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Chapter 30

Crystal Collimation of Heavy-Ion Beams

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Crystal collimation is an advanced technique where a silicon crystal, only a few millimeters long and bent to a curvature of about 50 μrad, coherently deflects the beam halo onto a collimator absorber. This technique can improve beam collimation in the HL-LHC. Since 2015, a test stand has been operational in the betatron cleaning insertion of the LHC for beam tests at the unprecedented hadron beam energy of up to 6.5 Z TeV, where Z is the atomic number. For the first time, channeling was observed at this energy and the crystal collimation concept was validated, demonstrating that the cleaning of lead heavy-ion beams at 6.37 Z TeV can be improved by up to a factor 10. Crystal collimation has become part of the HL-LHC baseline in 2019 and will be the key upgrade for improving the cleaning efficiency for ion beam operation in Run 3.

1. The Crystal Collimation Concept and its Applications to HL-LHC

Planar channelling is a phenomenon where charged particles impinging with specific impacting conditions on a crystal are trapped by the potential produced by the parallel lattice planes. Particles follow the "channel" along the crystal. If the crystal is bent the trajectories of channelled particles [1] are deflected. For the applications discussed in this chapter, silicon (Si) crystals are used. Equivalent bending fields of up to hundreds of tesla can be achieved in a few mm long crystal, bent to produce a deflecting angle of about 50 μrad. Provided that a sufficiently high efficiency is reached, channelling allows, in principle, an efficient collimation system to be built: a crystal intercepting the beam

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halo, as a primary collimator, steers halo particles coherently to a well-defined point where dedicated absorbers are located. Crystals of very high purity, e.g. with atomic dislocations below 1 unit per squared cm, can nowadays be produced and bent to the required accuracy. Together with the development of goniometers for precise angular control in an accelerator environment, these advancements open the possibility to use crystals also in high-intensity, high-energy accelerators.

The crystal collimation scheme is shown illustratively in Fig. 1 (bottom plot) and compared to the LHC multi-stage collimation system based on amorphous materials (top plot), which was introduced in Chapter 8. The present collimation system, located in a dedicated insertion region (IR7), requires several secondary collimators and absorbers to catch the products developed through the interaction of the primary beam halo with collimators and to suppress the emerging secondary and tertiary halos. One single absorber per collimation plane would instead be sufficient, in theory, in a crystal-based collimation where a bent crystal replaces the primary collimator. Indeed, nuclear interactions are much reduced in this case, which translates into a reduction of dispersive losses downstream of the cleaning insertion that limit the present collimation performance (Chapter 8).

Crystal collimation might be used for betatron or off-momentum halo cleaning systems where the crystal replaces the primary collimators in the planes of interest. It cannot be used as part of the collimation systems around the experiments, e.g. to locally protect the inner triplet (a goal that is achieved by tertiary collimators) or to clean collision products (done with physics-debris absorbers). For example, the off-momentum particles emerging from the interaction points are too close to the beam core, and only separate from it where the dispersion is sufficiently large, which already occurs in the cold dispersion suppressors. The focus of crystal R&D for collimation upgrade studies has therefore been put on the betratron cleaning.

Simulations indicate a possible gain in collimation cleaning of proton beams by a factor between 5 and 10 [2], for a layout that uses the existing secondary collimators as absorbers. This is currently not possible with high stored energies: we do not have a validated solution for the design of a collimator absorber capable to dispose with sufficient efficiency of the ~1 MW power extracted by the crystal for the design loss scenario with 0.2 h beam lifetime in nominal HL-LHC proton operation (see Chapter 8). The

