FCC Integrated Programme Stage 2: The FCC-hh

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Contribution to the European Strategy for Particle Physics Update 2025

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Abstract

The Future Circular Collider (FCC) 'integrated programme' consists of an initial electron-positron collider FCC-ee, which is later followed by a proton-proton collider, FCC-hh. This comprehensive programme is well matched to the current scientific landscape after 15 years of LHC operation. The proposed staging takes into account: (1) the physics priorities as developed and stated by EPPSU 2013 and 2020; and (2) the relative technology readiness and costs of FCC-ee and FCC-hh.

Both FCC-ee and FCC-hh are installed in the same $91\,\mathrm{km}$ circumference tunnel close to CERN, which allows reuse of all FCC-ee civil engineering and much of the technical infrastructure for the subsequent FCC-hh, thus maximising the return on investment and ensuring sustainable long-term use of the infrastructure. Taking advantage of a perfect four-fold superperiodicity, FCC-ee and FCC-hh each accommodate four experimental detectors. The two FCC stages, FCC-ee and FCC-hh, are optimised so as to enable the widest possible physics programme, with ample complementarity and synergies between Stage 1 and Stage 2.

The hadron collider, FCC-hh, operates at a centre-of-mass energy of about $85\,\mathrm{TeV}$, extending the energy frontier by almost an order of magnitude compared with the LHC, and providing integrated luminosity 5–10 times higher than that of the upcoming High-Luminosity LHC. The mass reach for direct discovery at FCC-hh amounts to several tens of TeV, and allows, for example, the direct production of new particles, whose existence could already be indirectly exposed by precision measurements at FCC-ee. The FCC-hh hadron collider can also accommodate ion-ion, ion-hadron, and lepton-hadron collision options, allowing for complementary physics explorations.

A project implementation scenario has been developed and an analysis of the current environmental status has not revealed any showstoppers. The dialogue with the public has begun. The project implementation scenario, the analysis of the environment, and engagement with the public, representing about seven years of past activities, are necessary prerequisites for the authorisation processes with the host states and facilitate convergence towards a credible implementation schedule and planning security. For the FCC-ee, a wider socio-economic impact assessment has revealed a positive net present value under conservative assumptions and implementation conditions. An equivalent assessment remains to be done for FCC-hh.

The three volumes of FCC Feasibility Study Report are available for download [1–3].

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1 Scientific Context

The 2013 Update of the European Strategy for Particle Physics (ESPP) [4] declared, as its second highest priority, that "*to propose an ambitious post-LHC accelerator project. . . .., CERN should undertake design studies for accelerator projects in a global context,. . . with emphasis on proton-proton and electron-positron high-energy frontier machines*". Consequently, in 2014 the global Future Circular Collider (FCC) study was established to design a $100 - \mathrm{TeV}$ proton collider (FCC-hh) housed in a new $\sim 100\,\mathrm{km}$ tunnel near Geneva, with a high-luminosity electron-positron collider (FCC-ee) as a potential intermediate step. This study, which was partly supported by the EU co-funded EuroCirCol project [5], resulted in four volumes of Conceptual Design Report (CDR), notably Volume 3 [6], and in a preliminary cost estimate.

Following the 2020 ESPP Update [7], the CERN Council next launched the FCC Feasibility Study (FS) [8, 9]. Like the earlier FCC CDR study, the FCC FS was organised as an international collaboration with about 150 participating institutes from around the world. Parts of the FCC FS efforts were carried out within the framework of the EU co-funded FCC Innovation Study [10]. The FCC FS was mandated to deliver a Feasibility Study Report (FSR). This FSR, which has been submitted as input to the 2025/26 ESPP update [1–3], addresses not only the technical design but also numerous other key feasibility aspects, including tunnel construction, costing, sustainability, and environmental conditions, as requested.

The FCC integrated programme is also fully aligned with the 2023 US P5 recommendations [11], which include "*An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson ...*" and "*an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM [parton centre-of-mass] collider*".

Finally, the FCC integrated programme is a consistent response to the 2024 "Draghi report" on European competitiveness [12].

2 Objectives

The goal is developing, implementing and operating the most versatile and sustainable post-LHC experimental infrastructure to address key open questions of particle physics, in a coordinated world-wide effort. This goal is achieved by an integrated programme, which starts with a highest-luminosity electron-positron collider, FCC-ee, serving as Higgs, top and electroweak factory, and continues with a highest-energy hadron collider, FCC-hh. The long-term vision of an enduring infrastructure also implies important planning security for the participating institutes and countries.

More specifically, in a first stage, over a time span of 15 years, the FCC-ee operates at centre-of-mass energies between about 90 and $365\,\mathrm{GeV}$, always delivering the highest possible luminosities to four experiments, in a sustainable and energy-efficient way. The FCC-ee also prepares for the future highest-energy hadron collider, as its tunnel, surface sites, and its technical infrastructure are fully reused for the second FCC stage, the FCC-hh, thereby maximising the return on investment and ensuring a sustainable long-term usage of the infrastructure..

This hadron collider FCC-hh provides proton–proton collisions with a centre-of-mass energy of the order of 80–90 TeV and an integrated proton-proton luminosity of about $20\,\mathrm{ab}^{-1}$ in each of two multi-purpose experiments during 25 years of operation. Two specialised detectors shall be located in the remaining two experiment straights. In addition to colliding protons with protons, also proton-ion and ion-ion collisions, as with the LHC [13–15] but at much higher energy, are envisaged. Furthermore, one interaction point is upgradeable to electron–proton and electron–ion collisions.

3 Methodology

The most efficient method for the thorough exploration of the open questions in modern high-energy physics is a staged, integrated research programme consisting of a high-intensity lepton collider to achieve an exhaustive understanding of the Standard Model, including thorough searches for physics beyond it, so as to guide the optimised design of a subsequent cost-effective and sustainable energy-frontier hadron collider that reuses the entire existing technical and organisational infrastructures. This staged approach, which allows the control of technical and financial risks, will contribute to strengthening European cohesion and competitiveness of the European research landscape [12]. It will ensure contributions from outside the European Research Area. The entire project will be a platform which is continually open to new institutes, new countries, and industrial companies.

The hadron collider FCC-hh extends both centre-of-mass energy and peak luminosity by about an order of magnitude compared with the upcoming HL-LHC, as illustrated in Fig. 1.

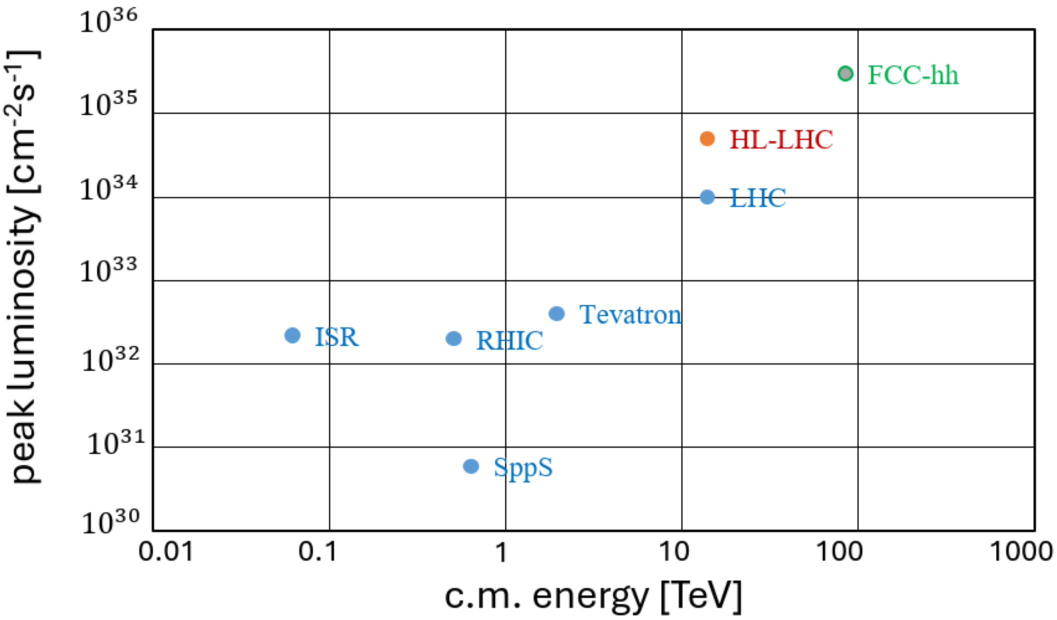

Fig. 1: Peak luminosity versus centre-of-mass energy for past and present hadron colliders (blue), the HL-LHC collider under construction (red), and the proposed FCC-hh (green).

