FCC Civil Engineering Optimisation and Design Development

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With acknowledgements to I&O and all FCC study teams

Outline

- Brief history of previous layouts and positions
- Layout & siting progress since Rome 2016
- Design development of structures
- Cost & Schedule study
- Future steps

Brief History of Previous Layouts and Positions

- European Strategy, Krakow 2012: 80km Options

During pre-feasibility an 80 km layout was considered with 2 distinct positions: Jura mountains v lakeside

- Kick-off meeting, Geneva 2014

The two 80 km options were reviewed in addition to a 47 km option.

- Washington 2015: Multiples of LHC Considered in 80 km, 87 km , 93 km, 100 km

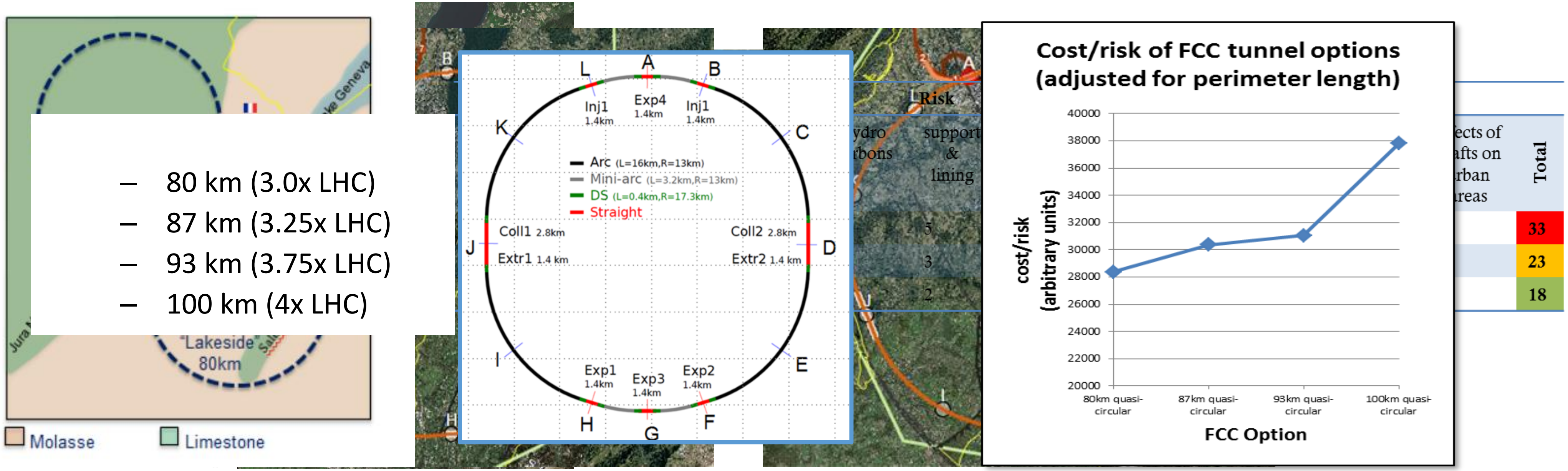
In addition to the 80 km option, other multiples of the LHC were considered: 87 km, 93 km, 100 km.

- Rome 2016: Intersecting v non-intersecting 100 km options considered

- August 2016: 97.75 km options introduced in comparison to Intersecting option (V1)

A variety of options were considered to identify the optimal layout for the machine whilst fitting within the geological constraints.

- 80 km (3.0x LHC)
- 87 km (3.25x LHC)
- 93 km (3.75x LHC)
- 100 km (4x LHC)



Comparison Criteria

1. Geology along alignment:

- Maximum proportion of tunnel in molasse.
- Avoid limestone formations wherever possible due to associate risk of water ingress and karsts.
- Avoid water bearing moraines wherever possible due to risk of water ingress and potential contamination of water sources.
- Minimise overburden.

2. Shaft length:

- Minimise total shaft length.
- Avoid individual very deep shafts, particularly at experimental points where there are multiple shafts.

3. Geology of shafts and caverns

- The greater the depth of the moraine before reaching the molasse layer, the more costly/ time consuming the construction.
- Cavern construction requires good ground conditions.

4. Environmental Constraints

- Avoid protected water sources.

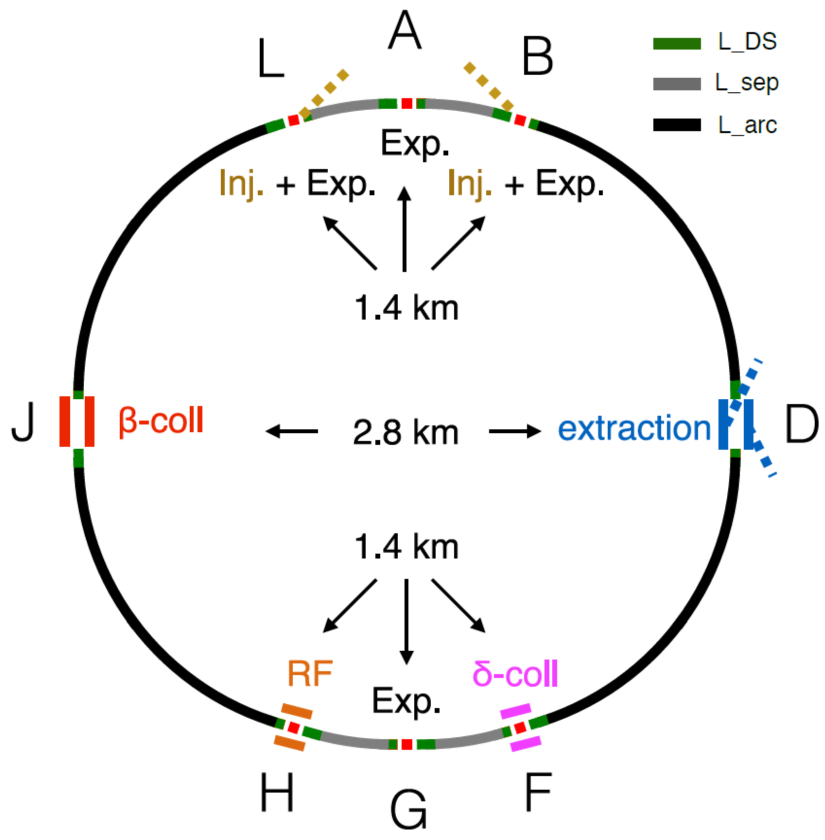
5. Shaft Surface Locations

- Initial assessment to avoid clashes with buildings, natural features or protected zones.
- Followed by a more refined assessment of feasibility including potential access to the site.

6. Injection Line Length

+ Additional 'softer criteria'

- The round of optimisation undertaken in August 2016 led to the selection of the current 97.75 km layout.
- In early 2017 small variations on this layout were assessed that incorporated increased L_sep.



- Reduced straight sections at points J & D enabled the tunnel to fit between Jura and Pre-Alps limestone.
- Introduced potential for significant shaft depth savings.

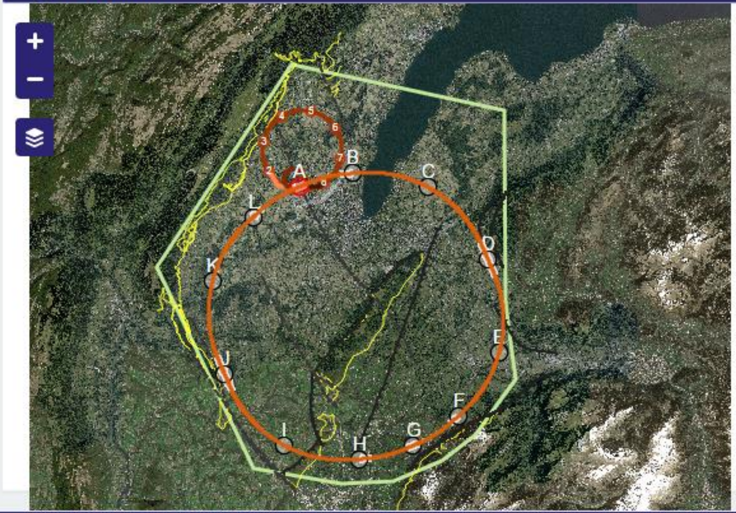
Selected Baseline – Berlin97.75

Alignment | Shafts | Query

Highlights:

- Avoids Jura and Pre-Alps limestone.
- Only one sector containing limestone.
- Significantly reduced total shaft length.
- Experimental Site at Point A on existing CERN land.
- Avoids extremely large overburden.

