FCC-hh HADRON COLLIDER — PARAMETER SCENARIOS AND STAGING OPTIONS*

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Abstract

FCC-hh is a proposed future energy-frontier hadron collider, based on dipole magnets with a field around 16 T installed in a new tunnel with a circumference of about 100 km, which would provide proton collisions at a centre-of-mass energy of 100 TeV, as well as heavy-ion collisions at the equivalent energy. The FCC-hh should deliver a high integrated proton-proton luminosity at the level of several 100 fb^{-1} per year, or more. The challenges for operating FCC-hh with high beam current and at high luminosity include the heat load from synchrotron radiation in a cold environment, the radiation from collision debris around the interaction region, and machine protection. In this paper, starting from the FCC-hh design baseline parameters we explore different approaches for increasing the integrated luminosity, and discuss the impact of key individual parameters, such as the turnaround time. We also present some injector considerations and options for early hadron-collider operation.

BASELINE PARAMETERS

The FCC hadron collider FCC-hh will provide pp collisions at a centre-of-mass energy of 100 TeV using 16-T Nb_3Sn magnets in a tunnel of about 100 km circumference (FCC-hh baseline) [1, 2, 3, 4].

The FCC design beam current of 0.5 A is about equal to the LHC design and obtained with 10^{11} protons per bunch at a bunch spacing of 25 ns. An alternative parameter set with a reduced bunch spacing of 5 ns and correspondingly scaled charge and emittance will also be explored.

Scaling the interaction region from the LHC design, the free distance from the interaction point (IP) is increased, from 23 m to more than 40 m, and the IP beta function is doubled, to $\beta^*_{x,y} = 1.1$ m. With these parameters the FCC baseline luminosity becomes 5×10^{34} cm^{-2}s^{-1}, equal to the luminosity of the High-Luminosity LHC (though with more energetic collision debris), and, as for the HL-LHC, the integrated luminosity per year is about 250 fb^{-1}, assuming 180 days per year scheduled for physics operation, and an availability of 70%.

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PHYSICS GOALS

The key physics goals of the FCC are the complete exploration of the Higgs boson and a significant extension, via direct and indirect probes, of the search for physics phenomena beyond the Standard Model [5]. The baseline FCC-hh integrated-luminosity goal of 3 ab^{-1} translates into a discovery reach of about 32 TeV for Standard-Model like couplings. Raising the luminosity by a factor of 10 increases the discovery reach only by about 20% in energy. The higher luminosity leads to much increased event rates, and better statistics, at low masses, and would, for example, allow measuring the Higgs self coupling to better than 5%. Synthesizing the discussions from several theory workshops, an ultimate integrated luminosity goal of 10–20 ab^{-1} for the FCC-hh seems well justified [5].

INCREASING INTEGRATED LUMINOSITY

The FCC-hh luminosity can be increased in a number of ways. First, the IP beta function may be reduced. An advanced interaction-region (IR) optics is already being developed, which can reach $\beta^*_{x,y} = 30$ cm [6], yielding almost a factor 4 gain in peak luminosity. Second, the beam-beam limit of $\Delta Q_{\rm tot} = 0.01$ assumed in the baseline, appears conservative as the LHC and the Tevatron have routinely been running with two times larger values, and as more than three times higher tune shifts have been obtained in LHC beam experiments without any noticeable impact on beam lifetime or emittance growth [7]. Much stronger radiation damping at the FCC-hh (transverse emittance damping time of 1 h) might further boost the achievable beam-beam tune shift if the effect of the radiation damping is similar to the one found on lepton colliders [8]. In addition, head-on beam-beam compensation by electron lenses, recently demonstrated at RHIC [9], is likely to support even higher tune shifts. For all the above reasons we consider the possibility of a total beam-beam tune shift as high as $\Delta Q_{\rm tot} = 0.03$ (sum of two IPs). Third, we assume that the initial turnaround time t_{ta} (the period from the end of one physics fill to the start of the next physics collisions) can be reduced from 5 hours in the baseline to 4 h, after a couple of years of beam operation.

