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COLLIMATION OF PARTIALLY STRIPPED ION BEAMS IN THE LHC*

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Abstract

In the scope of the Physics Beyond Colliders studies, the Gamma Factory initiative proposes the use of partially stripped ions as a driver of a new type, high intensity photon source in CERN's Large Hadron Collider (LHC). In 2018, the LHC accelerated and stored partially stripped $^{208}Pb^{81+}$ ions for the first time. The collimation system efficiency recorded during this test was found to be prohibitively low. The worst losses were localised in the dispersion suppressor (DS) of the betatron-cleaning insertion. Analytic arguments and simulations show that the large losses are driven by the stripping of the remaining electron from the Pb nucleus by the primary collimators. The rising dispersion in the DS pushes the resulting off-rigidity, fully-stripped ions into the aperture of the superconducting magnets. In this study the measured loss maps are compared against results from simulations. Different mitigation strategies are outlined, including a dispersion suppressor (DS) collimator, crystal collimation or an orbit bump.

INTRODUCTION

The goal of the Gamma Factory initiative is to study the possibility of creating high-intensity, high-energy photon beams at the Large Hadron Collider (LHC) [1]. This is achieved by accelerating and storing partially stripped ion (PSI) beams and exciting their atomic degrees of freedom using a laser. The energy of the photons emitted during the de-excitation of the excited atomic states is proportional to the square of the Lorentz factor of the ion beam, which allows photon energies of up to 400 MeV in the LHC. In 2018, the first test with PSI beams was performed in the LHC with the goal of studying the beam lifetime and characterising the beam losses [2]. During the test, $^{208}Pb^{81+}$ ions with one electron were injected and stored in the LHC (Beam 1 only).

This test provided also the first opportunity to study empirically the collimation of PSI beams. The cleaning performance was tested in so-called loss maps, where a safe low-intensity beam was excited to artificially create losses, while measuring their distribution around the ring using more than 4000 beam loss monitors (BLMs) [3, 4]. Loss maps were measured at injection (450 Z[1] GeV) and at flat-top energy (6.5 Z TeV). In both cases severe losses were observed in the DS of IR7. These losses turned out to be a real operational limitation, when a beam dump was triggered at top energy by regular losses on the collimation system, with only 24 low-intensity bunches (1.1×10^{10} charges/bunch) in the machine, causing an unusually high-loss leakage to cell 11 in the DS of IR7. The loss maps at flat-top were taken during a subsequent fill with only 6 bunches of even lower intensity (0.75×10^{10} charges/bunch). Still the losses reached around 60 % of the dump threshold and this is potentially a show stopper for LHC operation with PSI beams. The measurement of those losses, the understanding of the mechanism that drives them, and the potential mitigation strategies are presented in this paper.

RECAP OF LHC COLLIMATION

In order to protect the machine from steady-state and anomalous beam losses, a state-of-the-art collimation system is installed in the LHC [5]. Its primary function is to safely dispose of the beam halo and provide passive machine protection. The beam halo is continuously repopulated by processes in the beam core or in the tails and any losses pose a risk of quenching superconducting magnets or damaging sensitive equipment. There are two warm insertions dedicated to cleaning the halo - the betatron-cleaning insertion (IR7) to remove beam particles with large spatial trajectory excursions and the off-momentum cleaning insertion (IR3) to remove beam particles with large momentum offsets. The primary collimators (TCPs) are the devices closest to the beam and their purpose is to absorb or scatter halo particles to collimators at larger apertures [6]. The secondary collimators (TCSGs) are designed to intercept the particles outscattered from the TCPs. All collimators used in IR3 and IR7 have two jaws. It is important to note here that beam halo particles interacting with the TCPs are not always deflected onto the TCSGs; in some cases they can escape the collimation insertion and complete further revolutions around the ring. Beam particles with momentum offsets induced by the scattering in the TCPs can escape the collimation section and be lost on the cold aperture in the dispersion suppressor (DS) immediately downstream, where the rising dispersion affects their trajectories. This is the dominating process for cold losses, and the DS in IR7 is thus the main bottleneck for beam halo losses in the LHC. In the case of nominal ion operation these losses are a limiting factor for the achievable intensity [7–9]. The collimation system in the LHC has been designed and optimised for proton operation and it is important to evaluate its performance for PSI beams.

