CIVIL ENGINEERING FOR THE FUTURE CIRCULAR COLLIDER

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Contents

FCC Overview and Status

CERN

15 January 2024

Michael Benedikt, CERN

on behalf of FCC collaboration & FCCIS DS team

http://cern.ch/fcc

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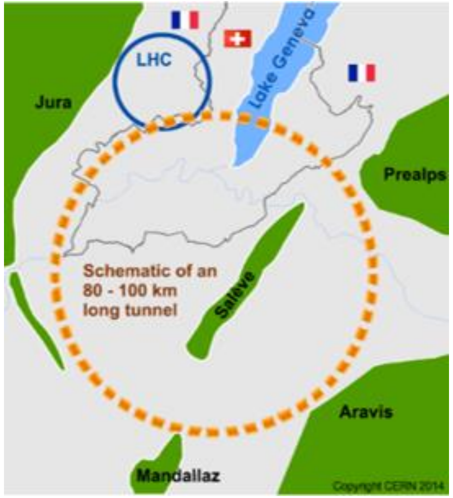
photo: J. Wenninger

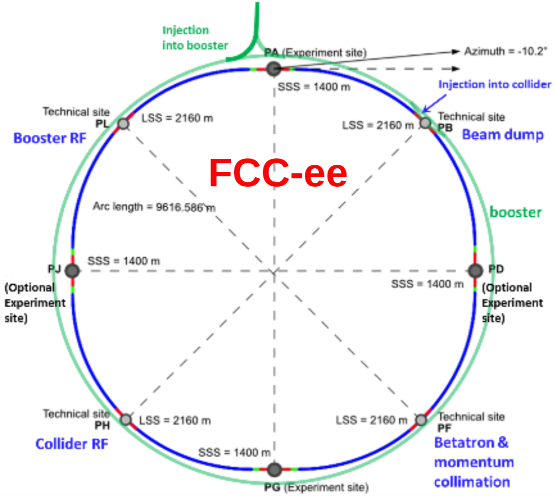
FUTURE CIRCULAR COLLIDER

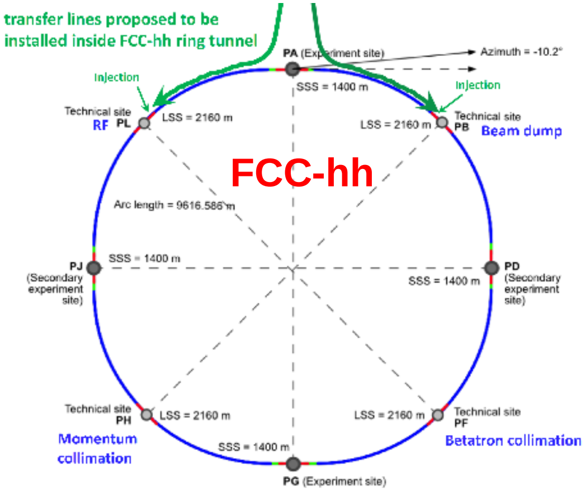
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



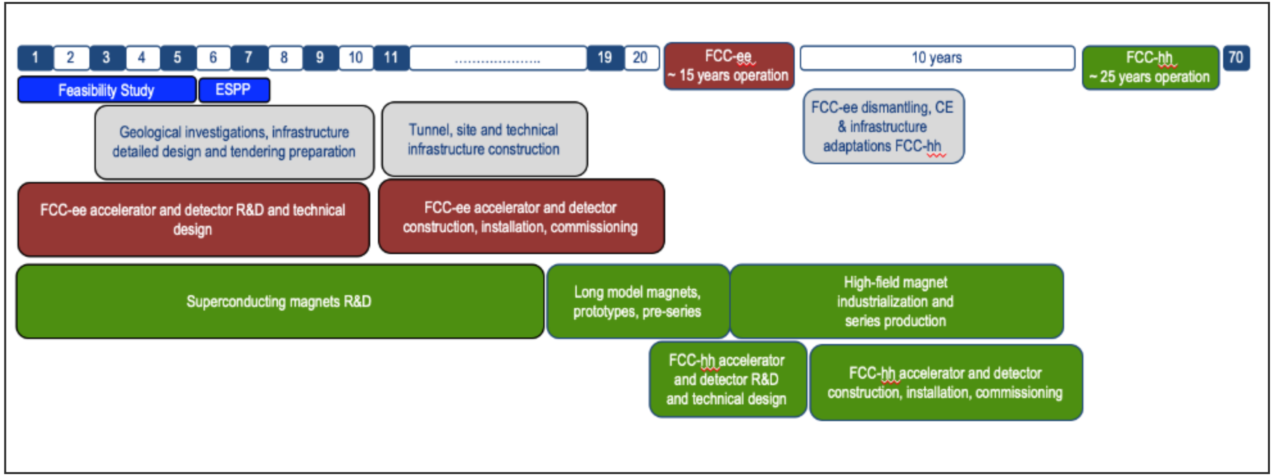




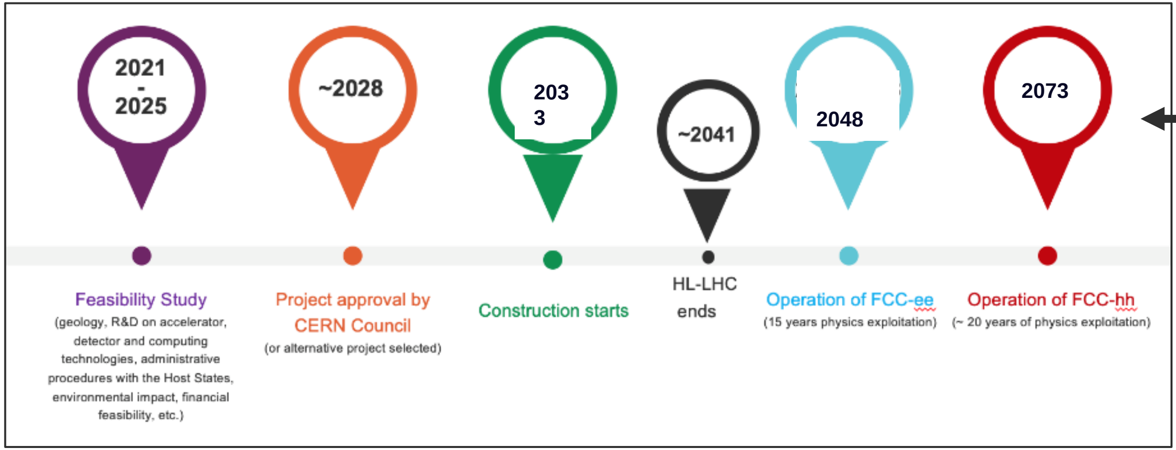
2020 - 2046 | **2048 - 2063** | **2073 -**

FCC integrated program - timeline

FUTURE CIRCULAR COLLIDER



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



Realistic schedule takes into account:
- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

FCC Feasibility Study 2021-2025: main objectives

- Demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of the placement and layout of the ring and related infrastructure.

- Pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval.

- Optimisation of the design of FCC-ee and FCC-hh colliders and their injector chains, supported by R&D to develop the needed key technologies.

- Elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency.

- Development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation.

- Identification of substantial resources from outside CERN's Budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee).

- Consolidation of the physics case and detector concepts and technologies for both colliders.

Objectives and deliverables presented to SPC and Council in June 2021:
https://indico.cern.ch/event/1038466/contributions/4386283/attachments/2259574/3834905/spc-e-1161-c-e-3588_FCC_MainDeliverables.pdf

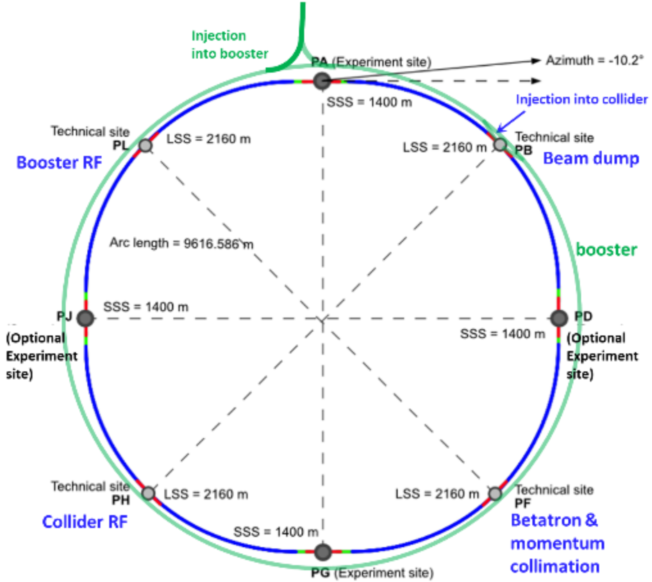
Feasibility Study funded from CERN budget: 100 MCHF total over 5 years; in addition: ~ 20 MCHF/year for high-field magnet R&D
Additional funding from the European Commission and collaborating institutes (e.g., CHART collaboration with Switzerland)

Optimized placement and layout for feasibility study

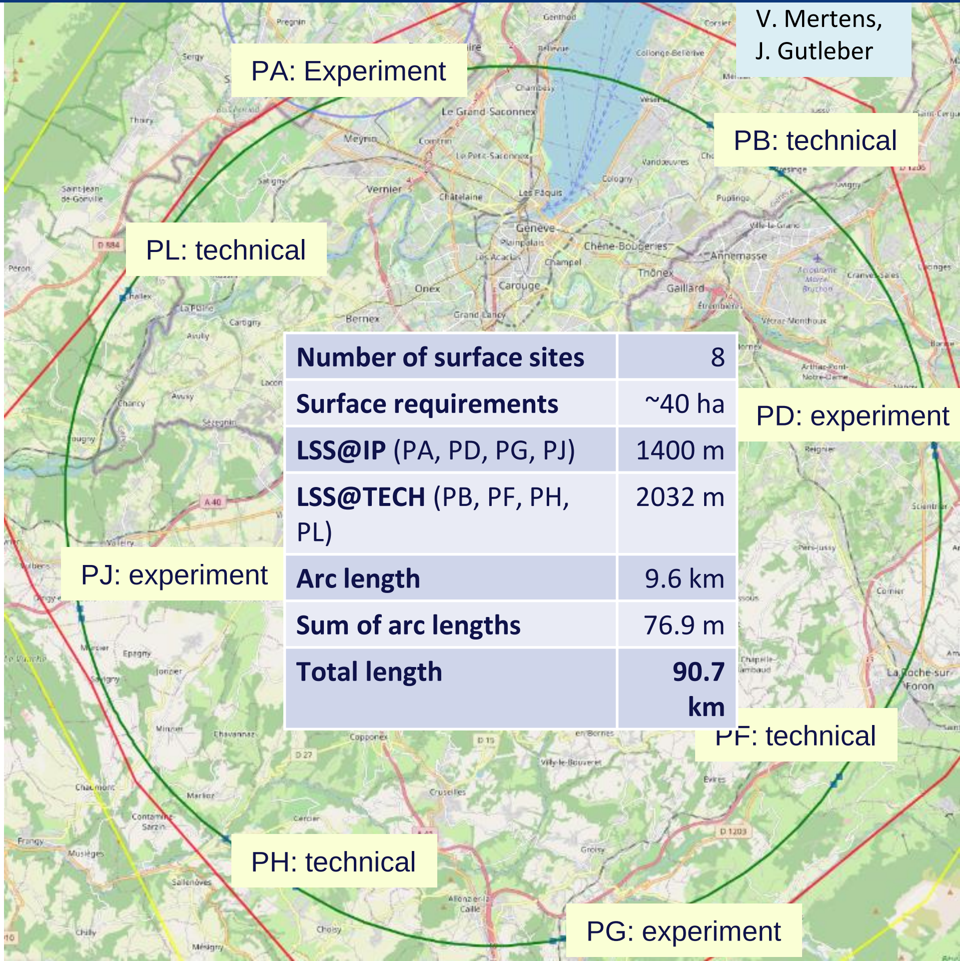
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce -compensate" principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement



V. Mertens, J. Gutleber



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

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progress with implementation baseline PA31 90.7 km

