FCC WEEK
Civil engineering status and plans

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The Future Circular Collider
Civil Engineering (CE) constraints

Collision energy: 100TeV
Circumference: 80km-100km
Physics considerations: Enable connection to the LHC (or SPS)
Construction: c.2030-2037
Aims of the civil engineering feasibility study: Is 80km-100km feasible in the Geneva basin? Can we go bigger? What is the ‘optimal’ size? What is the optimal position?
Geology in the FCC region

Main geological units:

**Molasse**
- Mixture of sandstones, marls and formations of intermediate composition
- Relatively weak rock (Average compressive strength: 5.5–48 Mpa)
- Considered good excavation rock
- Relatively dry and stable
- Faulting due to the redistribution of ground stresses
- Structural instability (swelling, creep, squeezing)

**Moraines (Quaternary Deposits)**
- Glacial deposits comprising gravel, sands, silt and clay
- Water bearing unit

**Limestone**
- Hard rock
- Normally considered as sound tunneling rock
- In this region fractures and karsts likely present
- High inflow rates measured during LEP construction (600L/sec)
- Clay-silt sediments in water
- Rockmass instabilities
"Lakeside" vs "Jura" options in pre-feasibility stage

- Lakeside option selected to avoid Jura limestone due to previous issues experienced during LEP construction of sector 3-4.
- Molasse considered as a good rock for tunneling.
- Good knowledge and experience from LEP construction in molasse.
- Spoil re-use was not the primary goal in the CE pre-feasibility studies.

### Tunnelling in limestone – one of the main civil engineering constraints!

<table>
<thead>
<tr>
<th></th>
<th>water ingress</th>
<th>heaving ground</th>
<th>weak marls</th>
<th>hydro carbons</th>
<th>support &amp; lining</th>
<th>ground response &amp; convergence</th>
<th>hydrostatic pressure &amp; drainage</th>
<th>Pollution of aquifers</th>
<th>effect of shafts on nature</th>
<th>effects of shafts on urban areas</th>
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<td>Jura 80</td>
<td>5</td>
<td>3</td>
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<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
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<tr>
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<td>3</td>
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<td>2</td>
<td>5</td>
<td>18</td>
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</table>
Civil engineering constraints

Tunnelling under Lac Léman
Civil engineering constraints

Tunnelling under Arve Valley and Rhone Valley

- Data available from deep destructive drillings for water research in the vicinity of the crossing.
- Aquifers nearby Rhone valley

The alignment was lowered deep enough for the tunnel to sit in the molasse to avoid changing TBM mode for a relatively short distance, avoid placing large span caverns in saturated moraines and minimise the environmental risks.
FCC Study Boundary

The Study Boundary was defined by:

**Jura**
High overburden
Karstic limestone

**Vuache**
Highly fractured limestone with karsts

**Pre-alps**
High overburden

**Lac Léman**
Lake depth increases quickly in NE direction

**Connections to LHC**
Multiple tunnel shapes and sizes studied within the boundary.
Tunnel Optimisation Tool

1. The location (x,y), depth (z), rotation (°) and slope (%) can be changed for any of the stored tunnel shapes and

2. Information about the shafts is given including their depth, the geology intersected by each shaft and the total shaft depth for each tunnel alignment

3. As the tunnel is moved around, the alignment profile shows a basic projection of the geology intersected along the circumference of the tunnel

4. The percentage of each rock type intersected by the tunnel is given
Data interpretation and input into TOT

Molasse rockhead contours + Limestone rockhead contours
Overview of tunnel alignment development

- **2014**
  - Kick-off meeting, Geneva 2014

- **2015**
  - Multiples shapes (racetracks and quasi-circulars) and sizes considered within the study boundary: 80km, 87km, 93km, 100km

- **2016**
  - Optimisation of 97.75km option, intersecting the LHC in plan view and fitting within geological constraints

- **2017**
  - Alignment update following geological review of key areas such as lake crossing

- **2018**
  - Decision to focus on 100km options with lake crossing vs non-intersecting

- **2019**
  - CDR volumes submitted to European Strategy update for Particle Physics

- **2020**
  - European Strategy Update 2020
    - ILF/GADZ study Kick-off for definition of High-Risk Areas;
    - Collaboration with UNIGE to develop a 3D subsurface model

Baseline Footprint:
- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)
- experimental Site at Point A on existing CERN land

- Surface sites placement optimization;
- Civil Engineering review in TOT of various scenarios varying between 91 – 100 km circumference;
- Development of a GIS database for FCC
Present baseline position was established considering:

