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CRYSTAL COLLIMATION OF 20 MJ HEAVY-ION BEAMS AT THE HL-LHC*

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Abstract

The concept of crystal collimation at the Large Hadron Collider (LHC) relies on the use of bent crystals that can deflect halo particles by a much larger angle than the standard multi-stage collimation system. Following an extensive campaign of studies and performance validations, a number of crystal collimation tests with Pb ion beams were performed in 2018 at energies up to 6.37Z TeV. This paper describes the procedure and outcomes of these tests, the most important of which being the demonstration of the capability of crystal collimation to improve the cleaning efficiency of the machine. These results led to the inclusion of crystal collimation into the LHC baseline for operation with ion beams in Run 3 as well as for the HL-LHC era. A first set of operational settings was defined.

INTRODUCTION

The High-Luminosity LHC (HL-LHC) project [1,2] aims to achieve a total integrated proton luminosity about 10 times larger than the estimated reach of the LHC at the end of Run 3, in order to explore the full performance reach of the machine. Collisions with high-intensity ion beams are also part of the HL-LHC physics program and will be delivered already during Run 3 [3], starting in 2022. The upgrade of the collimation system is crucial, since losses caused by heavy ion beams were already close to magnet quench limits in Run 2 [4,5].

The IR7 Dispersion Suppressor (IR7-DS) was identified as the limiting location due to its vicinity to the betatron cleaning insertion. The baseline upgrade strategy for the collimation system includes the exchange of two main dipoles in this area with two shorter 11 T dipoles each, making room for the installation of new dedicated collimators. However, due to performance and schedule issues, the 11 T dipoles are not going to be installed during the Second Long Shutdown (LS2). For this reason, crystal collimation was considered as a mitigation solution to allow safe ion operation in Run 3 and has now been included in the HL-LHC baseline programme.

A set of four crystal primary collimators (two for each of the circulating beams, one in the horizontal and one in the vertical plane) have been installed in the LHC between 2015 and 2018 [6–8]. Extensive studies have been carried out to assess the performance of this advanced collimation scheme with ion beams [9–12]. The 2018 Pb ion run at the LHC was crucial, as it was the first time the full system could be tested with Pb ion beams, and the last opportunity to assess its performance before LS2 and the final decision on the use of crystal collimation in Run 3. An extensive program of machine studies was devised to assess the performance provided by crystal collimation, as well as to explore and define operational settings for its potential use in Run 3 [13].

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CLEANING PERFORMANCE COMPARISON

One of the most important means of assessing the halo cleaning performance of the LHC collimation system is by using the Active Transverse Damper (ADT) to intentionally excite the beam and generate controlled losses around the machine. The resulting signal is detected by Beam Loss Monitors (BLMs) [14], ionization chambers installed all around the ring to detect secondary showers produced by beam particles hitting the machine aperture. The longitudinal loss pattern around the ring is displayed in a *loss map* and allows to measure the *cleaning inefficiency* of the system, i.e. the fraction of particles entering the collimation system but being finally lost at particularly sensitive locations. This quantity can be used to compare the performance of the standard and crystal collimation system: the same beam excitation is applied with either system in place and the loss patterns are then compared. Figure 1 shows the typical patterns observed in IR7, where the betatron collimation insertion is located, for a loss map on the horizontal plane of Beam 1 with Pb ions at 6.37Z TeV.

The comparison is performed by dividing the cold IR7-DS region into four different sections [12], which are identified by the quadrupoles they respectively enclose (Q7, Q8-9, Q10-11 and Q12-13, with the respective longitudinal range delimited by green dashed lines in Fig. 1 for Beam 1).

The cleaning inefficiency η_c in each of the above defined IR7-DS regions is evaluated as the highest normalized BLM signal in the respective longitudinal range. In order to compare the performance of the crystal-based system to that of the standard system, a *local leakage ratio* is defined as:

$$LLR_i = \frac{\eta_c^{\mathrm{STD}}(i)}{\eta_c^{\mathrm{CRY}}(i)}, \tag{1}$$

where i indicates the specific IR7-DS region considered, while STD and CRY stand for standard and crystal system respectively. With this definition, if $LLR_i > 1$ for a certain region i, then the cleaning inefficiency is reduced in that