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – site experimental

PB – Présinge/Choulex (CH) – site technique

PD – Nangy (FR) – site experimental

PF – Roche sur Foron/Etaux (FR) – site technique

PG – Charvonnex/Groisy (FR) – site experimental

PH – Cercier (FR) – site technique

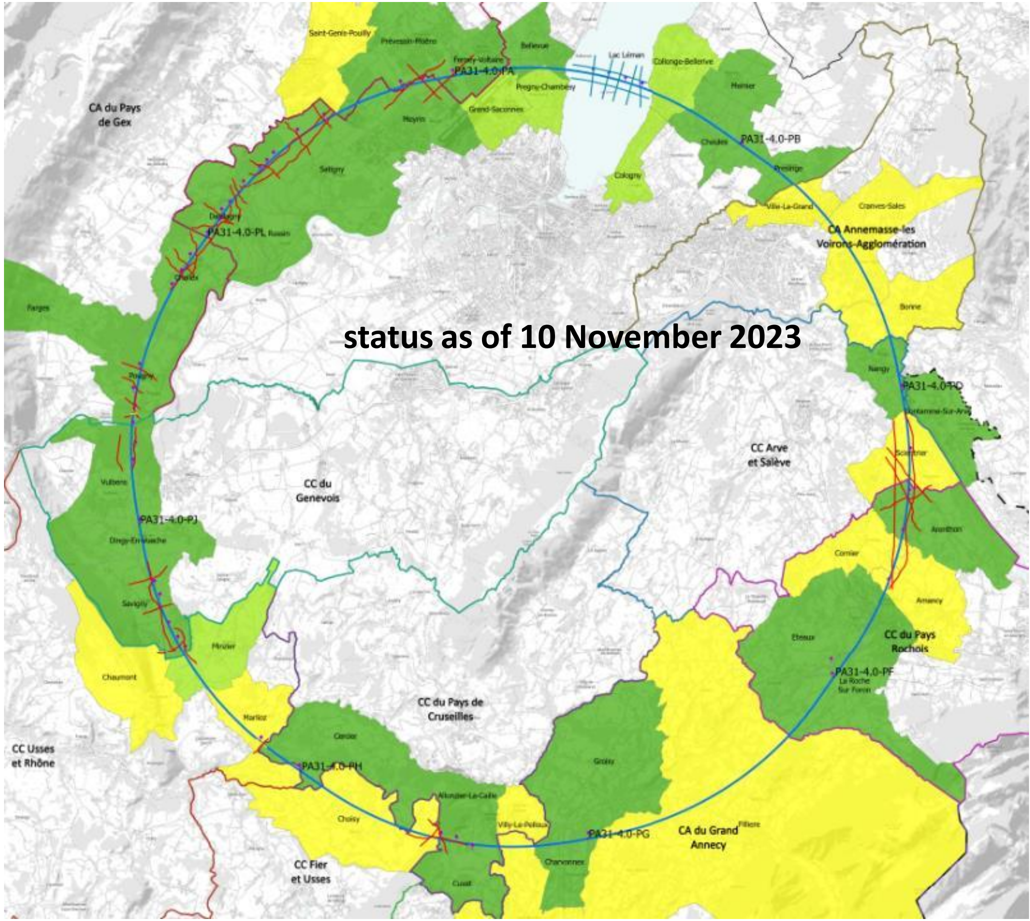
PJ – Vulbens/Dingy en Vuache (FR) site experimental

PL – Challex (FR) – site technique

Individual meeting

Individual meeting planned

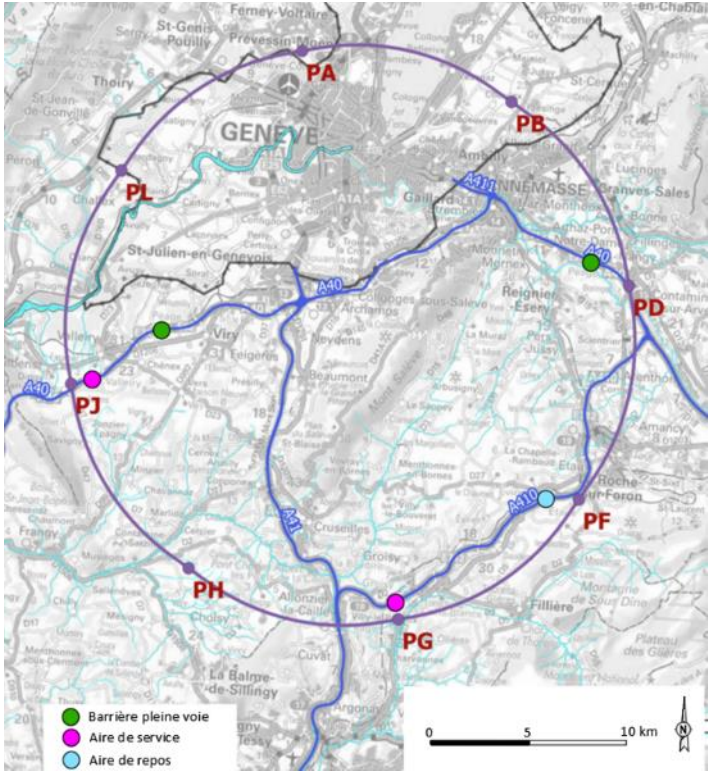
Collective meeting

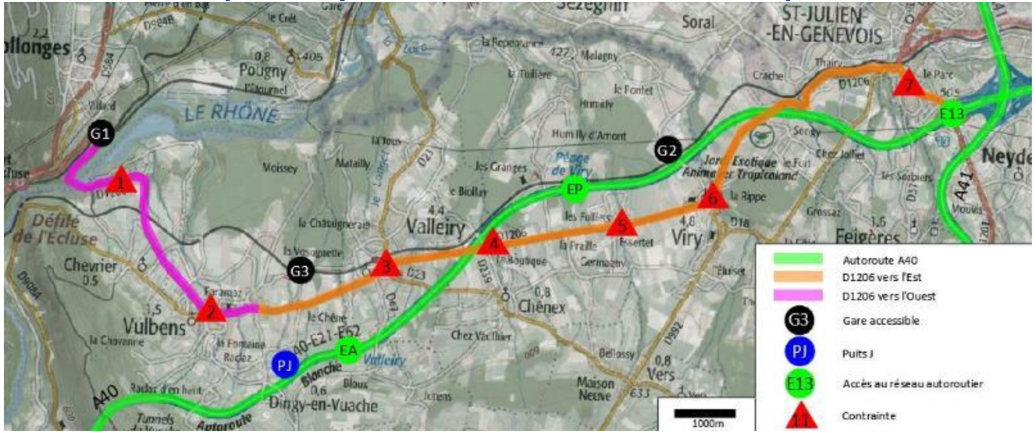


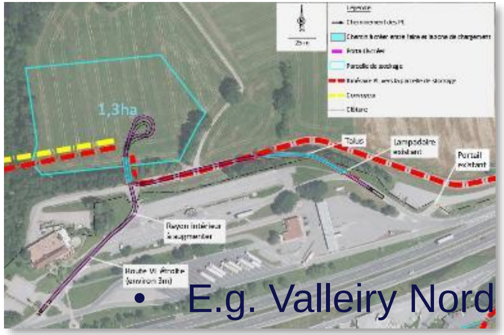
The support of the host states is greatly appreciated and essential for the study progress!

Connections to transport infrastructure

- Road accesses identified and documented for all 8 surface sites
- Four possible highway connections defined (materials transport)
- Total amount of new roads required < 4 km (at departmental road level)





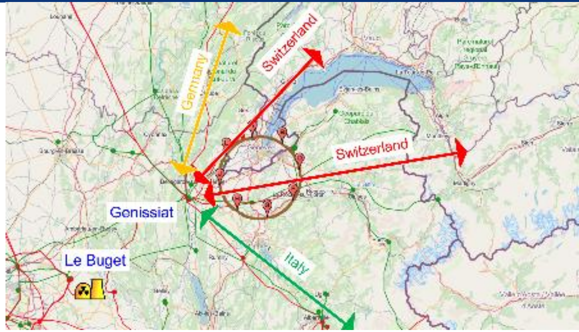


- E.g. Valleiry Nord

Detailed road access scenarios & highway access creation study **carried out by Cerema, including regulatory requirements in France**

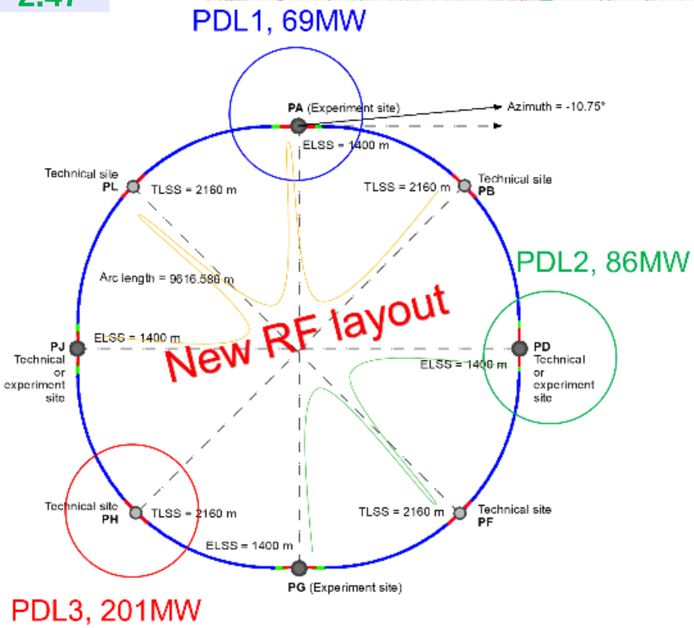
Connections to electrical grid infrastructure

Updated FCC-ee energy consumtion	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. Power during beam operation (MW)	222	247	273	357
Average power / year (MW)	122	138	152	202
Total FCC-ee yearly consumption (TWh)	**1.07**	**1.2**	**1.33**	**1.77**
Yearly consumption CERN & SPS (TWh)	0.70	0.70	0.70	0.70
Total yearly consumpt. CERN & SPS & FCC-ee (TWh)	**1.77**	**1.90**	**2.03**	**2.47**



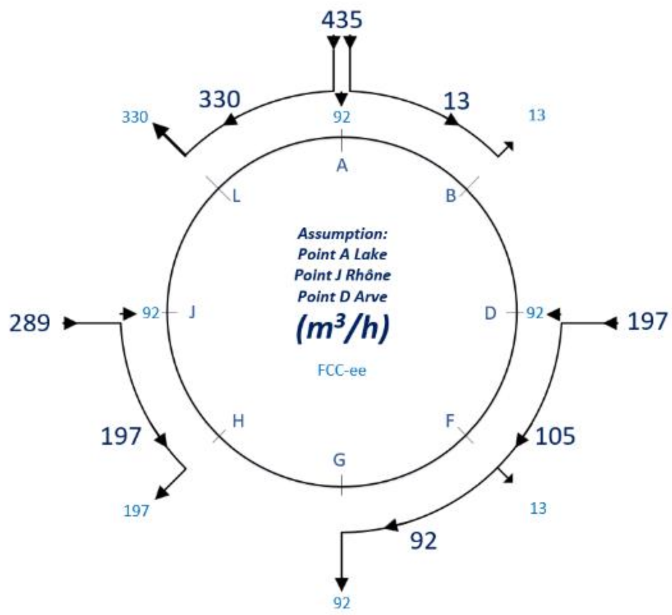
The loads could be distributed on three main sub-stations (optimally connected to existing regional HV grid):

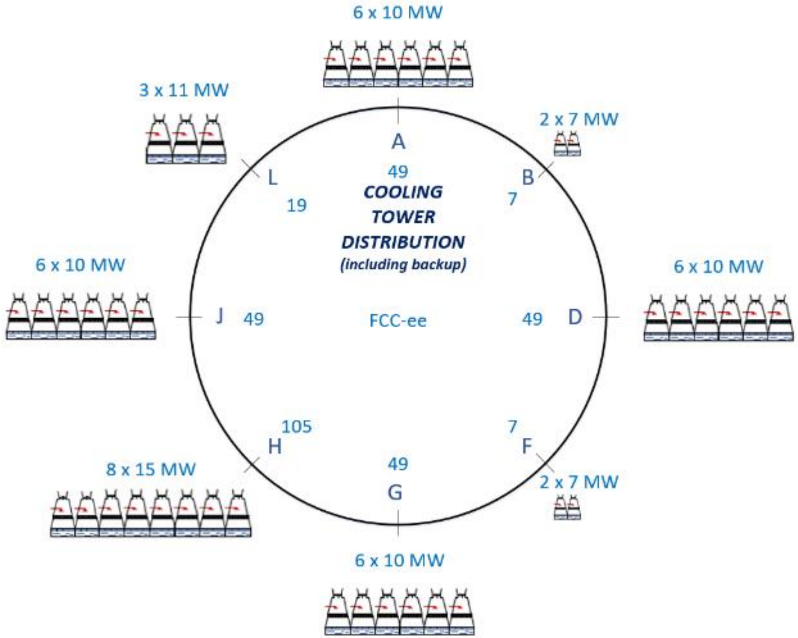
- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ



