

SYNCHROTRON RADIATION LEVELLING AT THE FUTURE CIRCULAR HADRON COLLIDER

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Abstract

At the proposed future circular hadron collider, FCC-hh, the synchrotron radiation emitted inside the cold superconducting magnets represents a significant heat load, which is likely to limit the total beam current. Here, we discuss a new approach, namely synchrotron radiation power levelling, where the beam energy is adjusted during a physics store, either continuously or in a few discrete steps, while the beam current decreases due to proton burn-off in collision, so as to keep the synchrotron radiation power at or below a certain limiting value. In this way, both peak and integrated luminosity of the FCC-hh are increased, compared with operation at a fixed beam energy, thereby maximising the physics output.

INTRODUCTION

At the Large Hadron Collider (LHC) [1] and, especially, its High-Luminosity upgrade, the HL-LHC [2], the luminosity during a physics run is, or will be, leveled in order to limit the event pile up in the detectors [3–9].

For a future “100-TeV”-scale collider, such as the proposed Future Circular hadron Collider, FCC-hh [10–13], the transverse emittance damping time is likely to be shorter than the proton burn-off time. As a result, at such a machine, the total beam-beam (b.-b.) tune shift increases during the store. In [14], we derived analytical expressions for the optimized integrated luminosities and for the optimum store lengths at high-energy hadron colliders limited either by the maximum acceptable event pile up or b.-b. tune shift, in the presence or absence of strong radiation damping.

At the FCC-hh, the synchrotron radiation (SR) emitted inside the cold superconducting magnets, shielded by a beam screen, represents a significant heat load. Either through the total power consumption or by the limited capacity of the installed cryogenic systems, it is likely to limit the total beam current. In this situation, SR power leveling becomes a natural choice to maximize the physics output [15]. Here, the beam energy is adjusted during a physics store, either continuously or in a few discrete steps, while the beam current decreases due to proton burn-off in collision, so as to keep the SR power at or below a certain limiting value. SR leveling allows for significantly higher initial beam currents than when starting with collisions at the maximum beam energy. In this way, both peak and integrated luminosity of the FCC-hh are increased, compared with operation at one fixed (high) beam energy.

We first consider two standard FCC-hh scenarios with a fixed arc dipole field of either 14 or 12 T (cases “FCC-hh-14” and “FCC-hh-12”), corresponding to a centre-of-mass

collision energy of 84 or 72 TeV, respectively. Following this, we present two scenarios for physics operation with SR leveling, at or between these two energies. The first considers running, in each physics store, at two different beam energies. The second is a continuous energy change during each store. We compare their performances with those obtained when running only at one fixed energy.

We consider collisions of round Gaussian beams with equal beta functions at the collision point, $\beta^* \equiv \beta_x^* = \beta_y^*$, and equal transverse emittances, $\varepsilon \equiv \varepsilon_x = \varepsilon_y$, which may initially shrink due to radiation damping, and are later controlled by noise excitation [14], as for the longitudinal plane [16]. Further, we assume a perfect crab crossing at each collision point, and we neglect the hourglass effect.

PERFORMANCE AT FIXED ENERGY

The operation at one constant beam energy was described in [14]. For the two scenarios FCC-hh-12 and FCC-hh-14, after a time t_1 of 2.4 h and 4.0 h, respectively, the emittance has shrunk so much that the assumed maximum total b.-b. tune shift $\Delta Q_{\max} = 0.025$ is reached. The optimum run times $t_{r,\text{opt}}$ for maximum integrated luminosity (at a turnaround time of 5 h) are about the same for both fields, namely 4.4 h and 4.5 h. Figure 1 shows the time evolution of the instantaneous luminosity during an ideal day.

