double the beam brightness and also the total intensity of the beam available for injection into the LHC.

The High-Luminosity LHC upgrades during LS2 and LS3 include: new final-triplet quadrupoles with larger aperture, based on Nb_3Sn superconductor with a peak field at the coil of about 12 T; additional collimators in the dispersion suppressors of the betatron cleaning insertion, enabled by more compact Nb_3Sn dipoles with a field of 11 T – the first time this type of superconducting magnet is installed in a collider; new low-impedance robust collimator jaws; novel crab-cavity RF systems; a novel cold powering scheme based on superconducting links; etc.

2.13.4 **Outlook**

The lessons learned from the LHC and the novel technologies developed for HL-LHC prepare the ground for future higher-energy hadron colliders like HE-LHC or FCC-hh, which will require 100's or 1000's of Nb_3Sn dipole and quadrupole magnets with a peak field in excess of 15 Tesla, bright proton beams, robust absorber and collimator materials, low impedance components (collimators and vacuum system) and RF crab cavity systems.

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2.14 FCC-hh Design Highlights

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2.14.1 **Introduction**

The FCC-hh will provide proton-proton collisions with 100 TeV centre-of-mass energy, about seven times more than LHC, with a luminosity much higher than in HL-LHC. For the ultimate parameters the luminosity can reach up to $3x10^{35}cm^{-2}s^{-1}$ and allows to reach an integrated value of $17.5ab^{-1}$, corresponding to the physics goals [1].
In the following, the layout and main parameters of FCC-hh are presented first followed by the luminosity considerations. Limited space then allows for only a few key design highlights and prevents to cover the full range of important topics.

2.14.2 **Layout and Key Parameters**

The layout of FCC-hh is shown in Fig.1 and the key parameters are shown in table 1, both taken from [2]. The layout fulfils a number of criteria:

- The accelerator fits into the Geneva area [3]. In particular, the layout limits the tunnel in limestone as much as possible to reduce the risk and cost of the civil engineering. Similarly, it avoid going under the deep part of lake Geneva. In addition, the injection insertions are positioned such that one can conveniently inject beam either from the LHC or the SPS tunnel. To achieve this design, a range of layout options has been evaluated and the best picked.
- The two high luminosity experiments are located on opposite insertions (A and G). This ensures highest luminosity and best compensation of beam-beam effects independent of the beam-filling pattern.
- Two additional, lower luminosity experiments are located together with the injection in insertions B and L.
- The transverse beam cleaning is located in insertion J and the beam extraction in insertion D. Both systems are challenging due to the high energy in the beams. Hence the insertions are twice as long than the others to give more flexibility to the optics design and leave more room for protection devices.
- The longitudinal beam cleaning is placed in insertion F.
- The RF systems and the fast feedback are placed in insertion H.

2.14.3 **Energy considerations**

The beam energy E that one can reach in the collider is given by the ability of the dipole magnets in the arc to keep the beam on a circular orbit:

$$E = 0.0476\,TeV\,\frac{B}{T}\frac{\eta(C-L)}{km}$$

Here, C is the circumference of the collider, L is the length reserved for straight insertions, η the fraction of the arcs filled with magnets and B the magnetic field strength of the dipoles. A total of 14 km has been allocated for the insertions and a filling factor for the arcs of about 80% has been achieved [4]. Consequently, a circumference of 97.75 km and a magnetic field of 16 T have been chosen. This size is consistent with the site boundaries close to CERN and with the expected maximum field reach that the superconducting TiNb3 technology can provide. An important R&D programme is ongoing to achieve this field level and to reduce the cost of the technology to an acceptable level.