- **Connection concept was studied and confirmed by RTE (French electrical grid operator) ➔ requested loads have no significant impact on grid**
- **Powering concept and power rating of the three sub-stations compatible with FCC-hh**
- **R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh**

Cooling water supply concept

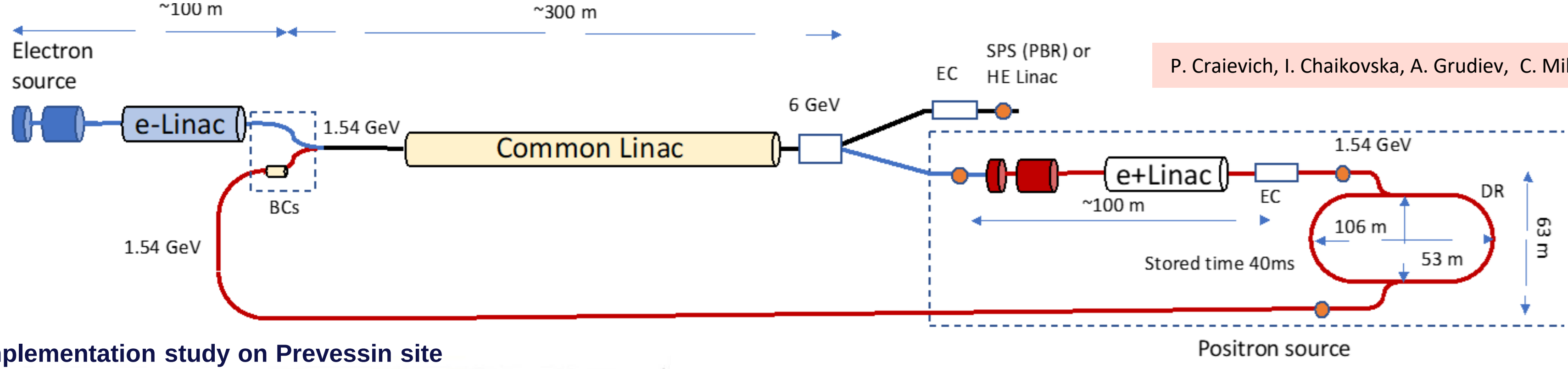




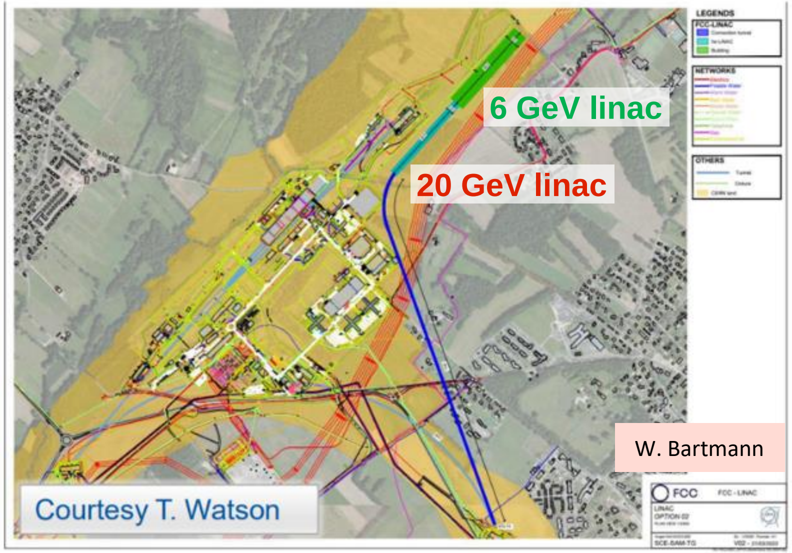
- Potential sources of cooling water Geneva lake (PA), Rhone (PJ) and Arve (PD).
- Existing line with lake water provided by SIG to CERN LHC P8 (LHCb) sufficient for FCC-ee.
- Pipework in the tunnel will connect the remaining points to points PA, PD and PJ.
- Main cooling towers placed at experiment points (PA, PD, PG, PJ), and RF sites (PL, PH).

FCC-ee injector layout & implementation

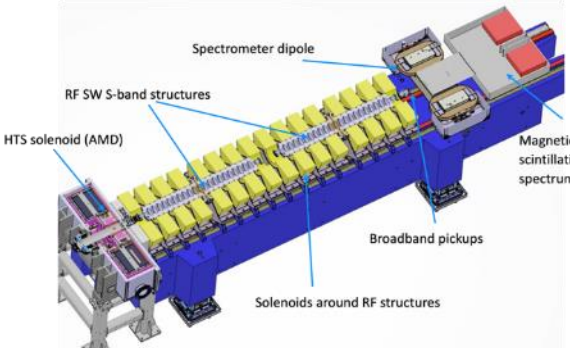
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

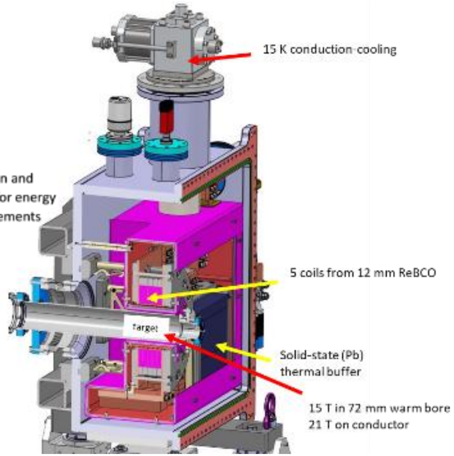


implementation study on Prevessin site



"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26





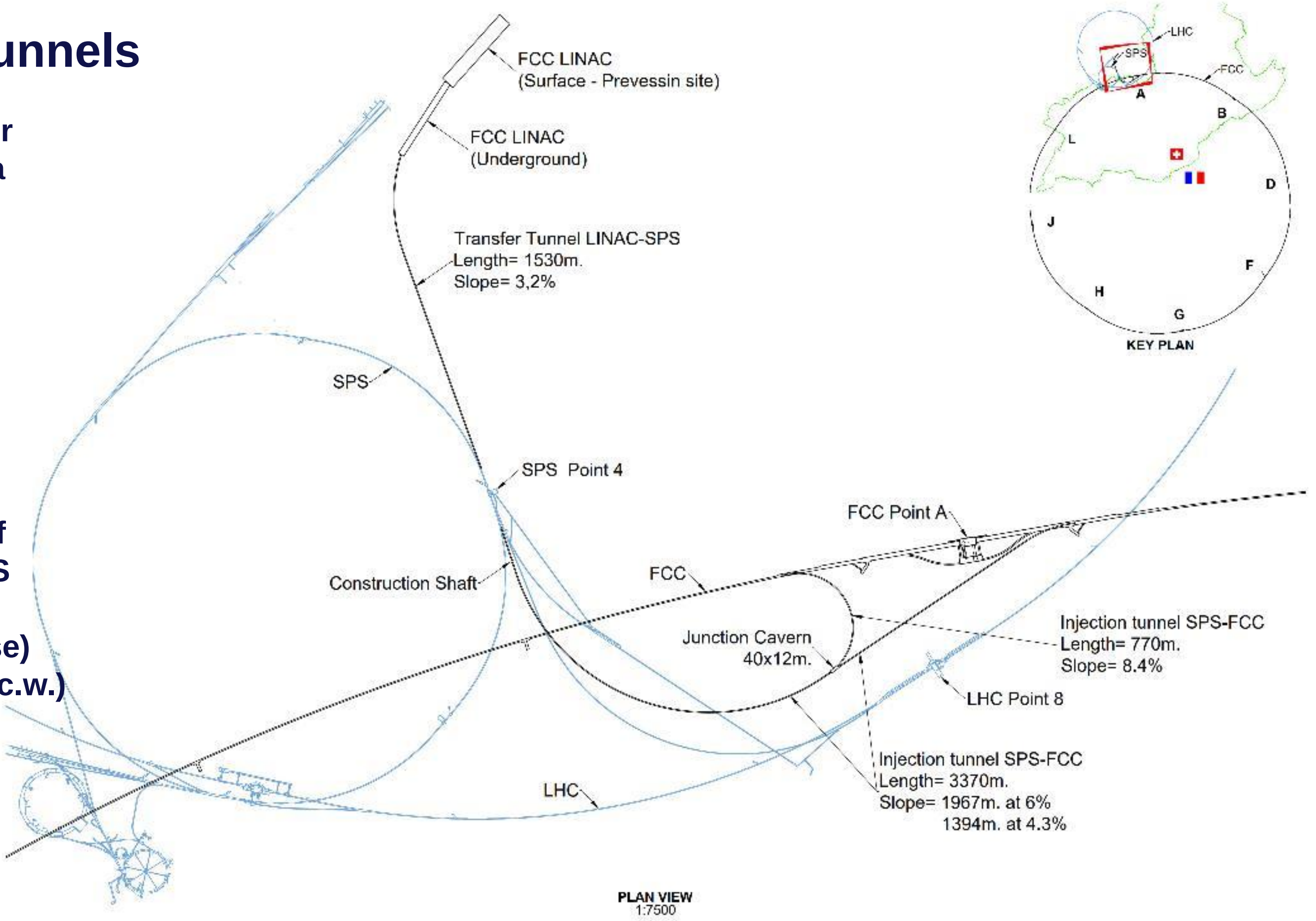
HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

Transfer lines and overall integration

LINAC and Injection Tunnels

- Designed to enable injection either from SPS as pre-booster or from a new HE Linac sited at Prevessin
- Single tunnel with spur to enable anti-clockwise injection
- Design allows re-use for FCC-hh if injector in the SPS tunnel (SC-SPS option)
  - SPS Point 4 to FCC (clockwise)
  - SPS Point 6 to FCC (counter-c.w.)



