BEAM CLEANING AND BEAM LOSS CONTROL

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Abstract

The Large Hadron Collider (LHC) will collide two proton beams with an energy of 7 TeV each. The stored energy and intensity exceeds the quench level of the superconducting magnets and the damage level of the machine components by far. Therefore a robust and reliable collimation system is required which controls the losses on the superconducting magnets below the quench limit and protects the accelerator components from damage in the event of beam loss. The layout and design of the LHC collimation system is presented and the expected system performance is shown. The calculated losses around the ring were provided as input for energy deposition studies in the cleaning insertions themselves but also close to experimental insertions. In addition the results from studies on proton losses originating from p-p interaction in the experiments are shown.

INTRODUCTION

The LHC accelerates two proton beams to 7 TeV and brings them into collision in four dedicated experimental insertions. The stored energy of each circulating beam is $360\,\mathrm{MJ}$, whereas an energy deposition in the order of $5\,\mathrm{mW/cm^3}$ is already sufficient to quench a super conducting magnet [1]. Therefore a robust and reliable collimation system is required to control the beam loss on the superconducting magnets below the quench limit and to protect the accelerator from damage in event of beam loss. The LHC collimation follows a staged approach to meet the requirements. Phase 1 collimation uses fibre reinforced carbon as jaw martial for primary and secondary collimators to achieve the required robustness [2, 4]. Dedicated locations around the ring were reserved for the phase 2 efficiency upgrade, especially at the location of each phase 1 secondary collimator.

LHC COLLIMATION

The LHC uses a multistage cleaning system to keep the losses to the superconducting magnets below the quench level. The primary halo, which is continuously filled by beam dynamics processes, is intercepted by the primary collimator, generating showers and the secondary halo, which is still above the quench level of the magnets. Therefore secondary collimators are placed to intercept the secondary halo. In addition absorbers are placed at end of the cleaning insertions (movable devices) intercepting the tertiary halo and showers generated in the cleaning insertion. Furthermore in front of the triplet magnets around the experimental insertion collimators are located to protect the triplet magnets from quenches and dump failures, see figure 1.

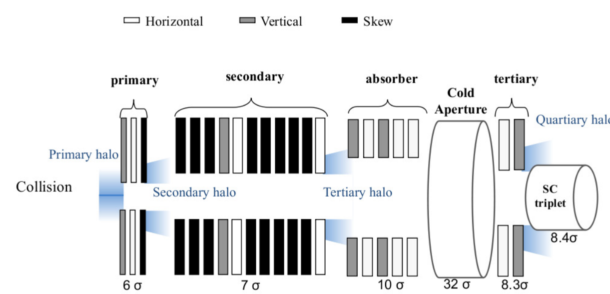

Figure 1: Schematic of a multistage cleaning system as implemented in the LHC betatron cleaning insertion. Primary and secondary collimators are complemented by absorbers to reduce the halo load to superconducting magnets below the quench limit. Tertiary collimators are placed in front of the triplet magnets in the experimental insertions to protect these magnets from quenching and kicker failures [3].

Table 1 summarises the specified maximum allowed loss rates for safe operation of the LHC and its collimation system. This means for example that a $0.2\,\mathrm{h}$ beam lifetime can be tolerated for $10\,\mathrm{s}$ at $7\,\mathrm{TeV}$ before the beam has to be aborted. For nominal LHC operation at $7\,\mathrm{TeV}$ the beam lifetime is $20\,\mathrm{h}$, resulting in a loss rate of $R_{loss} = 0.4 \times 10^{10}$/p/s. Beside the continuous losses driven by beam dynamic processes, there could be also losses from operational instabilities and machine failures. The LHC collimators are designed to sustain injection failures, one full injection batch lost to one collimator, or dump failures, such as a kicker pre-fire or an asynchronous dump.

Mode	**T** $[s]$	$\boldsymbol{\tau}$ $[h]$	$\mathbf{R_{loss}}$ $[p/s]$	$\mathbf{P_{loss}}$ $[kW]$
Injection	cont.	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Ramp	≈ 1	0.006	1.5×10^{13}	1200
Collision	cont.	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

Table 1: Summary of the specified minimum beam lifetimes τ, their durations T, the corresponding proton loss rate R_{loss} and the maximum power deposition P_{loss} in the cleaning insertion [4].

DESIGN, PRODUCTION, INSTALLATION

There are several different types of collimators installed in the tunnel and transfer lines. To ensure the required robustness the collimator jaws of the injection protection, dump protection, primary and secondary collimators are made of graphite, whereas the jaws of the absorbers and and tertiary collimators are made of copper and tungsten. An active cooling of the jaws and vacuum tank assures the full functionality during peak beam loss rates [5, 6].