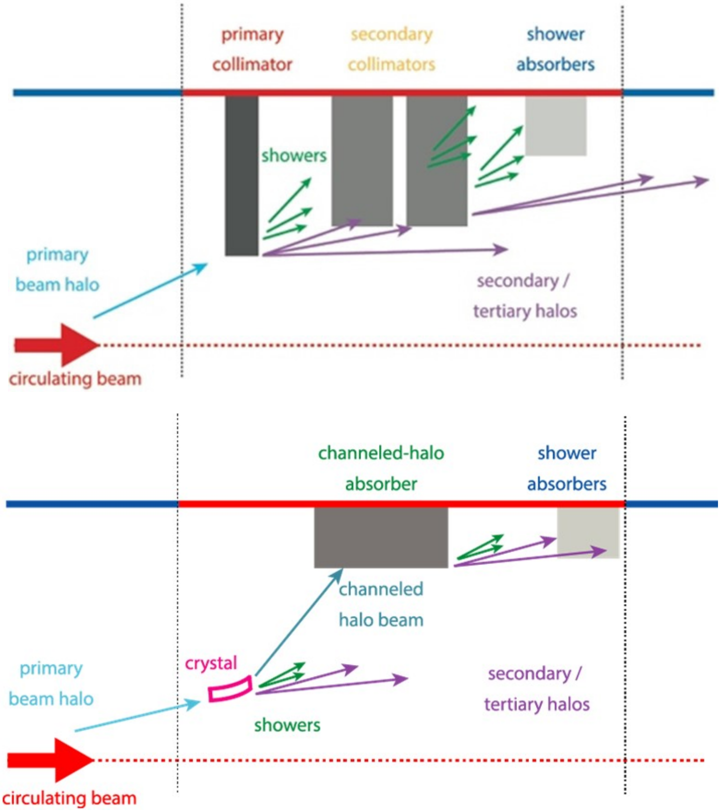

Fig. 1. Schematic illustrations of the standard multi-stage betatron cleaning system in the LHC IR7 (top) and of a conceptual implementation of a crystal-based cleaning system.

crystal collimation option is, however, directly applicable for collimating heavy-ion beams, which have a much lower intensity. Improved cleaning can be achieved thanks (see below) to the reduced probability of electromagnetic dissociation and nuclear fragmentation compared to the present primary collimators. The extracted power for design failures is more than 30 times lower and the present secondary collimators are adequate as absorbers of channelled ions. The integration of crystals into the present layout is possible for ion collimation, since crystals can be inserted into the present hierarchy without further modifications or major changes of the collimators that are used for proton operation. This approach can be seen as an “adiabatic” improvement of the collimation system, only applicable for ion beams.

The crystal collimation R&D within HL-LHC was initially motivated by the new IR7 dispersion suppressor upgrade layout, featuring only one TCLD/11 T dipole assembly per side of IR7 (see Chapter 8) instead of two as foreseen in the previous layout. The present baseline solution is satisfactory for the nominal ion and proton operation during HL-LHC and crystal collimation has been chosen as a mitigation measure for the delayed 11 T dipole installation and for a further improvement of the cleaning efficiency for ion operation once the 11T TCLD assemblies are installed in the LHC.

2. Experimental Validation with LHC Beams

2.1. *Test stand for crystal collimation tests in the LHC*

A unique crystal collimation test stand has been available in the LHC during Run 2 [2]. The initial 2015 installation with 2 crystals in Beam 1 was extended in 2017 with the addition of 2 crystals in Beam 2, enabling complete collimation tests for both beams and both horizontal and vertical planes. The layout for the horizontal plane of Beam 1 is shown in Fig. 2. The crystal primary collimator assembly is shown in Fig. 3, and the key crystal parameters

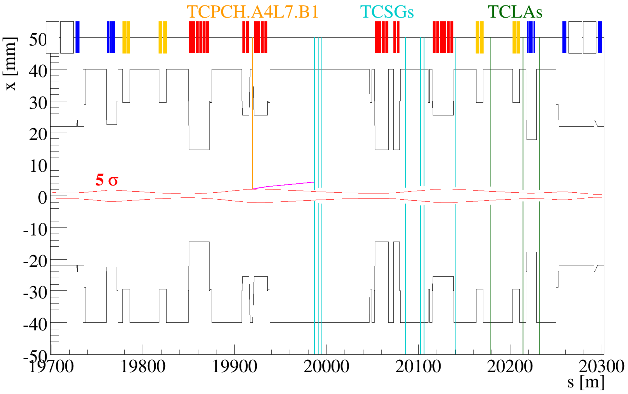

Fig. 2. Simulated horizontal trajectory of channeled halo particles for Beam 1 (magenta line) and mechanical aperture of the beam pipe (black) versus longitudinal position along the betatron cleaning insertion. The crystal (orange line) is set at 5 nominal beam sigmas (computed for a 3.5 μm emittance). Cyan and green lines indicate positions and settings of the secondary (TCSG) and shower-absorber (TCLA) collimators used to dispose of the channeled halo and of the products of its interactions with collimators.