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[1] Where Z is the charge number of the ion.

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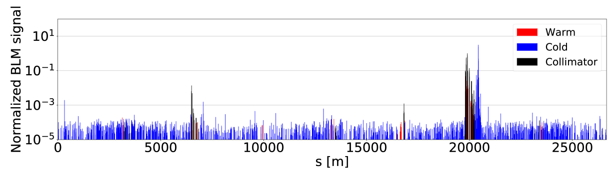

Figure 1: BLM signals around the ring during a loss map for B1H at flat-top energy clearly showing the highest cold losses in the DS of IR7 (S ≈ 20 000 m). A zoomed-in plot of IR7 can be seen in Fig 2 (middle).

OBSERVATION AND UNDERSTANDING OF BEAM LOSSES

The highest cleaning inefficiency, defined as the fraction of total losses leaking to the cold aperture, was observed for Beam 1 in the horizontal plane (B1H) at flat-top energy and the measured loss map for this case can be seen in Fig. 1. The peak cleaning inefficiency of the collimation system with PSI beams is about 4 orders of magnitude higher than for protons and about 2 orders of magnitude higher than for fully stripped $^{208}Pb^{82+}$ ion beams [9, 10]. The recorded magnitude of losses on the cold aperture of the DS is even larger than on the collimators and is prohibitive for high-intensity operation.

The reason for the reduced collimation efficiency is theorised to be the stripping action of the collimators in combination with the rising dispersion in the DS. When interacting with the TCP, $^{208}Pb^{81+}$ ions from the beam halo can lose their electron, while receiving insufficient angular deflection to be intercepted by the TCSGs. The resulting fully stripped $^{208}Pb^{82+}$ ions have an energy close to nominal, but have an altered charge-to-mass ratio and thus a different magnetic rigidity to the nominal beam. If they escape IR7, the dispersion in the DS pushes their trajectories onto the cold aperture.

To test this hypothesis, the trajectories of the fully stripped $^{208}Pb^{82+}$ ions originating at either jaw of the TCPs were calculated using MAD-X [11, 12], with an effective $\delta p/p = -1/82$. Those trajectories are tracked through IR7 and the downstream DS, where the point at which they are intercepted by the aperture is observed. The interaction with the collimators was not modelled in this study. A range of the trajectories with the beam vacuum aperture overlaid is shown in Fig. 2 alongside a zoom of the measured and simulated B1H loss maps at flat-top. The calculated trajectories of $^{208}Pb^{82+}$ indicate a loss position similar to the measured one. This result supports the hypothesis on the origin of the large DS losses. Furthermore, it shows that since the loss mechanism involves a change of magnetic rigidity, the longitudinal loss location does not depend strongly on which TCP and jaw caused the stripping.

Tracking simulations of the beam passage through the collimation insertion were also performed, including the aperture definition and the ion-matter interactions in the collimators. Using the coupling [13–15] between the