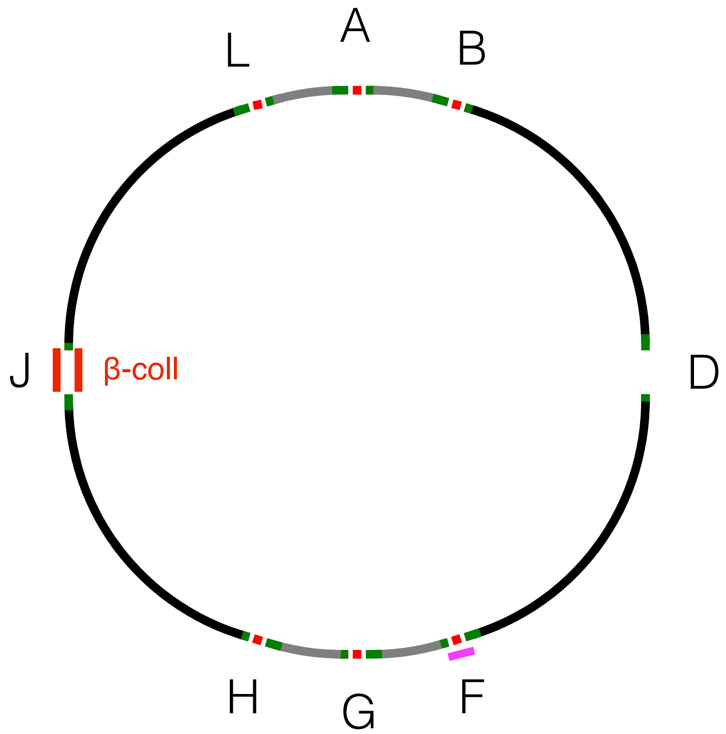

Figure 1: The FCC-hh conceptual layout.

2.14.4 **Injector considerations**

Different injector options are being considered [5], the baseline is to use the LHC to inject the beam at an energy of 3.3 TeV into the FCC. This option requires some changes of the LHC. In particular the powering of the magnets needs to be modified in order to allow to ramp the LHC much faster than today [6]. This choice of injection energy leads to a range from minimum to full field in the magnets of a factor 15, similar to the LHC. The collider has been designed to ensure that the injected beam is stable at this energy and that enough beam stay clear is provided in the machine and collimation system.

Table 1: The main FCC-hh parameters.

	LHC (Design)	**HL-LHC**	**FCC-hh baseline**	**FCC-hh ultimate**
c.m. Energy [TeV]	14		100	
Circumference C [km]	26.7		97.75	
Dipole field [T]	8.33		<16	
Arc filling factor	0.79		0.79	
Straight sections	8 x 528 m		6 x 1400 m + 2 x 2800 m	
Number of Ips	2 + 2		2 + 2	
Injection energy [TeV]	0.45		3.3	
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0	< 30.0
Peak no. of inelastic events / crossing	27	135 (lev)	171	1006

Alternatively, a new machine in the SPS tunnel could provide beam at 1.3 TeV using fast ramping and cost effective superconducting magnets with a field of 6 T. As an other alternative, a new superferric accelerator in the LHC tunnel could be envisaged or an injector in the FCC tunnel could be considered. However, using a lower injection energy than 3.3 TeV will reduce the beam stay clear and stability at injection. Studies are ongoing to precisely identify the safe limit.

2.14.5 **Luminosity Considerations**

The luminosity of the collider can be expressed as a function of the beam current I, the beam-beam tune shift ξ, the beam gamma factor γ, and the beta-function at the collision point β^* as

$$L = \xi \frac{I}{e} \frac{\gamma}{\beta^*} \frac{1}{r_p} F$$

Here, r_p is the classical proton radius and e its charge. The form factor F includes geometric luminosity reduction effects, for example the hour glass effect; it is neglected for the further discussion. Hence, to reach high luminosity, one has to use a very brilliant beam, achieve small betafunctions and use a large beam current.

The useable brilliance of the beam is limited by beam-beam effects. We have assumed that one can tolerate a beam-beam tuneshift of up to 0.03 for the two main experiments together. Simulation studies [7-10] for the current working point confirm that this value is acceptable. The fraction of beam that is lost into the transverse tails due to beam-beam effects remains below 10^{-3} per hour and also the emittance growth induced by beam-beam jitter would remain limited. In contrast, a slightly larger tuneshift would increase the loss rate rapidly and the beam emittance would increase significantly faster for the same jitter amplitudes. Studies indicate that other working points might allow a larger tuneshift; further investigations are planned. For the ultimate parameters, a crossing angle of about 200μrad is required to limit the impact of parasitic beam-beam crossings. The associate luminosity reduction is mitigated by the use of crab cavities.

A small betafunction at the collision point makes the design of the experimental insertion optics demanding. It also leads to a large beam in the focusing triplets around the experiments. This poses challenges for the magnet design and protection and the collimation system that has to scrape off tails that can hit the triplets.

The beam current is limited by the synchrotron radiation that even the proton beam emits at these high energies. In FCC-hh both beams emit about 5 MW of radiation that has to be removed by the cryogenics system. The magnets are protected from the radiation by a beamscreen as in LHC. These screens are operated at around 50 K. In this case the power required to drive the cryogenic system is about 100 MW, due to the Carnot inefficiency and the technical inefficiency of the system [11].

