Civil engineering at CERN for physics projects

01 December 2020
11th Einstein Telescope Symposium

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CERN tunnels and geology

- Large Hadron Collider:
  - 27km long
  - 50-175m depth
  - 4.5m Ø TBM tunnels
  - Molasse and limestone

Total underground tunnels >70km
More than 80 Caverns
‘CERN’ Geology

Rock properties

Moraines
- Glacial deposits comprising gravel, sands silt and clay
- Water bearing unit
- Low strength

Molasse
- Mixture of sandstones, marls and formations of intermediate composition
- Considered good excavation rock
- Relatively dry and stable
- Relatively soft rock
- However, some risk involved
- Weak marl horizons between stronger layers are zones of weakness
- Faulting due to the redistribution of ground stresses
- Structural instability (swelling, creep, squeezing)

Limestone
- Hard rock
- Normally considered as sound tunneling rock
- In this region fractures and karsts encountered
- Risk of tunnel collapse
- High inflow rates measured during LEP construction (600L/sec)
- Clay-silt sediments in water
- Rockmass instabilities

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<th>Rock type</th>
<th>Average σc (Mpa)</th>
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<td>Sandstone</td>
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Molasse Compression strengths

Model of tunnel collapse caused by Karsts
LHC Civil Engineering costs

TOTAL COST IN THE ORDER OF 490 MCHF

- Consultants
- Architects
- Geotechnical

- Consultants
  - 53.9 MCHF
  - (36.7 M€)

- Surface works
  - 116.8 MCHF
  - (79.4 M€)

- Underground works
  - 272.4 MCHF
  - (185.3 M€)
High Luminosity LHC
High Luminosity LHC: Contract Strategy

Point 1 - ATLAS:
- 1a : Architect for building permit submission (CH)
- 1b : Consultant for design of underground and surface works
- 1c : Contractor for underground and surface works

Point 5 - CMS:
- 5a : Architect for building permit submission (F)
- 5b : Consultant for design of underground and surface works
- 5c : Contractor for underground and surface works
Underground Works at Point 1

ATLAS

PM17 Shaft
(Ø = 10 m; H ≈ 60 m)

US/UW17 Cavern
(A_{exc} ≈ 270 m²; L ≈ 50 m)

UR15 Gallery
(A_{exc} ≈ 60 m²; L ≈ 300 m)

12 Vertical Cores
(Ø = 1 m; H ≈ 7 m)

2 Emergency Staircases
(A_{exc} ≈ 25 m²; H ≈ 10 m)

4 Secondary UA/UL Galleries
(2 x A_{exc} ≈ 45 m²; L ≈ 70 m)
(2 x A_{exc} ≈ 20 m²; L ≈ 50 m)
Civil Works at Point 5

Point 5 Site
≈ identical to Point 1, with different engineer & contractor
Construction Contracts

- **Point 1 Contractor:**
  - Joint Venture Marti Meyrin (JVMM);
  - Accepted Contract Amount ≈ 67 million CHF;
    contract duration of 53 months (until 31.08.2022)
  - Country of origin: Switzerland, Austria, Germany;

- **Point 5 Contractor:**
  - Consortium Implenia Baresel (CIB);
  - Accepted Contract Amount ≈ 58 million EUR;
    contract duration of 54 months (until 30.09.2022)
  - Country of origin: Switzerland, Germany, France;
• High Luminosity LHC Project (HL-LHC)
High Luminosity LHC Project (HL-LHC)
Excavation virtually complete, lining on-going
Point 1 Underground Works – UR15
Point 5 Underground Works – UA57

February 2020

August 2020
HiLumi Point 1 Site

Point 1 Surface Works
CERN Circular Colliders + FCC

- **1980** - Design
- **1985** - Constr.
- **1990** - Physics
- **1995** - LEP
- **2000** - Design
- **2005** - Proto
- **2010** - Construction
- **2015** - Physics
- **2020** - LHC
- **2025** - Design
- **2030** - Construction
- **2035** - HL-LHC

**Future Collider**

- **20 years**
- **2020** - Feasibility
- **2025** - Proto
- **2030** - Design
- **2035** - Construction
- **2040** - Physics
The Future Circular Collider

Collision energy: 100TeV
Circumference: 80km-100km
Physics considerations: Enable connection to the LHC (or SPS)
Construction: c.2030-2037
Cost: ~6Billion CHF for Civil engineering works

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?

Spoil:
~10million m³ of excavated material
Compact Linear Collider (CLIC) Studies at CERN

Legend

- CERN existing LHC
- Potential underground siting:
  - CLIC 380 GeV
  - CLIC 1.5 TeV
  - CLIC 3 TeV

Jura Mountains

Lake Geneva

Geneva
Physics Beyond Colliders (PBC)

PBC is a programme aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders.

• Main studies:
  • Beam Dump Facility (BDF)
  • electrons in the SPS (eSPS)
  • ForwArd Search ExpeRiment (FASER)
  • Neutrinos from STORed Muons (nuSTORM)
  • Plasma Electron Proton/Ion Collider (PEPIC)
  • Advanced Proton driven Plasma Wakefield Experiment (AWAKE)++
  • Electric Dipole Moments (EDM) Storage Ring
  • MAssive Timing Hodoscope for Ultra Stable neutraL pArticles (MATHUSLA)
European Strategy Update 2020

Core sentence and main request “order of the further FCC study”:

“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. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

Feasibility study to be delivered end 2025 as input for ESPP Update expected for 2026/2027.
Brief history of alignment development

Kick-off meeting, Geneva 2014

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

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

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

2013 - European Strategy Update 2013
- 80km “Jura”
- 80km “Lakeside”
- 47km “Lakeside”

2014 - Decision to focus on 100km options
- Intersecting vs non-intersecting

2015 - Alignment update following geological review of key areas such as lake crossing

2016 - CDR volumes submitted to European Strategy update for Particle Physics
“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

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<th>Risk</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>
<th>Total</th>
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Typical ‘Molasse’ tunnel/cavern cross section from LHC construction. Individual units typically vary in thickness between approximately 0.1m and 3.0m.