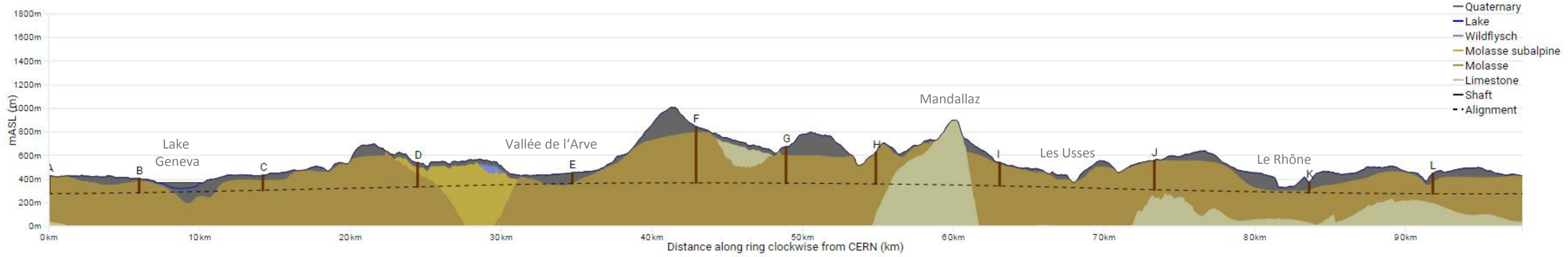
Alignment Location



Geology Intersected by Shafts | Shaft Depths

Point	Shaft Depth (m) Actual	Molasse SA	Wildflysch	Quaternary	Geology (m) Molasse	Urgonian	Limestone
A	152	0	0	0	152	0	0
B	121	0	0	26	95	0	0
C	127	0	0	44	83	0	0
D	205	66	0	40	100	0	0
E	89	0	0	89	0	0	0
F	476	0	0	49	427	0	0
G	307	0	0	73	234	0	0
H	266	0	0	0	266	0	0
I	198	0	0	11	187	0	0
J	248	0	0	1	247	0	0
K	88	0	0	70	18	0	0
L	172	0	0	89	83	0	0
Total	2449	66	0	492	1892	0	0

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

Key Issues and Possible Solutions – Berlin97.75

Issue: Tunnel excavation through water bearing moraines

Possible Solutions:

a) Excavation using a multi-mode earth pressure balanced TBM.

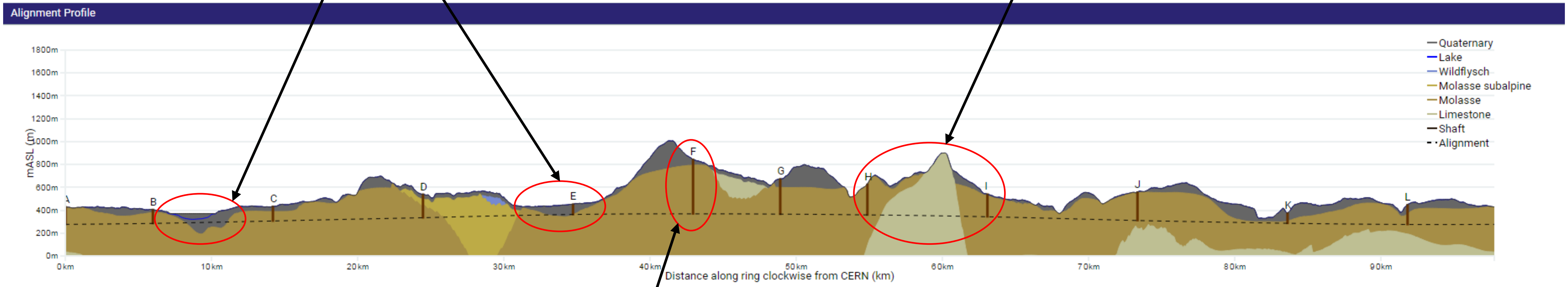
b) Employ a double-lining method for waterproofing.

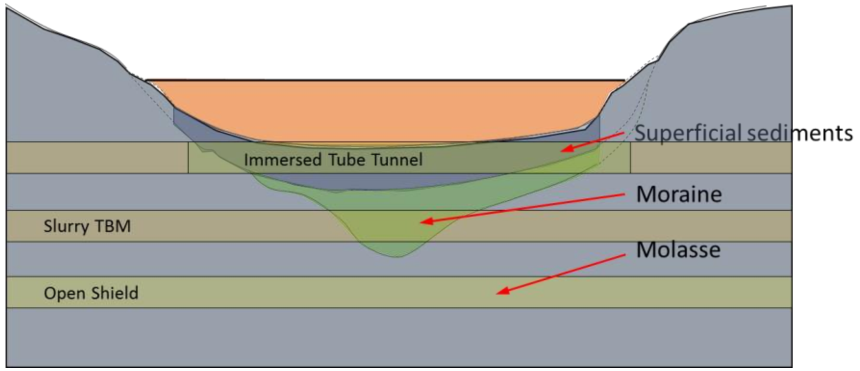
Issue: Unavoidable Mandallaz Limestone formation

Possible Solutions:

a) Drill & Blast excavation method

b) Systematic exploration ahead of excavation





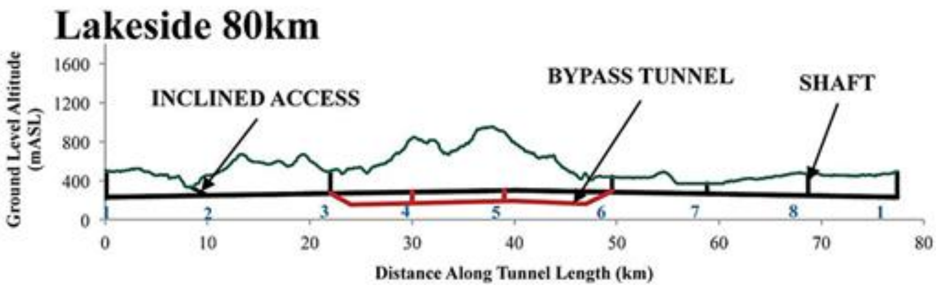
Issue: Exceptionally deep shaft at point F

Possible Solutions:

a) Remove shaft

b) Replace with a shaft of a smaller diameter

c) Replace with an inclined access tunnel



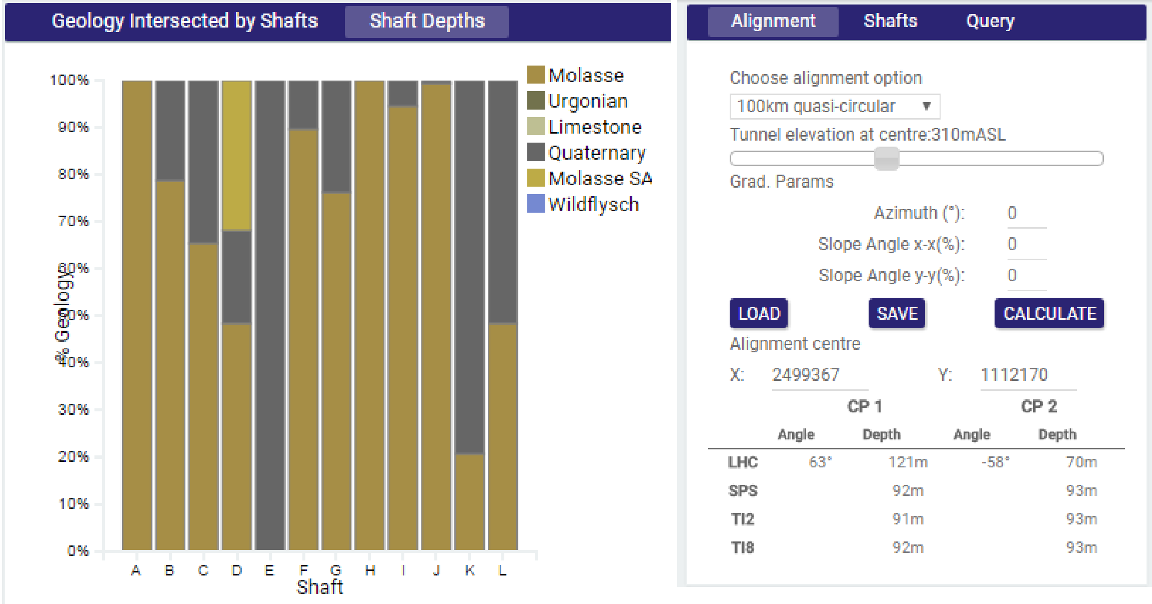
TOT capabilities & Limitations

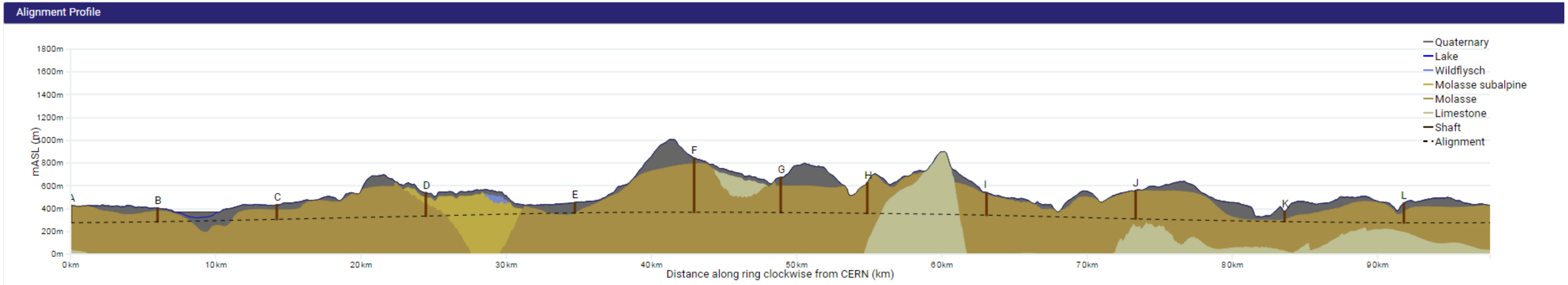
- TOT is a bespoke, web-based geological tool.