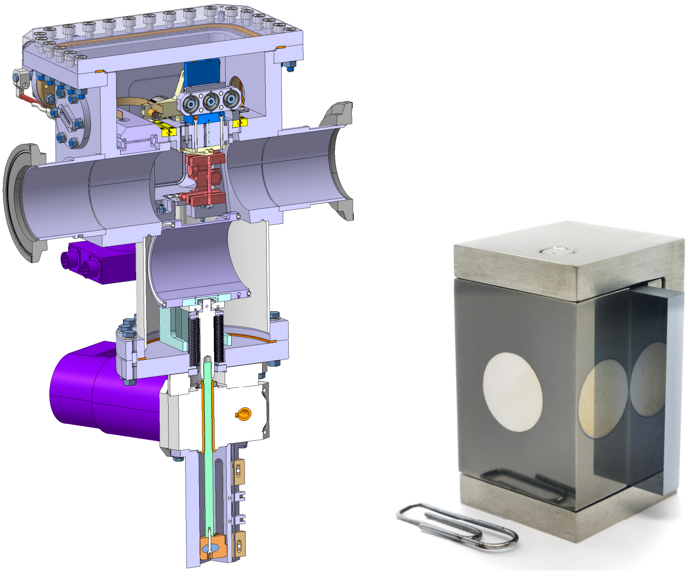

Fig. 3. Design of the prototype crystal primary collimator installed in the LHC (left) and photograph of the crystal mounted on his holder (*Courtesy of Y. Gavrikov*, PNPI). The four LHC crystal collimators use a special design of a moveable chamber that hides the crystals from the high-intensity beams when they are not used.

Table 1. Main parameters of the HL-LHC crystals

Crystal length along the beam	4±0.1 mm
Total height	< 55 mm
Total weight	< 150 g
Miscut for planar channeling	< 40 μrad
Torsion	< 1 μrad/mm
Bending	50.0±2.5 μrad
Dislocation density	< 1 / cm^2

are listed in Table 1. The bent crystal is usually operated at 5 σ and existing downstream collimators are used to intercept the channelled particles, while upstream collimators are fully open. Crystal locations and parameters have been optimized to achieve the best cleaning performance with this IR7 layout that, for protons, can only be used at low beam intensities. Silicon crystals are used in all cases, and the design specification [2] is to have 50 μrad bending. The crystal length is 4 mm.

2.2. *First demonstration of hadron channeling up to 6.5 Z TeV*

The observation of planar channeling of circulating beam halos is delicate. One way to do it is by inserting the crystal in the beam as a primary collimator and by recording local losses while varying slowly the angular orientation of the crystal with respect to the circulating beam, typically with a rotational speed as low as a fraction of μrad/s [3,4]. This so-called angular scan allows identifying the optimum crystal orientation, obtained when the impinging halo particles are nearly orthogonal to the crystal front face. The probability that they undergo channeling is, then, maximum. In this ideal condition, local beam losses directly downstream of the crystal are at a minimum because channeled particles travel within lattice planes with reduced probability to experience nuclear interactions and are instead lost at the absorber further downstream.

Beam losses at the horizontal crystal of Beam 1 as a function of the crystal orientation angle [5], re-centered to have the optimum channeling orientation at a zero angle, are shown in Fig. 4. This is a high-resolution scan performed at 0.2 μrad/s while the beam was continuously excited with the transverse

