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POWER DEPOSITION STUDIES FOR CRYSTAL-BASED HEAVY ION COLLIMATION IN THE LHC*

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Abstract

The LHC heavy-ion program with $^{208}Pb^{82+}$ beams is foreseen to benefit from a significant intensity upgrade in 2022. A performance limitation may arise from ion fragments scattered out of the collimators in the betatron cleaning insertion, which risk quenching superconducting magnets during periods of short beam lifetime. In order to mitigate this risk, an alternative collimation technique, relying on bent crystals as primary collimators, will be used in future heavy-ion runs. In this paper, we study the power deposition in superconducting magnets by means of FLUKA shower simulations, comparing the standard collimation system against the crystal-based one. The studies focus on the dispersion suppressor regions downstream of the betatron cleaning insertion, where the ion fragment losses are the highest. Based on these studies, we quantify the expected quench margin expected in future runs with $^{208}Pb^{82+}$ beams.

INTRODUCTION

Within the scope of its heavy-ion physics program, the Large Hadron Collider (LHC) will store and collide fully stripped $^{208}Pb^{82+}$ beams with energies up to 7 Z TeV and beam intensities up to 2.23×10^{11} ions [1, 2]. In case of beam losses, even a small fraction of this energy can perturb the accelerator performance by leading to magnet quenches, a phenomenon during which a superconducting (SC) magnets transit from SC to normal-conducting state due to the heat deposited by particle showers. While the stored beam energy in the high-luminosity (HL) era [3] is expected to reach 20 MJ [2] for heavy ions, only a few 10 mW/cm^3 of energy deposited in SC coils is enough to quench a magnet [4, 5]. Therefore the multistage betatron and momentum collimation systems of the LHC are essential to protect the machine against unavoidable beam losses [6].

Collimators are the closest elements to the circulating beam and represent the last line of defense against potential damage in case of accidental beam losses. They are also essential for preventing beam-induced quenches, which would limit the integrated luminosity due to the lengthy recovery of cryogenic conditions. The design goal is that no quenches occur in case of a beam lifetime drop to 0.2 h over a period of ten seconds [3], which translates into a maximum allowed halo loss rate of 3.64×10^8 ions/s in the HL era. However, the betatron collimation system, located in the insertion region 7 (IR7), exhibits a reduced cleaning efficiency for $^{208}Pb^{82+}$ ions compared to protons due to ion fragments scattered out of the collimators. Extrapolating from previous simulations [7] and experimental studies [8, 9], those fragments risk to induce magnet quenches during HL operation if the lifetime drops to the design value. The most exposed cold magnets are located in the dispersion suppressors (DS) and arcs downstream of IR7 [7–10]. Novel collimation measures had to be developed accordingly to avoid such quenches [3].

As a primary solution to reduce the risk of halo-induced quenches in heavy-ion operation, it is considered to substitute a dipole in the DS with shorter, but higher field magnets (11 T), creating space for an additional collimator [3]. Presently, the installation of this assembly is, however, postponed. As an alternative solution, a crystal-based collimation setup will be used featuring bent crystals of a few millimeters length [11–13]. Making use of the electromagnetic potential in their crystalline structures, bent crystals will deflect halo particles through their atomic planes. This phenomenon called channeling can deviate incoming particles at large angles of up to tens of řad onto an downstream absorber, as illustrated in Fig. 1. Due to the reduced probability of hadronic fragmentation and electromagnetic dissociation in the crystal and due to the large impact parameter on the channeled beam absorber, the crystal-based system reduces the fragment leakage to the DS and arc. So far the crystal-based collimation setup has only been used during dedicated tests [11–13] and in low-energy proton physics runs [14], but will be employed in regular heavy-ion operation from 2022.

