several hundred metres in length.

For a comprehensive discussion on environmental considerations, including landscape integration, readers are referred to the relevant sections in Chaps. 2 and 3 in this Volume.

The engineering designs of the surface site constructions that are eventually part of the project authorisation files need respond to the requirements of the equipment that will eventually be housed at each site. Noisy equipment will be adequately noise insulated and placed in constructions that permit containing the residual noise within

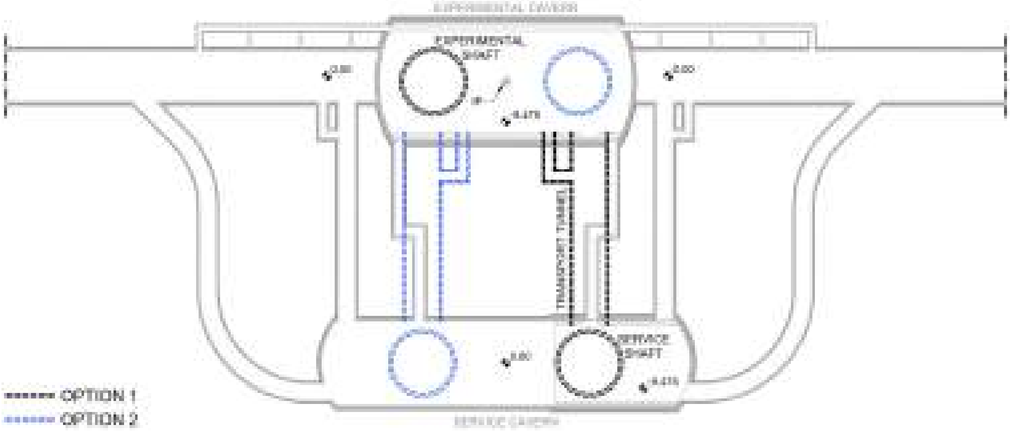


Fig. 1.20 Options for experiment and service shaft locations relative to the interaction point

the applicable regulatory frameworks in place at the time. Examples of structures that may require such specific measures include:

- Cryogenic plants comprising compressors.
- Cooling and ventilation equipment with pumps, motors and fans.
- Electrical equipment such as transformers.

The choice of construction materials and techniques for surface site buildings is guided by multiple factors, including durability, safety, cost and environmental considerations such as landscape integration and regulatory constraints such as urbanism prescriptions. Newly emerging materials and technologies, as well as continuous monitoring of the environmental and regulatory prescriptions, including applicable energy efficiency standards, will be considered during the subsequent design phase. In line with CERN's governance framework, the territorial principle applies, i.e., the national laws and guidelines apply for infrastructure on the surface sites in the Host States.

At this stage, no architectural strategies have been adopted. This will be done in the next design phase. The development of the architectural solutions will include a robust consultative process with the Host States, regional stakeholders and local communities. A more detailed discussion can be found in Sect. 2

For technical feasibility and costing purposes, the U.S. Fermi National Accelerator Laboratory has analysed the technical needs of two of the eight surface sites in the framework of the international FCC collaboration. The study used an experiment site (PA) and a technical site (PB) as generic examples. The work resulted in the production of detailed drawings of the buildings at the sites. These designs were used as the basis for an initial cost estimate for the surface works. It should be stressed that these designs represent preliminary input for technical and financial feasibility and construction planning purposes only and are not approved designs.

The subsections below present simplified versions of these concepts that permit further development of site configurations and cost estimates.

The Chaps. 2 and *Territorial implementation* provide a further detailed examination of the contextual considerations, planning strategies, and logistical challenges associated with the surface sites, offering further insight into how these elements are being harmonized within the broader project vision.

1.3.1 Surface site - PA

The surface site PA will be the location for one of the four experiment areas. The site is located close to the existing CERN LHC surface site P8 which allows the re-purposing of some of CERN's existing LHC facilities and infrastructure to support the FCC-hh activities at site PA.

The buildings and other necessary civil engineering surface infrastructure for all surface sites have been identified and included within the civil engineering product breakdown (PBS) structure, which is shown for PA only in Table 1.5.

A significant feature of this and all experiment area surface sites is the large assembly hall that will be used for the sub-assembly and preparation prior to the transfer of the detector components to the underground experiment cavern. It is to be noted that any future assembly hall for an FCC-hh detector may need to be larger than that for an FCC-ee detector, and therefore, a footprint is reserved on the site for such a future expansion/reconfiguration of the assembly hall. The final details of a conceptual design for this building at the FCC-hh phase will be determined in parallel with a future fabrication and assembly strategy for the associated detector.

Table 1.5 PBS for PA surface structures

PBS Level					PBS Description
0	1	2	3	4	
	2				**Civil Engineering**
	2	**2**			**Surface Structures**
	2	**2**	**1**		**Site PA**
	2	2	1	1	Roads, parking spaces, footpaths, fences, gates, landscaping, drainage
	2	2	1	2	Technical galleries
	2	2	1	3	Fire fighting equipment and medical station
	2	2	1	4	Control building
	2	2	1	5	Assembly hall
	2	2	1	6	Magnet storage
	2	2	1	7	Shaft head building
	2	2	1	8	Tunnel ventilation
	2	2	1	9	Chilled water production facility
	2	2	1	10	Experiment cavern ventilation
	2	2	1	11	Service cavern ventilation
	2	2	1	12	Cooling plant and waste heat recovery
	2	2	1	13	SF annex
	2	2	1	14	Warm compressor
	2	2	1	15	Helium gas tanks foundations
	2	2	1	16	Liquid Nitrogen storage tank foundations
	2	2	1	17	Power converters building
	2	2	1	18	Electrical equipment building
	2	2	1	19	Electrical substation
	2	2	1	20	Waste material storage building

The site location has some specific constraints, including:

- The presence of a gas pipeline running adjacent to but outside the site. The layout of the buildings within the site takes into account the presence of this pipeline and, in the future development of the design, how to cross the pipeline to allow services to connect to the existing LHC site P8 prior to the FCC-hh construction.
- Likely urban development in the close vicinity of the proposed site, with direct views across Geneva to Mont Blanc. These views have been taken into account and building heights have been kept as low as possible, and the overall elevation of the platform has been minimised. To this end, the requirements brief included a target roof elevation no greater than that of the buildings located adjacent to the proposed site.
- The presence of a protected environmental compensation area immediately to the north of the site, an existing development to the south of the site and a major arterial road to the west of the site restricts the available area and layout of buildings within the surface site.

The functional requirements of the surface buildings at PA are similar to those built for previous CERN experiment areas. Some key requirements are:

- A large assembly hall for the pre-assembly of the detector. This building will house at least one crane capable of lowering the detector subcomponents from the surface down to the underground cavern located about 200 m below. The precise crane dimensions and weight will need to be considered during the detailed design phase.
- A shaft head building to accommodate the lifts, cranes, and staircases needed for personnel access to the underground areas and for the movement of material, equipment, and services between the surface and underground areas. This building also houses an unloading bay for trucks transporting material and equipment for installation in the underground areas.
- Buildings to house the equipment necessary to ventilate the underground areas. The equipment for ventilating the experiment cavern is housed separately from that for ventilating the rest of the underground areas, since these two systems enter and exit the underground areas via different shafts. This equipment requires effective noise insulation, therefore these buildings will either be made of reinforced concrete or have specific noise reduction measures incorporated or attached to the building structure.

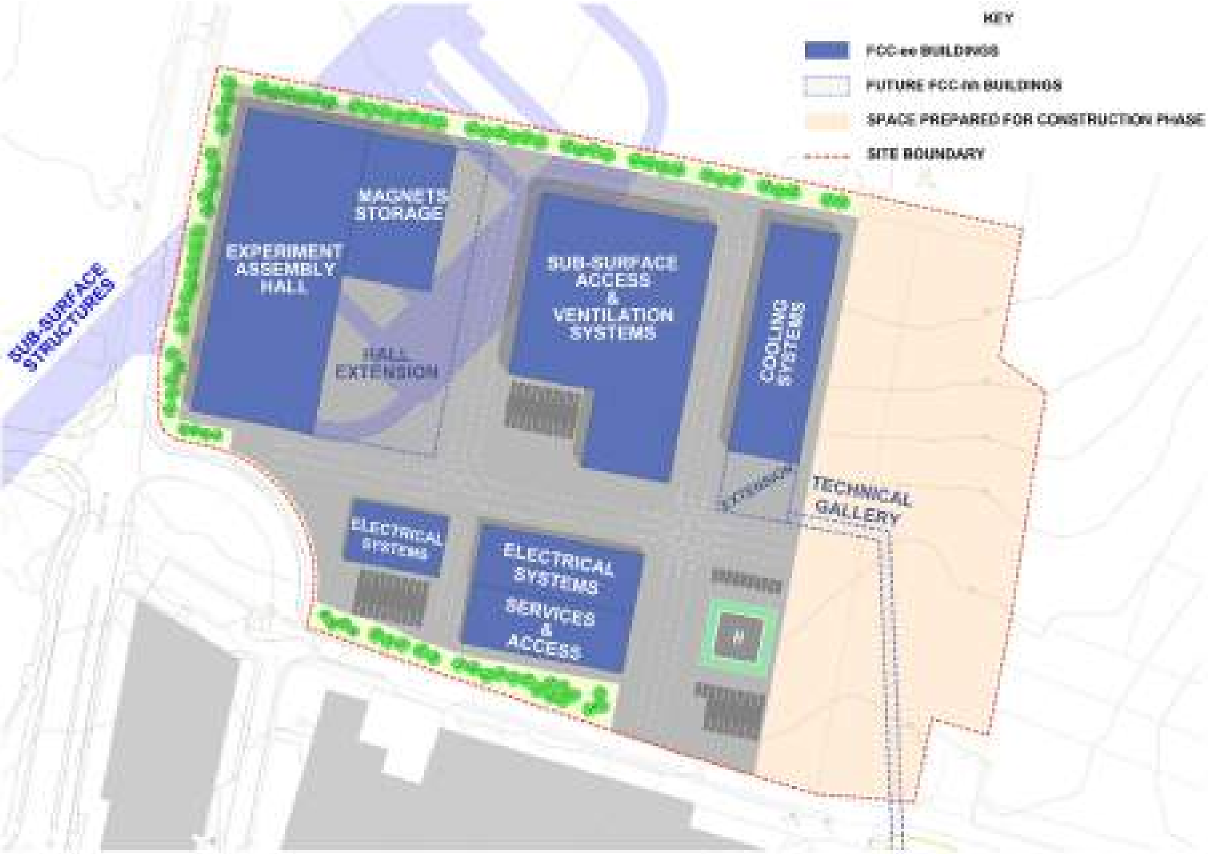


Fig. 1.21 Preliminary simplified surface requirements for PA site

- Buildings to accommodate the compressors and other equipment necessary for the cryogenic systems that will be used by the detector. Similar noise abatement measures to those used for the ventilation buildings will be necessary.
- Cooling plant buildings will include the cooling towers and associated pump houses, basins etc. Although traditionally constructed in reinforced concrete, the use of prefabricated fibreglass reinforced polyester (FRP) may be considered, in which case the civil engineering component would be reduced to the provision of the cooling basin and appropriate supporting foundations, with the towers themselves delivered as part of cooling, mechanical, and electrical infrastructure. In this case, additional noise abatement measures may be needed around these pre-fabricated cooling towers.
- Control building to house offices and control room for the operation of the detector. This building would also house areas for receiving visitors, noting that as PA is the closest FCC experiment area to the CERN main campus, it is likely to be an important focal point for CERN visitors.
- Buildings and support structures for transformers, switches, pylons etc. will be required for the electrical infrastructure.
- Other smaller buildings for various purposes as listed in the PBS given in Table 1.5.

Based on initial conceptual layouts developed by the Fermi National Accelerator Laboratory and evolving requirements for the PA surface site, the conceptual designs have been further refined to develop site layout scenarios, elevations, and earthwork estimates suitable for cost and schedule planning. It should be noted that these representations merely serve early-stage feasibility inputs for planning purposes and have not been reviewed, validated and approved. Figure 1.21 presents a simplified view of the proposed civil engineering buildings and associated works, while Fig. 1.22 illustrates a streamlined cross-section of the site.

One aspect in which PA differs from the other three experiment sites, PD, PG and PJ, is the presence of an existing LHC surface site (P8) in the immediate vicinity. This presents an opportunity to reduce the land required for FCC-hh by re-purposing the existing LHC P8 site after the LHC finishes its physics programme. A technical gallery from the existing site to PA would need to be constructed prior to FCC-hh to connect the services of the two sites together.

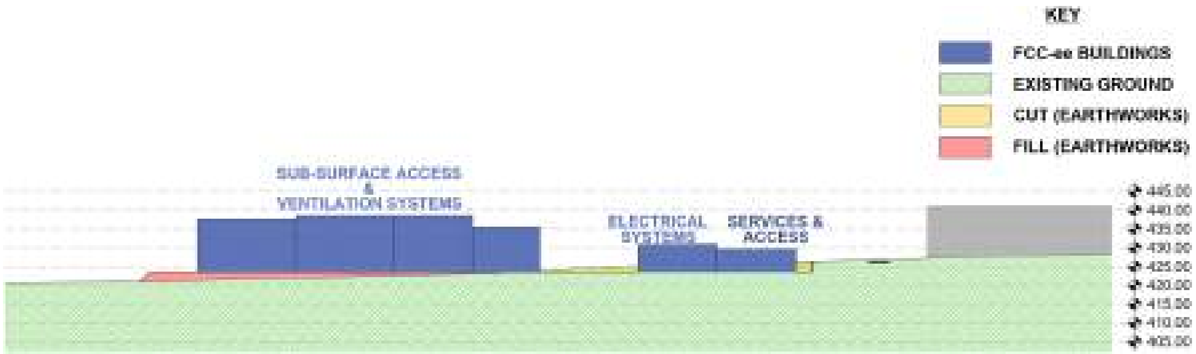


Fig. 1.22 Preliminary cross-sectional diagram of PA site

Table 1.6 PBS structure for surface site PB

PBS Level						PBS Title
0	1	2	3	4	5	
	5	3				PB Construction, testing, commissioning
	5	3	1			Surface works
	5	3	1	1		Roads, footpaths, parking, fences, gates
	5	3	1	2		Technical galleries
	5	3	1	3		Access control building
	5	3	1	4		Fire fighting equipment and medical station
	5	3	1	5		Shaft head building
	5	3	1	6		Ventilation building
	5	3	1	7		Chilled water production building
	5	3	1	8		Cold box and control Building
	5	3	1	9		Cooling plant Building
	5	3	1	10		SF Annex (demineralised water)
	5	3	1	11		Power converters building
	5	3	1	12		Electrical building
	5	3	1	13		Electrical substation (foundations)
	5	3	1	14		Waste material storage

1.3.2 Surface site PB

Site PB is a technical site. At this site, there will be no experiment area, and therefore, civil engineering is limited to the provision of buildings necessary to support the FCC-ee machine and the associated beam absorber, which will be sited in the underground areas of PB. The site also reserves the necessary space for the civil engineering required to accommodate a future hh machine, although these buildings will not be constructed during the FCC-ee phase. The space reserved will be used temporarily during the construction phase to house the civil engineering contractors plant, equipment, material etc. This surface site is the only one planned to be located on Swiss territory. The collaboration with the Fermi National Accelerator Laboratory also studied the need for a technical site, taking PB as an example. Building on the initial work, CERN has developed further layout scenarios for cost and planning purposes.

The product breakdown structure (PBS) for the buildings and associated civil engineering works to be constructed at site PB is given in Table 1.6.

Site PB is one of the smaller technical sites. Nonetheless, its location close to a protected water-course and within sight of nearby residential and agricultural properties will require rigorous integration studies to be carried out. The smooth integration in the existing landscape will be further studied during a subsequent project preparatory phase.

At FCC-ee phase, the principal surface infrastructure at site PB consists of:

Fig. 1.23 Preliminary simplified area requirements for PB surface site

- A shaft head building to accommodate the lifts, cranes, and staircases needed for personnel access to the underground areas and for the movement of material, equipment, and services between the surface and underground areas. This building also houses an unloading bay for trucks bringing material and equipment for transportation via the shaft to the underground areas. This building must be located directly over the associated shaft. The position of this building and the associated shaft could be adjusted within the site boundary to accommodate any changes or additions to the surface requirements and constraints. This building would typically be constructed as a steel-framed building on reinforced concrete foundations and a reinforced concrete slab to sustain the load imposed by the vehicles entering the building for unloading. The building would include a secure access area to ensure appropriate access control to the underground areas.
- A building will be constructed to house the equipment necessary for ventilating the underground areas, including the shaft, access gallery, accelerator tunnel, and beam absorber cavern. As this equipment includes motorised components that may generate noise, the building design will incorporate appropriate noise-reduction measures to ensure that noise levels at the site boundary remain within the required limits. The choice of construction materials and noise mitigation solutions will be determined based on technical and environmental considerations.
- Cooling plant buildings, including the cooling towers and associated pump houses, basins and the demineralised water plant building.
- Various buildings and structures to house electrical equipment, including buildings for power converters and an emergency power system.
- An access control building to house personnel undertaking security and safety operations at the site.

The location of site PB in flat, open countryside requires careful consideration of its integration into the surrounding landscape. To ensure minimal environmental impact, particular attention will be given to architectural and noise mitigation measures, both during the construction phase of FCC-ee and its subsequent operation.

As with site PA, the FCC-ee layout for site PB has taken into account the needs of a future FCC-hh collider, and space has been reserved for the necessary civil engineering. The site boundary fence at the FCC-ee phase will already encompass these future needs.

Figure 1.23 shows a simplified view of the PB surface site. The specific buildings required for FCC-ee are illustrated, along with the necessary space reservations for future FCC-hh civil engineering. A simplified cross-section is shown in Fig. 1.24.

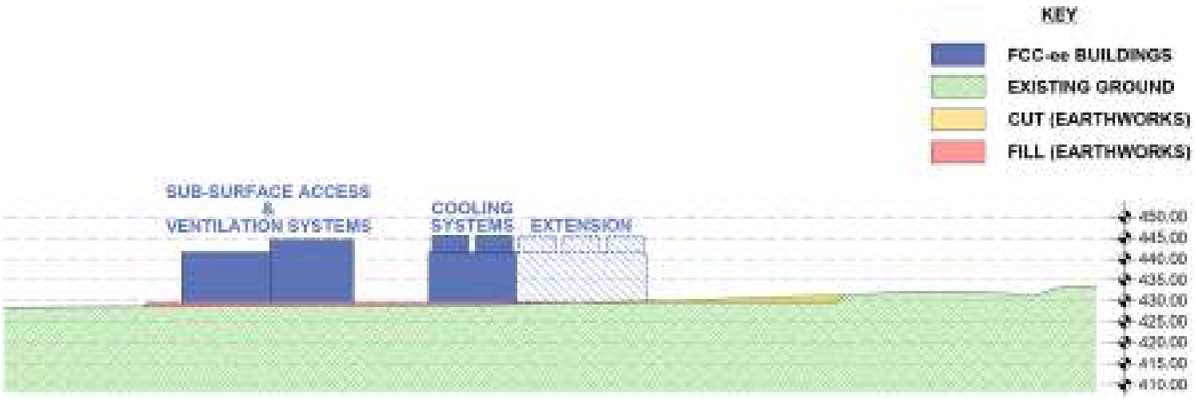


Fig. 1.24 Preliminary simplified cross-section of PB surface site

1.3.3 Surface site PD

Site PD has an identical function to site PA, namely, to house an experiment and provide support to the accelerator. As such, the requirements for civil engineering are almost identical, although the specificities of the local terrain and land plots require a different approach to the layout of the site.

The layout of the PD site has a number of constraints that need to be addressed. The main constraint is the planned future extension of the public road network in these areas, which reduces the potential land space for FCC at PD and requires a site access scenario that is compatible with the future layout. After several iterations, a site layout that meets CERN requirements and is compatible with the road development project has been developed. The proposed PD site is located on sloping agricultural land. The elevation change from one end of the site to another is about 20 m. This will require earthworks to be carried out to create a single flat platform on which to site the surface structures.

Other specific features of the site which will need to be addressed after the feasibility study include:

- The scheduling compatibility of the FCC-ee civil engineering works with the planned road extension project
- The proximity of a medical facility to the site will be taken into account in the site's design. Measures such as tree planting and landscaped features may be incorporated to ensure a well-integrated and visually harmonious environment.
- The need to pass under bridges local to the site may result in a limitation on the height of oversized components that can be transported to the site.

A simplified view and section of the civil engineering structures at PD are given in Fig. 1.25 and Fig. 1.26.

1.3.4 Surface site PF

PF is a technical access point with surface civil engineering structures similar in function to PB. In order to avoid siting surface buildings within an existing village, the PF surface site is offset by about 600 m from the axis of the accelerator tunnel.

The site is adjacent to a major road, minimising the need for new external roads to access the site. The necessary platform needed for the surface buildings will be of sufficient size to accommodate the future FCC-hh buildings. A simplified view and cross-section of the PF site are given in Fig. 1.27 and Fig. 1.28.

The main constraints at PF relate to the presence of a so-called 'humid zone'in the vicinity of the proposed site. This will require specific attention during the detailed design of the civil engineering structures to ensure that water run-off during the construction and operational phases does not impact this zone.

In summary, the construction of the surface civil engineering required for FCC-ee at PF is considered technically feasible. Particular attention will be given to implementing measures that ensure minimal environmental impact.

1.3.5 Surface site PG

PG is an experiment point with civil engineering requirements similar to those of PA. The site is situated on a plateau that is currently partially used for pasture and partially forested. To minimise the impact on the forested area, the surface buildings associated with the cooling plant and some of the electrical systems will be positioned in a secondary location approximately 300 m from the main site. This approach follows the example of the existing

Fig. 1.25 Preliminary simplified area requirements for PD surface site

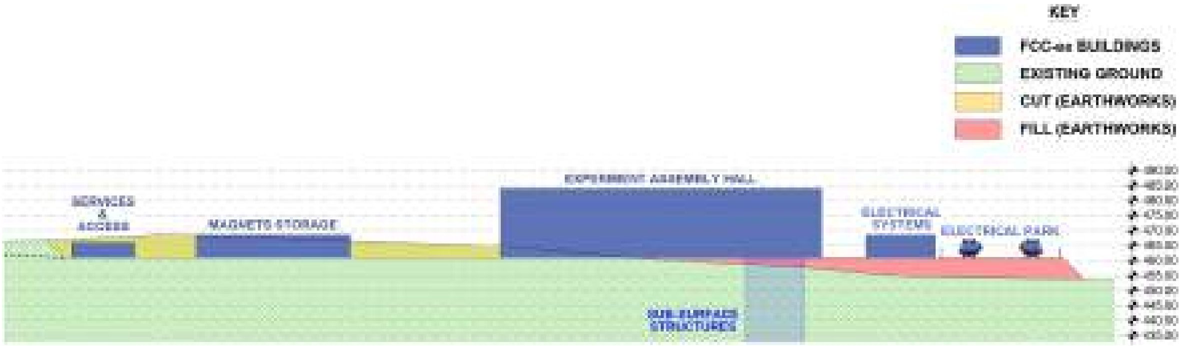


Fig. 1.26 Preliminary simplified cross-section of PD surface site

CERN LHC Point 4, where cooling towers and pump stations are located in an area remote from the main site, in this case, to reduce their visual impact. A simplified layout for PG is given in Fig. 1.29 and a simplified cross-section is given in Fig. 1.30.

In addition to mitigating visual impact, the layout of PG will be designed to ensure efficient use of space while maintaining accessibility for operations and maintenance. Noise reduction measures will be implemented where necessary to minimise any potential disturbances to the surrounding environment. Furthermore, efforts will be made to integrate the site harmoniously into the landscape.

1.3.6 Surface site PH

PH will be a technical area that will support not only the access and ventilation systems necessary for the accelerator tunnel, but also the infrastructure associated with the RF systems installed at this site.

Fig. 1.27 Preliminary simplified area requirements for PF surface site

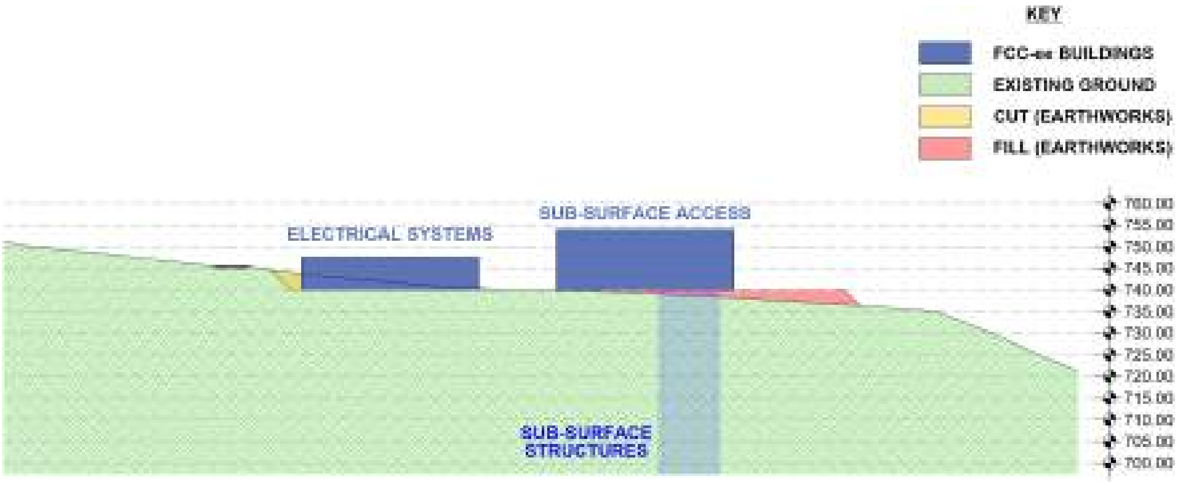


Fig. 1.28 Preliminary simplified cross-section of PF surface site

The surface site will have a larger footprint than PB and PF, as the power and cryogenics associated with the RF systems require additional buildings and dedicated foundations for infrastructure such as tanks and transformers.

The layout will be designed to optimise space efficiency while ensuring accessibility for maintenance and operations. Additionally, consideration will be given to minimising environmental impact and integrating the site with its surroundings through appropriate architectural and landscaping measures.

A preliminary simplified layout of PH is given in Fig. 1.31 and a simplified cross-section is given in Fig. 1.32

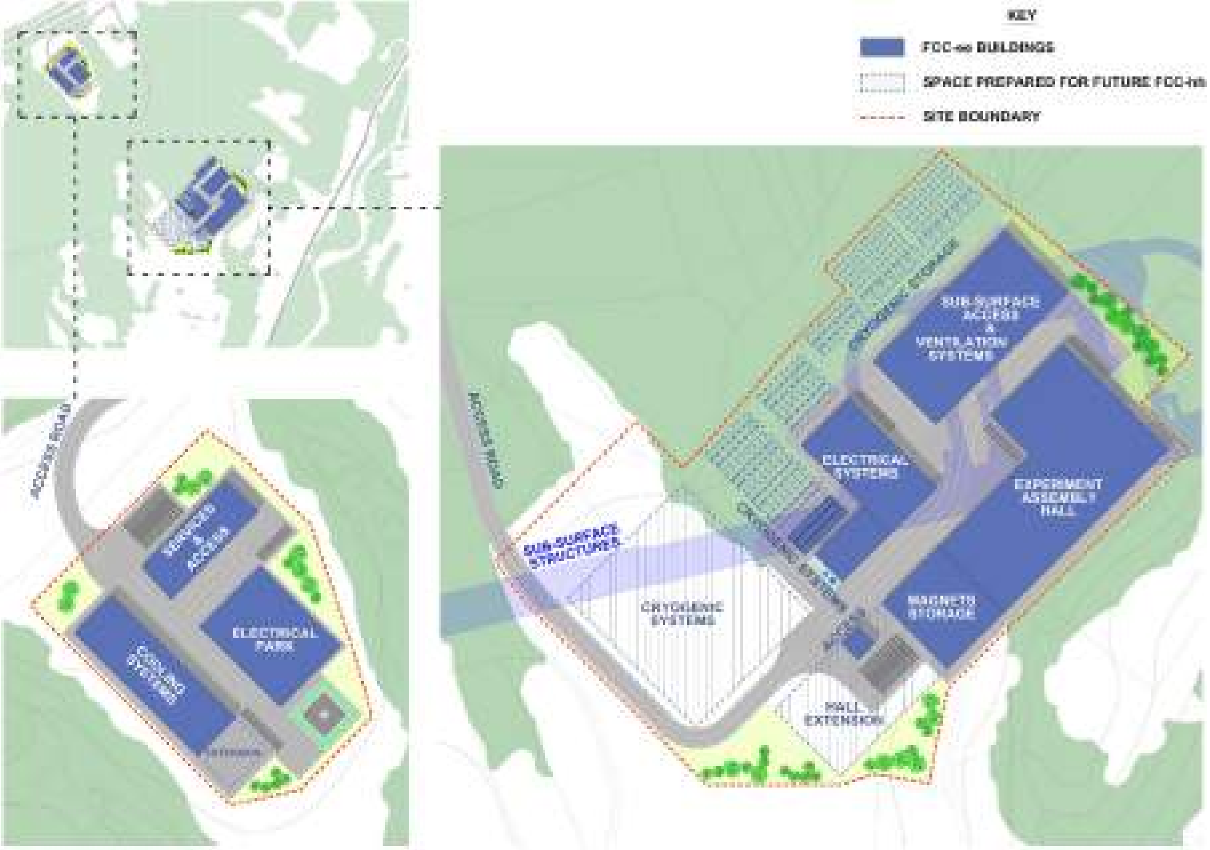


Fig. 1.29 Preliminary simplified area requirements for PG surface site

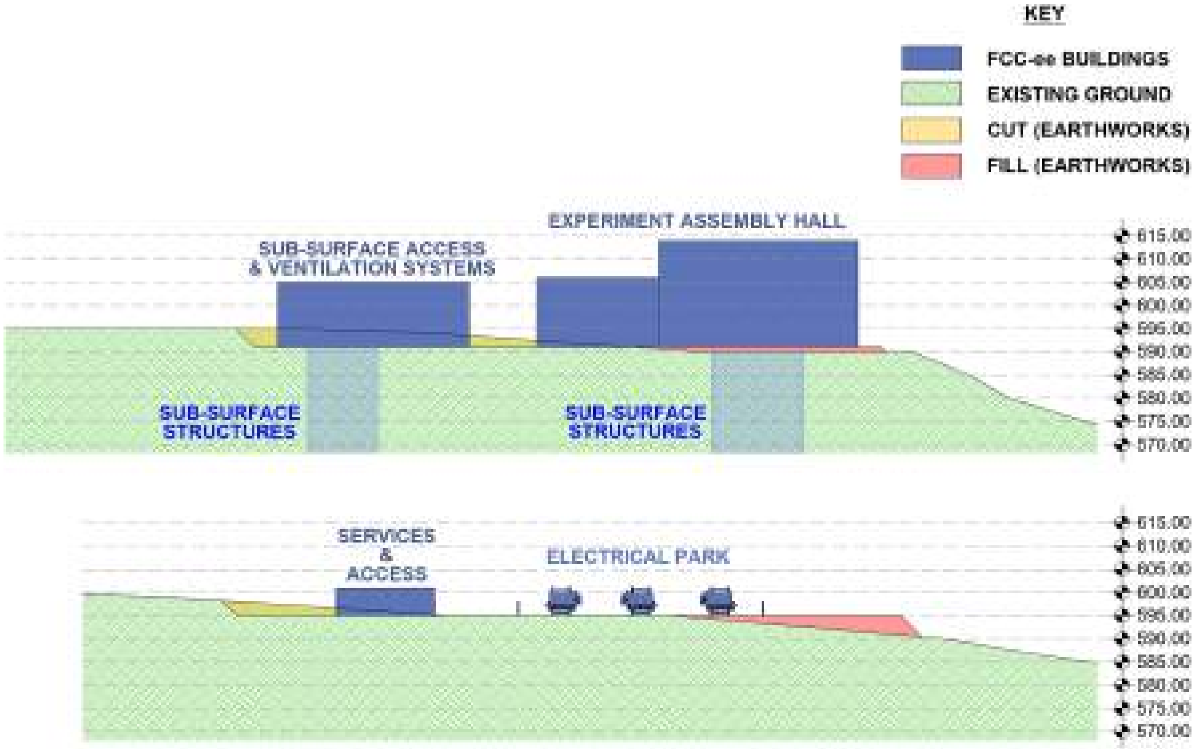


Fig. 1.30 Preliminary simplified cross-section of PG surface site

Fig. 1.31 Preliminary simplified area requirements for PH surface site

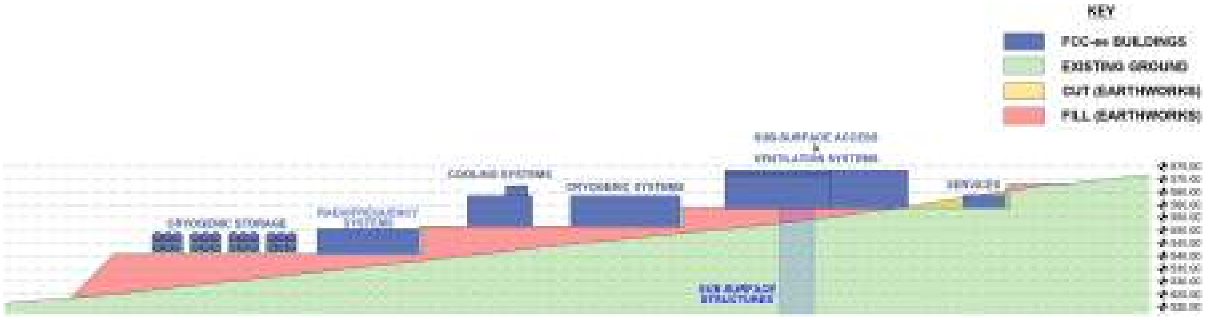


Fig. 1.32 Preliminary simplified cross-section of PH surface site

Site PH is currently located on sloping ground within an agricultural and forested area, with some houses in the near vicinity. This site will require specific studies into the visual impact of the site in order to identify measures that could be taken to reduce its visual impact on the surrounding area.

1.3.7 Surface site PJ

PJ will be an experiment area with similar civil engineering structures to those described for site PD. The site is located within agricultural land close to an autoroute. Beyond ensuring that the site is visually integrated into its surroundings, no significant challenges have been identified at this stage. A simplified layout for PJ is given in Fig. 1.33 and a simplified cross-section is given in Fig. 1.34

Fig. 1.33 Preliminary simplified area requirements for surface site PJ

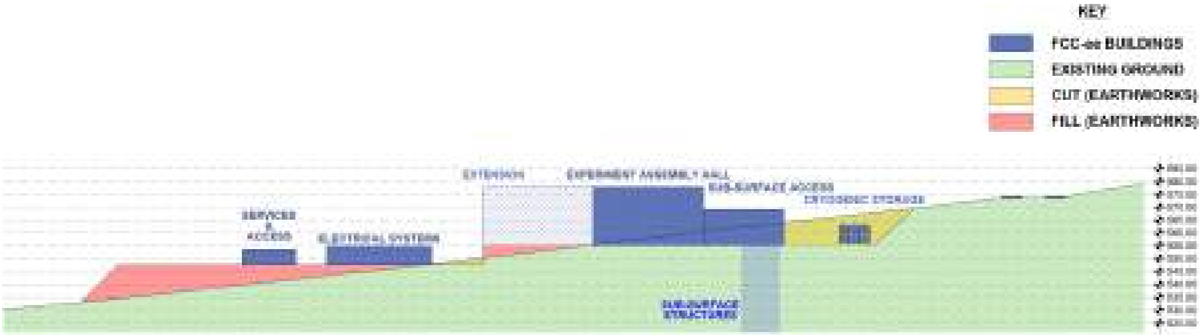


Fig. 1.34 Preliminary simplified cross-section of site PJ

1.3.8 Surface site PL

PL will be a technical area with similar requirements to PH due to the location of the Booster RF systems at this point. The potential presence of an aquifer linked to a potable water supply will need future investigation and if necessary, construction techniques and processes will need to be selected to ensure the aquifer is protected. A simplified layout for PL is given in Fig. 1.35 and a simplified cross-section is given in Fig. 1.36

In summary, preliminary requirements for all eight surface sites have been gathered and **preliminary** plan views and sections have been developed to a level sufficient for costing and planning purposes. The construction of these sites is considered technically feasible. However, a project preparatory phase will need to focus considerable effort to ensure that these sites are carefully integrated into their specific local environments. This process will need to be carried out in close collaboration with appropriate architectural specialists and must include a consultative process with the local inhabitants and other stakeholders. It may be necessary during this process to **adjust and**

Fig. 1.35 Preliminary simplified area requirements for surface site PL

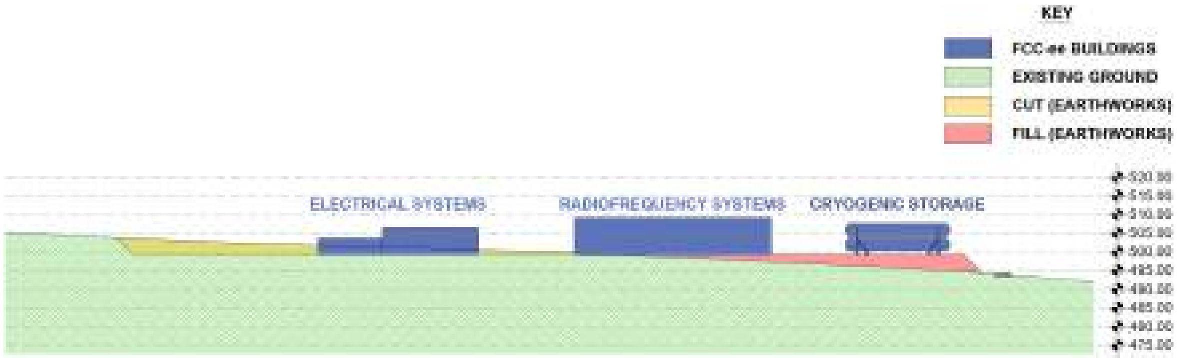


Fig. 1.36 Preliminary simplified cross-section through site PL

optimise the current preliminary layouts and locations to achieve an acceptable outcome for all stakeholders that conforms with technical requirements.