- Datasets imbedded:
  - Interpreted geological data, simplified to major types of geology.
  - Topography
  - Hydrological Information
  - Protected areas
  - Existing Boreholes and Geothermal farms

- <u>Very powerful tool for early stage feasibility</u>
  - Quickly assess different layout options.
  - Clear visual outputs for communicating results

ARUP

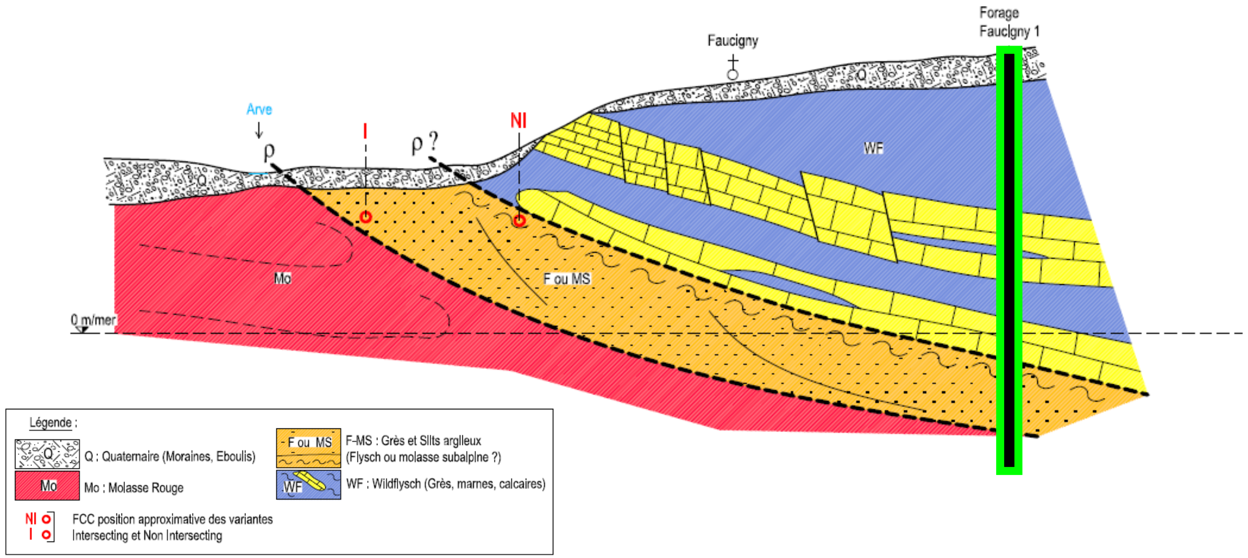


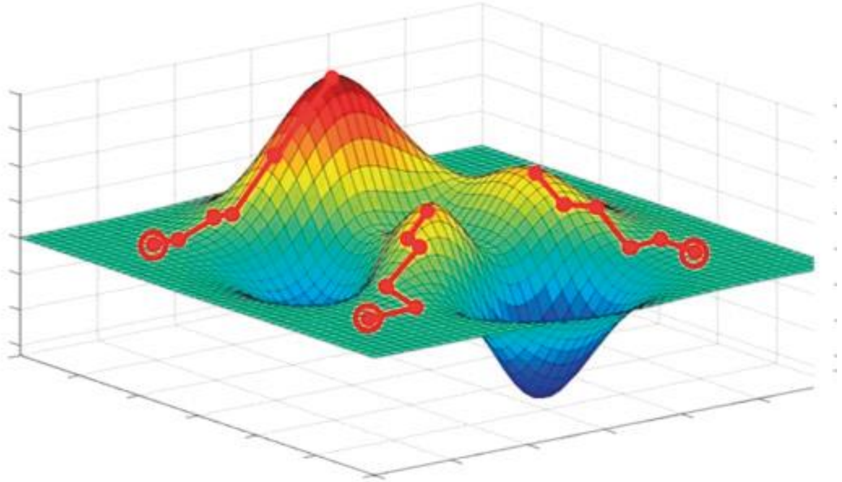


TOT capabilities & Limitations

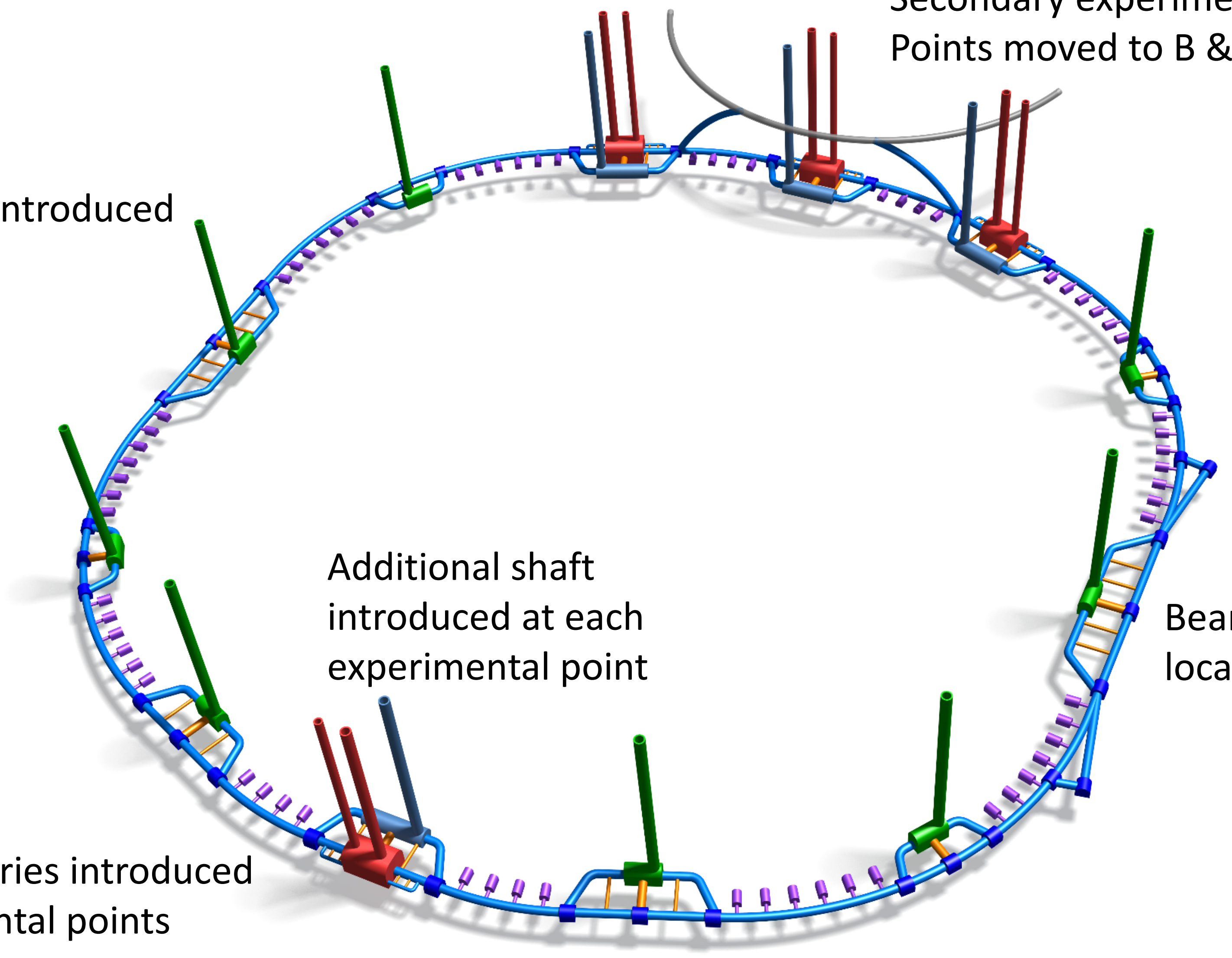
- TOT is only as powerful as the data behind it.
  - Topographical data is very accurate
  - Certain areas of geological data more accurate than others.
  - Interpreted data from existing maps and boreholes.
  - Site Investigation is required to significantly improve understanding.