During series production all important parameters like jaw flatness and minimum achievable gap were recorded and compared with the specified tolerances. In case a collimator did not meet the required specification, a location with more relaxed tolerances was chosen for this collimator. Furthermore a full 3d survey was done to access the inside gap from outside reference points, since all position sensor are located outside the vacuum tank.

For the start up 76 collimators are installed in the LHC tunnel and its transfer lines. The hardware commissioning is completed [7] and extensive test on steering of the collimators are ongoing. Figure 2 shows three primary collimators installed in the betatron cleaning insertion on their tunnel support. Electrical and water connections are established by a quick plug in integrated in the support allowing together with quick connection flanges an easy and fast installation exchange of the collimators in the tunnel, minimising the exposure of workers to radiation.

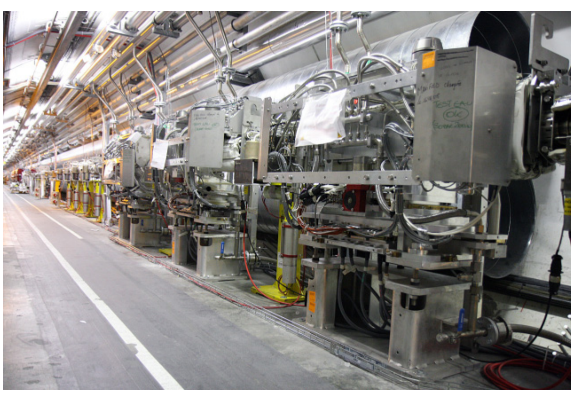

Figure 2: Three primary collimators installed in the betatron cleaning insertion on their tunnel support. The electrical and water connections are established by a quick plug in integrated in the supports.

SYSTEM PERFORMANCE

For simulating the performance of the LHC collimation system a set of programs is used. MadX for generating the optics input, an extend version of SixTrack [8, 9] for tracking the particles around the ring, including a scattering routine treating the impacts of the particles with the collimator. Afterwards the LHC aperture model is applied to the particle trajectories to receive the losses to the machine aperture with a 10 cm resolution and cleaning up the losses to the collimators to avoid double counting [10].

The local cleaning inefficiency η_c used to describe the performance of the collimation system is defined as:

$$\eta_c = \frac{N_{local}}{N_{total} \cdot \Delta s}, \tag{1}$$

where N_{local} is the number of protons lost within an aperture bin of size Δs and N_{total} the total number of lost particles. The required local cleaning inefficiency, to protect the super conducting magnets from quenching, can be calculated using following relation

$$\eta_c = \frac{\tau R_q}{N_p}. \tag{2}$$

Where τ is the beam lifetime, N_p the number of protons in the machine (nominal 3.2×10^{14} p) and R_q the rate of continuous losses which induce a quench. Using $R_q = 7.0 \times 10^8$ p/m/s at 450 GeV and $R_q = 7.8 \times 10^6$ p/m/s at 7 TeV as given in [1], one needs to achieve a local cleaning inefficiency of 7.8×10^{-4} /m at 450 GeV for 0.1 h beam lifetime and 1.9×10^{-5} /m at 7 TeV for 0.2 h beam lifetime, to protect the superconducting magnets from quenching.

Figure 3 and 4 show the proton loss pattern at 7 TeV for horizontal betatron and an ideal machine around the ring and a zoom into the cleaning insertion of IR7. Most of the losses occur at the location of the collimators (black bars), but also at the end of the cleaning insertion in the dispersion suppressor there are two broad loss peaks close to or already exceeding the quench limit (dashed red line) of the magnets for an assumed beam lifetime of 0.2 h and nominal intensity. The collimation efficiency and energy deposition of this system is compatible to 40% of nominal intensity [2]. However applying additionally errors like closed orbit and mechanical misalignment can reduce further the local cleaning efficiency of the system [9].

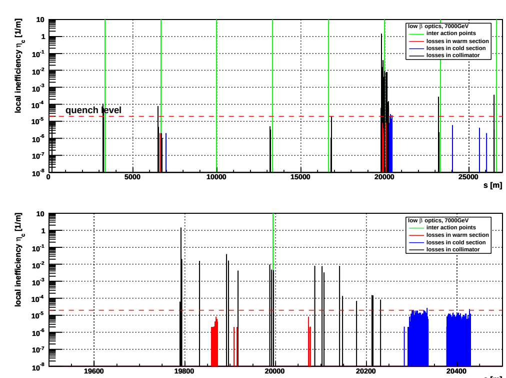

Figure 3: Proton loss pattern for 7 TeV beam 1 horizontal betatron halo around the ring (top) and the betatron cleaning insertion in IR7 (bottom). The black bars indicate losses to the collimator, red bars losses to the warm elements and blue bars losses to the superconducting elements. The quench level is evaluated for 0.2 h beam lifetime and nominal intensity.