Spoil from TBM’s will be a mixture of Marls, Sandstones etc. which makes ‘filtering’ for re-use challenging

~9 million cubic meters of spoil
The Study Boundary was defined by:

- Topography (avoid *Jura, Vuache, Pre-Alps*)
- Geology (maximise tunnelling in *molasse*)
- **Geneva Lake** (lake depth increases in NE direction)
- Connection to LHC

Multiple shapes and sizes studied within the boundary
(1) The location \((x,y)\), depth \((z)\), rotation \((\theta)\) and slope \((\%)\) can be changed for any of the stored tunnel shapes and circumferences.

(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

This data was then processed by Geneva Geo Energy to create a Limestone rockhead depth map covering the FCC study area. GGE cautioned that due to interpolation over large distances, local inaccuracies of up to ±50m are possible.
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.
• feasible positions for large span caverns (most challenging structures)
• experimental Site at Point A on existing CERN land.
FCC Civil engineering overview

**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 1.5km 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)
Cost and Schedule Study

2016 - **Call for tender**: launched for full cost and schedule estimate orders worth approximately 200kCHF: Study separated into Phases 1, 2 & 3 with the intention of having 2 sets of consultants for phases 1 & 2 for comparison purposes.

**Phase 1**
Cost & Schedule estimate for “baseline” single tunnel design.

**Phase 2**
Cost & Schedule implications of variations considered:
- Double tunnel design
- Shallow option
- Alternative tunnel diameters
- Alternative shaft diameters
- Alternative cavern dimensions
- ee machine requirements
- Alternative schedule + Inclined access tunnels

**Phase 3**
Refinement of results from Phases 1 and 2:
- Review to include updates made to baselined design.
- Incorporate desirable variations from Phase 2.

- **ILF** and **Geoconsult + Synaxis** selected for Phases 1&2 of the study.
- **ILF** retained for phase 3 due to more robust methods and results from Phase 1&2.
- Phases 1 to 3 took approximately 1.5yrs
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
Construction Strategy

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

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

**Project divided in 12 construction lots**

**Intermediate Access Adits**
- Necessary to cope with overall time schedule to meet deadlines for machine installation

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

**Mixshield/Slurry TBM used for tunneling under Lake Geneva**
At the moment, ‘double shield’ TBM’s have been proposed for FCC, except for in Moraines under the lake (Slurry TBM)
(For LEP and LHC works ‘Gripper’ and ‘Double shield’ TBM’s were deployed)
Construction Schedule

Sector L-A-B: 4.5 years

Sector D-E-F: 6.5 years
FCC pre-construction planning

Next step: Site Investigations

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<th>Civil engineering FCC pre-construction schedule</th>
<th>2019</th>
<th>2020</th>
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Definition of ‘high risk areas’ for the preferred scenario(s)

- Input into footprint exploration – Civil Engineering Risks Assessment of the preferred scenarios
- 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
- Technical Specifications to define the Scope of Services for the JV and cost estimate and schedule of the JV deliverables

- Information near to CERN is strong due to previous experience on LEP/LHC.
- Multiple deep boreholes in the area.

- Alignment close to limestone rockhead
- The exact location and angle of the limestone/molasse interface undefined.

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

- Limestone formation known, but characteristics and locations of karsts unknown.

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

- Location of the interface between molasse and molasse subalpine not certain, tunnel alignment in proximity.

- Moraine/molasse interface not certain, cavern close to interface.
- Lack of deep boreholes in area.

- No deep borehole information available in the area.
- Complex faulted region.
- Quality of molasse is uncertain. Large span experimental caverns should be constructed in good molasse.
- Molasse/limestone interface not certain.
Current tools, software and central database

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

Tunnel Optimisation Tool
- J. Osborne, A. Tudora

FCC-GIS Web App
- M. Jones

3D geological modelling
- UNIGE
- A.-L. Verdier et al.

Central, unique data repository
- Future External Consultants Software
  - J. Gutleber, V. Mertens

Survey high precision calculations
- FCC-GIS Web App
- A.-L. Verdier et al.

Transfer line calculations
- Petrel
- Y. Robert

Future External Consultants Software
- J. Gutleber, V. Mertens

High precision calculations
- FCC-GIS Web App
- A.-L. Verdier et al.

3D geological modelling
- UNIGE
- A.-L. Verdier et al.
Main Objectives

- Understand the local impact of the regional tectonic activity
- Monitoring low-level seismicity
- Proposed the monitoring of the Vuache fault which is the best candidate for the generation of seismic and aseismic activity in the area
- Investigate the micro-structure of faults
- Following advancements of tunnel works
- GPS network installation could be coordinated with FCC activities for the future geodetic network

Legend:
White stars – proposed seismic stations
Blue circles – Proposed GPS locations (2 GPS already installed in Satigny)
Conclusions and Overall Summary

- CERN has valuable experience on siting of physics projects, e.g. LHC, CLIC, ILC, Muon Collider
- 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;
- 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.
Thank you for your attention!

Any Questions?