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Status and challenges of the Future Circular Hadron Collider FCC-hh

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The Future Circular Collider (FCC) study was launched as a worldwide international collaboration hosted by CERN with the ultimate goal of pushing the energy frontier far beyond the LHC. FCC covers two accelerators, namely an energy-frontier hadron collider (FCC-hh) and a highest luminosity, high-energy lepton collider (FCC-ee) serving as electroweak Higgs factory, as a possible first stage. The mass of particles that could be either directly produced at FCC-hh or indirectly detected at FCC-ee is increased by an order of magnitude, relative to today's reach, and the subatomic distances that can be resolved are decreased in the same proportion. Importantly, FCC-hh and FCC-ee share the same ∼100 km tunnel infrastructure. This paper focuses on the FCC-hh, summarising its key features, such as accelerator design, performance reach, and underlying technologies. The discussion is based on the 2019 conceptual design report (CDR) [1], which represents a study milestone, but also describes more recent design activities and indicates future directions.

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1. Introduction

The completion of the HL-LHC programme will set a new, high, bar to the measurement reach of future collider facilities. As a minimum, future colliders must improve the precision of Higgs boson measurements, generically by an order of magnitude, with the ultimate goal of shedding light on the deep origin of the mechanism of electroweak (EW) symmetry breaking [2]. Future e^+e^- Higgs factories, such as FCC-ee [3], will deliver such improvement for several Higgs couplings, but limited statistics and energy constraints penalise the study of Higgs phenomena mediated by small couplings or requiring large energy to achieve useful rates. A proton-proton collider with energy in the 100 TeV range, such as FCC-hh [1], with integrated luminosities in the range of $20\,\mathrm{ab}^{-1}$, is the ideal complement to FCC-ee, able to measure rare decays with subpercent precision such as $H \to \gamma\gamma$, $Z\gamma$ or $\mu^+\mu^-$, and Higgs self-coupling to better than 5%. The huge dynamic range of FCC-hh induces multi-TeV reactions, directly probing a possible short-distance structure of the Higgs boson.

Beyond the guaranteed deliverables offered by the Higgs physics programme, a future collider must maximise the potential to push further the boundary for the search of direct evidence for new physics and to seek the origin of new phenomena, possibly seen by the HL-LHC or a Higgs factory. Should new physics appear at HL-LHC, the FCC-hh would increase by orders of magnitude the statistics available to study in more detail those new phenomena. For example, the rate to produce a 3(4) TeV final state by gluon-gluon collisions is 10^3 (10^4) times larger at 100 TeV compared to 14 TeV [4]. No other accelerator, except an even higher energy proton collider, can match this. In the absence of (in)direct indications on the existence of new physics from previous colliders, FCC-hh can extend by a factor of 6 the mass reach of HL-LHC, with sensitivity to a huge domain of possible manifestations of new physics. In particular, the CDR [2] has shown the FCC-hh potential to conclusively explore multiple scenarios of weakly-interacting massive-particle dark matter candidates, or of strong first-order EW phase transition. As studies of the FCC-hh physics potential continue, also in view of new questions that may arise from the LHC, we focus here on a brief report of the activities dedicated to the accelerator design and the ensuing technological challenges.

2. Overview of FCC-hh as presented in the 2019 CDR

The FCC-hh [1, 5, 6] is designed to provide proton–proton collisions with a centre-of-mass energy of 100 TeV, a circumference of about90 km, and an integrated luminosity of $\approx 20\,\mathrm{ab}^{-1}$ in each of the two primary experiments during about 25 years of operation. Similarly to the present LHC, the FCC-hh physics programme includes collisions of both protons and heavier ions. The ring design also allows for one interaction point to be upgraded to electron–proton and electron-ion collisions. In this case, an additional three-pass energy recovery linac would provide the electron beam to collide with the protons or ions circulating in one of the two FCC-hh rings.

The FCC-hh will use the existing CERN accelerator complex as the injector facility. One injector chain scenario, consisting of CERN's Linac4, PS, PSB, SPS, and LHC, could deliver beams at 3.3 TeV to the FCC-hh, thanks to transfer lines using 7 T superconducting magnets that connect LHC to FCC-hh. As an alternative, direct injection from a new ~7 km superconducting synchrotron (scSPS) [7], which would replace the existing SPS in the same tunnel, at 1.0–1.3 TeV proton beam energy, is also being considered. In this case, simpler transfer lines with normal-conducting magnets operating below 1.8 T or even with permanent magnets could be sufficient. Either choice would also allow the continuation of CERN's rich and diverse fixed-target physics programme in parallel with FCC-hh operation, in the case of the scSPS at 2–3 times today's energy. Injector scenarios rely on beam stability in the collider at injection, which is linked to magnet design and technology.