Based on the above considerations we envisage two operational phases of the FCC-hh. "Phase 1" corresponds to the baseline with a peak luminosity of 5×10^{34} cm^{-2}s^{-1} and an average luminosity production of 250 fb^{-1} per year. "Phase 2" achieves about a factor 6 higher peak luminosity of $\sim 3 \times 10^{35}$ cm^{-2}s^{-1} and produces more than 1000

fb^{-1} per year. Depending on the final operation schedule, an overall integrated luminosity of a few tens of ab^{-1} can be expected over a period of, e.g., 20-30 years.

Figure 1 presents the luminosity evolution for both phases over 24 h of running, and Fig. 2 the corresponding luminosity integration. Here we assume that the injected beam corresponds to the baseline parameters and a beam-beam tune shift of $\Delta Q_{\rm tot} = 0.01$. In phase 2 the emittances are allowed to shrink until the higher tune-shift limit of $\Delta Q_{\rm tot} = 0.03$ is reached. From this moment onwards the further emittance damping is counterbalanced by a controlled blow up keeping the beam brightness constant. Only the proton burn-off in collision and the natural, or — after reaching the beam-beam limit — the controlled emittance shrinkage due to radiation damping are taken into account. Other additional phenomena like gas scattering, Touschek effect, intrabeam scattering, and space charge are insignificant for the 50-TeV beams, in the scenarios considered.

A few key parameters of FCC-hh phases 1 and 2 are shown in Table 1. The integrated luminosity values are obtained assuming that on average 180 days per year are scheduled for physics operation (after accounting for shutdowns, maintenance, machine developments, etc.). In the physics period the availability is taken to be 70%.

Table 1: "Phase-1" and "Phase-2" parameters for the FCC-hh. The values for emittance and pile up refer to a bunch spacing of 25 ns. For a bunch spacing of 5 ns both these numbers would be a factor of 5 smaller. The peak luminosity is computed assuming the presence of crab cavities, which recover any geometric luminosity loss due to a finite crossing angle.

parameter	phase 1	phase 2
total beam-beam tune shift (2 IPs)	0.01	0.03
IP beta function β^* [m]	1.1	0.3
turnaround time [h]	5	4
peak luminosity [10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	5.1	29
initial beam lifetime [h]	18	5
optimum run time [h]	11.6	3.5
peak pile up	180	940
luminosity per year [fb^{-1}]	≥ 250	$\geq$1000

Figure 3 illustrates the effect of radiation damping for phase 2 operation. The nominal emittance damping time is 1 hour at 50 TeV. For a shorter damping time the beam-beam limit would be reached earlier at a higher peak luminosity (with more unspent protons), while for a longer damping time of 1.5 h (e.g. corresponding to a lower beam energy of $\sim$44 TeV) the luminosity would be almost constant during the physics fill, as a result of "natural leveling" thanks to the synchrotron radiation.

We assume that the FCC-hh beam current is limited by synchrotron radiation, that is by the cryogenics cooling power available for the cold arcs [10], and that, therefore, the beam current at top energy cannot be increased beyond

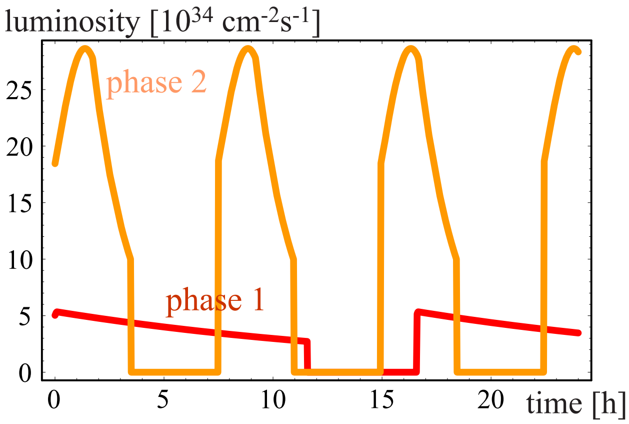

Figure 1: Instantaneous luminosity for FCC-hh phases 1 and 2 from Table 1 as a function of time during 24 hours.