The design of the FCC-hh hadron collider is based on LHC experience. The key challenges are magnet technology and cryogenic power consumption in the presence of strong synchrotron radiation. To limit the latter and also because the radiation damping during the store is significant, the beam current and the bunch population are reduced compared to those of the HL-LHC [16, 17].

The synchrotron-radiation heat, which must be extracted from inside the cold magnets, is a major contribution to cryogenic power. The baseline FCC-hh dipole magnets with a target field of $14\,\mathrm{T}$ are based on $\mathrm{Nb_3Sn}$ superconductor operating at a temperature of $1.9\,\mathrm{K}$ with an elevated temperature of the beamscreen intercepting the synchrotron radiation. The cryogenic power could be further reduced by operating these magnets at a temperature of $4.5\,\mathrm{K}$ instead of $1.9\,\mathrm{K}$, and even further for magnets based on high-temperature superconductor (HTS) technology if these were operated at even higher temperature. However, heating of the conductor and magnet coils during the energy ramp is a concern, especially for HTS. These are active research directions of the HFM programme.

The layout of the FCC-ee and its injector design are fully compatible with the demands of the future hadron collider FCC-hh, and do not compromise the latter's performance. Taking advantage of a perfect four-fold super-periodicity, FCC-ee and FCC-hh can each accommodate four experimental detectors. The two FCC stages, FCC-ee and FCC-hh, are optimised so as to enable the widest possible physics programme, with ample complementarity and synergies between Stage 1 and Stage 2.

The existence of a single tunnel of this kind, exploited over at least half a century and serving the global particle physics community, exemplifies the discipline's commitment to sustainability. Moreover, the choice to propose the project in France and Switzerland, where electricity already is largely decarbonised, demonstrates a serious and proactive approach to environmental considerations.

The general implementation of FCC is driven by the principles of cost optimisation and sustainability, as described in Volume 3 of the FS Report. Examples include minimisation of the number of surface sites and the length of access roads by optimising tunnel placement, the planned processing of the excavated spoil for multiple purposes of societal importance, the local use of waste heat, and responsible consumption of water.

As for the accelerators themselves, storage rings are intrinsically highly sustainable machines, as they collide the same beams again and again, at multiple interaction points and over millions of turns. Their efficiency is limited primarily by the cryogenic power required to remove the energy deposited by synchrotron radiation, which, in the case of the FCC, is minimised by its large circumference.

The principal technology for constructing a collider like FCC-hh is the high-field magnet system. The energy consumption of the FCC-hh accelerator is restricted by a variety of measures and design choices, such as the introduction of low-power *eco-mode* for the cryogenic plants, elevated temperature of the beamscreen that intercepts synchrotron radiation (50 or 70 K), and possibly also a higher temperature of the magnet cold bore, etc.

The experimental research at the FCC will be based on international collaborations with long-term open access to experimental detector data and on a community-based scientific analysis supported by a worldwide data processing infrastructure, as is best practice in high-energy physics. This programme is complementary to other ongoing research activities (e.g., long-baseline neutrino experiments in the US and Japan) and leverages cross-disciplinary synergies to expand our understanding of the universe (e.g., dark-matter searches complementing astroparticle-physics research projects).

4 Readiness and Expected Challenges

Technically, the project comprising tunnel and subsurface structures, surface sites, territorial developments, technical infrastructures, injector (options) and associated transfer lines, particle collider, and up to four experiments is ready (TRL 2 to 9, depending on the domain) for detailed technical design followed by preparation and implementation. Significant work on the development of a feasible territorial implementation has been anticipated in a positive and forward-looking way. These activities facilitated the development of a credible implementation schedule with planning security. After about seven years of preparatory work, the FCC-ee study is now ready to embark on a detailed design and project authorisation phase.

The performed preparatory work includes: the development of a feasible alignment of the tunnel and placement of the surface sites; the preliminary design of subsurface structures; a comprehensive analysis of the environment in which the infrastructure would be placed; an analysis of the resource needs (electricity, water) and the carbon budget of construction based on credible state-of-the-art low-carbon construction products and techniques; consideration of the authorisation processes and implementation conditions in both host states; limited-term protection of the concerned land surfaces; development of site accesses; a comprehensive socio-economic appraisal for Stage 1 as part of the project authorisation process by both host states; the development of a strategy for the management of the excavated materials; and the start of the dialogue with the public as formally requested for project authorisation. The "Avoid-reduce-compensate" principle has been adopted from the start to ensure that the entire development process, in line with the requirements of the host state authorisation process, can be seamlessly documented.

The formal authorisation processes will require detailed designs for the assessment of the environmental impact and the development of further avoidance, reduction, and compensation measures. These include the development of agreements with owners of affected plots of land (surface sites, temporary and permanent access roads, conveyor belt traces, paths for electricity, raw water, drinking water, and sewage), off-takers of excavated materials for deposit and reuse, and the development of territorial synergies (e.g. waste-heat supply, site-related tourism, mobility).

Based on the experience of LHC operation and on the parameters of the hadron beams presently provided by its injector complex, the projected luminosity performance of the FCC-hh should be attainable, after building this machine. However, the technical readiness of the FCC-hh depends on the availability of the high-field magnets. The about 5000 arc magnets considered are either based on Nb_3Sn superconductor, like the 24 triplet quadrupoles being presently produced for the HL-LHC project, or on advanced HTS. A baseline field of $14\,\mathrm{T}$ is considered, significantly higher than the $8.1\,\mathrm{T}$ for the Nb-Ti magnets of the LHC arcs at $6.8\,\mathrm{TeV}$ beam energy. Ongoing and future R&D, over the next few decades, aims to develop high-performance conductors, prototyping short and long magnet models, and ultimately industrialisation and series production at an affordable cost. The layout of the FCC-hh cryogenic system for an operation scenario with $14\,\mathrm{T}$ dipole magnets at $1.9\,\mathrm{K}$ is shown in Fig. 2.

