PROCEEDINGS OF SCIENCE

Towards Future Circular Colliders *

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The international Future Circular Collider (FCC) study, launched in 2014, is finalizing a multi-volume conceptual design report. The FCC develops high-energy circular collider options based on a new 100 km tunnel. Long-term goal is a 100 TeV center-of-mass proton-proton collider (FCC-hh). The study includes a high-luminosity electron-positron collider (FCC-ee) as a possible first step, and it also examines lepton-hadron scenarios (FCC-he). In addition, the FCC study includes the design of the High Energy LHC (HE-LHC), housed in the LHC tunnel, and based on the same high-field magnet technology as the FCC-hh. The FCC study further includes an elaboration of the physics cases, including for heavy-ion collisions, and detector concepts, as well as staging and implementation scenarios. This report summarizes the study achievements with special emphasis on the HE-LHC.

Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)
4-9 June 2018
Bologna, Italy

*This work was supported by the European Commission under the HORIZON 2020 projects EuroCirCol, grant agreement no. 654305; EASITrain no. 764879; and ARIES no. 730871.

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1. Motivation, History, and Scope

The LHC design was launched in 1983, 35 years ago. The physics programme of the LHC [1] and its high-luminosity upgrade, the HL-LHC [2, 3], will extend through the 2030's. In view of these time scales, the 2013 Update of the European Strategy for Particle Physics requested preparations for a post-LHC collider at CERN [4]. European studies of highest-energy highest-luminosity large circular colliders had started already a few years earlier, in 2010–2012, for both leptons [5, 6] and hadrons [7, 8, 9], under the names LEP3/TLEP and VHE-LHC, respectively. In early 2014 these efforts were combined and expanded as global Future Circular Collider (FCC) study [10, 11].

The center-of-mass (c.o.m.) energy reach of a hadron collider is directly proportional to the dipole magnetic field B and to the bending radius ρ, or machine circumference. Dipole magnets with a field of 16 T together with a ring circumference of about 100 km result in a c.o.m. energy of 100 TeV, an order of magnitude above the LHC. This goal for a future circular hadron collider (FCC-hh) defines the overall infrastructure requirements for the FCC accelerator complex. The FCC study scope also includes the design of a high-luminosity e^+e^- collider (FCC-ee) operating at c.o.m. energies of 90–365 GeV, as a possible first step, as well as a proton-electron collision option (FCC-he) at one interaction point, where a 60 GeV electron beam from an energy recovery linac would be collided with one of the two 50 TeV proton beams circulating in the FCC-hh. The design of a higher-energy hadron collider in the LHC tunnel with a c.o.m. energy around 27 TeV, based on FCC-hh magnet technology — the so-called High-Energy LHC (HE-LHC) — is yet another part of the FCC study. The FCC study comprises accelerator design, technology development, detector design, physics cases, conventional infrastructure, implementation scenarios and cost estimates, for all collider scenarios.

2. Physics and Design Targets

The lepton collider FCC-ee will explore the 10–100 TeV energy energy scale via couplings with precision measurements [12]. It will yield a 20–50 fold improved precision for many electroweak quantities (equivalent to a factor 5–7 in energy), such as m_Z, m_W, m_t, $\sin^2\theta_W^{\rm eff}$, R_b, $\alpha_{\rm QED}(m_Z)$, $\alpha_s(m_Z, m_W, m_t)$, Higgs boson and top quark couplings. To accomplish these goals, the machine is designed for highest possible luminosities at four working points (Z, WW, ZH and $t\bar{t}$).

The FCC-hh will provide collisions at highest c.o.m. energy for direct production up to 20–30 TeV. There will also be huge production rates for single and multiple production of SM bosons (H, W, Z) and quarks [13]. The machine is designed for 100 TeV c.o.m. energy with an integrated luminosity of 20 ab^{-1} over 25 years.

The HE-LHC design aims at approximately doubling the LHC collision energy with FCC-hh 16 T magnet technology in the 26.7 km LHC tunnel. The c.o.m. energy of 27 TeV is obtained by scaling with the magnetic field from the LHC's 14 TeV with 8.33 T dipole field. The HE-LHC target luminosity is more than 10 ab^{-1} over 20 years. The HE-LHC machine is designed within the constraints of the existing LHC infrastructure, and it incorporates both HL-LHC and FCC technologies.

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FCC-ee and FCC-hh designs are well advanced as presented in [14]. In the following we focus in the recent HE-LHC design progress.