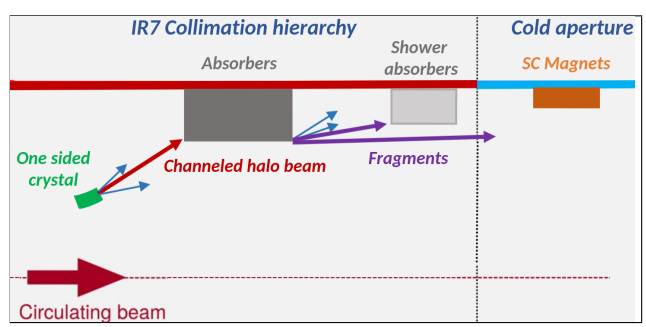

Figure 1: Principle of a crystal-based collimation setup, deflecting the primary beam halo onto an absorber. In reality, many more collimators are used (not shown for simplicity). Figure inspired by Ref. [3]

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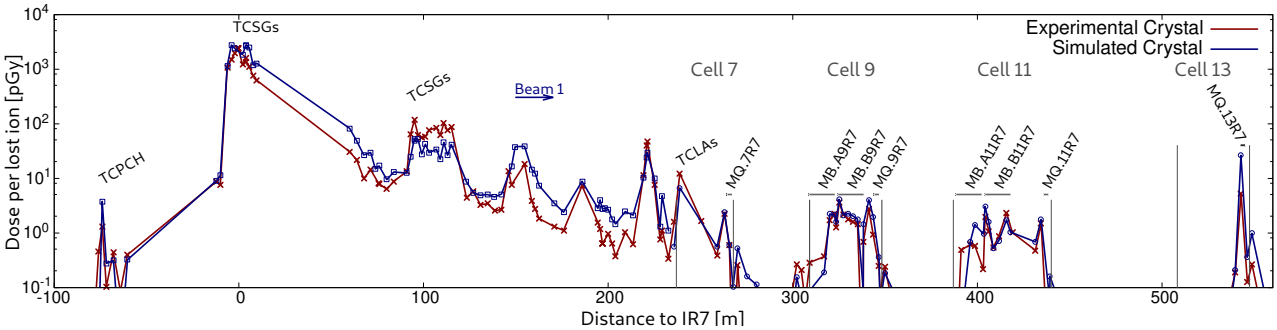

Figure 2: Simulated and experimental BLM signals for crystal-based Pb collimation in IR7 (6.37 ZTeV). The exerimental data derive from a test in 2018. The beam direction is from left to right. The acronyms TCPCH, TCSG, TCLA, MB, MQ represent the horizontal crystal, secondary collimators, shower absorbers, dipoles and quadrupoles, respectively.

Numerical simulations are indispensable for understanding and predicting the power deposition in the coils of magnets with this collimation technique. A simulation chain has been developed previously at CERN [15], where the energy deposited by lost particles is computed through a coupling of the particle tracking code SixTrack [16–18] with the Monte Carlo code FLUKA [19–21]. The simulation chain has been benchmarked for standard Pb collimation cleaning (without crystals) by comparing simulated and measured Beam Loss Monitor (BLM) signals [10, 22, 23]. Recently, a model describing coherent effects of high-energy particles in crystals [24] has been incorporated into FLUKA [20], making it possible to simulate a crystal-based setup through the same simulation chain. First particle loss map simulations with this new routine are presented in [25]. In this paper, we present a first quantitative comparison of simulated BLM signals with a crystal channeling study carried out in the 2018 heavy-ion run at 6.37 ZTeV [12, 13]. Based on this new benchmark, we then quantify the power deposition inside SC coils during operation with HL-LHC beams, comparing the standard collimation system with a crystal-based one.

