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FCC-ee CIVIL ENGINEERING AND INFRASTRUCTURE STUDIES

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Abstract

The European Organisation for Nuclear Research (CERN) is planning a Future Circular Collider (FCC), to be the successor of the current Large Hadron Collider (LHC). Significant civil engineering is required to accommodate the physics experiments and associated infrastructure. The 91.2 km, 5.5 m diameter tunnel will be situated in the Geneva region, straddling the Swiss-French border. Civil engineering studies are to incorporate the needs of both the FCC lepton collider (FCC-ee) and the FCC hadron collider (FCC-hh), as the tunnel will host both machines consecutively.

INTRODUCTION

At completion, the FCC tunnel will house the world's largest particle accelerator. The study, currently in the feasibility stage, officially commenced in 2013 following recommendations made by the European Strategy for Particle Physics Update (ESPPU). To support the physics requirements, the CERN civil engineering team has been studying the feasibility of constructing a 91.2 km circumference tunnel project beneath the Geneva region.

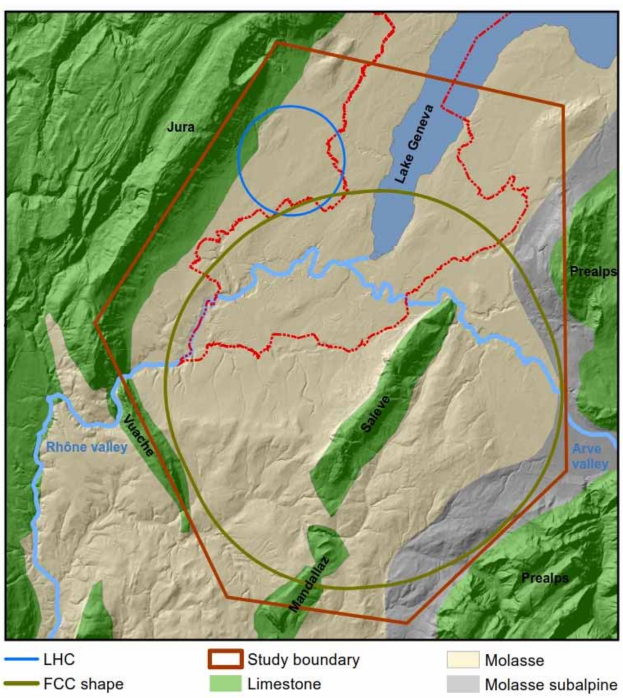

Figure 1: FCC study area (CERN).

CERN has a history of completing large civil engineering works to facilitate physics research. When CERN completed construction of the LEP (Large Electron-Positron) in 1989 [1], it was the largest physics facility ever built. This made Europe a worldwide leader in science and technology [2].

To validate the physics case of FCC, the tunnelling studies must satisfy requirements for both a lepton (ee) and a hadron (hh) machine, as well as reuse the existing LEP/LHC infrastructure.

Like the LHC before it, the FCC will extend into the territories of both France and Switzerland. As a result, the main challenges encountered by the civil engineers will be the geological features, local stakeholders, environmental constraints, and project costs.

Geological site investigations are therefore required to validate the geological assumptions made at the conceptual design stage. An initial site investigation campaign is planned to start in 2023 in the areas of highest geological uncertainty.

This paper describes the present state of the civil engineering feasibility studies for the FCC tunnel.

FEASIBILITY STUDY

Project Description

Following studies of various locations and geometries of the accelerator machine, the conceptual design of the FCC considers a quasi-circular tunnel, with a circumference of 91.2 km situated in the Geneva basin. The tunnel will be buried underground at an average elevation of 300 m ASL.

In addition to the main tunnel, approximately 10 km of transfer tunnels, 4 km of beam dump tunnels, 6 km of bypass tunnels, 14 shafts, 12 large caverns and 8 surface sites are required.

The primary objective of the civil engineering studies so far has been to locate the tunnel within the topographical and geological boundaries of the Geneva basin. While also ensuring adequate connection to existing LHC infrastructure.

The locations of the surface sites have been selected to match the machine's layout, for example the predefined experimental points, but also considering surface access and local environment factors.

Approximately 9 million cubic metres of spoil will result from the excavations of FCC tunnels and structures [3]. Around 95% of this will be molasse, the reuse potential of which – although it has proved to be a good rock for tunnelling – is not obvious. Research is currently being undertaken to investigate opportunities to reuse or recycle tunnel spoil rather than resorting to typical landfill disposal.