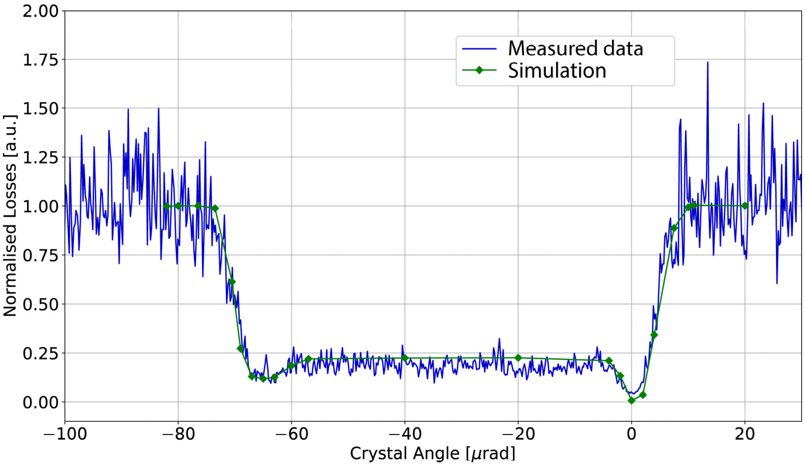

Fig. 4. Beam losses at the horizontal crystal of beam 1 as a function of the crystal orientation angle during an angular scan with proton beams at 6.5 TeV [5]. The green line shows simulations for the same conditions. The zero angle corresponds to a minimum of local losses. Losses are normalized by the values recorded in amorphous-like orientation, when channeling is prohibited, and interactions of the proton beam are like with a Si collimator of the same dimensions.

damper to obtain a desired level of primary beam losses. Data were collected with proton beams at 6.5 TeV. The green line shows simulations performed for the same conditions, proving an excellent prediction power of the tools that were developed for crystal collimation studies [6]. The flat region of losses between -60 μrad and zero corresponds to the volume reflection [7] region.

Similar measurements, leading to the same qualitative observations, were obtained for all crystals and planes, both at injection and at top energy. Measurements are available for proton, Pb and Xe beams. A comprehensive review of available data was given at the Crystal Collimation Day event [8].

2.3. *Crystal collimation cleaning and other operational aspects*

The collimation cleaning inefficiency is measured by inducing beam losses in a controlled way, by injecting white noise via the transverse damper that excites the beam core until particles impinge on the IR7 collimators. The same procedure is applied with either conventional or crystal primary collimators in use, for a direct comparison of the performance of the two schemes. Figure 5 compares the standard collimation cleaning of Pb ion beams (top graph) with a crystal-based system (bottom). Losses in the most exposed cold magnets are about 8 times lower using crystals.

More systematic studies demonstrated that, with settings in IR7 similar to those used for the conventional system in 2018, the addition of one crystal at a setting 0.25 σ closer to the beam than the primary collimators (i.e., 4.75 σ instead of 5.0 σ) could improve the cleaning for both beams and planes, by factors between 1.5 ± 0.4 and 8.0 ± 1.4 depending on the beam and plane [10]. This depends on the type of crystal used and the smallest improvement is achieved with the quasi-mosaic crystal used for the Beam 2 vertical collimation, while the strip crystals provided the best performance. Further improvements could be obtained by tightening the IR7 hierarchy in a crystal-optimized configuration that was tested in dedicated machine studies [10].

The LHC beam tests also validated critical hardware components like the high-precision goniometer that controls the crystal angle with sub-μrad resolution [9]. This is a very important result because crystal collimation should be deployed in all phases of the operational cycle, not only in static conditions. Continuous channelling was achieved during the energy ramp from 450 GeV to 6.5 TeV and in the betatron squeeze. For example, Ref. 5 shows the crystal angle measured during the energy ramp, showing an angular RMS value below 1 μrad throughout the range. Note that the crystal moves towards the beam core by about 5 mm to keep normalized settings of 5 σ, while the rotational stage moves by about 30 μrad to keep the channelling orientation. Throughout the process, and excellent angular control must be achieved to remain within the critical angle for channeling, which is reduced to about 2.2 μrad at top energy.

