ENERGY DEPOSITION IN THE BETATRON COLLIMATION INSERTION OF THE 100 TeV FUTURE CIRCULAR COLLIDER

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Abstract

The FCC proton beam is designed to carry a total energy of about 8500 MJ, a factor of 20 above the LHC. In this context, the collimation system has to deal with extremely tight requirements to prevent quenches and material damage. A first layout of the betatron cleaning insertion was conceived, adapting the present LHC collimation system to the FCC lattice. A crucial ingredient to assess its performance, in particular to estimate the robustness of the protection devices and the load on the downstream elements, is represented by the simulation of the particle shower generated at the collimators, allowing detailed energy deposition estimations. This paper presents the first results of the simulation chain starting from the proton losses generated with the Sixtrack-FLUKA coupling, as currently done for the present LHC and for its upgrade. Expectations in terms of total power, peak power density and integrated dose on the different accelerator components are presented.

INTRODUCTION

The CERN hadron-hadron Future Circular Collider (FCC) is designed to provide proton-proton collisions at a centre of mass energy of 100 TeV. For a nominal total beam intensity of 10^{15} protons, the total stored energy per beam will be about 8500 MJ, a factor of 20 above that of the Large Hadron Collider (LHC). Assuming the same beam lifetime of 12 minutes as for the design of the LHC system, this would correspond to a peak loss rate of 11.8 MW. This poses stringent requirements on the control of beam losses. The main purpose of the collimation system is to provide efficient cleaning of the beam halo ensuring an operation safely below quench limits. A crucial ingredient to estimate its performance is represented by energy deposition calculations.

In this paper we present the first simulations of the particle shower generated at the collimators of the FCC betatron cleaning insertion and the expected energy deposition in the different elements of the warm section. Results are normalised to the design beam lifetime of 12 minutes (supposed to be withstood for at most 10 s before dumping) and they are compared to the LHC case, considering the same beam lifetime and the present beam energy of 6.5 TeV.

BETATRON CLEANING INSERTION: OPTICS AND LAYOUT

The baseline FCC layout [1] includes a dedicated insertion for betatron cleaning with ad-hoc optics; its first conceptual design [2] considers a system derived from the present LHC, scaled-up by a factor of 5. The scaling factor was chosen to achieve collimator gaps that are similar to the LHC ones, in order to avoid excessive coupling impedance and to guarantee mechanical stability. The number of collimators and their phase advances are the same as in the LHC and were optimised for three-stage cleaning [3]. A dedicated momentum cleaning insertion is also foreseen, but it was not yet implemented at the time of the quoted proposal and it is not relevant for the purpose of this paper.

Primary collimators (TCPs), closest to the beam, intercept beam proton losses and give rise to a secondary halo that is intercepted by secondary collimators (TCSs). Active absorbers (TCLAs) catch showers from upstream collimators. Similarly to what proposed in the context of the High-Luminosity LHC (HL-LHC) upgrade [4], two collimators (TCLDs) are installed in the dispersion suppressor downstream of the betatron cleaning system to intercept protons that would otherwise be lost in cold areas with large dispersion. Tertiary collimators (TCTs) are installed in the low-β insertion regions, about 220 m upstream of the interaction point, to provide the inner triplets with local protection. In this first study, the same collimator materials as those used at the LHC are assumed: carbon-fibre composite for TCPs and TCSs, and tungsten alloy for TCLAs, TCTs and TCLDs.

The insertion dipoles are 17 m long warm magnets, generating a field of 1.85 T. The implemented magnet model is very similar to the LHC one, except for the return coils. Since at the LHC a dedicated tungsten shielding is required in order to avoid excessive radiation damage [5], their design has been changed, bringing them farther from the beam axis as shown in Fig. 1. The warm quadrupoles have a length of 15.54 m and a gradient of 8.9 T/m. A very simplified design has been used at this stage. Three passive absorbers have been included in the insertion region. They have the same length, material composition and geometry as in LHC.

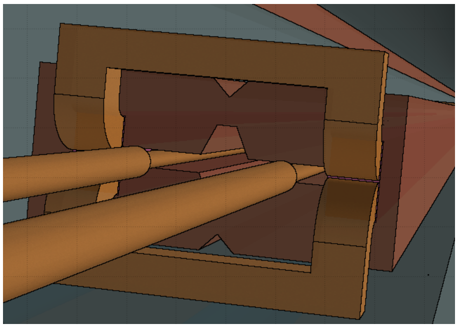

Figure 1: Warm dipole return coil as modelled in Fluka.