- lowest risk for construction
  - Avoid Jura limestone and the Pre-Alps
  - Only one sector containing limestone. ~90 % molasse – suitable ground for tunneling
  - Significantly reduced total shaft length. Deepest shaft at PF proposed to be replaced with an inclined tunnel
  - Avoids extremely large overburden.
  - 0.3% slope
- feasible positions for large span caverns (most challenging structures)
- experimental Site at Point A on existing CERN land.
FCC Overview of Underground Structures
Conceptual design

Shafts:
- Experimental Shafts: 15 m dia. + 10 m dia.
- Service shafts: 12 m dia.
- Magnet delivery shaft: 18 m

Service Caverns
- 25 m x 15 m x 100 m

Alcoves
- 25 m x 6 m x 6 m
- Located at 1.5 km spacing

Large Experimental Caverns
- 35 m x 35 m x 66 m

Small Experimental Caverns
- 30 m x 35 m x 66 m

Beam Dump Caverns
- 10 m x 10 m x 50 m

Tunnels:
- 97.75 km of 5.5 dia. machine tunnel
- Approx. 8 km 5.5 dia by-pass tunnels

Underground civil infrastructure for FCC - 3D schematic (not to scale)
Steel structure with passive fire protection. Connection:

- Pre-cast concrete segmental lining
- Cast-in-situ concrete invert
- Pre-cast concrete element
Tunnel lining conceptual design

Lining Type 1
- TBM tunnel in ‘good’ molasse
- 30cm thick pre-cast segmental lining

Lining Type 2 & 3
- TBM tunnel in jointed molasse with high risk of groundwater infiltration
- Precast concrete thickness: 30cm
- Lining type 3 (under Geneva Lake)
- Precast concrete thickness: 45cm
- Segments with higher steel bar density

Lining Type 4
- Mined tunnels in limestone
  - 10cm shortcrete + 20cm thick cast-in-situ lining in poor rock
  - 20cm shortcrete + 30cm thick cast-in-situ lining in good rock

Legend:
- CAST INSITU CONCRETE
- GROUT
- PRE-CAST CONCRETE
- STEELWORK
- PASSIVE FIRE PROTECTION
In the conceptual design, ‘double shield’ TBM's have been proposed for FCC, except for in Moraines under the lake (Slurry/Mixshield TBM)

(For LEP and LHC works ‘Gripper’ and ‘Double shield’ TBM’s were deployed)
Construction Strategy

Additional construction lots
• 2 no. Shafts near the LHC for the connection tunnels LHC-FCC
• 2 Beam transfer tunnels

Project divided in 12 construction lots

Construction techniques:
1) TBM tunnels (red)
2) Mined tunnels (blue)

Access to main tunnel works through:
• Shafts at 11 points
• Sloped Access adit at 1 point (instead of 570 m shaft)

Intermediate Access Adits
• necessary to cope with overall time schedule to meet deadlines for machine installation
Construction Schedule (CDR)

Sector L-A-B: 4.5 years

Sector D-E-F: 6.5 years
Civil engineering objectives for the Next European Strategy

**ESPPU 2020:**

More comprehensive feasibility study to be delivered end 2025 as input for ESPP Update expected for 2026/2027:

- *Feasibility study of the 100 km tunnel*
- *High-risk areas site investigations*, to confirm principle feasibility - **10-15 MCHF budget**
- *Feasibility Study Report* including design and cost and schedule updates

To achieve these objectives, the CERN civil engineering team are launching a site investigation campaign for High-Risk Areas for FCC.

*High Risk Areas include:*
- Areas along the FCC tunnel alignment where there is high uncertainty in the geological boundary layers and ground conditions, critical to determine the vertical and the horizontal alignment of the FCC tunnel.
- Areas to avoid where the complexity of the ground and hydrogeological conditions would dramatically increase the costs/risks during construction works and/or maintenance

The Civil Engineering team is looking only at the underground constraints and not surface sites!
Geological uncertainty and high-risk areas

**Lake Geneva**
- Very few seismic and borehole information for lake crossing from proposed road tunnel, but layered nature of lake bed leads to uncertainty.
- Reliable borehole data missing.

**Arve Valley**
- Moraine/molasse interface not certain, cavern close to interface.

**Mandallaz**
- Limestone formation known, but characteristics and locations of karsts unknown.
  - Alignment close to limestone rockhead
  - Limestone/molasse interface undefined.