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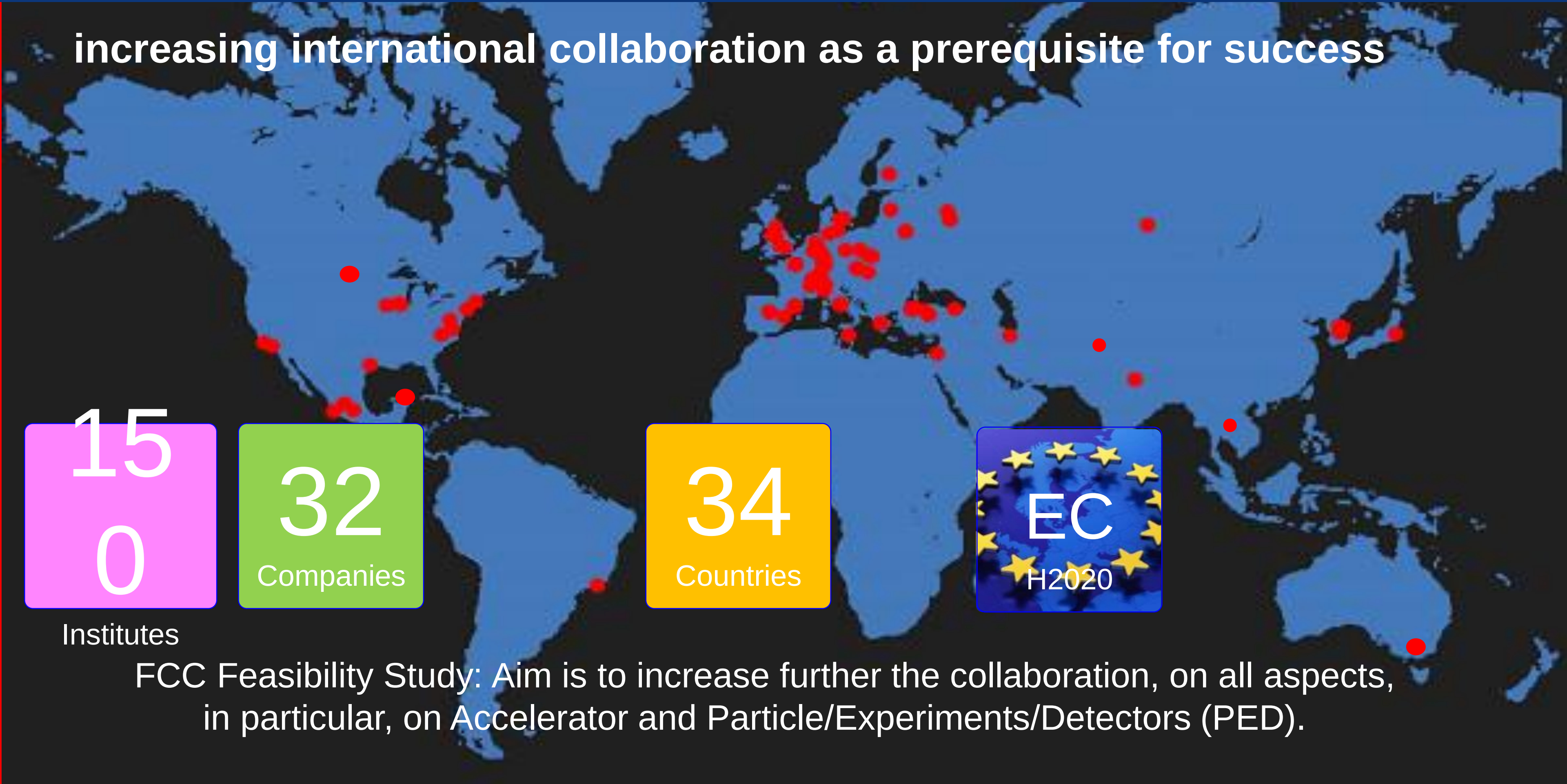
Status of FCC global collaboration

increasing international collaboration as a prerequisite for success



150 Institutes

32 Companies

34 Countries

EC H2020

FCC Feasibility Study: Aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED).

FCC Feasibility Study –status summary

Focus 2021 - 2023:

- identifying best placement & layout and adapting entire project to new placement
- this provided the input for the mid-term review documentation and cost estimate update

Fruitful collaboration between scientific & technical actors, in close cooperation with the host state services concerned, at departmental/cantonal and local level. Direct exchange in place with communes concerned by surface sites. Environmental studies ongoing.

Focus 2024 - 2025:

- Subsurface investigations, further optimization of implementation, surface sites, synergies, etc.
- Full design iteration in view of technical and cost optimisation of entire project.
- Development of project implementation plan, possibly aiming at start of CE construction early 2030ies.

Civil Engineering

CERN has been undertaking civil engineering project since the “first stone” was laid in 1953. The early civil engineering consisted of surface buildings and cut and cover structures for the accelerators (for radiation protection).

Premier Pierre, Juillet 1953

1957

1961

1968

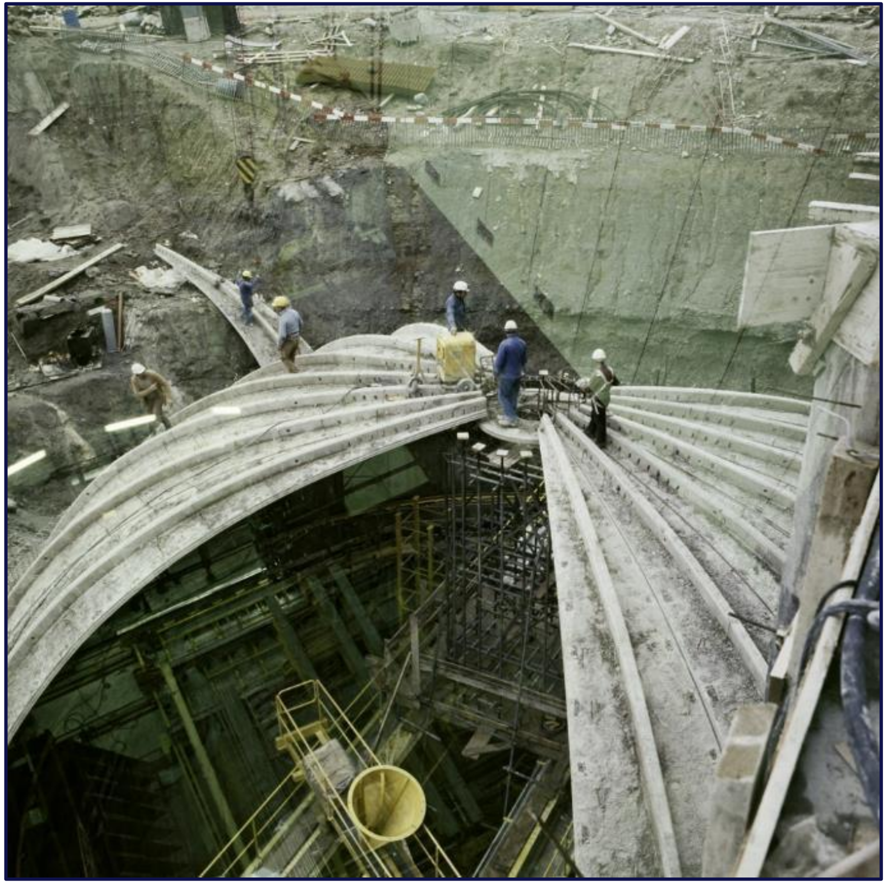
- Up to 1976 the cut and cover method was used for housing the accelerators (radiation protection)

Proton Synchrotron en construction - 1956

Complexe ISR en construction – 1967 (Dumez et Hochtief)

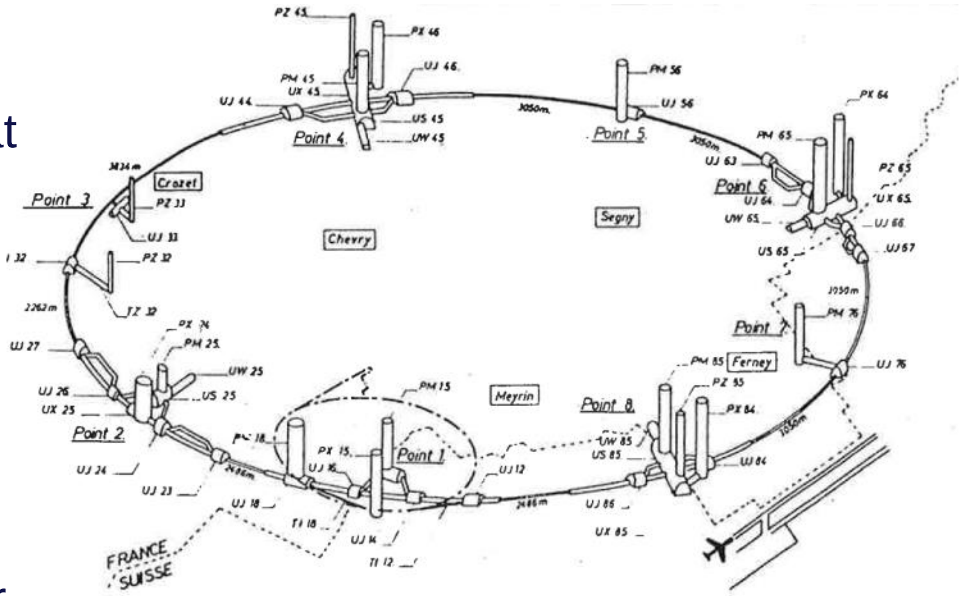
Histoire de la construction souterraine

- In 1974, CERN completed the construction of its first underground accelerator , the Super Proton Synchrotron (SPS).
- This accelerator is still in operation today and serves as an injector for the Large Hadron Collider (LHC).
- The tunnel was 7 km long and had an average depth of about 40 m.
- The tunnel crosses the French-Swiss border six times.
- 24 months with a single Robbins TBM
- Hochtief, GTM and Eiffel.

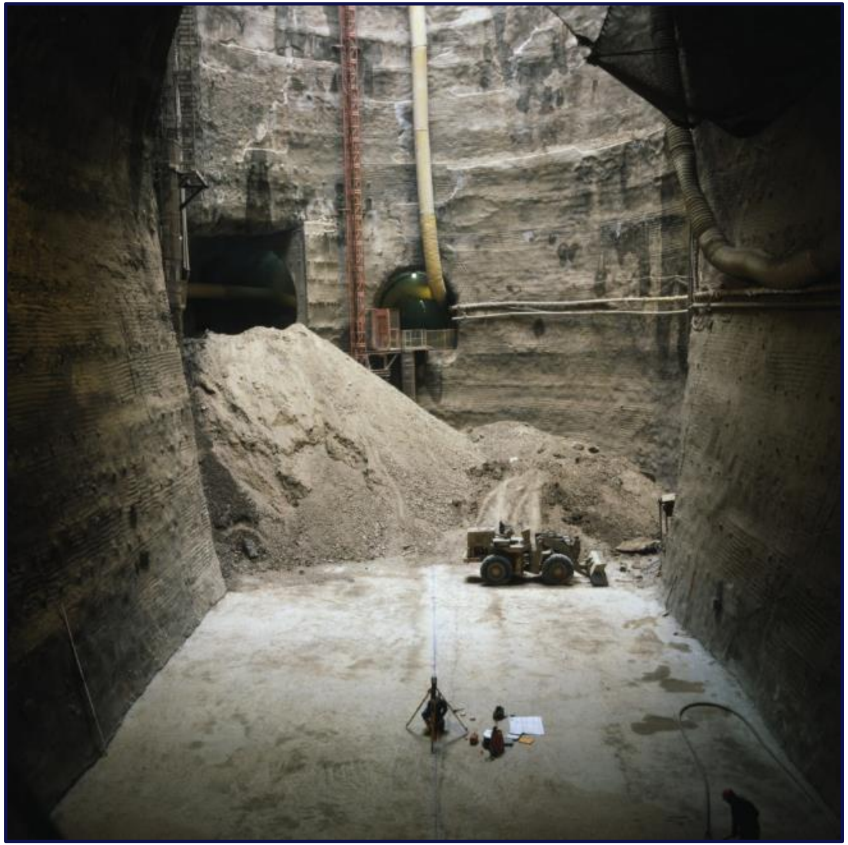


LEP

- In the 1980s, CERN built the 27 km LEP machine.
- The tunnel of this machine was located at depths of between 60m and 140m and was located mainly in molasse rock but also partly in the Jura limestone.
- The tunnel was dug using three Wirth TBMs (1 open front and 2 double shield).
- 18 access shafts were built as well as numerous caverns up to 20m in diameter and 80m deep.
- The tunnel was subsequently used for the LHC, the current flagship accelerator