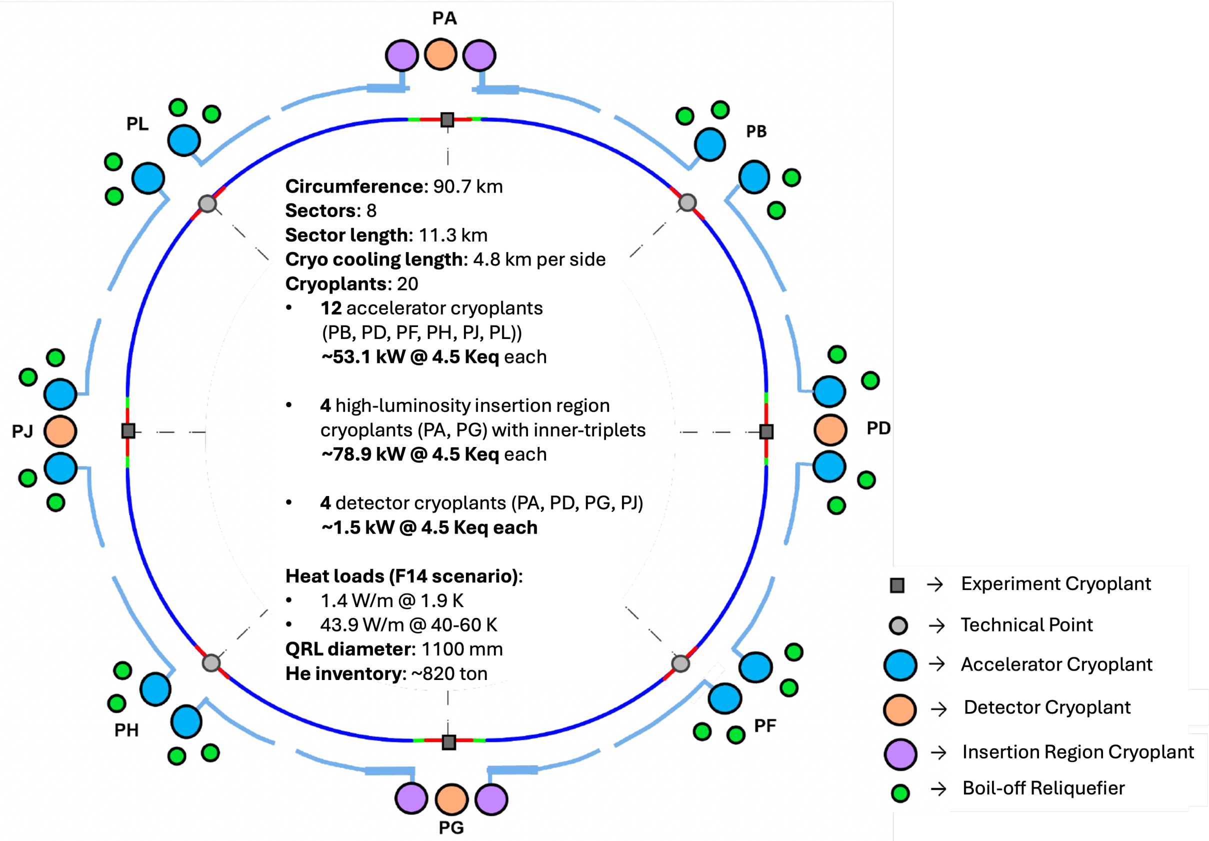

Fig. 2: Updated layout of the FCC-hh cryogenic system for $14\,\mathrm{T}$ dipole magnets at $1.9\,\mathrm{K}$.

The conductor critical non-copper current density required to produce $14\,\mathrm{T}$ at 80% loadline fraction is already attained with the best Nb_3Sn conductor available today. It corresponds to $1200\,\mathrm{A/mm^2}$ at $16\,\mathrm{T}$ and $4.22\,\mathrm{K}$. Further development of usable magnet wires based on this technology with even higher performance is under way, reaching and exceeding $1500\,\mathrm{A/mm^2}$, but efforts have not yet begun to industrialise the technology. The margins for the FCC-hh Nb_3Sn dipoles are shown in Fig. 3. The 2025 baseline for FCC-hh guarantees a $4.6\,\mathrm{K}$ temperature margin and a 60% current margin. The margins for the FCC-hh Nb_3Sn dipoles are compared with those of the LHC Nb-Ti arc dipoles and for the HL-LHC

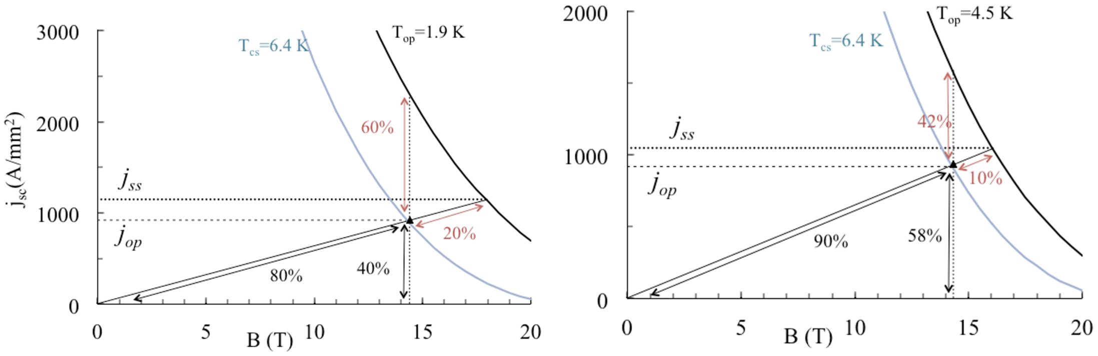

Fig. 3: Margins for FCC-hh Nb_3Sn dipoles at $1.9\,K$ (left) and at $4.5\,K$ (right).

Table 1: Margins for LHC dipoles, HL-LHC triplet, and FCC-hh dipoles, operating at $1.9\,K$.

	Beam energy (TeV)	Bore field (T)	Peak field (T)	Loadline margin (%)	Current margin (%)	Temperature margin (K)
LHC dipole	7.0	8.3	8.7	14%	43%	1.3
HL-LHC triplet	7.0	9.9†	11.3	22%	54%	4.9
FCC-hh dipole	42.5	14	14.5	20%	60%	4.5

† The quadrupole gradient times the aperture radius is given here.

Nb_3Sn triplet magnets in Table 1.

The data on HL-LHC Nb_3Sn quadrupole magnets show that they can all operate at $4.5\,K$, as shown in Fig. 4 [18, 19]. In addition, performance-limiting instabilities are more severe at $1.9\,K$ than at $4.5\,K$. This could open the possibility of operating the FCC-hh Nb_3Sn dipoles and quadrupoles at $4.5\,K$. Keeping the same magnets with 20% loadline margin at $1.9\,K$ would imply a reduced loadline margin of 10% at $4.5\,K$, a current density margin of 42% and a temperature margin of $1.9\,K$, as shown in Fig. 3. The $4.5\,K$ option could rely on dry magnets (cold mass not filled with liquid helium); this would reduce the He inventory, although it would pose challenges for magnet cooling during the ramp, and for magnet insulation.

Nb_3Sn accelerator dipole models have been developed since the late 80s. The target magnetic field can be achieved with various magnet and coil designs, each presenting opportunities and challenges [20]. The cross sections of the various designs pursued in the 'High-Field Magnet (HFM) programme are shown in Fig. 6. Since 2015, triplet quadrupoles of the HL-LHC interaction region [18, 19, 21] showed very good reproducibility of performance ($11.3\,T$ peak field under nominal conditions), nominal currents were also achieved at $4.5\,K$ in all models, $13\,T$ was achieved in many short models, scaling to $7.15\,m$ lengths, and there was no degradation of performance after the thermal cycle. The project is halfway through production at the time of writing.

In the second half of the 2010s, the MDPCT1 dipole reached $14.5\,T$ at $1.9\,K$ in a $60\,mm$ aperture. This magnet, built at FNAL, is a four-layer $\cos\theta$ dipole with grading, and is the first dipole to reach fields above $14\,T$ at $4.5\,K$ [22] with a coil width of the order of $50\,mm$, making it a fully functional accelerator magnet. After reassembly and a thermal cycle, the performance degraded irreversibly by more than 10% [23].

