EVOLUTION OF THE BEAM PARAMETERS DURING LUMINOSITY PRODUCTION IN THE FUTURE CIRCULAR HADRON COLLIDER

X. Buffat, D. Schulte, CERN, Geneva, Switzerland

Abstract

The evolution of the beam parameters during luminosity production in the Future Circular Hadron Collider (FCC-hh) is described based on basic models of the effect of synchrotron radiations, intra-beam scattering, luminosity burn-off and beam-beam limitations, allowing for an estimation of the luminosity performance in different running scenarios. It is shown that a large variations of the beam parameters is expected during a cycle. Potential operational schemes adapting to these variations are considered.

INTRODUCTION

The FCC-hh features a significant emittance damping mechanism at high energy due to synchrotron radiation, which drastically modifies the behaviour of the beam parameters during luminosity production with respect to lower energy hadron colliders. Nevertheless the damping rate normalized to the revolution frequency is lower than previous and existing lepton colliders by at least one order of magnitude. The behaviour of the beam parameters in the FCC-hh is therefore very different than previous colliders. This paper provides a description of the expected machine and beam parameter evolution starting from the baseline parameters summarised in Tab. 1 based on first-order estimations of the dominant effects, such as to provide a basis to evaluate the performance in term of luminosity production rate.

Table 1: Baseline parameters of the FCC-hh, further details may be found in [1].

Parameter	Value	
Bunch spacing :	25 ns	5 ns
Beam energy [TeV]	50	
Circumference [km]	100	
Bending radius [km]	10.4	
Bunch intensity [p]	10^{11}	$2 \cdot 10^{10}$
Number of bunches	10600	53000
Norm. transverse emittance [μm]	2.2	0.44
Bunch length [cm]	8	
Relative energy spread	$1.1 \cdot 10^{-4}$	
β^* [m]	1.1	
Maximum beam-beam parameter	0.01	
Normalised long-range beam-beam separation	12	
Turn around time [h]	5	

MODEL

The bunch intensity $I(t)$ is mainly affected by the particles lost due the collision at the interaction point. The first equation of the luminosity model (Eq. 4) shows the dependency on the instantaneous luminosity per interaction point $\mathcal{L}_{IP}(t)$, the number of interaction points n_{IP}, the number of bunches per beam n_b and the total cross section for proton-proton collisions $\sigma_{tot} = 1.53 \cdot 10^{-25}$ [cm^{-2}] [2]. Several other loss mechanisms may affect the bunch intensity, they are modelled as a brightness independent lifetime τ_l.
Due to the emission of synchrotron radiations, each turn the particles lose energy given on average by [3]:

$$\Delta E = \frac{e^5}{3\epsilon_0(m_p c^2)^4}\frac{E_0^4}{r_b} \approx 4.4 \text{ [MeV]}. \quad (1)$$

As a consequence, the transverse emittances $\epsilon_x(t)$ and $\epsilon_y(t)$ are subject to damping due to synchrotron radiations with :

$$\tau_{rad} = \frac{\Delta E}{E_0} \approx 1.1 \cdot 10^7 \text{ [turn]} \approx 1 \text{ [h]}, \quad (2)$$

the longitudinal emittance $\epsilon_s(t)$ is also subject to synchrotron damping with $2\tau_{rad}$. While in the transverse plane the large tune spread caused by beam-beam interaction allows the emittances to be largely reduced without expecting coherent instabilities, coherent instabilities in the longitudinal plane impose a limit on the minimum longitudinal emittance. Assuming that the design parameters are at the limit of longitudinal stability, the minimum emittance may decrease proportionally to $(I(t)/I_0)^{2/5}$ [4].
The quantum nature of the synchrotron radiations provokes an excitation, which in realistic configurations is only relevant in the horizontal plane. Assuming a lattice with a phase advance of 90◦ and a bending angle $\theta = 8$ [mrad] per cell [5], we find the normalised equilibrium emittance [3]:

$$\epsilon_{x,equ} = 2\sqrt{2}\frac{55\hbar}{32\sqrt{3}m_p c}\gamma_r^2\theta^3 \approx 0.04 \text{ [}\mu\text{m]}, \quad (3)$$

with γ_r the relativistic factor.
The intrabeam scattering causes a growth of the beam emittances proportional to the six-dimensional phase space density and on lattice parameters [6]. Using the Bjorken-Mtingwa algorithm [7] implemented in MAD-X [8] with the first lattice design [5] and the beam parameters listed in Tab. 1 one obtains a growth time of $\tau_{x,IBS} = 361$ hours in the horizontal plane and $\tau_{s,IBS} = 1504$ hours in the longitudinal plane. While negligible with these initial beam parameters, the relative effect of intrabeam scattering can increase strongly as the beam emittances are reduced. We will neglect coupling between the three planes as well as the dispersion in the vertical plane, as a result the emittance growth rate in the vertical plane is neglected.
Other mechanisms are modelled as a brightness independent growth times $\tau_{\epsilon_x,\epsilon_y}$ for the horizontal and vertical planes