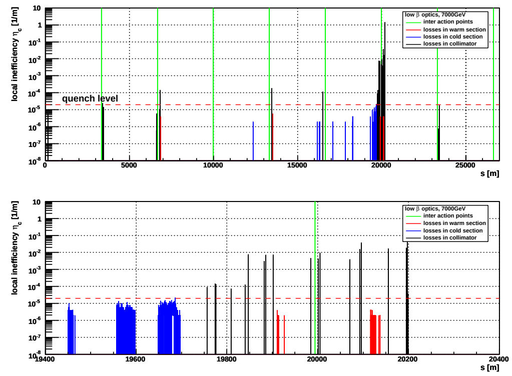

Figure 4: Proton loss pattern for 7 TeV beam 2 horizontal betatron halo around the ring (top) and the betatron cleaning insertion in IR7 (bottom). The black bars indicate losses to the collimator, red bars losses to the warm elements and blue bars losses to the superconducting elements. The quench level is evaluated for $0.2\,\mathrm{h}$ beam lifetime and nominal intensity.

Beside the losses originating from the betatron halo and momentum cleaning, there are also losses coming from proton-proton interactions in the experimental insertions. Figure 5 show these proton losses in region between IR1 and IR5. The tracked particle distribution was generated with an event generator [may be put Ref. here]. The loss rate are scaled to the expected event rate for single diffractive and double pomeron exchange events at peak luminosity. There are some localised loss peaks in the same order of magnitude as the quench level (7.8×10^6p/m/s for continuous losses) especially close to Q6 in front of the momentum cleaning insertion and at the end of the experimental insertions, see lower plot. This may make it necessary to add additional absorbers in these locations.

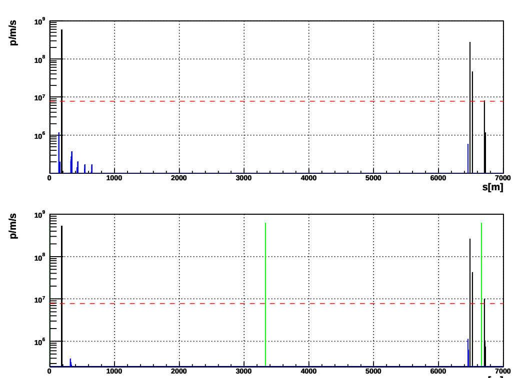

Figure 5: Proton losses from pp interaction generated in the experimental insertions. The upper loss map shows losses coming from IR1 in beam 1 direction up to IR3 and the lower loss maps the losses coming from protons interacting in IR5 travelling in beam 2 direction to IR3.

ENERGY DEPOSITION STUDIES

The loss distributions around the ring and particles lost in the collimators provide input for energy deposition, activation and background studies. The region of interest are for example the collimation insertions for studies on the material activation and radiation damage to machine components and electronics, or the experimental insertions to calculate the expected background rates to the experiments and energy deposition on the superconducting triplet magnets [11].

Figure 6 shows the transverse energy deposition map in the MQY magnet coil downstream of the dump protection collimators, for nominal intensity, 7 TeV and $0.2\,\mathrm{h}$ beam lifetime. The peak energy deposition is $3.1\,\mathrm{mW/cm^3}$, whereas the quench limit is at $5.0\,\mathrm{mW/cm^3}$ [12].

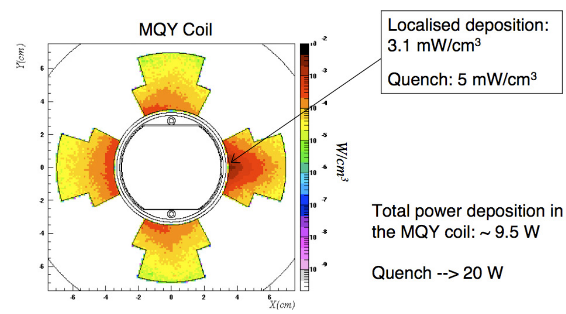

Figure 6: Transverse energy deposition map in the MQY magnet coil downstream of the dump protection collimators. For nominal intensity, 7 TeV and $0.2\,\mathrm{h}$ beam lifetime [12].

