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Future Circular Collider Study

Hadron Collider Parameters

WBS PATH

1.2.1.2

ABSTRACT:

The goal of the hadron collider designed in the scope of the Future Circular Collider study is to provide proton-proton collisions at a centre-of-mass energy of 100 TeV. The machine is compatible with ion beam operation. Assuming a nominal dipole field of 16 T, such a machine would have a circumference of the order of 100 km. The machine is designed to accommodate two main proton experiments that are operated simultaneously. The machine delivers a peak luminosity of 1 - 5 x 10^{34} $cm^{-2}s^{-1}$. The layout should allow for two additional special-purpose experiments. This document summarizes the baseline parameters for this collider.

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1. Introduction

1.1 Purpose

The purpose of this document is to define a parameter baseline for the hadron collider of the Future Circular Collider study (FCC-hh).

1.2 Scope

The goal of the FCC-hh is to provide proton-proton collisions at nearly an order of magnitude higher energy than the LHC. The target centre-of-mass energy is 100 TeV. This could be achieved with advanced super-conducting magnet technology based on Nb_3Sn. Assuming a nominal dipole field of 16 T, such a machine would have a circumference of the order of 100 km. The machine should support two main proton experiments operated simultaneously and have a peak luminosity of 1 - 5 x $10^{34}cm^{-2}s^{-1}$. The layout should also allow for two additional special-purpose experiments. Operation of the collider with ions should also be possible.

1.3 Definitions, Acronyms and Abbreviations

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

c.m.	Centre of Mass
FCC	Future Circular Collider
FCC-hh	Hadron Collider within the Future Circular Collider study
FODO	Focusing and defocusing quadrupole lenses in alternating order
HE-LHC	High Energy - Large Hadron Collider
HL-LHC	High Luminosity – Large Hadron Collider
IBS	Intra Beam Scattering
IP	Interaction Point
LHC	Large Hadron Collider
Nb_3Sn	Niobium-tin, a metallic chemical compound, superconductor
Nb-Ti	Niobium-titanium, a superconducting alloy
RF	Radio Frequency
RMS	Root Mean Square
SR	Synchrotron Radiation
SSC	Superconducting Super Collider
TBC	To Be Confirmed
TBD	To Be Done

1.4 References

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1.5 Overview

Section 1 provides an overview of the document, explains abbreviations and terms and lists references.

Section 2 introduces assumptions and constraints that impact the baseline parameter set.

Section 3 contains the table of baseline parameters.

2. Collider Parameters

2.1 Layout Baseline

Two different basic configurations are possible for the ring layout:

1. A layout similar to the LHC, with arcs of equal length that are separated by straight sections. The straight sections could all have the same length or they could have different lengths, respecting some symmetry condition; i.e. the exactly opposite straight sections should have identical length.
2. A racetrack layout in which one has two arcs with almost 180^{o} each, connected by two long, almost straight sections. Such a layout has been used for the SSC.

A choice between these options will need to be made based on more detailed considerations, also including constraints from the candidate site.

The total length of the arcs is defined by the strength of the dipoles and the filling factor, i.e. the fraction of the arc that can be filled with dipoles. One can expect superconducting magnets that are based on the use of Nb_3Sn to reach operating fields of about 16 T. High temperature superconductors may achieve even higher fields; for such option we assume a field of 20 T. In the arcs, the LHC has a filling factor of 79%. This factor takes into account the length of the dispersion suppressors and the effective magnetic length of the dipoles. We assume that we can achieve a similar value for FCC-hh and use this value for both basic layouts. Consequently the arcs should have a total length of 82.9 km for the 16 T design and about 66.3 km for the 20 T case.

The straight sections need to accommodate two main experiments, two special experiments, the injection and extraction systems, the RF system and two lines for collimation. The current working assumption is to use a dedicated part of a straight section for each of the nine beam lines mentioned above. The separate injection and extraction insertions should simplify the corresponding designs, which are expected to be critical given the high beam energy. However one should also explore the alternative of merging a number of beamlines into a single straight line. In the case of an LHC-type layout, each beamline would be located in a separate straight section, in the case of an SSC-type layout the beamlines would sequentially form the two straight sections.

Tentatively we have assumed that the integrated length of all straight sections is 4 times that of the LHC; this corresponds to 16.8 km. In the case of an LHC-type layout the length of the different straight sections would need to be determined based on the different system. In the case of a racetrack layout the two straight sections would each be 8.4 km long. Detailed studies are required to review this estimate.

Based on these considerations the tunnel circumference should be 99.7 km for the 16 T design and 83.1 km for the 20 T design.

2.2 Injection Energy Considerations

The minimum injection energy is defined by the field quality of the high-energy ring magnets when operated at the lower fields corresponding to the injection energy and during the start of the ramping to full field. We assume the same ratio of injection to full energy as for the LHC, which translates into an FCC-hh injection energy of 3.3 TeV. Studies of the magnet design and the associated magnet properties will have to confirm this value.