SIMULATION BENCHMARK

Different experiments with Pb beams were performed in 2018 to test crystal-assisted collimation configurations [12, 13]. The installed and tested crystals were single-sided devices intercepting one side of the beam halo in the horizontal or vertical plane. The objective of these tests was to assess the collimation system performance for low intensity beams at injection and top energy. The measured BLM patterns indicated a significant reduction of fragment leakage to SC magnets in the DS and arc. Figure 2 presents an absolute comparison between BLM simulations and measurements for one of the beam tests at 6.37 ZTeV. The test was performed with the clockwise rotating beam (Beam 1) using the collimator settings summarized in Table 1 (first column). The test was carried out by inserting a strip-crystal (called TCPC in Table 1) in the horizontal plane. The regular primary collimators (TCPs) as well as secondary collimators upstream of the crystal (TCSGs$_{upstream}$) were retracted compared to their nominal position. The secondary collimators downstream of the crystal (TCSGs$_{downstream}$) and the active shower absorbers (TCLAs) were maintained at their usual gap. The BLM dose values recorded during the test (red curve) were normalized by the number of lost ions in IR7 using fast beam current transformer measurements. The simulation results are shown by the blue curve. As initial condition in the simulation, it was assumed that the $^{208}Pb^{82+}$ beam halo impacts at a certain distance from the horizontal crystal edge, located on the left side of the beam. The actual impact parameter is not well known and might vary between loss events. Here a value of 1 µm was assumed [25]. The statistical error of simulated BLM signals is at most a few percent for the highest signals in the insertion region, but can be up to 20 % in the DS and the arc.

The overall agreement between simulation and experiment in Fig. 2 is remarkably good. The simulation reproduces well the measurement pattern over several orders of magnitude for more than 130 monitors distributed over 700 m of beam line. A factor 3 discrepancy is observed at some collimators and needs further investigation. Nevertheless, the BLM pattern provides an even better agreement in the DS compared to what was achieved for the simulation of standard heavy ion collimation [10, 22, 23]. The simulated BLM patterns in cell 9 and 11 are almost identical to the measurements, giving confidence that the FLUKA model accurately reproduces the power deposition inside the SC magnets in both cells. A previous benchmark for Beam 1 standard collimation indicated an underestimation by a factor 5 in cell 13

Table 1: Beam 1 Collimation Apertures as Defined in [10] during the 2018 Test and for HL-LHC Heavy-Ion Simulation Studies [12,13]

Collimators	Crystal test	Standard HL	Crystal HL
TCPs	9	5	5
TCSGs$_{upstream}$	8.6	6.5	6.5
TCPC	5	/	4.75
TCSGs$_{downstream}$	6.5	6.5	6.5
TCLAs	10	10	10

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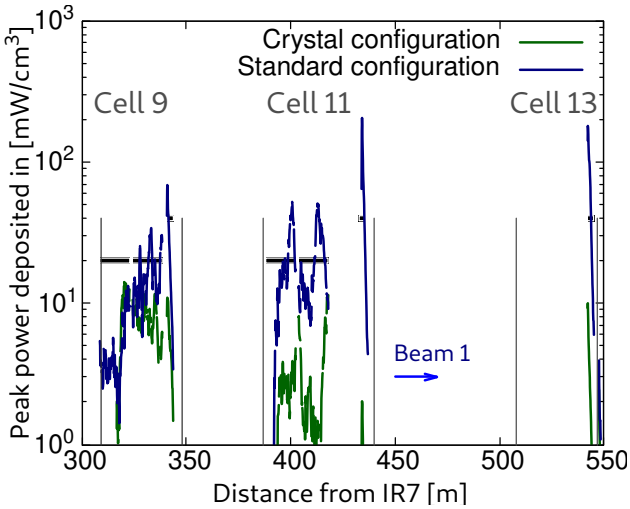

Figure 3: Radially averaged peak power density profile in the cold magnet coils for HL-LHC Pb ion operation (beam lifetime of 0.2 h) comparing the use of crystal collimation with the standard configuration. Horizontal black lines indicate the respective estimated magnet quench levels.

[23], which was attributed to possible machine imperfection (e.g. magnet alignment). An overestimation of a factor 5 is now observed for the Q13, which is yet to be understood.

