Scenarios for the FCC-hh

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Abstract

In preparation for the 2026 Update of the European Strategy for Particle Physics, various FCC-hh options are being proposed. Here, we present a few operational scenarios that could be considered, spanning c.m. energies from about 70 to 120 TeV, and the corresponding luminosity forecasts.

1 Introduction

For the present layout of the FCC, and after diligent optimisation of the bending-magnet filling factor [1], a dipole field of 17 T, reachable by HTS technology, would provide a c.m. energy of just above 100 TeV. With 20 T magnets, also based on HTS technology, a c.m. energy of 120 TeV could be achieved. With dipole fields of 14 T, the c.m. energy would be 84 TeV, with 12 T magnets (corresponding to the peak field of the HL-LHC quadrupole magnets), the c.m. energy would be 72 TeV. When increasing the c.m. energy beyond 96 TeV, it is fair to assume that the synchrotron-radiation power could not increase, beyond a total of about 4 or 5 MW (which must be removed from inside the cold magnets). On the other hand, when decreasing the beam energy, one can hold either the synchrotron-radiation power or the beam current constant. We have selected six scenarios, that could represent well-defined discrete and distinct options for a future FCC-hh, namely:

- A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
- A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
- The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
- A machine based on 14 T dipoles, and 0.5 A current (F14).
- A machine based based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV centre-of-mass, and still considering a beam current of 0.5 A (F17).
- A machine, also based on High Temperature Superconductor (HTS) dipole magnets, but with a field of 20 T, and limiting the beam current to 0.2 A, so that the synchrotron-radiation power remains close to 2 MW per beam (F20).

In the following we will elaborate on the collider parameters for the six options.

2 Main Collider Parameters

The options outlined in the previous section are detailed in Table 1, which compiles the main machine and magnet parameters. The figures reported there are a combination of results from the literature, and scaling applied to such options. Note that for the discussion we only report the required dipole field. It is clear that a complete analysis of any option would require devising quadrupoles and dispersion suppressor

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magnets, as well as adapted insertions. Indeed, simple scaling does not necessarily produce consistent and feasible configurations, as the optics for the different energy options may differ considerably. Still, in spite of the simple approach taken here, our basic considerations suffice to provide a rough perspective of different FCC-hh scenarios.

In Table 1, the centre-of-mass collision energy increases in proportion to the arc dipole field.

It is natural to assume high-luminosity collisions in $n_{\rm IP} = 2$ primary collision points, and possible lower-luminosity secondary collisions at two other IPs, as for the LHC and HL-LHC. We take the total number of bunches n_b to be 9500, scaling from the LHC with the length of the circumference. Higher beam energies will, however, require a revision of the dump and injection kicker system, which may have an impact on the maximum number of bunches permitted.

The FCC-hh optics for a centre-of-mass energy of 96 TeV achieved an interaction point (IP) beta function β^* of 0.30 m. We extrapolate around this value by keeping the initial beam size at the interaction point and in the final quadrupoles constant, which implies $\beta^* \propto \gamma$, where $\gamma = E_b/(m_p c^2)$ denotes the relativistic Lorentz factor, with m_p the proton mass and c the speed of light.

We assume that the FCC-hh uses crab cavities to compensate for the effect of the crossing angle.

The initial luminosity is given by

$$L_0 = \frac{f_{\rm rev} n_b N_b^2}{4\pi {\sigma^*_{x,y}}^2} \ , \tag{1}$$

where $f_{\rm rev}$ denotes the revolution frequency, and $\sigma^*_{x,y} = \sqrt{\beta^* \varepsilon_n/\gamma}$ the rms beam size at the IP, assuming round beams ($\sigma^*_y = \sigma^*_x$).