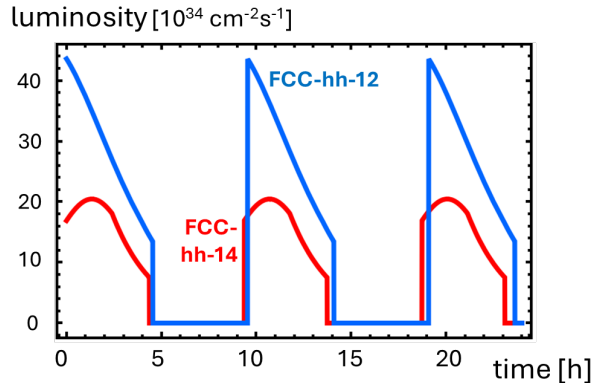


Figure 1: Ideal instantaneous luminosity during 24 h for fixed energy running in scenarios FCC-hh-12 (12 T field) and FCC-hh-14 (14 T dipole field).

ONE-STEP LEVELING

The SR power emitted per beam is

$$P_{\text{SR}} = f_{\text{rev}} n_b N_b C_\gamma E^4 / \rho, \quad (1)$$

where f_{rev} denotes the revolution frequency, n_b the number of bunches per beam, N_b the bunch population, E the beam

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energy, $\rho = (B\rho)/B_{\text{dip}}$ the bending radius, with $(B\rho)$ the magnetic rigidity and B_{dip} the arc dipole field, and $C_\gamma = (4\pi/3)r_p/(m_p c^2)^3 \approx 7.8 \times 10^{-18} \text{ m GeV}^{-3}$.

According to Eq. (1), the energy could be increased from a value E_1 to a new level E_2 , when the bunch intensity has decreased to $N_b = N_0 (E_1/E_2)^4$. This happens at time

$$t_{2,\text{step}} = \tau \ln \left(1 + \left(\frac{E_1^4}{E_2^4} - 1 \right) / \tilde{B} \right), \quad (2)$$

where

$$\tilde{B} \equiv \frac{\sigma_{\text{tot}} f_{\text{rev}} n_{\text{IP}} \tau N_0}{4\pi \beta^* \varepsilon_0}. \quad (3)$$

with τ the initial transverse emittance damping time, N_0 the initial bunch population, etc. [17].

Now suppose we start running at a dipole field of 12 T. At time $t_{2,\text{step}} = 2.0$ h, the beam current is so low that we can increase the arc dipole field to 14 T. Already after a total time $t_{1,2} \approx 2.5$ h, the maximum b.-b. tune shift is reached. The optimum run time is $t_{r,2,\text{opt}} = 5.8$ h. Including time for adjustments we assume an interval of $\Delta t_{\text{ramp}} = 5$ minutes between the stop of colliding at 12 T and the start of collisions at 14 T.

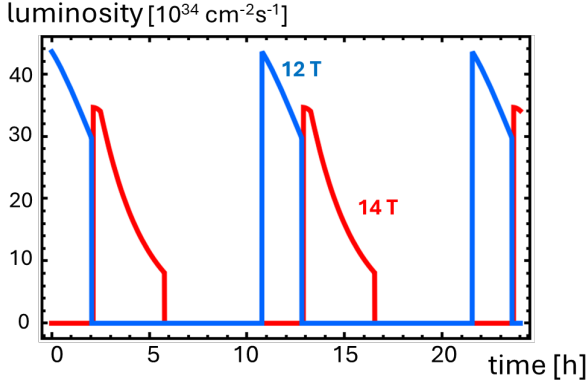


Figure 2: Ideal instantaneous luminosity during 24 h with one-step leveling increasing the dipole field from 12 and 14 T about 2.0 h into each physics fill, starting with the parameters of FCC-hh-12.

Figure 2 presents the ideal luminosity time evolution over 24 hours with one-step leveling at fields of 12 and 14 T.

CONTINUOUS LEVELING

We can maintain a constant SR power throughout a physics fill, by continuously adjusting the beam energy. From (1), a constant SR power implies an increase in beam energy E , as the bunch intensity N_b decreases, according to

$$\frac{dE}{dt} = -\frac{1}{4} \frac{E(t)}{N_b(t)} \frac{dN_b}{dt}, \quad (4)$$

leading to the relation

$$E(t) = E_0 (N_0/N_b(t))^{1/4}. \quad (5)$$

This scheme assumes an adequate optics control throughout the energy ramp.