respectively.
The beam-beam interactions around the interaction points enforces the presence of a crossing angle ϕ between the beams at the interaction point in order to avoid head-on collisions outside of the detector centre. The required crossing angle is defined by the stability of the single particle trajectories under the influence of the non-linear fields of the long-range beam-beam interactions. Studies at the LHC suggest that this limitation scales with the normalized separation between the beams in the drift space around the interaction point S_{drift} [9]. The FCC-hh design value is scaled from the LHC design value [10] proportionally to the bunch charge and the number of long-range beam-beam interaction, such as to obtain an identical tune spread ($\propto S_{drift}^{-4}$ [11]). We shall assume that the crossing angle can be adjusted to the evolution of the transverse emittance, as described by the last equation of the model (Eqs. 4).
Putting together the effect of luminosity burn-off, synchrotron damping, quantum excitations, intrabeam scattering and long-range beam-beam interactions, we obtain the following system of equations for the relevant machine and beam parameters :

$$
\begin{cases}
\frac{\partial I}{\partial t}(t) & = -\frac{I(t)}{\tau_l} - \sum_{IP} \mathcal{L}_{IP}(t)\frac{1}{n_b}\sigma_{tot} \\
\frac{\partial \epsilon_x}{\partial t}(t) & = \frac{\epsilon_x(t)}{\tau_{\epsilon_x}} - \frac{\epsilon_x(t)}{\tau_{rad}} + \sqrt{\frac{2\epsilon_{x,equ}}{\tau_{rad}}} \\
 & + \frac{1}{\tau_{IBS}}\frac{I(t)}{I_0}\frac{\epsilon_{x,0}\epsilon_{y,0}\epsilon_{s,0}}{\epsilon_x(t)\epsilon_y(t)\epsilon_s(t)} \\
\frac{\partial \epsilon_y}{\partial t}(t) & = \frac{\epsilon_y(t)}{\tau_{\epsilon_y}} - \frac{\epsilon_y(t)}{\tau_{rad}} \\
\epsilon_s(t) & = \left(\frac{I(t)}{I_0}\right)^{\frac{2}{5}} \epsilon_{s,0} \\
\mathcal{L}_{IP}(t) & = \frac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^*(t)\sqrt{\epsilon_x(t)\epsilon_y(t)}} \frac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma_t(t)^2}tan\left(\frac{\phi(t)}{2}\right)^2}} \\
\phi(t) & = \sqrt{\frac{\epsilon_x(t)}{\beta^*(t)\gamma_r}} S_{drift}.
\end{cases}
\tag{4}
$$

The luminosity is computed neglecting the effect of hourglass, since $\beta^* >> \sigma_s$. The geometric reduction factor due to the crossing angles depends strongly on the choice of crossing angles in the different interaction points. Since we scaled the effect of long-range beam-beam interactions from the LHC, we shall consider an identical crossing scheme, i.e. the crossing angles of the two IPs are alternated horizontal and vertical. In this case $\sigma_t = \sigma_x$ and σ_y in the two interaction points respectively. While this scheme is very robust, other schemes might have other advantages, however the required studies are beyond the scope of this paper.
The effect of head-on beam-beam interactions plays an important role in the evolution of the beam parameters during luminosity production, yet it is not included in this simple model. Conservatively, the nominal configuration is based on a limit of the total beam-beam tune shift at $\xi_{tot} = 0.01$ [1], with [12] :

$$
\xi_{tot} = \sum_{IP} \frac{N r_0}{4\pi\epsilon} \frac{1}{\sqrt{1+\frac{\sigma_s^2}{\sigma_t^2}tan\left(\frac{\phi}{2}\right)^2}} \tag{5}
$$