In order to reduce the magnet cost the beam aperture must be minimised. This leads to important collective effects in combination with the high beam current. The best compromise thus has to be found using possible mitigation methods to stabilise the beam. Finally the high amount of kinetic energy stored in the beam leads to important challenges for the machine protection system. This is in particular the case for the collimation section, which cleans the beams and protects the machine from high losses, and the beam extraction section.

Table 2: Other key FCC-hh parameters.

	LHC (Design)	**HL-LHC**	**FCC-hh baseline**	**FCC-hh ultimate**
Number of bunches n	2808		10400	
Bunch population $N[10^{11}]$	1.15	2.2	1.0	
Nominal transv. normal. emittance [µm]	3.75	2.5	2.2	2.2
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.03
RMS bunch length [cm]	7.55		8	
IP beta function [m]	0.55	0.15 (min)	1.1	0.3
RMS IP spot size [µm]	16.7	7.1 (min)	6.8	3.5
Full crossing angle [µrad]	285	590	91	200
Stored energy per beam [GJ]	0.392	0.694	8.4	
SR power per ring [MW]	0.0036	0.0073	2.4	
Arc SR heat load [W/m/aperture]	0.17	0.33	28.4	
Longitudinal emittance damping time [h]	12.9		0.5	
Horizontal emittance damping time [h]	25.8		1.0	
Dipole coil aperture [mm]	56		50	
Minimum arc beam half aperture [mm]	~18		13	
Installed RF voltage (400.79 MHz) [MV]	16		48	
Harmonic number	35640		130680	

During the luminosity operation the beam parameters will change strongly [12]. The beam current is rapidly reduced due to beam burn-off in the experiments. At the same time the transverse emittances will shrink due to the emission of synchrotron radiation. As a result the luminosity will first increase and then decrease during a run, see Fig. 2. The synchrotron radiation also damps the longitudinal emittance. The RF system will be used to heat the beam to keep the emittance and bunch length constant.

The total time of luminosity operation is limited for each fill. This is another reason to maximise the beam current. However, the turn-around time from the end of one luminosity run to the beginning of the next is important for the integrated luminosity. A goal of 4 h has been set. Studies of the LHC performance indicate that a minimum turn-around time of about 2 h can be reached in FCC [13,14]. The studies also indicate that the main reason for longer turn-around times is given by the need to repair the machine after a failure before the new beam can be injected. The injection process itself is not much slower than predicted.

It is assumed that the operational cycle of the machine will take 5 years [15]. During this cycle a shut-down of 1.5 years is foreseen. Machine commission, development and technical stops are estimate to take a total of 12 months, leaving a scheduled operation time for luminosity production of 2.5 years. We assume that the effective luminosity operation time is 70% of the scheduled time [16,17]. Based on these targets, the machine will operate an effective 625 days over the full five-year cycle. With the baseline parameters 2 fb^{-1} per day can be achieved. This allows to provide 1250 fb^{-1} for each five-year operation cycle. The ultimate parameters yield 8 fb^{-1}/day resulting in 5000 fb^{-1} per five-year period. A scenario with 10 years of operation using the baseline parameters followed by 15 years of ultimate, would reach 17.5 ab^{-1}.

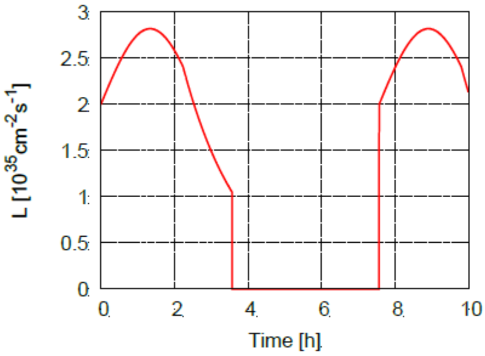

Figure 2: Luminosity evolution during a run with ultimate parameter set.

2.14.6 **Key Design Components**

2.14.6.1 ***Lattice Design***

A complete lattice has been developed for the collider ring that is consistent with the layout and the energy reach [4]. The arc lattice consists of FODO cells of more than 200 m length and with a phase advance of 90°. Integrated studies of the lattice performance are ongoing and already gave important feedback on the magnet design, in particular for the field quality. With the previous design good dynamic apertures have been reached [18]. With the current change in beam separation in the arcs, the field quality of the magnets has degraded significantly and a new round of studies tries to address this. The alignment tolerances are similar to LHC with some tighter values for the quadrupoel alignment [19].