Impedance effects are reduced at higher injection energy, which can potentially simplify the large ring design and could lead to cost reduction. In particular, it may be possible to reduce the beam screen and magnet aperture. Similarly the reduced beam size at injection might relax the requirements on the good field region of the magnets. The impact of both effects remains to be studied in detail.

The injection energy is obviously a critical parameter for the injector design. We tentatively consider three injector options: injecting from a machine in the SPS tunnel, from a machine in the LHC tunnel and from a machine in the same tunnel as the high-energy collider:

• An injection energy of 3.3 TeV requires 1 T magnets for an injector in the 100 km ring and 1.3 T magnets in the 80 km ring. These values can be exceeded with iron based dipoles, so it would be possible to reduce the filling factor of the injector to save cost.

• If the injector were installed in the LHC tunnel a field strength of about 3.6 T would be required, so that superconducting magnets (Nb-Ti) would be needed. In this case one could also consider taking advantage of the potential to go to higher injection energies with the same magnet technology.

• In the SPS tunnel a field strength of 13.5 T would be needed, so that the use of Nb_3Sn would be necessary.

A reduction of the injection energy to 1.8 TeV would allow using superconducting magnets based on Nb-Ti in the SPS tunnel. A reduction to 1.7 TeV would allow using SPS-type magnets with 2 T in the LHC tunnel. It remains to be studied if such options are viable. In particular, the power consumption of the different injectors also needs to be studied. This could be a main factor in the choice.

2.3 Beam Parameters

2.3.1 Introduction

A wide parameter space exists for the beam parameters, which is constrained by many different limitations. In the following we describe how the example parameter sets were chosen. Detailed studies will be needed to confirm their validity and to determine an optimum parameter set.

Most critical for the experiments are beam energy and luminosity. The number of background events per bunch crossing is also important. It is proportional to the integrated luminosity per bunch crossing. The ability to deal with the resulting background is also affected by the extent of the luminous region (for FCC-hh determined by the bunch length), which allows special separation of background events from the main events, and by the bunch spacing, which affects the ability to separate the events of different crossings.

In the scope definition, the target centre-of-mass energy and the peak luminosity have been chosen to be 100 TeV and 5 x 10^{34} $cm^{-2}s^{-1}$, respectively.

2.3.2 Beam time structure

For the bunch spacing, we use 25 ns as a baseline and 5 ns as a case indicating the lower limit of the bunch spacing that one can reasonably expect to be able to achieve. The shorter bunch spacing will lead to reduced background per collision, since the integrated luminosity per collision is smaller. How much the detectors can profit from this will depend on the time resolution that they can achieve. The machine however might suffer at short bunch spacing from detrimental effects such as electron build-up. LHC shows no problem with a bunch spacing of 50 ns while currently some problems exist at 25 ns. We remain optimistic that these limitations can be overcome. With the smaller beam-pipe diameter of the FCC-hh the electron cloud build up is expected to be less severe than for the LHC, at the same bunch spacing of 25 ns. We aim for a bunch length similar to the one in LHC, in order to maximise the luminous region and hence the special separation of background and main events.

We assume that 80% of the circumference of the machine are filled with bunches. This is a value similar to LHC.

2.3.3 Luminosity and bunch parameters

Luminosity 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 crossing angle between the two beams. In the case of FCC-hh it is close to 1 and is neglected for the further parameter discussion.

We assume an upper limit for the total beam-beam tune shift in the two interaction points of ξ_t=0.01, i.e. a value of ξ=0.005 per interaction point. This value is conservative.

A lower limit for the beta-function arises from the final focus triplets. The pole-tip field of the magnets is tends to be normally at the limit, since this tends to yield the best lattice design. With increasing beam energy the magnet gradient has to increase proportionally if the layout is not changed. Within limits, this can be achieved by decreasing the magnet aperture inversely proportional to the beam energy. In addition, an increase of the beta-function at the collision point proportionally to the beam energy will lead to a reduction of the beta-function in the magnets proportionally to the inverse of the beam energy. Together with the higher beam energy, this leads to a reduction of the beam size proportional to the beam energy and hence proportional to the magnet aperture. However, by scaling all lengths with $\sqrt{E}$ one can stay with the same magnet design. In this case the beta-function will also increase proportionally to $\sqrt{E}$. Since the chromaticity of the system (L^*/β^*) remains constant, the difficulty of the system design remains also constant. Based on an LHC insertion design that allows for β^*=0.4 m we find our choice of β^*=1.1 m. The required insertion length will be about 1400 m using this scaling.