1.4 Staged approach

An assessment has been made of both the underground and surface civil engineering to identify structures that will only be needed for a subsequent FCC-hh machine and its associated detectors and to classify the identified structures into those for which construction can be deferred until after the completion of FCC-ee physics and those which need to be constructed simultaneously with the civil engineering for the FCC-ee machine. Consideration was given to both the cost and practicality of undertaking civil engineering for FCC-hh in a second stage after the operation of the FCC-ee machine.

1.4.1 Underground structures

Several underground civil engineering structures have been considered for staging as follows:

Experiment detector caverns The experiment detector caverns required for the FCC-hh are almost 100% larger by volume than those required for the FCC-ee detectors. The possibility of constructing the smaller experiment caverns in the initial FCC-ee phase and then enlarging them prior to FCC-hh was investigated. However, this scenario was eventually rejected as a feasible approach since very few of the first-phase structural elements of the cavern would be retained for the second phase, and it would be necessary to demolish the majority of the first-phase works. This would not only be prohibitively expensive and create significant quantities of waste material, but it would also represent a significant risk from a safety perspective since the reinforced rock around the periphery of the smaller FCC-ee cavern would need to be removed and re-supported for the larger FCC-hh caverns.

Service caverns The possibility of undertaking the construction of the service caverns that are adjacent to the experiment caverns at points PA, PD, PG and PJ was also considered. The driver for this was the possibility of co-locating the systems that would traditionally be housed in the service cavern, such as air treatment and demineralised water systems, in the experiment cavern. Alternatively, it was considered only to construct a part of the service cavern for the FCC-ee phase and construct the remaining part necessary for FCC-hh at a second stage. Constructing the second phase would require a complete re-mobilisation of the construction site at the surface and removing all systems from the service cavern and partially, at least, from the machine access shaft. It was eventually concluded that neither a full nor partial staging of the service cavern would bring any major benefits since the cost of relocating the services from one cavern to another and the cost of remobilising the construction site would increase costs considerably compared to completing the service cavern in one stage only.

Civil engineering for beam absorber The beam absorber system for FCC-ee requires only a localised enlargement of the beam tunnel over a length of 708 m. This will be constructed at PB.

The FCC-hh beam absorber system, although not yet fully designed, will be more complex and located at PF. It will require the construction of over two kilometres of additional tunnels, two beam dump caverns and several junction caverns. Since none of the FCC-hh beam absorber structures can be used at FCC-ee phase and given the criticality of PF for the overall construction schedule, it was deemed preferable to defer the construction of the FCC-hh beam absorber civil engineering to a second stage. The downside to this approach will be the need to re-establish a construction site and remove all services from the beam tunnel over several hundred metres on either side of PB. Furthermore, it will not be possible to transport personnel or equipment through the main tunnel in this area for a period of about two years while the FCC-hh beam absorber civil engineering is being carried out.

FCC-hh transfer tunnels The FCC-ee civil engineering includes a single transfer tunnel from the Prévessin site down to the FCC machine. The tunnel bifurcates to provide clock-wise and anti-clockwise injection into the FCC-ee. For a future FCC-hh machine, the pre-injection complex is likely to utilise either the current SPS or LHC tunnels with two new transfer tunnels for the clock-wise and anti-clockwise injection into FCC-hh. In the case that the SPS tunnel is re-configured to house the FCC-hh injector system, then a single additional transfer line with an approximate length of 3000 m and shaft for constructing the tunnel will be required. In the case that the LHC tunnel is re-purposed then two transfer tunnels each of about 2500 m length will be required, each with a single temporary shaft for construction purposes. A tunnel diameter of about 4 m would be required, and connection caverns would be created to connect the transfer tunnels to the FCC main tunnel.

Additional by-pass tunnels The FCC-ee civil engineering only includes by-pass tunnels at the four experiment sites PA, PD, PG, PJ. At the technical sites, by-pass tunnels are not required since a continuous transport corridor can be maintained through the accelerator tunnel.

For FCC-hh there is a possibility that at PB and PH new by-pass galleries may be required in order to avoid the need for personnel to frequently pass through areas of higher radiation (due to the presence of collimators). If a definitive need for these additional by-pass tunnels can be confirmed prior to FCC-ee civil engineering design works being completed, then it may be more efficient to include them at FCC-ee phase. In the case that the need is not fully confirmed, they can be constructed after the FCC-ee machine operation is complete. These would be constructed similarly to the additional by-pass tunnels that were constructed for the LEP 200 upgrade in 1995.

1.4.2 Surface structures

Staging of surface civil engineering for a future FCC-hh presents less technical difficulty than underground civil engineering since access to the construction zones is readily achieved. Although detailed assessments of civil engineering requirements for all eight surface sites have not yet been fully completed, initial studies at points PA and PB suggest that the following buildings could be constructed after FCC-ee physics is completed and before FCC-hh commissioning and operation.

Assembly halls for FCC-hh detectors elements Assessments of the assembly space needed for the larger FCC-hh detector elements, such as the superconducting magnet coil, indicate that for at least the two larger detectors, some components will have physical dimensions and weights that will make it impossible to transport them on the existing public roads without modifications to the existing public infrastructure. As such, it is likely that larger spaces and buildings will be required for the associated assembly activities.

This additional space would be required for manufacturing activities that would not normally be carried out at the site, such as coil winding. Since the precise needs for a potential FCC-hh detector are not known at this stage and since there will be at least a 20-year gap between the facilities needed for FCC-ee and FCC-hh detector assembly, it is not considered efficient or necessary to construct the larger facilities already at FCC-ee phase. However, to avoid unnecessary demolition and re-construction work in the future, the necessary space reservation for larger assembly halls will already be made at each of the four experiment sites. The space may be used for easily transferable facilities such as car parks or storage areas, but no complex facilities will be installed within these reserved areas, and, as far as possible, underground utilities will be avoided, including technical galleries.

Cryoplants A future FCC-hh machine will require greater cryoplant capacity than during the FCC-ee phase. It is currently expected that the four experiment sites and sites housing RF systems will require cryoplant facilities for the FCC-ee phase. However, a future FCC-hh would require upgraded larger plants at sites PA, PD, PG and PJ as well as new plants at Points PB and PF where no cryoplants are planned for FCC-ee. The same approach as the one adopted for the assembly hall will be taken, whereby space will be kept available and free of FCC-ee infrastructure for the currently expected FCC-hh cryogenics infrastructure. Furthermore, the landscaping and tree planting carried out for FCC-ee will, as far as possible, be executed in a manner that also serves the future FCC-hh needs.

Cooling and ventilation buildings Although cooling and ventilation systems will be required at all surface points for the FCC-ee phase, it is currently anticipated that cooling needs for the machine and experiments at FCC-hh will require plant upgrades including a possible increase in the cooling capacity and therefore number of cooling towers. This will be accommodated in the same manner as the cryoplant, with due account taken of potential space needs and visual/acoustic screening for the FCC-ee phase.

1.5 Subsurface site investigations

A dependable and comprehensive 3D geological model is essential for assessing the feasibility of underground civil engineering projects. Reliable geological and geotechnical data integrated into the model are required to design tunnels, caverns, and shafts. As the model evolves, the understanding of subsurface geology improves, enabling the identification of potential risks and constraints that could affect these structures. These factors may influence design, costs, and scheduling, making it vital to gather extensive subsurface information during the early stages of planning.

Since the autumn of 2024, CERN has been making a series of subsurface site investigations (SSI) using a combination of data acquisition methods. Once complete, the information obtained from these SSI will be used to enhance confidence in the 3D geological model for the FCC study area. The phase one SSI is currently about 40% complete, and the preliminary results are positive when compared to the model's predictions.

1.5.1 Geology in the region

For the purposes of the feasibility study and the targeted depths of the underground infrastructure, CERN has considered that the Geneva region features three primary geological strata: moraines, molasse, and limestone. A plan view of the Geneva basin geology is shown in Fig. 1.37.

The glacial moraines, characterised by their low strength, overlay the sedimentary molasse, which consists of horizontally bedded layers of marl and sandstone that vary significantly in strength. The thickness of the moraines ranges from just a few metres to over 100 metres. Bordering and intersecting the molasse are limestone formations, including the Alpine foothills and the Jura, Vuache and Salève chains. Limestone in the Jura and Vuache foothills can potentially contain karsts caused by chemical weathering. These karsts, often filled with water and sediment, can lead to water inflow and structural instability if encountered during excavation.

Beneath Lake Geneva, prior investigations have revealed very soft deposits, including lacustrine clayey silts and glacial-lacustrine silts and clays, with compressive strengths ranging between 2 MPa and 10 MPa. These deposits extend from the lakebed to approximately 260 metres in depth. Limited data exists for the Arve and Rhône Valleys, but soft deposits, including alluvial and alluvial-glacial moraines, are expected to reach depths of up to 100 metres. To mitigate construction risks and reduce water inflow challenges, the tunnel alignment has been situated at a depth that is expected to remain entirely below the moraines.

Fig. 1.37 Geology of the Geneva area

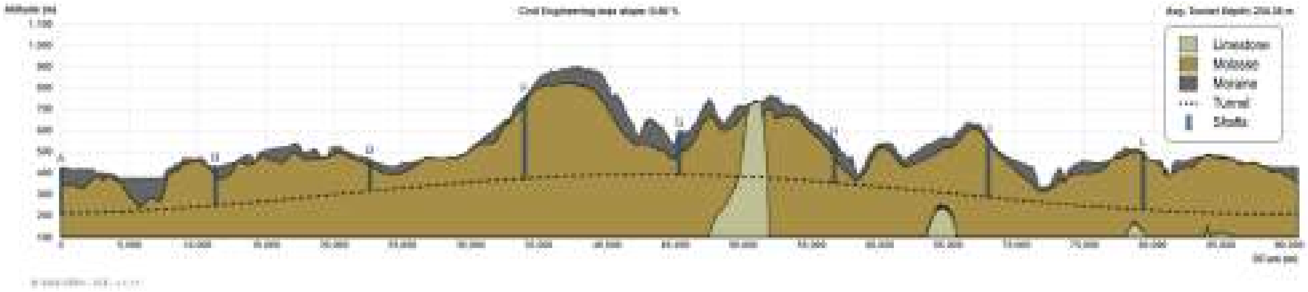


Fig. 1.38 FCC long geological profile

The molasse is composed of horizontally bedded layers of marl and sandstones. These layers can vary in strength but are considered to be mostly stable and dry. Molasse is generally considered a favourable geological stratum for tunnel boring machine excavation. For large-span caverns, constructing in stronger sandstone layers is preferable. The objective throughout the feasibility study has been to locate underground infrastructure within the molasse, as can be seen in Fig. 1.38, wherever possible.

1.5.2 Development of geological 3D model

Within the feasibility study, one of the primary objectives was to identify and locate the interfaces between the moraines and the molasse, and between the molasse and the limestone more precisely. Although data on the individual sub-strata of each layer exists, its quality is inconsistent and does not currently allow a clear separation of the moraines, molasse, and limestone into distinct sub-layers.

In collaboration with the University of Geneva (UNIGE) and specialist consultants from CERN's Member States, CERN has been developing a 3D geological model. This model is based on data from previous borehole investigations, geophysical surveys in the study region and the ongoing SSI campaign. Urban areas such as Geneva and its suburbs benefit from numerous logged boreholes, which provide a high level of confidence for the upper 50 metres of the subsurface. In contrast, rural areas have fewer logged boreholes, and certain locations, such as the foot of the Bornes and Mandallaz limestone outcrops, extend several kilometres without relevant geological data at the depths where the FCC underground infrastructure is proposed.

To improve understanding of the geological conditions along the proposed FCC tunnel, a targeted subsurface investigation campaign has been designed and is currently underway in areas of greatest geological uncertainty.

This campaign, which commenced in October 2024 and will continue until December 2025, combines geophysical surveys with deep borehole drilling. Geophysical surveys are first conducted using seismic refraction to examine shallow strata and seismic reflection to explore deeper layers. The collected data is then processed and interpreted to guide targeted drilling at depths ranging from 70 to 500 metres. By integrating these complementary methods, the reliability of the geological model in previously uncertain areas is significantly enhanced. This, in turn, increases confidence in the estimated construction costs and schedules, provides valuable information for the preliminary civil engineering design stage, and establishes key geological and geotechnical parameters prior to more targeted investigation campaigns.

Once the updated geological model is finalised, it, along with all individual borehole logs and geophysical interpretations, will be made publicly available. This data will contribute to a broader understanding of the geology in the region of the FCC, serve as a foundation for academic research, and potentially support future infrastructure projects beyond the FCC.

1.5.3 Phase 1 subsurface site investigations

To identify the site investigation to undertake in the first phase, three main criteria were considered:

1. Areas where there is a risk of the tunnel crossing the molasse interface into moraines or limestones.
2. Areas where crossing limestone is unavoidable.
3. Areas where there is a complete lack of relevant geological information.

Using these three criteria, the phase one SSI campaign has been divided into nine separate sections namely; Jura 1, Jura 2, Lake, Arve, Bornes, Mandallaz, Usses, Vuache and the Rhône.

The individual sections depicted in Fig. 1.39 each present unique uncertainties and challenges. The following sections will describe the current uncertainties in each area, explain the objectives of the subsurface investigations, and present the preliminary results from the investigations already completed.

Jura 1 Section Jura 1 is situated at the base of the predominantly limestone Jura mountain range, extending for approximately eight kilometres from Challex in France in the south to Satigny near CERN in Switzerland in the north. The proposed alignment is located at depths ranging from about 140 metres beneath the Allondon Valley at its shallowest point to 250 metres at its deepest on either side of the valley.

The understanding of the subsurface conditions in this section has been enhanced through recent investigations by other parties. In 2021, an extensive campaign of 2D and 3D geophysical investigations was conducted by the Canton de Geneve and the Services Industrial de Geneve as part of the *GEothermies* programme. Additionally, borehole data obtained near Satigny clearly identified the molasse-limestone interface, and encountered artesian water flows near this interface. The data from this campaign was incorporated into a 3D geological model developed in collaboration with UNIGE, which allowed a reduction in the planned scope of further investigations and provided an updated prediction that, in the northern part of the section, the limestone is located at a greater depth than previously expected.

Despite these advances, residual uncertainties remain—most notably in accurately defining the interface between the limestone and the molasse. As confidence in the updated data diminishes toward the southern portion of the section, further subsurface investigations remain necessary. Such investigations are required to confirm the current hypotheses and to ensure that the tunnel and associated underground infrastructure avoid limestone wherever feasible, thus mitigating the risks associated with unforeseen high water pressures and challenges associated with tunnelling in limestone.

The SSI in Jura 1 are scheduled to begin in mid-2025 and will continue until the end of 2025. The following is planned:

- thirteen boreholes ranging from 230-270 m in depth:
  - one fully cored
  - twelve destructive and cored
  - three boreholes are optional, depending on the results achieved from geophysics and adjacent boreholes
- 13 high-resolution seismic reflection profiles with a total length of 23,510 m

The locations of the SSI in the section Jura 1 are shown in Fig. 1.40.

Jura 2 Section Jura 2 is located between Lake Geneva and the base of the Jura mountains, extending approximately three km from Meyrin in Switzerland to Ferney-Voltaire in France. The civil engineering infrastructure in this area is planned to be situated at about 200 m below the surface. At this depth, 3D geological models indicate the potential for limestone to be present near the tunnel and primary infrastructure, similar to the risks identified in Jura 1.

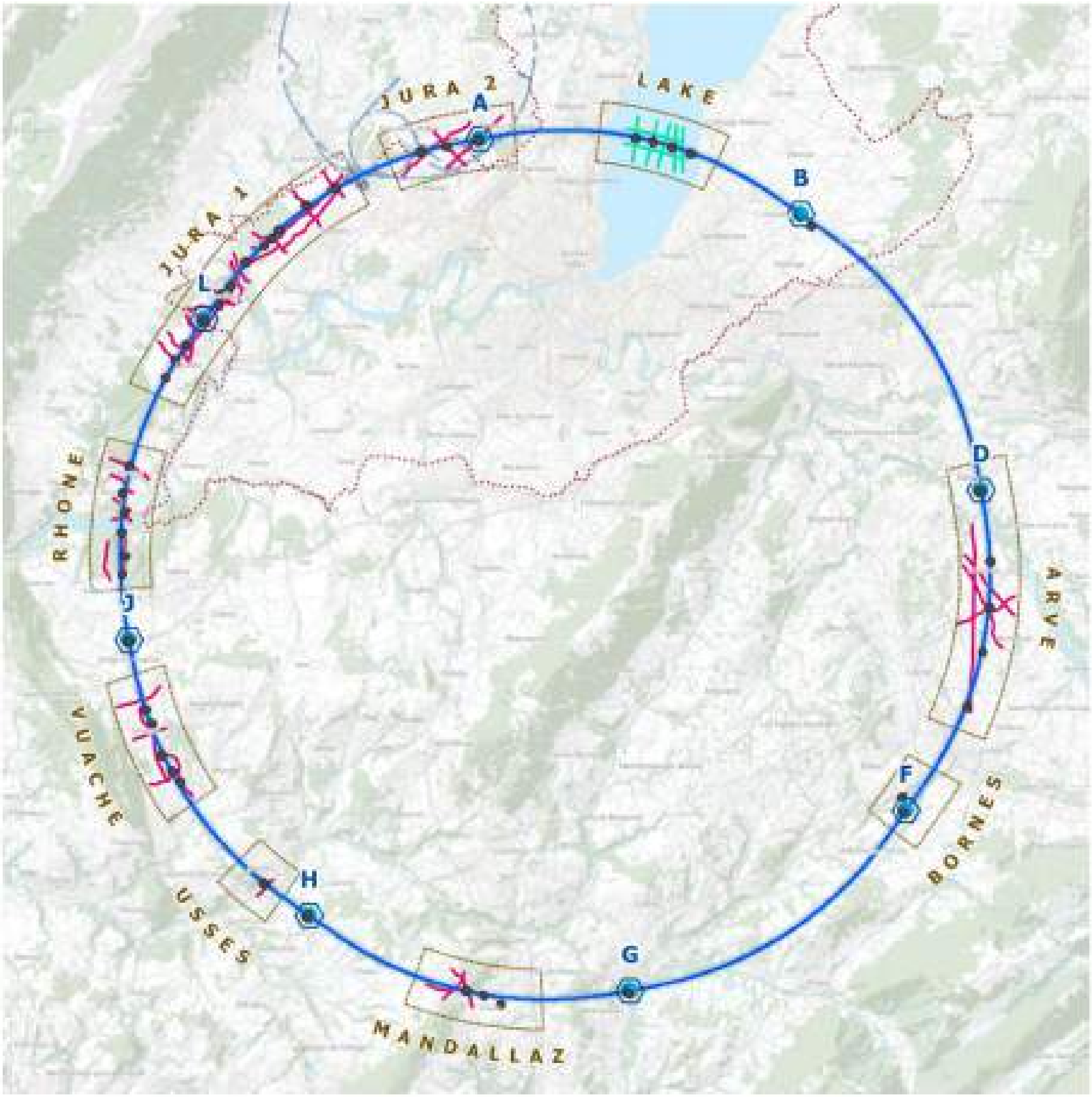


Fig. 1.39 Areas of geological uncertainty

Recent improvements in understanding have been achieved by incorporating seismic data from the nearby *GEothermies* programme into the geological models. This updated information suggests that the top of the limestone is deeper than predicted.

The targeted SSI will enable further improvements to the understanding of the molasse-limestone interface.

The following SSI is planned to start in mid-2025 and will last until late 2025:

- three boreholes ranging from 240-250 m in depth.
  - one destructive and partially cored.
  - one fully cored.
  - one optional destructive and partially cored depending on the results of the geophysics and adjacent boreholes.
- 7300 m of high-resolution reflection seismic geophysics.

The locations of the proposed SSI are shown in Fig. 1.41.

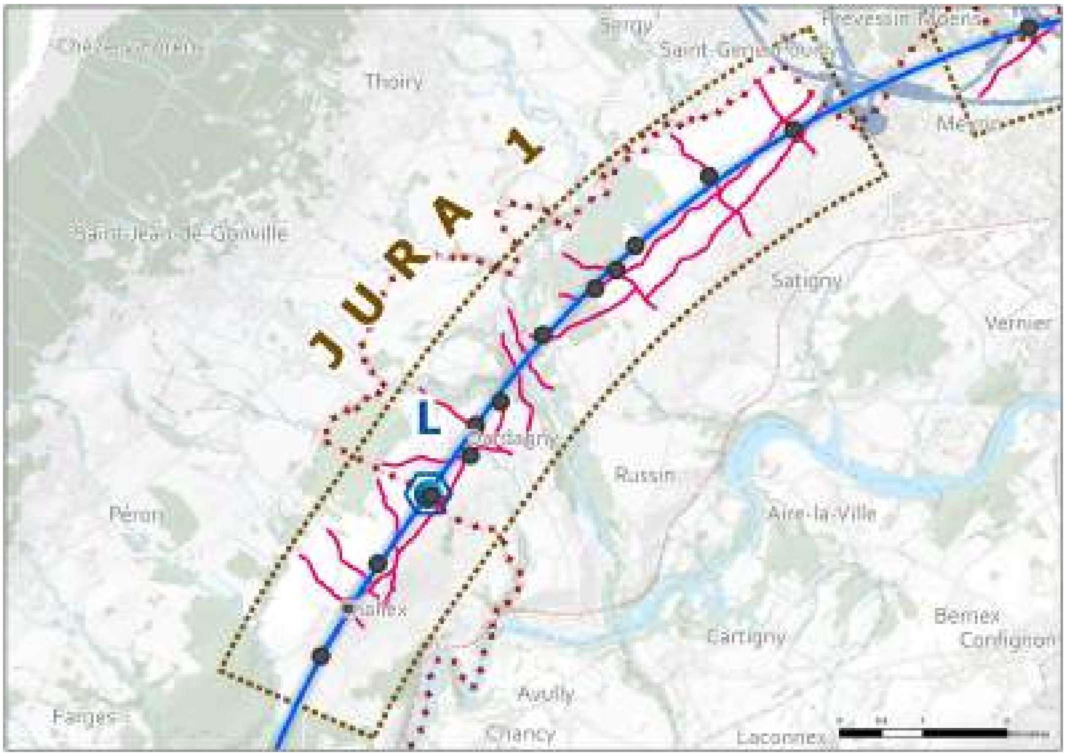


Fig. 1.40 Jura 1 section showing the locations of the investigations

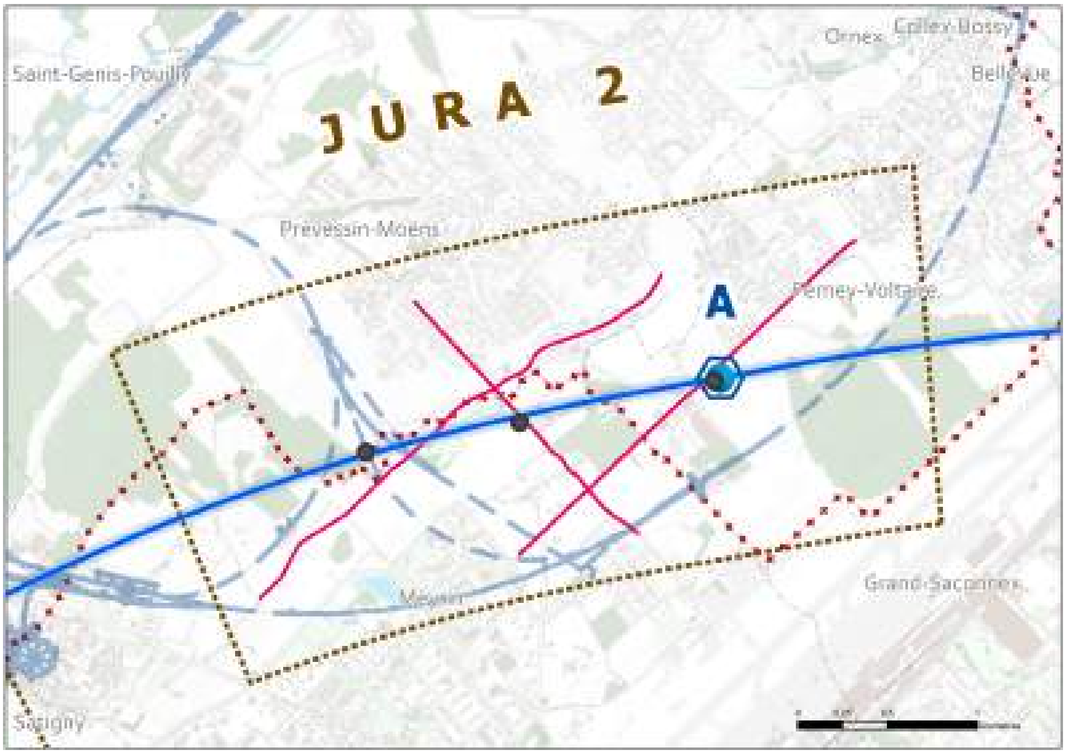


Fig. 1.41 Jura 2 section showing the locations of the investigations

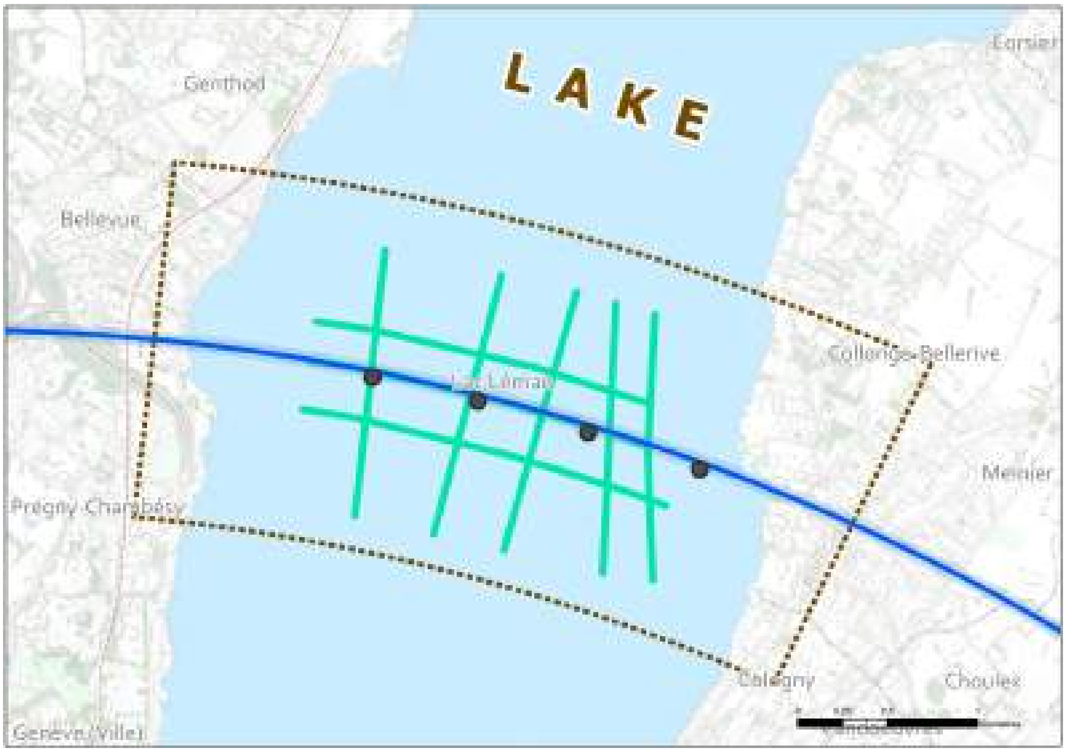


Fig. 1.42 Lake section showing the locations of the investigations

Lake Under Lake Geneva, the proposed FCC tunnel is at a depth of approximately 100 m below the bottom of the lake. The subsurface geology is characterised by moraines of mixed characteristics; however, the absence of pre-existing borehole data in this area has led to uncertainty in the geological model.

Improvements in understanding have been achieved by incorporating data from the GEothermies programme (acquired south of the proposed alignment) into the 3D geological model. Although this data does not clearly define the interface between the moraines and the underlying molasse to the north where the proposed FCC tunnel is foreseen, it does indicate that the interface is located at a higher depth than previously considered.

Avoidance of the moraines is considered a key design priority, as tunnelling in water-bearing moraines can be challenging. This will be confirmed after the SSI campaign.

The following SSI is planned to start in mid-2025 and will last until late 2025:

- four fully cored boreholes ranging from 130-180 m in depth.
- 16,340 m of offshore seismic reflection.

The locations of the proposed SSI are shown in Fig. 1.42.

Arve The Arve section, located at the eastern extremity of the proposed FCC tunnel, extends approximately eight km in length, with the proposed FCC tunnel depth varying between 140 and 170 m. Situated within the Arve Valley and adjacent to the Arve River, the area is known to be made up of a mixture of molasse and glacial moraines near the surface, although geological data at the proposed FCC tunnel depths is limited.

Further investigations will confirm the depth of the molasse-moraine interface and ensure that the tunnel remains within the molasse, thereby avoiding the potentially water-bearing moraines.

The following SSI is planned to start in early 2025 and will last until mid-2025:

- five destructive and cored boreholes totalling 990 m in depth.
  - ○ Up to three of these boreholes may not be undertaken following results from geophysics.
- three high-resolution seismic reflection lines totalling, 13,150 m.

The locations of the proposed SSI are shown in Fig. 1.43.

Bornes The area adjacent to the Bornes Plateau is the deepest section of the project, with depths ranging from 500 to 560 m over five km. The deepest access shaft at PF, approximately 400 m deep, is also located within this section.

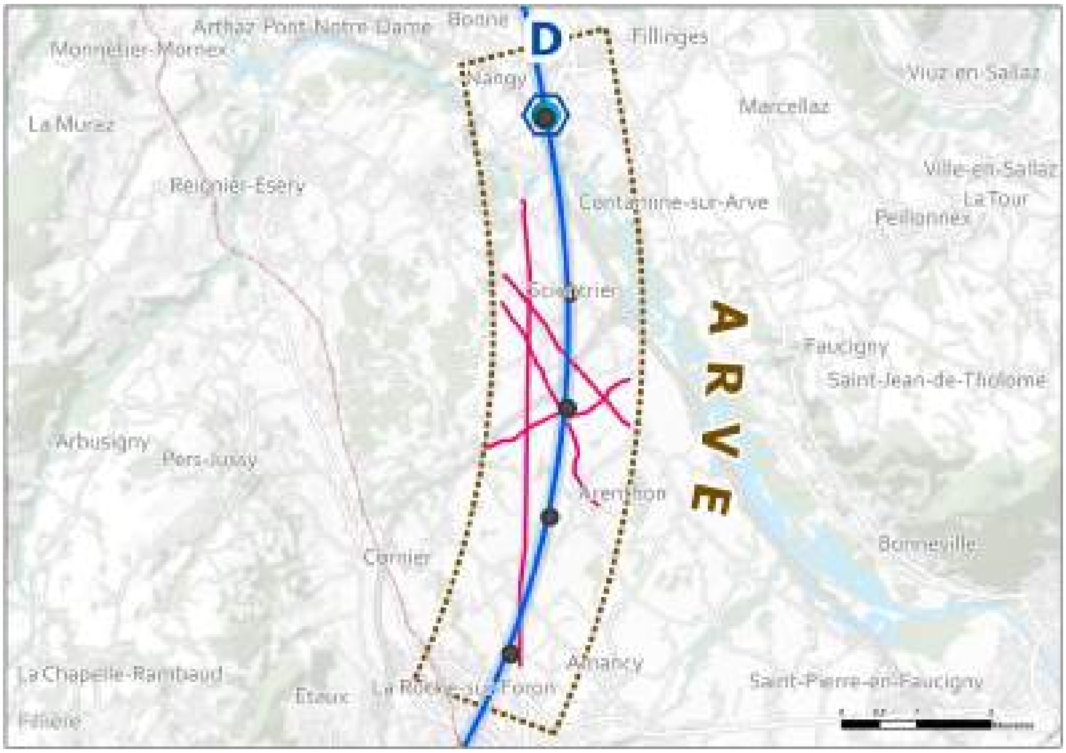


Fig. 1.43 Arve section showing the location of the investigations

The proposed FCC tunnel will remain within the molasse, as the limestone is situated much deeper—nearly 1000 m below the surface. However, little is known about the characteristics and quality of the molasse. Additionally, thrusts, faults, and potential tectonic materials have been identified in the region.

Given these factors and the high overburden, further investigations are required to obtain detailed information on the molasse and reduce geological uncertainties in this sector.

The following SSI is planned to start in early 2025 and will last until mid-2025:

- one fully cored borehole totalling 425 m in depth.

The locations for the SSI are shown in Fig. 1.44.

Mandallaz The Mandallaz is an anticline limestone range characterised by faulting and thrusting over the underlying molasse on its western side. Little detailed geotechnical information was available prior to the start of the SSI campaign. This presented uncertainties regarding the extent of the limestone and the nature of its structure.

Improvements in understanding have been achieved through geophysical investigations as part of the SSI. Data acquisition has been completed, and provisional interpretations indicate that the limestone at the depth of the proposed FCC tunnel is narrower than modelled before the campaign. This revised interpretation suggests that the section requiring tunnelling through limestone is shorter than initially foreseen. Additionally, preliminary borehole data have revealed the presence of small karsts and traces of hydrocarbons, and provisional geophysical interpretations have identified an east-west strike-slip fault across the Mandallaz mountains, although this has yet to be confirmed by the boreholes.

The following SSI has been carried out or is taking place:

- three fully cored boreholes totalling 1240 m in depth
  - one of these boreholes is inclined at 30° from vertical
  - one of these boreholes may not be required to be undertaken following the results of the first two boreholes.
- three high-resolution seismic reflection lines totalling, 5100 m.

The locations for this SSI are shown in Fig. 1.45.

Usses The Usses, a small section extending roughly one km, is where the proposed FCC tunnel is closest to the surface, with about 50 m of cover above the tunnel at the lowest point in the Usses Valley.