2.14.6.2 ***Experimental Insertions***

The key challenge of the high luminosity experimental insertions is to obtain very small betafunctions in the collision point and to protect machine and experiments from the large power of the collision debris.

The ambitious luminosity goal requires beta functions of only 0.3 m in the collision points for the ultimate parameters. This is more challenging than the goal of 0.15 m envisaged for HL-LHC due to the higher beam energy. Different designs have been developed that can reach even smaller betafunctions [20]. They use long final triplets with large aperture and leave a distance of 40 m from the end of the magnet to the collision point. Also a flat optics is being investigated as an alternative.

The high luminosity leads to a large rate of proton-proton collisions in the collision points, i.e. a high power of the collision debris, which can reach about 500 kW in the high luminosity detectors. This threatens the magnets of the beam lines surrounding the experiments. In particular, the final triplets next to the experiments are exposed. To protect them a masking system has been designed that absorbs most of the power [21]. The shielding has also to protect the inner bore of the magnets. This requires a large magnet aperture in order to leave enough space for the beam inside of the shielding. Hence the magnetic field gradient is limited which is the main reason to use a very long triplet.

A similar approach has been chosen in the design of the additional experimental insertions [22]. One can expect luminosities of the order of $2x10^{34}cm^{-2}s^{-1.}$

2.14.6.3 *Arc Vacuum System*

Due to their high energy each proton beam emits about 30 W/m of synchrotron radiation in the arcs. The cold bore of the magnets is protected protected from this radiation by a beamscreen [23] that is cooled at 50 K. The beamscreen removes the heat from the synchrotron radiation, ensures very good vacuum, provides an acceptable impedance and suppresses the electron cloud effect.

The vacuum quality has to reach at least 100 h of beam lifetime, preferably 500 h. At 100 h, the protons lost by beam-gas scattering will induce a total power in the arc dipole magnets that requires about 30 MW of power for cooling. The beamscreen has pumping holes, as in the LHC, to achieve the required vacuum. Unlike in LHC, these holes are shielded from the beam since they would produce a very high impedance otherwise that would render the bema unstable. The minimum aperture of the beamscreen is 26 mm and it is coated with 0.3 mm of copper in order to limit the impedance effect at injection energy. Adding the required space for the cooling fluids and beamsreen led to the choice of 50 mm for the magnet aperture.

In order to prevent the build-up of electron clouds to render the beams unstable a secondary emission yield of below 1.0-1.1 has to be reached [24,25]. Two technical solutions are being considered. One is to coat the beamscreen with amorphous carbon and the other to roughen the inner surface with a laser treatment. Both solutions can achieve the required secondary emission yield. The increase of the impedance by the carbon coating is acceptable. For the laser treatment further investigations are onging since the impedance depends on the details of the treatment.

Also, the direct production has to be suppressed of electrons that are generated in the main part of the beamscreen by backscattered synchrotron radiation. The goal to have less than 0.01 electrons per photon is addressed by using a sawtooth pattern on the side of the beamscreen to suppress the backscattering of photons into the main part of the chamber.

2.14.6.4 *RF, Impedance and Collective Instabilities*

The baseline RF system design [26] is similar to the one of LHC, and has an RF frequency of 400.8 MHz. The installed voltage will be 48 MV, three times more than in the LHC. In the longitudinal plane, already a lower value of 16 MV corresponds to the minimum necessary to ensure beam stability, assuming an inductive longitudinal impedance budget of $ImZ/n = 0.2\ \Omega$ similar to the one of LHC ($0.1\ \Omega$). Due to synchrotron radiation damping, controlled longitudinal emittance blow-up (by band-limited RF phase noise) will be required not only during the acceleration ramp but also in the coast at 50 TeV beam energy.

In FCC-hh, transverse impedance effects are important design drivers [27-31]. We require that the impedances remain a factor three below the estimated limit of beam stability. This margin is consistent with the observation that in the LHC a factor two difference can be found between calculated and measured impedance effects.