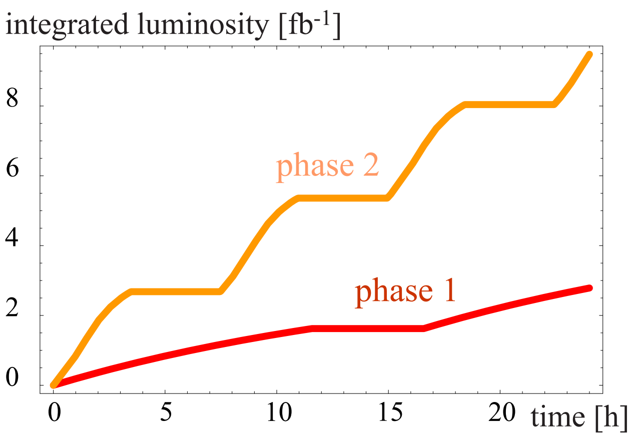

Figure 2: Integrated luminosity for FCC-hh phases 1 and 2 from Table 1 as a function of time during 24 hours.

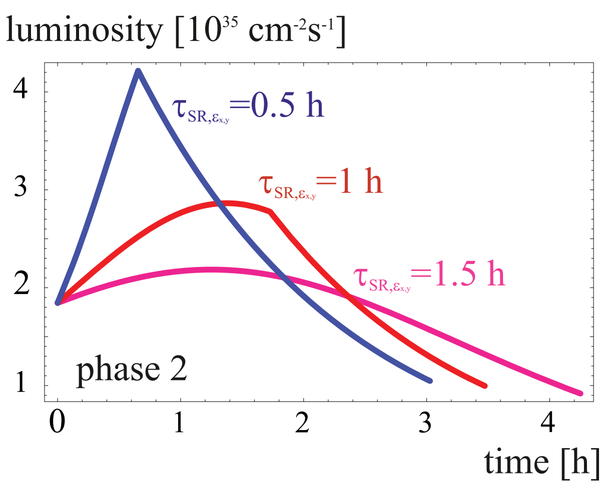

Figure 3: Luminosity evolution for FCC-hh phase 2 from Table 1 for three different values of the transverse emittance damping time (nominal value: 1 hour).

the baseline. When considering only this aspect, the beam current could be increased as the inverse fourth power of beam energy, in order to achieve a higher luminosity running at lower beam energy, should such a scenario be of interest for particle physics. For example, at 80 TeV c.m. energy the beam current could be 2.4 times higher, though the concomitant increase of geometric emittance and β^* at the lower energy would reduce the net luminosity gain to about 60%. However, this option of higher beam current is presently not considered in the baseline design.

Figure 4 illustrates the importance of the turnaround time for the integrated luminosity. Especially for phase 2, where protons are burnt quickly and runs are short, the fastest possible turnaround time would be desired. The total turnaround time comprises the ramp-down/ramp-up times of the FCC-hh main ring, as well as the filling time at injection, which depends on the injector complex.

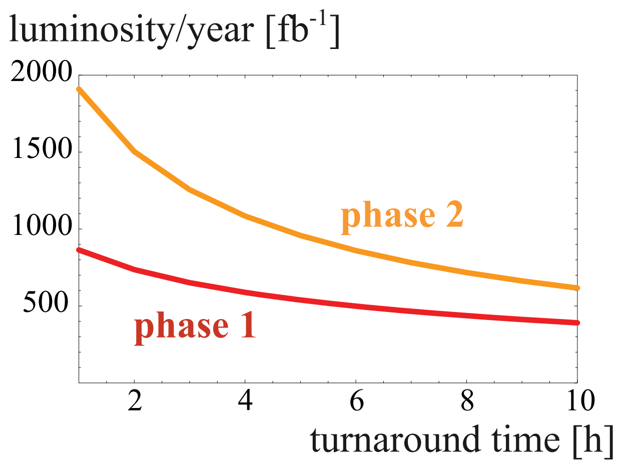

Figure 4: Integrated luminosity per year for FCC-hh phases 1 and 2 from Table 1 as a function of turnaround time.