**Rhone Valley**
- Moraine/molasse interface not certain, cavern close to interface.
  - Proximity to protected area

**Placement for Conceptual Design**
- Reliable information near to CERN from previous experience on LEP/LHC.
- Multiple deep boreholes in the area.
- No deep borehole information available in the area.
- Complex faulted region.
- Geotechnical parameters for molasse need to be confirmed for large span caverns.
ILF/GADZ study of High-Risk Areas

ILF/GADZ High Risk Areas SI preliminary study (November 2020 – August 2021)

- **Definition of ‘high risk areas’** for the preferred scenario(s)
- **Input into footprint exploration** – Comparison of scenarios and Geological Risks Assessment
- Propose **site investigations in the HRA** to reduce the uncertainty of the geological condition
- **Cost estimates and schedule** of the SI in the HRA
- **Procurement strategy** for HRA SI and Main SI
- **Input into the Technical Specifications to define the Scope of Services for the SI Consultants** and cost estimate and schedule of the deliverables of SI Consultants
- Expert advice from GADZ – local geological expert with previous experience at CERN, LEP and LHC

- ILF/GADZ study is focused on the construction risks for underground works and not the impact on machine operations or the environmental impact
Collaboration with University of Geneva to develop a 3D geological model (October 2020 – August 2022)

- Received an updated molasse and limestone rockhead maps
- Updated fault lines layers
- Ongoing analysis of new boreholes and data integration in the model
- New acquisition of BRGM seismic lines and re-processing
Footprint Exploration

- Surface sites placement optimization – environmental, administrative and legal requirements from the host states.
- **Input from civil engineering is essential to evaluate the feasibility of tunnel alignments and caverns and shaft locations**
- Currently still using **TOT (Tunnel Optimisation Tool)** to provide initial feedback on the suitability of the tunnel placement for each scenario, **elevation**, tilt, shafts depth, information for transfer lines design.
- **TOT limitations:** geological data uncertainties, difficult to make updates and maintain libraries, accuracy of geodetic survey conversions between TOT and other GIS tools, different reference coordinate systems need to be taken into account.
- The longitudinal profiles are then developed by ILF/GADZ using updated geological data provided by UNIGE (to be presented later by ILF/GADZ)
Scenarios reviewed at Placement studies workshop

5 MAIN scenarios
Two scenarios with 12 points:
Three scenarios with 8 points:

Additional 2 scenarios evaluated by ILF/GADZ and recommended to avoid because they intersect the Vuache and Jura limestone.

The aim is to identify one feasible scenario before starting tendering for SI.
Two scenarios with 12 points

**96km PB17-0.8**
- Tilt: 0.5% x-x and 0.07% y-y
- Total Shafts Depth: 2580 m
- Deepest Shaft is PF 352 m
- 93.6% Molasse
- 5.3% Limestone
- 1.1% Moraines

**90km PB38-0.1**
- Tilt: 0.5% x-x and 0.1% y-y
- TOT Shafts Depth: 2740 m
- Deepest shaft: PG 402m
- 94.7% Molasse
- 4.3% Limestone
- 1% Moraines
Three scenarios with 8 points

92.6 km
PB35-0.6
- Tilt: 0.1% x-x
- TOT Shafts Depth: 1858 m
- Deepest shaft: PF 402 m
- 90.4 % Molasse
- 7.1% Limestone
- 2.5% Moraines

90.9 km
PB31-0.4
- Tilt: 0.6% x-x
- TOT Shafts Depth: 1859 m
- Deepest shaft: PF 359 m
- 95.4 % Molasse
- 4.6% Limestone

94.8 km
PA37-0.3
- Tilt: 0.1% x-x
- TOT Shafts Depth: 1907 m
- Deepest shaft: PJ 411 m
- 92.5 % Molasse
- 4.8% Limestone
- 2.7% Moraines
Two scenarios rejected

91.3 km PB19-0.3
- Tilt: 0.8% x-x and 0.3% y-y
- Depth of experimental shaft at PG is below 300m if a tilt of 0.8 x-x and 0.3 y-y is applied
- Tunnel alignment depth below lake surface: ~175m
- Total Shafts Depth: 3072 m
- Deepest Shaft is PH 323 m
- PG 291 m
- 72 % Molasse
- 28% Limestone

95.85 km PA21-0.3
- Tilt: 0.5% x-x and 0.1% y-y
- TOT Shafts Depth: 1834 m
- Deepest Shaft is PF 302 m
- 76 % Molasse
- 22% Limestone
- 2% Moraines

Vuache
Jura
FCC current tools and software

- Surface point exploration
  - Footprint Explorer Web App
    - J. Gutleber, V. Mertens