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TRACKING SIMULATIONS

The input to energy deposition studies is generated with the Fluka-SixTrack coupling [6], as currently done for LHC [5, 7] and its upgrade; in this case, the proton beam nuclear interactions are simulated by DPMJET-III [8, 9] event generator embedded in Fluka [10, 11]. The initial particle distribution is an annular halo at 7.6 σ with a thickness $\Delta\sigma = 0.0015$ in the horizontal plane, a normal distribution cut at 3 σ in the vertical plane and no energy spread. The average impact parameter at the TCP is about 4 µm. 13.7 million particles are tracked for 200 turns for the case of a perfect machine and using collimator settings from Table 1. These correspond to the LHC design settings scaled to the FCC normalised emittance of 2.2 µm and result in collimator gaps that are comparable to the LHC ones.

Table 1: FCC Collimation System at 50 TeV Energy Used for the Tracking Simulations: families, length and material of jaws, and normalised settings. The latter are expressed in units of σ for a normalised emittance of 2.2 µm in both vertical and horizontal planes.

Description	Name	Len. [m]	Mat.	Setting [σ]
Betatron Cleaning	TCP	0.6	C	7.6
	TCS	1.0	C	8.8
	TCLA	1.0	W	12.6
Dispersion	TCLD	1.0	W	24.0
Tertiaries	TCT	1.0	W	10.5

RESULTS OF SHOWER SIMULATIONS

The calculated sharing of the beam energy deposition is reported in Table 2 for both the FCC and the LHC. The fraction named "Missing" is mainly due to energy to mass conversion and to escaping neutrinos. A small fraction of the order of permil is expected to leak into the cold section. The 8 modules of the FCC warm dipoles absorb 16% of the energy. The 24 quadrupole modules absorb only 4.6% of the total and the maximum power on a module is about 100 kW. Recently, a test has been done on an LHC quadrupole to assess the damage induced by beam losses [12]. In the case of steady state losses, with a beam lifetime of one hour, an average power per meter of 1 kW/m is foreseen. The test has shown that the induced temperature increase is acceptable. At the FCC, in the same scenario, a similar value of 1.3 kW/m is expected. The higher fraction of energy impacting on dipoles with respect to the LHC can be understood considering that the FCC dipoles are 5 times longer, while the upstream collimators and absorbers are identical. On the other hand, the FCC longer quadrupoles are less impacted, thanks to the protection offered by the upstream dipoles.

Table 2: Sharing of Beam Energy Deposition in the Collimation Betatron Cleaning Insertion for FCC (50 TeV) and LHC (6.5 TeV)

Element	FCC	LHC
Warm dipoles	16%	8.5%
Warm quadrupoles	4.6%	9.5%
TCP and TCS jaws	5.1%	10.5%
Passive absorbers	8.6%	13.5%
Tunnel and other elements	47.5%	42.4%
Beam pipe	14.2%	8.6%
Missing	4%	6.5%

Energy Deposition on the Warm Dipoles

The two most exposed warm magnets are the two dipoles after the TCPs. The total power is 0.8 MW on the first one (MBW.B6L) and 1 MW on the second one (MBW.A6L), more than a factor 35 higher of what it is expected at the LHC. Figure 2 shows the longitudinal distribution of the total power absorbed. In both cases, the maximum is reached at the entrance of the magnet and it is about 200 kW/m for MBW.B6L and 300 kW/m for MBW.A6L. The two passive absorbers in front of the two dipoles are identical to the LHC ones. An optimised design, planned for future studies, could certainly have a positive impact on the magnets load.

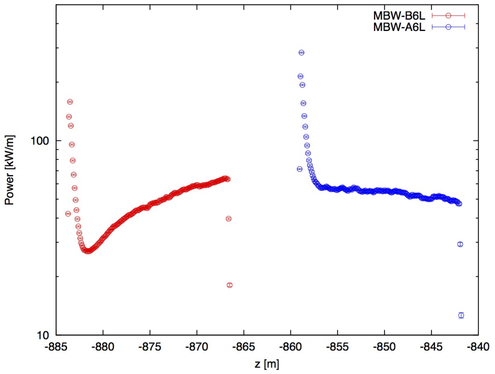

Figure 2: Longitudinal distribution of the total power on the two most exposed dipoles, for a beam lifetime of 12 minutes.

The accumulated dose per year on dipole return coils has been assessed to estimate the effectiveness of the new design. The maximum value, assuming 10^{16} protons lost per year (i.e. the LHC design value), is 10 MGy. With an LHC-type return coil design, the dose would be ten times higher.

Energy Deposition on Collimators

The most impacted collimators in terms of absorbed total power are the last TCP and the first TCS, with 209 kW and 233 kW deposited on both jaws, respectively. These values are about a factor 15 higher than the maximum value expected at the LHC. The other collimators are significantly less exposed: their load is an order of magnitude lower. Despite the fact that the horizontal TCP absorbs a total power of only 23 kW, it is the most impacted in terms of peak power density. The expected value is above 40 kWcm^{-3}, considering a resolution in the x-y plane of 5 μm × 5 μm. For secondary collimators, the maximum peak power density is reached in the first TCS. Figure 3 shows the transverse distribution of the power density at the longitudinal peak position (20 cm from the collimator entrance) on the most exposed jaw. The maximum value is 0.9 kWcm^{-3}, almost a factor 100 higher than at the LHC, and it is reached not in the active jaw material but on the collimator support. Robustness considerations are reported in the following section.