The total and inelastic proton-proton cross sections, $\sigma_{\rm tot}$ and $\sigma_{\rm inel}$, are weakly dependent on the collision energy as indicated. This dependence is described by Eqs. (6) and (7) in Ref. [2], which are based on Refs. [3, 4, 5, 6, 7, 8]. The total cross section $\sigma_{\rm tot}$ increases from about 111 mbarn at 14 TeV (LHC) to 160 mbarn at 120 TeV centre-of-mass energy (F20), the inelastic cross section $\sigma_{\rm inel}$ from 85 to 113 mbarn. The inelastic cross section roughly relates to the number of events per bunch crossing recorded in the detector (the so called event pile up), as

$$n_{\rm event} = \frac{\sigma_{\rm inel} L_0}{n_b f_{\rm rev}} \ . \tag{2}$$

The initial pile up varies between 600 and 3000 events per bunch crossing for the FCC-hh versions considered. With perfect crab crossing and for Gaussian bunch profiles, the rms extent of the luminous region is equal to the rms bunch length divided by $\sqrt{2}$.

The total cross section $\sigma_{\rm tot}$ determines the initial proton burn off time $\tau_{\rm bu}$ as

$$\frac{1}{\tau_{\rm bu}} = -\frac{\dot{N}_b}{N_b} = \frac{\sigma_{\rm tot} L_0 n_{\rm IP}}{N_b n_b} \ . \tag{3}$$

The energy stored per beam scales exactly with beam energy and beam current, and for the 16 T case it is about 7 GJ, or about 10 times higher than for the HL-LHC.

The proton energy loss per turn due to synchrotron radiation grows as the fourth power of beam energy, increasing from 6.7 keV at the LHC to 10.1 MeV at F20.

At constant beam current and bending radius, also the total synchrotron-radiaton power increases as the fourth power of energy. While for the nominal LHC, the SR power of one beam is 3.6 kW, for F16 and F20 it exceeds 2 MW per beam, or about 4 MW in total, and the synchrotron radiation per unit length reaches 27 W/m per aperture. This implies that the SR heat can still be removed from inside the arcs with the FCC-hh beam screen design. At F20, the maximum allowable synchrotron radiation heat load is taken to limit the maximum beam current.

The radiation damping time scales as ρE_b^{-3}, where ρ denotes the dipole bending radius. The interplay of proton burn off and radiation damping determines the optimum physics run time (i.e. the moment the two beams are dumped for a new injection) as a function of the average turnaround time (the time between the dump and the start of the new physics fill).

For all FCC-hh scenarios, the proton burn-off time, of a few hours, is much longer than the transverse emittance damping time, of order half an hour. As a result, both the luminosity and the beam-beam tune shift increase with time in store, and for the latter we must assume a maximum acceptable value, which, once reached, is maintained by controlled emittance blow up through transverse noise excitation

[2]. The time evolution of the luminosity and the optimum run length t_r then follows from Eqs. (33)–(54) in Ref. [2].

For the purpose of illustration, we consider a maximum beam-beam tune shift of 0.025, which is close to the value of 0.03, previously assumed for the "phase 2" of the FCC-hh [2, 9]. The ideal evolution of instantaneous and integrated luminosity during 24 h is shown in Fig. 1, for all six FCC-hh versions. The increase of the instantaneous luminosity during the early store for F12LL, F14, and F16 also is a measure of the increase of the event pile up from its initial value, which is of order 50%.

For the average turnaround time and for the number of physics days per year, we adopt the canonical values of Ref. [10] (5 hours and 160 days). The ideal integrated luminosity per day is then computed for the optimum run time t_r and the assumed average turnaround time. The luminosity delivered per year is finally obtained by multiplying the latter with the number of physics days scheduled and the postulated availability of 75% [10], which is slightly lower than for the LHC and HL-LHC.

Finally and importantly, further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.

Table 1: Key parameters of six FCC-hh options compared with HL-LHC and LHC, for operation with proton beams. All values refer to the collision energy. The ring circumference is 90.7 km and the experimental straight section length 1400 m. We note that reducing the synchrotron radiation power by, e.g., a factor 4 to lower the overall power consumption, would decrease the peak and integrated luminosity values by the same factor.