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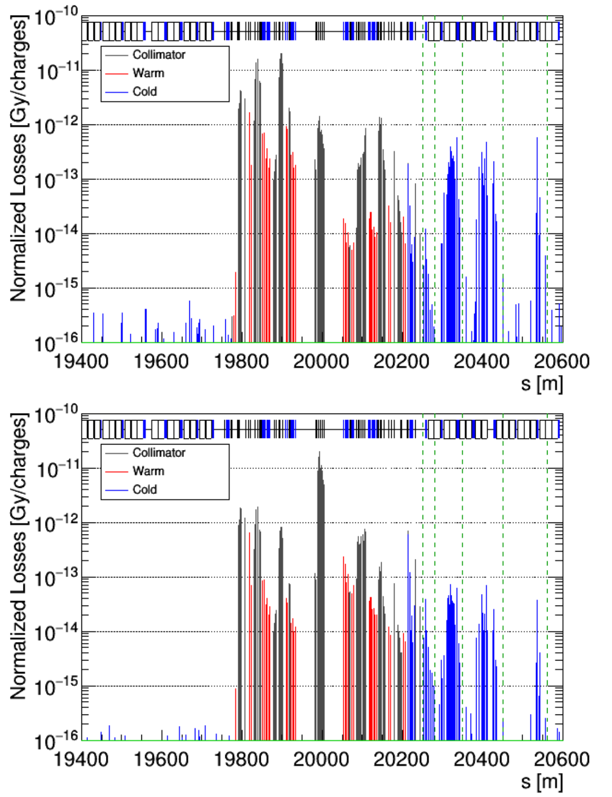

Figure 1: BLM signal recorded in the IR7 collimation insertion of the LHC during a loss map on the horizontal plane with Pb ions at 6.37*Z* TeV, using standard (top) and crystal (bottom) collimation. The values are normalized to the flux of particles lost during the loss map.

region when crystals are deployed, leading to a performance improvement of the collimation system.

For the purpose of evaluating the performance of the system in view of potential use in operation with ion beams, another interesting aspect is the global cleaning improvement achieved across the whole IR7-DS. A *global leakage ratio* can be defined as:

$$GLR = \frac{\max \eta_c^{\mathrm{STD}}(i)}{\max \eta_c^{\mathrm{CRY}}(i)}. \quad (2)$$

This quantity allows to directly evaluate the overall improvement provided by crystal collimation.

CRYSTAL COLLIMATION TESTS IN OPERATIONAL CONFIGURATION

During operational tests with Pb ion beams, the standard collimation system was kept in place with the usual settings used for LHC operation [4, 5, 15] in order to guarantee the required passive machine protection. However, crystal collimators were *adiabatically* inserted into the system, with each crystal set at a slightly tighter aperture than the primary collimator on the corresponding beam and plane. In this configuration, all primary beam losses impinge first on the crystals for classical loss mechanisms. The crystal system configurations tested with Pb ions at 6.37*Z* TeV are reported in Table 1. Settings are listed for primary collimators (TCPs), secondary collimators (TCSGs), crystal collimators and absorbers (TCLAs) in IR7, in units of the beam r.m.s. width σ. These configurations were compared with the nominal standard system (i.e. configuration 1a without crystals).

Table 1: Crystal System Configurations in Operational Tests

Configuration	Collimator Opening [σ] 1a	2a	3a	4a
TCPs	5.0	5.0	5.0	5.0
Upstream TCSGs	6.5	6.5	6.5	6.5
Crystal	4.75	4.75	4.75	4.75
Downstream TCSGs	6.5	6.5	6.5	6.5
TCLAs	10.0	9.0	8.0	7.0

The measured local leakage ratio (Eq. (1)) is reported in Fig. 2 for each IR7-DS region for the horizontal plane on Beam 1. Overall, a clear improvement in cleaning inefficiency is observed when crystals are used in conjunction with the standard system. Most notably, certain critical losses are reduced by a factor ~10 and by a factor ~2-3 by the horizontal crystals on Beam 1 and Beam 2 respectively.

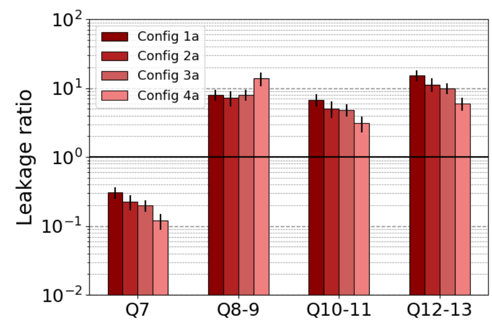

Figure 2: Local leakage ratio measured in the IR7-DS during operational tests with 20 Pb ion bunches at 6.37*Z* TeV, for the horizontal crystal on Beam 1.

All beams and planes show increased losses at the Q7 location. However, losses in this region, while increased with respect to the standard system, are still lower in absolute than losses recorded at downstream locations, as shown in Fig. 3 for the horizontal crystal on Beam 1 in configuration 1a. As such, they are not at risk of becoming the limiting location.

Among the various configurations tested, configuration 1a allows to achieve a satisfactory cleaning improvement in the IR7-DS region, without increasing the loads on other areas of the machine by too large a margin. Table 2 reports the measured global leakage ratio (Eq. (2)) for each plane, which can be considered an estimation of the performance reach of the machine when the crystal system is used in operation.