The necessary total beam current can now easily be calculated:

$$I = e\frac{\beta^*}{\gamma}\frac{r_p}{\xi}L \approx 0.5A$$

The bunch charge *N* is derived for the different bunch spacings by distributing the circulating charge accordingly, over *n* bunches. The normalised transverse emittance ε that is consistent with the beam-beam limit can then be calculated as $\varepsilon = Nr_p / 4\pi\xi$.

The bunch length has been chosen to be similar to LHC. However it may be advantageous to increase it.

This choice of parameters implies that the total synchrotron radiation power emitted by the beam is independent of the bunch spacing since the beam current is the same. It also implies that the luminosity lifetime is identical. The luminosity lifetime is fundamentally limited by the burn-off of the protons, i.e. their destruction in the proton-proton collisions at n_{IP} interaction points. Under the assumptions described further below the luminosity lifetime equals the beam lifetime and can easily be calculated as

$$\tau = \frac{Nn}{Ln_{IP}\sigma_{proton}}$$

For fixed luminosity, the lifetime is hence proportional to the number of protons in the circulating beam and inversely proportional to the total proton cross section σ_{proton}, which does not change strongly as a function of the energy. The value found is of the order of 15-20 h, which appears acceptable, as will be detailed in the following section.

It should be noted that in order to reduce the synchrotron radiation, it would be advantageous to reduce the circulating charge for a given luminosity. This could for example be achieved by reducing the beta-function, which makes the insertion design somewhat more difficult. The resulting reduced beam lifetime would reduce the average integrated luminosity. Different methods to mitigate this can be envisaged, including a shorter turn-around time.

The full crossing angle $2\theta_c$ is chosen to provide a beam-beam separation of n_s=12 RMS beam sizes for the parasitic crossings, i.e. $2\theta_c = n_s\sqrt{\varepsilon/\beta\gamma}$. From the LHC experience this should avoid issues due to the long-range beam-beam kicks for bunch spacings above 25 ns. However detailed studies will be required to confirm this. For the smaller bunch spacing of 5 ns, together with a lower emittance, more parasitic crossing will take place, so that it may be necessary to use a larger normalized separation. We currently assume the same normalized separation as for 25 ns.

Due to the large beta-function the Piwinski angle Φ is small. i.e. $\Phi = n_s \sigma_z / (2\beta^*)$. Consequently the crossing angle will have limited impact on the luminosity. Increasing the bunch length however would increase the Piwinski angle leading to a more substantial luminosity loss, which might call for a compensation mechanism, e.g. crab cavities.

Other limitations for beam parameters need to be studied, e.g. collective instabilities and electron cloud effects. These may restrict the range of choices available.

2.4 Lattice Considerations

The lattice design work has not yet started. However, as a baseline we assume that the lattice would be a similar FODO design as in the LHC. In the LHC the cell length is 106.9 m. For FCC-hh a value in the order of 200 m appears adequate. This would lead to a $Q_{x,y}$ of the order of O(120) in the 100 km long collider. The quadrupole field gradient required in this design needs to be about twice that of the LHC, which is can be achieved due to the larger field capabilities of Nb_3Sn and the reduced aperture.

2.5 Luminosity Evolution and Emittance Control

In FCC-hh, the synchrotron radiation emitted by the beam will cause a damping of the longitudinal and transverse emittances. This will be beneficial since it will overcome effects such as intra-beam scattering that increase the emittance with time. However it will be necessary to keep the emittance at the desired level by heating the beam in order to counteract the emittance damping. In order to remain at the nominal beam-beam tuneshift, one can allow the emittance to remain proportional to the bunch charge. This leads to $N = N_0 \exp(-t/\tau)$, $\varepsilon = \varepsilon_0 \exp(-t/\tau)$ and $L = L_0 \exp(-t/\tau)$. As the emittance decreases, the crossing angle could be decreased accordingly ($\vartheta_c \propto \sqrt{\varepsilon}$), which keeps the beam separation constant. The average luminosity $\langle L \rangle$ can then be calculated as

$$\langle L \rangle = L_0 \left(1 - \exp(-t_r/\tau)\right) \frac{\tau}{t_r + t_{TA}}$$

The time t_{TA} between the end of a luminosity run and the beginning of the next is assumed to be 5 h. With this one finds find optimum run times of about 12.4 h and 11.3 h for the 16 T and the 20 T design, respectively. The integrated luminosity per day is 2.1 fb^{-1} and 2.21 fb^{-1}. Hence one obtains an average luminosity of about 50% of the maximum.

It should be noted that the emittance at injection does not necessarily have the same value as the one at the start of luminosity operation. It appears possible to take advantage of the set-up time of the run in order let the emittance decrease due to the short damping time. A detailed study remains to be performed.