Discovered in the mid 80s in the family of cuprates, HTS have many interesting features that make them a game changer in superconducting technology; see Fig. 7 [24]: (i) high values of critical current density (>2000 A/mm^2) also above $20\,T$, opening the way to high fields; (ii) the ability of sustaining high current densities and fields at and above $20\,K$, opening the path to cheaper cooling systems (even

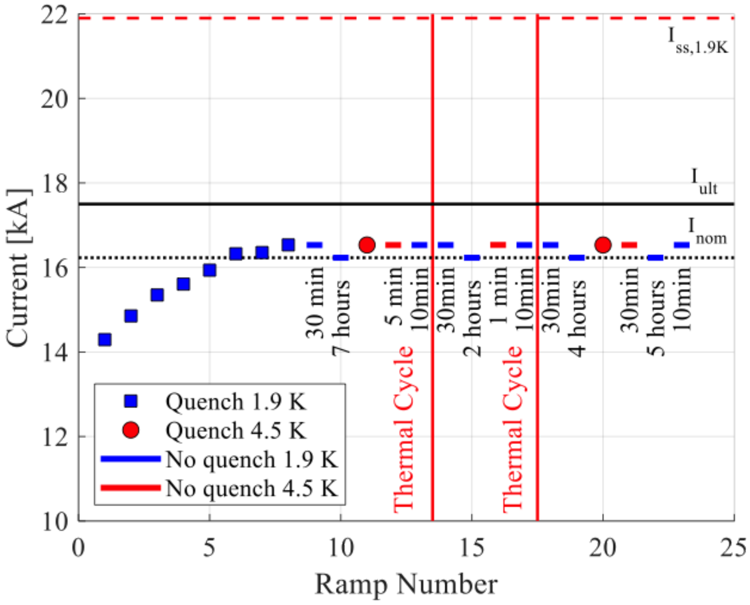

Fig. 4: A typical HL-LHC Nb_3Sn quadrupole magnet training, reaching nominal current also at 4.5 K.

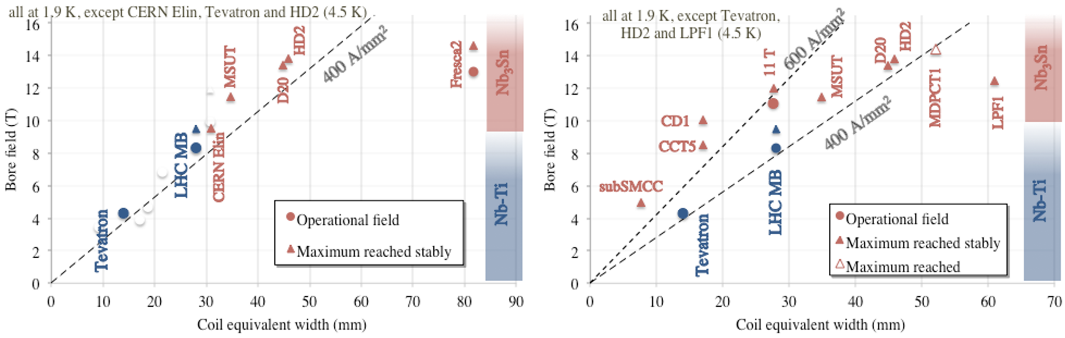

Fig. 5: Operational and achieved field versus coil width in LHC and Tevatron colliders, and in Nb_3Sn short models (left), and 11 T, MDPCT1 dipoles, and common coil and CCT demonstrators (right).

though liquid nitrogen cooling is still considerably out of reach for high field magnets); and (iii) a much higher stability versus thermo-mechanical perturbation due to the increase in enthalpy margin at higher operating temperatures. The HFM programme is exploring the options of dipole magnets in the 14 to 20 T range, at temperatures between 4.5 K and 20 K, thus covering a centre-of-mass energy in the range of 85 to 120 TeV.

Two types of HTS are commercially available: BSCOO 2212 and REBCO. The conductor BSCOO 2212 [25], produced mainly by a company in the US, has the advantage of being available as round wire with small filaments. Its use is complex since, like Nb_3Sn, it needs a reaction after winding, but at 900° in oxygen rich ∼50 bar atmosphere. A process-compatible electrical insulation system must be selected. Moreover, BSCOO 2212 is brittle and, hence, requires careful handling in coil manufacturing and appropriate mechanical structures to respect stress limitations. Several short magnet models have been successfully built in the US.

The superconductor REBCO [26] is produced by multiple suppliers worldwide; this conductor is produced in the geometry of a tape, and its industrialisation recently profited from large private investments aiming at ultra-compact magnet systems for fusion (solenoids and toroidal field coils) with ∼20 T

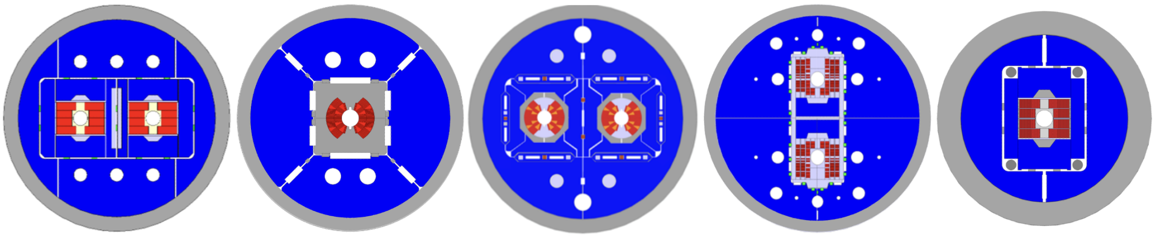

Fig. 6: Conceptual design of 14 T and 12 T magnets: BOND (left), FalconD INFN (centre left), FalconD CERN (centre), SMACC1 (centre right), F2D2 (right).

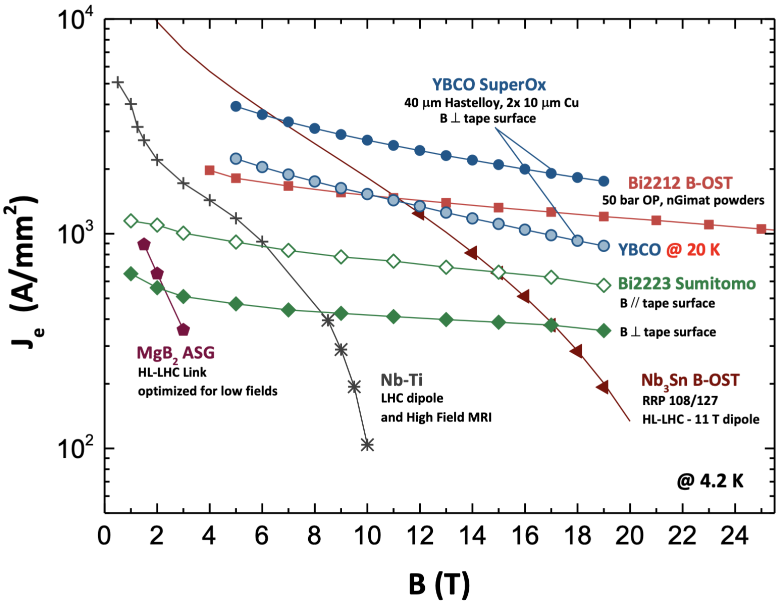

Fig. 7: Critical (engineering) current densities of different HTS conductors, Nb_3Sn, and Nb-Ti. Reproduced from [24].

coil field. This has reduced the price in the last ten years by a factor of three. The conductor does not require heat treatment after winding. On the other hand, (i) unit lengths are still typically short ($\sim$300 m) and longer lengths today affect the cost, (ii) REBCO is a highly anisotropic conductor (anisotropy factor of $\sim$5). The challenge is not only to make a fully transposed (Rutherford-like) cable from tape to wind a coil, but also to deal with mechanical properties: while very robust against tension and transverse compressive stress, de-lamination of the tape under tensile transverse stress causes degradation. Another challenge is to control hysteresis losses and field quality as the equivalent filament size is very large in the plane of the tape (typically 4-12 mm).