Summary of Main Structures

- 1 machine tunnel of 91.2 km length, 5.5 m diameter
- 14 vertical shafts of 12 – 18 m diameter, 140 – 400 m depth
- 8 service caverns, 100 to 150 m length, 15 m high, 25 m wide

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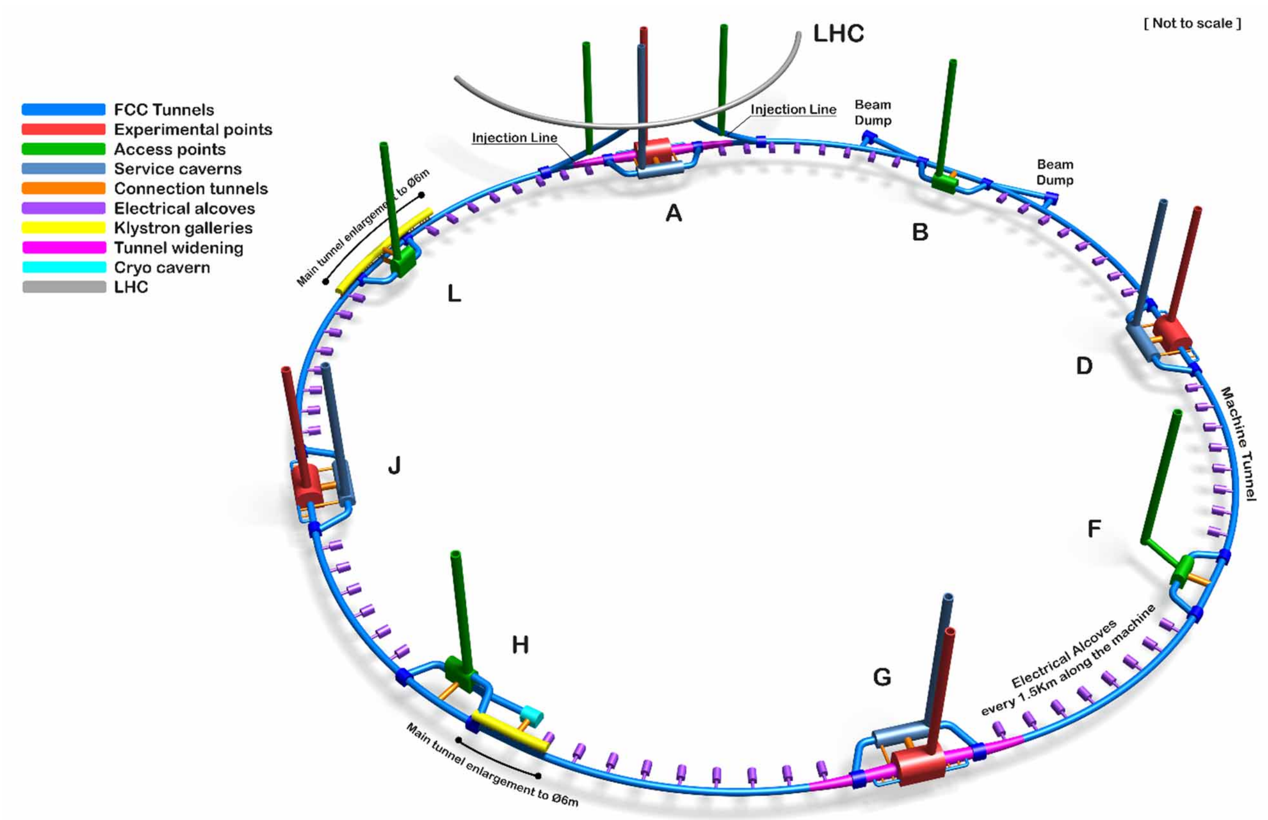

Figure 2: FCC schematic diagram. (Angel Navascues Cornago, CERN).

- 4 experiment caverns, 66 m length, 30 m high, 30 m wide
- 2 beam transfer tunnels from the LHC, 4.1 and 6.1 km in length, 5.5 m diameter
- 2 beam dump tunnels, 2 km length, 5.5 m diameter
- Several 5.5 m diameter bypass tunnels, totalling approximately 5 km
- 18 junction caverns of varying dimensions
- 2 Klystron Galleries, one at point H, 1078 m length and one at point L, 1990 m length. Both galleries with a span of 9.8 m and a height of 5.4 m
- 60 electrical alcoves, at 1.5 km spacing around the ring, 25 m length and 6 m diameter

The structures listed above form the 'Baseline Design', which is the infrastructure required for a hadron or 'FCC-hh' accelerator. However, the tunnel will also accommodate a lepton collider 'FCC-ee' prior to the hadron machine installation. To meet the lepton machine requirements the tunnel will require widening at the two experimental sites, A and G. This widening will be to a maximum span of 11 m and for a length of 1000 m each side of the experimental caverns at the two points. The FCC-ee will also require beam injection from the existing CERN Super Proton Synchrotron (SPS) housed in beam transfer tunnels. Exact layouts of these transfer tunnels are to be confirmed.