At injection, the arcs will be the largest source of impedance. The larger beam stiffness, compared to LHC, is roughly compensated by the larger circumference and arc beta-functions. Hence, the smaller aperture, needed for cost reduction, increases the impedance effects beyond those of LHC by a significant factor. The beamscreen aperture has been chosen to be still consistent with a stable beam. Currently, estimates of the different impedances are being made and show that one can expect to achieve the goal to stay away from instabilities. This requires that the several collimators are coated with molybdaenum. Fast transverse dampers will be used to suppress rigid multi-bunch instabilities at injection and collision, even without chromaticity [32]. They can cure instabilities with rise times of up to 20 turns at injection and 100 turns at top energy. Only non-rigid bunch modes, which have slower rise times, need to be cured by the use of octupoles. Alternatives using electron lenses or RF quadrupoles are also being explored [33-35].

2.14.6.5 *Beam Power, Collimation System*

Each FCC-hh beam has a total energy of 8.4 GJ; this exceeds the energy in the LHC beams by more than a factor 20. Consequently, losses pose an even larger threat than in LHC and machine protection and beam cleaning are more demanding.

Fast failures are mitigated by passive and active protection. The operational limit is set to a minimum beam lifetime of 12 minutes, i.e. a beam loss of about 12 MW. Such a short lifetime is rare in the LHC and it might be possible to relax this requirement.

First designs of the collimation insertions exist and are being refined [36-39]. A free aperture of 15.5 times the RMS beam size is required in the machine and the primary, secondary and tertiary collimators will have gaps of 7.2, 9.7 and 13.7 RMS beam sizes, respectively, and the extraction protection 11.4 sigmas.

For 12 minutes lifetime high power loads are seen in some collimators [38] and the collimators are being redesigned to reduce these loads. Proton losses that can lead to quench of magnets in the arcs are captured with a dedicated protection system. The system also limits the leakage into the arcs of showers induced by the captured protons [40].

2.14.6.6 *Injection and Extraction*

Also the injection and extraction insertions as well as the dump lines have been designed[41,42]. The injection and extraction strategies are similar to LHC. The largest risk exists in the extraction insertion. Here, the beam can be extracted by firing a series of kickers during a gap in the bunch train to move the beam into a septum, which increases the deflection, into a transferline toward the beam dump. To avoid that the high energy beam drills a hole into the beam dump fast kickers have will be used that move the point of impact on the beam dump rapidly. While a similar scheme is used in LHC it has to be greatly refined for the FCC-hh.

Another risk arises from the extraction kickers. Their power supplies habe to be permanently charged in order to be able to guarantee that the beam can be extracted at any time. However, an extraction kicker can thus fire unvoluntarily. In the LHC the beam is in this case extracted rapidly (asynchronous dump) without waiting for the extraction gap. Hence, a few bunches can escape into the arcs with larger amplitude or be lost on the extraction devices. The protection from these loses is more demanding in the FCC-hh due to the high beam energy. An alternative solution is therefore studied, where the failure of a single kicker allows to leave the beam in the machine until the next abort gap arrives.

2.14.7 **Ion Operation**

A first parameter set for the ion operation has been developed [43-45]. A preliminary estimate has been made of the integrated luminosity that can be achieved per experiment in 30 days, assuming that two experiments are operating. The expectation is 6 pb^{-1} and 18 pb^{-1} for proton-lead ion operation with baseline and ultimate parameters, respectively. For lead-ion lead-ion operation 23nb^{-1} and 65 nb^{-1} could be expected. More detailed studies will be carried out to address the key issues in the ion production and collimation and to review the luminosity predictions.

Table 2: Tentative FCC-hh baseline parameters for ion operation.

	LHC achieved	**HL-LHC** baseline	**FCC-hh** baseline	**FCC-hh** ultimate
Bunch population $N[10^8]$	2.2	1.8	2.0	
Nominal transv. normal. emittance [μm]	1.5	1.65	1.5	1.5
Number of bunches n	518	1256	2760	5400
IP beta function [m]	0.6	0.5	1.1	0.3
Beam energy E [Z TeV]	6.5	7	50	50

2.14.8 **Conclusion**

The FCC-hh design addresses the key issues of a high-energy hadron-hadron collider. It is progressing very well toward the CDR.

2.14.9 **Acknowledgements**

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2.14.10 **General References**

Information is mainly available in presentations given in the FCC week 2017 in Berlin (they can be found at https://indico.cern.ch/event/556692/) and in the EuroCirCol meeting 2017 at CERN (https://indico.cern.ch/event/669849/). Detailed information will become available with the FCC-hh conceptual design report that is to be published next year.

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