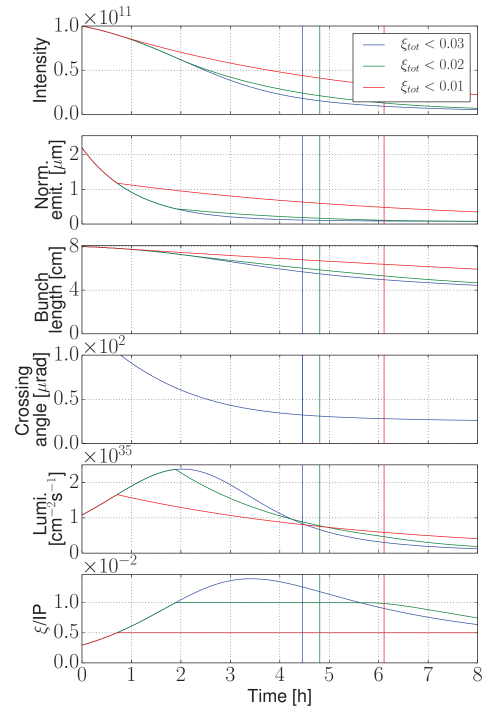

Figure 1: Evolution of the beam parameters in the baseline configuration (Tab. 1), with $\beta^* = 0.3$ m. The vertical emittance is adjusted to the horizontal one, such as to keep round beams in the transverse plane.

BEAM PARAMETER EVOLUTION

Solving the system of differential Eqs. 4, using finite differences with a constant time step of 30 s, one characterise the performance of a given configuration with its average luminosity production rate. The results for the baseline scenario as well as a few variations about the baseline are shown in Tab. 2. The baseline scenario is strongly limited by the large β^*, since recent studies suggests that $\beta^* = 0.3$ $[m]$ can reasonably be achieved [13], we focus on that option. The behaviour of the beam parameters shown in Fig. 1. This scenario is significantly limited by the constraint on the head-on beam-beam parameters, a detailed description of the limiting mechanisms is critical to obtain an accurate modelling of the evolution of the beam parameters and therefore of the performance. Relaxing the constraint on the beam-beam parameter allows to double the performance.
Figure 2 shows the evolution of the strength of the growth rate mechanisms during luminosity production. Both the vertical and longitudinal emittance can shrink to very small values, assuming in particular that the longitudinal stability can be insured for example with Landau cavities. Yet this leads to a runaway situation were the effect of the intrabeam scattering in the transverse emittance increases due to the increase of the 6D phase space density. While smaller emittances could be considered, both the longitudinal and vertical emittance will need to be controlled such as to optimise the overall perfomance. In the round beam configuration, the

ISBN 978-3-95450-147-2

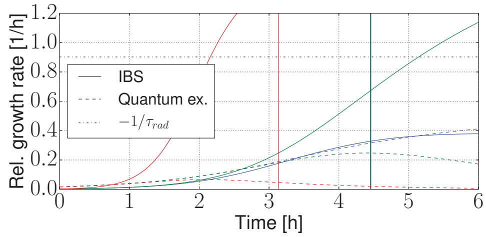

Figure 2: Comparison of the contributions to the transverse emittance growth. The blue lines correspond to the round beam configurations shown in Fig. 1. Letting the vertical emittance shrink, the green lines are obtained. Letting the longitudinal emittance shrink, the red lines are obtained. In the latter two, the performance is lower than the round beam option.

emittance growth mechanisms that drives the asymmetry between the beams become important in the second part of the fill. The possibility to be optimal for round beams at the beginning of the luminosity production and for flat beams towards the end is a challenge for the insertion design.
The beam-beam parameter increases at the beginning of luminosity production due to synchrotron damping, which is faster than luminosity burn-off, leading to an increase of the transverse beam brightness. In that respect, achieving high luminosity, e.g. with small β^*, is highly beneficial to reduce the limitations due to the beam-beam tune shift.

Table 2: Average luminosity production rate in different configurations, the left column mentions the difference with respect to the baseline parameters (Tab. 1). The last line corresponds to the ultimate scenario defined in [1].

Configuration Bunch spacing :	**Performance [fb^{-1}/day]** 25 ns	5 ns
Baseline	2.3	2.3
$\beta^* = 0.3$ m	5.2	5.1
$\beta^* = 0.3$ m, $\xi_{tot} < 0.03$	7.2	6.0
$\beta^* = 0.3$ m, $\xi_{tot} < 0.03$, Crab cavities	7.9	7.1
$\beta^* = 0.3$ m, $\xi_{tot} < 0.03$, Crab Cavities, 4h turn around time	9.0	8.0

LIFETIME

Except for the luminosity burn-off, two mechanisms dominates the particle losses : Rest gas scattering and particle diffusion due non-linearities and/or noise. The first defines the vacuum quality that needs to be achieved, while the second depends on the quality of several components and on the machine configurations. The effect on the performance is shown in Fig. 3, for most configurations lifetimes higher than 30 hours are required to reduce the performance by less than 10%. Similarly, relative emittance growth rates

