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Abstract. The Future Circular Collider (FCC-hh) is being designed as a 100 km ring that should collide 50 TeV proton beams. At 8.3 GJ, its stored beam energy will be a factor 28 higher than what has been achieved in the Large Hadron Collider, which has the highest stored beam energy among the colliders built so far. This puts unprecedented demands on the control of beam losses and collimation, since even a tiny beam loss risks quenching superconducting magnets. We present in this article the design of the FCC-hh collimation system and study the beam cleaning through simulations of tracking, energy deposition, and thermo-mechanical response. We investigate the collimation performance for design beam loss scenarios and potential bottlenecks are highlighted.

1. Introduction

The FCC-hh is a design study for a future 100 km long 50 TeV proton collider [1]. It features an unprecedented total stored beam energy of 8.3 GJ, a factor 28 higher than what has been achieved at the Large Hadron Collider (LHC) [2]. The uncontrolled loss of even a tiny fraction of the beam risks quenching a superconducting magnet or causing damage. It is therefore crucial that an ultra-efficient collimation system can intercept and absorb any beam losses. This article shows the conceptual design of the FCC-hh collimation system and its estimated performance in simulations. Previous studies of FCC-hh collimation are found in Refs. [3, 4, 5, 6].

The design goal for betatron losses in the FCC-hh is that a temporary beam lifetime (BLT) drop down to 0.2 h should be sustained over 10 s without a beam dump or quench. It is the same goal as set for the LHC [7] and the high-luminosity LHC (HL-LHC) [8]. It is pessimistic compared to LHC observations [9], which provides a safety margin. In the FCC-hh, it corresponds to an instantaneous beam loss power of 11.6 MW impacting on the collimation system.

The collimation system must not only protect against unavoidable losses during regular operation but also protect from losses during failures [10, 11], help optimisation of the experimental backgrounds [12, 13], and provide satisfactory beam cleaning for ion operation, while keeping the impedance at acceptable levels, which is not treated in detail in this article.

2. The FCC-hh collimation system

The FCC-hh collimation system is based on the LHC system design [14, 15, 16, 10, 11], as well as foreseen upgrades for HL-LHC [8, 17, 18]. Similar collimators are assumed with two movable jaws and the beam in the middle. There are two dedicated collimation insertions: the 2.8 km long point J (PJ) for betatron cleaning and the 1.4 km long point F (PF) for momentum cleaning. The β-functions and the length have been scaled up by a factor 5 to achieve collimator gaps that are similar to the LHC both in mm and in beam σ. This ensures mechanical stability and acceptable impedance at σ-settings small enough to protect the aperture.

The betatron system consists of a multi-stage hierarchy with robust primary collimators (TCP) at 7.6 σ, followed by secondary collimators (TCSG) at 8.8 σ, intercepting the secondary halo. Active tungsten absorbers (TCLA) at 12.6 σ form a third cleaning stage. Most TCSGs are made of Mo-graphite with a 5 μm Mo coating as in the HL-LHC [8] to ensure a tractable impedance [19]. The most loaded collimators (the first TCSG in PJ and the TCPs), are made of carbon-fibre-composite (CFC) with jaws that are thicker than for LHC collimators.

In the TCP, protons may suffer a significant energy loss in single-diffractive scattering, but only a small betatron kick. Such protons risk to bypass downstream collimators in the straight section and be lost in the dispersion suppressor (DS) where the dispersion rises. Special collimators (TCLD) are therefore installed in the DS to intercept these losses, as in the HL-LHC [17, 18]. TCLDs are also installed in the insertions for experiments and extraction. In addition, tertiary tungsten collimators (TCTs) at 10.5 σ are installed upstream of the experiments to protect the final-focus triplets.