3. High-Energy LHC

The HE-LHC must be installed in the existing LHC tunnel, with an inner diameter of only 3.8 m, compared with 5.5 m for the FCC. These space limitations result in significant constraints on the HE-LHC machine layout, magnets which must be compact and curved, and on the HE-LHC cryogenics system, which needs to be more powerful than the LHC one. A large variety of layouts has been explored for the HE-LHC [15] concluding with the two most promising options: 23x90 (23 cells per arc with 90° phase advance) and 18x90. A sketch of the two cells is shown on Fig. 1.

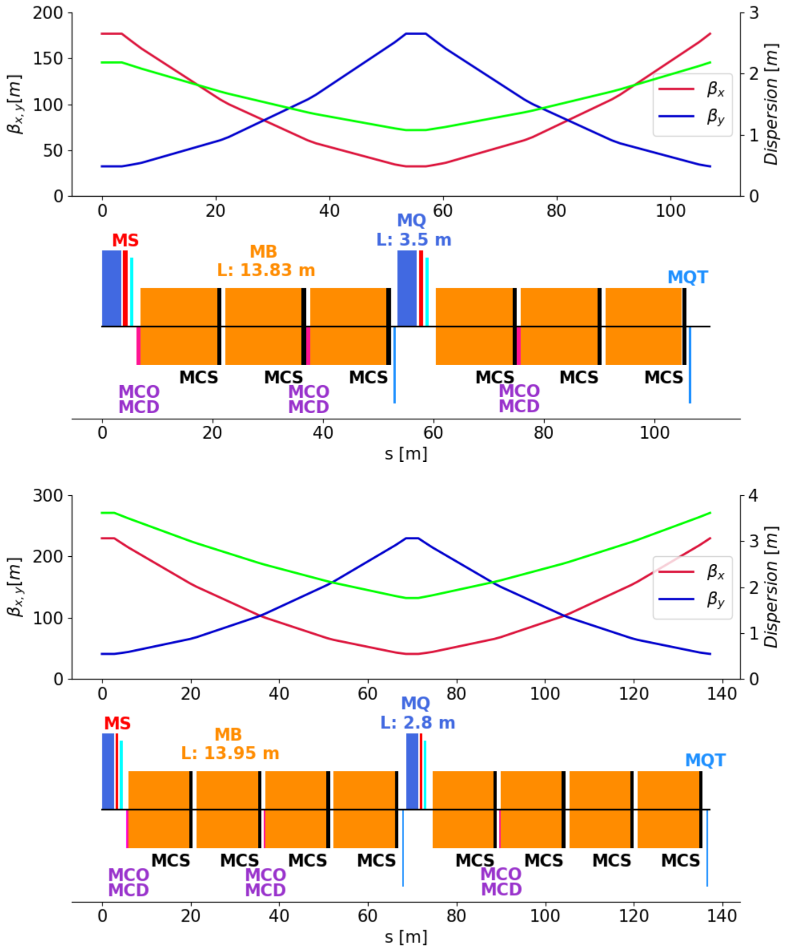

Figure 1: Optics functions and layout configuration of the two HE-LHC design options. Top: 23x90 cell. Bottom: 18x90 cell. Dipoles are shown in orange, quadrupoles in blue and sextupoles in red.

The horizontal deviation of the machine position with respect to the LHC is shown in Fig. 2 for both options. The configuration 23x90 only deviates by few cm as it has the same number of arc cells as the LHC. The option 18x90 has a peak deviation of about 9 cm and it is currently being investigated if this deviation is acceptable or it can be further reduced.

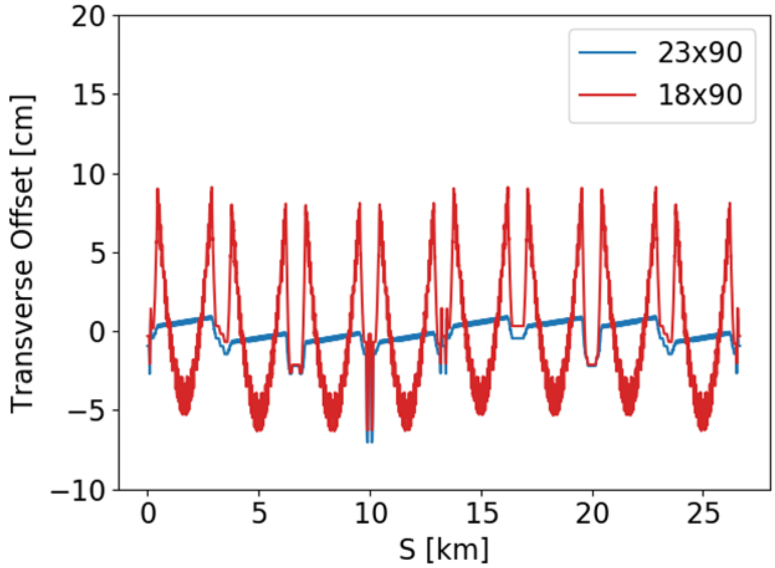

Figure 2: HE-LHC horizontal deviation with respect to the LHC for the two lattice options: 23x90 and 18x90.