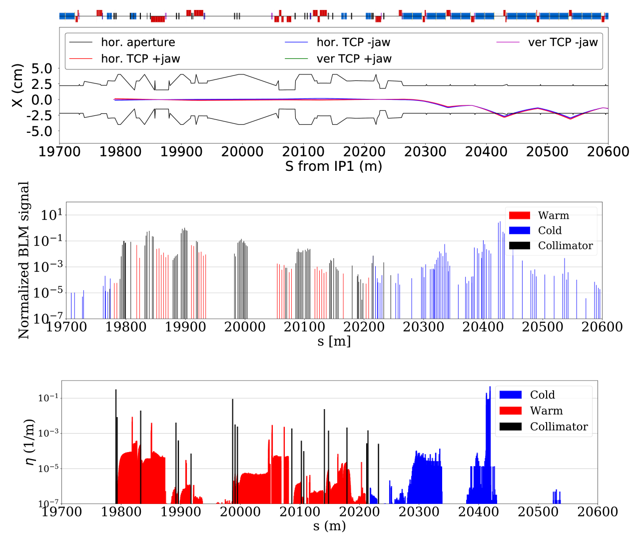

Figure 2: Top: Four trajectories of off-rigidity $^{208}Pb^{82+}$ ions escaping the TCPs, as calculated with MAD-X, originating from each jaw of the horizontal and vertical TCPs, shown together with the aperture. Middle: A zoom in IR7 of the measured loss map from Fig. 1. Bottom: Simulated B1H loss map for the configuration used in the test, depicting the cleaning inefficiency η, which corresponds to local energy loss normalised to total loss in the whole ring.

SixTrack [10, 16, 17] and FLUKA [18, 19] codes, we aimed at first reproducing the measurement results and then validating the proposed mitigation strategies (see later). Similar simulations of the loss pattern resulting from the collimation cleaning have been extensively compared to measurements in previous publications for protons [10, 20, 21] and Pb ions [9, 22]. Currently, FLUKA does not support PSI and therefore a simplified simulation setup was used, assuming that all PSI will be immediately stripped when they impact the collimator. A halo of fully stripped $^{208}Pb^{82+}$ ions was tracked starting at the TCP, but in a machine configured for the magnetic rigidity of partially stripped $^{208}Pb^{81+}$. Figure 2 (bottom) shows the simulation result. A good qualitative agreement is observed between the measured and simulated loss map. Particularly, the large loss peak at the aperture impact location predicted with MAD-X is well reproduced.

On the quantitative level some discrepancies can be observed, however, this can be explained by the fact that the BLM measurement is sensitive to the secondary shower particles that emerge outside of the impacted elements, while the simulations show the number of primary nuclei impacting on the aperture or disintegrating on the collimators. Previous studies for protons have shown that the agreement improves when a further simulation of the shower development and the BLM response is done [10, 20].

MITIGATION STRATEGIES

Different strategies are being studied to alleviate the losses in the DS and increase the intensity reach for PSI beams. The

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first method considered is a DS collimator (TCLD). During the current LHC long shutdown period (LS2, in 2019–2020) it is planned to install one TCLD (60 cm of tungsten alloy) in the DS of the outgoing beam on each side of IR7 as part of the HL-LHC project [23]. To install a TCLD, the main dipole MB.A9 in cell 9 will be replaced by two shorter 11 T dipoles with the collimator in the middle. The primary purpose of the TCLDs is to intercept dispersive losses from the upstream IR7 for both proton and ion beams [15, 24, 25]. Depending on its settings, The TCLD can intercept particles with a $\delta p/p$ similar to fully stripped $^{208}\mathrm{Pb}^{82+}$ ions. A plot of the off-rigidity $^{208}\mathrm{Pb}^{82+}$ MAD-X trajectories is shown in Fig. 3 with the machine aperture and the TCLD at the nominal opening of 14 σ. It confirms that the central trajectories are indeed intercepted by the TCLD.

To study the effect of the TCLD in more detail, a dedicated SixTrack–FLUKA study was performed using the HL–LHC Pb ion configuration V1.2 with the TCLD collimator in cell 9. The result in Fig. 3 shows a reduction of the DS losses by several orders of magnitude. Still, there could be a risk of quenching the downstream 11 T magnet due to the shower from the TCLD. To estimate this risk, we assume a quench limit of 70 mW cm^{-3} for the 11 T dipole [26], a 0.2 h minimum beam lifetime [27], and that each Pb ion impacting on the TCLD causes an energy deposition of 5×10^{-7} mJ cm^{-3} in the coils of the downstream magnet [28]. This number is extracted from a FLUKA simulation of betatron losses during standard $^{208}\mathrm{Pb}^{82+}$ operation, and since the impact distribution on the TCLD could be different in PSI operation, the simulation should be repeated for this case for an improved estimate. The total maximum $^{208}\mathrm{Pb}^{81+}$ beam intensity can then be calculated to 3×10^{11} Pb ions, which is beyond the baseline Pb intensity for the ion runs in HL–LHC [27]. Therefore, it is not expected that the total PSI intensity will be limited by the downstream 11 T magnet. To complete the study, energy deposition simulations should be performed also for the TCLD itself and for the neighbouring upstream and downstream elements, since limitations could arise also at other elements.