The eight underground sites (A to L) require large surface works that will accommodate the necessary infrastructure such as transformers, helium tanks, and cryogenic plants, as well as offices for operations and management. The four experimental sites will be roughly 6 Ha in surface area and the technical sites will be roughly 4 Ha in area. Exact layouts of the surface sites are being developed and final layouts will depend on machine requirements as well as local constraints.

Geology

The Geneva basin has three main ground types: moraines, molasse and limestone. The variable sedimentary rock, called molasse, is overlaid by low-strength glacial deposits, called moraines. The depth of the moraines varies from only a few metres up to 100 metres. Limestone features in the form of the Jura Mountains, the Alpine foothills, the Vuache and Saleve chains border and intersect the layers of molasse. The molasse is composed of horizontally bedded layers of marls and sandstones. The term sandstone refers to cemented sandy or silty rocks and the term marl refers to clayey rocks [4]. These layers can vary considerably in strength. The molasse is considered a suitable rock type for tunnel boring machine (TBM) excavation, as it is stable and dry; however, the heterogeneity of the rock leads to some uncertainty. Therefore, it is essential that the large span caverns are constructed in stronger sandstone.

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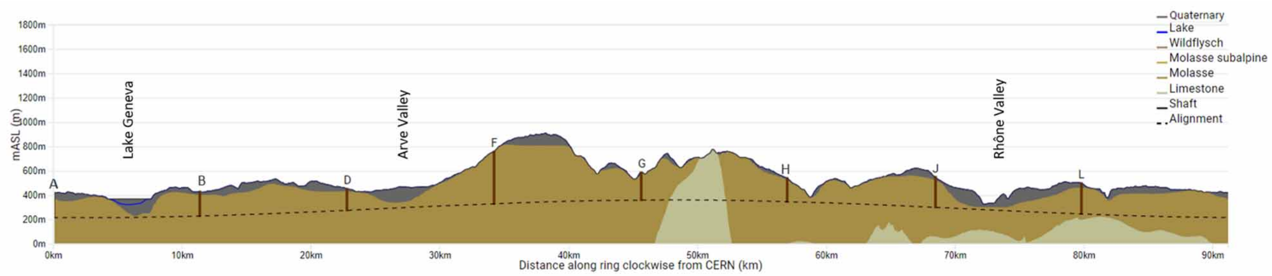

Figure 3: FCC Long section. (CERN).

Directly under the lakebed, there are very soft deposits which have been identified in previous site investigation campaigns along the proposed alignment. These have been identified as very soft lacustrine clayey silts and glacial-lacustrine silts and clays with elastic modulus between 2 MPa and 10 MPa, extending from the lakebed to a level of 260 m [3]. Despite little available information for the Arve Valley and Rhône Valley, it is expected that soft deposits, alluvial and alluvio-glacial moraines are to be encountered at depths of up to approximately 100 m below ground level. To avoid construction challenges and the risk of water inflow, the alignment of the tunnel has been lowered by a further 30 m to allow the tunnel to pass through the stronger rock.

There are some known faults within the molasse that will bisect the alignment of the tunnel. The LEP, and before that the Super Proton Synchrotron (SPS), passed through the significant fault of the Allondon near Meyrin, without encountering significant problems during construction. Though for the LEP and LHC, the faults have posed greater problems regarding long-term stability.

The Jura and Vuache limestone are challenging for excavation due to karstic features formed by chemical weathering of the rock. It is common for the karsts to be filled with water and sediment, which can lead to water inflow and instability during excavation. In comparison to the molasse, CERN has experienced significant issues with excavating in the limestone of the Geneva region. During the construction of the LEP, sector 3 to 4 was excavated in the Jura limestone where there were major issues with water ingress at the tunnel face [2].