- Automation of the tool is a possibility but challenging.
  - Optimisation algorithm such as ROXIE (previously used at CERN for magnet design optimisation) could be used.
  - The challenge is the large number of variables.
  - Not all variables are easily quantified.
  - Potential for automating certain features such as shaft positions once the layout and siting are fixed.





Underground Schematic



Secondary experimental Points moved to B & L

Electrical alcoves introduced at 1.5 km spacing

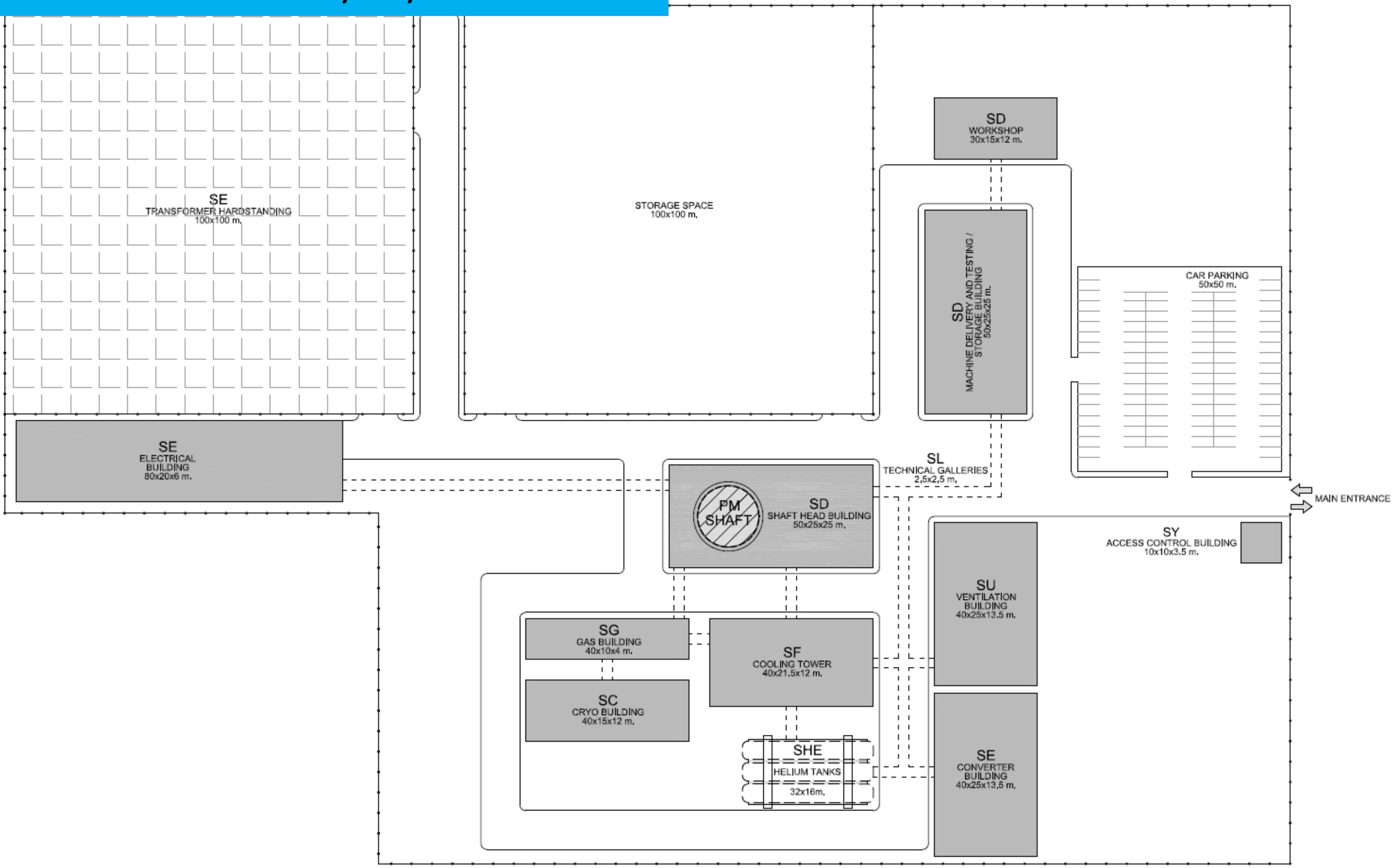
Additional shaft introduced at each experimental point

Beam Dumps both located at Point D

Survey Galleries introduced at experimental points

Surface – Initial Concept

Preliminary Layout



Concept for non-experimental point

- Concept based on LHC and Hi-Lumi reference structures.
- Some scaling where deemed appropriate.

Cost and Schedule Study

- Cost & Schedule Study launched in September 2016
- Two sets of consultants engaged to work independently.

ILF CONSULTING ENGINEERS

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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

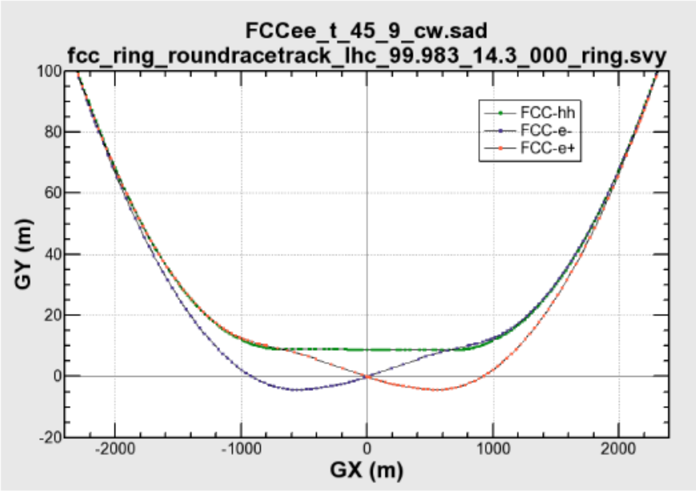
Phase 3

Refinement of results from Phases 1 and 2:

- Review to include updates made to baselined design.
- Incorporate desirable variations from Phase 2.

*Some changes have been made since the study was launched including raising the profile and introduction of third shaft at experimental points.

- Tunnel widening required around points A & G to accommodate ee lattice.
- Design is not fully developed: potential for a combination of double tunnel and enlargement caverns to accommodate lattice.
- For Cost & Schedule study: 1.8 km of tunnel widening on either side of IPs at A and G considered.