The 18x90 option has 8 dipoles per cell and a higher filling factor than the 23x90 one, implying a higher energy reach. Actually assuming 16 T dipoles the 18x90 option can reach 27 TeV c.o.m. energy while the 23x90 one stays at 26 TeV. At injection energy the situation is reversed and the 23x90 optics features a smaller transverse beam size and therefore larger physical and dynamic apertures for the same beam pipe and magnet designs. The 23x90 design could have a beam stay clear of 10σ at an injection energy of about 600 GeV, while the 18x90 design would need 800 GeV. The advantage of 600 GeV is that the current LHC injector, the SPS, would only require upgrading half of the dipoles with superconducting ones. Current quadrupoles and sextupoles are sufficiently strong to reach 600 GeV with an integer tune of 20. This partial upgrade of the SPS was already considered in 1972 [16]. Further studies are being pursued to find solutions that would allow to inject from the current SPS at 450 GeV.

Particle stability at injection is a great concern due to the required large energy swing of the dipole magnets and poor field quality at injection. Various approaches are being explored to maximize field quality and mitigate its impact on beam stability. Small filament size of 20 μm greatly lowers the field errors at injection related to persistent currents. A further improvement of the field quality at injection is expected from the addition of artificial pinning centers (APCs). The APCs decrease the critical current at low field levels and thereby the strength of the persistent current effects. After magnets are manufactured the field quality can be measured and dipoles could be placed in the accelerator according to their sextupolar component to maximize the particle phase-space stability region, called Dynamic Aperture (DA). Assuming 20 μm filament size and perfect APC the DA for the two lattice options with and without sorting is shown on Fig. 3 for three possible energies: 450 GeV, 900 GeV and 1.3 TeV. Former DA studies can be found in [18, 19].

Targeting a DA above 8σ would allow the 23x90 design to run at any energy equal or above 450 GeV while the 18x90 option would need injection energies equal or above 900 GeV.

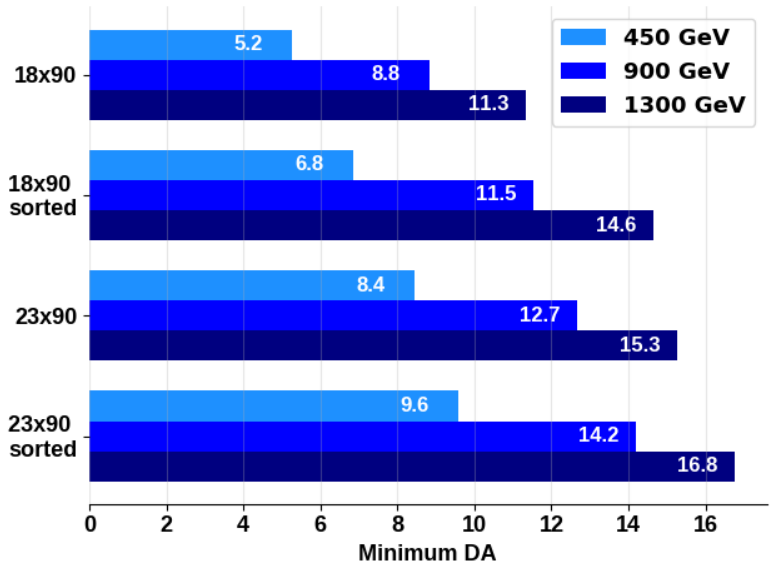

Figure 3: HE-LHC DA for magnets with 20 μm filament and perfect artificial pinning centers with and without sorting for three different energies.

3.1 HE-LHC performance

The current baseline HE-LHC foresees a β^* at the IP of 45 cm, a bunch population of 2.2×10^{11} protons, a normalized emittance of 2.5 μm and operation with crab cavities to recover head-on collisions [20]. Initial luminosity of about 15×10^{34} cm^{-2}s^{-1} and 430 events per bunch crossing are expected. After 5 hours in collisions the luminosity decreases by about a factor 3 since both bunch population and average emittance decrease by a factor 3. An integrated yearly luminosity of about 470 fb^{-1} can be achieved with 160 days of operation and 75% availability.