The development of iron-based HTS [27, 28], is being strongly pursued in China. The critical current density achieved is still lagging a factor 2-3 behind the expectations set ten years ago, but based on raw-material prices the material has the potential of a very low cost; this could become a significant advantage for a collider magnet where a large fraction of the price is the superconductor.

Between 2015 and 2020, three REBCO-based dipole magnets were built within the framework of the FP7-Eucard2 programme [29]. In CEA, a dipole technology demonstrator based on double REBCO ribbons and three racetrack coils, without aperture, reached 5.4 T [26]. In the same period, two magnets were built with Roebel cable: in CEA a 40 mm aperture dipole was manufactured with a $\cos\theta$ configuration, 12 mm coil width, reached only 1.16 T due to one degraded coil [30]. This magnet will be re-tested with a replacement coil. At CERN a dipole was built with the same cable, with an aligned block dipole configuration in a $40\,\mathrm{mm}$ aperture, reaching $3.35\,\mathrm{T}$ at $5\,\mathrm{K}$ and $4.3\,\mathrm{T}$ at $4.5\,\mathrm{K}$ (FeatherM2.12 and 2.34 [29, 31]).

More recently, the US magnet development programme, US-MDP, has developed several Bi-2212 racetrack coils and a canted cosine theta (CCT) magnet, which reached $1.6\,\mathrm{T}$ in a $31\,\mathrm{mm}$ aperture [32]. A CCT with a CORC® cable based on a REBCO tape reached $2.9\,\mathrm{T}$ in a $65\,\mathrm{mm}$ aperture [33], with a more recent test exceeding $5\,\mathrm{T}$.

The superconducting magnets for the FCC-hh will have a maximum external cryostat diameter of $1.2\,\mathrm{m}$, regardless of the technology used (Nb_3Sn, HTS, etc.), resulting in the tunnel cross section shown in Fig. 8.

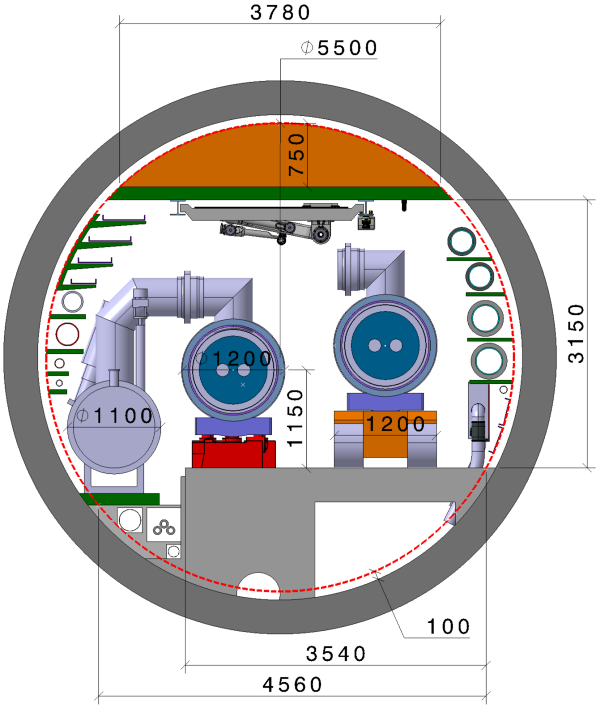

Fig. 8: Cross section of the FCC-hh tunnel in the arcs.

Three options for an FCC hadron injector are summarised in Table 2. All options can deliver the main beam parameters required, such as intensity, emittance, and bunch spacing. The main difference is the implied FCC-hh injection energy. An attractive option for a high-energy injector seems to be a new $4\,\mathrm{T}$ machine in the LHC tunnel. Another possibility, with intermediate beam energy, is a $2\,\mathrm{T}$ superferric machine. If a collider injection energy of $1.3\,\mathrm{TeV}$ is acceptable, a superconducting ring in the SPS tunnel (scSPS) becomes attractive.

5 Timeline

The timeline of FCC-hh as a second stage after FCC-ee is shown in Fig. 9. The preparatory phase encompasses the technical design, the authorisation processes in the two host states, and preparation for construction. The additional civil construction works will be integrated with the installation activities for the technical infrastructures and particle accelerators. The assembly of the experiment detectors is foreseen to be carried out to a large extent in the caverns. This schedule enables the start of FCC-hh beam operation by early or mid 2070s. Today, it is foreseen that the FCC-hh operation phase extends

Table 2: Comparison of high-energy booster options, a superconducting machine in the SPS tunnel (scSPS), a modified faster-ramping LHC and a new 4 T machine in the LHC tunnel. A further option (not listed here) with an intermediate energy of 1.75 TeV would be a superferric machine in the LHC tunnel.

	Unit	scSPS	modified LHC	4 T LHC
Circumference	km	6.9	26.7	26.7
Apertures		1	2	1
Injection energy	GeV	26	450	450
Extraction energy	TeV	1.3	3.3	3.3
Injection field	T	0.12	0.6	0.6
Maximum field	T	6	4	4
Energy/field swing		50	7	7
Number of dipoles		372	1232	1232
Number of bunches		640	2600	2600
Stored energy	MJ	15	167	167
Collider filling time	min	37	46	39

over about 25 years. Additional details can be found in the Appendix B.1. The timeline of the FCC-hh as a stand-alone project is shown in Fig. 10.

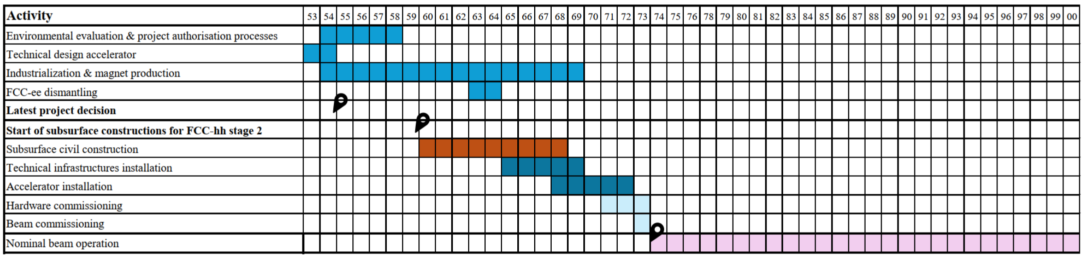

Fig. 9: Timeline of FCC-hh as second stage after FCC-ee from preparatory phase to the end of operation.

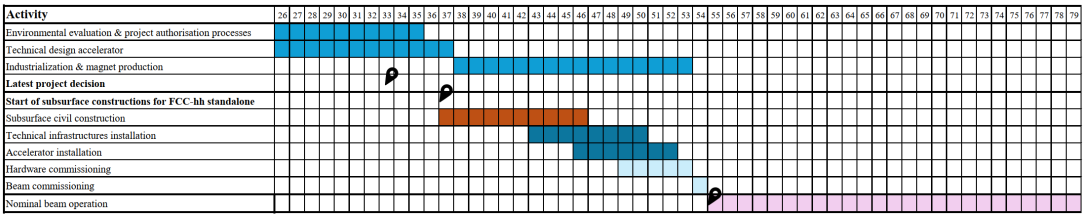

Fig. 10: Timeline of FCC-hh as stand-alone project from preparatory phase to the end of operation.

6 Construction and Operational Costs

6.1 Construction

The capital cost for FCC-hh construction, as a second stage of the integrated FCC programme, is summarized in Table 3. The total construction cost amounts to 18,880 MCHF. It is dominated by the collider magnets, amounting to about 10,000 MCHF.