3. Cleaning performance

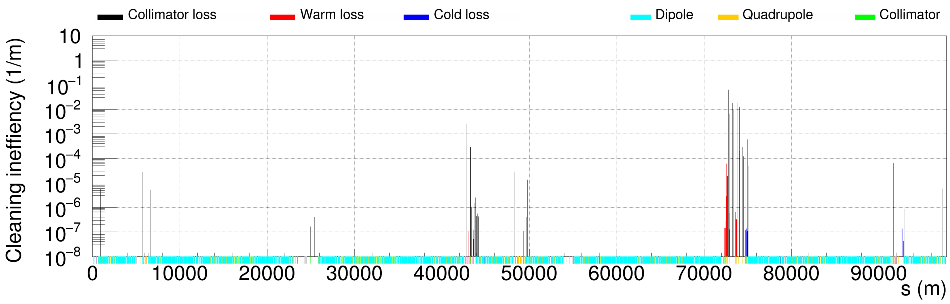

Figure 1. The simulated cleaning inefficiency for a 50 TeV horizontal betatron halo with collision optics (β^*=30 cm).

Tracking simulations are used to estimate the loss pattern around the ring using the coupling [20, 21, 22] between SixTrack [23, 24, 16, 25] and FLUKA [26, 27]. SixTrack tracks protons through the magnetic lattice and FLUKA simulates the proton-matter interactions in collimators. Protons are tracked until they hit the machine aperture or undergo a nuclear inelastic reaction in a collimator. This framework has shown good agreement with measurements of LHC beam losses [28]. The starting beam distribution is a halo with a large enough amplitude to hit the TCPs on the first turn as described in Ref. [16], at a very shallow 0.2 nm impact depth. In these studies, 10^8 protons are tracked for 200 turns.

Figure 1 shows the simulated pattern of horizontal betatron losses around the FCC ring for the most critical case of 50 TeV, expressed in terms of the local cleaning inefficiency $\eta_c(s) = \frac{E(s)}{E_{\text{tot}}\Delta s}$, where Δs is the longitudinal bin size of 10 cm, E is the energy that impacts the physical aperture in a given bin, and E_{tot} is the total energy deposited in the full simulation (including collimator jaws). The main losses occur, as expected, on the collimators in PJ ($s \approx$73 km). The TCLDs protect very efficiently the DS and only a very small fraction of protons leaks out of PJ.

The required η_c to avoid quenches is estimated at $\eta_{c,\max} = 3 \times 10^{-7}$/m at 50 TeV, assuming a 0.2 h BLT, and that losses of 4.3×10^5 p/m/s cause a 10 mW/cm^3 peak power [29], which is the assumed quench limit. Figure 1 shows that the collimation system successfully keeps the cold losses well below $\eta_{c,\max}$ all over the ring, in spite of the very challenging loss conditions. Studies with collimator imperfections as in Ref. [16] show that local losses could increase on average by a factor 2, bringing the average close to, but not above, the quench limit. Similar simulations have been performed also for vertical losses, for the cleaning at injection, for off-momentum cleaning, and for accidental impacts during asynchronous beam dumps, and no showstoppers were found. It should be noted though that, opposite to the LHC, there is no skew TCP in the FCC-hh, since it would receive unsustainable power loads if installed right downstream of the horizontal and vertical TCPs. The losses to cold magnets are still acceptable for a skew halo, however, primary losses would occur at the TCSGs, which might cause too high loads for a 0.2 h BLT. The limit remains to be quantified through thermo-mechanical studies, but the acceptable loss rate is lower in the skew plane than in the horizontal and vertical ones. In the LHC, no large skew losses have been observed, and if the FCC-hh behaves similarly, the lower tolerance in the skew plane is not a showstopper.

4. Energy deposition studies

The tracking simulations show that the primary proton losses are acceptable. However, for a detailed quench assessment, local energy deposition studies, including the shower development, are needed for the most loaded magnets. A FLUKA geometry was implemented, with the TCLD in cell 8 and two downstream magnets (a quadrupole and a dipole), which are expected to be most critical [30]. Magnetic fields were included, modelled as perfect quadrupolar or dipolar fields. Several layouts of TCLDs and fixed masks were tested. The collimators were modelled as two parallel blocks and the masks as cylinders made of tungsten. In total 4.57×10^6 50 TeV protons impacting the TCLD were simulated, with starting conditions from beam tracking, and the shower was tracked in FLUKA. The results, normalised to a power load for a 0.2 h BLT, show that the loads stay below 5 mW/cm^3 in all superconducting coils for a 1.0 m TCLD followed by a second 1.5 m TCLD, and a 0.5 m mask in front of the quadrupole, and an additional 1.5 m TCLD and a 0.15 m mask in front of the dipole. This number, a factor 2 below the assumed quench limit, includes already a factor 8 safety margin to account for the effects of both imperfections and the discrepancy between measurements and simulations found in LHC studies [16]. It is thus concluded that the baseline layout successfully protects the most exposed magnets.