The β^* of 45 cm is decided by triplet aperture and required crossing angle in the beginning of the fill. Since emittance reduces significantly it is conceivable to squeeze β^* while keeping beam divergence at the IP constant. Keeping also constant crossing angle ensures that no extra aperture would be required in the triplets. This mode of operation could increase integrated yearly luminosity up to 590 fb^{-1}. The final β^* would be around 15 cm. A comparison of the instantaneous luminosity and other beam parameters during the fill for both baseline and constant divergence scenarios is shown in Fig. 4. The same simulation code as in [21] is used.

4. Construction and Schedule

Following a geological review an optimized baseline tunnel was established, with the lowest risk, the fastest and cheapest construction, and suitable locations for large-span caverns (the most challenging structures).

All surface and underground structures can be constructed within 6.5–7 years. Already 5 years after groundbreaking, the first FCC tunnel sectors would be ready for the installation of technical infrastructure.

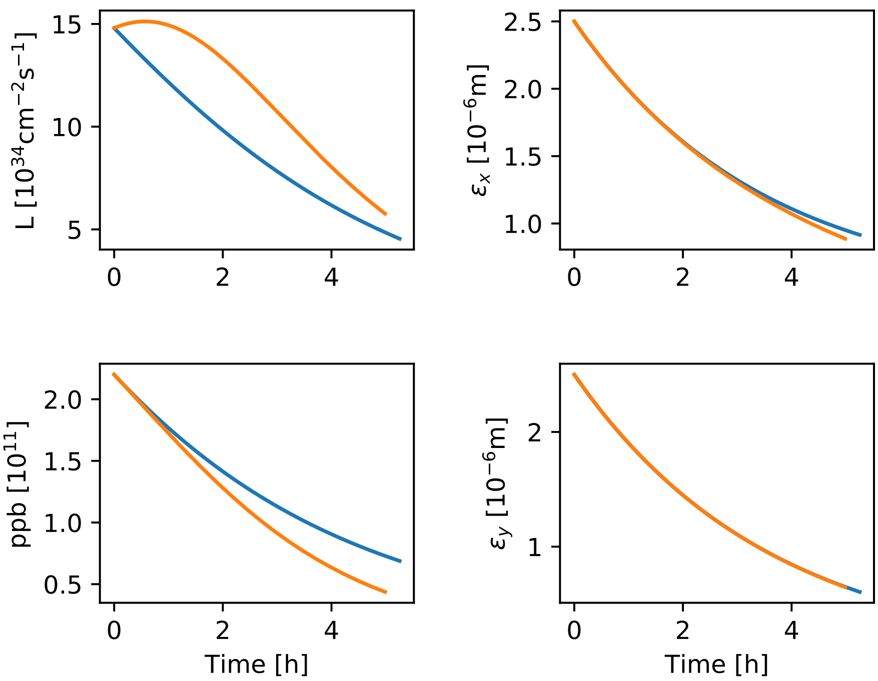

Figure 4: Simulated instantaneous luminosity, bunch intensity and horizontal and vertical emittances during a physics fill for both baseline (blue) and constant divergence (orange) HE-LHC scenarios at 27 TeV.

The first physics could be expected around 2040–45, for any of the three collider scenarios considered, in the case of FCC-ee about 5 years before FCC-hh.

5. Summary and Outlook

The FCC-ee and FCC-hh accelerator designs are ready for the conceptual design report (CDR). Recent developments of the HE-LHC design have been fundamental to identify the most promising lattice options for the CDR. A worldwide R&D program is in place, on efficient high-field magnets, Nb_3Sn superconductor, and on highly efficient SC RF. The international FCC collaboration is growing steadily. By now 124 institutes and 30 companies from 32 countries are participating. The collaboration is presently focusing on the completion of the conceptual design report (CDR). Prototyping and validation of key technical components are underway. The next phase of the FCC study, from 2019 to 2023, will focus on the implementation plan, and on the further development of key technologies, especially the high-field magnets.

6. Acknowledgement

This report summarizes results from the international FCC collaboration. Our warm thanks go to all collaboration members for their excellent, enthusiastic work and for many inspiring discussions. We are grateful to the colleagues who contributed the graphics of this article.

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