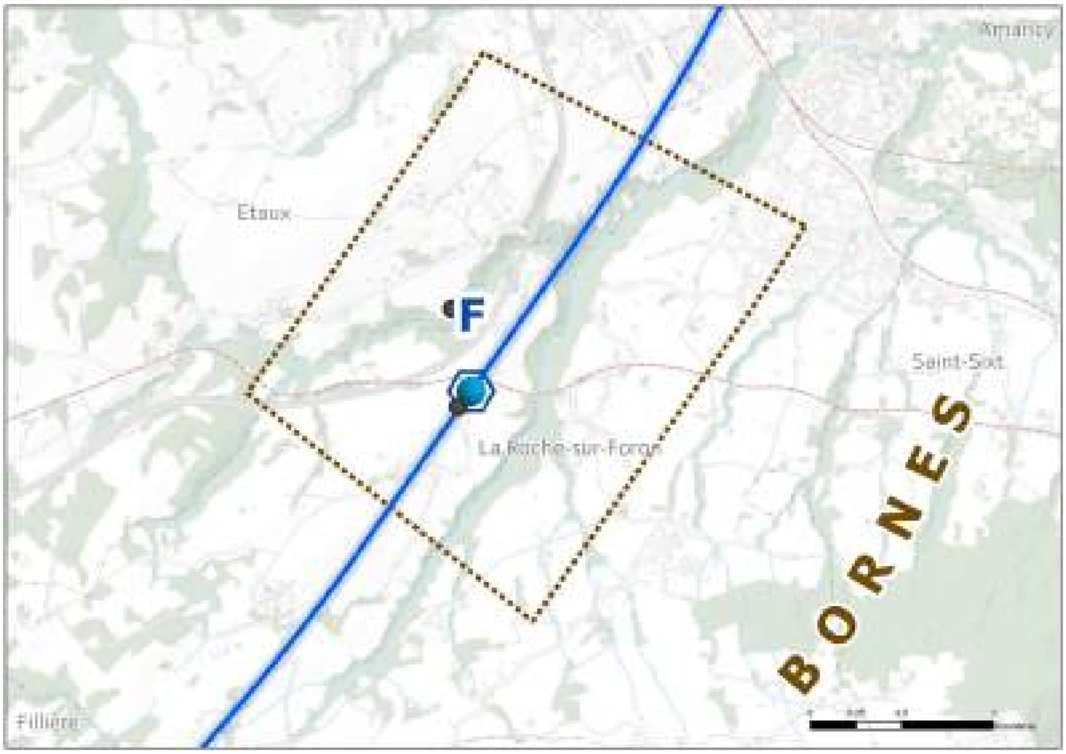


Fig. 1.44 Bornes section showing the locations of the investigations

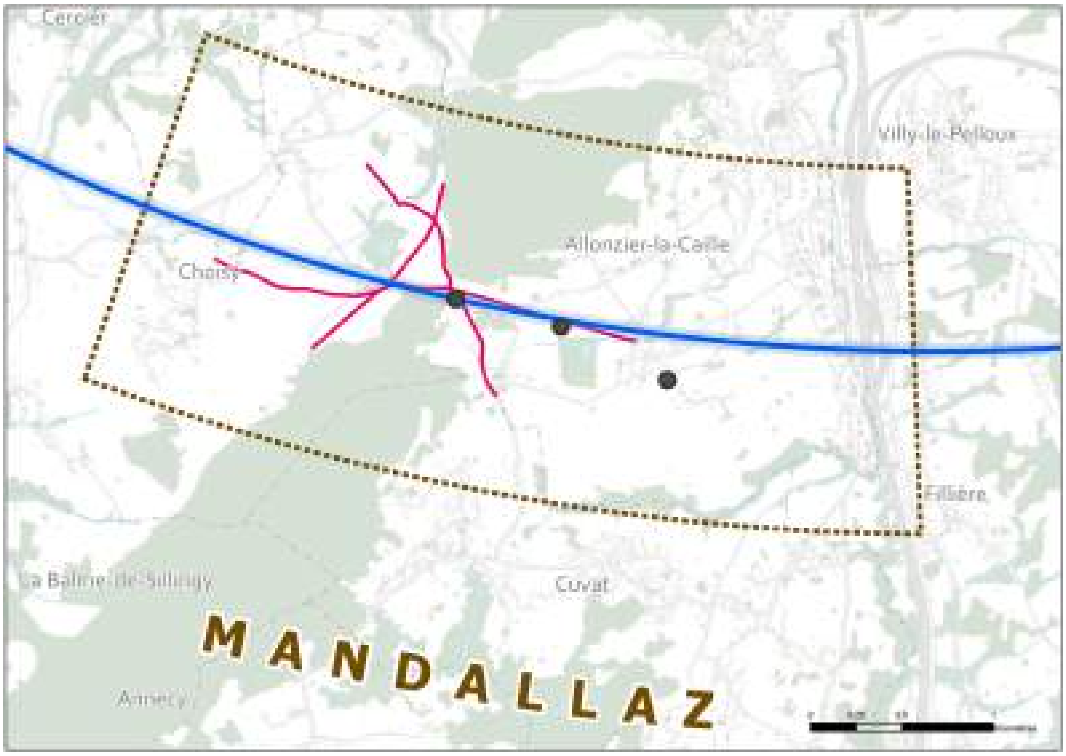


Fig. 1.45 Mandallaz section showing the locations of the investigations

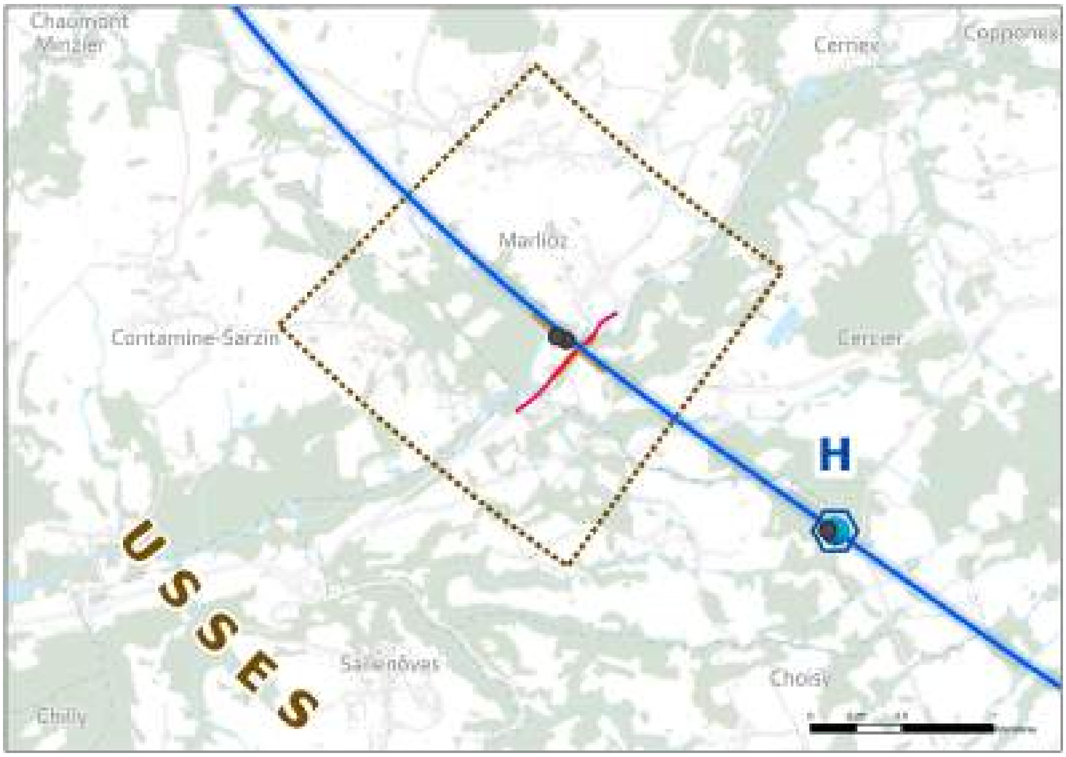


Fig. 1.46 Usses section showing the locations of the investigations

On-site investigations have improved the understanding of the subsurface conditions in this sector. All data acquisition has been completed, and the final interpretation of the geophysical data is underway. Borehole results indicate that the moraine-molasse interface is encountered at 15 m, shallower than modelled, suggesting that the proposed tunnel does not intrude into water-bearing moraines beneath the Usses River. This will be confirmed once the final geophysical interpretations are complete and compared against the borehole log.

The following SSI has been undertaken:

- one fully cored borehole of 70 m.
- two seismic refraction lines totalling 780 m, the first performed using an explosive source and the second utilising a weight drop source.
- one very high-resolution seismic reflection of 770 m in length.

The locations for the SSI are shown in Fig. 1.46.

Vuache The Vuache section at the southwestern extent of the proposed FCC tunnel extends over approximately four km, with proposed tunnel depths ranging from 190 to 300 m and an average depth of around 250 m. The Vuache mountain range, primarily an anticline structure bounded by thrust faults, underlies this section, with the prominent Vuache Fault located to its south-west. The geology is dominated by Jurassic-Cretaceous limestones and marls, overlain by the typical molasse found elsewhere in the Geneva basin.

Geo-physical investigations carried out as part of the SSI have improved the understanding of the subsurface conditions. One completed borehole has confirmed that molasse is present to about 30 m below the tunnel. The ongoing analysis of the geophysical data, along with additional borehole results, will identify whether this is also the case for the remainder of the section.

The following SSI has been carried out or is taking place:

- five destructive and partially cored boreholes totalling 1270 m in depth.
  - two of these will be optional, depending on the conclusions of the geophysics.
- five high-resolution seismic reflection lines totalling, 9370 m.

The locations of the SSI are shown in Fig. 1.47.

Rhône In the Rhône Valley, the proposed FCC tunnel is located approximately 50 m below the surface under the Rhône River and the environmentally sensitive Marais de l'Etournel. The overlying soils are predominantly

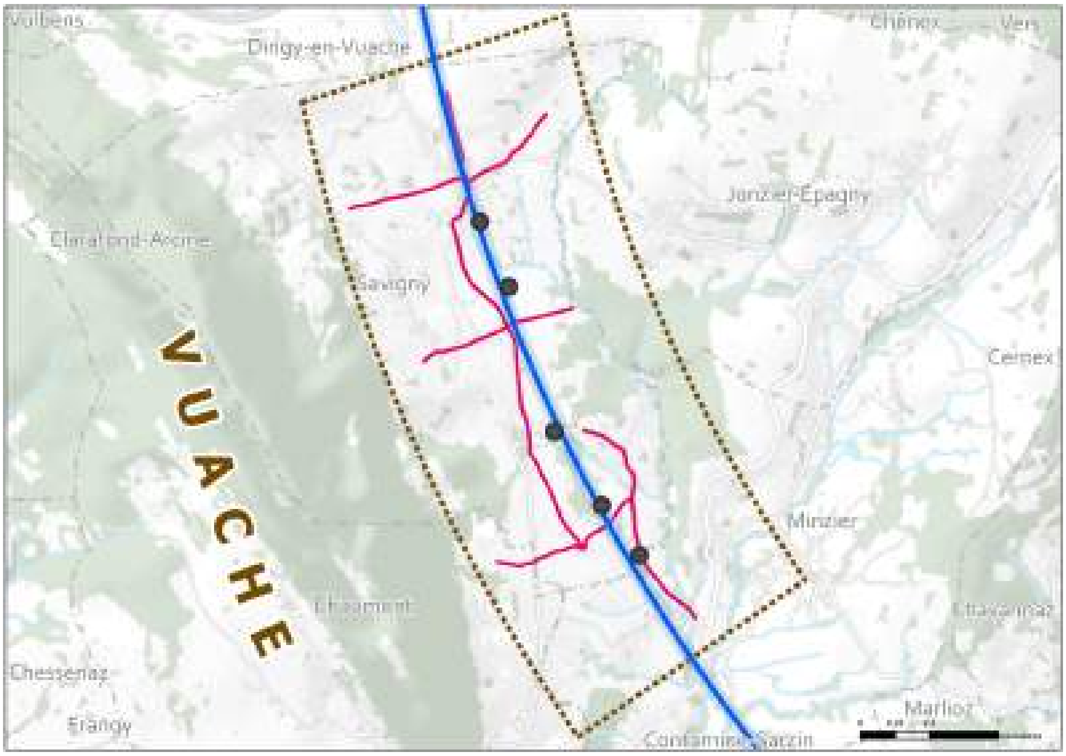


Fig. 1.47 Vuache section showing the locations of the investigations

composed of moraine or alluvial sands, gravels and boulders, and the area was formerly quarried as a source of gravel. These layers are saturated due to the influence of the Rhône River.

The current geological model predicts that the tunnel is situated entirely within the molasse, although the interface between the molasse and the overlying moraine is predicted to be close. While limited available data has allowed this initial interpretation, the scarcity of detailed geotechnical information limits its precision.

As a result, further investigations are required to accurately define the moraine–molasse interface and confirm that the proposed FCC tunnel remains fully within the molasse, thereby mitigating potential risks associated with the water-bearing overlying layers.

The following SSI could start in mid-2025 and finish by late-2025:

- six destructive and partially cored boreholes totalling 765 m in depth.
  - Four of these boreholes may not be required following results from geophysics.
- eleven geophysics seismic lines.
  - four profiles of high-resolution seismic reflection totalling 4920 m towards the upper part of the valley.
  - four profiles of very high-resolution seismic reflection totalling 2990 m towards the bottom of the valley.
  - four profiles of seismic refraction at the bottom of the valley using a weight drop source, totalling 240 m.
- five high-resolution seismic reflection lines totalling 9370 m.

The locations of the SSI are shown in Fig. 1.48.

1.5.4 Phase 2 sub-surface site investigations

After the completion of the first phase of the SSI at the end of 2025, a geotechnical and civil engineering specialist may be contracted in early 2026—subject to the decision-making process—to analyze the campaign results and the corresponding geological model. Working in collaboration with CERN, this specialist would define the scope and technical specifications for the second phase of the sub-surface site investigation and oversee the on-site operations.

This second phase would focus primarily on obtaining the necessary geotechnical data for the detailed design of all underground and surface works to be undertaken. In particular, the second phase would focus on the sites where experiment and service caverns are required since these require very detailed knowledge of the lithology and rock engineering properties in order to undertake the complex numerical analysis required to define the rock support necessary to create stable underground structures.

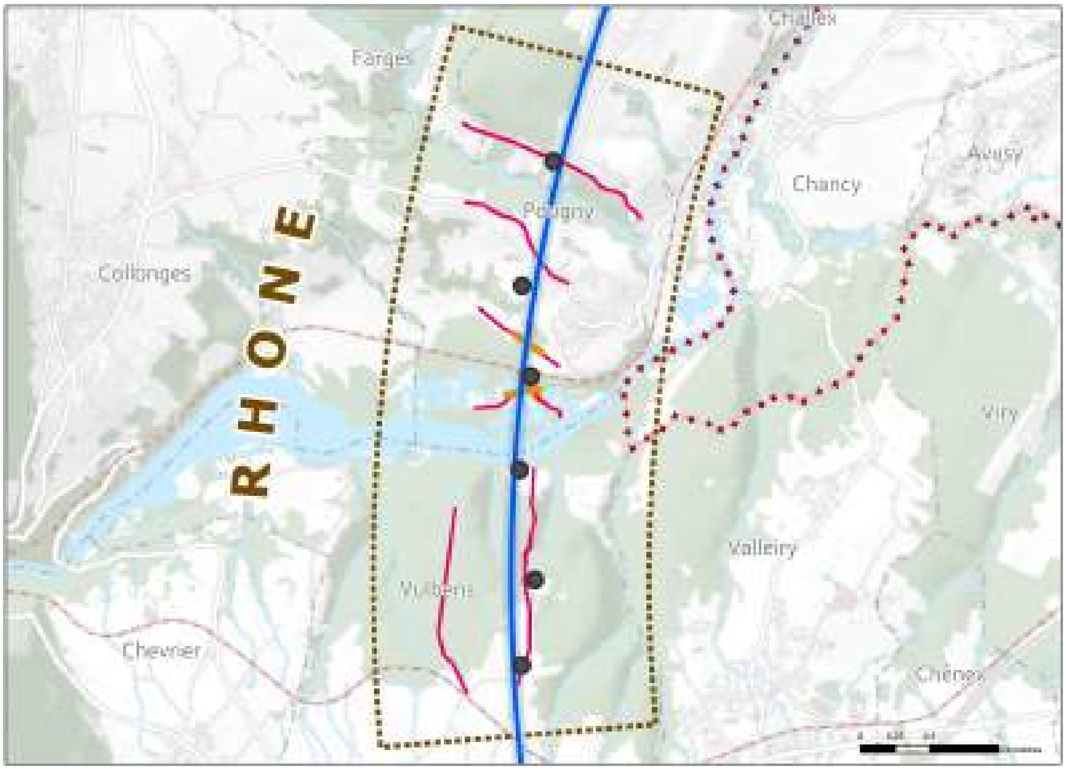
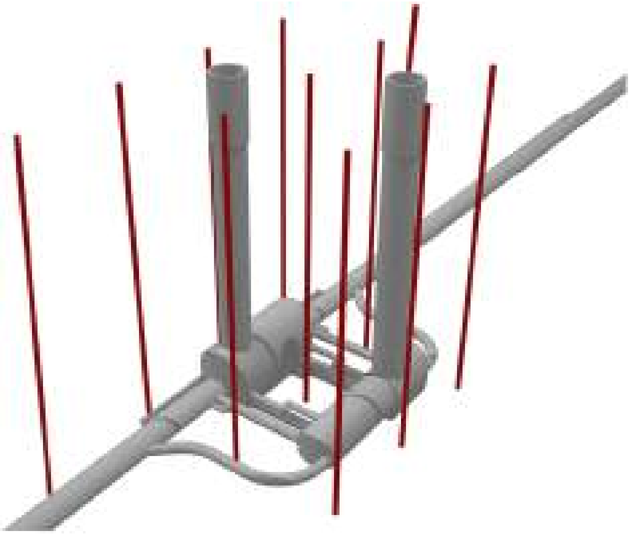


Fig. 1.48 Rhône section showing the location of the investigations

Fig. 1.49 Example of targeted borehole investigations for experiment cavern complexes



Detailed Investigations Around Key Infrastructure Precise geological, geotechnical, and hydrogeological data are essential for the effective design of both experiment and service caverns, which are typically located at depths of several hundred metres. This information ensures structural integrity and supports the selection of appropriate construction methodologies. An indicative example of a typical drilling configuration can be observed in Fig. 1.49.

These boreholes will accurately characterise the molasse at the cavern depth, identifying structural features such as fractures and weak zones that could affect cavern stability. Core samples and in-situ testing will determine the molasse's strength, deformability, and stress state, enabling precise structural analyses and the design of appropriate excavation and support systems. In addition, data on groundwater levels, permeability, and pore pressures will inform dewatering plans and help manage water ingress - factors critical to ensuring safety and stability during and after construction. Consequently, the borehole data from this campaign will be essential for optimising excavation methods, reducing risks, and estimating construction costs accurately.

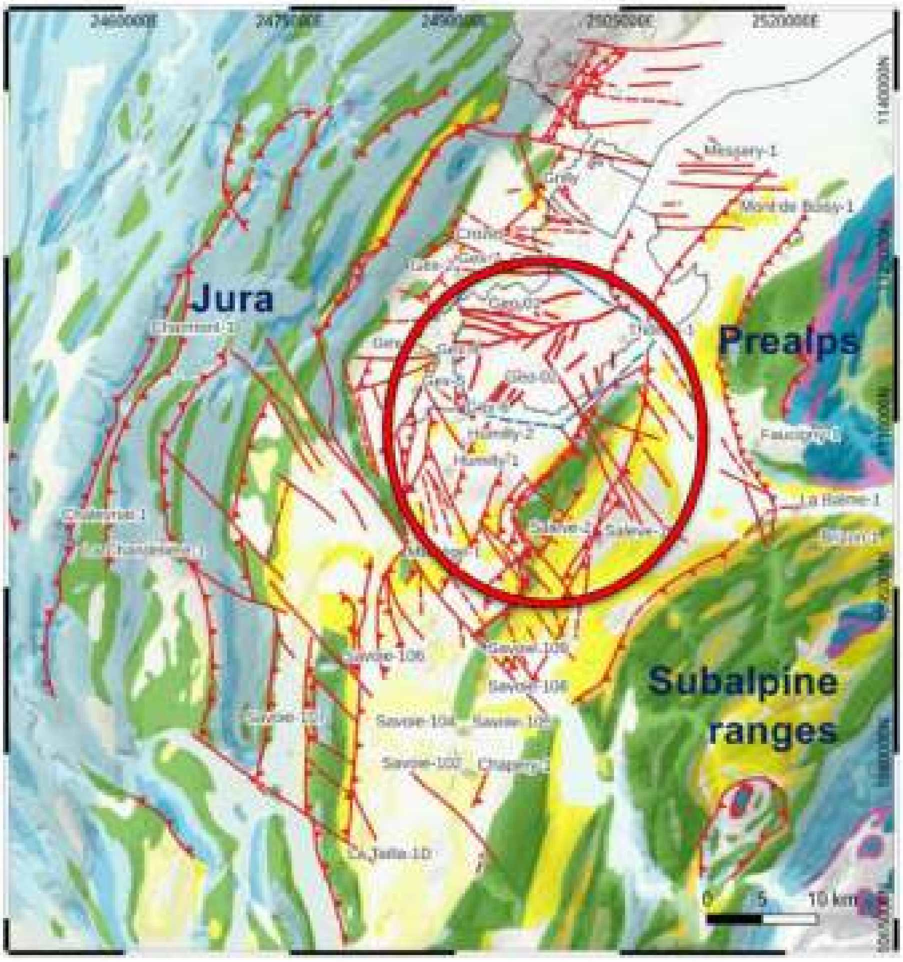


Fig. 1.50 Fault map of FCC study area

1.5.5 Fault Mapping and Seismic Modelling

The FCC study region is known to contain active or potentially active faults, including the Vuache Fault. Historical seismic events have provided valuable insights into the area's seismic behaviour.

While detailed study of seismic activity and structural faulting was not the primary focus of the first phase of the SSI, CERN, in collaboration with the University of Geneva, has utilised historical data to identify the main fault zones in the region, as shown in Fig. 1.50.

The proposed FCC tunnel is expected to pass through a zone with faulting, as illustrated in Fig. 1.51. In areas such as the Mandallaz and Jura sections, where faults are known to be present, further refinement of fault characterisation will be possible once the fully processed results from the phase one SSI campaign become available. This will continue to be developed in collaboration with external partners over the coming years.

1.5.6 Summary of the Subsurface Site Investigations

The subsurface site investigations that have already been carried out as part of Phase One have improved the reliability of the 3D geological model for the proposed FCC tunnel. The preliminary results from investigations in the key sections of Mandallaz, Usses, Vuache and Arve have been integrated into the model, and early results show promising signs that the FCC tunnel would be located within the molasse except in the Mandallaz section, where crossing the limestone is unavoidable.

The results from the remainder of the campaign will need to be fully acquired and processed before any definitive conclusions on the precise elevation of the tunnel can be made. However, current indications are that the tunnel might be shallower than currently planned. This would allow an overall reduction in shaft depth, reducing the impact and, therefore, have positive cost and schedule implications

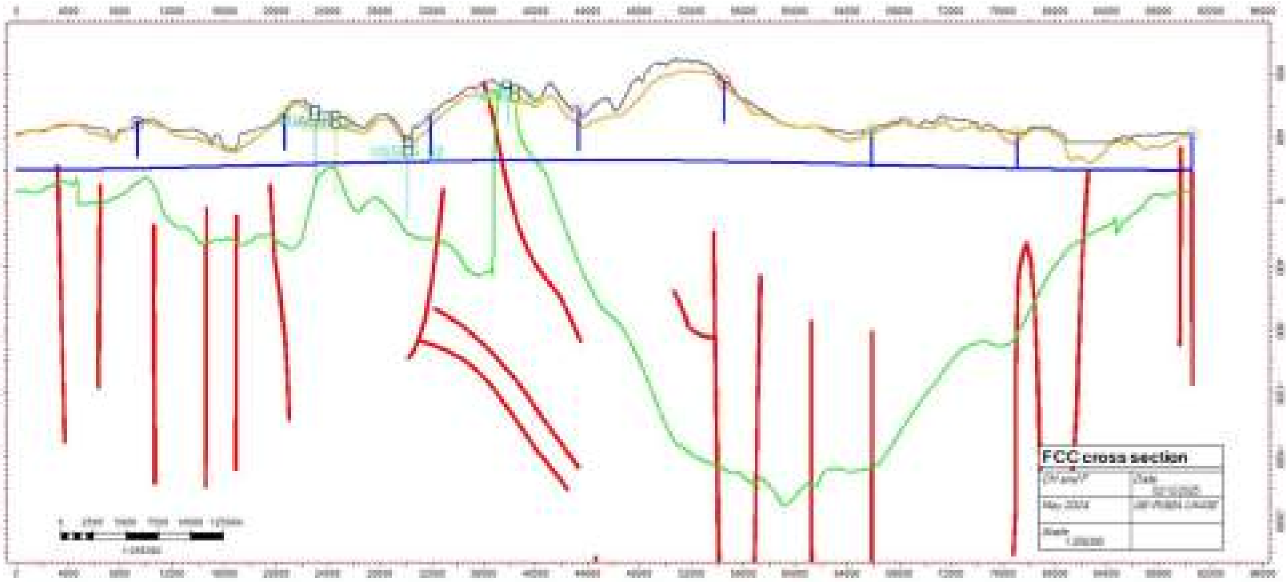


Fig. 1.51 FCC long profile with potential faults

1.6 Management of excavated materials

1.6.1 Introduction

Building the underground infrastructures of the Future Circular Collider (FCC) in the Franco-Geneva Basin would produce approximately 6.3 million cubic metres of excavated materials, mainly constituted by molasse, a soft heterogeneous rock (96%).

The management of excavated material stands as a key element in the realisation of the FCC within the local region. Furthemore, it exemplifies a visionary investment designed to reduce environmental impact and unlock benefits that extend well beyond the local context. Accordingly, from the earliest stages, an approach to the strategy for the excavated material management was incorporated into the feasibility study as part of the FCCIS project, co-funded by the EU under the H2020 programme (grant agreement no. 951754).

The French tunnel design centre, (CETU), the Centre for studies and expertise on risks, environment, mobility and urban planning, (CEREMA), the Montanuniversität Leoben (Austria) collaborated with the FCC study on this subject. Technical information and legislations were provided by the Swiss cantonal 'Service de géologie, sols et déchets' (GESDEC).

Current regulations still consider excavated materials as waste as soon as they exit the project boundaries, but the legislation is evolving in many European Countries. Excavated materials can be reused on-site (prevention of waste production) or recovered off-site. Final disposal as waste must be the last option when no reasonable recovery (even after suitable preparation or treatment) is possible. The successful management and use of excavated materials strongly depend on the early implementation of a management strategy shared and agreed upon with the Host States by the project owner.

The presentation of a management plan of the excavated materials is considered to be the responsibility of the future project owner, irrespective of who implements the actual tasks. To satisfy this requirement, a report outlining the approach to the strategy for the management of the excavated material (in French 'Stratégie de gestion et d'usage des matériaux excavés' [1] also available in English [2]) was developed. The following aspects are included:

- Quantities of excavated materials and current knowledge of the geological characteristics.
- General principles for the management of the materials.
- Identification of the potential risks.
- Legal framework in the two Host States.
- Potential reuse cases.

1.6.2 The excavated material quantities

The FCC excavation work is estimated to generate approximately 6.3 million cubic metres of excavated material, equal to approximately 8.2 million cubic metres of expanded material over nearly a decade. The quantities of

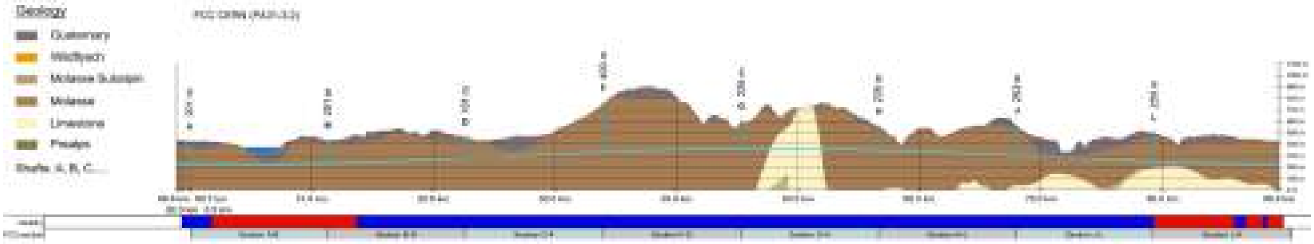


Fig. 1.52 Geological profile along the FCC path. The part of the tunnel under French territory is shown in blue; the part under Swiss territory is shown in red

excavated materials (see Table 1.4) were calculated on the planned design of the underground structures (shafts, tunnels, caverns, alcoves, etc.). They correspond to the materials in place and the expanded materials (applying an expansion factor of 1.3).

1.6.3 The excavated material characteristics

The material extracted will mostly comprise different types of heterogeneous soft rocks, called molasse (96%), along with limestone (2.5%) and quaternary deposits (1.5%).

The molasse is formed by a series of horizontal layers of cemented and silty sandstone interspersed with layers of marl and argillaceous rocks. Geogenic anomalies such as the presence of natural hydrocarbons or enhanced concentration of metals including nickel and chromium may exist naturally in varying quantities in parts of the various molasse layers.

The Lemanic basin features three main geological groups: quaternary formations (glaciolacustrine, fluvio-glacial and moraines), molasse and limestone bedrock. The reference placement proposed for the FCC has been optimised to place the tunnel infrastructure in the Franco-Geneva molasse basin (Fig. 1.52). The limestone elements of the Jura and Vuache mountains, along with the Mandallaz and Salève ranges, skirt and intersect the molasse layers. It is hard to excavate limestone in the region due to its karstic characteristics caused by chemical alteration of the rock. These deep karsts are likely filled with water and unconsolidated materials, which could penetrate the excavation because of strong water pressure. CERN experienced these effects when conducting excavations in the limestone of the Geneva region during previous projects (e.g., LEP in the '80 s). Because of these difficulties, the design deliberately avoids the Jura and the limestone of the Vuache. However, despite every effort to minimise crossing limestone strata, one stretch of the proposed tunnel still passes through the Mandallaz limestone.

The molasse in the region is generally made up as follows:

- 30 to 50% clay,
- 10 to 15% silt,
- 10 to 15% sand, with a grain size of between 63 µm and 4 mm,
- 15 to 20% sandstone particles larger than 4 mm.

The sandstones (detrital sedimentary rocks formed from grains of sand cemented by silica, calcite and iron oxide) in the Lake Geneva region are mainly made up of:

- 40 to 70% quartz,
- 20 to 45% calcite,
- 5 to 10% feldspar,
- 5 to 20% phyllosilicates (micas, chlorites, serpentinite, etc.)

The marls (sedimentary rocks containing clay and limestone) present in the region exhibit a wide variety of compositions. Marls are ductile, micro-cracked and subject to swelling following contact with air or significant changes in soil moisture.

The nature of the excavated materials depends on the longitudinal profile of the geological structures encountered. Different formations and different facies may be encountered. Homogeneity in terms of the nature and properties of the excavated materials is a key consideration, as it will determine their subsequent use.

A strategy will have to be devised during the construction phase to select the materials to be reused, based on the following:

- Initial visual selection at the face.
- Tests on the geological formations and updates in case of changes in petrographic properties or indications of lithological changes.

- Rapid and effective material quality control as soon as possible after the extraction of the material, or at the latest when the material reaches the surface.

Specific investigations would be required prior to the start of the excavation to determine the geological characteristics of the subsurface through which the FCC will pass and to assess the potential geological risks. CERN is conducting an initial investigation campaign (2024 - 2025) as part of the FCC feasibility studies. These first subsurface investigations could be later complemented by extensive subsurface investigations, devoted mainly to confirming the geological model and, therefore, to anticipating the possible risks and preparing adequate mitigation. Laboratory tests are being conducted on core samples extracted during the subsurface investigations to identify and characterise the rocks in view of their potential for reuse and to analyse the presence of geogenic anomalies.

1.6.4 Approach to the management of excavated materials and associated risks

Defining what could constitute a basis for a future strategy for managing and utilising excavated materials is a key feasibility criterion for the FCC study, reflecting both the alignment with the regulations of the Host States and a broader commitment to sustainability and environmental stewardship. The basic concept has been documented in a stand-alone deliverable of the FCCIS study [1]. The core principles, summarised here, present the high-level aspects, related constraints and the opportunities identified for treating the material as a resource instead of disposing of it as waste.

The approach to excavated materials management marks the initial step toward a comprehensive approach, conducted in accordance with the regulatory frameworks of both Host States. Its implementation, in the form of a preliminary operational management plan, can only begin once the first set of subsurface investigations is completed (by the end of 2025). Subsequently, this preliminary plan should be revised whenever significant new information is obtained, following an iterative process that would culminate in a final operational management plan to be shared and agreed with the Host States, and should be adopted before the start of excavation.

Approach to the excavated material strategy The studies carried out to develop an approach to the excavated material strategy were:

- Iterative development of a 3D subsurface geological model (see Sect. 1.5.2).
- Inventory of the regional opportunities for reuse in France and Switzerland.
- Investigation of the possible connection to the regional railway network.
- Investigation of the possible connection of the railway sidings to the extraction sites by conveyor belts, to avoid local nuisances due to truck transport.

The FCC schedule allows the possibility of optimising potential reuse scenarios. Accordingly, rather than centring on fixed solutions, the excavated materials management focuses on flexible approaches and guiding principles that can be adapted to accommodate:

- Evolutions in technology that could result in improvements in the techniques applied to the excavation and separation and treatment of the excavated materials.
- New recovery pathways which are better suited to the characteristics of the extracted materials that may become available in the future.
- Evolution of regulations governing the management of excavated materials for specific applications (e.g., use as soil improvers in agriculture).

The main parameters to be taken into consideration when building a strategy for the management of the excavated materials are:

- TBM kinematics (Fig. 1.4) and the logistic aspects that determine the output and availability of excavated materials within the area as well as the nearby storage and treatment areas required.
- Identified uses and streams: specifications, demand (quantities and variation over time), location, accessibility and service, criteria for acceptance of the material.
- Modes of transport and distances, as well as whether existing infrastructures can be used or whether new infrastructures will need to be built.

A schematic overview of the approach to the excavated materials management appears in Fig. 1.53. Experience from previous CERN projects shows that the proportion of materials affected by geogenic anomalies (such as hydrocarbons or elevated chromium and nickel levels) may vary, ranging from approximately 15% to 45%, in part due to different regulatory thresholds of the Host States. For the record, exemptions have been granted for specific materials, for example, in 2019, during the HL-LHC project, to facilitate higher recovery rates in various recovery streams.

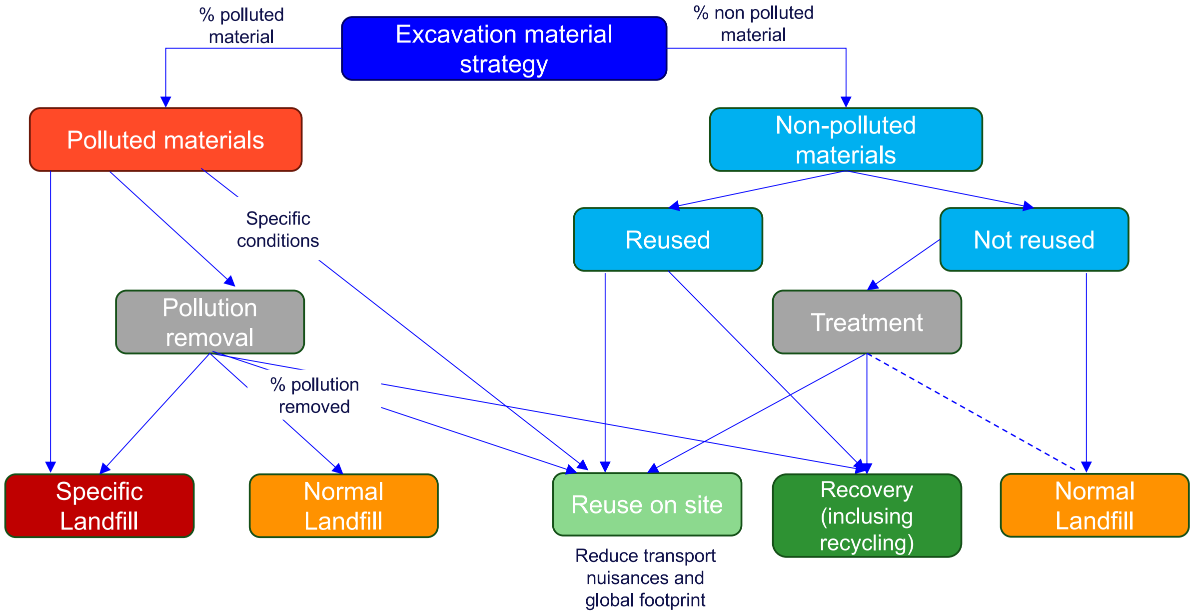


Fig. 1.53 Schematic diagram of the scenarios defined for the excavated material strategy. (not including transport)

Evaluation of risk in the management of excavated materials The fraction of re-usable excavated materials depends on the geochemical, mineralogical and geotechnical properties of the materials excavated from the tunnel. When preparing a management plan for these materials, particular attention must be paid to the management of both technical and non-technical risks, which have a direct effect on limiting costs, optimising transport and avoiding compromising the schedule. Typical technical risks relating to the external context for excavated materials are associated with:

- The nature of the materials, which determines their classification as a specific type of material and their potential reuse;
- The proportion of facies, in the case of a heterogeneous formation or a mixed facies with several types of material;
- The position of the contacts between geological formations, which has an impact on the distribution of the volume of material per formation.

The technical risks of the internal context, regarded as points to keep in mind by the project owner, are associated with:

- The impact of the excavation methods, chosen according to the characteristics of the excavated materials and, in particular, the additives necessary for the excavation, which can potentially pollute the materials and hinder certain reuse cases.
- The equipment used in the transport and in the treatment of the excavated materials, for the potential of unforeseen mixing and potential pollution of the excavated materials.
- The availability and extent of the temporary and final storage areas for excavated materials.

Along with the technical risks, non-technical challenges, such as political or administrative factors, should also be taken into account in the development plan. For example, there may be modifications to environmental regulations. These non-technical challenges must be considered from the study phase.

Excavation methods can have an impact on the potential use of molasse and other excavated materials, since they can alter their properties and quality. At this stage of the FCC study, the use of shielded Tunnel Boring Machines (TBMs) is likely to be possible for most of the main tunnel. Further studies should provide more detail for the data provided in Table 1.7, specifying the impact of the chosen excavation techniques on the quality of the excavated materials (type of TBM, explosives or road header).

1.6.5 Regulatory frameworks

In France, AFTES recommendation GT35R1F2 on the management and use of excavated materials [3] and the CETU information document on naturally occurring geological materials excavated in underground structures [4] are the main reference texts for the management of excavated materials.

Table 1.7 Quantity of excavated material by excavation method

	Using TBMs	Using conventional method	Shafts	Total
Collider infrastructure (m^3, in situ)	2,689,500	2,828,500	652,600	6,170,600
Connecting infrastructure to existing tunnels (injection) (m^3, in situ)	97,900	9800	14,600	122,300
Total (m^3, in situ)	2,787,400	2,838,300	667,200	6,292,900
Percentage of Total	44%	45%	11%	100%

In Switzerland, the ordinance on the avoidance and the disposal of waste [5], complemented by the ordinance on the movement of waste [6], the 'Aide à l'execution relative à l'OLED' (help for the execution of the ADWO, not available in English) and the 'Guide pour la réutilisation des matériaux d'excavation non pollués' (guide to the reuse of unpolluted excavated materials, OCEV), provide the framework for the subsequent steps.

The main regulations in force in the two Host States regarding the application of international agreements on the export of excavated materials are:

- In Switzerland, Article 15, paragraph 1 of VeVA 814.610 requires that anyone exporting waste (including unpolluted excavated materials) must obtain authorisation from the Federal Office for the Environment (VeVA 814.610, 2005).
- In France, since 12 July 2007, the cross-border movement of waste has been subject to the provisions of Regulation (EC) No 1013/2006 of 14 June 2006, which incorporates the provisions of the Basel Convention [7]:
  - Article 43 permits the importing of waste for the purposes of recovery from countries which are Parties to the Basel Convention to a European country.
  - Articles 40 and 41 prohibit the importing of waste for the purposes of disposal from countries which are Parties to the Basel Convention except where one of the countries (including Switzerland) presents a prior duly reasoned request (paragraph 4).

Article 4.2 of the Basel Convention [7] states that each country must take measures to reduce the generation of waste and ensure the availability of adequate disposal facilities located, where possible, within the country, with a view to the environmentally sound management of dangerous waste and other waste, whatever the place of its disposal.

In the north-west sector of the FCC, its path crosses the Franco-Swiss border at several points. If the excavated materials were to be managed by each state, this would lead to the excavation of additional shafts for the specific purpose of material evacuation, which is not realistic and does not respect the 'avoid, reduce and compensate' approach because it would increase the quantity of materials to be managed and the number of nuisance zones on the surface due to the extraction points. For this reason, it would be desirable to propose the adoption of the principle of each state managing the equivalent mass of spoil excavated on its territory. This adjustment, which remains to be agreed with the two Host States and in association with CERN, would make it possible to deal with the small enclaves that cannot be managed by the TBMs without changing the principle of division laid down in the Basel Convention.

A further point where an agreement between the project owner and the Host States seems appropriate concerns the country in which the materials are extracted. In principle, according to the Basel Convention, each country is responsible for extracting and managing its share of the mass on its territory and for dealing with the associated adverse effects (dust, noise, traffic, etc.). The distribution of the TBMs, however, does not necessarily correspond to this mass distribution (e.g., no TBM launched from site PB) for technical reasons. For such a scenario, compensatory measures will have to be agreed with and by the Host States.