The power deposition is a severe challenge also for the robustness of the collimators and other elements in the warm section. Therefore, the full 2.7 km PJ was modelled in FLUKA, including collimators, warm magnets and passive absorbers. Impacts of protons hitting collimators, from the tracking, were used as initial conditions to simulate the showers. The case of vertical beam losses with a 0.2 h BLT was considered as the most critical case, since there is more space for the shower development to the critical downstream elements for impacts on the most upstream TCP. Initial iterations showed the need to increase the thickness of the TCPs and the first TCSG, to shorten the TCPs to 30 cm, and to remove the skew TCP that would otherwise receive an unsustainable 260 kW power deposition.

The results show that almost half of the power is taken by the tunnel walls, while a significant fraction is absorbed by the beam pipes along 2.7 km. The first TCSG is the collimator with the highest total power (92 kW), as shown in Fig. 2. Despite an integral load 14 times lower, the directly-impacted TCP is exposed to the highest power density, due to the multi-turn ionisation by primary protons. The power density peaks at 50 kW/cm^3 on the surface, but 100 μm inside

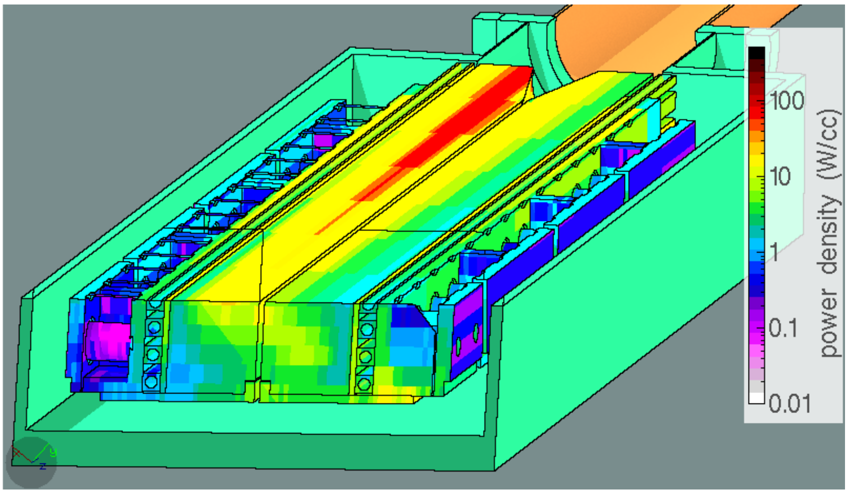

Figure 2. The simulated power density on the most loaded TCSG for a 0.2 h BLT.

it is one order of magnitude smaller.

Two 17 m long warm dipoles, which are used to create a chicane in the insertion, are particularly impacted as they are exposed to the TCP showers. At the front face, the second module reaches 270 kW/m, while the absorbed power is at about 60 kW/m over the rest of its length. The high loads at the face could be mitigated by an appropriate cooled shielding. As future work, the cooling of the rest of the magnet should be studied carefully, keeping in mind that these loads need to be sustained over 10 s.

5. Collimator robustness studies

Preliminary finite element analyses have been conducted with Ansys v18.2 to assess the risk for collimator damage, using as input the energy deposition from FLUKA. The first TCSG, with the highest total load, as well as the vertical TCP, with the highest peak power density, were both studied.