Another mitigation strategy considered is crystal collimation – a novel technique being investigated for the LHC and HL-LHC [29–31]. A bent silicon crystal is used instead of the amorphous carbon primary collimator in the standard collimation setup. Halo particles impacting the crystal can enter a channeling regime, in which their trajectories are guided by the potential between crystalline planes. The achieved deflection is much larger than that from scattering in an amorphous material, and the halo particles can be directed onto a single massive absorber. Crystal collimation has shown promise for improving the cleaning efficiency with heavy-ion beams and it is proposed to study if it can also alleviate the losses for PSI beams. The interaction of the PSI with the crystal is currently not well characterised, but it is theorised that the ions could be channelled by the bent crystal after their electron has been stripped and effectively removed from the beam halo well upstream of the DS.

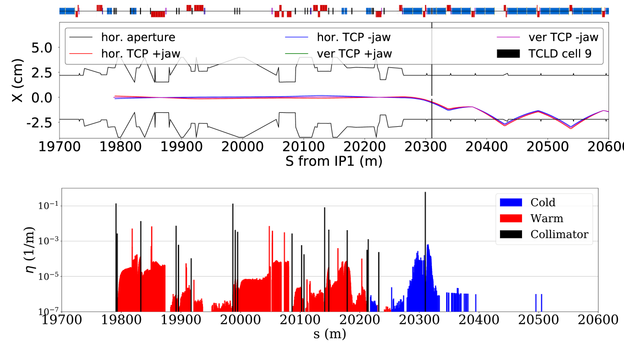

Figure 3: Top: Trajectories of off-rigidity $^{208}\mathrm{Pb}^{82+}$ ions escaping the TCPs, as calculated with MAD-X. The black lines show the TCLD with a 14 σ opening. Bottom: Simulated B1H loss map for a representative HL–LHC configuration with the TCLD in cell 9 at nominal opening of 14 σ.

Detailed studies are necessary in the future to confirm the feasibility of crystal collimation for PSI beams.

As the stripping action of collimators produces a secondary beam of identical particles, another mitigation strategy may involve an orbit bump, similarly to what is used operationally in the LHC to deviate secondary beams coming from Bound-Free Pair Production (BFPP) during heavy-ion collisions at the experimental IPs [32–34]. For PSI secondary beams, the losses could be moved to the connection cryostat in cell 11, and from the current results it is possible that the loss location is already not far from the optimal location. An orbit bump could be used to fine-tune the impact location, and the BLM thresholds could be adjusted based on energy deposition studies to avoid unnecessary beam dumps. However, if the TCLD collimator is found to be effective, it is considered a more robust solution.

CONCLUSION AND OUTLOOK

The Gamma Factory proposal for the LHC relies on operation with PSI beams, but the results from the first PSI experiment at the LHC show that the collimation cleaning efficiency is prohibitively low for high-intensity operation. Preliminary studies and dedicated collimation simulations demonstrate that the likely reason for the poor collimation performance is the stripping action of the primary collimators. Several mitigation strategies are under consideration for reducing the most critical losses. Simulations show that the TCLD collimator scheduled to be installed in LS2 can substantially reduce the losses and preliminary calculations did not reveal any showstopper for reaching the nominal HL-LHC Pb intensity with $^{208}\mathrm{Pb}^{81+}$ ions. Crystal collimation and an orbit bump are considered as alternative mitigation strategies that require additional investigation. Nevertheless, further energy deposition studies are necessary for final conclusions on the PSI intensity limit for safe operation and the effectiveness of the considered mitigation strategies.

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