The main additional civil engineering structures required for FCC-hh as as second stage are the beam dump tunnels and the transfer-line tunnels, with a total construction cost of 520 MCHF. For technical infrastructures, most of the electrical, cooling and ventilation installations are reused. The cryogenics infrastructure for the main magnet cooling, therefore, drives the capital cost that amounts to a total of 3,960 MCHF, including any adaption of the other technical infrastructure systems. The cost of the FCC-hh injector and transfer lines is estimated at 1,000 MCHF. The final cost will depend on which injector option of Table 2 is chosen. At the time of the CDR [6] (2018), the combined cost estimate for modifying the existing LHC and for the new transfer lines was 615 MCHF. The cost of the four FCC-hh experiments can be estimated only at a later stage, once more detailed designs of the detectors exist. The construction investments are distributed over a time frame of about 15 years.

Table 3: Estimated investment costs for different construction domains in 2024 Swiss Francs.

Domain	**Cost (MCHF)**
Civil engineering	520
Technical infrastructures	3,960
Injectors and transfer lines	1,000
Collider	13,400
FCC-hh total	**18,880**

The indicated costs include materials and personnel costs of contractors and suppliers. They do not include the cost of scientific, engineering, technical, and administrative personnel at the host organisation or at the collaborating institutes.

6.2 Operation

Operational costs for FCC-hh have not yet been determined.

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Appendices

Additional specific information

A Stages and parameters (2)

A.1 The main stages of the project and the key scientific goals of each

The first stage of FCC is the lepton collider FCC-ee, described in a companion submission, and the second stage is the hadron collider FCC-hh. Note that a schedule has also been developed for the case of FCC-hh as a stand-alone project.

The key parameters for FCC-hh are compiled in Table A.1. The bunch population (close to 1×10^{11} protons per bunch) and the beam current (0.5 A) are kept the same as in the 2018 CDR [6], although it refers to the baseline design with 14 T dipole magnets, which could be based on Nb_3Sn technology. The table illustrates how the synchrotron radiation strongly increases with higher magnetic field.

Table A.1: Parameters of FCC-hh compared with the HL-LHC and LHC. For the integrated luminosity, 160 days of operation per year, and 75% machine availability is assumed [34]. With 185 days of physics beam operation and 80% availability the annual integrated luminosity of FCC-hh would be ~20% higher. The regular bunch spacing is 25 ns for all three colliders.

	Unit	FCC-hh	HL-LHC	LHC
Centre-of-mass energy	TeV	84.6	14	
Circumference	km	90.7	26.7	
Dipole field	T	14	8.33	
Beam current	A	0.5	1.1	0.58
Bunch Intensity	10^{11} p	1.0	2.2	1.15
No. bunches / beam		9500	2760	2808
Synchr. radiation power	kW	2400	15	7
SR power / length	W/m/aperture	6.5	0.33	0.17
Longit. emit. damping time	h	0.75	12.9	
IP beta function $\beta^*_{x,y}$	m	0.3	0.15 (min.)	0.55
Normalised rms emittance	µm	2.2	2.5	3.75
Peak luminosity	10^{34} cm^{-2}s^{-1}	30	5 (lev.)	1
Peak no. events / bunch crossing		1000	132	27
Stored energy / beam	GJ	6.5	0.7	0.36
Int. annual luminosity / IP	ab^{-1}/y	0.9	0.25	0.05

The primary scientific goals of FCC-hh are as follows:

- Producing over 20 billion Higgs bosons to bring the absolute determination of the Higgs couplings to muons, to photons, to the top quark and to Zγ below the percent level, and accurately measuring the ratio of those couplings to couplings precisely measured at the FCC-ee, thereby enabling sub-percent absolute coupling measurements.
- Measuring Higgs self-coupling to the percent level.
- Studying Higgs boson production in very high Q^2 processes, to probe the existence of higher-dimensional effective operators.
- The direct search for new particles with a mass reach extending to the several tens of TeV range, in particular around 40 TeV. for s-channel produced electroweak or colour resonances.
- Exploring the behaviour of high-density and high-temperature strongly interacting plasmas, through the analysis of data collected in central lead-lead collisions at nucleon-nucleon collision energies up to $\sqrt{s} \approx 40$ TeV.

Many more details are presented in the 10-page FCC physics document and in the FS Report Volume 1

A.2 Whether the ordering of stages is fixed or whether there is flexibility

The hadron collider aims at highest energy and highest luminosity. There are not really any substages, but it is plausible to assume, based on LHC experience, that the highest beam energy will not be reached immediately, but only after a few years of operation.

A.3 Main technical parameters

The high-level parameters for FCC-hh are shown in Table A.2, which are complemented by the parameters listed in Table A.1.

Table A.2: High-level parameters for FCC-hh.

	Unit	FCC-hh nominal
Number of experiments		4
Number of high-luminosity IPs		2
Synchrotron radiation power per beam	MW	1.2
Energy consumption per year of nominal operation	TW h	2.34

A.4 The number of independent experimental activities and the number of scientists expected to be engaged in each

The baseline layout of FCC-hh with four collision points allows for the deployment of four detectors, i.e. two high-luminosity multi-purpose experiments and two special-purpose experiments, e.g. for B physics, heavy ions, or, more challenging, lepton-hadron collisions.

The total siz of the user community for the four FCC-hh collider experiments is estimated at about 12,000 scientists.

In addition, the FCC-hh complex could allow for other physics experiments, e.g. a highest-energy fixed-target programme fed by one or several of the FCC-hh injectors (e.g. a new ring in the LHC tunnel or an scSPC) [35], or forward-physics experiments.

B Timeline

B.1 The technically-limited timeline for construction of FCC-hh as a second phase after FCC-ee

The schedule for FCC-hh is mainly determined by the development of the high-field magnet and by the schedule for the FCC Stage 1, the FCC-ee.

The timeline of FCC-hh is discussed in Section 5, and a possible schedule for FCC-hh as the second stage of the integrated programme is illustrated in Fig. 9. The corresponding key dates are summarised in Table B.1, including work already accomplished.

B.2 The technically-limited timeline for construction of FCC-hh as a stand-alone project

A possible schedule for FCC-hh as a stand-alone project is shown in Fig. 10, with key dates summarised in Table B.2, including work already completed.

Table B.1: FCC-hh timeline as a second phase after FCC-ee.

FCC-hh	Years
Conceptual Design Study	2014 – 2018
Territorial implementation studies	2016 – 2025
Definition of the placement scenario	2022
Feasibility Report ready	2025
Technical Design Report ready	2054
Main technologies R&D completion	2054
Latest Project Approval	2054
Environmental evaluation & project authorisation processes FCC-hh	2054 – 2058
Industrialization & magnet production	2054 – 2069
Civil engineering - Collider	2060 – 2068
FCC-ee dismantling	2063 – 2064
TI Installation – Collider	2065 – 2069
Accelerator Installation – Collider	2068 – 2072
HW Commissioning – Collider	2071 – 2073
Beam Commissioning – Collider	2073
Nominal beam operation – Collider	2074 – 2100

Table B.2: Fastest possible FCC-hh timeline as a stand-alone project.