PROPOSAL FOR EFFICIENCY UPGRADE

The main intensity limitation in view of the cleaning efficiency are the losses in the dispersion suppressor region at the end of the cleaning insertions. These losses originating from protons interacting with a primary collimator passing through the cleaning insertion without interacting with any other collimator and being lost in locations where the dispersion starts to increase.

Therefore the idea for an efficiency upgrade is to place additional collimators at the location of the loss peaks in the dispersion suppressor. The upper schematic in figure 7 show the current layout of the dispersion suppressor region. The space available from the missing dipole, allows to symmetrically shift the two dipoles in front of Q8 and behind Q10. The shift of the magnets and the location of the collimators is indicated in figure 7. These collimators are in cryogenic regions of the machine requiring a special design or warm cold transitions.

Figure 8 and 9 show the system performance of the proposed upgrade solution. The simulation uses the phase 1 graphite secondary collimators at their injection opening, copper secondary collimators, at the reserved phase 2 locations and at standard settings (7σ) and two additional 1 m

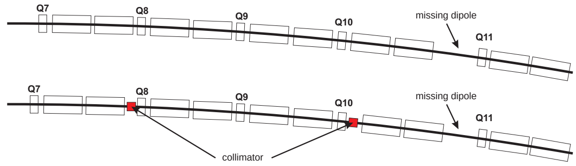

Figure 7: Schematic layout of the dispersion suppressor region at the end of the cleaning insertion in IR7 as built in the LHC (top) and the proposed symmetric shift of the two dipoles in front of Q8 and behind Q10 by three meters (bottom).

long copper collimators at $300\,\mathrm{m}$ and $387\,\mathrm{m}$ from point 7 with an opening of 15σ. A gain in cleaning efficiency of a factor 30 for this solution seems to be possible, giving additional freedom to relax the settings of the collimators in the cleaning insertion and therefore improve the situation of impedance.

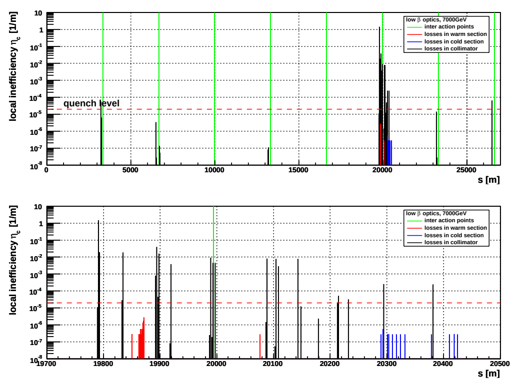

Figure 8: Proton loss pattern for 7 TeV beam 1 horizontal betatron halo around the ring (top) and the betatron cleaning insertion in IR7 (bottom). The black bars indicate losses to the collimator, red bars losses to the warm elements and blue bars losses to the superconducting elements. The quench level is evaluated for $0.2\,\mathrm{h}$ beam lifetime and nominal intensity.

CONCLUSION

The collimation system is ready for start up, 76 collimators are installed in the LHC tunnel and its transfer lines, additional ten secondary collimators and six special two-beam design collimator will be installed during the first shut down to complete the phase 1 system. The hardware commissioning of the system is completed, the steering and controls of the collimators are extensively tested. Simulation tools have been developed to calculate the performance of the collimation system [8, 10] and probable limitations due to losses in the dispersion suppressor at the end of the cleaning insertions were found. The proposed efficiency upgrade for phase 2 shows an improvement of the cleaning efficiency of the system by a factor 30.

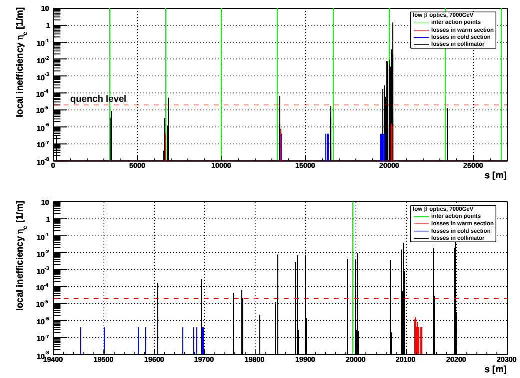

Figure 9: Proton loss pattern for 7 TeV beam 2 horizontal betatron halo around the ring (top) and the betatron cleaning insertion in IR7 (bottom). The black bars indicate losses to the collimator, red bars losses to the warm elements and blue bars losses to the superconducting elements. The quench level is evaluated for $0.2\,\mathrm{h}$ beam lifetime and nominal intensity.

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