The regular lattice in the arc consists of 90° FODO cells with a length of about 213 m, six 14 m-long dipoles between quadrupoles, and a dipole filling factor of approximately 0.8. Therefore, a dipole field around 16 T is required to maintain the 50 TeV beams on the circular orbit. The dipole concept described in the CDR [1] is based on Nb_3Sn superconductor technology, operated at 1.9 K. This technology is a key cost and performance driver of the collider. Efforts devoted to increasing the current density in the conductors up to the FCC design specification of $1500\,\mathrm{A/mm^2}$ at 16 T and 4.2 K were successful [8, 9]. Several dipole design concepts have been developed in the framework of the H2020 EC-funded EuroCirCol and Swiss CHART projects. The cosine-theta design was selected as a baseline because it minimised the amount of superconductor needed for the magnet coils. Several collaboration agreements are in place with partner organisations, such as the French CEA, the Italian INFN, the Spanish CIEMAT, and the Swiss PSI, to construct short-model magnets. In parallel, the US DOE Magnet Development Programme is actively working towards demonstrating a 15 T superconducting accelerator magnet and has already reached 14.5 T.

As the FCC integrated project foresees the sequential construction of FCC-ee and FCC-hh in the same underground infrastructure, the time scale for R&D and design for FCC-hh is of the order of 30 years. This time can be used to develop alternative technologies for magnets based on high-temperature superconductors, which could have a significant effect on collider parameters, facilitate infrastructure requirements (cryogenic systems), greatly reduce the electric power consumption, and increase energy efficiency (thermal loads and beam screen temperatures).

3. Progress since the CDR

Among the various domains that have been studied since the publication of the FCC-hh CDR, the intense effort of placement studies deserves to be highlighted. These reviewed and further improved the placement scenario described in [1], with the goal of obtaining a tunnel layout that satisfies multiple restrictions imposed by the geological situation, territorial, and environmental aspects. Furthermore, in the framework of FCC-ee studies, the possibility of hosting four experimental interaction points has emerged as an interesting option, and beam dynamics considerations impose a superperiodic positioning of the four experimental points. Hence, to allow sharing of the experimental caverns between the FCC-ee and its hadron companion, the same principle is applied to the FCC-hh lattice. This led to the new four-fold periodic layout shown in Fig. 1 with a circumference of approximately 91 km, and a reduction from twelve to eight surface sites. Although the symmetry requirements of the new layout make the search for suitable surface sites significantly more difficult, the smaller number of sites avoided areas incompatible from environmental and territorial points of view. The four locations at which beams cross and provide locations for experiments are PA, PD, PG, and PJ, and this assignment remains compatible with a physics programme

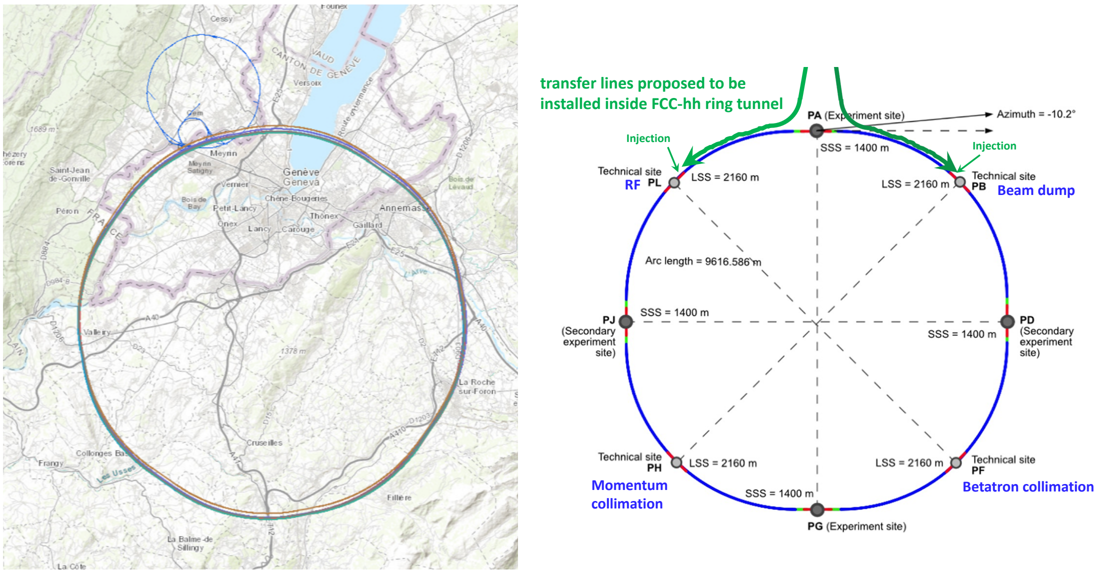

Figure 1: Left: Picture of some of the FCC implementation variants under study, including the LHC and the SPS accelerators. Right: Sketch of the proposed superperiodic FCC-hh layout with eight surface sites.

comprising proton-proton, ion-proton, ion-ion, and electron-proton collisions. The length of the straight sections has been revised: straight sections of 1.4 km in length like in the CDR lattice house the experimental interaction points; straight sections of 2.16 km in length (2.8 km in the CDR), house the key accelerator systems. Currently, it is proposed to install the beam dump in PB, the betatron collimation in PF, the momentum collimation in PH, and the RF system in PL. These preliminary assignments remain to be confirmed by detailed studies.