The energy changes continuously as

$$E(t) = E_0 / (1 - FE_0 t), \quad (6)$$

with

$$F \equiv \frac{\Delta Q_{\text{max}} \sigma_{\text{tot}} f_{\text{rev}}}{4\beta^* r_p m_e c^2}, \quad (7)$$

which is accompanied by a change in bunch intensity

$$N_b(t) = N_0 (1 - FE_0 t)^4. \quad (8)$$

For a maximum beam energy E_{max} , the leveling ends at

$$t_{\text{lev}} = \frac{1}{F} \left(\frac{1}{E_0} - \frac{1}{E} \right). \quad (9)$$

The integrated luminosity per unit energy during a fill is

$$\frac{d\Sigma_{\text{cont}}}{dE} = \frac{GN_0}{FE_0} \left(\frac{E_0}{E} \right)^5, \quad (10)$$

$$\text{where } G \equiv \frac{f_{\text{rev}} n_b \Delta Q_{\text{max}}}{r_p n_{\text{IP}} \beta^* m_e c^2} \quad (11)$$

and it extends from $E = E_0$ to $E_{\text{max}} = E_0 / (1 - FE_0 t_{\text{lev}})$.

Once E_{max} is reached, the collider continues to run at this energy, up to an optimum run time.

As an illustration, we consider a continuous leveling starting at a dipole magnet field of 12 T or a beam energy of 36 TeV, and ending at 14 T or 42 TeV, with otherwise the same initial parameters as for the 12 T case in the previous sections, so that the total b.-b. tune shift [17] is held constant at about $\Delta Q_{\text{tot}} = \Delta Q_0 \approx 0.0177$. In this case, the leveling stops after $t_{\text{lev}} \approx 2.15$ h. Almost the same amount of luminosity is accumulated at the final constant energy of 42 TeV. The optimum total run time is $t_{r,\text{opt}} \approx 4.6$ h and, hence, more than twice the continuous leveling time t_{lev} . The time evolution of the instantaneous luminosity during an ideal day is shown in Fig. 3.

For a higher constant b.-b. tune shift of $\Delta Q_{\text{tot}} = 0.025$, the instantaneous luminosity increases by about 40% and the physics fills are about 30% shorter.

DISCUSSION

The projected performance of the different scenarios is summarized in Table 1. For the continuous leveling, two examples are listed, corresponding to $\Delta Q_{\text{tot}} = 0.0177$ (as in the previous section) and $\Delta Q_{\text{tot}} = 0.025$, respectively. More details are presented in [17].

The various leveling schemes accomplish roughly the same total integrated luminosity of about 1.3 ab^{-1} per year per experiment, as the operation at the constant lower field of 12 T. The advantage is that more than a third of this integrated luminosity, namely $0.5\text{--}0.7 \text{ ab}^{-1}$ per year is delivered at 14 T. The continuous leveling produces another $\sim 1.0 \text{ ab}^{-1}$ at intermediate fields or collision energies between 72 and 84

Table 1: Optimized run parameters of FCC-hh at 12 T and 14 T dipole field (or in between), corresponding to proton-proton centre-of-mass collision energies of (or between) 72 and 84 TeV, respectively, for constant energy operation, one step energy leveling, and continuous energy leveling at two different values of constant b.-b. tune shift. The integrated luminosity per year and interaction point assumes 160 days per year scheduled for physics running and an operational efficiency of 70%.

	unit	12 T fixed	14 T fixed	one step leveling	continuous leveling	continuous leveling
initial bunch intensity N_0	10^{11} p	1.85	1.0	1.85	1.85	1.85
total b.-b. tune shift ΔQ_{tot}	10^{-3}	17.7–25.0	11.0–25.0	17.7–25.0	17.7	25.0
peak luminosity at 12 T	$\text{nb}^{-1}\text{s}^{-1}$	440	—	440	440	610
peak luminosity at 14 T	$\text{nb}^{-1}\text{s}^{-1}$	—	200	350	275	380
total fill length	h	4.4	4.5	5.8	4.6	3.7
int. luminosity at 12 T per IP	ab^{-1}/y	1.3	—	0.7	—	—
int. luminosity at 12–14 T per IP	ab^{-1}/y	—	—	—	0.8	1.0
int. luminosity at 14 T per IP	ab^{-1}/y	—	0.7	0.6	0.5	0.7
total int. luminosity per IP	ab^{-1}/y	1.3	0.7	1.3	1.3	1.7
unburnt fraction of protons $N_b(t_r)/N_0$	%	22	19	11	28	21
di-Higgs rate normalized to 14 T fixed	%	145	100	164	157	220