FCC-hh	Years
Conceptual Design Study	2014 – 2018
Territorial implementation studies	2016 – 2025
Definition of the placement scenario	2022
Feasibility Report ready	2025
Latest Project Approval	2033
Environmental evaluation & project authorisation processes	2026 – 2035
Technical Design Report ready	2037
Main technologies R&D completion	2037
Industrialization & magnet production	2038 – 2053
Civil engineering - Collider	2037 – 2046
TI Installation – Collider	2043 – 2050
Accelerator Installation – Collider	2046 – 2052
HW Commissioning – Collider	2049 – 2053
Beam Commissioning – Collider	2054
Nominal beam operation – Collider	2055 – 2079

B.3 The anticipated operational (running) time at each stage, and expected operational duty cycle

The machine availability A for the FCC-ee hadron collider, including the injectors, is assumed to be at least 75% to be compared with a target of 80% for the HL-LHC (similar to the 2017 LHC performance). The fraction of time in physics, f_{phys} is estimated through the optimum physics run time (without failure) t_{run}, the average turnaround time t_{ta} and the availability as [36]

$$f_{\text{phys}} \approx A \frac{t_{\text{run}}}{t_{\text{run}} + t_{\text{ta}}} \,. \tag{B.1}$$

Similarly, the effect of the availability A on the integrated luminosity after a time period T is approximated as

$$L_{\text{int}} \approx A T L_{\text{nom. per day}} \;, \tag{B.2}$$

where $L_{\text{nom. per day}}$ denotes the nominal integrated luminosity per day, for an ideal cycle without any hardware failure. The analytical expressions for $L_{\text{nom. per}}$ depend on the relative strength of radiation damping and proton burn off [36, 37], and on whether or not a levelling scheme is applied [36].

If the beam current is limited by synchrotron radiation and cryogenic capacity, there is further the possibility of energy-luminosity levelling, that is, increasing the collision energy as the beam current decreases. The energy-levelled luminosity would decrease approximately as $L \propto 1/E^3$.

The nominal integrated luminosity of FCC-hh, shown in Table A.1, is computed by assuming 185 days of physics run time per year and a hardware availability of at least 80%.

C Resource requirements

C.1 The capital cost of each stage in 2024 CHF

The capital cost is summarised in Table 3.

C.2 The annual cost of operations of each stage

The annual cost of operations has not been determined. The cost of electricity is of order 150–200 MCHF p.a.

C.3 The human resources (in FTE) needed to deliver or operate each stage over its lifetime, expressed as an annual profile

The human resources required for FCC-hh have not been estimated.

C.4 Commentary on the basis-of-estimate of the resource requirements

Only the investment cost for FCC-hh was estimated using input from the CERN groups concerned.

D Environmental impact

D.1 The peak (MW) and integrated (TWh) energy consumption during operation of each stage

For FCC-hh, the dominant power consumer is the cryogenic systems required for magnet cooling. The cryogenic capacity is determined primarily by two factors: the static heat load of the magnets and the synchrotron radiation deposited on the beamscreen. The cryogenic power demand varies depending on the operating temperature of the magnets and the beamscreen. Table D.1 presents the power demand for the present baseline scenario where Nb_3Sn magnets are cooled to $1.9\,\mathrm{K}$, with a total synchrotron radiation power of $2.4\,\mathrm{MW}$ and a beamscreen temperature ranging in the interval $40\,\mathrm{K}$ to $60\,\mathrm{K}$.

The cryogenic systems for arc magnets only require $185\,\mathrm{MW}$ of electrical power, with an additional $22.5\,\mathrm{MW}$ needed for the high-luminosity insertions inner-triplet magnets (two sets for two experiments). The RF power requirement is estimated at $23\,\mathrm{MW}$ during the energy ramp and decreases to $12\,\mathrm{MW}$ at flat top, during beam collisions.

For a configuration using Nb_3Sn magnets cooled to $1.9\,\mathrm{K}$ and generating $2.4\,\mathrm{MW}$ of synchrotron radiation, the total power demand is approximately $360\,\mathrm{MW}$, comparable to that of FCC-ee.

The accelerator's operational model determines the energy consumption. The power demand varies depending on the time of year and the operational state of the machine. The machine schedule defines six operational periods. The power demand for each period is shown in Table D.2.

Table D.1: FCC-hh power demand by technical systems at 85 TeV beam centre-of-mass energy.

System	**85 TeV**
Radio frequency [MW]	17
Cryogenics [MW]	207.5
Cooling & ventilation [MW]	40
Magnet powering [MW]	33
Experiments [MW]	24
Data centre [MW]	8
General services [MW]	26
Total power [MW]	**355**

Table D.2: FCC-hh power demand during different operational periods for operation at collision energy of 85 TeV.

Period	**85 TeV**
Shutdown [MW]	122
Technical stop [MW]	122
Downtime [MW]	122
Commissioning [MW]	324
Machine development [MW]	324
Beam operation [MW]	355

The introduction of a *eco-mode* for the cryogenic systems during shutdown, reducing power consumption to 83 MW, significantly reduces power demand during non-operational periods.

The annual schedule consists of:

- 120 days of shutdown,
- 30 days of commissioning,
- 20 days of machine development,
- 10 days of technical stops, and
- 185 days of physics (beam operation).

Machine availability is expected to be similar to that of LHC, with an operational efficiency of approximately 80%, corresponding to an expected period of beam collisions of 1700 hours.

Based on the operational schedule and the expected power demand throughout the FCC-hh programme, the estimated annual energy consumption at 85 TeV is shown in Table D.3. If the magnets were operated at 4.5 K the annual energy consumption would decrease to 1.8 TWh.

Table D.3: FCC-hh annual energy consumption at 85 TeV beam energy.

Beam Energy	**85 TeV**
Annual energy consumption [TWh/y]	2.34

Introducing an *eco-mode* has significantly reduced cryogenic power consumption during non-operational phases.

D.2 The integrated carbon-equivalent energy cost of construction

The GHG emissions (in kt CO_2 equivalent) for the construction and operation of FCC-hh are presented in Table D.4.

Table D.4: GHG emissions (in kt CO_2 equivalent), for FCC-hh following FCC-ee.

c.m. energy considered [TeV]	85
Civil engineering	
A1–A5 (construction, material, transport)	
Underground	50 ktCO2(eq)
Surface sites	10 ktCO2(eq)
B4–B5 (replacement & refurbishment)	
C1–C4 (end of life)	
Civil engineering — potential optimisations	
Optimizations	Optimised design and adaptation of materials
	Low carbon concrete
	Local production [38]
Underground	-16% [38]
Surface sites	-5% [38]
Accelerator and detector hardware	
	1500 ktCO2(eq) [a]
Electricity consumption during operation	
Carbon intensity (g CO_2 eq. per kW h)	12–18
Peak power consumption [MW]	<355
Optimization potential	50
TW h per year	2.34 (1.8)
kt CO_2 equivalent per year	28–42 (22–32)
Number of years of operation	25
Total	
without optimisations	2262–2613 ktCO2(eq)
with optimisations	2092-2362- ktCO2(eq)
Average per year over 35-year life cycle	
without optimisations	65–75 ktCO2(eq)
with optimisations	60–67 ktCO2(eq)

[a] 1234 ktCO2(eq) for 366kt of raw material used for the arc dipoles and quadrupoles (cold masses and cryostats) based on EPDs of raw materials available today on the market

Optimisations, in particular in terms of the use of an optimised design that corresponds to well-documented needs, materials with higher performance and reduced carbon footprint and requiring less steel, local production of construction materials, the use of recycled materials, and the optimisation of the construction process, allow further reduction of this number in the order of 20%.

D.3 Any other significant expected environmental impacts

The construction of the FCC infrastructure is comparable to that of larger public transport infrastructure projects. Efforts will be made to minimise nuisance during the construction phase (placement chosen with almost direct highway access close to the main work site; use of conveyor belts for large-scale material transport, etc.).

E Technology and delivery

The key technologies needed for delivery that are still under development, and the target performance parameters of each development are summarised in Table E.1.

Table E.1: Technical readiness and R&D requirements for FCC-hh.