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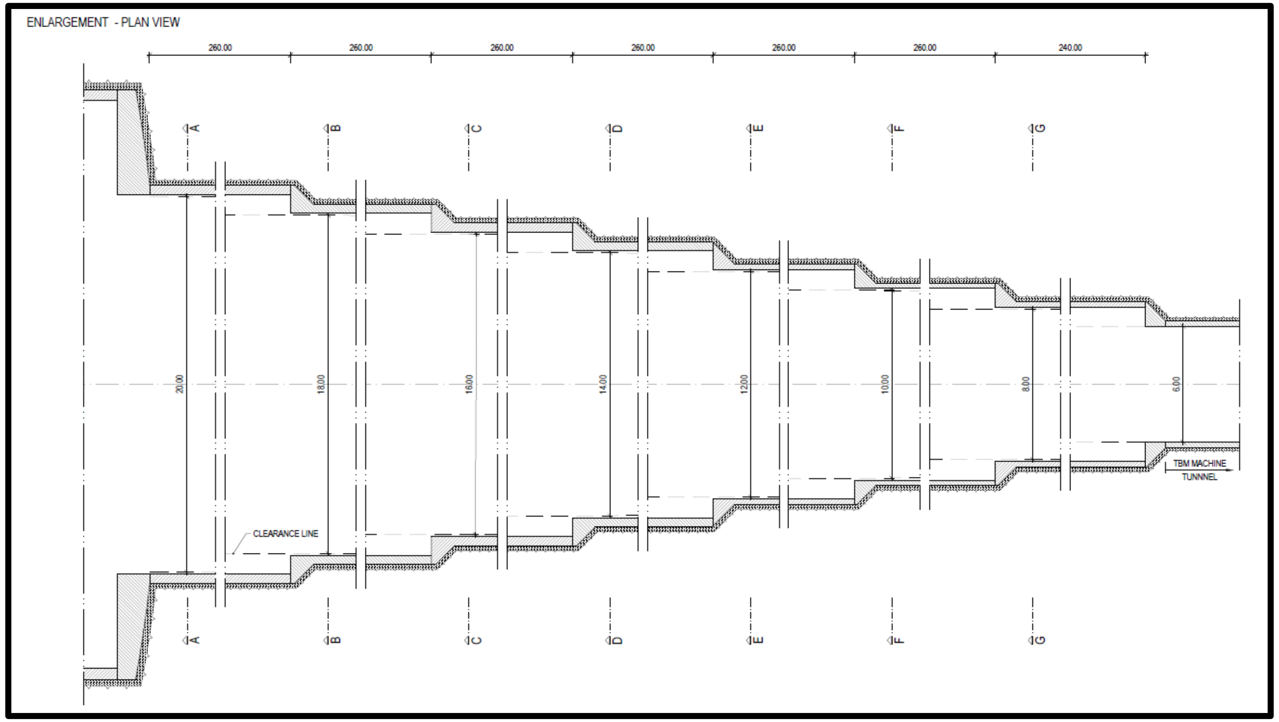
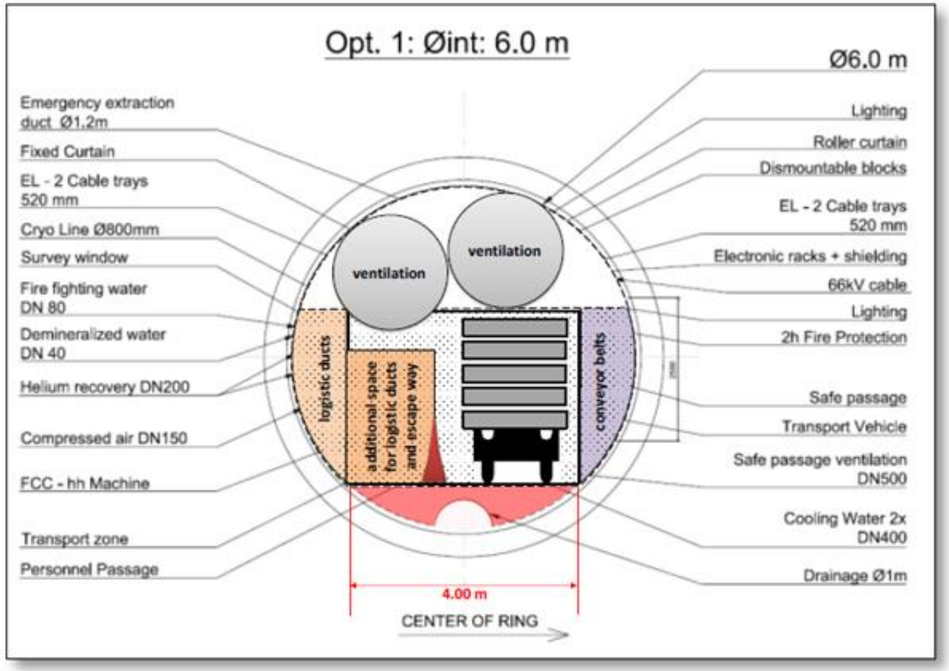
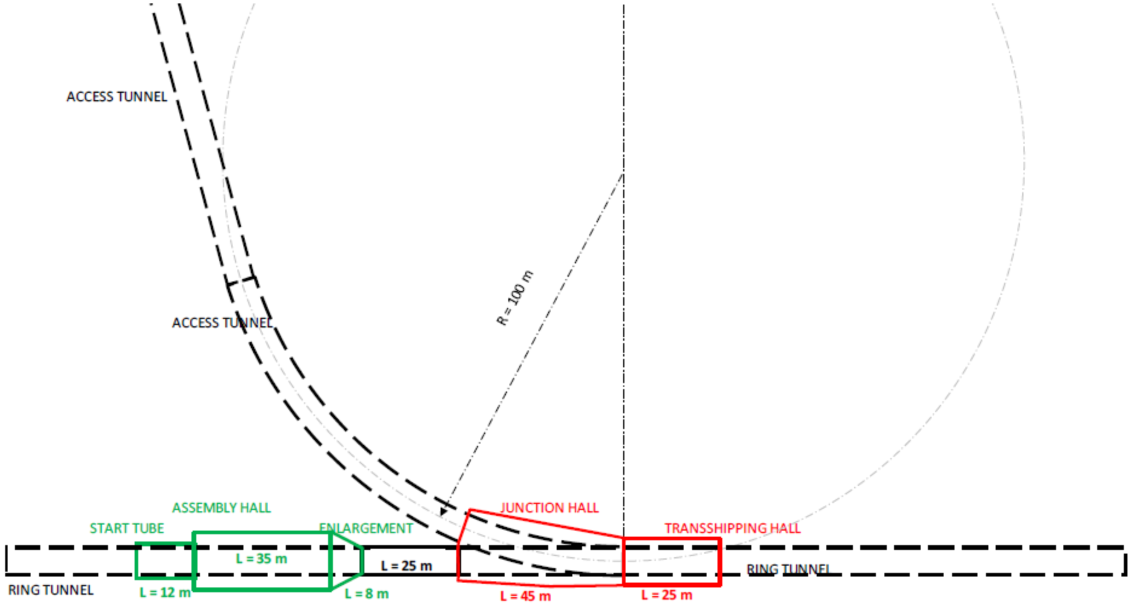


Inclined Access Study

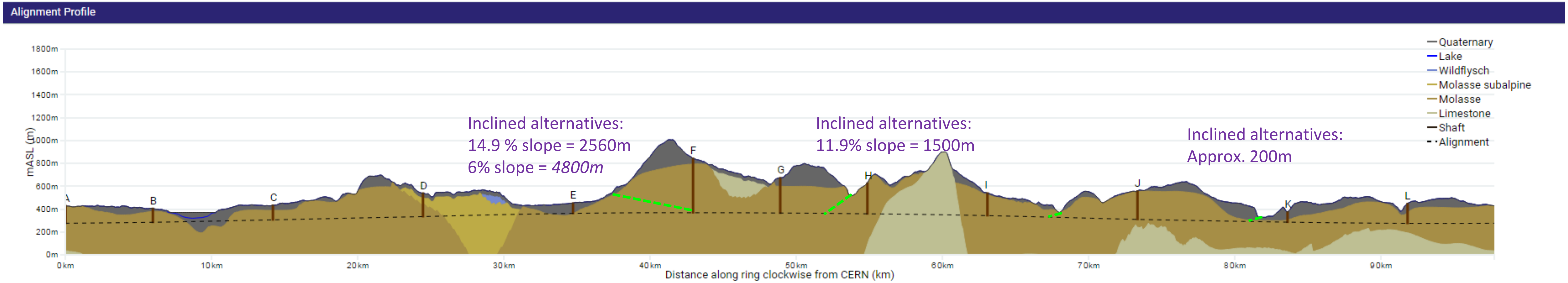
- Study launched with Amberg Engineering following FCC week 2016 to verify feasibility of inclined access tunnels.
- Main questions:
  - Can a shaft be replaced with a 6.0 m diameter tunnel and a TBM be launched from the bottom?
  - What is the estimate for possible time saving?





- Feasibility of logistics confirmed.
- Confirmed that some time reductions are possible – construction of inclined access can start during procurement of TBM.