Various tools will have to be developed to ensure that the management of the materials respects an established and agreed management plan that is part of the project authorisation files. These will have to be devised sufficiently early, in consultation with the Host States and relevant authorities, to ensure they are properly implemented when the time comes:

- Administrative tools for the authorisation procedures for spoil transport and storage to enable effective recovery of the material.
- Regulatory tools to enable the validation of the innovative processes, particularly in terms of characterisation, and to ensure they can be standardised.
- Cross-border agreements: if relevant optimisations are identified, these will need to be made explicit, substantiated and submitted for joint approval by the two Host States.
- Agreements with offtakers of materials and owners of land plots that would receive materials before the start of the excavation process.

- Logistics tools: an adequate traceability system is the responsibility of the owner and it provides a useful way of improving the recovery of the materials and acts as a guarantee that the spoil is of sufficiently high quality.

The first three points could be governed by a bilateral international agreement.

Materials excavated during underground works are considered as ‘waste’ in the European Union (EU) countries and Switzerland unless they can be reused on the site of the project. The definition of the status of excavated soil and its classification as ‘waste’ or ‘non-waste’ are fundamental aspects, as they determine the legal framework to be followed for managing the excavated materials. The status of the excavated soil must be specified according to the various on- and off-site management scenarios with the French and Swiss authorities.

To develop an integrated plan for the management of the excavated materials that is part of the authorisation process, it would be advisable that the FCC is treated as a single indivisible and transnational project in the meaning of 1.c) of Article 2 of the ‘waste’ directive 2008/98/EC of 19 November 2008 [8]. The integrated approach facilitates the development of the agreements between the project owners and the customers for the materials that must be in place before the construction works start. It also enables the possibility to reuse materials on either side of the border, independent of their extraction site of the unique, indivisible project.

1.6.6 Scenarios envisaged for the management of the excavated materials

As a long-term project offering sufficient lead time, the FCC may represent an opportunity to develop innovative approaches for the management of excavated materials. For this reason, the study invested already in launching the research and development of new technologies and solutions that have the potential to reduce the amount of waste that needs to be transported to deposit sites.

The identification of uses must comply with the waste hierarchy put forward by the European Union parliament (‘waste’ Directive 2008/98/EC) and implemented in the French and Swiss regulations. The national policy for the prevention of waste production and reduction of waste impacts, outlined in the Environment Code (Art. L-541-1), supports the transition to a more sustainable management of the excavated materials, by fostering the application of the waste hierarchy: avoid waste production (including reuse), preparation for reuse, recovery and disposal. It also includes achieving a total ‘material’ recovery of the waste stemming from the building and public works sector of 70%. This target is evaluated at the regional level.

The general principle of avoid/reduce/compensate will also be applied to the management of excavated materials of the FCC: the ‘avoid’ and ‘reduce’ principles are applied mainly at the time of the subsurface infrastructure planning (i.e. avoiding producing unnecessary spoil and reducing the overall excavations by optimising location, design, and depth of underground infrastructures) and in the choice of the excavation methods (minimisation of pollutants during the excavation, thus reducing the quantities of excavated materials that will need specific land filling).

The various types of reuses and recovery call for material storage and treatment areas close to the extraction sites. The surface areas necessary depend on the detailed technical concept of the construction work, the construction schedule and the dimensional design of the treatment unit on the sites. These elements will have to be developed at a later stage.

Among the identified pathways, the most likely to be realised are:

- **Use for development requirements within the project** (e.g., FCC worksite tracks, landscaping purposes, etc.)
- **Use in earthwork (backfilling of quarries and mines and rewilding) and development projects**. This reuse case concerns most of the materials, as it can be applied for both the inert material and the polluted excavated materials, after appropriate decontamination. As each quarry is subject to specific environmental impact restrictions, specific acceptance criteria for the backfilling materials must be respected. In total, it is estimated that all material that will not be addressed to specific land filling due to pollution can, in principle, be reused for quarry landscaping, after treatment. However, in order not to saturate the region, other reuse cases are investigated at the same time.
- **Use of the limestone fraction** in concrete production and stabilisation of structures. The limestone, marl and clay deposits of the Jura and the northern Alps have provided the raw material for lime and cement since ancient times. Produced by calcining limestone, lime is used to improve soils and whitewash walls; mixed with sand and water, it produces a mortar that is very easy to produce and therefore very common. All limestone that will be extracted during the FCC construction project will be destined to these reuse cases. Due to the costs of production of these resulting construction materials, it is assumed that the reuse of limestone is at zero gain and zero cost for the project.
- **Use of the sand fraction in concrete production**. Direct reuse of sand and gravel could be envisaged, eventually after treatment of sieving and /or washing of the excavated materials. The use of cyclones for the washing of excavated materials is an established treatment method that allows separation of the clay and other materials and obtains good-quality materials. The study on the efficiency of this separation method remains to be performed.

- **Transformation of the molasse into fertile soil** for applications in the development of brownfield sites, urban recreational areas and forest areas, as well as improving the fertility of acidified land and/or as technical areas along the verges of roads and motorways (pollutant filtration). The use of excavated materials transformed into reconstructed soil requires the identification of areas for backfill in agricultural areas. The locations desired include hollows, slopes, areas of poor ground quality such as polluted or acidic soils, or of poor agronomic quality (e.g., low water retention potential). The application may be different depending on the type of land and topography. This type of measure could be particularly suitable for certain rural areas in the Auvergne-Rhône-Alpes region and in several cantons in Switzerland and would also allow deposits to be made near drilling sites. Due to the unknown topography of the chosen areas, it is currently difficult to identify the location and total areas. It is estimated that about 2 million cubic metres (about 4 million tons) of excavated materials could be reused via this pathway, provided the appropriate areas are identified.
- **Use of a part of the molasses as technical materials**: trench cover (e.g., roads), acoustic screens, farm tracks, forest paths etc. Both the French and Swiss neighbouring landscapes are constituted by woods of different nature or of rural areas. In particular, the zone in the proximity of Annecy has approximately 500 km of rural paths and tracks. In total, there are approximately 705,000 km of rural and forest paths in France. These paths and tracks must be maintained regularly; for this, inert materials are necessary to ensure their stability. Raw molasse is also suitable for the implementation of vegetation-free strips near roads. With the installation of noise-reducing and privacy-screening gabions, this scenario can generate significant savings in the development and maintenance of public roads. Support from the relevant authorities is required to identify suitable roads and locations near extraction sites, establish certifications, and grant permits necessary to carry out this type of application. A further application in the layout of roads is the use of reconstructed soil based on molasse as landscaping of trenches of covered streets or highways.
- **Development of building components** by compression (bricks or compressed earth using 'sandwich' technology) for use within the scope of the project where possible or outside the project (opportunities within the region to be investigated).
- **Development of new building materials** containing a part of the molasse (e.g., shotcrete ingredients, supporting materials, insulating panels for surface buildings), to be used within the scope of the project where technically feasible or outside the project (opportunities within the region to be investigated). Literature shows that considering excavated materials for the reuse as recycled concrete aggregates (RCA) in the structural concrete of the tunnel or of the basement of the tunnel could turn out to be not feasible because of the decreased strength and therefore further thorough studies are required. A prudent approach, until more complete studies are performed, could be to use RCA in shotcrete with fibre-reinforcement for non-structural parts only.

Some of these pathways are listed in excavated material management guides used in France e.g., from Cerema/UMTM (publication pending) and from the Ministère de la transition écologique et solidaire [9] and in Switzerland from the OCEV [10] and also in the AFTES recommendation GT35R1F2 [3] (currently in revision). The other pathways must be identified and a framework for cross-border use could be proposed to the respective authorities in the Host States.

The first four in the list correspond to traditional reuse cases already in use in other tunnel construction projects. These are taken into consideration and will be applied in priority whenever the geo-mechanical, mineralogical and chemical characteristics of the material are suitable for these applications.

In addition to these traditional reuse cases, innovative reuse pathways were identified during the 'Mining the Future®' international competition carried out in 2021 and 2022. The competition aimed to identify innovative pathways for excavated material from tunnel construction which could be profitable not only to the FCC but to any further projects in the subalpine region. The competition was launched under the Horizon2020 project 'Future Circular Collider-Innovation Study' (Grant Agreement n. 951753) and was jointly organised by CERN and Montanuniversität Leoben. The submissions were scrutinised by a jury panel of international experts. The four finalists' concepts ranged from the manufacturing of substrates for agriculture and forestry to the production of raw construction materials like concrete and shotcrete, compressed earth bricks and other hydraulically bound building materials. They all need to analyse and separate the materials during the tunnelling process in real-time, with subsequent on-site pre-processing directly on the excavation surface sites. Geogenic contamination by hydrocarbons and heavy metals must be removed or at least be reduced to levels that are compatible with the proposed processes and end-use conditions. The consortium led by BG Engineering was selected as the most innovative and comprehensive concept and won the competition.

Some of the solutions are now being integrated into a unique design and evaluated in the field, in a project planned to reach maturity by 2030. The objectives of the evaluations are twofold. Firstly, to establish how to conduct the online identification, sorting and pre-treatment of the materials during the excavation process. Secondly, to prepare different reuse pathways to sort and pre-treat materials, including transforming molasse into usable soil for forestry and rewilding applications, in line with the principles of a circular economy. The quality-assured creation of the reconstructed soil is a lengthy process spanning several years and has been chosen as the first large-scale experiment with field tests at OpenSkyLab.

The OpenSkyLab, is a project based on a plot of about 10,000 m^2 located near LHC Point 5 (CMS, Cessy, France) that has been made available by CERN. Molasse extracted during the HL-LHC excavations will be transported to this field to be used in the tests. Initial laboratory analyses will be performed off-site to identify the most suitable mix of molasse and other natural additives (compost). These will be followed by field tests in the OpenSkyLab's controlled environment (monitoring of the field, weather, and plant growth conditions), using scientific protocols developed by a collaboration of universities working in this domain.

In keeping with CERN's long-standing tradition, this project relies on an open collaboration with academia and industry. Currently, the collaboration includes university and research experts in agronomy, pedogenesis and geology (HEPIA, BOKU, BRGM, Montan University Leoben) and industrial partners in soil engineering and phytoremediation (Microhumus, Edaphos), soil treatment techniques (WSP-BG) and monitoring and supervisory control systems (BECC).

In order to facilitate acceptance into the reuse pathways of the excavated materials, it will be necessary to set up material-separating units during the tunnel construction phase, at the starting point of two TBMs as a minimum. These units could combine the screening, sorting, sieving and cleaning operations of the extracted materials.

Assuming a two-shift 24-hour working day over 240 days per year, the consortium that won the Mining the Future competition proposed a facility that could treat approximately 750,000 tonnes per year at an hourly rate of 200 tonnes. Each facility would employ a team of five people. A pilot project for the testing of the efficiency of these sorting and treating facilities could be envisaged during the next phase.

The working hypothesis assumes that the previously listed solutions will account for a global reuse of about 70% of the overall excavated materials, among which the reconstructed soil reuse pathway could amount to up to 2 million cubic metres (corresponding to about 25% of the total). The backfilling of quarries as well as more traditional reuse pathways (e.g., limestone and sand direct use) should overall account for about 45%. These quantities remain to be confirmed during the next phase.

Regional opportunities CERN commissioned a study to identify the regional opportunities available in France and Switzerland for the evacuation of the excavated materials. This included:

- A global inventory of the final storages and of the opportunities for landscaping of quarries and mines at the end of their operational lifetime, but holding a prefectural permit valid beyond 2033.
- A study on potential industrial railway sidings for the evacuation of the materials.

Global inventory of regional opportunities This study started with a preliminary inventory of potential regional opportunities for landscaping (quarries, mines) and storage, which was carried out at the start of the feasibility study (2021-2022) in France and Switzerland to provide initial indications of potential host sites and the capacities for excavated materials of the various pathways. The current status of the inventory is presented schematically in Fig. 1.54. These detailed inventories list the existing and planned facilities (horizon 2030) with sufficient capacity to receive and treat the excavated materials from the FCC. They will need to be repeated once the excavated material management plan has been defined to take account of the final material extraction fluxes and the possible availability of new reuse cases. Subject to updating and optimisation with respect to transport, these studies show that it is possible to find a pathway for all the materials excavated from the potential future FCC project and provide an initial estimate that can be used as a basis to begin the optimisation process according to the 'avoid, reduce, compensate' principle. It should be underlined that the inventory of the potential recipients of the excavated materials was carried out with the aim of evaluating the financial envelope and identifying potential showstoppers for the FCC feasibility. It is not possible at this stage to identify the specific recipients without engaging in contractual agreements. This step will be performed during the establishment of the final material management plan.

Railway sidings The study investigated the option of constructing industrial rail sidings near the surface sites to take away the excavated materials. Potential locations near existing railway lines (shown on Fig. 1.55) were identified, and the feasibility of creating sidings was examined. To supplement this study, the feasibility of a conveyor belt link has been assessed for the two sites deemed most appropriate for the installation of sidings: Vulbens (removal of materials from PJ) and Charvonnex (removal of materials from PG). This exploratory phase was completed by an initial assessment of greenhouse gas emissions from transporting excavated materials by road and/or by rail from the production site to the disposal site or to the location of the hypothetical reuse cases.

The feasibility study of railway sidings only took technical factors into account. The weighing of certain factors linked to the acceptability of creating a railway siding (e.g., environmental aspects such as the nuisance factor in a densely populated area) must be carried out before a decision is reached.

The creation or refurbishment of railway access, already considered to lower the nuisances due to truck transport, would further facilitate the use of quarries and reuse cases not in the immediate vicinity. A technical study could be conducted to analyse the possibility of cross-border transport by conveyor belts from Challex (PL) to the railway network at La Plaine in Switzerland and from Ferney (PA) to the rail network at the Geneva Airport in order to use the existing railway infrastructure for the transport of the materials to their final destination.

Fig. 1.54 Schematic diagram of the inventory of the regional opportunities for material reuse (status 2021)

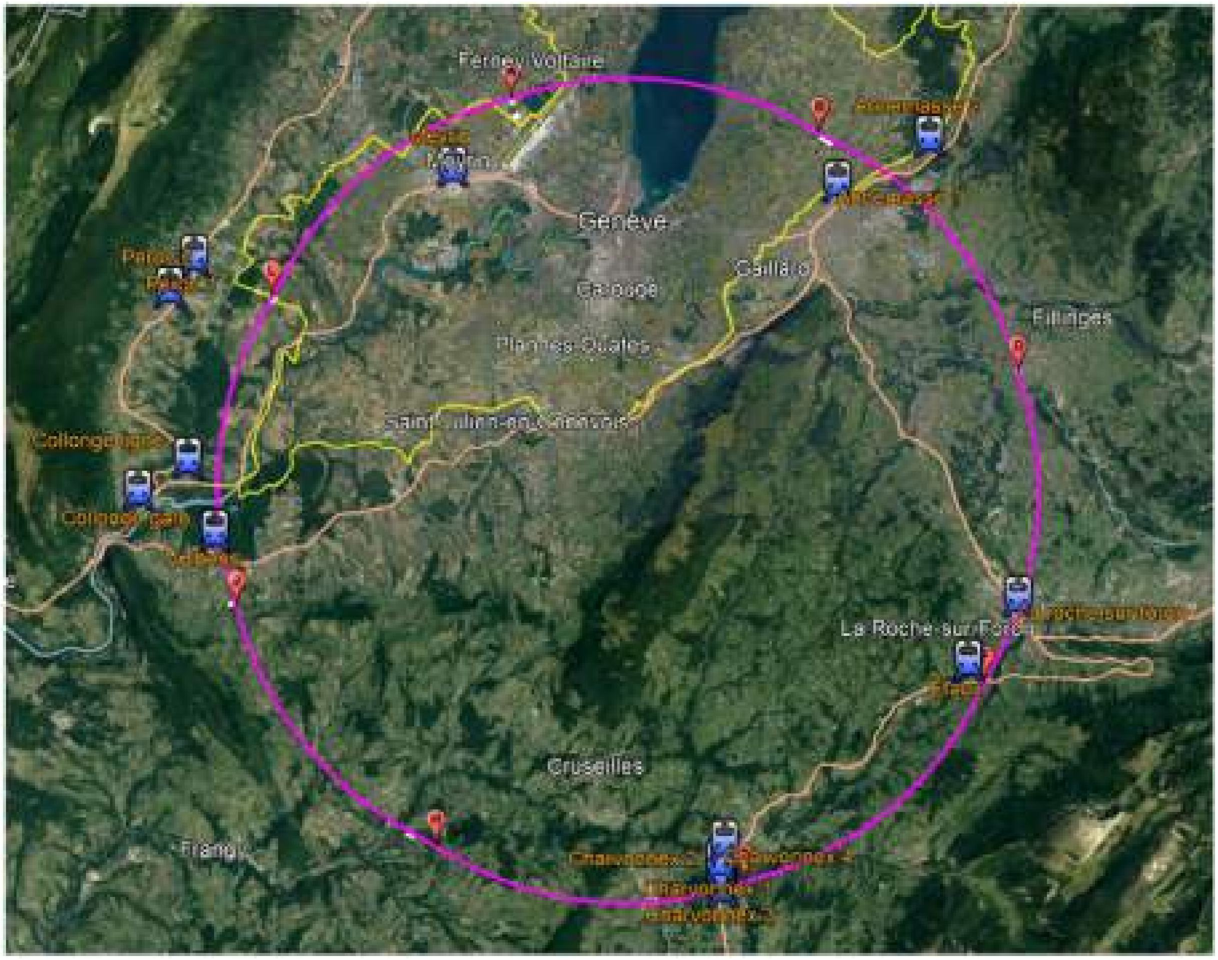


Fig. 1.55 Study of the potential locations for railway sidings

1.6.7 Outline of the next studies

The scenarios for the reuse of excavated materials are based on preliminary assumptions regarding the proportion of materials with geogenic or anthropogenic characteristics that may require specific handling. At this early stage,

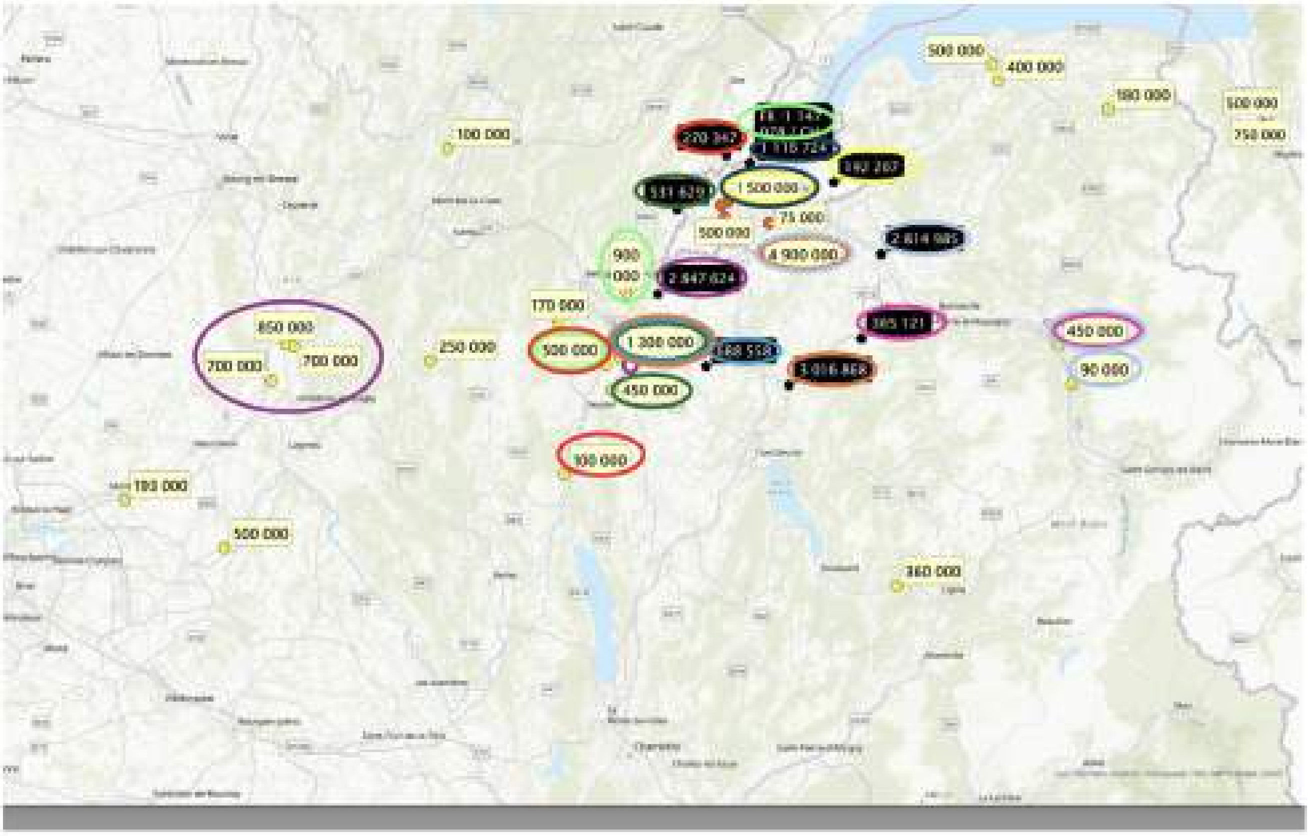


Fig. 1.56 Example of possible distribution of unpolluted excavation materials to the quarries nearest to the material extraction sites (the figures in black are the value in tonnes). The colours of the circles link a given extraction site to one or more quarries or backfilling sites. The figures in yellow show the quantity of materials that can be accepted by the quarries during the excavation. Swiss pathways are represented by a red dot, and French pathways by a yellow dot

and in the absence of more detailed geochemical analyses, a working assumption of 30% of materials exhibiting natural geogenic variations appears to be the most reasonable.

As part of the FCC feasibility study, additional insights may be gained by examining recent projects related to the enlargement of certain LHC accelerator caverns (HL-LHC project). Underground excavations for this project indicated the presence of hydrocarbons in approximately 15% of the materials in France and nearly 50% in Switzerland. This difference is influenced not only by actual variations in subsurface conditions but also by differences in environmental regulations between the two countries.

Based on these initial inventories, presented in Sect. 1.6.6, a preliminary approach to the management of the excavated material was drawn up and used to assess the transportation costs from the extraction sites to the storage facilities and backfilling sites. The average transport distances are estimated to be 20 km in Switzerland and 40 km in France for uncontaminated materials and approximately 100 km in both countries for materials requiring specific treatment. This is because treatment facilities are generally located outside the Lake Geneva region, where the FCC will be installed.

Figure 1.56 presents the results obtained for uncontaminated materials. In this figure, the values displayed on black backgrounds indicate the quantities of material expected to be extracted per site, while the colours of the circles correspond to the quarries or backfilling sites designated for the disposal of outgoing materials. It should be noted that only quarries with a prefectoral permit valid beyond 2033 have been considered.

These scenarios will require updates, as the annual intake capacity of each site may be revised based on regional requirements. The extracted quantities are provided as an indication of each quarry's backfill capacity. However, further studies will be necessary to assess the feasibility of this operation, and agreements with quarry operators should be established in due course.

Subject to updating and optimisation with respect to transportation, these studies show that it would be possible to find a pathway for all the materials excavated from the potential FCC project sites and provide an initial financial estimate which could be used as a basis to begin the optimisation process according to the 'avoid, reduce, compensate' principle.

The distribution of excavated materials should integrate the identified reuse cases as soon as the technical information on their feasibility becomes available. Therefore, the current distribution should be viewed as a preliminary benchmark assessment, expected to evolve positively as studies progress. Close collaboration between the FCC and the Host State authorities is essential to refine and better adapt the principles of the strategy of the excavation material management in alignment with the regional framework.

A subsequent project preparatory phase should include the development of a roadmap along the following points:

- Confirmation of the characteristics of the excavated material and correlation to the potential reuses via the analysis of the ongoing and future subsurface investigations;
- Study of the technical methods for the real-time analysis of the materials and their sorting according to their characteristics and potential reuse.
- Pilot projects on the potential reuse cases: on the example of the ongoing OpenSkyLab project for developing processes for using excavated materials for landscaping, other projects could be started for testing, for example, the possible reuse as construction or isolation materials. This study should include an evaluation of the environmental, economic and societal impact due to the potential injection on the market of the products based on excavated materials;
- Definition of the regulatory framework for the management of the excavated materials with the host States;
- Update of the regional treatment and disposal opportunities (e.g., availability of quarries, final deposits, treatment facilities) and related regulation;
- Study on the excavation material logistics (traceability, fluxes, conveyors etc.), including the evaluation of environmental and societal impacts and the potential limitations.

Certain activities can be carried out in parallel. Others must follow a sequential process, leading to the development of a preliminary excavation material management plan. Based on this plan, more concrete discussions can be initiated with the administrations of the Host States and the owners of potential final deposit and reuse sites.

Chapter 2

Territorial implementation

2.1 Introduction

To be able to take an informed decision for a future particle-collider based research infrastructure and to undergo the necessary project authorisation process with national authorities, a specific implementation scenario needs to be conceived. Such a geo-localised scenario must be well-balanced, considering the three main dimensions:

1. Scientific excellence.
2. Territorial compatibility.
3. Risks related to the implementation that affect cost and schedule.

While the exploratory phase of the FCC study between 2014 and 2018 [11] focused on the ‘in principle’ feasibility of the accelerator and the territorial boundary conditions, the studies between 2019 and 2024 included the development of a well-balanced project scenario considering the three above-cited dimensions.

This chapter summarises the methodology adopted to carry out this work as documented in [12], sheds light on the variants considered and the evolution towards a reference scenario. The resulting scenario presented serves as a reference to design the various elements of the future circular collider-based research infrastructure if the global science community decides to make such a facility their priority.

The reference scenario presented is the result of a total of 10 years study of a large variety of scientific, technical, cost, societal and environmental aspects. It represents an infrastructure with a circumference of approximately 91 km, including eight surface sites. It is conceived to be able to host two distinct particle colliders, a high intensity lepton collider first and a high energy hadron collider in subsequent phases. The second machine and its experiments profit significantly from the assets put in place for the first phase due to the residual asset value of that infrastructure, contributing to the overall sustainability of this long-term science programme. The iterative process that was used to develop the reference implementation scenario is summarised in the following sections.

The presence of a sufficiently large community of users committed to carrying out scientific research with the particle colliders for several decades is a prerequisite for justifying the construction of a research infrastructure of this scale. Scenarios involving a much smaller collider with a circumference of less than 90 km, would not allow the provision of a performance and a research programme that could attract a critical mass of scientists for a sustained period of time. The doubling of the interaction regions from two to four reflects the aim of attracting as many scientists as possible to such an infrastructure. The size and the characteristics of the infrastructure also permit additional scientific activities with the injector and particle colliders, as is the case today at CERN with the LHC programme.

In terms of compatibility with the geological conditions that affect the construction risks and costs, only two types of configurations meet all requirements: an infrastructure with a circumference of between 89 and 91 km and eight surface sites, and a layout with a circumference of between 97 and 98 km and twelve surface sites. Concerning the availability of suitable surface site locations, however, layouts and placements suitable for scenarios involving a collider with a circumference well in excess of 91 km and comprising more than eight surface sites turned out to entail unacceptable risks concerning their implementation.

To date, only scenarios around 91 km circumference and eight surface sites seem capable of satisfying the following three requirements:

1. Good scientific performance of the particle collider and four experiment sites.
2. Compatibility with territorial constraints at the surface and the subsurface.
3. Understanding of the implementation conditions from cost and risk perspectives.

One of the scenarios named PA31 stands out from all of those iteratively developed following the ‘Avoid-reduce-compensate’ methodology [13] and analysed with a multi-criteria approach recommended for industrial installations [14, 15]. It has been further studied and optimised in depth involving bibliographic research, field work, and continuous discussions with the public administration services in both countries involved and with key stakeholders in the implementation area. In case of a decision to move forward with the implementation of a project, the conditions for this scenario will have to be further analysed, the scenario will have to be further improved, and detailed designs have to be developed before implementation can start.

Territorial constraints and legal frameworks in host countries and within the European Union are constantly evolving. Between 2014 and 2023, several layout and placement scenarios had to be ruled out due to these changes. The information contained in this document and the working hypothesis described here are therefore provisional. For the project to come to fruition, the validation and definitive freeze of a scenario securing the required surface areas and subsurface volumes should be done as soon as possible.

2.2 Methodology to develop a sustainable project

2.2.1 Approach

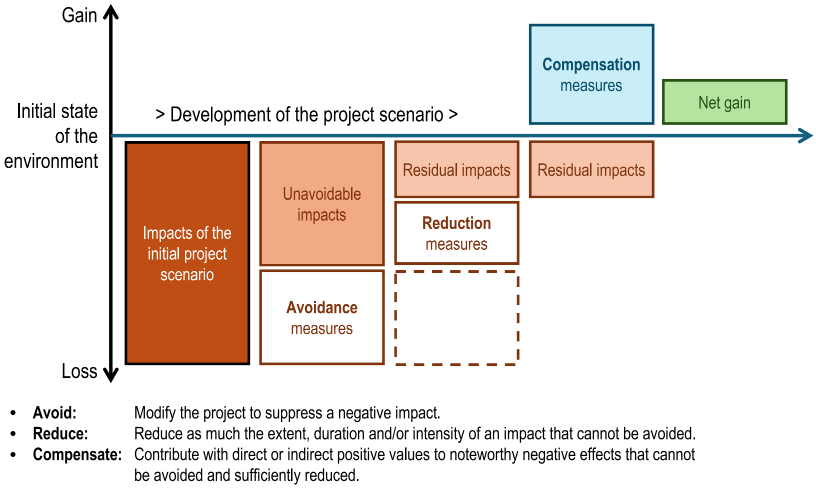
From the outset, the objective of the study was to draw up a scientific research infrastructure that reconciles, in an eco-design approach [16, 17], i) scientific excellence, ii) territorial compatibility and iii) consideration of acceptable risks associated with project implementation. A systematic process therefore had to be set up to develop scenarios through an iterative approach, taking these three essential aspects into account at all times. The eco-design approach adopts the ‘Avoid-Reduce-Compensate’ methodology (see Fig. 2.1), which takes into account both constraints and opportunities.

This process, which complies with the French Environmental Code, the Environmental Protection Act and the Swiss Federal Ordinance relating to the Environmental Impact Assessment Regulation, is perfectly in line with the desire and objective to arrive at a proposal based on a balanced scenario.

Ideally, all stakeholders are involved in the process from the outset. However, an iterative approach had to be taken given that in the beginning the placement of the infrastructure was not defined, the knowledge of evolving territorial conditions was incomplete, the possibilities of effectively involving stakeholders at all levels of society were limited, the knowledge of the technological choices to be made for periods longer than twenty years is evolving, and the availability of resources for conceptual studies and personnel at this very early stage is limited.

Despite these constraints, the international science community is committed to transparency and public participation. The aim is to obtain a “social licence to operate” [18] by developing a scientific peaceful endeavour in the context of a systematic and structured public participation process. To this end, the feasibility study phase laid the foundation for the implementation of an approach in line with the regulatory frameworks and the best practices in France and in Switzerland. The approach goes beyond informing the public, engaging affected stakeholders in the discussion of the various segments of the project and, as far as possible, involving them in design considerations that affect their territory. A consultation process will therefore be carried out in an equitable manner on both sides of the border, respecting the approaches and procedures specific to each country.

The scenario development process first used the bibliographic information available. It gradually integrated further aspects as they became relevant and stakeholders as they were identified. This is the case, for example, for the participation of local elected representatives (municipalities, intercommunal structures, departments, regions). Depending on the layout, the number of surface sites and their location, between twelve and twenty communes



- **Avoid:** Modify the project to suppress a negative impact.
- **Reduce:** Reduce as much the extent, duration and/or intensity of an impact that cannot be avoided.
- **Compensate:** Contribute with direct or indirect positive values to noteworthy negative effects that cannot be avoided and sufficiently reduced.

Fig. 2.1 The "avoid-reduce-compensate" approach, known as "Éviter-réduire-compenser (ERC) in France and anchored in the French environmental law that determines the project authorisation process

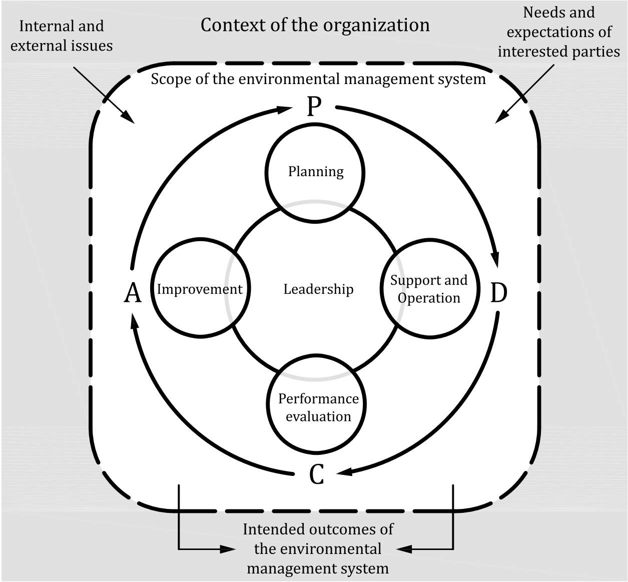


Fig. 2.2 The Plan-Do-Check-Act approach for environmental management, defined in standard NF EN ISO 14001, Sect. 0.4, page vii, is the basis for 'eco-design'

were at any time directly concerned and had to be consulted. A further 30 or so municipalities could be indirectly affected, in terms of access needs or infrastructure connections, or simply because the tunnel passes under their territory. Other stakeholders will need to be added for the development of a detailed design scenario. These additional stakeholders include local infrastructure operators (e.g., water, canals or road networks), representatives of local authorities responsible for certain subjects (e.g., traffic and nature) and associations (hunting, fishing, tourism, environmental protection, heritage preservation, economic development, etc.). It is prudent to approach these representatives as soon as the likelihood of their community being affected in some way is sufficiently high, i.e., when a specific scenario and an intent for a project exist. In this way, their availability to be informed about the project vision can be taken into account, the relevant contacts can be designated and the limited availability of the study group members can be taken into account. This study has involved selected elected representatives of directly affected locations. A systematic involvement of a wider domain of stakeholders is potentially appropriate at a subsequent phase, when a project intent is formulated and when a reference scenario that permits a useful involvement exists.

The international standards applicable, NF EN ISO 14001 (environmental management [19]) and (for eco-design) NF EN ISO 14006 [16] (see Fig. 2.2) require an iterative approach.

This approach is also set out in greater detail in the good practices guidelines for environmental impact assessments, established by the French Ministry for the Ecological Transition, Biodiversity, Forests, Marine Affairs and Fisheries, and in the NF EN ISO 31000 [20] standard on risk management (page 8 of the ISO standard) (see Fig. 2.3).

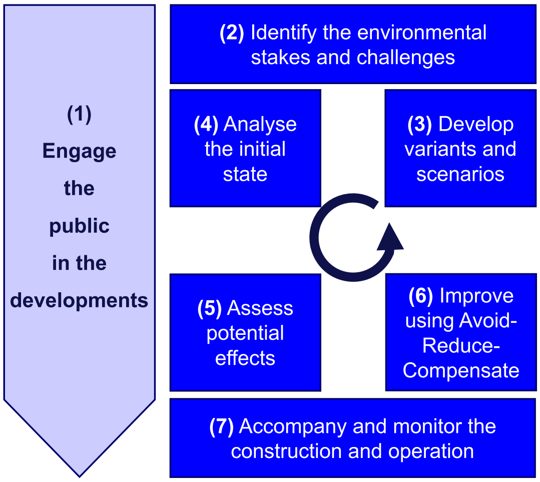


Fig. 2.3 Diagram from iterative impact study, French Ministry of Territorial Development and the Environment, 2001, p. 27, see footnote 6). Although this guide is from 2001 and specific regulations have changed, the principles described in the diagram are still valid and recommended for use today

Table 2.1 Definition of the territorial sensitivity levels, representing constraints for determining the configuration and location. Each colour-coded level represents several data layers that can be shown on a map in a geographical information system (http://cern.ch/fcc-sensitivity-grid)

Level	Designation	Description
4	Unacceptable	The level of constraint is such that the zone cannot be considered for a surface site. These zones are considered to be exclusion zones and should be avoided.
3	High	The zone is not recommended for the location of a surface site, but may be considered if it is decisive for the feasibility of the project, with additional reduction, compensation, or mitigation measures.
2	Acceptable	The zone is acceptable for the location of a surface site with appropriate reduction, compensation or mitigation measures.
1	Low	The zone can be considered for a surface site without further significant measures. Compensation may still be necessary.

2.2.2 Iterative process

The scenario development process is based on the iterative Plan-Do-Check-Act (PDCA) approach, and incorporates the Avoid-Reduce-Compensate (ERC) approach.

The process starts at a macroscopic level to identify the major constraints and opportunities. The constraints are recorded in a geographical information system (GIS) so that a map-based identification of areas to be avoided and areas in which a surface site or a subsurface passage would need to be limited can be rapidly identified. Such a system includes many data layers. Today, GIS-based Environmental Information System (EIS) for the FCC study comprises more than 120 layers that contain detailed information and are also used to build summary layers that are colour coded as shown in Table 2.1. The individual territorial sensitivity grid levels differ for French and Swiss territories [21]. They are based on national legal and regulatory constraints and concern particular regional and local constraints that are the result of exchanges with expert companies in the areas of environmental impact studies and project development as well as with public administration services. Typically, the constraints considered for the development of the future collider layout and placement scenario are highly conservative and sometimes exceed required legal and regulatory constraints in several domains to ensure that good territorial compatibility can be achieved by respecting known local and cultural heritage.

Scenarios were explicitly checked against such different interest zones, and a weighting took place whether to continue considering locations with known constraints or to discard the scenario due to its particular local high-value nature. The same strict constraint was applied to enlarged drinking water perimeters that were excluded as surface site locations, despite the fact that from a regulatory point of view, surface site constructions would be allowed in such zones.