LEP



LHC

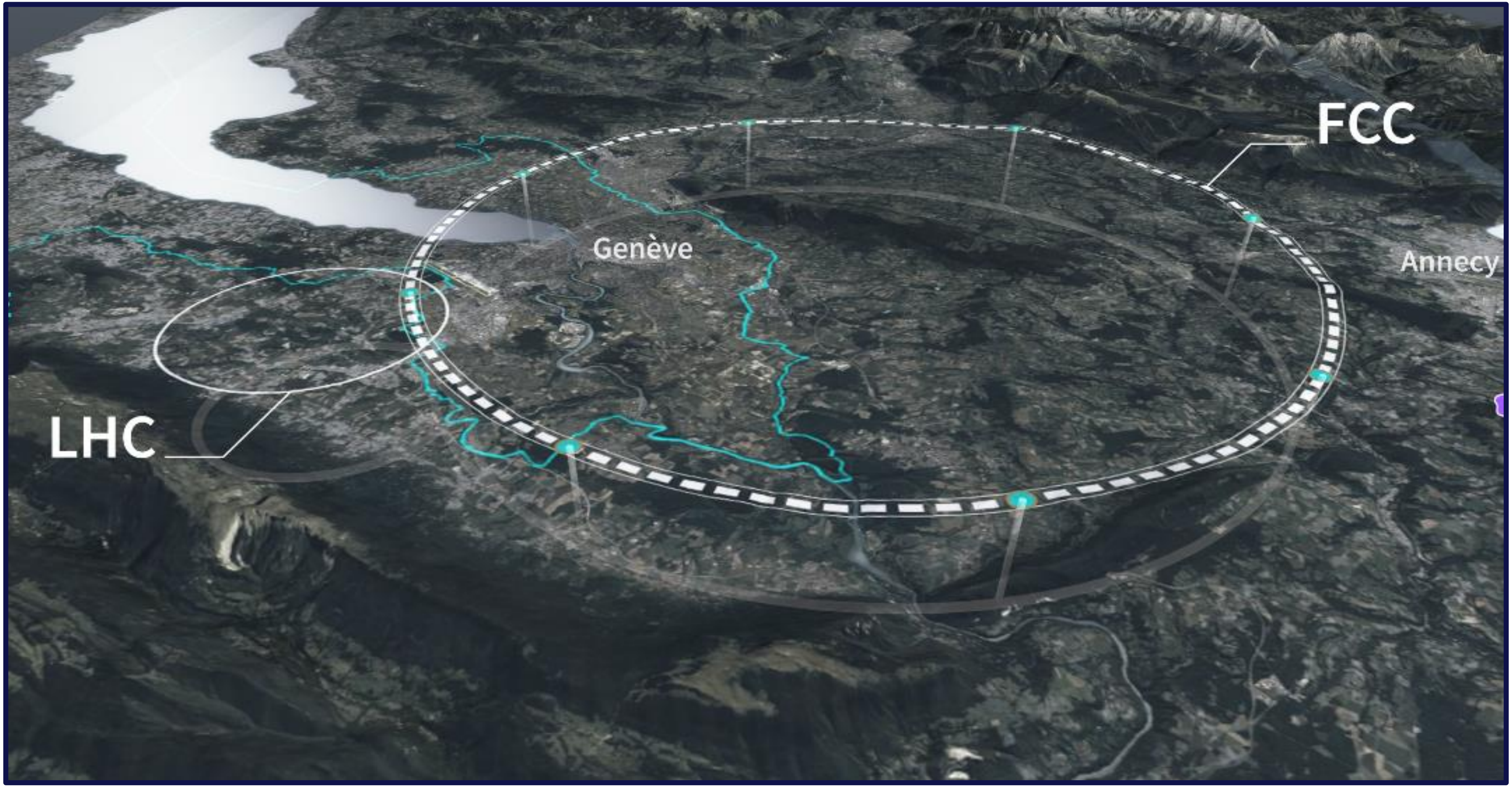
- In 1998, CERN began civil engineering work on the new accelerator, the Large Hadron Collider (LHC).

- This machine required the construction of two new injection line tunnels, as well as new tunnels and caverns for the beam absorbers.
- Two new experimental areas have also been built for the CMS and ATLAS detectors

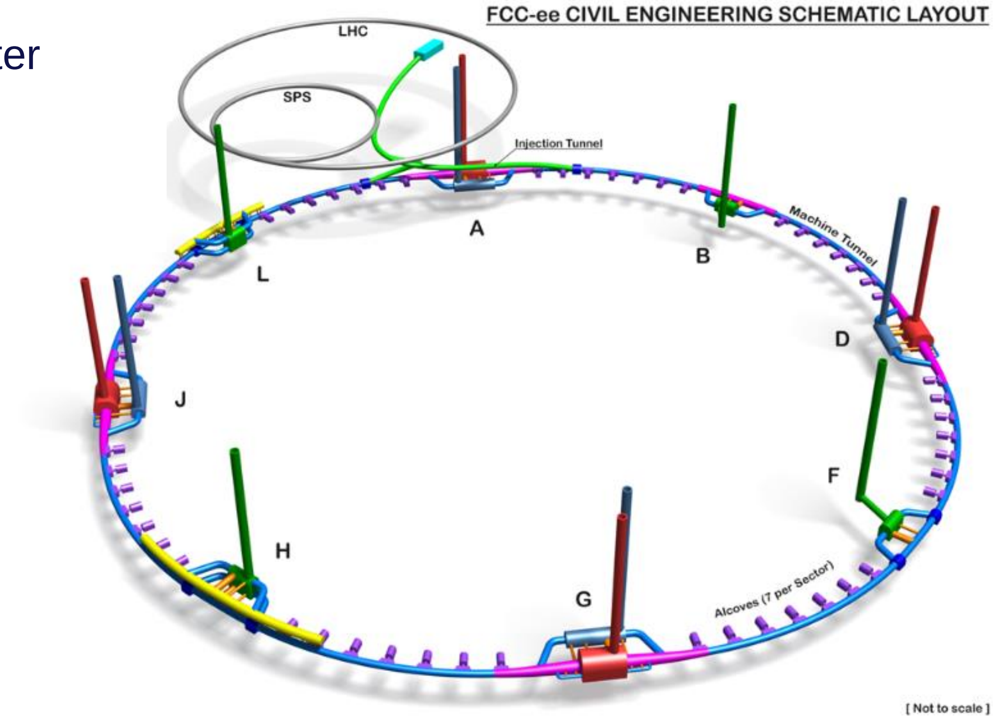
Cavern for the ATLAS Detector

Cavern for the CMS Detector


CMS
LHCb
ALICE
ATLAS


FCC
Genève
Annecy
LHC

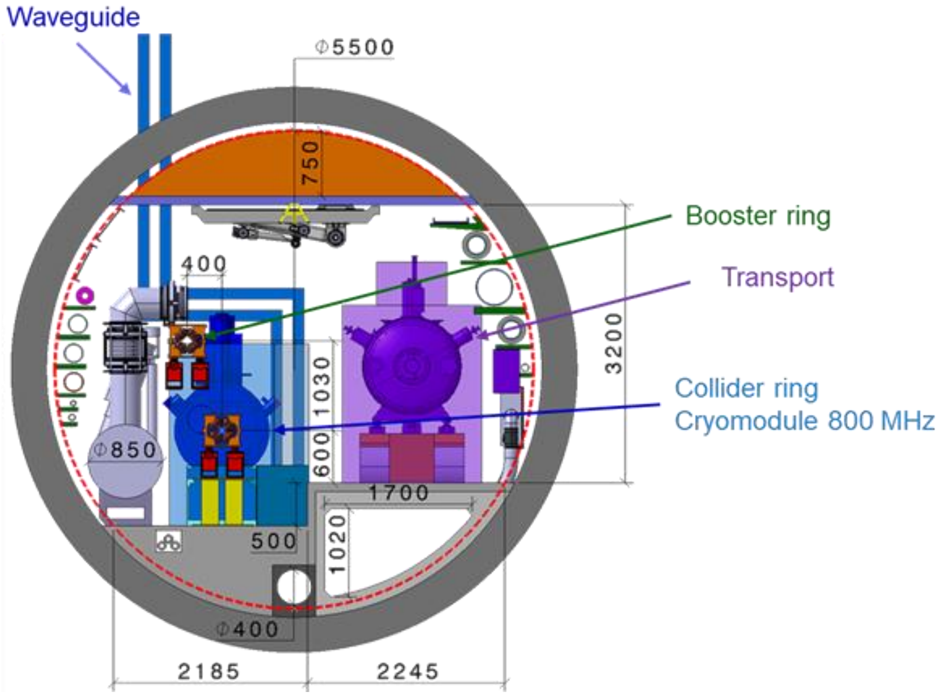
- 92 km main tunnel with a internal diameter of 5.5 m.
- Depth varies between 50m and 600m.
- 12 shafts up to 400 m deep and 18 m in diameter.
- 2 very large caverns (35m span).
- 2 large caverns (span 25m).
- >70 small caverns.
- 4 km transfer tunnel from the surface.
- 3.2 km of Klystron Gallery tunnels.
- 8 surface sites up to 7 ha each



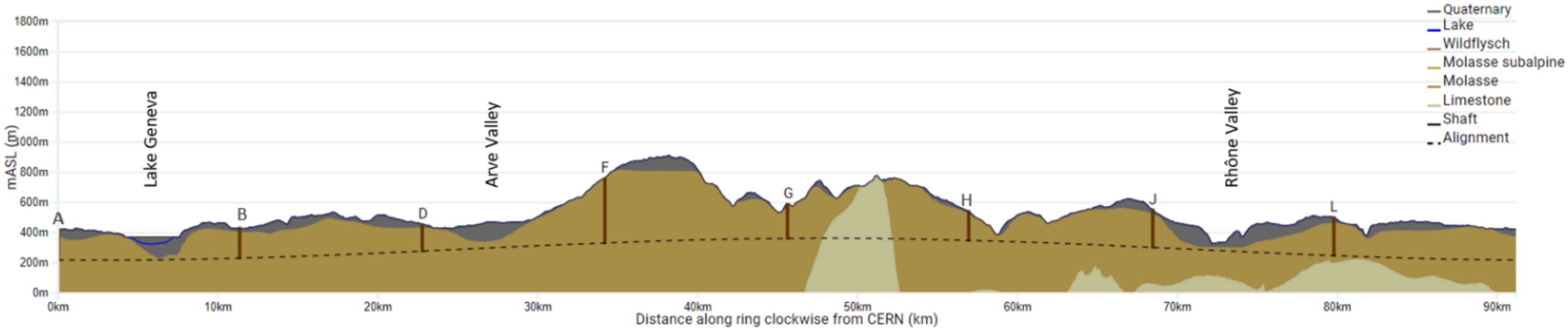
Schematic Layout of the FCC ee Underground Works as Baselined for the Mid-term Review

FCC – Civil Engineering

- The main tunnel will house the accelerator, booster and all the necessary technical infrastructure.
- A corridor for an automated vehicle to circulate is required.
- Ventilation ducts on the floor and ceiling will allow compartmentalized ventilation.



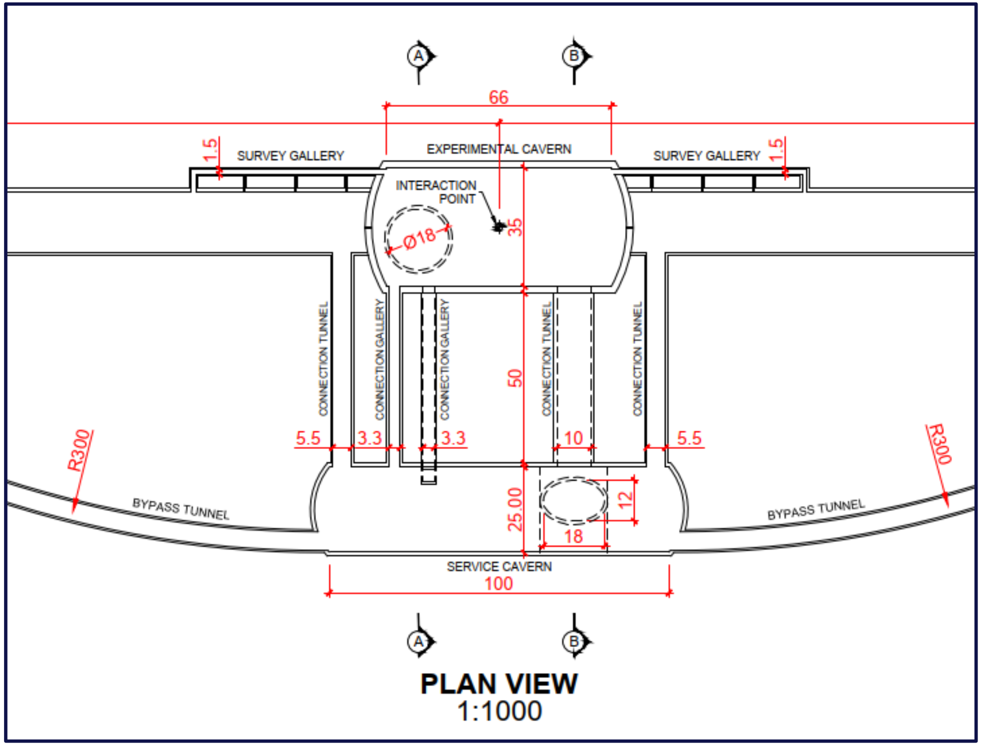
Simplified Long Profile

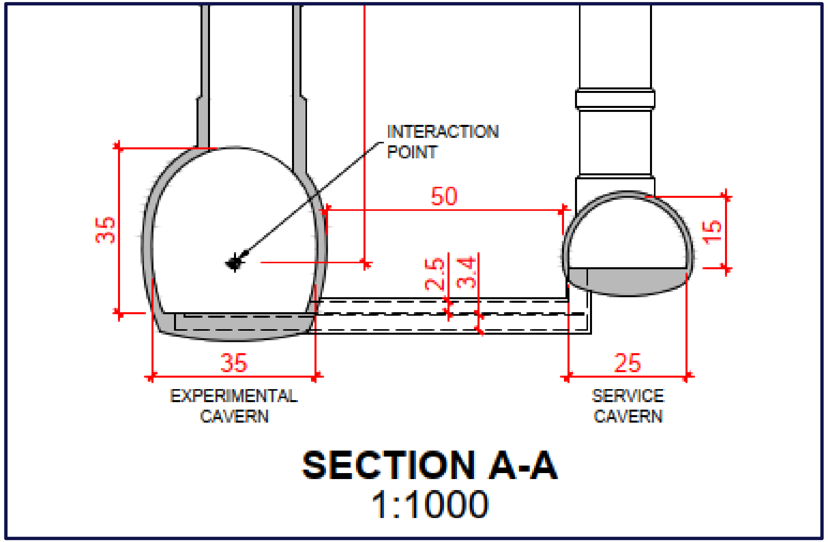


Shaft Depths:

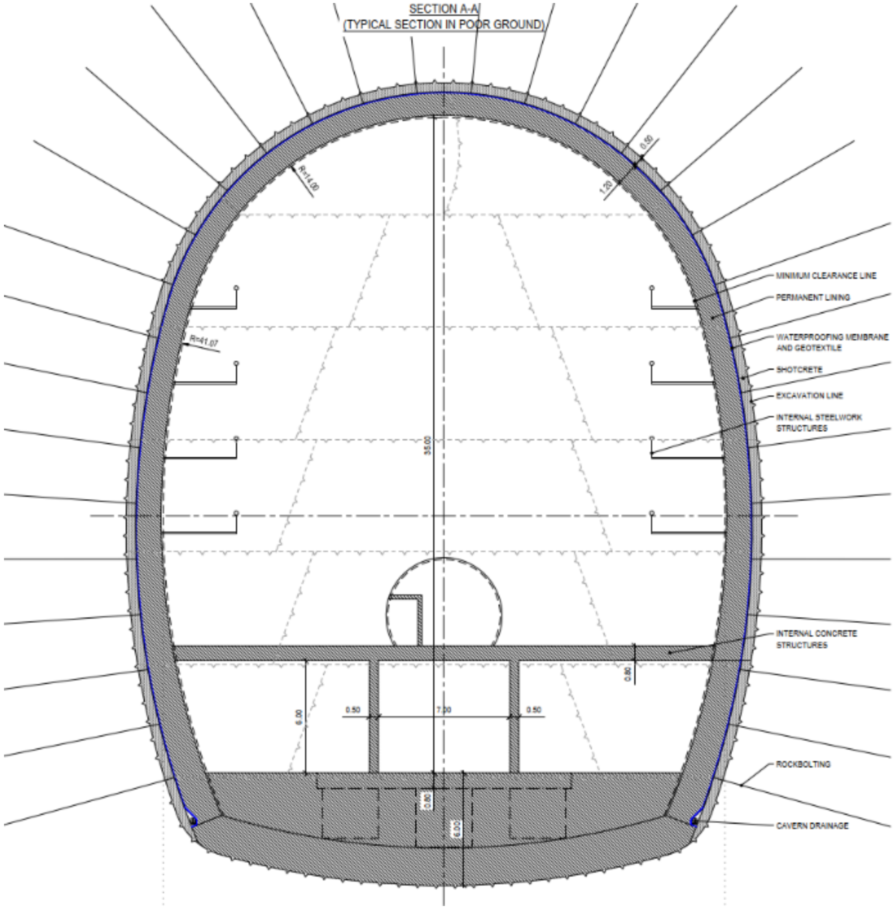
A: 201 m B: 201 m D: 181 m F: 400 m G: 226 m H: 235 m J: 253 m L: 250 m

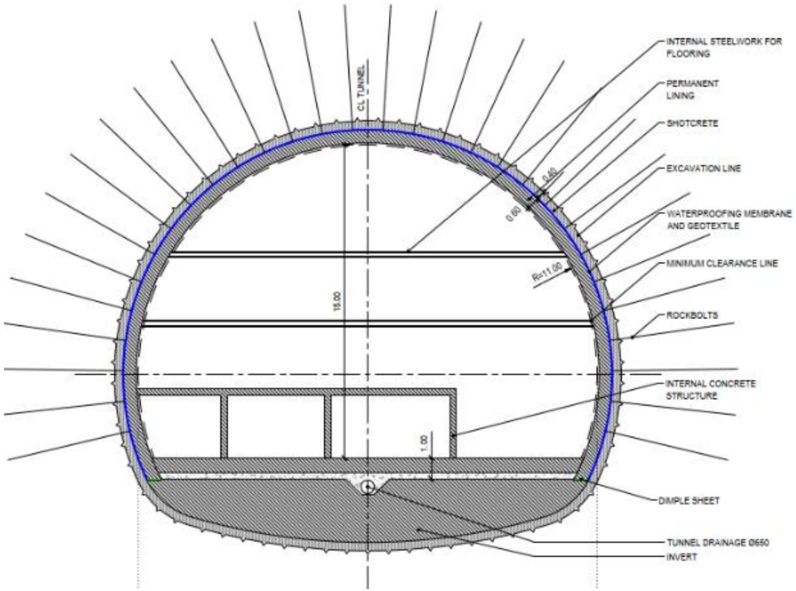
Large Cavern Complex



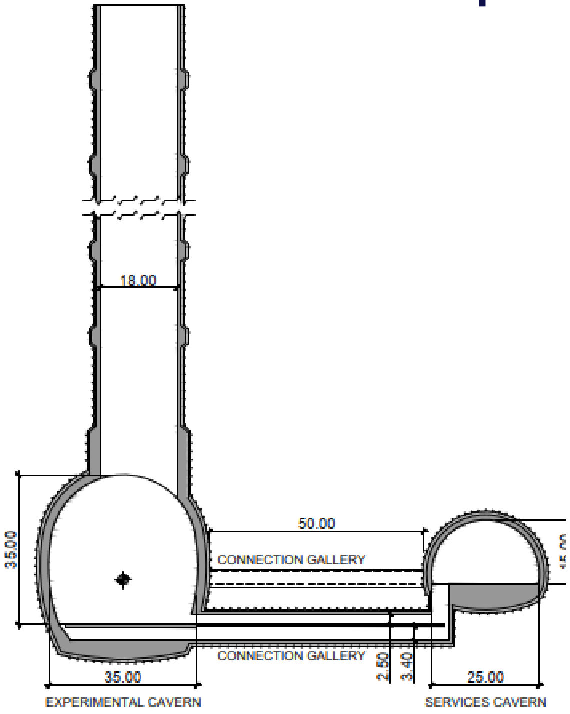


Designs from Concept Design Phase

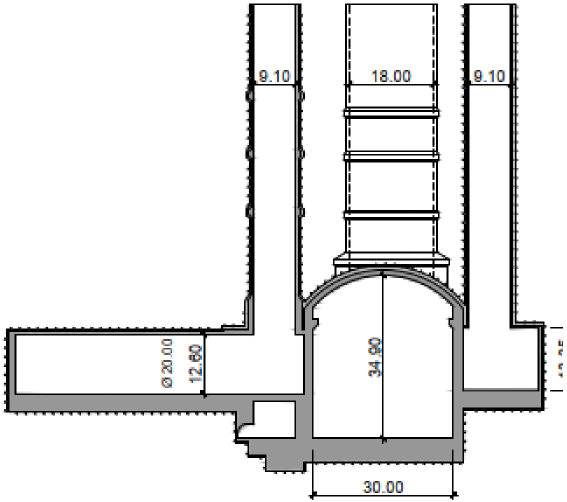




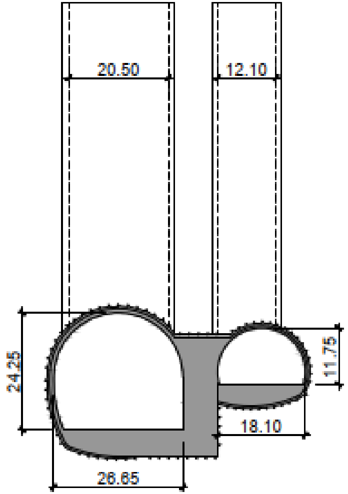
FCC Proposed Large Caverns and ATLAS / CMS Caverns