Possible Inclined Access Tunnel Locations

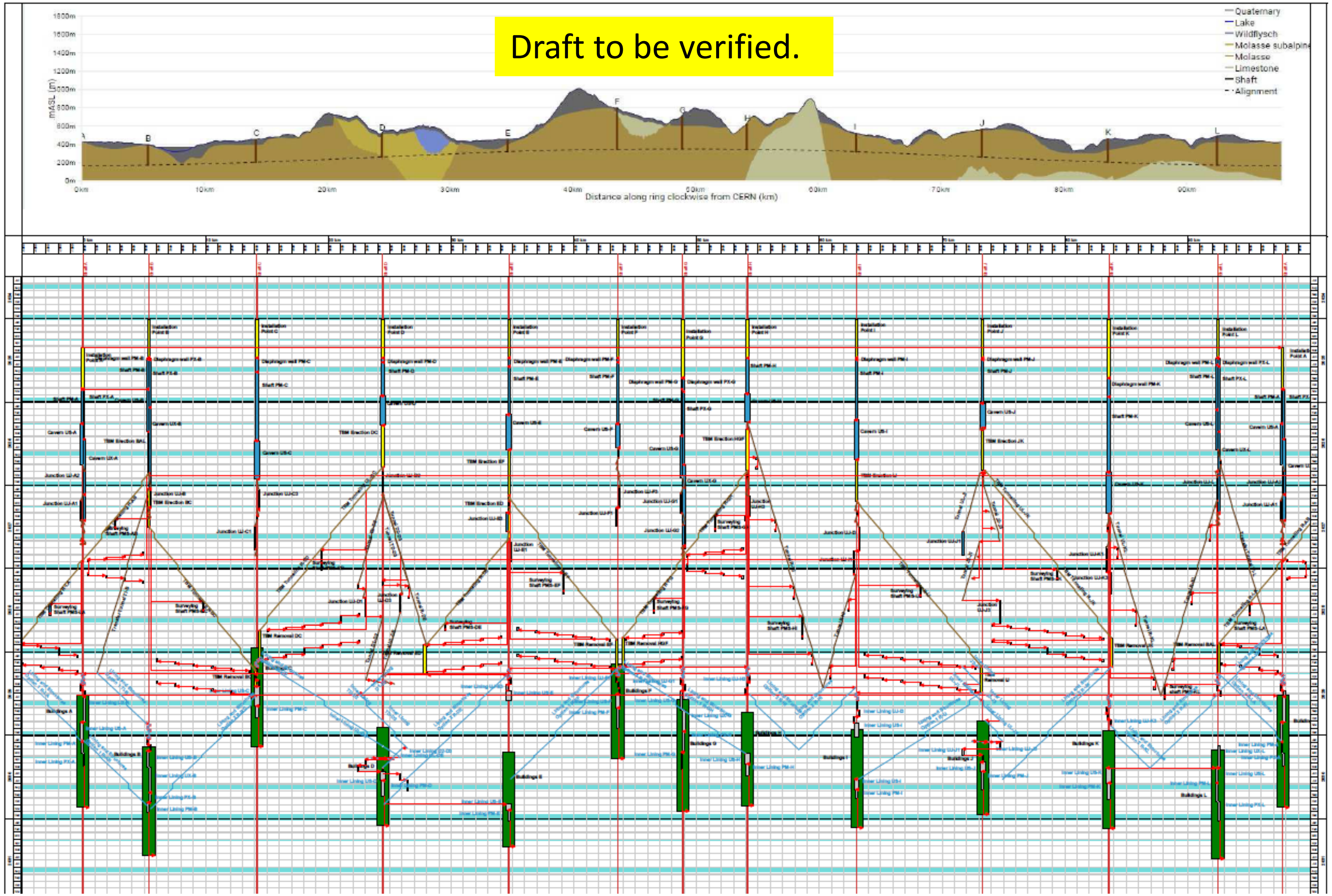


1) Replacing shafts with inclined access tunnels:
   - Shaft F

2) Inclined access between shafts to accelerate program:
   - Option a: between I & J and J & K
   - Option b: between G & H

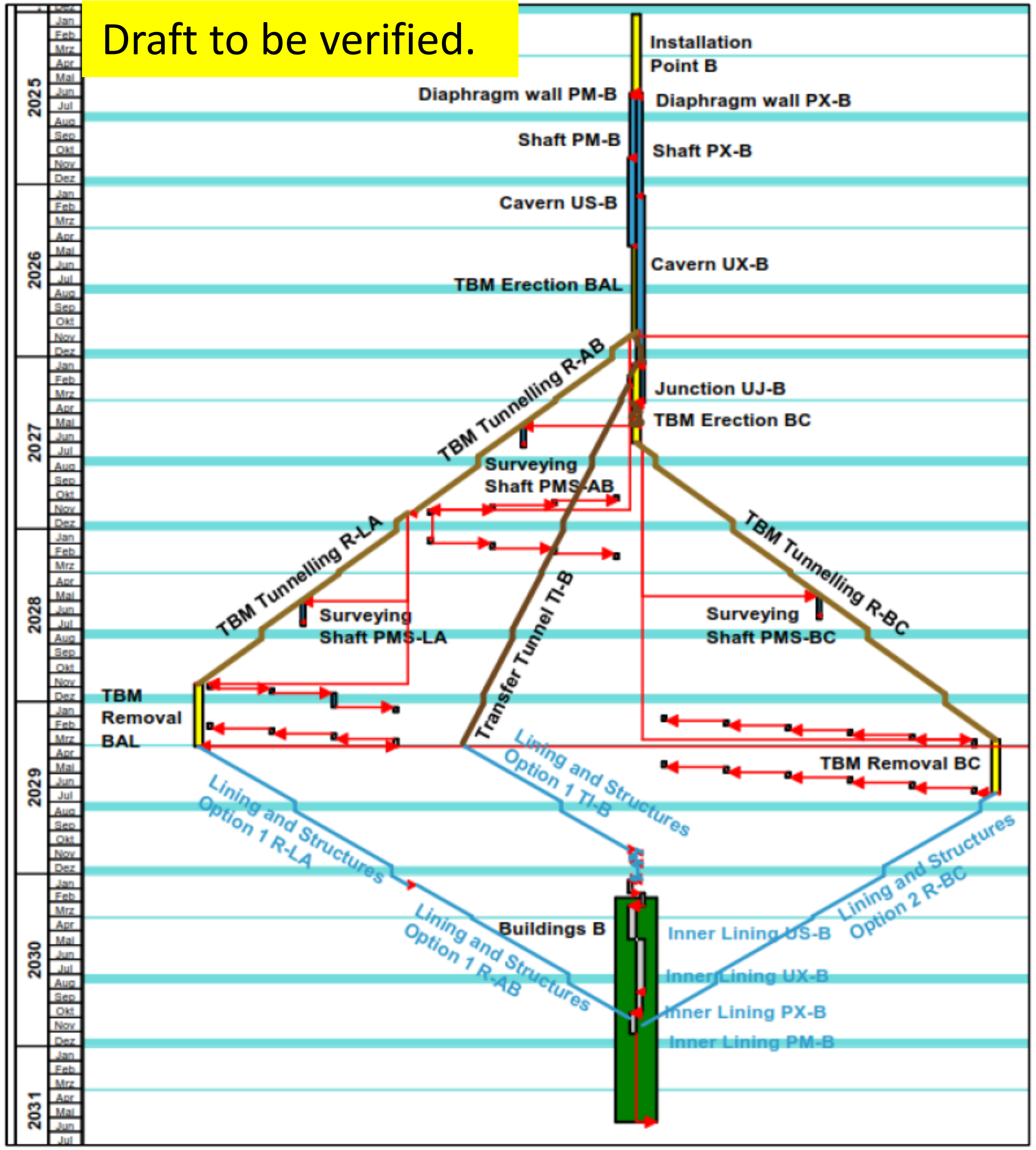
Option b is favourable as it is desirable for the installation schedule for 2 of the shorter sectors to be delivered first.

Early schedule results – Baseline

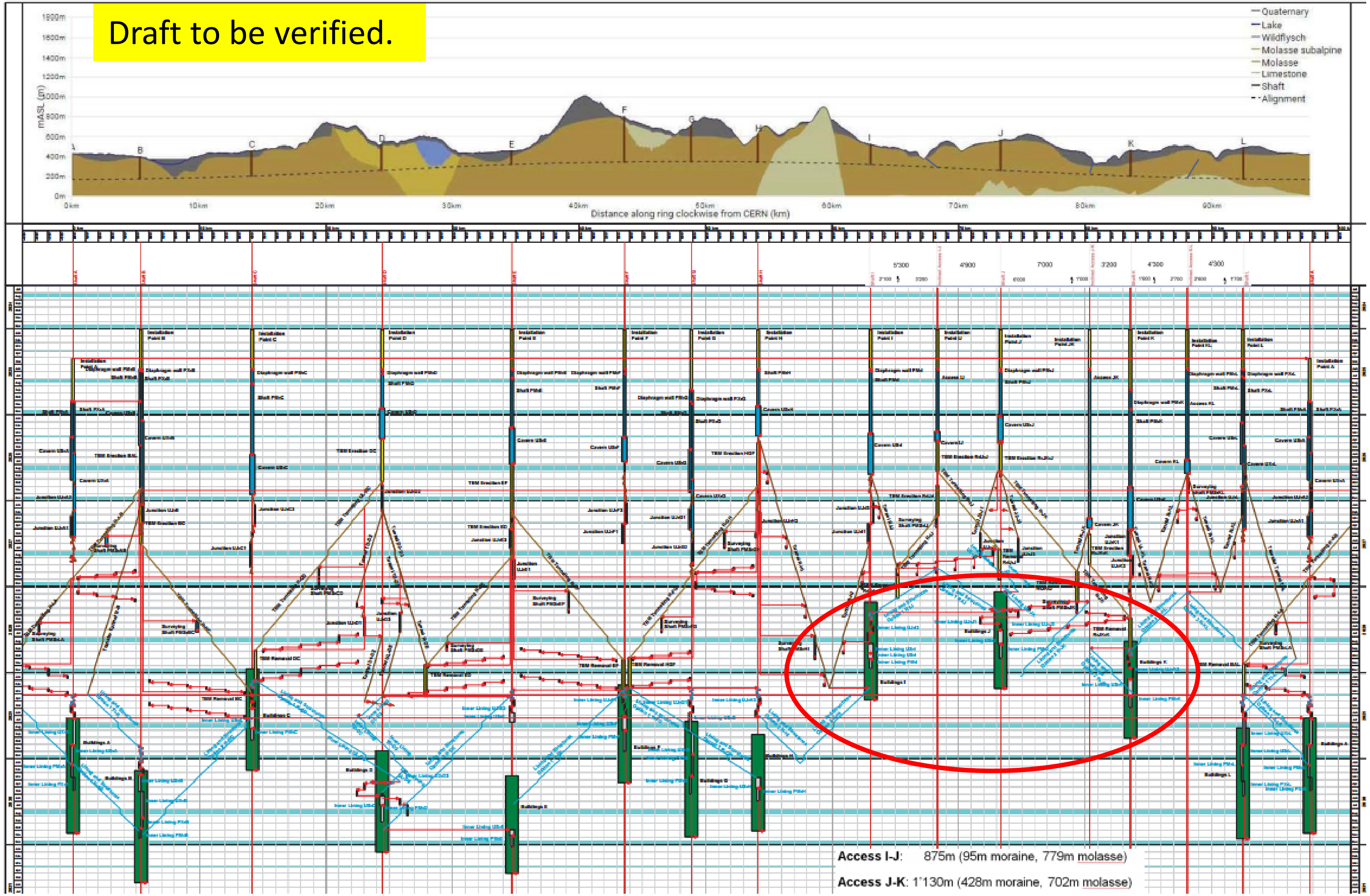


Construction complete in 6 years, 5 months.