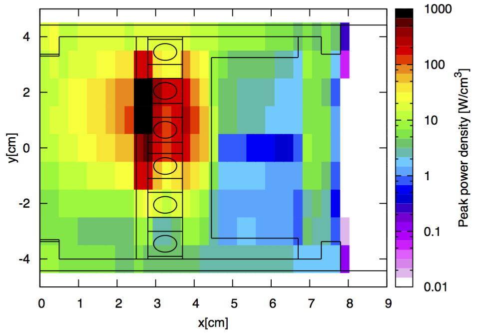

Figure 3: Power density at longitudinal peak on the most exposed jaw of the first secondary collimator (skew), assuming a beam lifetime of 12 minutes. The beam travels on the left of the frame, perpendicularly to the x-y plane.

Finite Element Analysis on the Most Loaded Secondary Collimator Jaw

A preliminary finite element analysis has been carried out on the most loaded TCS jaw in the case of 12 minutes beam lifetime, corresponding to a power deposition of 147 kW on the single jaw. This load is applied for 10 s, with transient ramps of 10 ms. The simulation assumes cooling water at the constant temperature of 27 °C inside the cooling pipes. For achieving this temperature at the FCC, the cooling flow and the design itself of the cooling circuit will have to be changed with respect to the LHC one. With the current water flow in fact, water would increase in temperature by about 80 °C between inlet and outlet, experiencing a change of phase. The maximum temperature on the jaw is almost 400 °C after 10 s, as shown in Fig. 4. This induces thermal stresses on the different components, because of the gradient and the thermal-expansion coefficient mismatch.

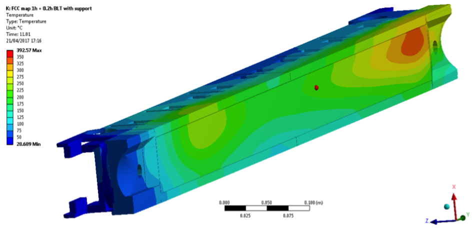

Figure 4: Temperature on the jaw after 10 s, assuming a beam lifetime of 12 minutes.

In particular, the cooling pipes experience plasticity, since the elastic limit for the constituting material, CuNi 90-10, is about 100 MPa and is largely overcome. Another effect of the thermal load is a bending deformation in the order of 0.5 mm, which is above the specification for the LHC case (see Fig. 5). A breaking in the collimator hierarchy will likely be the consequence of this deformation, and the beam will be dumped.

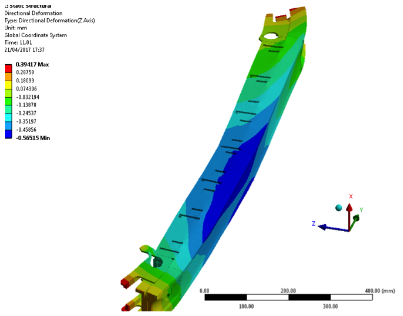

Figure 5: Bending deformation of the jaw.

This exercise allowed evaluating the directions of improvement of current collimators in the case of an use in the FCC. A summary of proposals includes:

- higher diffusing absorber material, to enhance the cooling transfer to the CuNi circuit: replacement materials of interest are ceramic-graphite composites, such as Molybdenum-Graphite or Titanium-Graphite [13]; however the implications of their higher density, leading to a higher thermal load, have to be evaluated;
- lighter absorber, to minimise the energy density on the jaw, e.g. carbon foams [14];
- more rigid housing and stiffener;
- higher water flow in the cooling pipes;
- monitoring, and possibly deformation-correcting, systems: on this topic, a collaboration between CERN and the University of Huddersfield [15] has been already launched in the framework of HL-LHC.

Several of these proposals will be conceptually tested in the HiRadMat facility, at the end of 2017, with a test bench featuring a sample holder hosting multiple materials and instrumentation systems, conceived for HL-LHC studies [16].

CONCLUSIONS

The first results of energy deposition simulations for the FCC betatron cleaning insertion have been reported in this paper. For a beam lifetime of 12 minutes, the most impacted dipole would absorb a total power of 1 MW, with a peak of 300 kW/m. The new design of the return coil is mandatory to minimise radiation damage. The two most loaded collimators are expected to absorb a power of more than 200 kW each. The maximum peak power densities are 40 kWcm^{-3} on the horizontal TCP and 0.9 kWcm^{-3} on the first TCS. A finite element analysis has been run on the latter and the obtained results highlight that the radiation would induce severe deformations, with dramatic consequences. Directions of improvements for the collimator design will be explored in the next months.

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