INJECTOR CONSIDERATIONS AND OPTIONS FOR EARLY OPERATION

The choice of injection energy is important with regard to beam instabilities and dynamic aperture. The baseline injection energy for FCC-hh has been chosen as 3.3 TeV, resulting in the same energy-swing factor as for the LHC. A powerful preinjector chain, further strengthened by the LHC injector upgrade (LIU), does already exist, consisting of Linac4 (160 MeV), PS Booster (2 GeV), PS (25 GeV), and SPS (449 GeV kinetic energy). As final element in the chain, using the existing LHC as FCC-hh injector is attractive. The LHC dipole field at an extraction energy of 3.3 TeV would be 3.9 T, less than half the LHC design value. At the present LHC ramp rate of 7 mT/s the minimum filling time for both FCC-hh rings would be 77 minutes assuming the injection of 4 LHC fills into the collider [11]. To shorten the injection time, it is planned to speed up the LHC dipole-magnet ramp rate by a factor of 5 to 35 mT/s, which would reduce the time for complete FCC-hh filling (injecting 4 fills from the LHC) to 32 minutes [11]. For early FCC-hh operation, to reduce complexity, one could consider injecting only a single LHC fill, so that the injected beam would occupy only a quarter of the FCC-hh circumference. Doing so, with the nominal FCC-hh bunch charge and emittance about 75 fb^{-1} could be accumulated per year.

The impressive potential of this approach becomes evident when assuming the injection of the nominal HL-LHC beam with a higher charge of $N_b = 2.2 \times 10^{11}$ protons per bunch at a normalized emittance of 2.5 μm [which is not the present FCC baseline]. This would result in a higher tune shift of $\Delta Q_{\rm tot} = 0.02$ (instead of the value 0.01 taken for phase 1 before), and more than 250 fb^{-1} per year, with single LHC fills. The beam current in this case would be about half the nominal (i.e. half the synchrotron radiation power), but the pile up would be four times higher (though still lower than for phase 2).

The luminosity performance with single LHC fills is illustrated in Fig. 5, considering both the FCC-hh baseline and the LIU/HL-LHC beam parameters.

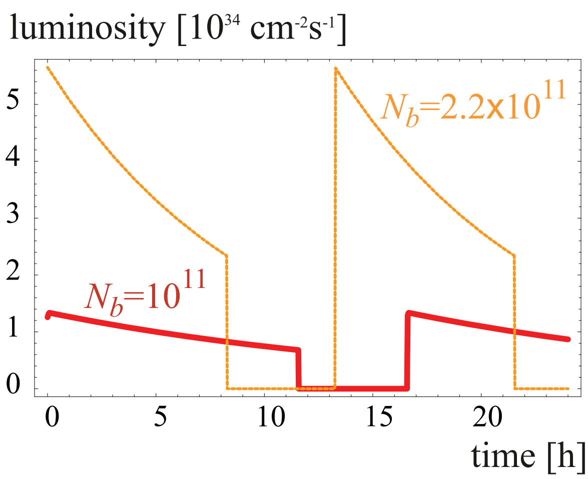

Figure 5: Instantaneous luminosity for early FCC-hh operation based on single injections from the LHC as a function of time during 24 hours.

CONCLUSIONS

Over a total operation period of 25 years, the FCC-hh is expected to deliver a total integrated luminosity of a few tens of ab^{-1}.

A first phase of operation may see a peak luminosity of 5×10^{34} cm^{-2}s^{-1}. Profiting from growing operational experience the FCC-hh performance will be improved continuously, and after a couple of years reach the phase 2 parameters with about 5 times higher peak luminosity.

The LHC is suitable as FCC-hh injector. Even when injecting single LHC fills, with beam occupying a quarter of the FCC-hh ring only, the luminosity target for the FCC-hh phase-1 operation can be obtained.

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