This step permits the definition of entire classes for particle collider layout and placement candidates. Picking a representative candidate of a class permits the choices between the various configurations and locations under consideration to be progressively refined, introducing additional information obtained from the study of promising variants and discarding variants as soon as obstacles are detected. If a scenario is discarded, the main exclusion reasons are analysed and the entire class of scenarios is analysed with respect to those conditions. In many cases, this permits the elimination of an entire class of scenarios and the establishment of major exclusion criteria

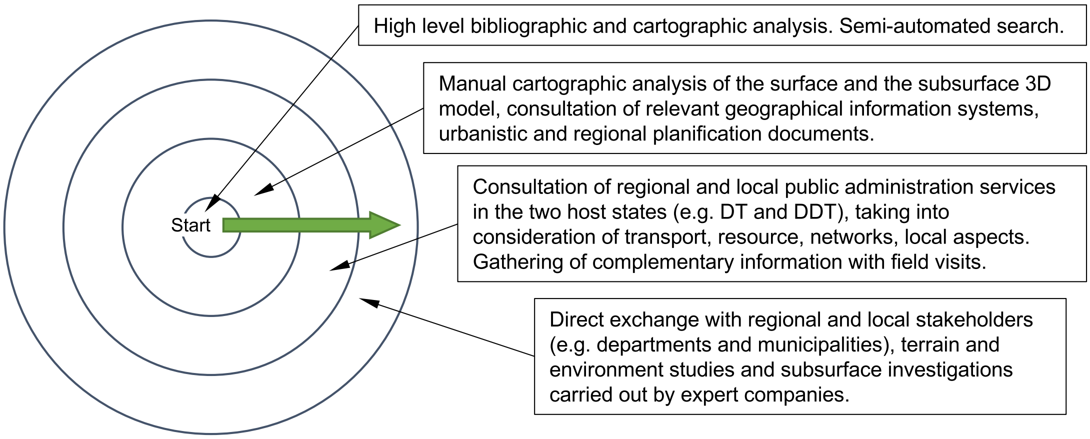


Fig. 2.4 As the layout and placement studies progress, additional information and stakeholders are included in the process to create a balanced scenario that meets the needs of all stakeholders

and constraints at the macroscopic level. The approach helps to reduce the solution space and to avoid further consideration of unfeasible scenarios in the subsequent steps.

Scenarios that are considered potentially feasible are further analysed with more detailed information and further stakeholders are involved. The same elimination process as above is applied.

This approach leads to a gradual definition of exclusion criteria and zones, and to a selection of likely layouts and placements that can eventually be optimised.

With regard to the territorial analyses, the analysis process begins at a level that considers topography, bathymetry, geology, hydrography, protection zones and urban development. It then gradually expands to include additional aspects such as accessibility, transport, disturbances, potentially conflicting planned developments and the availability of technical and natural resources (e.g., electricity or water). It then incorporates additional elements, such as social factors, local preservation and development objectives, visibility, shared visibility, or disturbances for stakeholders affected directly (e.g., neighbours) and indirectly (e.g., communities affected by construction site traffic).

The scenario-building process requires a more detailed analysis phase, aimed at the direct participation of stakeholders and local players in order to draw up a scenario adapted to the specific plot of land, always taking into account the three main issues (science, territory, implementation) within the framework of the iteratively improving avoid-reduce-compensate project development approach.

With the choice of a reference scenario as a prerequisite for field studies, environmental impact assessment, and technical design work, also the dialogue with public stakeholders could be gradually defined and initiated. Considering the valuable accompaniment of the two CERN host states and their advice in engaging the public in territorial development projects, the study collaboration requested CERN to consult the French “Commission nationale du débat public (CNDP)” (english: National Commission for Public Debate) in 2024. A first analysis resulting in a list of recommendations were made public on 6 March 2025 [22]. Taking account of these recommendations and considering the transborder context of the particle collider scenario, it was decided to extend the collaboration with the CNDP and engage with the Swiss authorities to prepare subsequent public engagement processes in both Host States, should the international scientific collaboration express an intent to develop the study into a project and enter a preparatory phase.

Informal and formal processes engaging the public are ideally carried out as early as possible, and the French government reminds the principle and need of anticipation on various occasions. At the same time, care must be taken to time engagement appropriately. This approach aims at assuring that the project scenario can be adapted based on the involvement of stakeholders and having sufficient technical information at hand to inform he engaged stakeholders about the needs and constraints that govern the project and the environment in which it would eventually be embedded.

As new information is integrated into this iterative process, automated and cartographic research must be progressively completed, followed by manual research, interviews with people with good knowledge of the region, field visits and consultation with stakeholders (see Fig. 2.4).

2.2.3 Scenario assessment

To determine the value of a scenario, to assess if it should be further optimised or discarded and to be able to compare the merits of different scenarios among each other, a multi-criteria analysis scheme has been developed, based on an approach presented by the French organisation Cerema in its guidelines for the environmental analysis of linear transport infrastructures [14]. This approach was completed using the UNIDO International Guidelines for Industrial Parks, published in November 2019 [15].

As required by the regulatory environmental authorisation frameworks in France and Switzerland, a development project is to be considered in broad terms, extending the analysis to various non-technical relevant aspects such as indirectly affected stakeholders; legal, regulatory, social and economic factors; networks (roads, railways, water, electricity, canals, public service and safety infrastructures); heritage sites; visual aspects; disturbances (noise, dust, light, smells, pollution) and potential benefits. As recommended in the Cerema guide, this approach was used to assess the relative merits of each variant, and contribute to the development of reduction, compensation, and support measures in an open and transparent process. In Switzerland, and more specifically in the canton of Geneva, a parallel can be drawn with the cantonal guide for the strategic environmental assessment tool (EES) [23]. When plans, programmes or projects (PPPs) are drawn up, the EES is sometimes used to ensure that environmental and human health issues are taken into account systematically and at an early stage, as defined in the Environmental Protection Act [24]. As such, it can be used as a decision-making tool, assessing the merits of different scenarios.

The multi-criteria analysis results use standardised qualitative indicators to compare the suitability of different scenarios. Its application during the scenario-building process makes it possible to quickly identify the types of scenarios that present significant advantages or disadvantages, and to determine whether the differences between the scenarios are major or minor. This approach also offers the advantage of clarifying which elements have the greatest or least influence on the value of the scenario, and thus guides the development of new types of scenarios. This approach is then used in the subsequent optimisation stages, for example with regard to moving shaft and surface sites to more suitable locations and taking into account the availability of existing infrastructures (e.g., roads, railways, water supply and treatment, electricity), urban planning documents (PLU, PLUi, PADD, SCoT, PDcn, PDcom) and synergies and opportunities (e.g., supply of residual heat, sharing of technical infrastructures, reduced transport distances).

The criteria list is made up of nine topics, each comprising several detailed criteria. These criteria cover the various themes that are relevant for an implementation. 32 environmental factors, the scenario configuration determining the performance for scientific research, implementation costs and risks were taken into account:

1. Land status
    (a) Availability of plots
    (b) Clearly defined ownership
    (c) Plot price
    (d) Acquisition time and expected difficulties in obtaining rights
    (e) Plot development cost
2. Road connections
    (a) Distance from transport, industrial and other infrastructures
    (b) Distance from populated areas
3. Raw materials and services
    (a) Availability of raw materials for construction and resources for operation
    (b) Proximity to service providers
4. Physical characteristics
    (a) Plot size and shape
    (b) Topography
    (c) Shaft depth
    (d) Drainage and sanitation requirements for construction
    (e) Surface soil condition
    (f) Water resources
    (g) Accessibility
    (h) Subsurface conditions (physical)
    (i) Subsurface conditions (regulatory)
5. Infrastructure
    (a) Accessibility of electrical power
    (b) Communication network
    (c) Water for industrial use
    (d) Drinking water
    (e) Waste water discharge, rainwater collection, disposal and treatment points
    (f) Temporary storage and processing areas during construction
6. Environmental and social factors
    (a) Existing environmental constraints
    (b) Fauna and flora

   (c) Existence of construction constraints
   (d) Adjacent constraints
   (e) Disturbances
   (f) Availability and accessibility of workforce
   (g) Involvement of local authorities
   (h) Support from civil society
7. Configuration
   (a) Geometry
   (b) Size
   (c) Transfer lines
8. Implementation cost
9. Risks related to the implementation

For each scenario, six sets of criteria were evaluated individually for each of the surface site candidate locations for the surface sites in that scenario (land status, road connections, raw materials and services, physical characteristics, infrastructure, environmental and social factors) and three high-level criteria were considered for the overall scenario (configuration, costs, and risk).

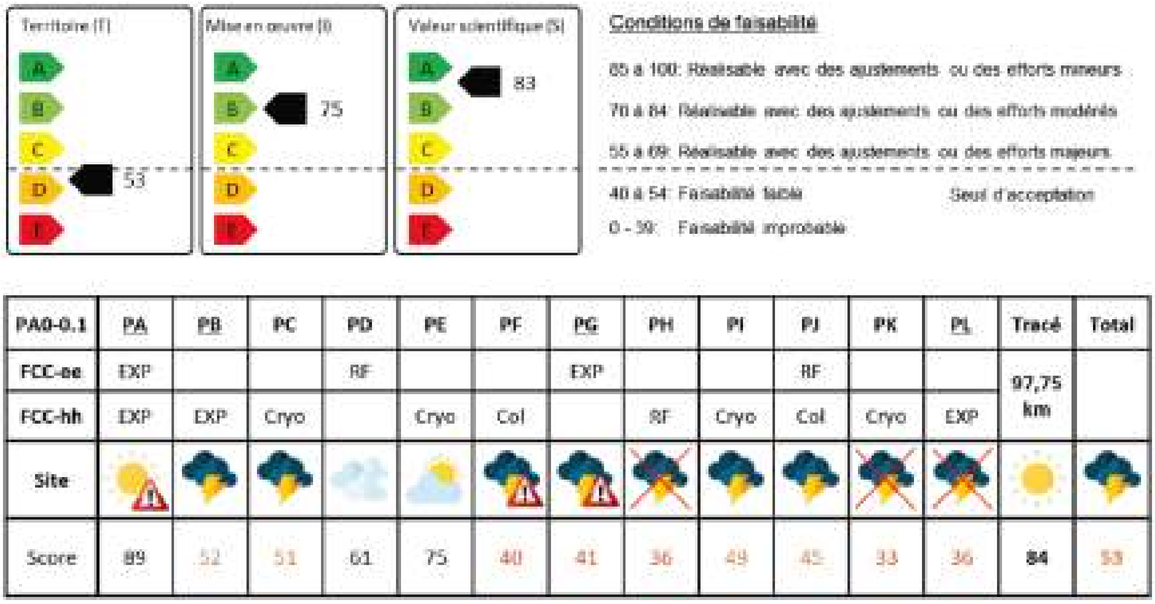
Spreadsheets for each scenario were created to assign each criterion a qualitative score between −2 and +2, according to a pre-defined evaluation grid with standardised conditions. A score of '0' represents a neutral assessment of the indicator. For each high-level criterion, the scores of its sub-criteria were added together to provide an indicator for that criterion. The spreadsheet also shows the macro-criteria scores, and presents a final score for all criteria in the form of a percentage between 0 and 100. Lastly, the values of the criteria are synthesised to provide indicators for 1) scientific excellence, 2) territorial aspects and 3) appropriateness of project implementation. This approach not only makes it possible to quickly estimate the value of a scenario and compare it with others, but also to highlight criteria that are insufficiently known and require in-depth study.

Values were assigned for the qualitative indicators through a collaborative process by the multidisciplinary team, based on bibliographic and cartographic studies, database analysis, geographical information system queries, simulation and modelling. There were also field trips and field investigations; interviews to discuss the most suitable footprint with staff from the administrative departments of the two host states (e.g., DT, GESDEC, OCEV, OCAN, OCT in Switzerland; DDT 01 and DDT 74 in France); consultation with experts working in different technical fields (Cerema, Ecotec, HydroGéo, ILF, GADZ, particle accelerator designers working in many partner institutes, geologists employed in many partner universities); and feedback from local players during working meetings with municipalities, inter-communal entities, and elected representatives.

A disadvantage of this approach is that it simply adds up and averages all values. In some cases, there may be an obstacle related to territorial or scientific aspects or to project implementation. However, averaging means that a single low value will just lower the overall ranking but will not necessarily show the blocking point in the summary. The multi-criteria analysis was therefore complemented by an overall assessment of the scenario, which permitted the highlighting of the potential benefits of one scenario that make it particularly preferable to others or which indicate whether the scenario is difficult or not feasible. Thus, scenarios presenting obstacles continue to be analysed and recorded, but they are rejected even if the value of a thematic indicator (scientific performance, territorial compatibility or project implementation) is higher than the acceptable threshold value for that element. Examples of such situations include the strong probability of encountering geological features that would expose the project to an unacceptably high risk (karst, potentially conflicting water-bearing layers, crossing a major fault, presence of high-pressure aquifers), patrimony sites that represent incompatibilities with a technical installation, too dense residential zones, incompatibilities with local or regional development policies, a collider circumference that would not allow the scientific research programme to be conducted for technical reasons or would not allow its operation to be viable (for example, a collider circumference significantly smaller than 90 km). The ranking is highlighted in summary diagrams such as the one outlined as an example in Fig. 2.5. The illustration also shows the limitations of multi-criteria analysis: for example, two surface site locations in the PA0 scenario with twelve sites developed during the first exploratory phase are located in areas considered to be blocking points, but this is only visible in the individual sheet for each site. The three-column summary alone, however, does not show these exclusion criteria and must, therefore, be supplemented by a brief text description.

Territorial (T), implementation(I), and scientific (S) issues can, in fact, be easily visualised and compared thanks to this standardised qualitative approach. Figure 2.6 highlights the merits of the current scenario working hypothesis PA31, which makes it a preferred scenario for the detailed territorial and technical analysis. Such overviews also helped to understand that scenarios involving twelve sites do not meet the required conditions to undergo an in-depth study. The approach permitted further optimisation by understanding how the improvement on one site could potentially lower the performance of another and thus retain scenarios for further optimisation that improved all sites individually and the entire scenario as a whole.

With additional information becoming available, the assessment changes and therefore further optimisation of the scenario will be required until a decision to proceed with a construction project can be taken. The advantage of



Conditions de faisabilité

85 à 100: Réalisable avec des ajustements ou des efforts mineurs

70 à 84: Réalisable avec des ajustements ou des efforts modérés

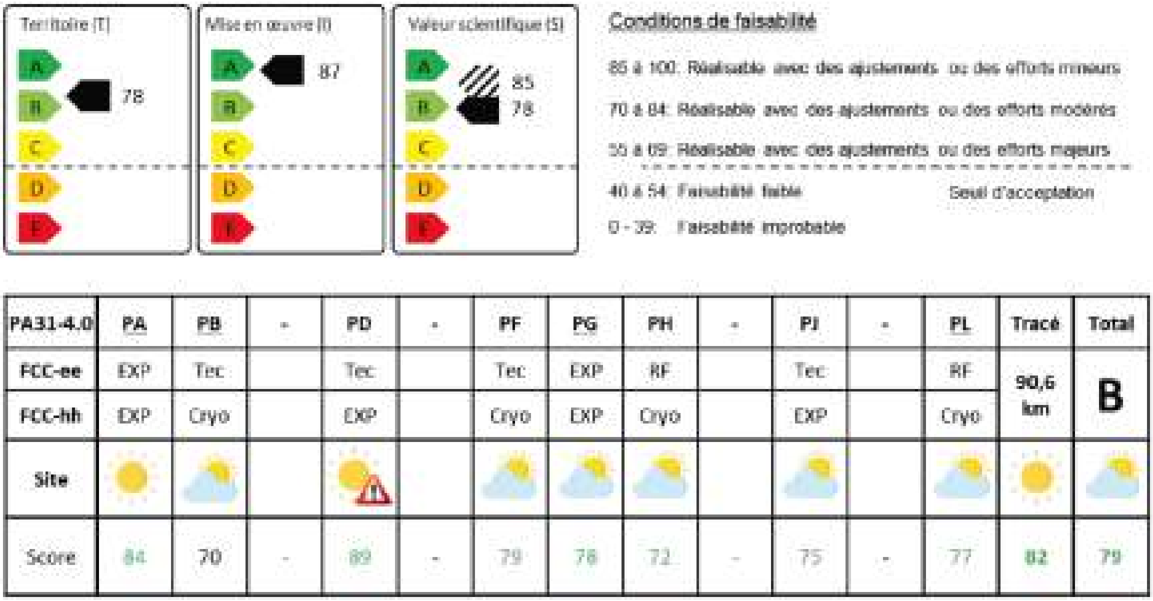
55 à 69: Réalisable avec des ajustements ou des efforts majeurs

40 à 54: Faisabilité faible Seuil d'acceptation

0 - 39: Faisabilité improbable

PA0-0.1	PA	PB	PC	PD	PE	PF	PG	PH	PI	PJ	PK	PL	Tracé	Total
FCC-ee	EXP			RF			EXP			RF			97,75 km	
FCC-hh	EXP	EXP	Cryo		Cryo	Col		RF	Cryo	Col	Cryo	EXP		
Site	☀ ⚠	⛈	⛈	☁	⛅	⛈ ⚠	⛈ ⚠	⛈ ✗	⛈	⛈	⛈ ✗	⛈ ✗	☀	⛈
Score	89	52	51	61	75	40	41	36	49	45	33	36	84	53

Fig. 2.5 Example of a summary view of the multi-criteria analysis of an scenario (PA0-0.1). The scenario seems feasible, even if the territorial feasibility would be low. However, a closer look at each site reveals many blocking points



Conditions de faisabilité

85 à 100: Réalisable avec des ajustements ou des efforts mineurs

70 à 84: Réalisable avec des ajustements ou des efforts modérés

55 à 69: Réalisable avec des ajustements ou des efforts majeurs

40 à 54: Faisabilité faible Seuil d'acceptation

0 - 39: Faisabilité improbable

PA31-4.0	PA	PB	-	PD	-	PF	PG	PH	-	PJ	-	PL	Tracé	Total
FCC-ee	EXP	Tec		Tec		Tec	EXP	RF		Tec		RF	90,6 km	B
FCC-hh	EXP	Cryo		EXP		Cryo	EXP	Cryo		EXP		Cryo		
Site	☀	⛅		☀ ⚠		⛅	⛅	⛅		⛅		⛅	☀	⛅
Score	84	70	-	89	-	79	78	72	-	75	-	77	82	79

Fig. 2.6 Summary of the multi-criteria analysis of reference scenario PA31-4.0

the systematic approach is that it permits the demonstration that there is a continuous improvement of the project scenario based on the growing understanding of the boundary conditions and the consideration of stakeholder input during an environmental evaluation and project authorisation process.

Around a hundred different scenarios have been developed and individually analysed (see Fig. 2.7). Eventually, the ten most promising scenarios (PA0-0.1, the scenario developed for the Conceptual Design Report, turned out to be not feasible and serves as a performance reference baseline only) have been retained for a review with experts from different project development domains. The scenarios were ranked using the VIKOR [25] quantitative method that was applied to the established multi-criteria analysis (see Fig. 2.8). The algorithm permits the evaluation of different multi-criteria factors with different units and scales and with different, potentially even conflicting, minimisation and maximisation goals. The following VIKOR criteria were set for the establishment of the ranking:

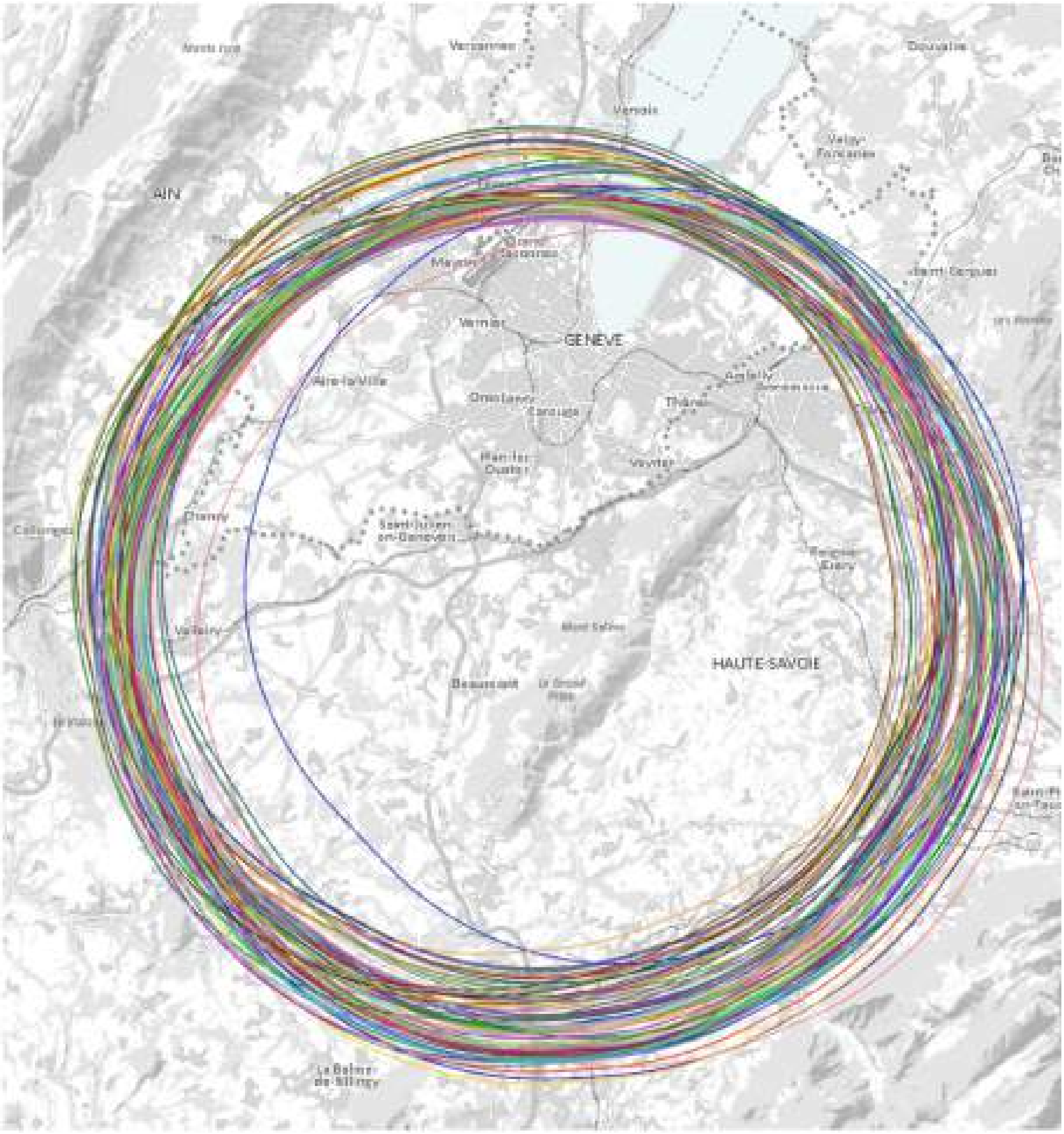
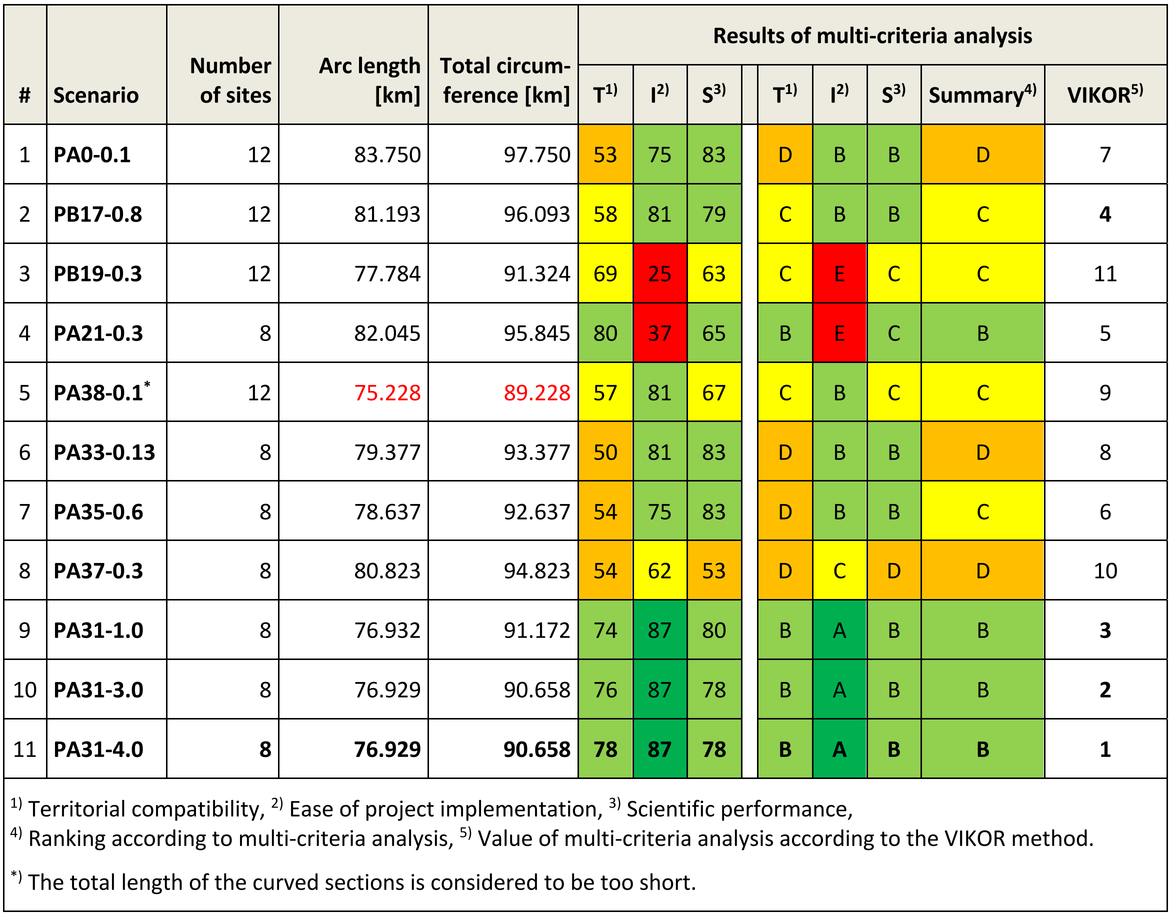


Fig. 2.7 Around one hundred different layout scenarios were studied and individually analysed

1. **Number of sites:** An eight-site configuration offers four interaction points for the lepton collider, compared with just two interaction points for the twelve-site configuration. Therefore, the goal was to minimise the number of sites with a weight contribution of 5%.
2. **Total length of curved sections:** A longer circumference length provides higher scientific performance or simpler design. Therefore, the goal was to maximise the circumference with a weight contribution of 5%.
3. **Territorial compatibility:** Territorial compatibility, ease of implementation and scientific performance are given equal weights of 30% each. Each of these three pillars must be maximised, and all three need to be balanced to ensure the feasibility of the scenario. The feasibility of each scenario can only be determined through detailed analysis.
4. **Compatibility of technical implementation and construction with geological constraints, configuration, and layout:** Maximise with a weight of 30%.



#	Scenario	Number of sites	Arc length [km]	Total circumference [km]	Results of multi-criteria analysis							
					T1)	I2)	S3)	T1)	I2)	S3)	Summary4)	VIKOR5)
1	**PA0-0.1**	12	83.750	97.750	53	75	83	D	B	B	D	7
2	**PB17-0.8**	12	81.193	96.093	58	81	79	C	B	B	C	**4**
3	**PB19-0.3**	12	77.784	91.324	69	25	63	C	E	C	C	11
4	**PA21-0.3**	8	82.045	95.845	80	37	65	B	E	C	B	5
5	**PA38-0.1***	12	75.228	89.228	57	81	67	C	B	C	C	9
6	**PA33-0.13**	8	79.377	93.377	50	81	83	D	B	B	D	8
7	**PA35-0.6**	8	78.637	92.637	54	75	83	D	B	B	C	6
8	**PA37-0.3**	8	80.823	94.823	54	62	53	D	C	D	D	10
9	**PA31-1.0**	8	76.932	91.172	74	87	80	B	A	B	B	**3**
10	**PA31-3.0**	8	76.929	90.658	76	87	78	B	A	B	B	**2**
11	**PA31-4.0**	**8**	**76.929**	**90.658**	**78**	**87**	**78**	**B**	**A**	**B**	**B**	**1**

1) Territorial compatibility, 2) Ease of project implementation, 3) Scientific performance,
4) Ranking according to multi-criteria analysis, 5) Value of multi-criteria analysis according to the VIKOR method.

*) The total length of the curved sections is considered to be too short.

Fig. 2.8 Multi-criteria analysis based ranking of the most promising implementation scenarios in 2022 with the performance of the gradual improvements of reference scenario class PA31

5. **Scientific performance, taking into account the configuration and technical difficulties of the scenario:** Maximise with a weight of 30%.

The result was that the most promising scenario is an 8-site layout with a total circumference of the order of 91 km. This scenario gave sufficient residual margins for further optimisations. Meanwhile, all the other scenarios developed are no longer considered feasible, either because of the loss of site locations during the study years, because of unacceptable incompatibilities with territorial or geological conditions, or because their scientific performance is not sufficient to attract researchers from all over the world over the long term. Therefore, PA31 was considered for further detailed studies, in particular involving subsurface investigations and detailed field studies concerning environmental aspects. Optimisations lead to the versions 3.0 and 4.0 for which the performance is also displayed.

2.3 Requirements and invariants

2.3.1 Science and technology motivated requirements

Layout A set of parameters fundamental to particle accelerator design makes up the starting requirements for scenario development. The design parameters determining the overall size of the configuration cannot be chosen arbitrarily. These parameters include the geometry of the configuration (for example, a symmetry or periodicity of sectors involving a specific number of surface sites), the length of the basic curved cells, called ‘arcs’ (which repeat like the parts of a chain, to build the curved sectors), the number of arc accelerator cells to be repeated and the lengths of the various types of straight sections between the arcs. Figure 2.9 shows two basic configuration geometries used in configuration and layout studies. The first geometry (image on the left) serves as a starting point: it groups together three experiment sites in the upper part of the geometry. It offers greater freedom in terms

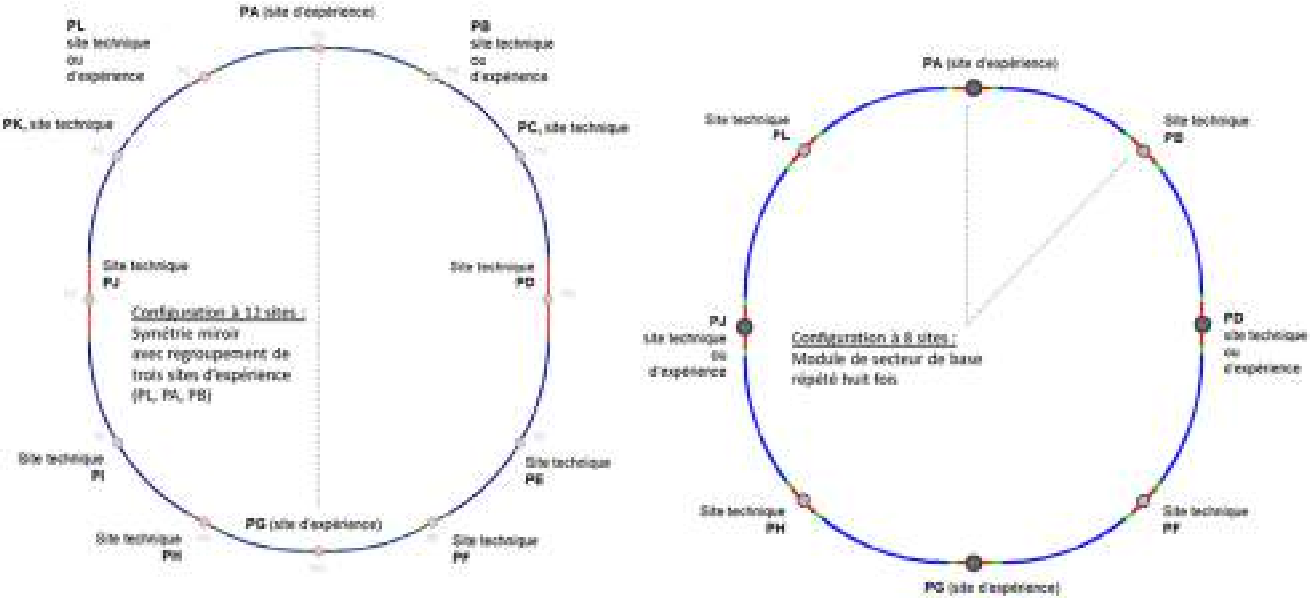


Fig. 2.9 Two different collider layouts. The image on the left shows a configuration comprising twelve sites based on a geometry with mirror symmetry. The image on the right shows an eight-site configuration based on the repetition of a basic sector module. The arcs (blue) are separated by straight sections (green and red segments)

of moving the various surface sites but requires twelve surface sites. The second geometry (image on the right) represents the current development: the four experiment sites are evenly distributed (top, right, bottom, left), and only eight surface sites are required. However, the freedom to move sites is less than with the first geometry.

The following requirements were initially set and had to be adapted during the development of a scenario that aimed at satisfying the territorial implementation constraints.

The initial simple mirror symmetry was discarded in favour of a 4 times repetition of a 90° sector, i.e., a four-fold symmetry. The initial configuration (12 sites) made it possible to group 3 experiment sites close to each other near the main CERN site, leading to shorter distances between surface sites and greater flexibility to lengthen and shorten the north and south sides. The current geometry (8 sites) enables a more regular design and thus facilitates performance optimisation processes. The lepton collider can also have four interaction points.

Total circumference The initial objective was to design a particle collider infrastructure with a circumference of around 100 km. A reduction of 10%, to a circumference of 90 km, is considered to be the lower acceptable limit, below which the performance obtained for scientific research would become too limited. The smaller the circumference, the smaller the radius of the curved sections and the more pronounced the curvature, resulting in greater energy losses, leading eventually to an unsustainable scenario from an energy efficiency perspective and the need for more powerful magnets for the hadron collider, which could then become technologically unattainable.

Number of surface sites The initial 12 sites were reduced to 8 sites with the advent of the four-fold symmetry layout. It proved too difficult to find a suitable layout scenario with 12 sites featuring intermediate access points compatible with the territorial constraints and risks involved in implementing the project. A scenario with eight sites offers less flexibility for the layout study since the fixed interaction sites are geographically opposed. Still, the number of necessary suitable locations to be found is lower.

Number of interaction points For the hadron collider, both geometries offer the possibility of four interaction points. However, only the four-fold symmetry layout provides the possibility of having four interaction points with the lepton collider. The 12-site scenario also proved difficult due to the need to combine experiments and injection at two points (PL and PB).

Arc cell length The hadron collider arc cell length drove the overall circumference of the layout. Initially, a cell length of 213.03 m was considered. It was eventually extended to 275.79 m. The total circumference depends on the multiples of that arc cell length and cannot, therefore, be arbitrarily chosen. In this case, the lepton collider adapts to the more stringent requirement of the hadron collider.

Total number of arc cells The size of the hadron collider curve can only be increased or decreased by inserting or removing an arc cell in each curve. The overall configuration must remain symmetrical. The initial 12 site layout required 4 sectors of 19 short cells and 4 sectors of 73 long cells. The current 8 site layout requires 8 sectors with 26 cells, i.e., a total of 208 cells. This requirement determines the total circumference of the infrastructure. In this case, the lepton collider adapts to the more stringent requirement of the hadron collider.

Total arc length The 12-site configuration featured four short arcs and four long arcs. The long arcs were too long to remain without intermediate access points for technical and personnel safety reasons. Therefore, an additional site had to be placed at the midway point, at a distance of around 8 to 10 km from each end. The 8-site layout no longer has this requirement. The total arc length should, however, permit safe operation and the possibility to evacuate personnel in case of emergency efficiently. The current distance between access sites of about 11.5 km is considered acceptable.

Radio frequency system harmonics The stability and performance of the radio-frequency system used to accelerate the subatomic particles depend on the circumference of the collider. It also concerns the transfer of particle beams from the existing SPS and LHC tunnels. For a 91 km long collider, 3 possibilities have been identified, which provide sufficient flexibility for the radiofrequency system design. A collider with a circumference of between 90.7 and 90.8 km is the best option. A length of 90.6 km is feasible but reduces the frequencies of the cavities in the radiofrequency system more than the others. In this case, the lepton collider adapts to the more stringent requirement of the hadron collider.

Length of straight section at interaction points At least 700 m are needed on either side of the interaction point to focus the collider beams to be able to achieve the high beam densities needed for high luminosities. The two colliders (lepton and hadron) have different space requirements for crossing the two beam lines, so the tunnel needs to be widened by around 10 m to a distance of 1400 m on either side of the interaction point.

Length of straight section at radiofrequency locations A distance of 2800 m between 2 straight sections was initially deemed adequate to accommodate the radiofrequency equipment that accelerates the beams. After various equipment integration studies, it was found that this value could be reduced. A distance of 2030 m is now considered the acceptable lower limit required for the systems and the integration of the ancillary equipment.

Cooling water requirements With the aim of conserving resources responsibly, ongoing studies have already helped to reduce requirements from an initial 4.9 million m^3 per year to a range between 1.6 million m^3 (Z mode) and 3.0 million m^3 per year ($t\bar{t}$ mode). Further reductions can be expected due to the inclusion of the concept of heat reuse, taking into account technological developments and the development of water reuse synergies.

Electricity requirements Initial powering requirements of the lepton collider ranged between 1.2 and 2.0 TWh per year, depending on the operation mode. Gradual advances in the concept development reduced these values to a range between 1.0 and 1.77 TWh per year. Since the current scenario has four interaction points rather than two, further reductions are possible by limiting the radiofrequency power if a reduction of the annual integrated luminosity is acceptable for the scientific research programme. Further optimisations are to be expected from an adaptive operation concept and energy consumption reduction of systems that are powered down or set to an energy-saving mode when not required for operation and maintenance.

For the hadron collider, an initial annual energy consumption estimate was based on current superconducting magnet technology at very low cryogenic temperatures. This estimate has been revised by developing a design that works at higher cryogenic temperatures to allow significantly lower energy consumption. Leveraging a high-temperature superconducting magnet technology would allow the cryogenic operation temperature to be further increased. Together with adapting the operation plan and introducing an annual energy consumption ceiling, this would bring the annual energy consumption into the range of the lepton collider. However, a focused R&D programme is required to develop the technology. A window of opportunity in the range of more than 35 years is available to achieve this goal if a decision to proceed is taken.