FCC



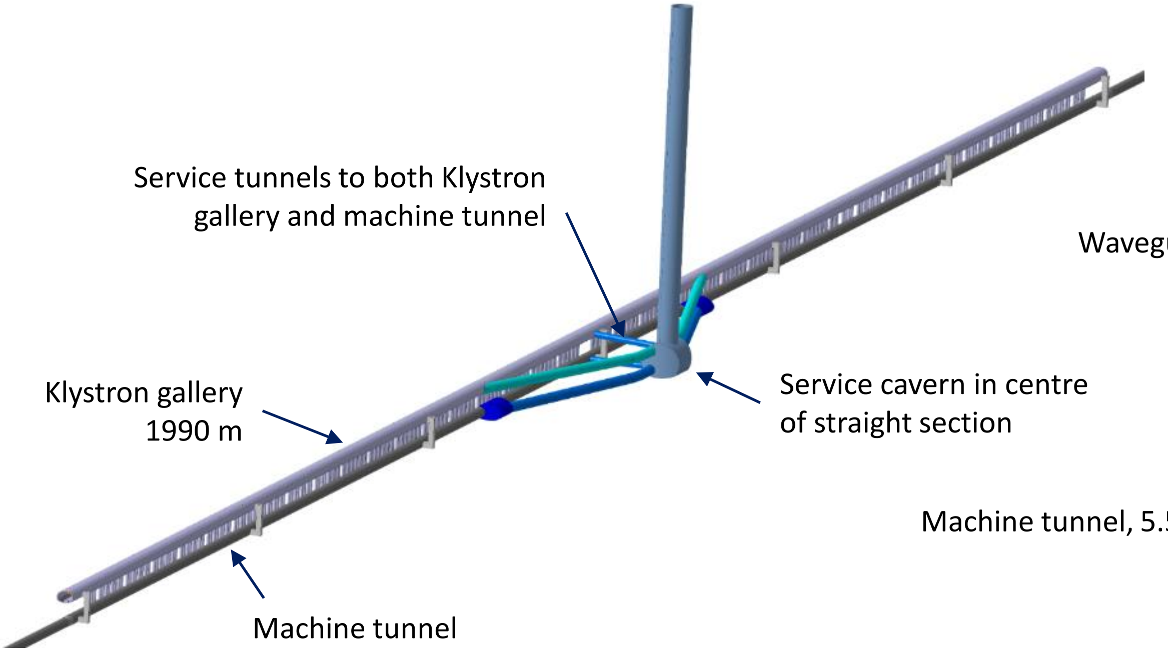
ATLAS

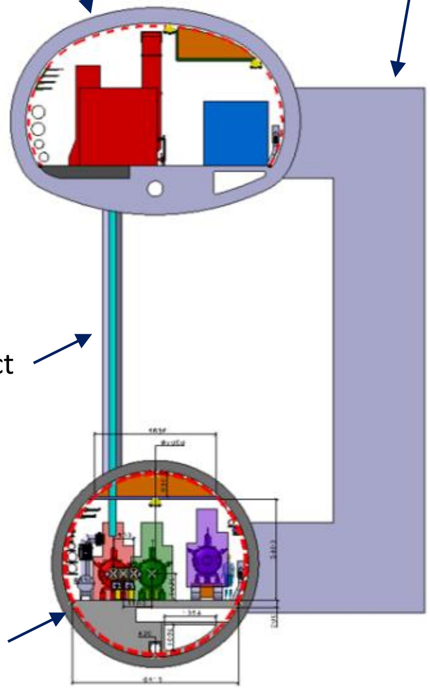


CMS

Klystron Gallery - Point H

1990 m length Klystron gallery



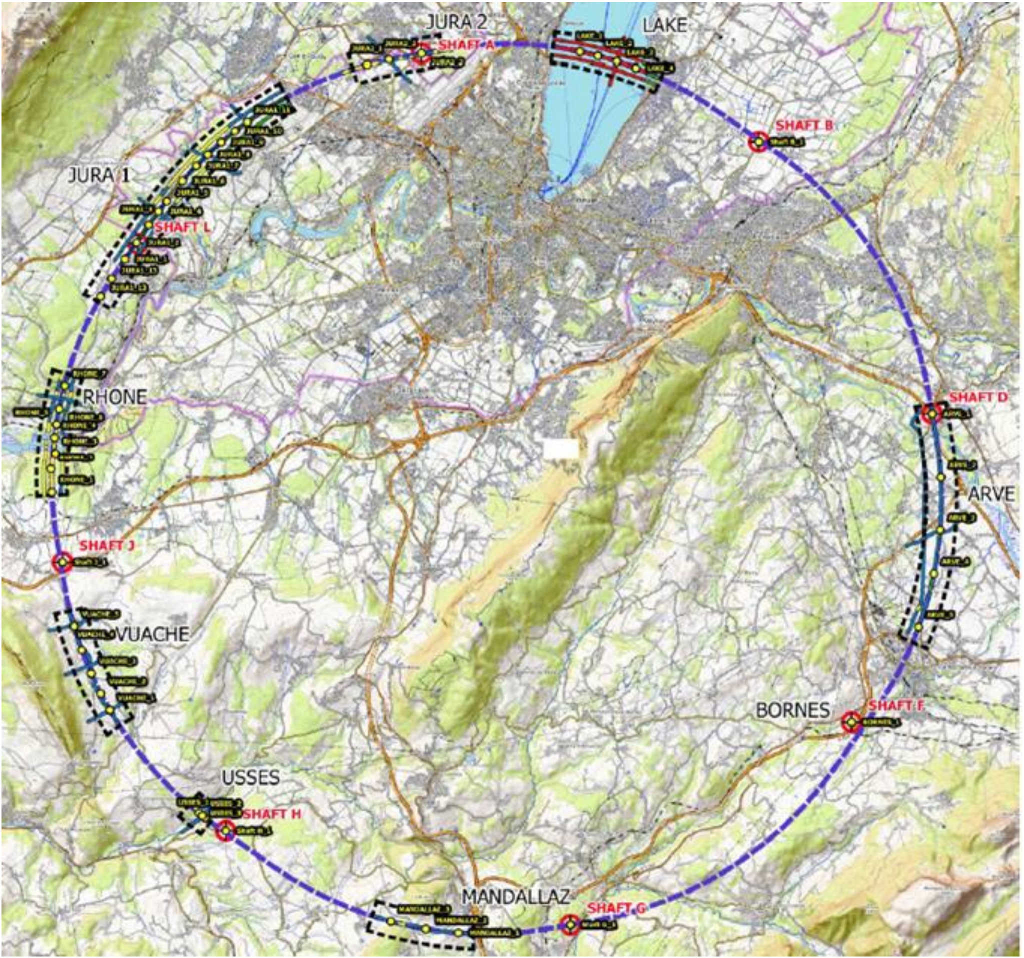


Credit: Fani Valchkova-Georgieva

FCC – Initial Site Investigations

- Ideally, CERN would like the tunnel to remain in molasse rock as far as possible.
- A subsurface investigation campaign is underway with approximately 48 deep drill holes and 80 km of geophysical lines planned.
- These will target areas where information is currently limited, for example under Lake Geneva, under the Rhone and near the Jura Mountains.
- The results will be used to update our 3D geological model which will then be used to optimize the depth and inclination of the tunnel to minimize the total depth of the shaft while remaining in the molasse.
- Further site surveys will be carried out after 2025 to obtain more detailed information on the specific characteristics of the rocks.

Campagne d'investigation du sous-sol



- Site investigation campaign in areas where geological conditions are uncertain:
- The optimization of the location of drilling sites continues with site visits since the end of 2022.
- Alignment with host countries (FR and CH) on the process of obtaining authorization procedures. Underway for the start of drilling in Q2/2024.
- Contract Status:
- Engineering Services Contract and Engineer Role During Construction, Active Since July 2022
- Tender underway for contract award in December 2023 and mobilization from January 2024.

Sondage A09 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)

Drilling works on the lake

Planning

The schedule takes into account the following parameters:

Availability of 1 or 2 shafts at each access point.

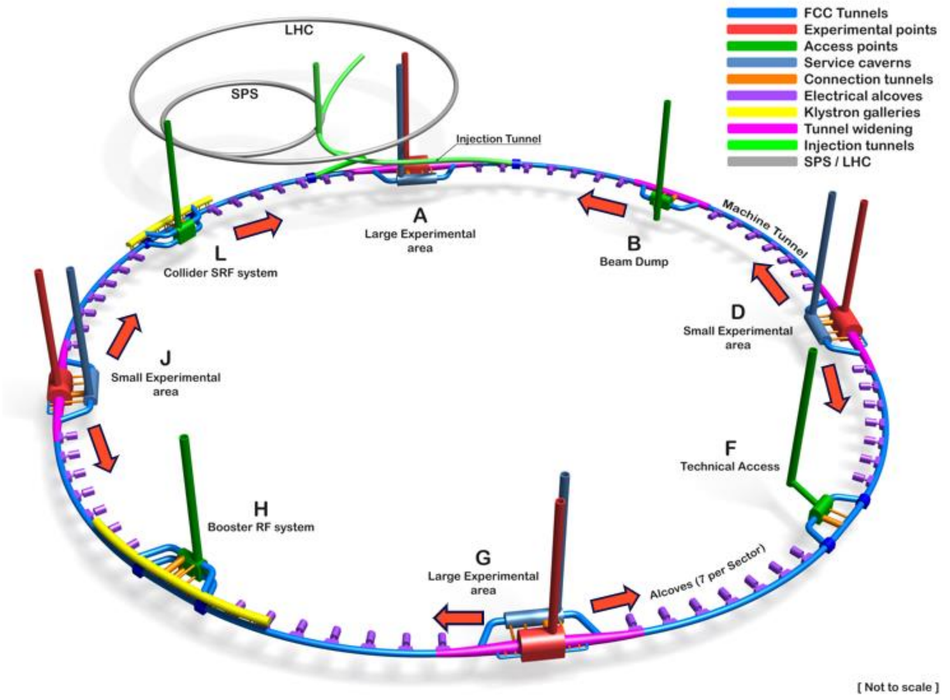
Surface constraints in the vicinity of shafts.

Potential opportunities for spoil removal at each point.

Each TBM will be driven from one access shaft to the other.

The removal of the TBM may have to be done through a construction site under the responsibility of another contractor.

Each 11 km section with it associated shafts, cavern, etc is expected to take between 6 and 8 years



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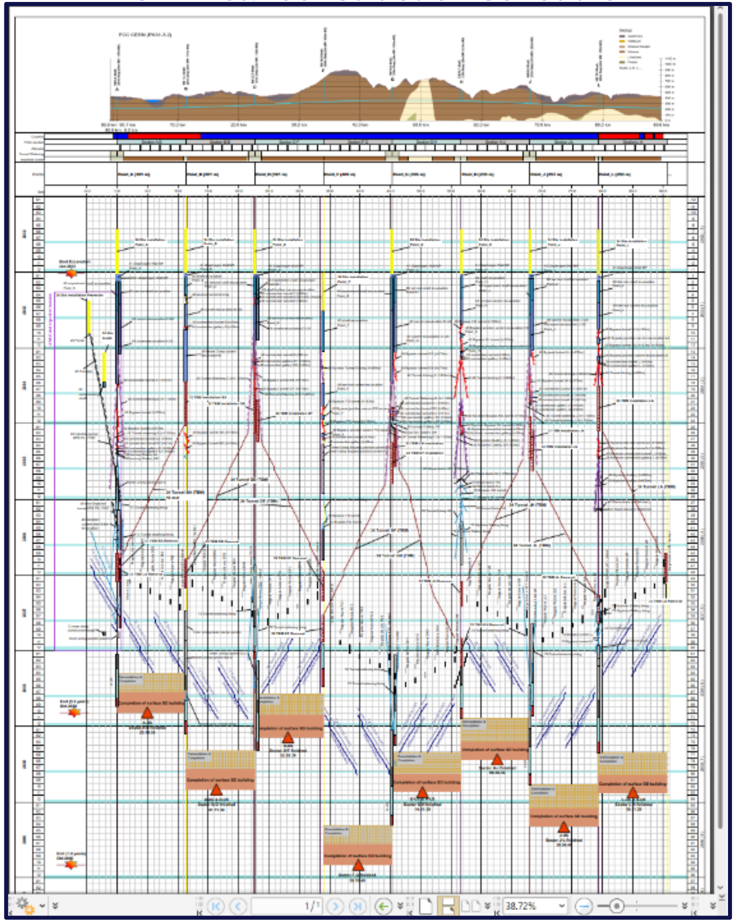
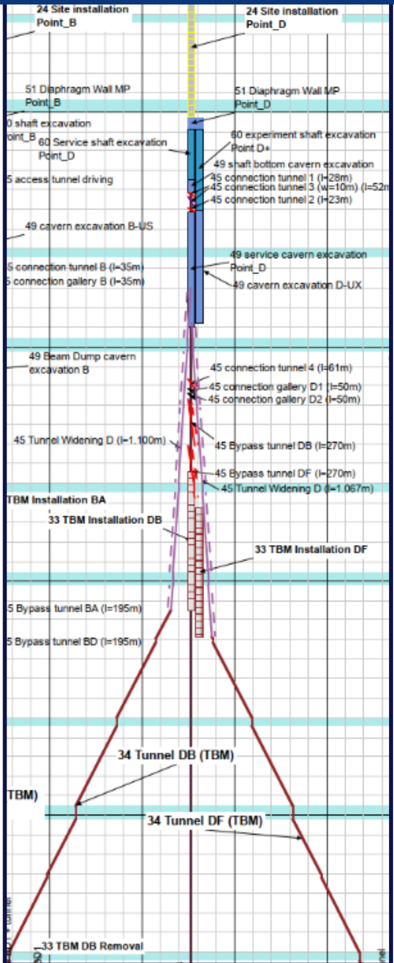
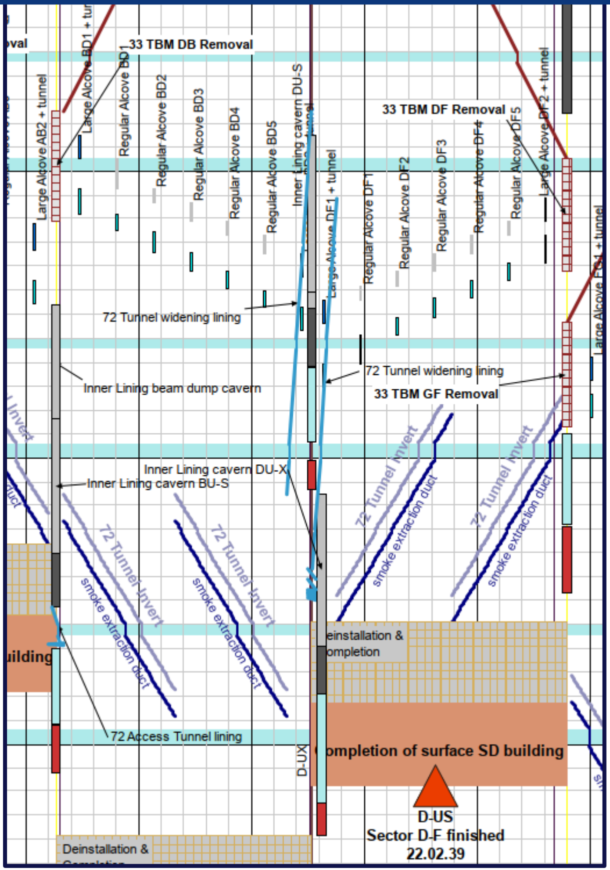
Schedule (examples)