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
Centre-of-mass energy	TeV	72	72	72	84	102	120	14
Peak arc dipole field	T	12	12	12	14	17	20	8.33
Beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
Bunch population	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
Bunches / beam		9500						(2760) 2808
Rf voltage	MV	30	30	30	35	43	50	(16) 16
Rf frequency	MHz	400						(400) 400
Momentum compaction	10^{-4}	1.5						(3.22) 3.22
RMS bunch length	mm	~ 80						(90) 75.5
Bucket half height	10^{-3}	0.17	0.17	0.17	0.16	0.16	0.14	0.36
RMS momentum spread	10^{-4}	0.57	0.57	0.57	0.57	0.57	0.57	1.129
Longit. emit. ($4\pi\sigma_z\sigma_E$)	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
Bunch spacing	ns	25						25
Norm. tr. rms emittance	µm	2.5						(2.5) 3.75
IP beta function $\beta^*_{x,y}$	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
Initial IP beam size $\sigma^*_{x,y}$	µm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min.) 16.7
Initial luminosity / IP	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, levelled) 10
Total cross section	mbarn	148	148	148	151	156	160	111
Inelastic cross section	mbarn	105	105	105	107	110	113	85
Initial events / crossing		580	2820	955	590	732	141	(135) 27
RMS luminous region	mm	~ 57						(64) 45
Stored energy / beam	GJ	5.4	12.0	12.0	6.4	7.8	3.6	(0.7) 0.36
Energy loss / p / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power / beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
SR power / length	W/m/ap.	8.4	18.8	18.8	15.6	34.6	26.2	(0.33) 0.17
Transv. emit. damp. time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
No. of high-luminosity IPs	—	2						(2) 2
Initial proton burn-off time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40
Physics time / yr	days	160	160	160	160	160	160	160 (160)
Average turnaround time	h	5						4 (5)
Optimum run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18–13) ~10
Accelerator availability	—	75%						(80%) 78%
Ideal luminosity / day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3.1	(1.9) 0.4
Luminosity / yr	fb^{-1}	950	≥2000	1300	920	920	370	(240) 55

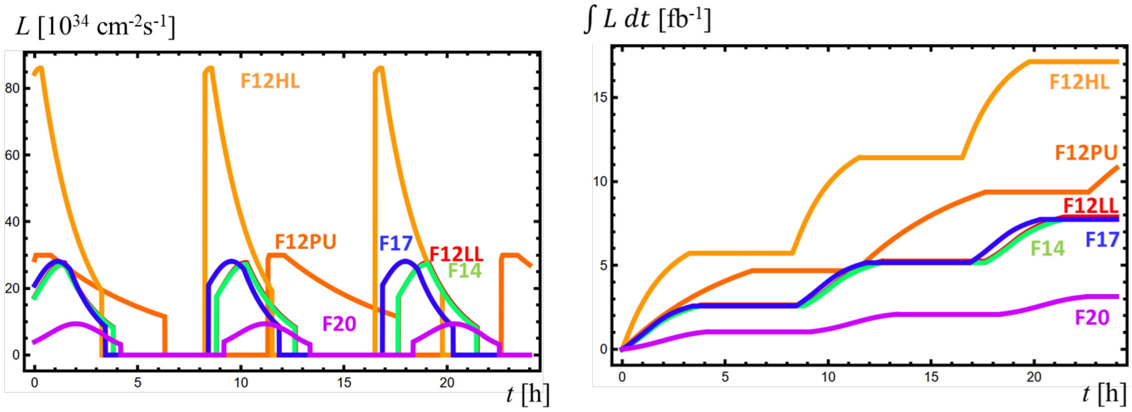

Figure 1: Instantaneous (left) and integrated luminosity (right) as a function of time during 24 hours for various options with 25 ns bunch spacing and a maximum total beam-beam tune shift of 0.025.

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