Space requirements of technical surface sites The space requirements of the technical surface sites are determined by the technical infrastructures that both particle colliders will need. Although the lepton collider has significantly fewer requirements than the subsequent hadron collider, the surface sites must be able to host the additional equipment that will only be put in place for the second phase.

The minimum equipment required on each site comprises an electrical substation, power converters to drive the particle accelerator equipment for the sectors in both directions of that site, power amplifiers where there is a radiofrequency system, tunnel and cavern ventilation, raw water-based accelerator cooling systems, raw water treatment systems, heat exchangers and refrigeration towers. Since the actual design of the particle accelerator is yet to come, it is challenging to estimate the space requirements for such systems. Therefore, the most advanced systems are used as a reference to estimate the space requirements.

In addition to the technical systems, space is required for temporary storage of the particle accelerator systems to be installed underground and for the handling of the technical systems at the surface. In the case of sites with a cryogenic refrigeration system, space is required to store the cryogens (liquid and gaseous helium as well as nitrogen). While the lepton collider will require only two sites with relevant cryogenic refrigeration systems for the radiofrequency systems, each site will host a cryogenic refrigeration plant for the hadron collider. Additional minor space requirements emerge from the roads on the site, such as the need to provide limited office space and storage of spare parts, cranes, and handling equipment.

The working hypothesis is that in the order of 100 technicians and engineers per day can be present during installation, major maintenance and upgrade interventions. During the operation phase, the presence of personnel is limited to the strict minimum, leveraging remote operation and intervention as much as possible. No permanent presence of personnel is planned during ordinary operations.

The current lepton collider net space requirements for construction elements on technical sites are: 2.2 ha for PB, 2 ha for PF, 4.4 ha for PH and 2.6 ha for PL. Additional space is required for the hadron collider cryogenic refrigeration plants and cryogen storage, as well as for additional technical equipment. Including the requirements for green buffers and landscape integration bring the requirements to about 3.5 ha to 4 ha for the technical sites PB, PF, PL. About 8 ha are required for PH due to the initial large cryogenic refrigeration system and the topographical challenges that call for a terrace-based landscape integration. The indicated space requirements do not include the requirements emerging from the need to accommodate the different topographical constraints, the need for green buffers and landscape integration. Hence, the specific local requirements are higher.

Subsequent architectural designs and landscape integration will aim to reduce land consumption as much as possible.

Space requirements of experiment surface sites In addition to the requirements of the technical sites, each experiment site also requires a pre-assembly hall for the experiment detector. To limit the surface space requirements, the working hypothesis is that the detector will be assembled underground. However, elements will need to be quality checked, pre-assembled and tested on the surface in a hall that measures about 1250 m^2. Sufficient space of about 1000 m^2 for handling of parts and a temporary buffer for magnets to be installed is also required.

An experiment site typically also hosts a data centre, workspace for a group of about 50 scientists and engineers, meeting rooms and a few offices, small workshops, a data centre and visitor facilities.

For the hadron collider, the largest detector part, a superconducting magnet coil, cannot be transported directly to the sites. It needs to be manufactured on-site. For this process, about 7500 m^2 are required in addition to each surface site. The space will remain untouched by construction during the first, lepton collider, phase, and it will be rewilded after the assembly and lowering of the magnet coil at the end of the hadron collider installation phase.

The working hypothesis is that up to 300 scientists, technicians, and engineers can be present per day during installation and major maintenance and upgrade interventions. During operation, only a small team of less than 20 people would be present on site. Additional personnel would be present to operate the visitor facilities.

The current lepton collider net space requirements for construction elements on scientific sites are listed below. 3 ha for site PA due to the possibility of leveraging the space of the existing LHC surface site Pt8. Including the temporary space required for the production of the superconducting magnet coil of the hadron collider experiment, the space requirement increases to about 4 ha. The sites PD, PH and PJ require about 4 ha for the lepton collider phase and 5 ha for the hadron collider phase. The space requirements indicated do not include the requirements emerging from the need to accommodate the different topographical constraints, the need for green buffers and landscape integration. Hence, the specific local requirements are higher.

Subsequent architectural designs and landscape integration will aim to reduce land consumption as much as possible.

2.3.2 Initial invariants

A set of invariants was established in the beginning to guide the development of an implementation scenario to ensure that a minimum set of criteria concerning scientific excellence, territorial compatibility and project risk control can be satisfied. They are a combination of avoidance and reduction constraints, goals and high-level requirements.

- Avoid karstic limestone formations, risks of high-pressure water penetration, known major faults and areas of seismic instability, as well as significant overburden.
- Place the underground structures in the molasse layer as much as possible.
- Provide a technically feasible connection to CERN's SPS underground infrastructure and, if possible, to the LHC infrastructure.

- Dig the tunnel to a sufficient depth below the lake bed to ensure stability and long-term low maintenance. The alignment can be optimised by identifying the minimum depth based on subsurface geophysical and geotechnical investigations for a preferred scenario. The current assumption is that the tunnel alignment crossing the Geneva lake is 100 m below the lake bed.
- Dig the tunnel deep enough under the Arve, Rhône and Usses rivers to guarantee the micro-stability required for precise alignment of the accelerator and to avoid adverse effects with any, potentially existing, surface constructions.
- Limit overburden under the Mandallaz, Fillière and Bornes zones (minimum depth to be defined by specific subsurface investigations).
- Avoid elevations above 750 m for surface sites to limit the depth of shafts and ensure good site accessibility.
- Aim for shaft depths of less than 250 m for scientific sites and 400 m for technical sites to avoid excessive challenges for the installation of the accelerator equipment and the experiment detectors.
- Avoid areas considered ‘exclusion zones’ in an established territorial sensitivity grid drawn up with contracted organisation Cerema, Direction Départementale du Territoire in France, collecting information from the Direction Régionale de l’Environnement, de l’Aménagement et du Logement and with contracted company Ecotec in Switzerland with additional information collected from the cantonal DT services. This grid lists environmental, spatial planning, zoning and strategic constraints, as well as public health and safety constraints with different relevance levels that lead to the definition of zones to be avoided and zones at surface and subsurface constructions will need to be limited if they cannot be avoided.
- Give preference to proximity to strategic project infrastructures (e.g., grid power lines, certain types of roads, autoroute stations, railway lines) and stay clear of certain other infrastructures (e.g., geothermal probes, gas pipelines, oil pipelines).
- Remain outside of town and village centres and hamlets to limit potential nuisances associated with the construction and operation activities.
- As far as possible, avoid areas subject to a set of less critical territorial constraints, and if avoidance is not possible, reduce surface areas in these zones.
- Respect the fact that it is not possible to individually displace the locations planned for scientific sites where particle beams cross and where the experiment detectors are located.
- Respect the limits for displacing technical sites along the straight sections of the ring within the lengths of those sections, according to the possibilities offered by the various technical systems required at the technical sites for the operation of the accelerators.
- Consider the constraint for positioning the shafts inside the ring to facilitate access to the transport zone in the tunnel.
- Limit the length to around 400 m for the horizontal connection tunnels from the technical sites to the shafts inside the ring. Building a longer tunnel is not out of the question, but it would entail additional costs and difficulties.
- If technically possible, limit the total occupied surface area of technical sites to 5 ha and the surface area of experiment sites to 8 ha. These areas include buffer zones, storage, and transport areas and take account of rewilding, reconstitution, replacement, or compensation measures. Wherever possible, seek synergies with existing infrastructures to reduce surface areas.
- Avoid areas with difficult topography (steep and potentially unstable slopes, unstable soils, areas at risk of flooding, discontinuous terrain).
- Ensure adequate road connections (7 m wide, 2 lanes, 20 m curvature radius, gradient well below 10%, minimum clearance height of 4.4 m, compatibility with heavy goods vehicles of 44 t to the main road network in accordance with article R312 of the French highway code).
- Maintain a minimum distance of 100 m between residential areas and sites. Depending on topographical conditions and the site’s noise and visibility attenuation features, this distance can be as much as 250 to 300 m.
- Avoid protected agricultural areas unless they are essential to ensure technical feasibility.
- Avoid natural and historic heritage sites, avoiding shared visibility between the sites.
- Preserve the views and landscape protection zones as far as possible.
- Avoid rivers and streams (to avoid having to modify or stabilise riverbanks).
- Avoid wetlands and strictly protected areas.
- Avoid protected forests because of the need to clear them and preserve existing biodiversity and because of their inaccessibility and topography, unless these areas are essential to ensure feasibility. In the latter case, the land occupation should be limited.
- Give preference to areas in proximity to high-capacity power lines (225 kV and 400 kV).
- Look for opportunities with a connection or access to the autoroute system.
- Look for opportunities with a connection or access to the railway system.
- Consider the use of known brownfield sites for the installation of technical infrastructures that may be remote from the sites (e.g., electrical substations, pumping stations, cooling towers) and for the development of compensation areas.

- Look for scenarios that enable all surface sites to be reached within a reasonable time (30 minutes by car) from strategic service and supply points (e.g., CERN and CNRS/LAPP).
- Avoid creating new border crossings and do not consider sites that straddle the border.
- Avoid vineyards and areas with fruit trees.
- Give preference to public land over private land, undeveloped land over developed land, unused land, overused land (special agricultural uses such as vineyards and protected fruit crops) and brownfields.

2.3.3 General objectives

The multi-year study also led to the development of a number of objectives that would help make the project more territorially compatible. They have been taken into account in the evolution of scenarios and in the development of a preferred layout scenario that serves as a reference, which is presented in later sections of this document.

Sustainable operation and maintenance Ensure that the scenario can be operated and maintained sustainably. To achieve this, relevant technical facilities (high-tech workshops, offices) must be in proximity to the sites. Therefore, give preference to scenarios that take advantage of synergies with existing CERN sites and/or are close to the LAPP of CNRS/IN2P3.

Protecting farmland Limit the consumption of farmlands in both host states. Avoid protected agricultural areas, unless they are essential for feasibility.

Road access to surface sites To limit the need to build new roads and to avoid consuming land, surface sites must either be located directly on existing departmental roads or only require an improvement to existing access roads. If new roads are essential, then the requirements should be minimised.

Disturbances Limit direct disturbances for local inhabitants. Avoid proximity to residential areas, visibility, and shared visibility. Avoid locations on roads passing through residential areas. Avoid proximity to natural and historical heritage sites. Provide means of evacuating spoil by conveyor belt to avoid truck traffic where possible.

Landscape integration Aim to preserve views and landscape protection zones wherever possible. Specific studies by landscape architects are required for a preferred scenario during a subsequent design phase.

Protection of water Avoid water protection zones, rivers, and streams. Do not take in water from water-bearing layers, and avoid the use of drinking water for systems that require raw water. Avoid having to stabilise or modify riverbanks. Specific studies are required for a preferred scenario during a subsequent design phase.

Forests Respect protected forest zones and trees. Limit clearing forests or felling trees in both host countries to maintain biodiversity. Avoid high-quality forest zones whenever possible. Improve climate resilience by restoring impaired forests.

Synergies Give preference to locations that can create synergies with nearby private and public facilities and infrastructures. This includes, for instance, the availability of emergency rescue stations and fire brigades, hospitals, commercial and industrial development zones, food processing companies, infrastructures that support public works, electricity lines, major transport axes, autoroute service stations, train lines and school development projects. Identify the possibility of supplying residual heat within a 5 km radius, preferably to public facilities and major companies and residential housing. This is an approach that has already been put in place by CERN in Ferney-Voltaire and such an infrastructure serves as a demonstrator for the feasibility (see Fig. 2.10). Examples include, but are not limited to, milk processing companies (cheese production), hospitals and health service infrastructures, schools, fire brigades, prisons, offices, airports, train stations, and leisure facilities (pools and spas). Locating surface sites in the proximity of public services can lead to tangible added value for the region. For example, the significantly enlarged geographical extent triggered the need to develop an emergency intervention concept based on cooperation with regional fire departments and first-aid services. Other locations are particularly suited to foresee additional leisure activities around experiment surface sites that feature visitor centres. Additional services including exhibitions, restaurants, and meeting facilities have potential for indirect and induced economic value generation, but they need to be agreed with the local stakeholders to integrate with the local economic and tourism development strategies and plans.

Reduced need for electrical infrastructure To limit the effects and impacts of infrastructure development for electrical power, give preference to scenarios located near substations and high-capacity power lines.

Fig. 2.10 CERN powered heat network under construction in Ferney-Voltaire, France

Excavated materials Limit the annually excavated volume of materials excavated and reduce road transport wherever technically and economically feasible. Facilitate local reuse. The aim is to keep the volume of materials excavated annually to less than 10% of the volumes generated in each region (Auvergne-Rhône-Alpes in France: 24.2 Mt in 2021 [26], cantons of Geneva [27] and Vaud [28] in Switzerland: 3.071 Mt in 2022).

Land use The goal for the scenario development is to develop a scenario that keeps land consumption as low as possible by still meeting the needs of the required surface site installations. The scenario development process avoids protected agricultural spaces, keeps interactions with multiple private landowners for land plot acquisition low, as a multitude of negotiations and complicated ownership situations can significantly impact project implementation preparation and lead to unsatisfactory results for them. Consequently, prioritise the use of public land over private property and steer clear of areas with planned development projects and prefer non-protected agricultural spaces over protected ones.

The surface site candidate location in Switzerland is mainly located on publicly owned land. The surface site candidate locations in France concern mainly privately owned land plots, subject to the typical urbanistic planning evolution. After exchanges with municipalities to determine the territorial conditions and constraints of possible locations for surface sites, CERN asked the Prefect of the Auvergne-Rhône-Alpes region in France to set aside the land plots to assure their availability for field studies. This process and the orders signed by the Prefect of the region mitigate the risk of unanticipated use of the land plots for other territorial developments for the study time period, permitting a comprehensive and exhaustive investigation of the environmental conditions. As a result, the land considered for the surface sites will not compete with other emerging projects. The solution was made possible thanks to the support of France. It contributes to securing the studies while ensuring compliance with national legislative frameworks.

Biodiversity and nature Give preference to sites with low-quality nature characteristics. Through the ERC approach, preserve the elements of interest in terms of biodiversity and nature within the perimeter as much as possible. Study, together with design offices, the existing and projected conditions of the sites concerned, and carry out environmental, flora, and fauna surveys on the proposed site to identify valuable elements and the site's role in the ecological infrastructure. Propose appropriate restoration, replacement, and compensation measures based on the impacts identified by specialist consultants. Maintain or reinforce ecological infrastructure, particularly wildlife corridors.

The work on these voluntary goals was also considered during the development of the eco-design strategy and guidelines [29], which all project participants are required to consider during the subsequent design phase and which is also published in the report on the current state of the environment [30].

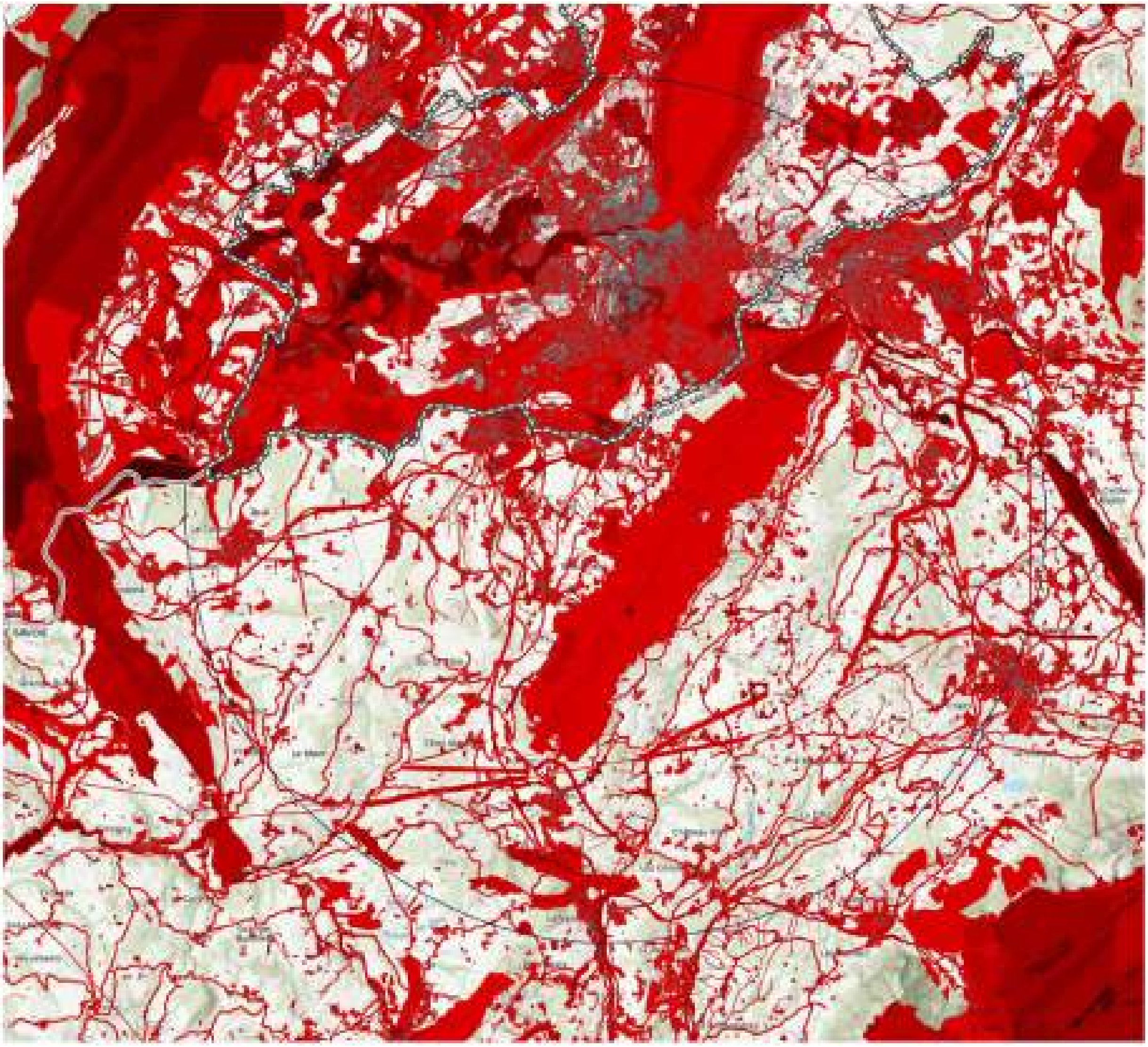


Fig. 2.11 Zones in the scenario development perimeter classified as to be avoided ('red'). Note that this map does not consider numerous other exclusion criteria such as slopes and high altitudes (see also online at http://cern.ch/fcc-sensitivity-grid)

2.4 Territorial constraints

2.4.1 Territorial sensitivity grid

The development of a territorial sensitivity grid with its four levels (unacceptable 'red', high 'orange', acceptable 'yellow', and low 'green') served as a starting point to integrate the territorial constraints into the implementation scenario development from the onset.

By applying the 'Avoid' approach, the analysis eliminated all the unacceptable zones to be avoided, shown in red (see Fig. 2.11), from the early development stages of the initial scenario at the macroscopic level. It should be emphasised that, in all cases, the scenario development process also aimed to avoid areas already developed if they were considered to be in active use (e.g., residences, farms, parking lots, industrial buildings and public infrastructures). Only brownfields or buildings that could be reliably described as unused (ruined houses, abandoned industrial warehouses, etc.) were examined on a case-by-case basis. In addition, for all the surface sites taken into consideration, choices have been made to avoid clearing protected forests, as well as avoiding the destruction of wetlands and hedgerows in agricultural areas.

Zones classified with high constraints, shown as 'orange' were generally avoided (see Fig. 2.12), but a more detailed manual analysis of the underlying rationale for this classification was always conducted to understand

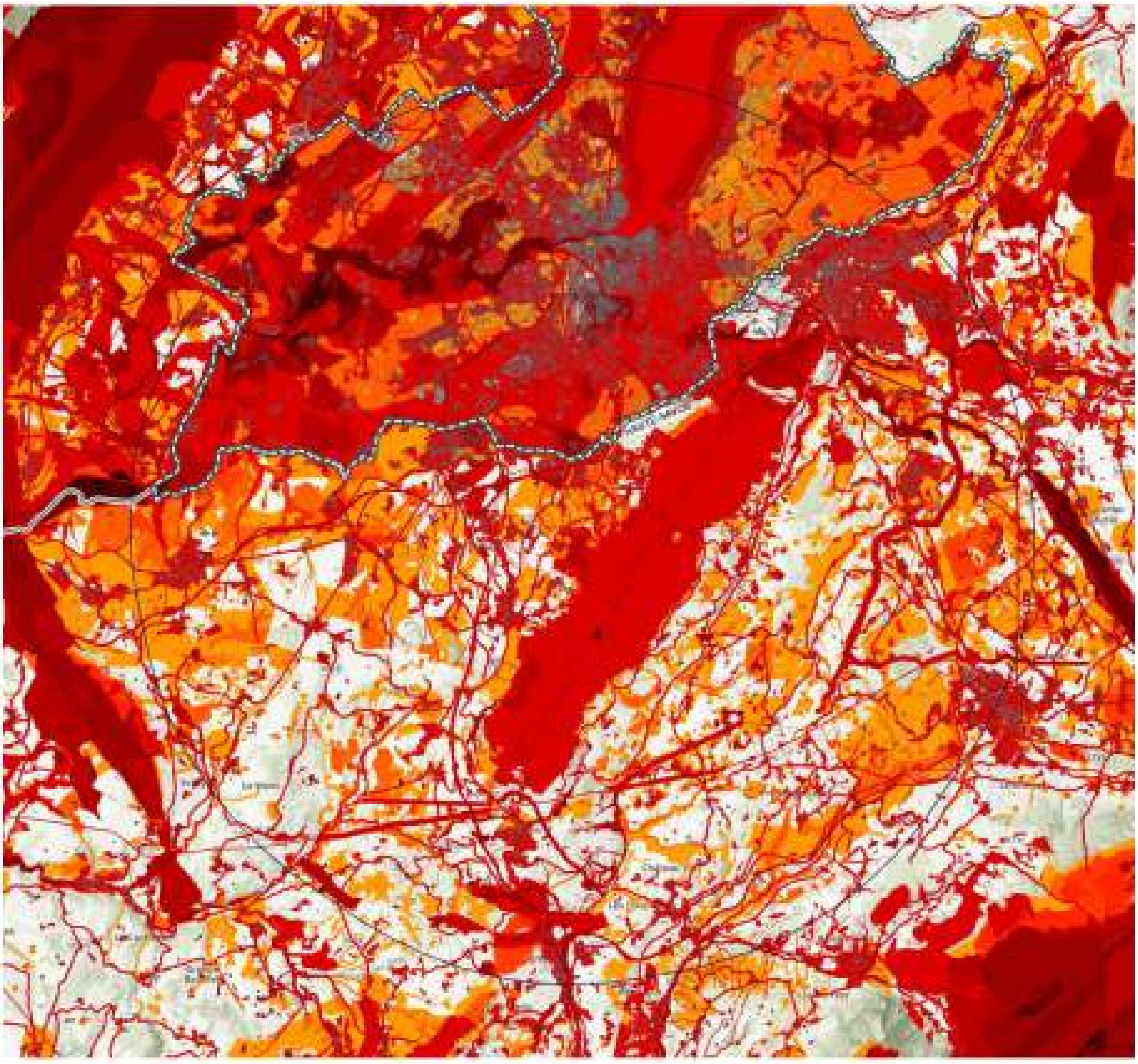


Fig. 2.12 Zones in the scenario development perimeter classified as to be avoided ('red') and with high constraints ('orange'). Note that this map does not consider numerous other exclusion criteria such as slopes and high altitudes (see also online at http://cern.ch/fcc-sensitivity-grid)

whether and under what conditions such a zone might be considered for certain parts of the research infrastructure. This step required a more detailed study of the different layers of constraint that make up the overall layers. It also required additional information that the regional and local planning authorities of the two host states were best placed to provide (for example, the various offices of the Département du Territoire and the Infrastructure Department of the canton of Geneva, the DREAL, the DDT 74 and the DDT 01 in France).

In France, the law of 22 August 2021, on combating climate change and strengthening resilience to its effects set a target of zero net artificialisation of soils (also known as ZAN). The ZAN initiative is a target set for 2050. It calls on local authorities, municipalities, departments, and regions to reduce the rate of artificialisation and consumption of natural, agricultural, and forest areas by 50% by 2030, compared to the consumption rate measured between 2011 and 2020. A similar instrument for crop rotation areas in Switzerland, 'surfaces d'assolement' known as SDA exists.

The scenario development follows the regulatory frameworks in both host states regarding land use efficiency. This concerns in particular the consideration of the principle of "zéro artificialisation nette (ZAN)" (english: "zero net land take") in France and the principle of the "Surfaces d'Assolement (SDA)" (english: crop rotation surfaces) in Switzerland. By considering these constraints in the "avoid-reduce-compensate" based development cycle, they support the development of projects that exhibit a high degree of territorial responsibility. The SDA

Fig. 2.13 Examples of regional changes. Left: 17 ha of new exclusion zones in Ferney-Voltaire (Ain, France). Right: 790 ha of peatland inventory on the banks of the Rhône in France: in light red, previously orange zones that have become red zones

imposed constraint was addressed by the development of an authorisation process for the territorial development of CERN at the federal level. Concerning ZAN it is noted that, on the recommendation of the prefect of the Auvergne-Rhône-Alpes region, the FCC segment on French territory is recognized among European and national large-scale projects (PENE) [31]. Consequently, the land areas potentially consumed by surface sites would be outside the regional quota, in accordance with the decree of May 31, 2024 [32], concerning the national pooling of the consumption of natural, agricultural, and forest spaces for projects of major general interest. However, this exclusion from the regional quota would not exempt the FCC from complying with the principles of land use efficiency and compensation. Through its transversal and eco-responsible approach, the study demonstrates its commitment in this area, thus affirming its intention to embed the project in a responsible and balanced dynamic.

Right from the start of the studies, it became clear that there were no areas with low constraints indicated with ‘green’ colour in the two host countries. The minimum number of constraints in both countries corresponds to the ‘yellow’ class, i.e., acceptable zones. In addition, Switzerland has special restrictions, imposed at the federal level, for a certain type of agricultural land, known as crop rotation areas (SDA), the best arable land in Switzerland. A federal sectoral plan sets a minimum surface area to be maintained per canton (distributed among the cantons by quota). The Confederation monitors the maintenance of the minimum SDA area. Under certain conditions, SDAs can be allocated to specific projects, provided that all stakeholders at the federal and cantonal levels agree and that the minimum is maintained. This constraint is high, but the SDA spaces have been classified as an ‘orange’ zone to leave the possibility of downgrading open and to provide an option for the development of a layout and placement scenario. Specific coordination at the federal and cantonal levels is nevertheless required to be able to release such land for a development project. SDA spaces will have to be compensated on a 1:1 basis by removing the topsoil and re-constructing the agricultural space on lower-quality plots or wastelands. Agricultural areas in the canton of Geneva outside the SDAs were classified as acceptable ‘yellow’ zones.

The initial classification of sensitivity layers is not fixed, but constantly changes as the territory evolves. Between 2014 and 2022, more than 1000 ha became ‘red’ exclusion zones (unacceptable constraints) in the Haute-Savoie department in France. In the canton of Geneva, around 100 ha have been affected by new restrictions and are now part of the exclusion zones, mainly due to stricter surface and groundwater protection rules resulting from improved knowledge of the subsurface. This led to the rejection of several candidate sites proposing a configuration and location initially considered as possible. These changes have made it even more difficult to continue developing scenarios, while at the same time highlighting the iterative aspect of the process.

Figure 2.13 shows two examples of these ‘lost spaces for layout scenarios’. The first concerns sectors of Ferney-Voltaire that are now intended for a development project (hospital project north of the D35, Route de Meyrin) and the classification of a sector as a compensation zone (south of the D35), which therefore cannot be compensated again. The second concerns a vast area north of the Rhône in France, which has been described as a ‘peatland inventory’.

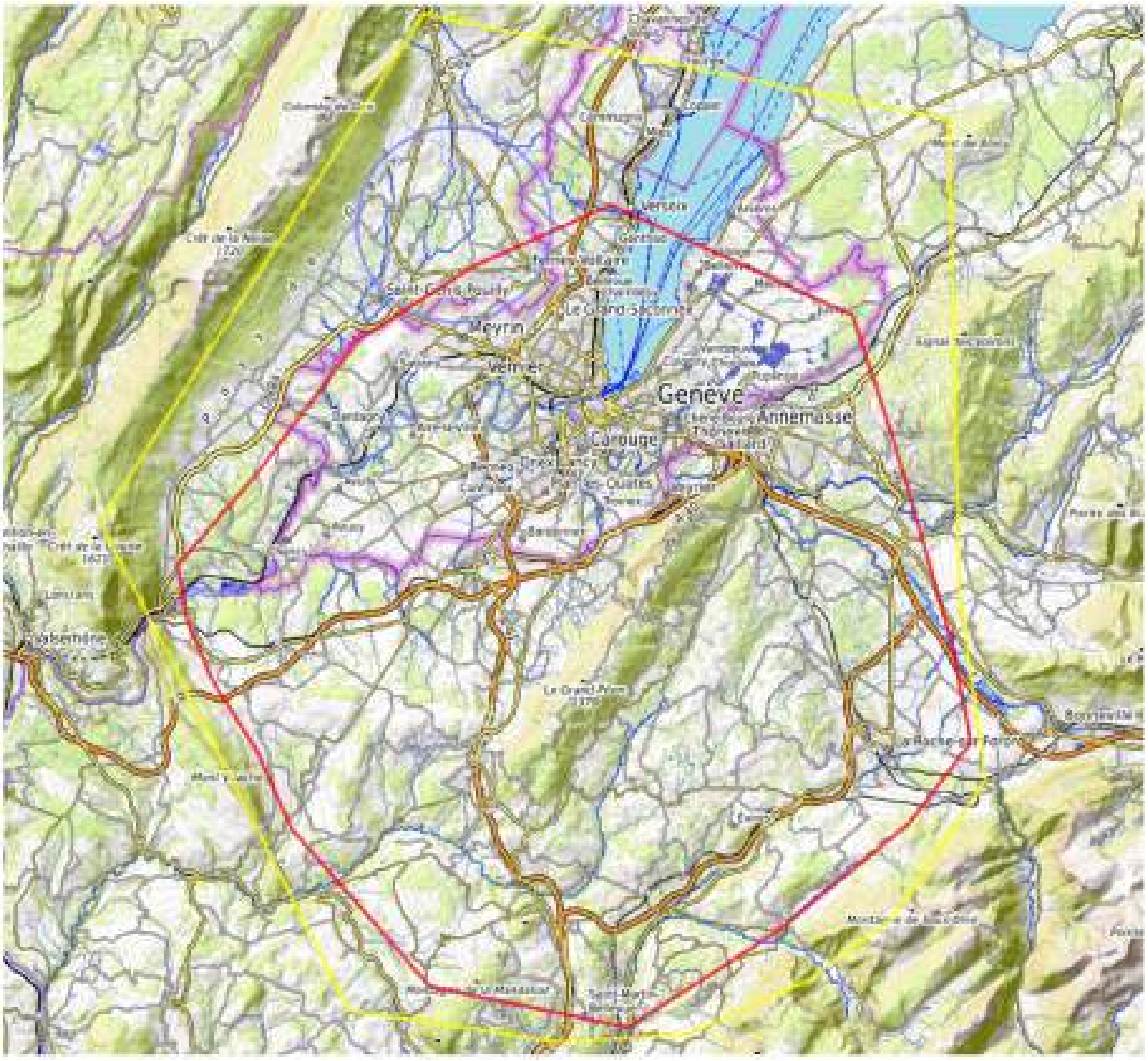


Fig. 2.14 After several years of analysing the subsurface conditions based on bibliographic data and modelling, the initial scenario development perimeter (yellow) had to be restricted (red) to assure compatibility with the known subsurface conditions

2.4.2 Subsurface constraints

Subsurface constraints, such as unfavourable geology, major faults, presence of strategic aquifers, drinking water catchment areas and buffer zones, pipelines, power lines and gas mains, as well as reserved areas of public interest such as geothermal exploration zones or no-drilling zones due to superimposed aquifers or other information, were considered from the onset. Geological exclusion zones have been defined by the geological consulting firms GADZ and ILF and the University of Geneva to take full account of geological conditions. These partners also examined the geological and hydrological situation based on the following elements:

1. Fault lines representing a high risk of seismic activity and that could cause tunnelling challenges.
2. The interface between limestone and molasse.
3. Potential high-pressure water penetrations or karstic formations that would expose the project to an unacceptable risk.

As a result, between 2014 and 2020, the project's initial study perimeter had to be significantly narrowed (see Fig. 2.14) as additional knowledge was acquired and integrated into a 3D model of the subsurface. Figure 2.15 shows two example images from the 3D subsurface model that was established to support the analysis of the subsurface constraints, to identify zones that are definitely to be excluded, preferred locations for the subsurface

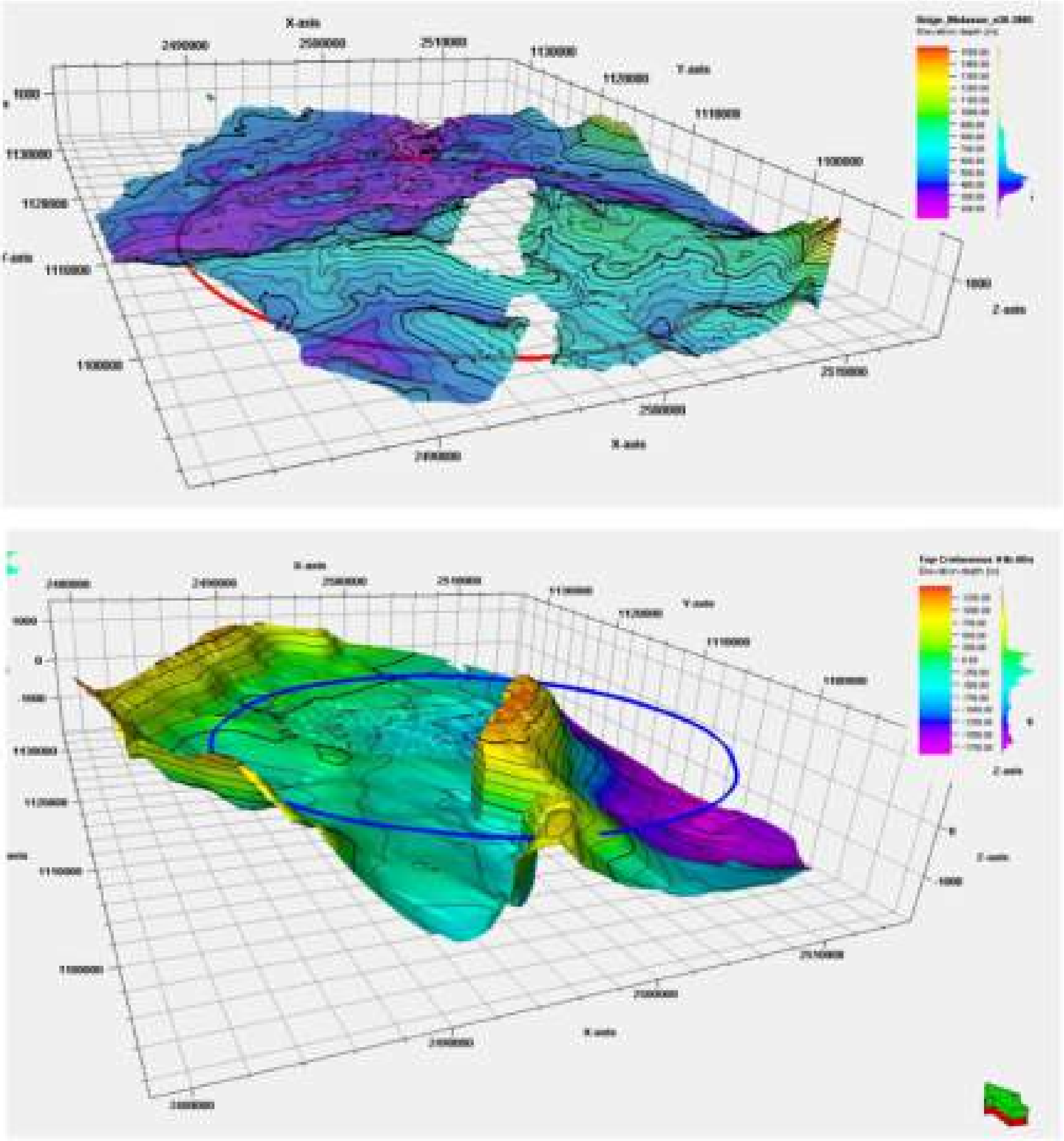


Fig. 2.15 Example images from the 3D model (here molasse and cretaceous formations) used to determine the geological constraints

structures, and to identify zones with particular challenges or insufficient data that require dedicated subsurface investigations.

Given the experience gained from the construction of the Large Electron Positron collider (LEP) underground structure and from the construction of underground transport structures in the region (e.g., the Vuache road tunnel), the risks of building a large tunnel and caverns, which could be unstable, move, collapse, or in which construction workers could be exposed to high-pressure water ingress that could lead to fatal accidents, are considered unacceptable and must be avoided. As far as possible, all underground structures should be located in the soft, stable molasse layer, which forms a reliable barrier against aquifers.