T. Watson

CE linear construction schedule

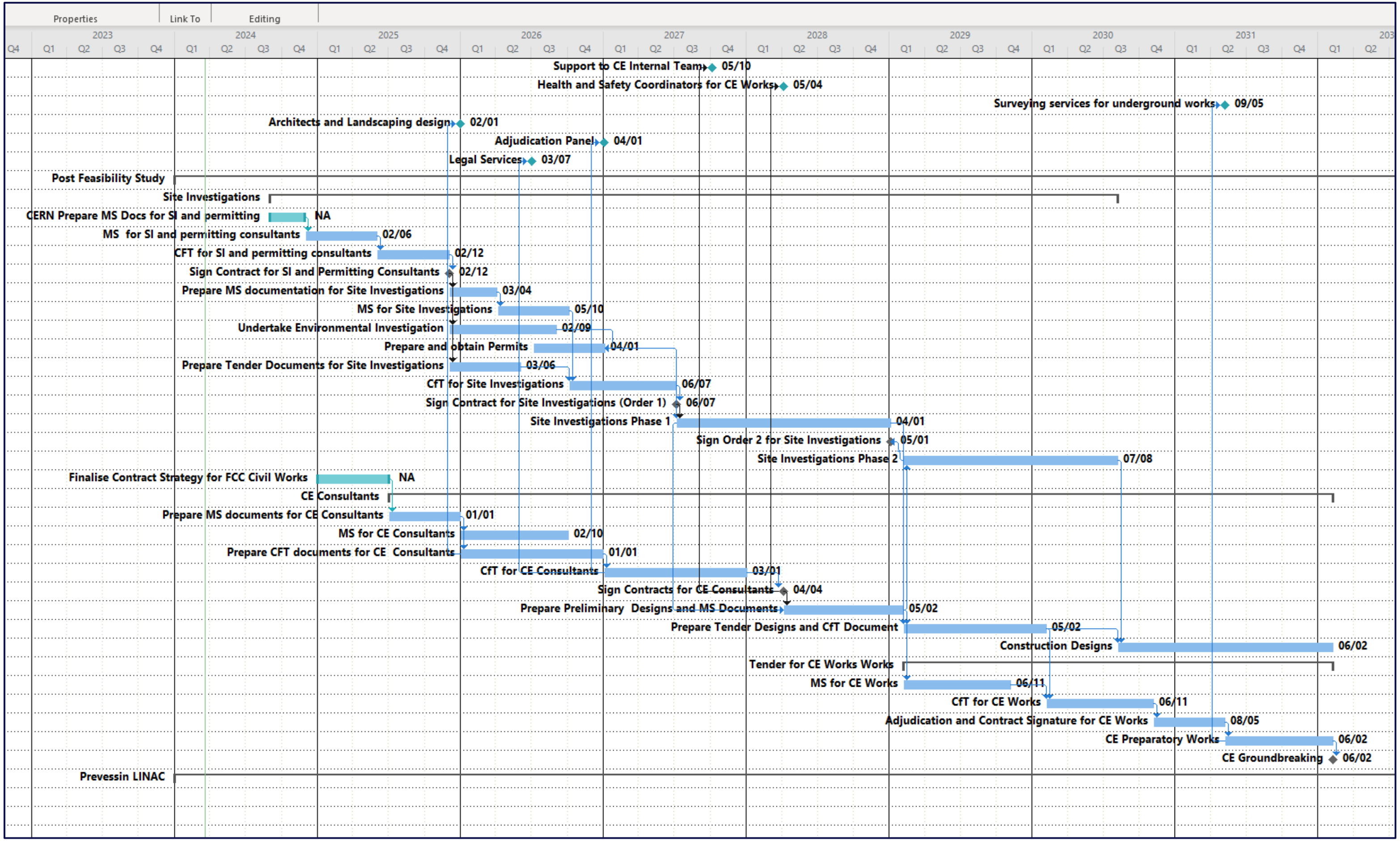






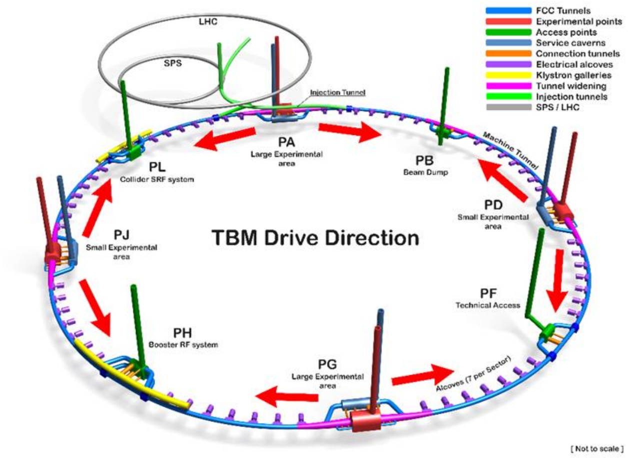
Point D – Example of linear schedule

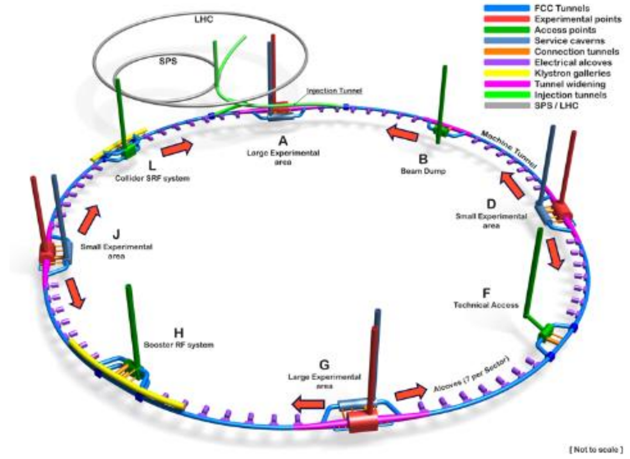
Current Planning for Critical Path activities to Start Construction



Contracts

- CERN will need to develop a strategy for the delivery of the civil engineering during 2024.
- The simplest strategy will be to follow previous CERN projects and divide the works up into geographical areas and assign an Engineering/Oversight contract and a Construction contract for each site.
- This would lead to 9 Engineering/oversight and 9 Construction contracts.
- Variations on this would include grouping the Engineering Contracts and possibly some of the construction contracts. There are numerous possible combinations for this.
- It seems difficult to avoid interfaces between contracts for the extraction of the TBMs.





Main Risks

- Obtaining permission for surface sites (host states to decide).
- Finalize an alignment that will allow the tunnel to be constructed as far as possible into the molasse rock.
- Disposal of 8 million m3 of excavated rock.
- Purchase of 8 TBMs at about the same time.
- Contracts with up to 9 engineering companies and 9 contractors.
- Workforce availability.
- Tunnelling through the limestone outcrop of Mandallaz.
- Setting up a CERN team to manage a project of this magnitude.


Experiment Site

Next Steps to Finalize the Feasibility Study

- Complete the on-site investigation campaign.
- Verify the safety, logistics and ventilation of a single 11 km long tunnel.
- Finalize plans and dimensions for all underground structures.
- Continue to find solutions for the disposal of 8 million m3 of excavated rock.
- Verify the tunnel design and the performance of the TBM in the molasse with water inflow.
- Develop contracting strategies.
- Consolidate the schedule.
- Consolidate the cost estimate.
- Review of technical challenges by professional entities from industry (consultants, contractors)

16 Novembre 2023

If I wanted to come here today, it's to show my confidence in the teams and our will, our ambition, to keep the first place in this field [particle physics]

END

Reasons for this early discussion with Porr

- CERN rarely undertakes large scale civil engineering projects.
- We are aware that the way infrastructure projects are delivered changes with time.
- We are aware that practices differ between countries and between continents.
- CERN is somewhat unique in terms of its status as an international organization which on one hand allows us to do things with some freedom from national rules or customs, but at the same time we are bound by the rules and regulations governing the organization.
- CERN is seeking early engagement with industry to obtain a wide view on the options open to us for delivering the project and which options may be most appropriate for the FCC.

Purpose of this early discussion with Porr

- Since the LEP, CERN has followed the traditional Engineer/Contractor route for delivering civil engineering under one of the FIDIC standard forms.
- Larger projects are sub-divided to allow spread of contracts and financial return to member states.
- Civil engineering has always been done in advance of and dis-associated from the HV/MV/LV electrical systems, Water networks, lifts, cranes and other mechanical systems.
- The FCC is an order of magnitude larger than LHC.
- For civil engineering (at least) CERN will need to ramp up a client team from the current handful of staff working on the FCC FS.
- CERN wishes to consider alternative options for delivery of the civil engineering and perhaps some of the other infrastructure to improve schedule and perhaps cost.

Purpose of this early discussion with Porr

CERN business as usual approach:

- Each discipline (civil, mechanical, electrical, HVAC, cooling) manages their own design, procurement, installation, commissioning without a strong centralized strategy.
- The civil engineering would be near-complete before handover to CERN and the commencement of the installation of the other infrastructure which would normally be coordinated by a central CERN team.
- The civil engineering would be divided into appropriate work packages, probably based on geographical location and CERN would have small teams of 2 or 3 people for each set of geographically based packages (a package being one contract for the design, one for the construction and possibly some common contracts for safety, architecture, legal support etc.)

Purpose of this early discussion with Porr

- For FCC a first consideration has been 9 sets of contracts for the 9 geographical areas concerned (8 surface sites each with a set of shafts, caverns and one 11km sector of the tunnel) and one contract for the injector/transfer lines. This would give an approximate value of the order of CHF 500MCHF for each of the 9 sites.
- There may be some logic to group some of the design and/or construction contracts thereby reducing to 3 or 4.
- This would require CERN to recruit, build and empower a client team of about 25 to 30 people just to set up and oversee the contracts (exclude resources for procurement, legal, administration, liaison with Host States).
- The same or similar process would be needed for each of the other infrastructure disciplines.
- A possible alternative would be to contract the overall responsibility (management) to a single industrial consortium who would undertake directly or through sub-contracting the works scope to deliver the final product.

Technical Questions

1. What are your immediate thoughts on the technical challenges for this project?
2. Do you consider that the CERN approach to use the sites with two shafts to drive two TBMs (in opposite directions) to be optimal?
3. What risks do you see associated with the depth of tunnelling (up to about 500m and with an average of about 200m)
4. What technologies are available for evacuation the excavated material through the deep shafts (up to 400m).
5. What technologies are available for excavating the shafts (moraine and molasse)?
6. Do you see an issue with using a single shaft for all access to the underground?
7. CERN is assuming an average advance rate of 18m/day in the molasse. Do you consider this achievable?
8. Do you have experience of leaving a TBM “buried” underground so that it does not have to be removed?
9. In case of removal what are the issues when removal needs to be carried out through another contractor’s worksite?
10. Are there alternative TBM suppliers in Europe other than Herrenknecht?
11. Do you see any advantage to include the installation of the classical technical infrastructure (pipes, cable trays, cable pulling) into the same contract as the civil engineering.
12. Carbon footprint of civil works (especially concrete) is an important topic. How do you see the industry evolving to meet this challenge? How do you foresee the situation in 10 years time?

Selection of non-technical Questions for Porr

1. Are there any specific strategies that would improve schedule? Or reduce cost? Lower risk?
2. To maximize the number of interested qualified bidders, would you propose several "smaller" contracts (e.g. 9 sets) or fewer "bigger contracts (e.g. 4-5 sets, or even less)?
3. What type of contracts would you recommend for this type of work? E.g. FIDIC Red book/Emerald, or other standard or bespoke?
4. We understand that NEC has been used as models for collaborative contracts. Are you familiar with these? What is your feedback? Do you have any thoughts on the SIA 2065 proposed model?
5. What kind of time would be required to prepare a bid for one construction contract assuming FIDIC remeasurement contract.
6. What companies would you ideally partner with for this type of work taking into account the location and the fact it is CERN contract?
7. What was your honest feedback from previous CERN contracts you have completed in the past?
8. What would you recommend CERN to do in order to ensure an equal opportunity to all member states for the contracts?

Selection of non-technical Questions for Porr

9. How would a project of this magnitude and technical complexity be constructed? Examples of previous large-scale projects would be useful to understand along with the successes and failures.

10. Are there benefits to early contractor involvement for underground civil works and how can this be managed within a competitive environment and where CERN is expected to aim for a so called “fair return” to its member states?

11. Does Porr have experience of projects where clients brought in contractor’s expertise early on to help develop appropriate technical solutions?

12. What is the position within CERN member states with regard to Project Management companies able to undertake the civil engineering as a turn-key venture?

13. Do you see a resourcing issue for such a large project with significant underground works?

14. CERN is currently looking into disposal options for the excavated material. What is Porr experience in this sensitive subject?