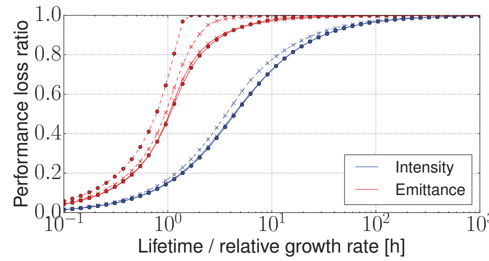

Figure 3: Ratio of the performance in term of average luminosity production rate for a given intensity lifetime or relative emittance growth rate to the maximum performance with infinite lifetimes. Round beams are enforced. Dashed lines correspond to configurations with $\xi_{tot} < 0.01$ and solid lines to $\xi_{tot} < 0.03$, the round and cross markers corresponds to the absence and presence of crab cavity respectively.

about 1-2 hours are required (Fig. 3). While the intensity lifetime required seems compatible with LHC observations, the required emittance growth rate imposes tight constraints on the external sources of noise, especially in configurations where small transverse emittances and large beam-beam parameters are critical. Considering the emittance growth due to beam-beam under external sources of noise [14, 15], in the most of the configuration considered the orbit jitter at the interaction point in the kHz range should stay below a few nm.

CONCLUSION

The current baseline parameters for the FCC-hh seem conservative, since there exist a number of reasonable scenarios that could achieve a significantly higher performance. A proper evaluation of the limits due to beam-beam interactions is needed to define possible improved interaction design, possibly profiting from the synchrotron damping mechanisms and mitigating the effect of intrabeam scattering. Several improved scenarios could be envisaged, nevertheless it is important to note that most variations saturate at a maximum average luminosity production rate of 10 fb^{-1}/day as the time spent in luminosity production becomes significantly smaller than the turn around time. Therefore higher performances requires a shorter turn around time and/or larger beam intensities. Finally, such scenarios rely on high instantaneous luminosities and would suffer from limitations on the event pile-up.

ACKNOWLEDGEMENT

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

REFERENCES

[1] A. Ball et al. *Future Circular Collider Study - Hadron Collider Parameters*. Tech. rep. FCC-ACC-SPC-0001. Geneva, Switzerland: CERN, Feb. 2014.

[2] C. Augier et al. "Predictions on the total cross section and real part at LHC and SSC." In: *Physics Letters B* 315.3 (1993), pp. 503–506.

[3] A. Wolski. *Beam Dynamics in High Energy Particle Accelerators*. London: Imperial College Press, 2014.

[4] Elena Shaposhnikova. *Longitudinal beam parameters during acceleration in the LHC*. Tech. rep. LHC-PROJECT-NOTE-242. Geneva: CERN, Dec. 2000.

[5] B. Dalena et al. "First Considerations on Beam Optics and Lattice Design for the Future Hadron-Hadron Collider FCC-hh." In: *Proceedings of the IPAC'15*. Richemond,USA, 2015.

[6] A. Piwinski. "Intra-Beam-Scattering." In: *Proceedings of the 9th International Conference on High Energy Accelerators*. Standford, USA, 1974, p. 405.

[7] J.D. Bjorken and S.K. Mtingwa. "Intrabeam Scattering." In: *Part. Accel.* 13 (1983), pp. 115–143.

[8] `http://cern.ch/mad`.

[9] W. Herr. *Dynamic behaviour of nominal and PACMAN bunches for different LHC crossing schemes*. Tech. rep. LHC Project Report 856. Geneva, Switzerland: CERN, June 2005.

[10] O. Brüning et al., eds. *LHC Design report*. Vol. 1 : The LHC Main ring. Geneva, Switzerland: CERN, 2004.

[11] D. Neuffer and S. Peggs. *Beam-beam tune shift and spreads in the SSC - Head on, long range and PACMAN conditions*. Tech. rep. SSC-63. Dallas, USA: Superconducting Super Collider Laboratory, Apr. 1986.

[12] F. Ruggiero and F. Zimmermann. "Luminosity optimization near the beam-beam limit by increasing bunch length or crossing angle." In: *Phys. Rev. ST Accel. Beams* 5 (6 June 2002), p. 061001.

[13] R. Martin, R. Thomás, and B. Dalena. "Interaction Region for a 100 TeV Proton-Proton Collider." In: *Proceedings of the IPAC'15*. Richmond, USA, 2015.

[14] V. A. Lebedev. "Emittance growth due to noise and its suppression with the feedback system in large hadron colliders." In: *AIP Conference Proceedings* 326.1 (1995), pp. 396–423.

[15] Y.I. Alexahin. "On the Landau Damping and Decoherence of Transverse Dipole Oscillations in Colliding Beams." In: *Part. Accel.* 59 (1998), pp. 43–74.

ISBN 978-3-95450-147-2