Crystal collimation was also tested in configuration 1a with up to 648 circulating bunches, for a maximum total intensity of 3.76×10^{12} charges and a maximum total stored energy of 4 MJ. This marked the very first use of crystal collimation with high-intensity Pb ion beams. A number of

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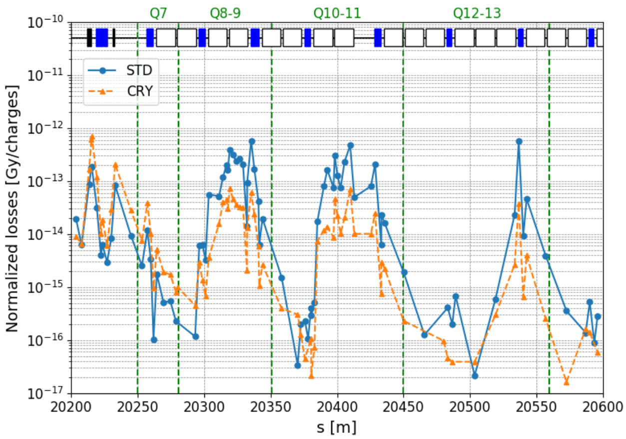

Figure 3: Loss pattern measured in the IR7-DS during operational tests with 20 Pb ion bunches at 6.37Z TeV for the horizontal crystal on Beam 1, using the nominal standard system and the crystal system in configuration 1a.

Table 2: Measured Global Leakage Ratio in Configuration 1a

Crystal	Global Leakage Ratio
B1H	8.0 ± 1.4
B1V	3.1 ± 0.1
B2H	3.5 ± 0.6
B2V	1.5 ± 0.4

additional tests aimed at ensuring that safe operation can be guaranteed in these conditions were carried out, such as channeling while generating high losses on all planes at the same time with 20 bunches, an asynchronous beam dump test and stable channeling for 2 hours with 648 bunches. The positive outcome of all these tests and the experience gathered over the entirety of Run 2 with crystals at the LHC [16] were key ingredients that testified the maturity achieved by this innovative collimation scheme. As a result, crystal collimation is now officially part of the HL-LHC upgrade baseline programme and is scheduled to be used during Run 3 for operation with ion beams.

PUSHING THE CLEANING PERFORMANCE FURTHER

Other configurations for the crystal collimation scheme were tested in dedicated machine studies with low-intensity Pb ion beams. A first set of configurations, reported in Table 3, used the same settings as configurations 1a-4a for the TCLAs, but crystals were set at the same opening used for standard primary collimators in nominal settings and all upstream collimators were set to open settings. Additional configurations were explored by setting the TCLAs and TCSGs downstream of the absorber of the channeled beam at the same aperture, which was then progressively reduced [11]. These configurations were compared with the standard system using the same arrangement of downstream collimators. As can be seen in Fig. 4 for the horizontal plane of Beam 1 for configurations 1b-4b, these settings allowed to achieve even larger local cleaning improvements than in operational configurations. This confirms earlier observations on the effect of upstream collimator settings in dedicated tests at the SPS [12]. However, since the standard primary collimators are completely retracted, additional validation from the machine protection point of view is required before considering these settings for use in operation.

Table 3: Crystal System Configurations in Machine Studies

	Collimator Opening [σ]			
Configuration	**1b**	**2b**	**3b**	**4b**
TCPs	Out	Out	Out	Out
Upstream TCSGs	Out	Out	Out	Out
Crystal	5.0	5.0	5.0	5.0
Downstream TCSGs	6.5	6.5	6.5	6.5
TCLAs	10.0	9.0	8.0	7.0

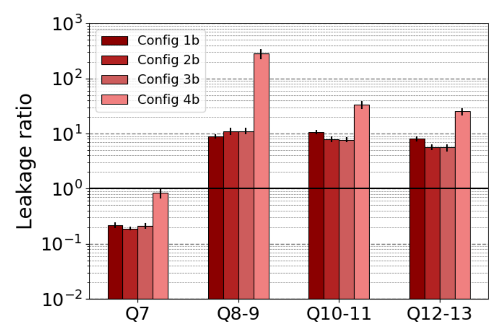

Figure 4: Local leakage ratio measured in the IR7-DS during machine studies with Pb ion beams at 6.37Z TeV for the horizontal crystal on Beam 1.

CONCLUSIONS

Over the course of Run 2, an extensive campaign of crystal collimation studies was carried out at the LHC with ion beams. In 2018, configurations for potential use in operation with Pb ion beams during Run 3 were tested, demonstrating the capability of this innovative collimation scheme to improve the cleaning efficiency of the machine. The same configurations were tested for the very first time with high-intensity Pb ion beams. Additional settings able to further improve the performance of the system were explored with low-intensity beams. The very encouraging outcome of these tests was a key ingredient in the decision to include crystal collimation in the HL-LHC upgrade baseline programme for use in operation with ion beams starting in Run 3.

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