Component/Sub-system	TRL	Main parameter to be improved	Improvement factor	R&D effort Manpower [FTEY]	Material [MCHF]	Timescale [years]
Nb_3Sn conductor[†]	7	cost& industrialisation (more manufacturers)	3	10	30	7
Nb_3Sn magnet short model	7	max. field[‡]	20%	100	20	5
Nb_3Sn scaling to 5 m	6	length	3	100	40	+5
Nb_3Sn scaling to 15 m	5	length	3	100	100	+5
HTS short model 20 T	3 +all accel. features	field*	5–10	100	50	10
HTS long magnet 20 T	1	length	15	100	150	+5

Note: these MPE and Material estimates apply to a work carried out at CERN, excluding collaborations

[†] This includes only contracts to lower the price and to have more manufacturers, not the conductor cost for the model and prototype that is included in the next lines

[‡] target of 15 T, for operation at 14 T

*2 to 4 T already achieved, but not with all requirements

E.1 The critical path for technology development or design

The critical path for FCC-hh is defined by the HFM development programme. An optimistic fastest schedule is presented in Fig. E.1.

E.2 A concise assessment of the key technical risks to the delivery of the project

A risk management framework with a risk register covering mainly cost, scheduling, and technical performance risks with their respective likelihood is currently under preparation, including mitigation measures, estimated cost for the mitigation, and risk owners. In the event of publication of the complete risk register, here are listed some key technical risks that were identified at the mid-term review of the FCC Feasibility Study:

- In some key technologies, there are only a very limited number of potential suppliers, such as for Nb_3Sn superconducting wire, for NEG coating of vacuum chambers, and for cryogenic refrigerators.

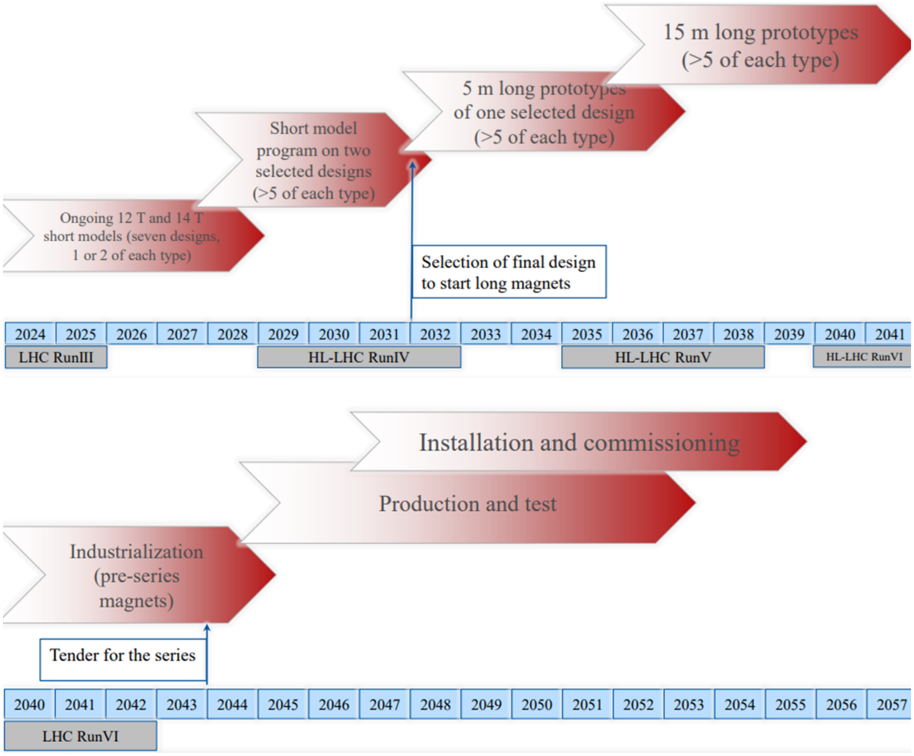

Fig. E.1: The “accelerated” roadmap for an FCC-hh based on 14 T Nb_3Sn magnets: short models & scaling in length (top); industrialisation, production, & commissioning (bottom).

- FCC-hh is based on advanced manufacturing methods, the maturity of which needs to be fully evaluated for large-series manufacturing. Such manufacturing methods must be further developed with suppliers and qualified for series production.
- The volatility of raw material prices and their impact on the supplies required (e.g. Nb_3Sn or ReBCO, copper, steel, and nickel) is a risk as regards the cost of the project.

F Dependencies

F.1 Whether a specific host site is foreseen, or whether options are available

The CERN laboratory is expected to be the host site. The territorial implementation study is very well advanced. The placement for the entire infrastructure, surface sites, and tunnel was developed and optimised over several years, using the “avoid, reduce, compensate” approach. This optimisation process took into account many areas, such as societal and environmental aspects, integration with existing infrastructures such as roads, railroads, high-voltage electricity grids, geological conditions to minimise tunnelling risks and physics performance. Following the location of the eight surface sites, a full four-season study of their present environmental state was performed that did not reveal any major obstacles. To enable fixing the exact depth of the tunnel and its inclination, subsurface site investigations have been ongoing since 2024 and are expected to be completed by the end of 2025.

F.2 The dependencies on existing or required infrastructure

The FCC-hh collider will reuse the entire LHC proton injector chain, with its established performance representing a significant cost savings and risk reduction.

The entire CERN laboratory and its administrative infrastructure are an essential basis for design and construction, and also avoiding the complexity associated with a green-field project.

Placement studies have demonstrated the possibility of a smooth, labour- and cost-effective integration of the FCC with the existing regional infrastructure (e.g., road access, electrical power, cooling water, etc.).

F.3 The technical effects of project execution on the operations of existing infrastructures at the host site

The schedule of the execution of the FCC project takes into account the long-term operation plan of CERN, in particular the exploitation of HL-LHC, which is expected to be completed in 2041. The civil engineering construction of the main tunnel, surface sites, and injector is not expected to have any impact on the operation of existing CERN facilities.

Both the FCC-ee and the FCC-hh will connect to and reuse existing technical infrastructures, e.g. cooling water supply and grid connection. These connections will be realised during shut-downs, so that there is no impact on operations and the physics programme of CERN.

G Commentary on current project status

G.1 A concise description of the current design / R&D / simulation activities leading to the project, and the community pursuing these

The classical high-field Nb_3Sn magnet concept is the $\cos\theta$ configuration, where a two-layer design can give $12\,\mathrm{T}$ dipoles [39] with a coil width of the order of 35-$40\,\mathrm{mm}$, and a third and fourth layer are needed to reach the operational field of $14\,\mathrm{T}$. This $\cos\theta$ option is being developed at INFN and at CERN (FalconD). The design based on block coils holds the field record today, and therefore is a natural alternative option, which is being pursued by CERN, with a two-layer coil and a $25\,\mathrm{mm}$ wide cable (BOND [40]), and by CEA-Saclay with a four-layer coil including grading (F2D2 [41]) and an intermediary step with flat racetrack coils (R2D2 [42]). A third option is the common coil design, which is an intrinsically double-aperture magnet, based on racetrack coils plus non-planar correction coils. This design approach has been adopted for the Chinese SppC dipole. For FCC-hh, the common coil path is followed by CIEMAT and PSI, which is currently looking to develop a stress-management asymmetric common coil as a candidate for $14\,\mathrm{T}$ (SMACC1) [43].

The HFM Programme is investing in REBCO tape technology development in the KIT/CERN Collaboration on Coated Conductor (KC4), as well as iron-based superconductor technology (CNR-SPIN/CERN), aiming at a round wire with a powder-in-tube layout [44].

Detector concepts for FCC-hh were presented in Ref. [45]. The detector upgrades for HL-LHC are the seed for the R&D towards FCC-hh detectors.

G.2 A statement of any major in-kind deliverables already negotiated

G.3 Any other key technical information points in addition to those captured above, including references to additional public documents addressing the points above.