Early schedule results – Baseline

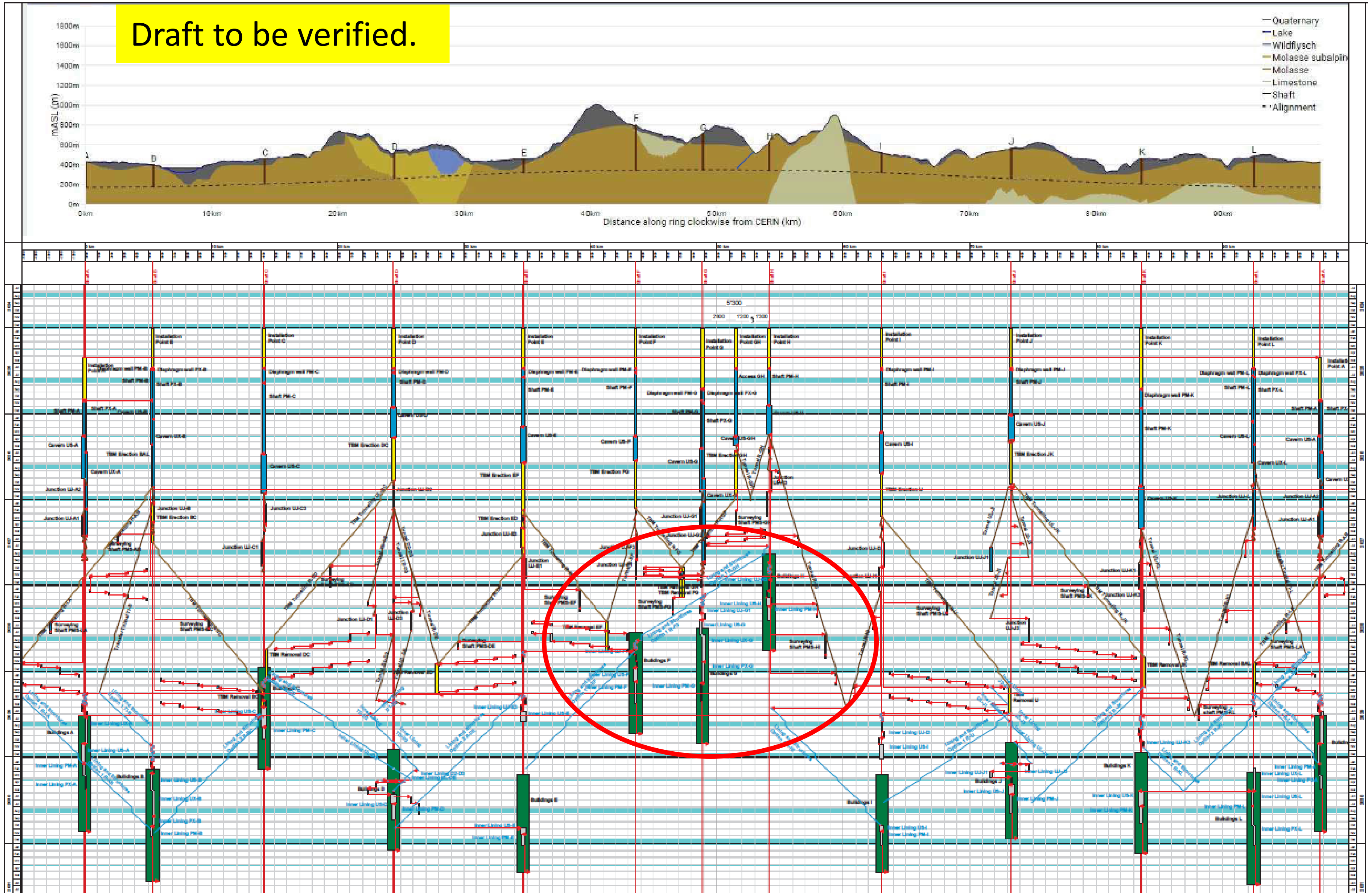


- Construction commences with site installation and diaphragm wall construction.
- PM-B excavated first followed by US-B, TBM launched from this cavern for sectors R-AB and R-LA.
- PX-B and UX-B excavated in parallel but have a longer duration due to their larger dimensions.
- Second TBM launched following completion of both caverns.
- Transfer tunnel excavated using Drill & Blast or roadheader.
- Alcoves excavated behind tunnel excavation front and lined during TBM removal.
- Lining of tunnels and caverns completes underground construction.



- First two sectors complete in 4 years, 8 months.
- Construction complete in 6 years, 5 months.

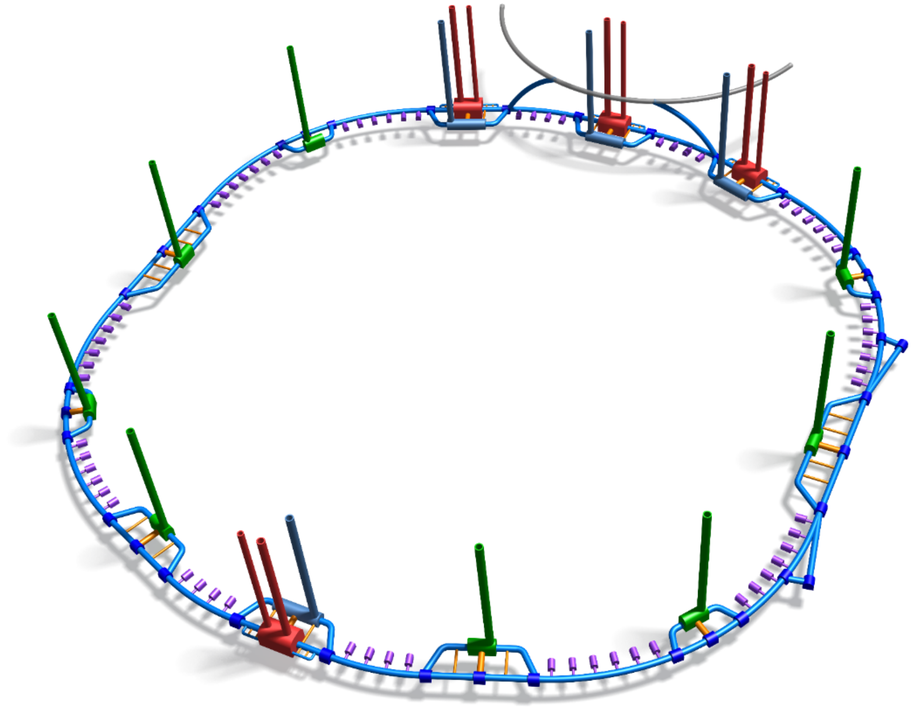
Early schedule results – Accelerated schedule (2)