POWER DEPOSITION IN MAGNETS

The ion beam intensity is expected to increase in future runs, from 1.54×10^{11} Pb ions (733 bunches) per beam in Run 2 to 2.23×10^{11} Pb ions (1240 bunches) per beam in Run 3 (starting in 2022) and beyond. The operational conditions will also become more challenging because of an increase of the beam energy to 6.8 ZTeV (Run 3) and further to 7 ZTeV (from Run 4). This will increase the power deposition in cold magnets, while at the same time the quench margin will reduce due to the higher magnet currents. In this section, we present power deposition studies for the cold DS and arc magnets downstream of IR7 for a beam energy of 7 ZTeV.

Compared to the benchmark study in the previous section, we assume for the HL crystal simulation setup that collimators remain at their nominal position, but the crystal (TCPC) is positioned 0.25σ closer to the beam than the TCPs, ensuring the deflection of the primary beam halo onto the absorber. This setup is compared to a standard configuration without crystal. The assumed collimator settings are summarized in Table 1 (second and third column). Figure 3 presents the longitudinal peak power density profile in the coils of DS and arc magnets for the standard and the crystal-assisted collimation system in green and blue, respectively. All results were scaled to HL-LHC beam intensities, assuming a beam lifetime of 0.2 h. During steady-state beam losses, the heat deposited by showers in the Rutherford cables has time to spread across the cable cross section [4]. The power density values shown in Fig. 3 were hence radially averaged over the cable width. Furthermore, the results were corrected empirically based on the differences found in simulation benchmarks. The Beam 1 benchmark study for the standard collimation system in Ref. [23] indicated that the simulation underestimates the power deposition in cells 9 and 11 by a factor 2 and in cell 13 by a factor 5. The corresponding factors were applied on top of peak power densities in Fig. 3. For the crystal-assisted system, a factor of 5 was applied only to the power density in cell 13, following the benchmark results in the previous section. As shown in the figure, the crystal-based setup reduces the maximum power density in all magnets by a factor of three or more, except in the most upstream MB.

Over the past two physics runs, a combination of electro-thermal simulations, FLUKA power deposition studies and dedicated experiments during LHC operation improved the understanding of quench levels [4, 9, 26]. Assuming steady-state beam losses, an energy of 7 ZTeV and the most pessimistic cooling model for the magnets, these amount to ~20 mW/cm^3 for the main bending dipoles (MB) and about ~40 mW/cm^3 for the main quadrupole magnets (MQ) [9]. Some uncertainty still remains since some of the past experiments [26] possibly indicate even lower values when extrapolating to 7 ZTeV.

The simulated power densities for the standard system indicate that a quench cannot be avoided. Similar conclusions were found previously for Beam 2 studies [7]. On the other hand, the simulated peak power density with the crystal-based setup is about factor 1.5 below the quench level in the most exposed MB and a factor 4 below in the most exposed MQ. The actual margin might, however, be less depending on the real quench level of dipoles at 7 ZTeV. In addition, not all crystals exhibited the same reduction factor as the one studied in this paper. The results nevertheless suggest that crystal-assisted collimation has the potential to avoid magnet quenches in case of lifetime drops to 0.2 hours.

Power deposition simulations for the DS collimator option with 11 T magnets, carried out for Beam 2, indicated a factor of 3 quench margin for the most exposed magnet (11 T dipole) [27]. The present studies suggests that a crystal-based setup cannot yield the same margin, but is still a very promising baseline for Run 3.

CONCLUSION

We presented for the first time an estimate of the quench margin for crystal collimation with a 7 ZTeV heavy ion beam in HL-LHC operation. The study relies on a first benchmark of measured BLM signals against FLUKA BLM response simulations for a crystal test carried out in 2018. The simulation indicates that crystal collimation provides a satisfactory reduction of the power density in superconducting magnets located downstream of the betatron cleaning insertion. Assuming HL-LHC beam parameters, the power deposition for losses on Beam 1 should remain below the expected quench limits in case of a 0.2 h beam lifetime. A separate assessment is needed for the counter-rotating beam.

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