A thermal analysis was performed first, which was later coupled to a static structural analysis to obtain the mechanical response of the system, as in Ref. [31]. A pessimistic steady-state condition with a 1 h BLT was assumed at the start, from which the losses were increased during 10 ms to a 0.2 h BLT, which was kept for 10 s. The losses were then ramped down to a 1 h BLT again. Some simplifying assumptions were made: a perfect bonding between the CFC absorbers and the Glidcop housing is assumed, as well as a linear constitutive law between stress and strain for the absorbers and a constant temperature profile for the water flowing inside the cooling circuit. The model of an LHC TCSP collimator was used as a starting point for the study, and minor modifications were performed to reflect the FCC-hh design updates. The study for 1 h BLT did not show worrying results and we focus in the following on 0.2 h BLT.

A 330° C peak temperature is found on the TCSG jaw. This induces thermal deformations, strains, and stresses on the different components, due to the temperature gradient and the thermal-expansion coefficient mismatch between the materials. No permanent damage occurs on the jaw, although temporary deflections of up to 375 μm are observed (see Fig. 3). The only permanent deformations occurred on the cooling pipes. This issue is not a showstopper, as it can be mitigated by adopting a higher yield-strength material.

The peak temperature on the TCP jaw is about 660 °C. This causes a maximum stress of 45 MPa and a strain of about 8000 μm/m in the absorber-housing contact region, theoretically leading to failure. However, similar temperatures have already been achieved repeatedly on

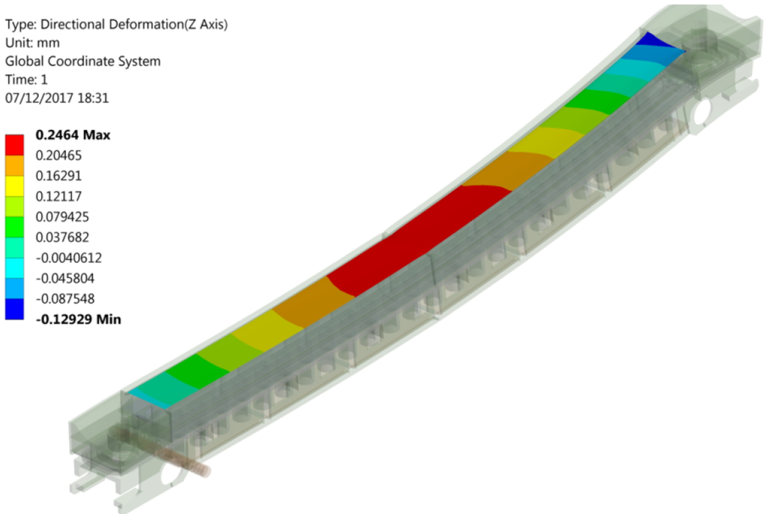

Figure 3. Deflections of the TCSG jaw for a 0.2 h BLT.

CFC absorbers during past experiments, without any sign of failure, and with thermal gradients largely exceeding those at hand in the present study [32, 33]. The high values of stress and strain are therefore thought to be due to the assumed simplified absorber-housing contact, as well as to the hypothesis of linear elasticity considered for CFC. Both these assumptions cause a stiffer structure than the real case. For the same reason, the obtained beam-induced deflection of 155 μm is believed to underestimate the real deformation of the jaw. Future studies should include refined assumptions. No permanent damage is found on other parts of the TCP structure.

Another potential concern is that the out-gassing from CFC risks to be very high at the simulated temperatures. The resulting beam vacuum and the possible need for dedicated pumping should be evaluated in future studies.

6. Conclusions

With a total stored energy of 8.3 GJ, the FCC-hh poses severe challenges for the protection against beam losses. We have shown a conceptual design of the FCC-hh collimation system, based on the LHC and HL-LHC but with several modifications and additions. Simulations show that the proposed design can efficiently protect the superconducting magnets from quenches even during a beam lifetime drop to 0.2 h at 50 TeV, corresponding to 11.6 MW loss power. The presented collimation design has thus demonstrated a satisfactory performance in spite of extremely challenging design requirements.

Thermo-mechanical analyses of the most loaded collimators highlighted some issues which, without representing any serious showstopper at this stage, will need to be followed up in future design developments. Points that need to be addressed include the material choice for the cooling pipes, an improved simulation model for the bonding between the absorber and the housing, the out-gassing from collimators due to high instantaneous temperatures, as well as the local shielding and cooling of the warm dipoles.

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