- Developing a Central data repository

- Tunnel Optimisation Tool
- Underground assessment
  - J. Osborne, A. Tudora

- Survey high precision calculations

- Transfer line calculations

- 3D geological modelling
  - Petrel

- Future External Consultants Software
  - UNIGE

- FCC-GIS Web App

- J. Osborne, A. Tudora
- F. Gutleber, V. Mertens
Moving from TOT to ArcGIS

- ArcGIS database and development of geoprofiler web application (under development).
- The web app will include similar functionalities as TOT (and some additional features), and updated geological model based on UNIGE data.
## FCC Trans-Jura scenario

### Civil Engineering Cost Estimate Comparison

<table>
<thead>
<tr>
<th>Description</th>
<th>CDR BASELINE SCENARIO</th>
<th>TRANS-JURA SCENARIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>€ 668</td>
<td>€ 668</td>
</tr>
<tr>
<td>Machine tunnels</td>
<td>€ 2,247</td>
<td>€ 3,140</td>
</tr>
<tr>
<td>Transfer line (tunnels &amp; shafts)</td>
<td>€ 175</td>
<td>€ 1,456</td>
</tr>
<tr>
<td>Shafts</td>
<td>€ 1,151</td>
<td>€ 533</td>
</tr>
<tr>
<td>Caverns &amp; alcoves</td>
<td>€ 836</td>
<td>€ 1,116</td>
</tr>
<tr>
<td>Connections (galleries, by-pass tunnels, connection tunnels)</td>
<td>€ 29</td>
<td>€ 392</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€ 5,374</td>
<td>€ 7,305</td>
</tr>
</tbody>
</table>

- **36% more expensive than the CDR baseline**

### CE cost increase mainly due to
- additional ~50 km of tunnel through the Jura limestone for the beam transfer line connection to the LHC.
- Main tunnel, caverns and shaft excavated in the soft ground of the Bresse formation.

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**Note:**
- SCE Site and Civil Engineering
- FCC closed panel
Ongoing machine design 12 points vs 8 points

Machine parameters presented at CDR: 12 points (2 experimental points for FCC-ee. 2 additional experiments added later for FCC-hh)

New scenarios being explored:
8 points with two experiments

- The tunnel diameter would increase to fulfill the requirements from ventilation, cryogenics, transport, electricity, survey, safety and other services which have not been taken into account at this stage.
- The construction strategy has not been updated for the proposed scenarios assuming 8 access points instead of 12 foreseen in the CDR. The increased distance between points will have an impact on construction schedule, both on the construction of the machine tunnel and caverns as well as the spoil removal schedule. Additional access tunnels could be added to have independent excavation points and to allow distribution of excavation spoil.
FCC Rail mounted robot – deformation and stress analysis of the tunnel ceiling/ventilation duct

Proposed tasks for the robot:
- Tunnel inspections
- Carrying tools/materials
- Preventive maintenance
- Performs repair work and reach areas which are difficult to be accessed by people
- Hazard detection (e.g. Measure radiation, oxygen levels, smoke, Helium leaks)
- Fire-fighting intervention
- Tests Sensors
- Alignment measurements
- Disconnects broken devices of the collimator

- Different layout options for the robot have been studied taking into account the allowable space and load increase.
- Civil engineering ILF study: Deformation and stress analysis of the tunnel ceiling / ventilation duct.

For more details follow the presentation from H. Gamper on Thursday 1 July at 16.40
In addition, launching the permitting approval process and environmental impact studies.
Site Investigations

Type of site investigations foreseen in the HRA would include walkover surveys at shaft locations, geophysical investigations, exploration drillings and laboratory testing to not only determine the geotechnical properties of the ground but also to include a chemical analysis for pollution testing and investigating the spoil re-use.
Summary

- Since the kick-off of the study, the civil engineering team have focused on finding the optimal placement and layout for the FCC tunnel, the conceptual design and a detailed cost and schedule estimates.

- FCC feasibility studies are ongoing and will deliver an input to the next ESPPU in 2026-2027;

- To confirm the principle feasibility of the 100 km tunnel, CERN is launching a site investigation campaign starting in the High-Risk areas; Site Investigation contracts will soon be awarded for 100km Future Circular Collider.

- The design of the underground structures, cost and schedule will be updated based on the outcome of the HRASI, footprint optimization process (including surface sites), machines design and compatibility between FCC-ee and FCC-hh.
Back-up
Main civil engineering constraints

Faults

Faults measured in surveys during LS2 with vertical movements of approx. 4mm.
Understand the local impact of the regional tectonic activity proposed the monitoring of the Vuache fault which is the best candidate for the generation of seismic and aseismic activity in the area

Following advancements of tunnel works

GPS network installation could be coordinated with FCC activities for the future geodetic network

**Tectonic Map of FGB** (Moscariello, 2019)