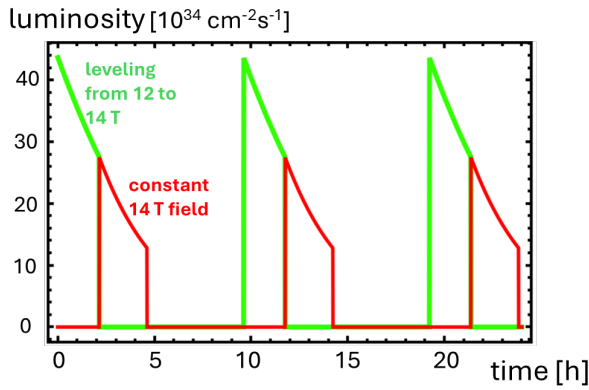


Figure 3: Ideal instantaneous luminosity during 24 h for a continuous leveling at a constant total b.-b. tune shift of $\Delta Q_{\text{tot}} = 0.0177$, with arc dipole field rising from 12 to 14 T (green), followed by a final period at fixed 14 T field (red).

TeV. Operation at a constant field of 14 T would only yield a total luminosity of 0.7 ab^{-1} per year.

In the same way as the LHC experiments run with different pileup conditions, the FCC-hh detectors could run at different collision energies. The SR power leveling offers 60% to 120% more luminosity than running at a constant energy with a fixed field of 14 T. The important di-Higgs production already occurs at rather low centre-of-mass (c.o.m.) energy. Using a quadratic log-log fit [18], the di-Higgs cross section in fb as a function of c.o.m. energy in TeV is

$$\sigma_{\text{di-H}} \approx 0.0352e^{-0.1646(\log E_{\text{com}})^2} (\log E_{\text{com}})^{3.061} . \quad (12)$$

The cross section for di-Higgs production at 84 TeV (1077 fb) is about 29% higher than at 72 TeV (838 fb). From these numbers and Table 1, we can estimate that with one-step levelling the FCC-hh would produce about 64% more di-Higgs events than with only 14 T operation, and still about 13% more di-Higgs events than with only 12 T operation.

To infer the average di-Higgs production rate with continuous leveling, we integrate in energy over the product of the

differential luminosity spectrum of Eq. (10) and the cross section of Eq. (12). Depending on the b.-b. tune shift value considered, the result is a di-Higgs production rate that is either about the same as, or up to 35% higher than for the one-step leveling. This means that the continuous leveling could yield a 2.2 times higher rate of di-Higgs events than operation at a constant dipole field of 14 T.

Lastly, the event pile up for FCC-hh-14 is 30% lower than for FCC-hh-12, with about 1300 and 2000 events per crossing, respectively. At fixed energy, the pile up is directly proportional to the instantaneous luminosity. If desired, a pile up leveling could be superimposed on the SR leveling.

CONCLUSIONS

SR power leveling is a possible novel operation mode for future highest-energy hadron colliders. Here, during each physics fill, the arc magnetic dipole field and, thereby, the collision energy is increased, either in steps or continuously, in order to maximize the total integrated luminosity, while extending the exploration and physics reach up to maximum reachable fields and energies.

The two leveling scenarios — stepwise or continuous — have their respective advantages. One would be easier to implement; the other would yield even higher average event rates. The significant increases in certain key production rates, e.g., a 64% or up to 120% rise in the number of di-Higgs events expected for the two leveling scenarios, would justify such new modes of operation. Therefore, the support from the FCC-hh experiments is highly probable [19].

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