Horizontal Alignment

Since the FCC study was launched in 2012 various shapes and sizes for the machine ring have been considered, these have ranged from 47 km to 100 km circumference rings in addition to less conventional "racetrack" shapes. The smallest options were ruled out early-on, even though they carried the lowest risk for civil engineering, as the accelerator would not be able to reach adequate energies. By 2016, an approximately 100 km diameter ring had been adopted by the project team. This ring was initially considered in two distinct positions, one under the Jura, and the other in the molasse basin passing below Lake Geneva. The Jura option was excluded due to the high risk of tunnelling through the karstic limestone with very high overburden.

From 2016 onwards small variations on the chosen position have been evaluated. In the Geneva basin there is limited scope to place a 30 km diameter ring with adequate connections to the existing particle accelerator, whilst avoiding the undesirable ground conditions. Therefore, the strategy for placement has been to avoid the limestone of the Jura and Pre-Alps, whilst also aiming to minimise tunnelling in the water-bearing moraine layer and keeping overburden to a minimum. This has led to the current position that fits tightly within the natural boundaries of the limestone formations, and the lake whose depth increases to the north-east.

Vertical Alignment

A key objective of the study so far has been to develop a vertical alignment that places all cavern excavations in rock and the remaining structures and connections in adequate ground conditions. These conditions tend to be met by deepening the vertical alignment. However, operation of the FCC and connections to the existing LHC are more efficient with a shallow alignment, so a compromise must be made.

Based on the available information, the vertical alignment has been chosen so that both conditions are satisfied in the best way. This has resulted in an alignment with tunnel ground covers of between 50 m and 650 m.

Shaft

A total number of 14 shafts are required to provide access to the subsurface tunnels. The two transfer tunnels between the LHC and FCC will each require a temporary construction shaft. The 12 permanent shafts will be situated at each of the 8 FCC surface sites, with two shafts (one to the service cavern and one to the experiment cavern) at each of the experimental locations (A, D, G, and L) and one shaft at each of the technical sites (B, F, H, and L).

The vertical shafts will be of various dimensions, from 12 to 18 m diameter. At the time of writing, the specific diameter of each shaft is to be confirmed following confirmation of the machine layout and access requirements.

Due to existing surface constraints, three of the service cavern access shafts are likely to require offset from the centre points of the machine straight sections. The point B service shaft requires a 440 m clockwise offset around the FCC ring, to reduce environmental impact at the surface in a sensitive area. Point F requires the shaft to be offset both 430 m anticlockwise and 400 m inside the ring, to avoid

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residential constraints at the surface. Whilst at point H the service shaft will be offset 800 m around the ring due to environmental and residential constraints.

Caverns

Sub-surface caverns are required at each of the FCC points, to accommodate the detectors, maintenance equipment, transport vehicles, service infrastructure and access. The experiment sites have both an experiment cavern and a service cavern, spaced 50 m apart. Initial design proposals had the two caverns side by side, with a concrete pillar as support, like the existing cavern arrangement at the LHC point 5. However, to provide shielding from stray magnetic fields, the caverns need to be spaced further apart. Consequently, construction risks will also be reduced because of the increased spacing.

At the four technical sites only service caverns are required, connected to the machine tunnel via bypass tunnels. Where tunnels intersect, junction caverns are also proposed, to help the TBM excavate from the bypass tunnels to the machine tunnel.

Tunnels

As well as the 91.2 km length main machine tunnel, there will be an additional 25 km of tunnels in the form of bypass, injection, beam dump and service tunnels connecting to the main tunnel. Most of the tunnels will be 5.5 m internal diameter, however, in certain places such as the Klystron galleries at Points H and L, the machine tunnel requires widening to 6 m to accommodate the extra machine infrastructure.

Figure 4 shows the typical tunnel cross section, with the tunnel floor arrangement, ventilation and smoke extraction

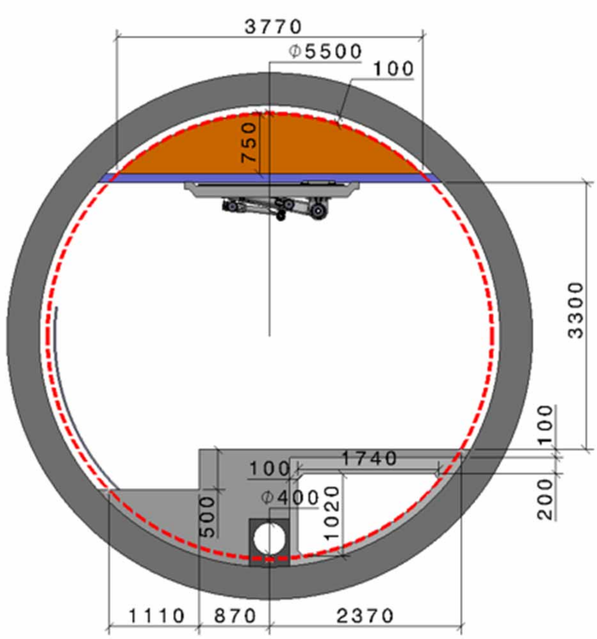

Figure 4: Typical FCC tunnel cross section. (Fani Valchkova-Georgieva, CERN).