It may be possible to also reduce the beta-function at the collision point during luminosity operation so as to stay proportional to the bunch charge. This increases the beta-function in the final triplet, which should be acceptable since the beam emittance is decreasing such that the beam size in the triplets remains constant. Such a scheme could allow for almost constant luminosity during the run. It should be noted that this does not impact the required field in the final triplet substantially.

In order to lower the synchrotron radiation, a reduced beam current would be beneficial. For a constant luminosity this would reduce the beam lifetime, since it is dominated by the burn-off of the protons due to proton-proton interaction in the collision point. Such a scheme would require either running at a higher beam-beam tuneshift or reducing the collision beta-function. It would also be necessary to reduce the turn-around time between two luminosity runs. It appears beneficial to investigate these options.

2.6 RF Parameters

An RF system similar to the LHC's, which has an RF frequency of 400.8 MHz with maximum voltage of 16 MV per beam, is able to provide, at the top energy, bunches with an RMS length of about 8 cm (Table 1) for a longitudinal emittance of 7.0 eVs (2 sigma). The minimum voltage for FCC-hh is 16 MV, but a higher value is beneficial for beam stability. Detailed studies are required before the voltage can be fixed.

At an RF voltage of 16 MV, the bucket area is 13.1 eVs, and for an emittance of 7 eVs (momentum filling factor of 0.77), the threshold value of longitudinal inductive impedance ImZ/n for the loss of Landau damping is 0.2 Ω. The impedance budget of the LHC is around 0.1 Ω and a similar value can be assumed for the FCC-hh. The maximum longitudinal emittance at injection depends on the injection energy and voltage. For example with the same RF voltage of 16 MV at 3.3 TeV it should be less than 4 eVs.

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.

A lower-frequency RF system (200 MHz) would offer certain advantages compared with the 400 MHz RF. However, the design of a SC 200 MHz system, for either LHC or FCC-hh, does not yet exist. In such a lower-frequency RF system and for the bunch lengths from Table 1, the longitudinal beam stability (ensured by Landau damping) will be at the limit. For an assumed 200 MHz RF voltage of 10 MV, beam stability could be recovered (with the same margin as for in the 400 MHz RF) only for bunches longer than 12 cm (RMS).

Another possibility to stabilise the beam is to use a double harmonic RF system, e.g. by employing a 400 MHz RF system in addition to a 200 MHz system.

Fast transverse dampers will be required in order to ensure the beam stability. These require detailed studies.

2.7 Other Parameters

The beam pipe radius has been assumed to be the same as for HE-LHC. Further studies should be performed to establish a more precise value. Integration of technical and beam induced limitations is required for this goal.

The other parameters follow from the ones that have been discussed above.

2.8 Further Studies

The presented parameter list is tentative and meant to provide a basis for further studies. More work is required to fully establish the feasibility of these parameters. Some examples of particularly important basic parameters that need to be reviewed are the bunch spacing, the number, lengths and distribution of the straight sections, the need for a single or double tunnel and the injection energy. Once feasibility of achieving the parameters has been established, further studies are required for optimisation.

3. Parameter Overview

Table 1: FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference C [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3
Physics performance and beam parameters				
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Total / inelastic cross section σ_{proton} [mbarn]	111 / 85		129 / 93	153 / 108
Luminous region RMS length [cm]				5.7 (5.3)
Beam lifetime due to burn off [h]	45	15.4	5.7	19.1 (15.9)
Beam parameters				
Number of bunches n at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population N[10^{11}] - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2
Nominal transverse normalized emittance [µm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.01

Beam current [A]	0.584	1.12	0.478	0.5
RMS bunch length [cm]	7.55		7.55	8 (7.55)
IP beta function [m]	0.55	0.15 (min)	0.35	1.1
RMS IP spot size [μm] - 25 ns - 5 ns	16.7	7.1 (min)	5.2	6.8 3
Full crossing angle [μrad] - 25 ns - 5 ns	285	590	185	74 n/a
Other beam and machine parameters				
Stored energy per beam [GJ]	0.392	0.694	0.701	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)
Energy loss per turn [MeV]	0.0067		0.201	4.6 (5.86)
Critical photon energy [keV]	0.044		0.575	4.3 (5.5)
Longitudinal emittance damping time [h]	12.9		1.0	0.54 (0.32)
Horizontal emittance damping time [h]	25.8		2.0	1.08 (0.64)
Initial longitudinal IBS ε rise time [h]* - 25 ns - 5 ns	57	23.3	40	1132 (396) 226 (303)
Initial horizontal IBS ε rise time [h]* - 25 ns - 5 ns	103	10.4	20	943 (157) 189 (29)
Dipole coil aperture [mm]	56		40	40
Beam half aperture [cm]	~2		1.3	1.3
Mechanical aperture clearance at any energy at any element				>12

*The growth times are only indicative. They have been calculated for a specific RF configuration and need to be estimated again once the RF system is defined.