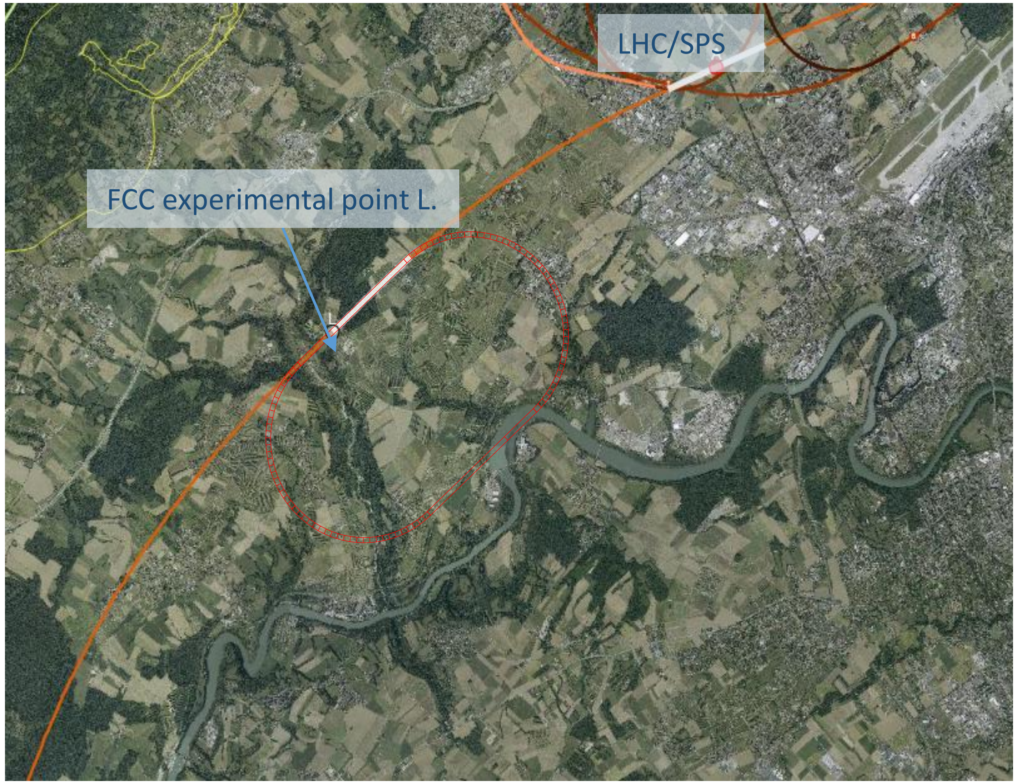


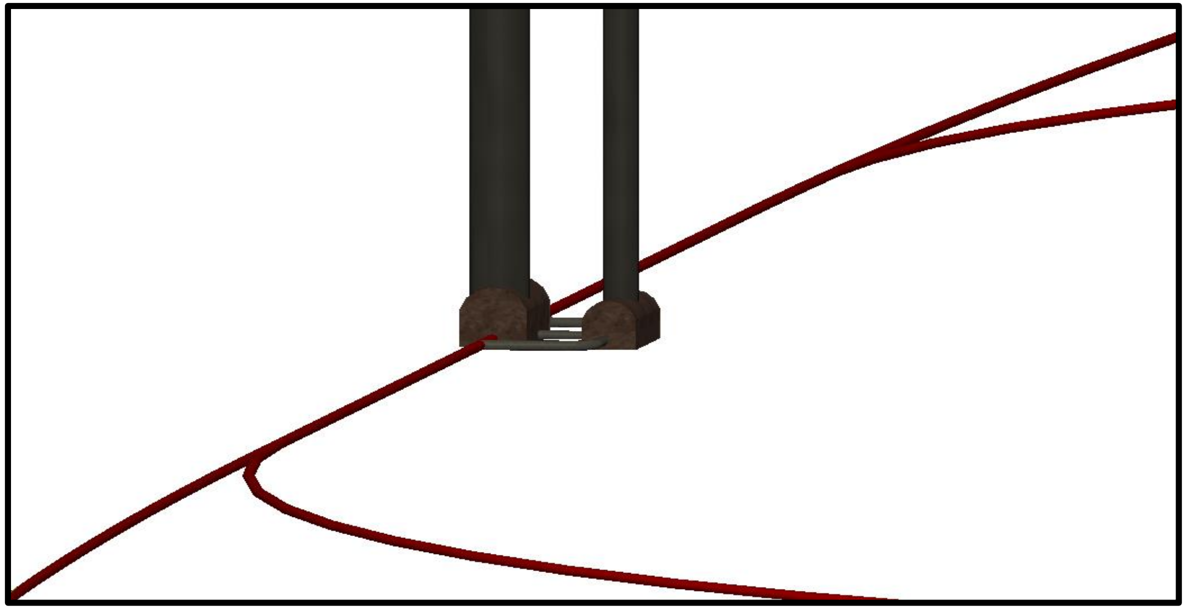
- First two sectors complete in 4 years, 11 months.
- Construction complete in 6 years, 5 months.

Future steps for Cost & Schedule study

- Work to refine a cost estimate to an accuracy of +/- 30%.
- Design updates to be incorporated into Phase 3:
  - Additional shaft at each experimental point.
  - New layout and position.
  - New cross-section.
- Fix inclined access positions and incorporate results into study.
- More closely study the schedule implications of the connection to the LHC or SPS.
- Scope for optimising the whole schedule once design and schedule constraints fixed.
- Iterative process of integrating the CE schedule into the full installation schedule.







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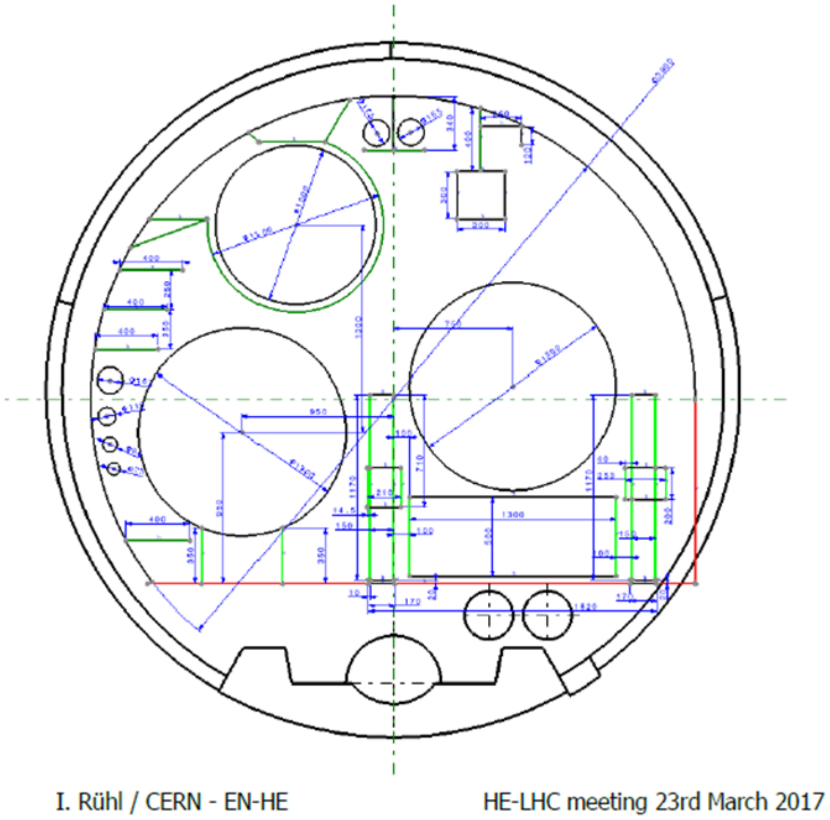

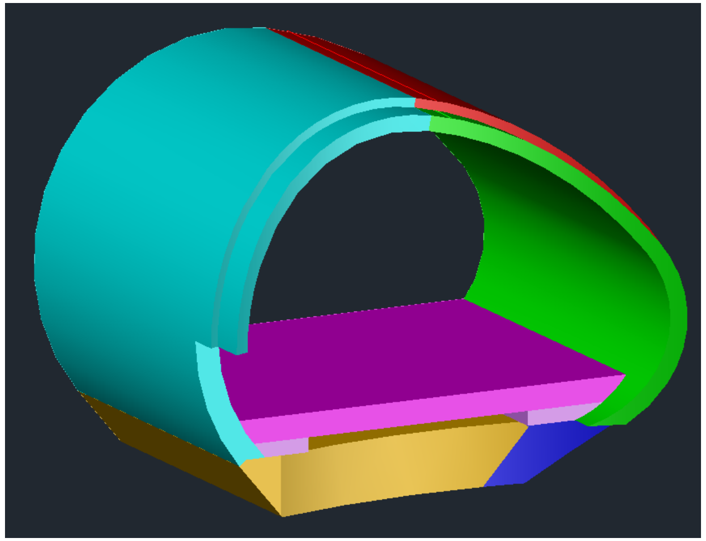

SPS beam dump tunnel enlargement

Crossrail – Cross Passage Temporary Frames

- If it is concluded High Energy LHC cannot fit into the current LHC envelope, a technical and cost and study will be launched to evaluate an option to enlarge the cross-section of the existing tunnel.

Future Steps

- Continue to evaluate new layout and position:
  - Confirm shaft and inclined access tunnel locations.
  - Evaluate the risk of construction in the moraines under the lake.
- Confirm civil engineering requirements for ee machine.
- Evaluate cavern and shaft construction methods.
- Develop TOT, potentially working towards automating some features.
- Environmental impact and spoil management study.
- Develop High Energy LHC and FCC-eh studies.
- Site investigation planning.

CERN