ducts, and the position of the rail mounted maintenance robot at the tunnel ceiling

Safety partitions are to be provided every 440 m along the tunnel, in the form of fire walls and doors, so that individual sections of tunnel can be isolated in the event of an emergency. This allows incidents themselves to be contained within tunnel compartments to restrict further spread, as well as providing safe compartments for evacuees to shelter in whilst awaiting rescue.

Construction

TBMs will be used for most of the FCC tunnel excavations. These utilise an integrated full-face excavation and support system that is available for various ground conditions. The head of the TBM is equipped with modern systems of excavation which allow high rates of advance while ensuring full support of the surrounding ground. A shield or tail skin provides initial support to the ground and protection to construction personnel [3].

The tunnelling method is driven by the ground characteristics and more importantly, the stand-up time. Soft ground has very limited stand-up time which makes it imperative that the excavation is supported immediately. In comparison, hard rocks allow the excavations to be done in advances up to 4 m, before supporting the excavated void. Choosing between a gripper TBM or a shielded TBM is dictated by controlling the stability of the ground during construction and the expected amount of water ingress [5].

For shorter runs of tunnelling, caverns, alcoves and areas of high geological risk (i.e. areas of limestone), more traditional methods of excavation are employed. Drill and blast is one such method where holes are drilled in the rock face and charged with explosives, which are then detonated and the fallen rock removed. Whilst this method of excavation does not match the speed of a TBM, it allows the rock face to be more closely surveyed and controlled. This is important in areas of geological risk such as the limestone, where encountering karst formations can result in water inflow. Furthermore, drill and blast is essential in excavating irregular tunnel shapes such as for the caverns, junctions, klystron galleries and tunnel widenings where a non-circular tunnel is required.

Thermal Heat Recovery

Engineering consultancy Arup recently completed a feasibility study into tunnel heat recovery from future CERN tunnels [6]. The study focused on the implementation of a heat recovery system into the tunnel lining of the Compact Linear Collider (CLIC). Whilst CLIC is a separate project to the FCC, the study can be deemed applicable, as FCC and CLIC share similar tunnel geometries and geological properties.

Ambient temperature increases with depth below the earth's surface. As a result, it is possible to extract heat from the ground to provide heating for residential and commercial properties. The study investigated the potential heat extraction available from the machine tunnel, considering the geothermal properties of the region and an estimate of the residential heating demand at the surface.

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The study concluded that heat recovery systems could be implemented in the tunnel lining, to provide 10-30 W/m2 of output, so long as energy balancing is provided by heat rejection during summer.

Costs

Total civil engineering costs were calculated to be around CHF 6 billion by the consulting engineers ILF when the FCC design included 12 points and a machine tunnel length of 97 km [3]. Since then, the FCC layout has been reduced to 8 surface sites and 91.2 km length as described above. Whilst this reduction in scope will reduce costs, a full assessment of the scheme is yet to be undertaken by the consultant ILF, so an accurate cost schedule for the updated design is not yet available.

The original cost estimate produced by ILF included direct costs (materials, equipment, and personnel) and indirect costs (management, support personnel, site preparation and dismantling). However, it did not include costs for land procurement or spoil disposal.

Material and labour costs were derived from previous project data, equipment costs were taken from the BGL Construction Equipment Register and building costs were calculated in accordance with the BKI Construction Costs [3]. ILF cross checked these estimated costs with the HL-LHC (High-Luminosity LHC) project and other tunnelling projects across Europe.

For the updated 8-point FCC, civil engineering costs are currently being updated as the design progresses.

CONCLUSION

The conceptual design for the FCC underground infrastructure ensures compatibility for hosting both the FCC-ee and FCC-hh consecutively. The geometry of the tunnel is strictly dictated by defined parameters of the machine and experiments. The project has been set out at the optimum location to achieve the best connections to the existing CERN accelerator complex, within the most favourable ground conditions. Some degree of change will be expected following the results from the planned site investigations, which will commence in 2024. The FCC location, alignment and construction methods will then be further refined.

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