Although maps and modelling work have provided additional information, reliable data on the exact depth of interfaces between different geological layers in the Vuache and Jura zones is still lacking. The unavoidable limestone zones of Mandallaz have yet to be studied. Furthermore, little is known about conditions under the lake, as well as the Arve and the Rhône rivers. Since these conditions have a major impact on the cost and schedule of

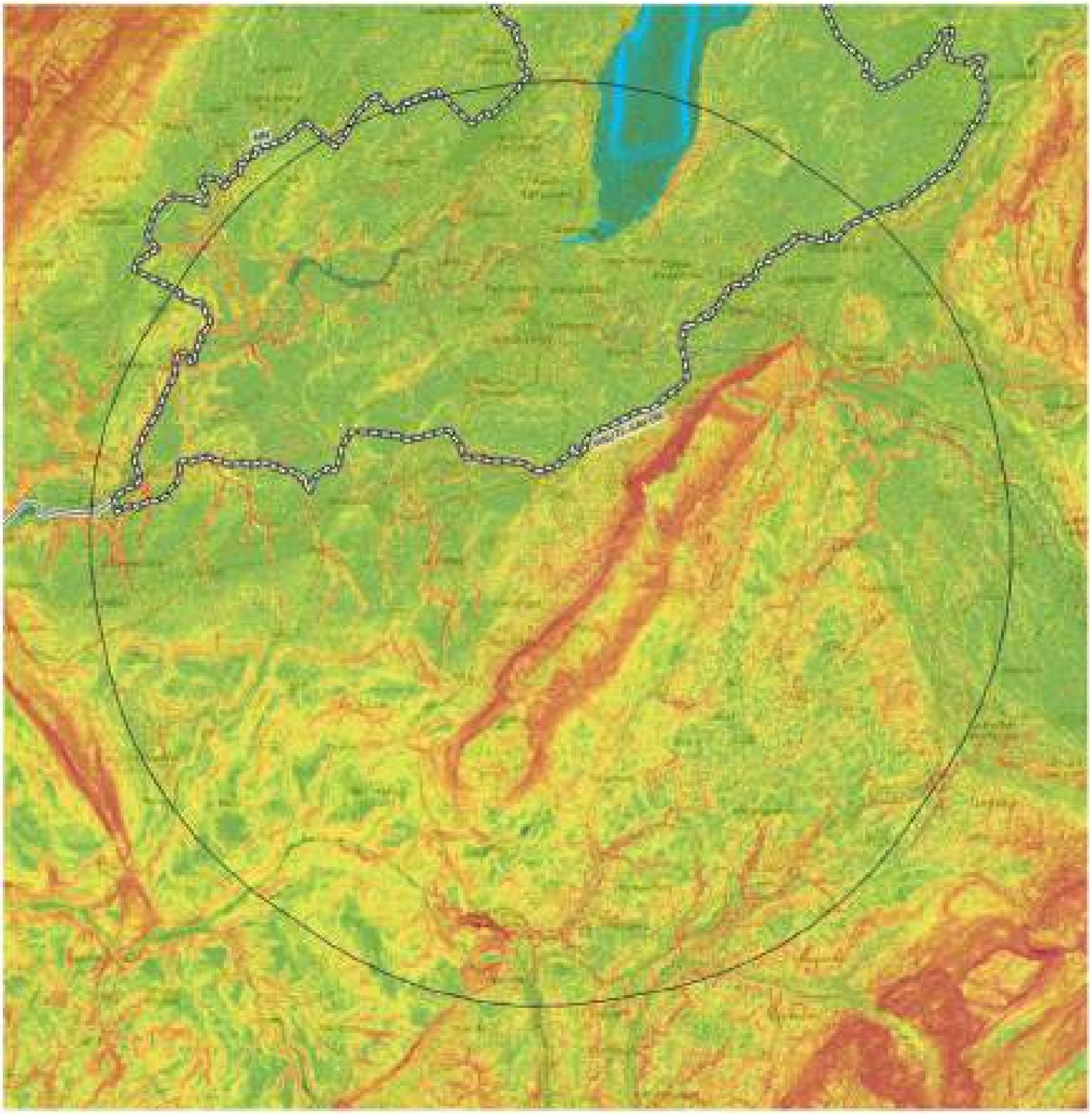


Fig. 2.16 Topography of the area. Red and orange colours indicate steep slopes

the tunnel boring, more information about the subsurface in the key areas is being gathered with geophysical and geotechnical exploration between 2024 and 2025.

2.4.3 Topography, bathymetry, and other surface features

Information on topographical surface conditions has also been taken into account from the outset of the study. Steep slopes (Fig. 2.16) in excess of 30% presenting risks of unstable terrain and landslides are excluded, as are cliffs, narrow valleys, and canyon-type formations. Since the tunnel must be placed at a sufficient depth below the lake bed, elevations above 750 m are an obstacle due to the depth of the shafts and unacceptable overloading (Fig. 2.17). High elevations also lead to high overburdens, which can become challenging for tunnel boring activities, calling for more costly construction and slower progress.

The bathymetry of the lake must be taken into account to ensure that the tunnel can be placed sufficiently below the lake bed with as short a crossing as possible. Lake Geneva is more than 50 m deep beyond the Versoix-Corsier line (see Fig. 2.18). To avoid the tunnel becoming too deep over its entire footprint, it is necessary to stay below this line. Crossing the lake where it is narrow avoids areas of instability and minimises the risks associated with the

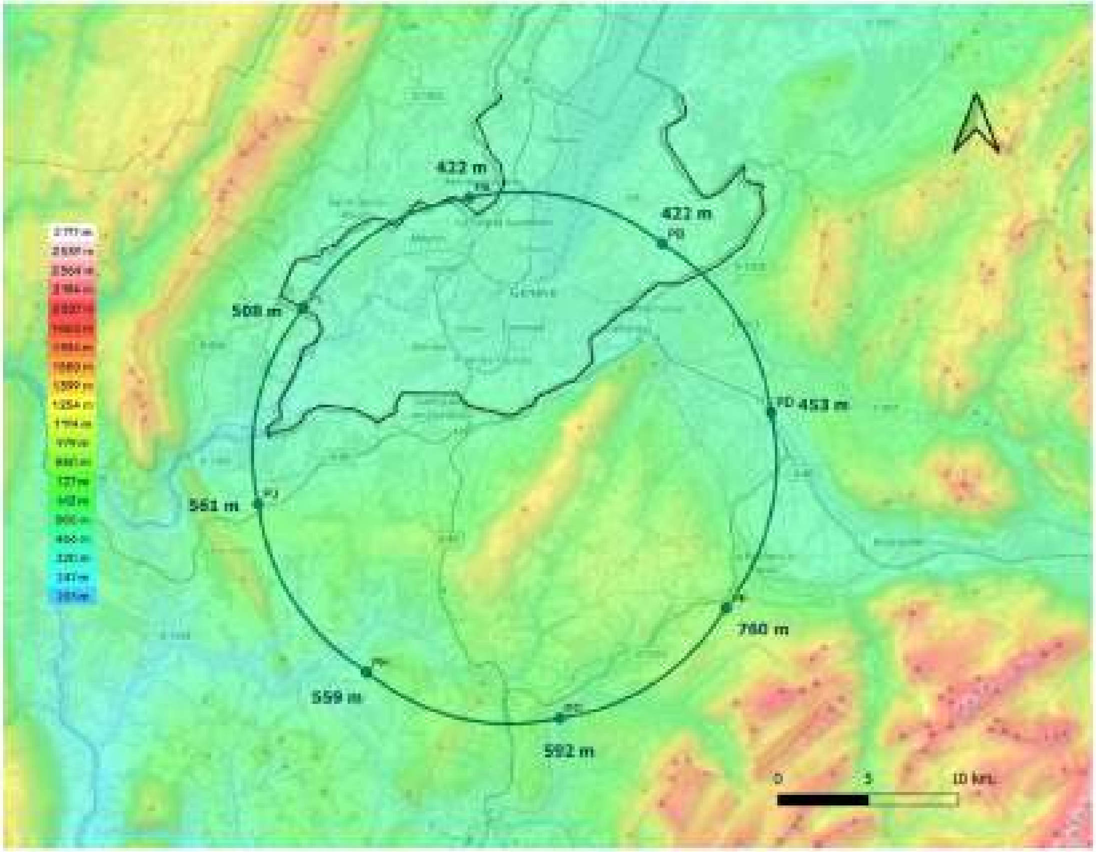


Fig. 2.17 Relief of the area. White and red colours indicate high elevations

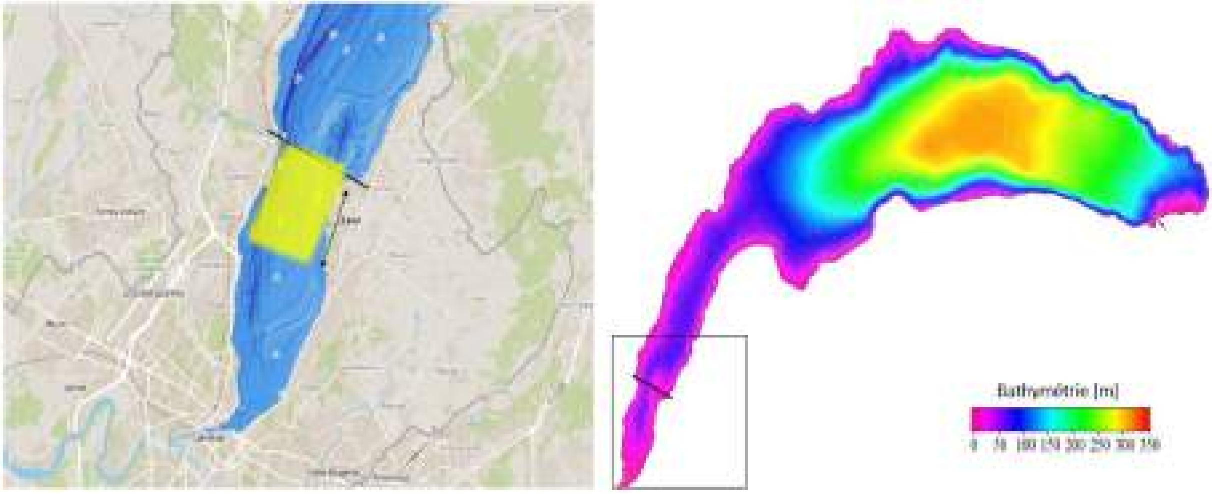


Fig. 2.18 Bathymetry of the Geneva lake

presence of water. At the same time, other parts of the tunnel should not be located too deep under mountainous areas.

2.4.4 Scenario development flexibility

The initial outline surface and subsurface constraints and many more constraints that are documented in detail in a specific report [12] provided a starting point for a semi-automated search to determine approximate exclusion

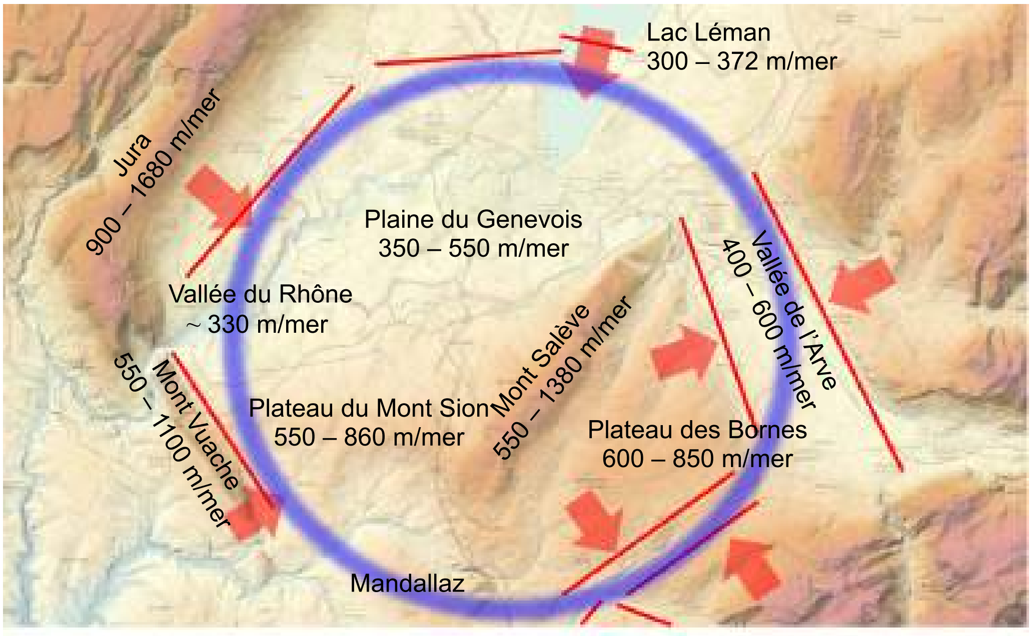


Fig. 2.19 Combination of subsurface and topographic constraints that lead to a ca. 300 m wide scenario development band and a diameter of about 28 km

and candidate zones. However, zones marked in orange (undesirable zones) and yellow (acceptable zones), which at first glance appeared compatible with the location of a surface site, proved in various cases to be unacceptable due to restrictions that are not 'encoded' in the maps and publicly accessible documents which are available. This additional information was obtained in part by studying high-resolution maps, orthophotographs and data, by interviewing regional and local public administration services and local stakeholders, domain experts and by means of walking tours (visual inspection of the surrounding area).

Such additional constraints included, but were not limited to, the following: unfavourably shaped land areas (surface available too small, too narrow, non-monolithic or too irregularly shaped), presence of adjacent constraints (nature protection areas requiring buffer zones, natural hazard areas such as flood zones or unstable banks, residential areas, sensitive areas), limited access (no road or no possibility of creating one due to topographical conditions or other restrictions, rudimentary road unsuitable for regular traffic and unable to be upgraded to meet requirements), likely opposition or known conflicting development policies, known conflicting projects.

The constraints, together with the currently known geological and topographical conditions, limit the circumference of a future circular collider to less than 100 km. The layout studies conducted between 2017 and 2021 concluded that to obtain a circumference of over 90 km that would deliver good performance and therefore yield a research infrastructure of excellence, and given the various constraints that the configuration must simultaneously meet in different locations, the available layout for the ring is limited to a strip with a width progressively reduced from 3000 m to 300 m depending on the area concerned (see Fig. 2.19).

2.5 Initial variants

2.5.1 Introduction

This section provides the background which explains how the implementation scenario in the Franco-Swiss border region was developed. It explains why alternative scenarios to the west of the Jura were examined and then discarded in favour of scenarios to the east of the Jura. It reviews how the layout and placement considered during the exploratory phase of the FCC study (2014-2018) demonstrated the in-principle feasibility of a new, large-scale research infrastructure and how the specific scenario examined presented prohibitive obstacles in certain locations. Finally, it mentions the variant involving a linear collider, which was not selected for further studies.

The development of a scenario for the configuration in the Geneva region was based on the motivation of taking advantage of existing CERN infrastructures and assets built up over 70 years for a new project. The construction of a circular collider requires existing particle accelerators in operation with technical infrastructures that can serve as injectors; the availability of workspace, workshops, equipment, and skilled workforce; as well as favourable

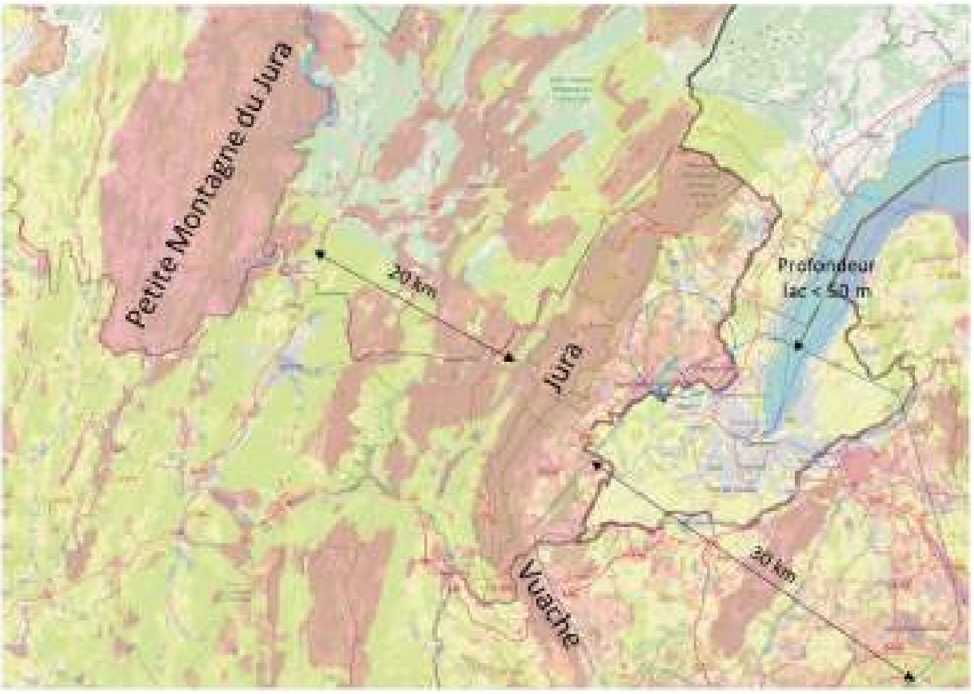


Fig. 2.20 Comparison of land areas and protection zones to the west and east of the Jura chain

legal, administrative, and project management frameworks. It is, therefore, essential that the chosen layout remain within reasonable proximity to an existing CERN site.

In addition, the particle collider must have a circumference greater than 90 km to accommodate two different particle colliders in the future (an electron-positron collider and a hadron collider), each of which must deliver the performance required to carry out the desired scientific research programme. The immediate research zone would be located to the south of CERN's Meyrin and Prévessin sites, away from the Jura mountains. Indeed, during the Large Electron Positron collider (LEP) construction phase, major obstacles were already encountered due to the presence of karstic formations and high-pressure water penetrations due to its proximity to the Jura mountains.

Nevertheless, as the next section highlights, an unbiased examination of the situation was conducted so as not to overlook any other possible scenario.

2.5.2 Scenarios west of the Jura

A study [33] examined a layout in the Bresse plain (Dolois region), to the west of the Jura Massif (see Fig. 2.20). These options had already been studied in 1997 and 2001 and were checked again between 2014 and 2019. The ring would have been located outside the Jurassic formations, at a depth of around 40 metres. Still, in any case, the infrastructure would have encroached on existing national and regional parks and vast nature conservation areas. In addition, the required link to CERN's particle accelerator complex would have required a long tunnel of around 60 km for the transfer lines. This tunnel through the Jura mountain range would have passed through very unfavourable geological formations with significant overburden. Given that the distance between the Jura mountains and the Petite Montagne du Jura is less than 20 km, it is considered unfeasible to place a sufficiently large circular particle collider in this zone.

This variant was definitely dropped from further studies for the following reasons:

- A long tunnel for the beam transfer line through the Jura mountain range would pose too many difficulties, both from a civil engineering and a technical point of view. Construction times and overall costs would increase considerably, by at least 30%.
- This scenario would require deep access shafts in difficult-to-access mountainous regions of the Jura massif, which are largely nature conservation areas. The rock is highly unstable, and the penetration of high-pressure water is certain.
- The loose soil in the Bresse region would require stabilisation and protection measures. Hydrophilic gypsum swells considerably (ground movements of roughly one metre recorded in the Chienberg road tunnel), which is not compatible with large-scale cavern construction nor with the requirement for a highly stable tunnel. Maintenance costs would be much higher than on stable ground.

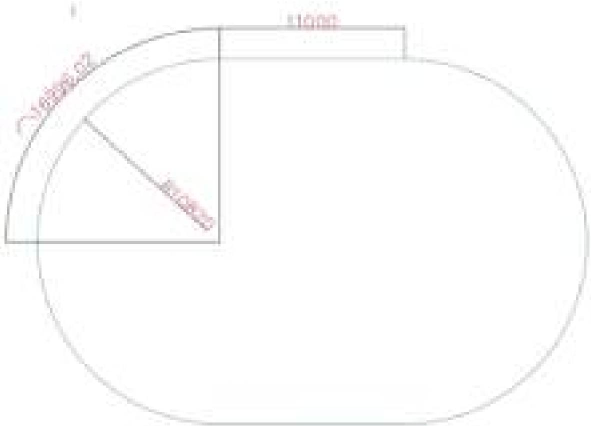


Fig. 2.21 Racetrack layout scenario with two 11 km long straight sections, leading to a total circumference of 90 km

- The installation would most likely interfere with nature protection constraints and cause significant disturbances to local residents during the construction phase.
- The space available between the Jura massif, its national park and the Petite Montagne du Jura area to the northwest is too small to accommodate a circular particle accelerator of sufficient size.
- There is no reasonable way of operating and maintaining the infrastructure from CERN or any other suitable partner organisation nearby.

2.5.3 Racetrack lakeside scenario

The conceptual feasibility investigations also comprised an analysis of the opportunities and constraints related to a racetrack layout with a lakeside placement of the particle collider ring that permits connecting the infrastructure to CERN's particle accelerator complex [34].

The concept was based on having straight sections about 11 km long that could potentially also house a linear accelerator or collider. The motivation was to combine the possibilities of a linear electron-positron collider as a first stage with a circular hadron collider during a second stage. An alternative particle acceleration concept with linear accelerators for a first-stage circular electron-positron collider could also have been imagined.

The availability of long straight sections comes with advantages for the radiofrequency acceleration systems in terms of ample space and avoiding bending fields. A minimum crossing angle, 20 mrad in the case of CLIC, is required, however, in order to prevent collision debris passing through the opposite linear accelerator arm. Realistically, some bended beam delivery section would be required for dispersion suppression, collimation and chromatic corrections. Such a layout would lead to a racetrack with a total circumference of 90 km, permitting both, housing linear and circular accelerators (Fig. 2.21).

This layout comes, however, with some significant disadvantages: It only permits up to two experiments for the circular collider and also requires the inclusion of collimation, dumps, and beam transfer sections in the two straight sections.

When it comes to placement options (Fig. 2.22) for such a layout, numerous geological and environmental constraints are encountered: as with all circular scenarios, this one also needs to cross the Mandallaz limestone sector. Some shafts could be very deep in their nominal locations (Fig. 2.23), i.e., more than 500 m, however, with a systematic optimisation process it is likely that acceptable alternatives for displaced shafts can be found. In terms of traversal of the lake, the bathymetry starts to impose constraints with depths of 65 m, which would need to be carefully evaluated.

The strongest limitations stem from the highly challenging needs to integrate 12 surface sites in a highly urbanised area on one side and into a highly mountainous zone on the other side (Fig. 2.24). For instance, a site PJ in Switzerland would be in the fully protected Allondon river zone, where any construction activities on the surface and subsurface are strictly forbidden. It remains unclear where and how a feasible experiment site potentially covering up to 9 ha could be identified and rendered acceptable, considering that also major transport and electricity infrastructures would have to be created in this area which, is entirely natural. It is a highly protected nature zone. Site locations around PI in France in the close vicinity of the river Rhône face similar constraints. Locations for a site PK in the Prévessin sector in France would fall in highly urbanised areas. Site locations in PL in Versoix in Switzerland are in fully protected lake border areas with absolute bans for subsurface activities and in highly urbanised locations. Locations for site PB in Switzerland are in a large nature preservation zone, in particular the home for amphibians which are highly protected. Potential locations could most likely be identified using the Avoid-Reduce-Compensate sequence for other sites. In terms of cost, the scenario would lead

Fig. 2.22 Placement option for a 90 km circular / 11 km linear racetrack scenario

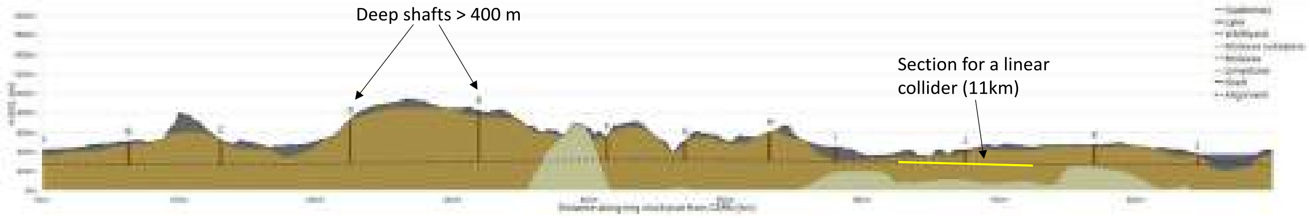


Fig. 2.23 Example racetrack alignment scenario

to significant increases for the circular collider scenario, since it is not optimised for a circular collider layout. The differences are in the order of 200 to 400 million CHF at least. Finally, the loss of at least 20% of arc sections directly leads to a corresponding loss in the maximum achievable energy or, in the case of a smaller radius in the curved sections, to significantly higher synchrotron radiation losses.

A racetrack layout is neither optimised for a linear collider nor a circular collider. It, therefore, creates additional complications and costs and leads to lower performance. The integration into the territory is extremely challenging and significantly more complicated than the finally adopted circular layout with eight surface sites. It will lead to higher environmental impacts and increased territorial development needs (e.g., access roads) and require more and deeper shafts. Therefore, further studies on this scenario have been discontinued.

2.5.4 Scenarios east of the Jura

For the zone to the east of the Jura, an initial large search perimeter was defined in 2014 based on the following geological conditions [35–37]:

- To ensure stability, the tunnel must cross Lake Geneva at a sufficient depth below the lake bed. Initial ideas of placing the tunnel in unstable ground (moraines, quaternary glacial deposits) or in a construction on the lake bed had to be rejected due to a) insufficient stability and b) the impossibility of creating suitable interfaces between the tunnel on either side of the lake and the construction in the lake.
- In order to be located at an acceptable depth below the lake bed and to remain as far as possible within the impermeable molasse layer, underground structures should be located at around 250 m above sea level, ideally avoiding crossing the limestone/molasse interfaces.
- A boundary line was drawn to the northwest (Jura zone) and to the west (Vuache zone) to ensure sufficient distance from high elevations leading to unacceptable overburdens, inaccessible and protected areas, unstable rocks, faults, seismically active zones, and unstable karstic formations where the penetration of high-pressure water is certain.

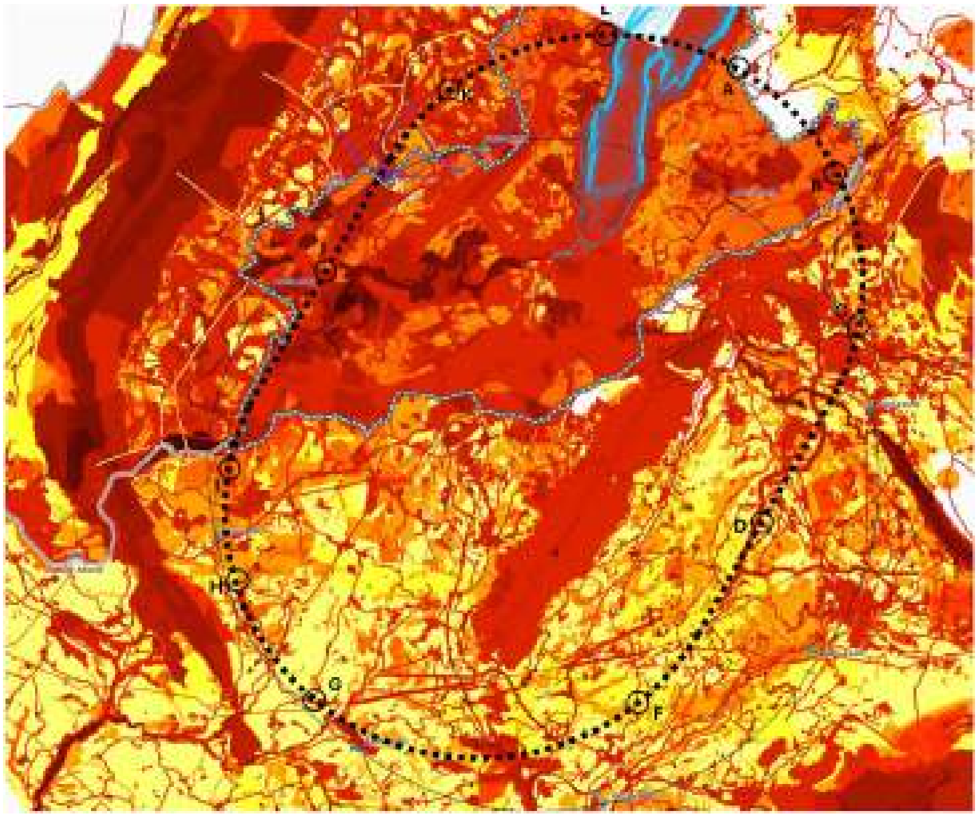


Fig. 2.24 Example of the racetrack layout placement with the environmental constraints indicated. Site locations I, J, L and B are in highly constrained zones, rendering the identification of a feasible and societally acceptable scenario highly challenging. The lake depth at the crossing between L and A is about 65 metres deep

- To the southwest, the Mandallaz mountainous zone forms a natural border. Its crossing cannot be avoided. Consequently, the preferred scenarios are those for which the overburden and crossing length are low.
- To the south, a boundary line has been drawn northwest of the Montagne des Frêtes nature reserve to avoid elevations above 750 m (unacceptable, as they would lead to excessively deep wells), inaccessible and topographically unacceptable zones, and protection zones to the south. This line crosses the Fillière valley at Thorens-Glières and spans the acceptable elevations of the Bornes plateau as far as La Roche-sur-Foron.
- To the east, a boundary line has been drawn to avoid mountainous zones and thus remain in the Arve River valley.

The perimeter obtained in this initial study turned out to be compatible with a circular infrastructure with a circumference of 90 to 100 km, and can meet geological, topographical, environmental and urban planning constraints (see Fig. 2.25). The maximum distance that can actually be used is 29 km from north to south and 30 km from west to east. The result is a zone capable of accommodating a circular collider with a circumference of up to 92 km for a configuration comprising eight sites or up to 98 km for a configuration comprising twelve sites.

2.6 Reference scenario

2.6.1 Introduction

Of the about 100 scenarios analysed [12], based mainly on bibliographical data and field visits, it was the PA31 scenario that seemed the most interesting to retain for further in-depth studies and optimisation. The trace of version 1.0 (PA31-1.0) stands out from the others. It proposes a balance between territorial placement, scientific performance that the particle collider and the four interaction regions can offer and technical feasibility in terms of manageable risks and costs. This working hypothesis, developed based on the Avoid-Reduce-Compensate (ERC) process described earlier, has made it possible to gain in-depth knowledge of the region, creating the basis for continuously improving the project considering territorial requirements and constraints as well as technological advances.

The scenario version 4.0 (PA31-4.0) shown in Fig. 2.26, presented in this chapter, is established as the reference scenario for a potential implementation project. It is the result of an optimisation process applied to the PA31-1.0 working hypothesis. It takes into account the progress made on design studies for the FCC-ee and FCC-hh colliders, infrastructure and civil engineering studies, as well as territorial information collected from local

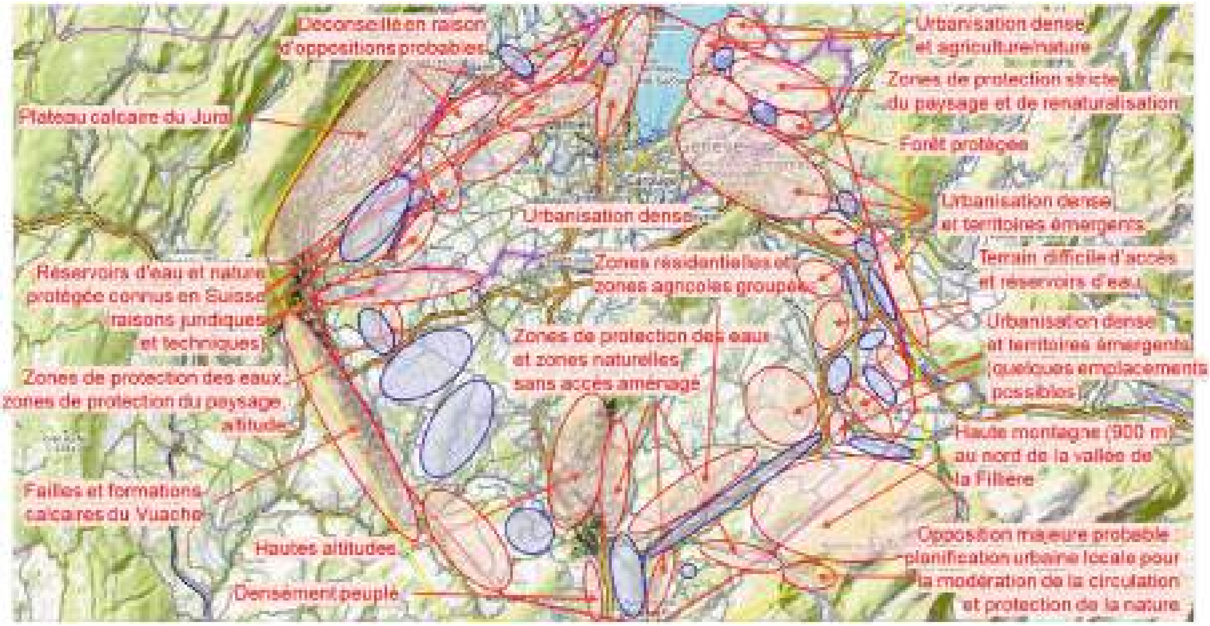


Fig. 2.25 Established study perimeter (red line). Exclusion zones and zones with too many difficulties for surface sites are indicated in red; favourable zones are indicated in blue

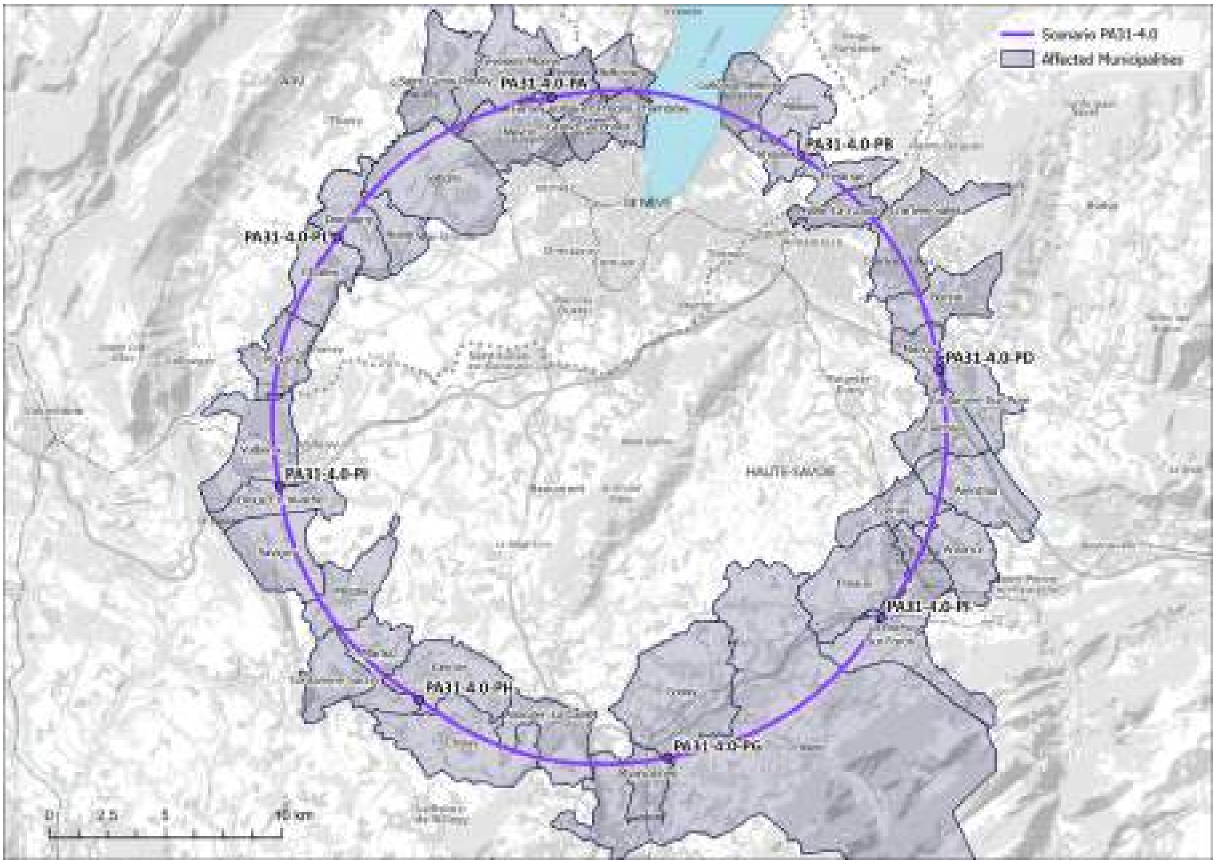


Fig. 2.26 The PA31-4.0 reference scenario that served as baseline for the subsurface investigations, the analysis of the state of the environment and studies concerning connected infrastructure projects. An interactive version can be consulted at https://cern.ch/fcc-overview

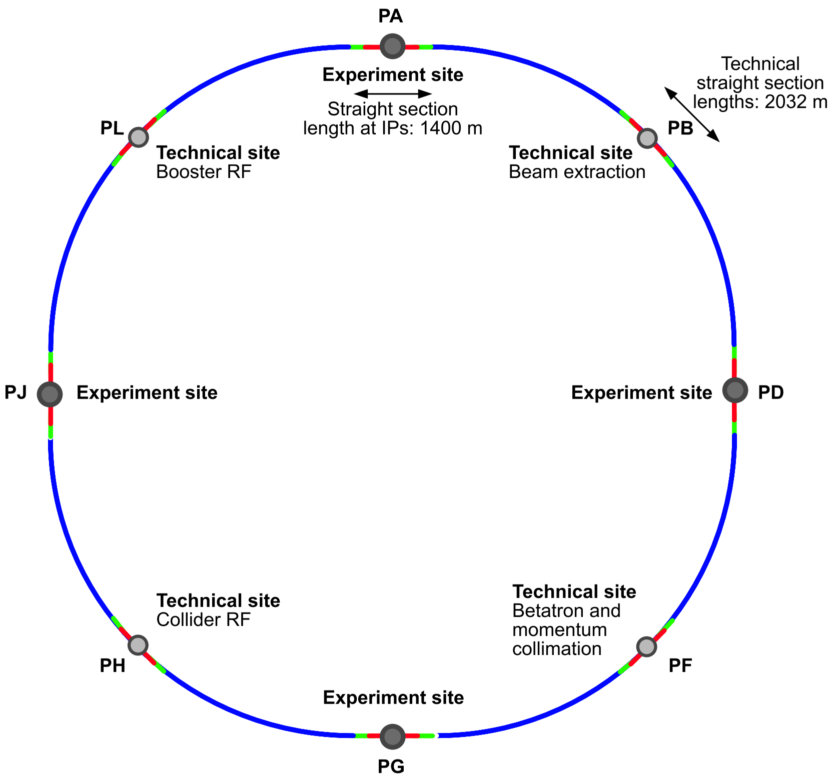


Fig. 2.27 The functions of the various sites in the PA31-4.0 scenario configuration

stakeholders (concerned municipalities, departmental directorates of the territories and the Direction Régionale de l'Environnement, de l'Aménagement et du Logement in France and the services of the Canton of Geneva). There still exists room for minor adjustments for some technical surface sites and the disposition of the experiment site shafts.