The total length of the arcs is 76.93 km, and, unlike the CDR configuration, all arcs have the same length. A reduced total arc length implies that, for a FODO lattice with 16 T dipole field, the proton collision energy falls short of 100 TeV by a few TeV, which is not considered a showstopper as mitigation options exist. The FODO cell length increases by 1% with respect to the CDR configuration.

The re-allocation of the experimental points affects the injection and transfer line design. The scenario being currently investigated consists of combining the injection with the beam dump in PB, and with the RF system in PL. The transfer lines can run in the main ring tunnel from PA to the injection point (see Fig. 1). This scenario leads to a reduction in the length of the transfer line tunnel with respect to the CDR configuration. The transfer line magnets in the ring tunnel might be made of normal-conducting or permanent magnets.

Alternative approaches to the generation of the ring optics have been pursued. The standard paradigm for collider optics uses separate-function magnets in the regular arcs, in conjunction with a FODO structure. A combined-function optics has the potential of providing a higher dipole filling factor, thus opening up interesting optimisation paths for dipole field and beam energy. Recent research explored the benefits of a combined-function periodic cell [10], optimised the cell length [11], and also provided a design for a combined-function dispersion suppressor [11]. Future investigations will consider the various systems of corrector magnets needed in the baseline FODO cell and optimise them in the context of a combined-function periodic cell.

4. Challenges

Detailed analyses of the several challenges implied by the FCC-hh study are discussed in, e.g. [12, 13], and some selected topics will be mentioned here.

The choice of the FCC-hh injector, namely LHC or a new scSPS, should be carefully studied and evaluated.

The FCC-hh collider complex as documented in the CDR, based solely on Nb_3Sn technology to demonstrate the technical feasibility of such an accelerator, is expected to require about 550–580 MW of electrical power. An energy-efficient cryogenic refrigeration infrastructure, based on a neon-helium light gas mixture, and a high-reliability and low-loss cryogenic distribution infrastructure would be used. Among all subsystems, the highest electrical power demand comes from the cryogenics, which requires about 276 MW, roughly half of which is needed to extract the ~ 5 MW of synchrotron radiation heat load from the cold arcs. This number depends greatly on the magnet cold-bore and beam-screen temperatures. Therefore, efforts are underway to significantly reduce electrical energy consumption. This might be achieved by alternative magnet technologies, to be developed on a time scale of 30+ years. Different types of high-temperature superconductors should be investigated, since they allow for higher fields, operation at higher temperature along with lower cryogenics power, and, ultimately, perhaps even lower cost. In this context, the FCC conductor programme explores the potential of ReBCO coated conductors. Sourcing, large-scale production, quality, and cost are the key challenges related to these technologies. Other energy savings are possible for the FCC-hh injectors. For instance, a scSPS would require much less operating power than the current SPS and the LHC.

The unprecedented beam energy of 8.3 GJ represents a challenge for all systems that protect the integrity of the collider hardware, such as collimation and dump systems. It translates directly into beam dynamics challenges and also into technological challenges in several areas, e.g. the materials selected for the collimators jaws and beam dumps, but also for the hardware of the kickers used to dump the beams and to dilute them before interacting with the dump material.

Highly segmented kickers, superconducting septa and transfer lines, and local magnet energy recovery are essential components of the machine design.

5. Conclusions

The FCC-hh baseline comprises a power-saving, low-temperature superconducting magnet system based on an evolution of the Nb_3Sn technology pioneered at the HL-LHC. Given the time scale of the integrated FCC programme, which allows for 30+ years of R&D and 10 years of industrialisation for FCC-hh, an increase in energy efficiency can be expected with the use of high-temperature superconductors for which R&D is carried out in close collaboration with industrial partners. Use of the existing CERN accelerator chain, also serving a concurrent physics programme, is an essential lever to achieve a sustainable global research infrastructure at the energy frontier.

The FCC-hh will stimulate economic and social development in all participating nations, thanks to its scale and intrinsic character of an international fundamental scientific research infrastructure, combined with the deep involvement of industrial partners, along with unlimited possibilities of training provided at all educational levels by this marvellous scientific tool.

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