The technical feasibility of the project based on the so-called PA31-4.0 reference scenario could be confirmed with the help of a diverse set of studies. However, it should be stressed that the territory and legal frameworks in France, Switzerland and Europe are constantly evolving. Since 2014, a number of surface site location candidates and scenario traces have no longer been feasible due to these evolutions. Therefore, the situation may further evolve and the conditions for implementing the reference scenario PA31-4.0 may also change. To ease the project authorisation process and to avoid potential interference with future developments and spatial planning, it is advisable to obtain the rights on the required land plots as soon as possible.

2.6.2 Scenario characteristics

The layout and functions of the PA31-4.0 reference scenario are shown in Fig. 2.27). The two shafts at the PA surface site (Ferney-Voltaire, France) were moved further north from the Route de Meyrin road to maintain a safe distance, to provide space for traffic on the surface site around the experiment assembly hall and shafts, and to protect against direct visibility. Moving the locations of sites PD and PJ further northward would be favourable, but is ruled out due to the presence of the departmental road at the northern limit of site PA. Moving them further eastward is also ruled out due to the presence of a compensation zone that is to be avoided and which will be turned into a fully functional wetland zone and natural habitat if the project is implemented. Such displacements would also move the surface site PG in Groisy and Charvonnex deeper into the forest and on a steep slope. Both are evolutions that are better avoided. The shafts at the PD surface site (Nangy, France) were rotated away from the autoroute to ensure compatibility with the RD 903 departmental road enlargement and integration with the A40 autoroute development project and to ensure the technical feasibility of creating a service shaft on the site without installing an additional cavern between the service and the experiment caverns. A move of site PA further southward is ruled out, as this would create incompatibility due to the presence of the A40 autoroute and the RD 903 road on the PD surface site, and topographical difficulties (steep slope) towards the D 1203 departmental road to Annecy on the PG site in Charvonnex.

The shifting and rotating of the scenario took into account the objective of placing the PG surface site in both the lower quality part of the forest affected and on the existing grassland plateau, where the soil turned out to be of poor quality for agriculture. In addition, the shafts should be kept away from the steep slope to the south to

Table 2.2 Coordinates WGS84 of the theoretical beam interaction points for scientific sites

Site	Location	Latitude	Longitude
PA	Ferney-Voltaire, Ain, France	46.2480475° N	6.0986019° E
PD	Nangy, Haute-Savoie, France	46.1453657° N	6.3169260° E
PG	Charvonnex and Groisy, Haute-Savoie, France	45.9938019° N	6.1693009° E
PJ	Dingy-en-Vuache and Vulbens, Haute-Savoie, France	46.0962036° N	5.9513024° E

Table 2.3 Coordinates WGS84 of the theoretical straight section midpoints for technical sites

Site	Location	Latitude	Longitude
PB	Presinge, Geneva, Switzerland	46.2271027° N	6.2374818° E
PF	Éteaux, Haute-Savoie, France	46.0490317° N	6.2865850° E
PH	Cercier and Marlioz, Haute-Savoie, France	46.0146646° N	6.0309816° E
PL	Challex, Ain, France	46.1926255° N	5.9810829° E

control construction risks and costs of building the shafts and buildings. It was not possible to move the shafts further away from the forest, towards the plateau, without creating a conflict for the PD experiment site (Nangy) with the autoroute, and for the PJ experiment site (Dingy-en-Vuache and Vulbens), due to the presence of a stream and topographical constraints. The PJ experiment site is therefore kept at a distance from the A 40 to the south, and from the creek and topographical constraints to the west. The wildlife corridor can be maintained. The placement of the PB technical site (Presinge, Switzerland) was optimised by taking into account maps concerning biodiversity and ecological indicators made available by cantonal services, and the results of a study of possible access routes carried out by a specialist firm in the canton of Geneva. The site would be located in Presinge, directly along the Route de Jussy road. A connection with the tunnel between the shaft and the service cavern, 98 m long, is required.

The working hypothesis of the location for the PF technical site is in Éteaux (France), directly adjacent to the RN 203 national road. It includes a connecting tunnel between the 400 m deep shaft and the service cavern at the collider tunnel. A variant further south is currently not considered since the creation of an inert waste deposit site (called I.S.D.I. in French) creates further constraints. However, in case the footprint of the main site is to be reduced, certain technical infrastructures that are limited to surface site constructions (e.g., ventilators, cooling towers, electrical substation) could be displaced to this area. The working hypothesis of the location for the PH technical site is across the border between the two communes Cercier and Marlioz (France), directly adjacent to the D 203 departmental road (Route de Choisy). Taking into account the analysis of fauna, flora and biodiversity, the state of the forest, topographical constraints and technical risks (gas pipeline north of the site), the site closely follows the Route de Choisy road to the north and stretches into the forest down a slope to the west. Should an adjustment become necessary, an alternative site location exists 900 m in clockwise direction directly at the D2 departmental road on a set of agricultural land plots. The significant displacement from the technical straight section mid-point would require the development of a design for the fitting and installation of the radiofrequency ancillary systems (cryogenic refrigeration, powering). The preferred location for the PL technical site (Challex, France) is on the nominal midpoint of the technical straight section to the east of the town, on a field and a plot of land containing two single-family homes. Another possible location, 600 m west of the nominal point, has been studied and discussed with the municipality. It is slightly less preferred due to the higher visibility from residential zones of the commune. This option is also characterised by additional technical challenges that would entail additional costs due to the need to build a shaft approximately 150 m outside the tunnel with additional civil engineering needs and more difficult access to the machine.

2.6.3 Scenario parameters

The geographical coordinates of the PA31-4.0 reference scenario resulting from this optimisation are shown in Table 2.2 for the scientific sites and in Table 2.3 for the technical sites.

Table 2.4 summarises the layout parameters of the particle colliders.

The functions of each surface site are shown in Table 2.5.

2.6.4 Multi-criteria performance of the reference scenario

Figure 2.8 shows the performance of a number of shortlisted scenarios that were studied in more detail before the PA31 scenario was chosen as a reference for further optimisation. Figure 2.28 shows the results of the multi-criteria

Table 2.4 Layout parameters of the particle collider

Parameter	Value	Comment
Elevation of the tunnel under the PA site shaft	202 m above sea level	The elevation is subject to further optimisation after the availability of the geophysical and geotechnical investigations.
Length of straight sections at PA, PD, PG and PJ sites	1400 m	These sections feature tunnel enlargements. The ee and hh machines may have beam-optics dependent, different machine straight section lengths in these sectors.
Length of straight sections at PB, PF, PH and PL sites	2032 m	This is the minimum space required to ensure that all radiofrequency systems can reliably be fit. Subject to optimisation, not all available space may be used after optimisation.
East-west rotation of the collider around the PA site	10.97 degrees	
Length of one hadron collider arc cell in the arcs	275.792 m	
Number of cells in a curved section (arc) per octant	26	
Total length of the arcs	78,684.476 m	The sum of the curved machine segments of the ee and hh machine may be different
Total circumference of footprint	90,658.745 m	The hh machine may be slightly shorter in the same tunnel (90,657.4 m)

Table 2.5 Layout parameters of the particle collider

Site	Function
PA	Scientific site with one experiment, injecting the beam line from a linear accelerator at the CERN Prevessin site into the pre-accelerator (booster) located in the same tunnel as the collider.
PB	Technical site with injection of booster beam line into the collider, extraction of beam line from collider.
PD	Scientific site with one experiment.
PF	Technical site with betatron and momentum collimation.
PG	Scientific site with one experiment.
PH	Technical site with radiofrequency particle acceleration system for the collider.
PJ	Scientific site with one experiment.
PL	Technical site with radiofrequency particle acceleration system for the booster pre-accelerator.

analysis for this scenario in terms of territorial compatibility (T), implementation and risk management (I) and scientific value (S) for each site location and the entire trace.

2.6.5 Site PA

Description of the site location The main site is located in Ferney-Voltaire, Ain, France, south of the Route de Meyrin road, east of the Espace Candide shopping centre (see Fig. 2.29 and Fig. 2.30). The site would be connected to Point 8 of the LHC by the Chemin des Prés Jins, a public road. An extension to the south of LHC Point 8, already planned as part of the HL-LHC project, would make it possible to accommodate technical infrastructures to reduce the land take for the main site. The surface area of the site along the Route de Meyrin is 5.2 ha, and the surface area of the LHC Point 8 site extension is 2.7 ha.

Known constraints The site is located in a protected agricultural (Ap) zone, close to an environmental compensation zone classified as protected nature zone (Np). The water supply network passes close by Point 8 of the LHC. A gas pipeline runs along the boundary of the main surface site, before crossing the border between France and Switzerland. There is a network along the Route de Meyrin that supplies waste heat from LHC Point 8 to

Fig. 2.28 Multi-criteria analysis percentage scores of each surface site location and the entire collider trace of scenario PA31-4.0. Note that site locations PC, PE, PI and PK do not exist in 8 site scenarios. Blue lines indicate the individual performance thresholds (green, yellow, orange, red). Green indicated bars exhibit a very good performance and yellow indicated locations correspond to a good performance)

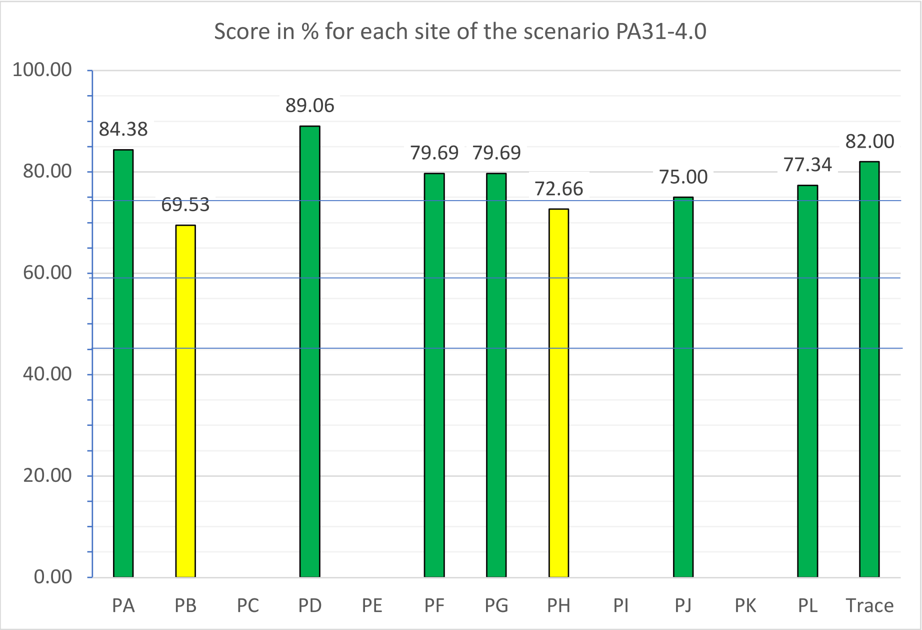


Fig. 2.29 Aerial view of candidate location for surface site PA

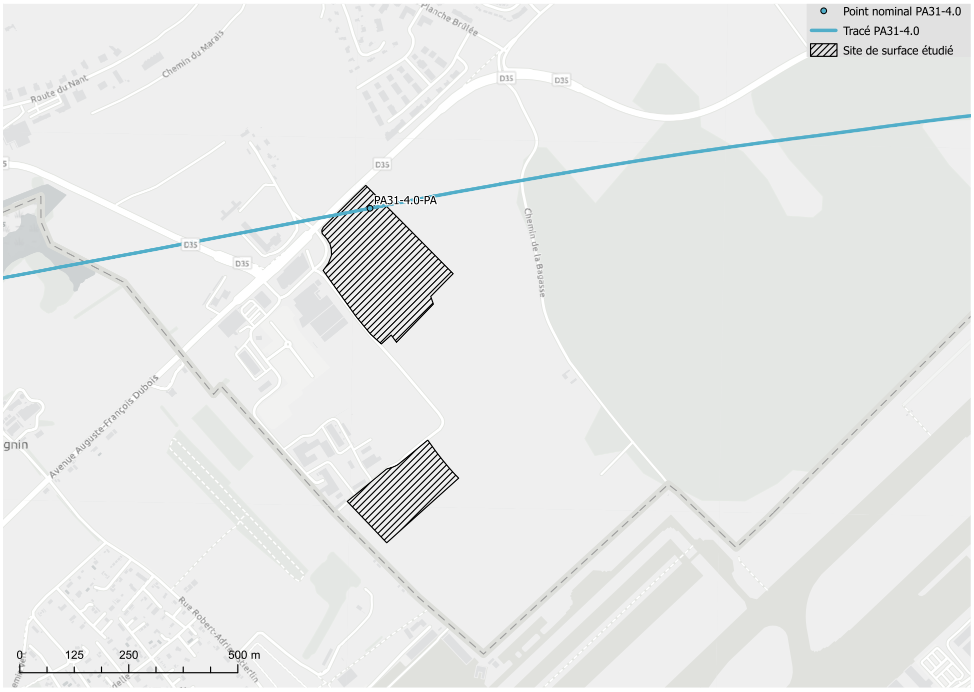


Fig. 2.30 PA surface site location in Ferney-Voltaire, Ain, France. The hashed space in the south represents an annex that is an extension of the existing LHC P8 site

dwellings and to the commercial zone (ZAC, mixed development zone). Good urban and landscape integration is necessary to preserve the view facing the Alps. Due to heavy traffic in the area, a concept must be developed together with the municipality's technical services for efficient site access. No dedicated access road is required, though.

Synergies and territorial potentials Waste heat from the particle collider cooling and the data centre can be recovered and supplied to the homes and business parks around the site, including the Geneva airport and industrial zone, building on the current heat supply network that has been put in place for the LHC programme. The existing but non-functional environmental compensation area can be turned into a fully functional natural habitat and wetland, providing substantially increased environmental quality in that area. Treated residual water from the cooling system can be used for this zone (the Poirier de l'Épine zone) and potentially for agricultural purposes close to the site. Synergy with LHC Point 8 would permit a substantial reduction of the footprint of the PA site. This requires good planning and sequencing of the new collider project with the HL-LHC programme. Synergy with the CERN site in Prévessin and the Bois-Tollot substation provides the electricity supply (existing 400 kV line to Prévessin and a dedicated 63 kV link from Prévessin to LHC Point 8). A visitor centre could be created in synergy with LHC Point 8 to exploit the location fully.

2.6.6 Site PB

Description of the site location The site lies in Presinge, canton of Geneva, Switzerland, to the south of the Nant du Paradis stream, on a field classified as a protected crop rotation area (in French: 'Surface d'Assolement' or in short SDA), bordering the Route de Jussy road (see Fig. 2.31 and Fig. 2.32). The surface area shown on the map indicates the site area covers 4.5 ha. The site is displaced south to the road, avoiding conflicts with nature protection zones and providing for improved access. An underground connection tunnel of about 100 m in length is required to connect to the service cavern that is located inside the collider tunnel.

Known constraints The prescribed protective distances between the Nant du Paradis creek that hosts an amphibian breeding area and the forest are respected. The environmental state analysis did not detect any interference with protected environments in the vicinity of the location, in particular the amphibian breeding site. The impact on the crop rotation area (SDA) should be kept to a minimum. The space consumed by SDA has to be compensated 1:1 by transporting the topsoil to another location that needs to be identified with the help of notified cantonal services. To blend in well with the surrounding landscape, the site needs to be as small and compact as possible and be ideally semi-underground. A study of the cooling system is necessary to reduce noise and visual disturbances. It is also necessary to develop a concept for reducing light pollution during the construction phase. The road access

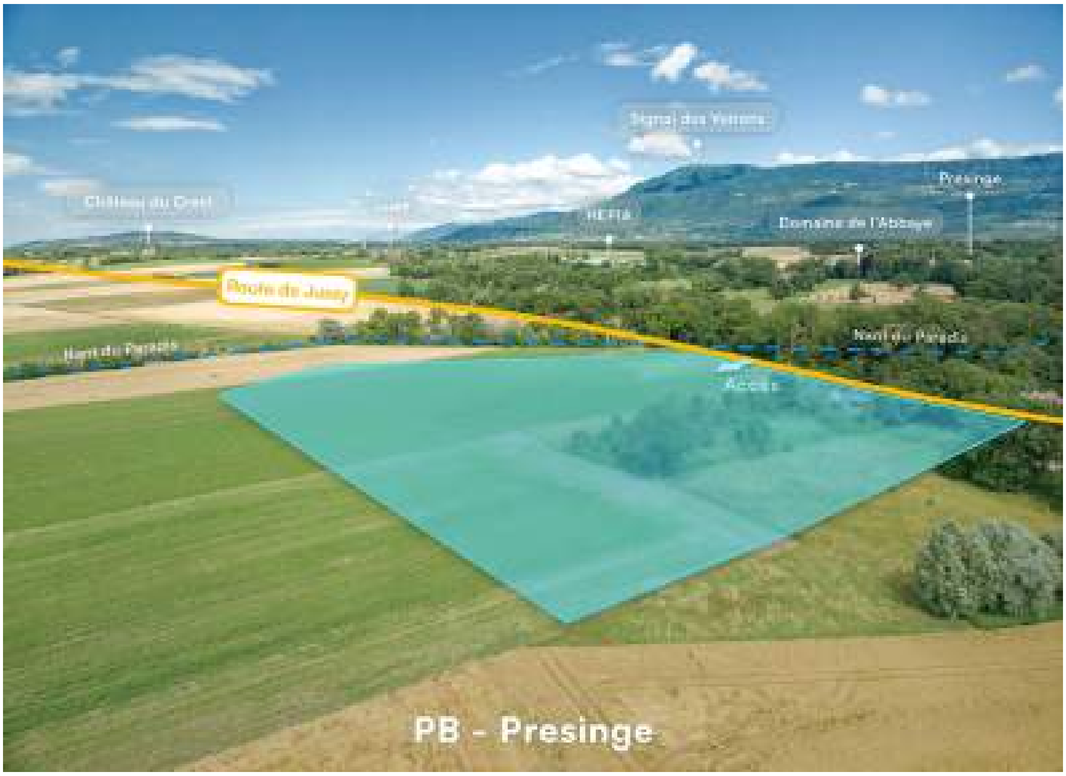
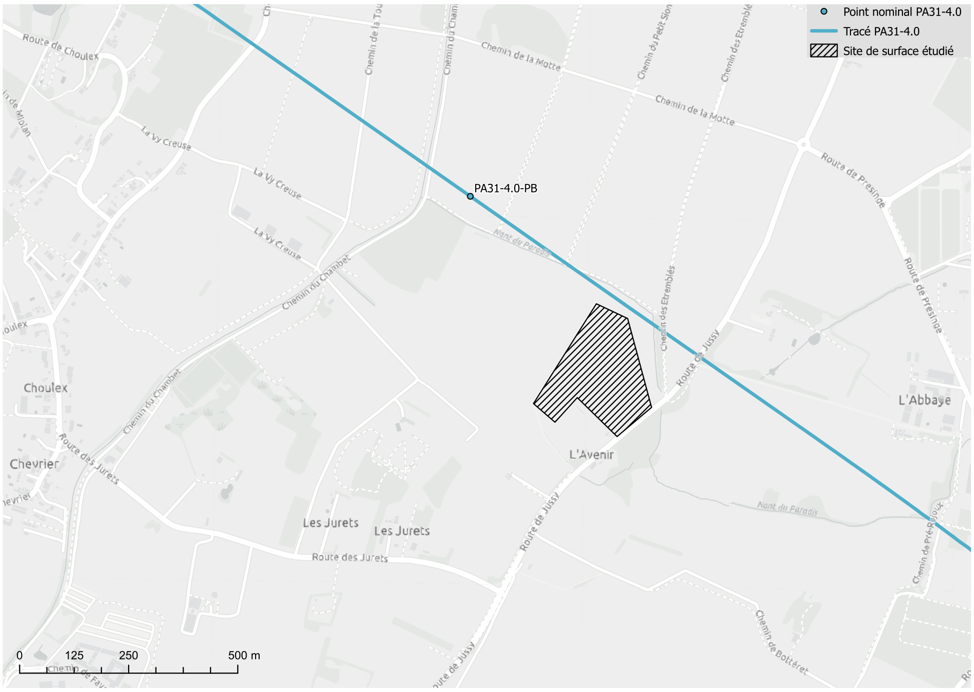


Fig. 2.31 Aerial view of candidate location for surface site PB

Fig. 2.32 PB surface site location in Presinge, canton of Geneva, Switzerland



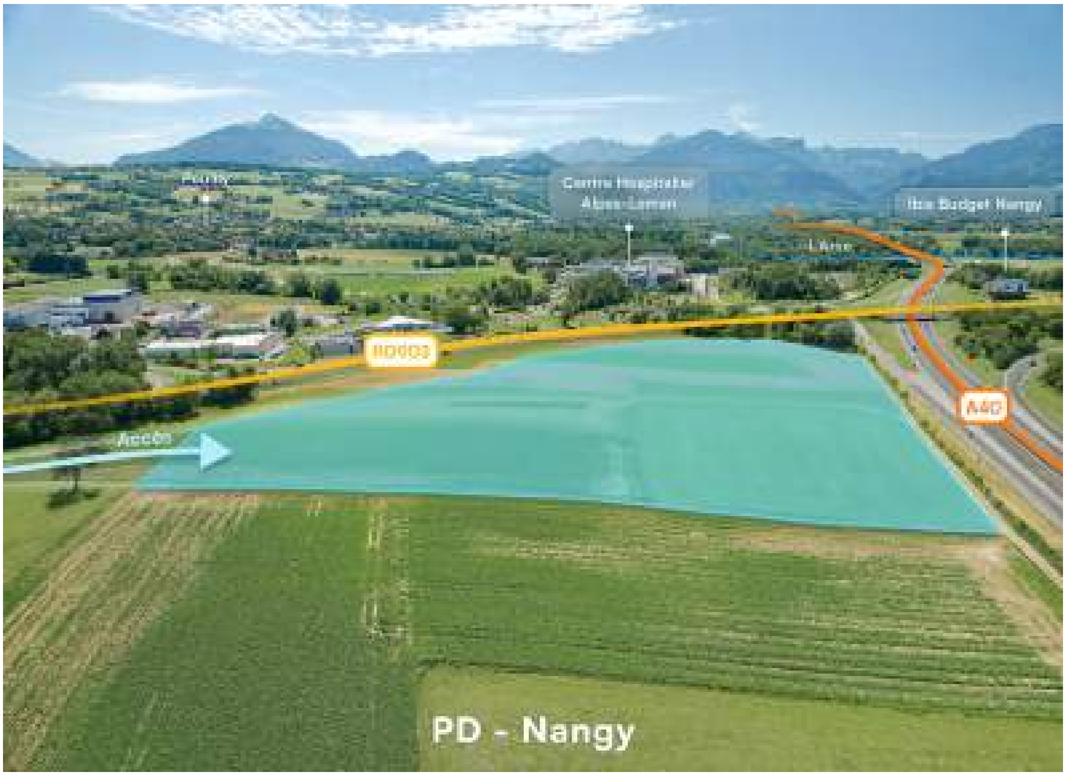


Fig. 2.33 Aerial view of candidate location for surface site PD

was studied by a specialised firm with in-depth knowledge of the sector. No new road needs to be constructed, but a junction would have to be created at the Route de Jussy. The detailed design and location of the recommended access option have to be validated by the notified bodies of the canton of Geneva once a construction project is proposed. A detailed technical access plan should be drawn up at a later stage for this purpose.

Synergies and territorial potentials According to the road access study carried out by the firm, direct access to the site from the Route de Jussy is technically feasible and preferable from the project perspective. This scenario would avoid the need to create a new access road. The green buffer zone around the site would reinforce and extend the natural environment in the vicinity of the Nant du Paradis watercourse. Surface sites that are semi-underground would not only improve the blending into the landscape but would also improve the overall ecological and biodiversity value of a non-agricultural habitat. The reinforcement of the local power grid, necessary for the construction phase, is seen as an opportunity to improve the infrastructure for the inhabitants of the entire area. Improved public transport, including cross-border transport as part of the FCC, also represents an opportunity for the area. Several opportunities exist, and demand for supplying heat recovered from the particle accelerator nearby, for example, with HEPIA and a new correctional institution slated for construction by 2030 on the Champ-Dollon prison site.

2.6.7 Site PD

Description of the site location The site is located in Nangy, Haute-Savoie, France (see Fig. 2.33 and Fig. 2.34) between the A40 autoroute and the RD903 departmental road on an agricultural field with zone 'A' classification in the local urban plan (in French: 'PLU'). The surface area of the site is approximately 4.9 ha.

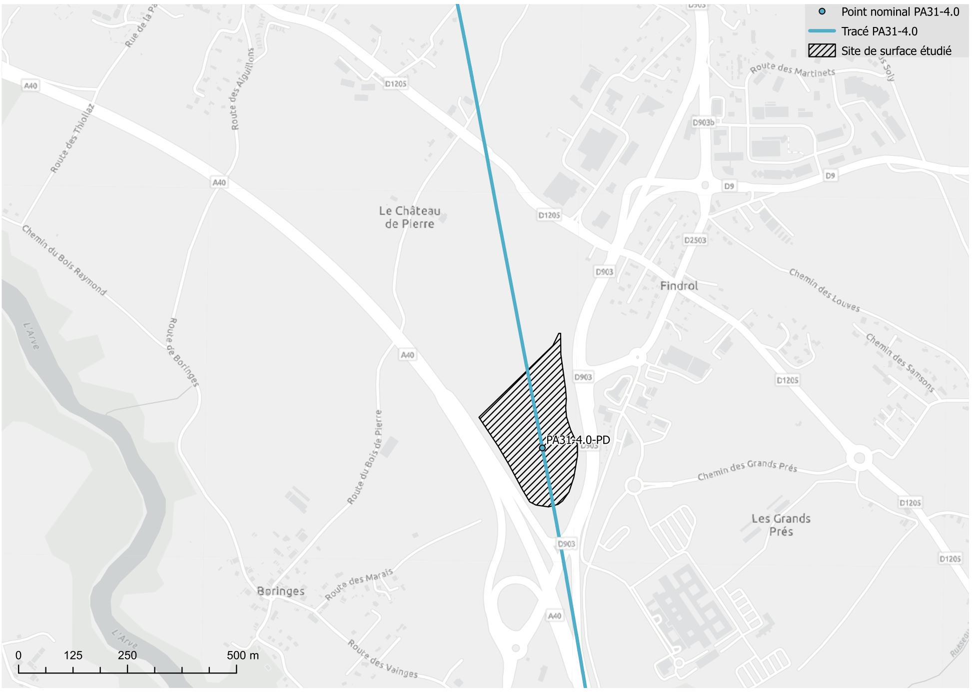


Fig. 2.34 PD surface site location in Nangy, Haute-Savoie, France

Known constraints The site is subject to space constraints to the west, east and south due to existing roads and plans to build a new connection between the roads. Road traffic is typically high, one reason for the road development project that is expected to integrate the departmental road with the autoroute. A study for the development of different access scenarios was carried out by a specialised firm. The scenarios were discussed with the Haute-Savoie department and with the mayor of the municipality. The commonly preferred scenario with the lowest impact is one that comprises a dedicated access road to the surface site. The access to the site would be via a roundabout, which would be built to the north at the D 1205 departmental road in Fillinges.

Synergies and territorial potentials The site is only accessible via the dedicated, approximately 250 m long access road. The site is not visible from residential areas, which facilitates its integration into the landscape. There are a number of possibilities for supplying residual heat from the cooling system, for example, to a nearby cheese factory, to an industrial and business park, to hotels, medical facilities, neighbouring communes such as Fillinges, Boringes, Scientrier, Contamine-sur-Arve and to the Alpes-Léman hospital complex. The heat can also be used for biogas production in the waste water treatment facility in Scientrier. Currently, a study is ongoing to source water from the waste water treatment facility 'SRB' in Scientrier for use in the accelerator cooling system. When the cleaned water is not used for the particle accelerator, it could be made available for agricultural and industrial purposes. A direct connection by conveyor belt to the autoroute during the construction phase has been studied. It would facilitate the removal and possibly also the supply of materials, thus largely avoiding the need for trucks. There are likely areas in the vicinity where excavated materials can be reused such as raised hedges, noise separation, covered trench creation, landfill and transport to quarries for rewilding purposes. To be able to develop a solid excavated materials management plan, these opportunities need to be identified with the help of local authorities and notified bodies (e.g., SAFER, DDT, DREAL).

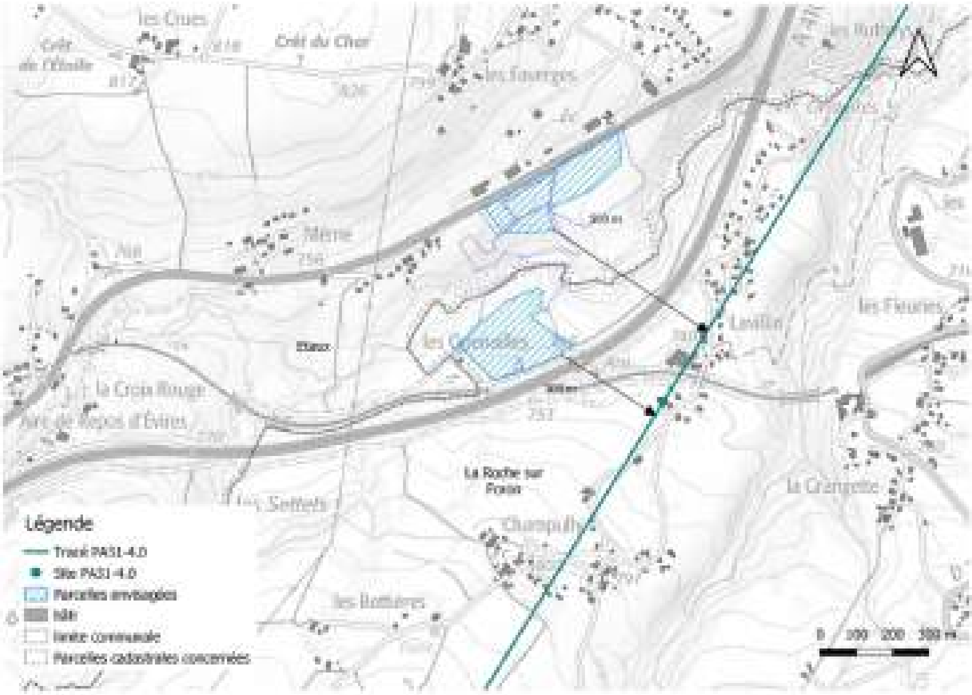
2.6.8 Site PF

Description of the site location A technical surface site at the nominal point PF in La Roche-sur-Foron, Haute-Savoie, France (see Fig. 2.35 and Fig. 2.36) is not feasible because:

- The site would be in the middle of a hamlet of single-family homes.
- The presence of the Lavillat road in the direction of La Roche-sur-Foron is incompatible with the construction and installation of the accelerator site and equipment.
- The nominal point is located on high ground (755 m) leading to a shaft which is too deep and with an unfavourable topography.
- A slight movement of the ring inwards is ruled out due to the presence of steep slopes and the risk of landslides.

Fig. 2.35 Aerial view of candidate location for surface site PF

Fig. 2.36 Nominal location of PF indicated with a spot on the collider trace. Two surface site candidate locations requiring horizontal access tunnels are indicated with black arrows



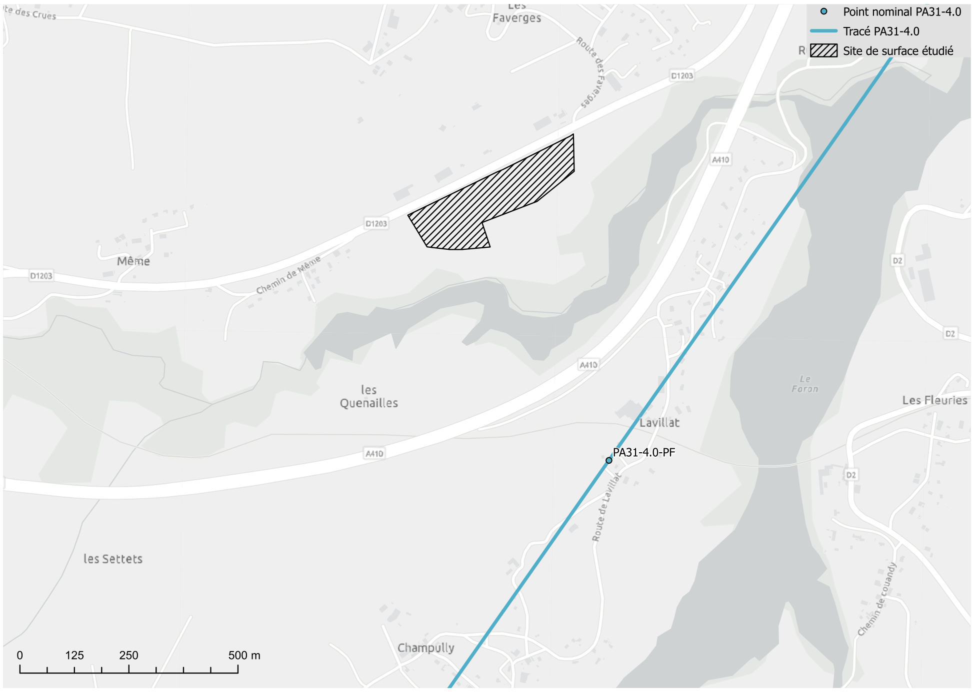


Fig. 2.37 PF surface site location in Éteaux, Haute-Savoie, France

The preferred alternative selected for a technical surface site PF is a location in Éteaux, Haute-Savoie France (see Fig. 2.37), alongside the RD 1203 road, with a surface area of 4 ha. An underground connection tunnel is required between the shaft to be located in the indicated surface site perimeter and the service cavern at the inside of the collider tunnel.

If the surface site area needs to be reduced, made more compact or certain constructions cannot be made compatible with the required landscape integration, then an annex to the south of the site, alongside the autoroute in La Roche-sur-Foron can be envisaged. The land is on the perimeter of a newly constructed inert waste storage facility (in French: 'I.S.D.I.'). Once the inert waste storage is full and no longer in use, it can host constructions that are limited to the surface such as ventilation systems, cooling towers and an electrical substation.

Known constraints

Main site in Éteaux The shaft of the site and the accelerator tunnel are 558.5 m apart, depending on the position of the shaft. The wetlands to the east of the site must be maintained and could be integrated into the site. A certain distance must be maintained between the site and the hamlet to the east. As a result, there is little space left for the surface site, and the size of the site should be reduced. Work should be undertaken with the local authority and government agencies (DDT, DREAL) to define zones for recycling excavated materials in the vicinity of the site. The area available for the surface site is very limited (4 ha). It may, therefore, be necessary to relocate certain elements, such as an electrical substation or cooling towers, to the south option for the site in La Roche-sur-Foron or to another nearby location.

Option of an annex in La Roche-sur-Foron The technical site is located on the site of an inert waste storage facility (in France: 'I.S.D.I.'), currently under construction, with the status of a facility classified for environmental protection (in France: 'ICPE'), i.e., subject to particular construction, operation and monitoring constraints. Following an analysis carried out by civil engineering contractors, the location was found, in principle, to be compatible with the construction of a surface site. However, this choice would entail significant additional costs and additional technical difficulties. For example, it would be necessary to employ pillars for construction on inert waste dumps to assure the stability of the groundworks and the construction of the shaft. It would be necessary to create an access road 2.4 km long that crosses the existing railway line, and to build an underpass under the autoroute. Lastly, this option is located in the immediate vicinity of an environmental protection zone (in French: 'ZNIEFF'), which is rich in biodiversity and includes a wildlife corridor that must be preserved. The available surface area is roughly the same as for the location in Éteaux (4.1 ha, versus 4.0 ha). However, if needed, the location could accommodate certain technical infrastructures that are compatible with inert waste deposits, such as an electrical substation or cooling towers. Further analysis will be carried out during the detailed technical design phase.

Fig. 2.38 Aerial view of candidate location for surface site PG

Synergies and territorial potentials For the location in Éteaux, it is possible to supply residual heat from the cooling system to public facilities and businesses in a radius up to 3 km. A zone that qualifies as wetland, but which today is not well preserved, can be rewilded, protected, and be well preserved together with the habitat in the vicinity of the Vuaz stream. Lastly, direct access from the main road is possible and would avoid the creation of a new access road. Electricity substations for the construction phase exist in the vicinity. If needed, a connection to the nearby autoroute service station could be implemented to facilitate the transport of excavated materials and the supply of construction materials.

2.6.9 Site PG

Description of the site location The experiment site PG lies to the north of the Route d'Annecy road on a plateau, crossing the border of the communes Charvonnex and Groisy, Haute-Savoie in France (see Fig. 2.38 and Fig. 2.39). The main site is partly in a forest and partly on grasslands. It is approximately 800 m south of the A410 autoroute area in Groisy. At this location, next to the autoroute service station, two smaller plots have been identified to host technical infrastructures that do not need to be close to the shaft. All plots are far from any dwellings. The area marked limits of the main site is 6.9 ha. However, only a fraction of that area would be constructed. Annexes of 1.9 ha and 1.7 ha for equipment storage, an electrical substation and cooling towers close to the autoroute are also indicated. An existing 800 m long, wide forest path has to be refurbished to serve as an access road to the main site.

Known constraints The forest is a classified wooded area (in France: 'EBC'), heterogeneous, valued for its biodiversity in some parts. The use of the forest for the site will be reduced and limited to the part with the lowest quality in terms of its natural environment. Clearing will be compensated for by, for example, reforesting the