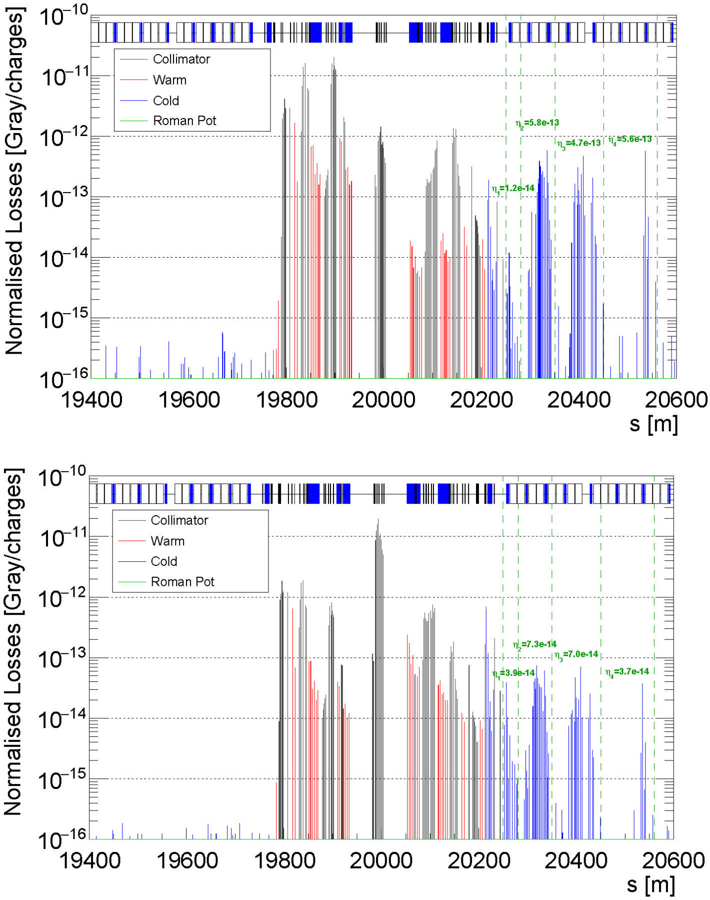

Fig. 5. Beam losses in IR7 recorded in a horizontal loss map for B1 with Pb beams at 6.37 Z TeV, for the standard (top graph) and crystal-based (bottom) system. Peak values over the selected ranges are reported in green. The crystal is installed at the coordinate 19919 m (see Fig. 2).

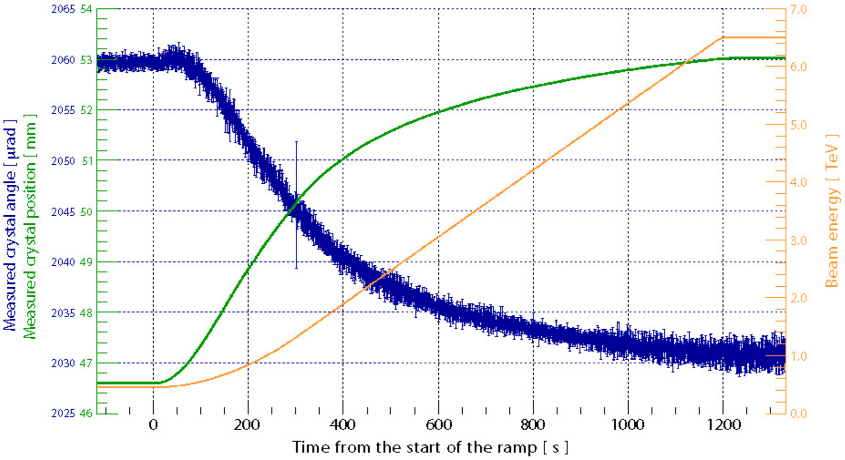

Fig. 6. Crystal position and angle as a function of time during the LHC energy ramp to 6.5TeV (right axis), from Ref. 5.

During Pb ion operation in 2018, crystal insertions were made part of the intensity ramp up, which is the phase where the number of bunches is progressively increased, in subsequent fills, to safely approach the maximum stored energies. Crystals were successfully used in studies at the end of physics fills with up to 648 lead ion bunches, using adiabatic insertions in the standard multi-stage cleaning of IR7 as described above [10].

An important milestone was achieved at injection energy, during the high-beta run in 2018, where crystal collimation was used operationally for the first time at the LHC, to reduce beam-induced background on forward physics detectors. The crystals were orchestrated through automated sequences as the other ring collimators. Although the run was relatively short, the system showed the required stability with crystals inserted directly in channelling orientation. Significant performance improvement with respect to a standard collimation approach was observed, in good agreement with numerical simulations [11].

3. Prospect for Crystal Collimation Deployment for HL-LHC

With the promising results obtained in Run 2, crystal collimation is considered as an option to further reduce IR7 losses with lead ion beams. Crystal collimation became part of the HL-LHC baseline after the 2019 Cost and Schedule Review and the present installation in the LHC is being upgraded during LS2 to address some non-conformities of the first prototype installations and to improve operation reliability for Run 3. Following the decision not to install 11 T dipoles during LS2, it is planned to use crystal collimation for the heavy ion beams throughout Run 3. For a complete crystal-based system, one would also add one crystal per beam and plane, for a total of 8 devices, in order to constrain the beam from both sides in each plane. The present one-side setup might indeed not be fully adequate in case of orbit drifts on the side opposite from the crystal. The specifications of four additional crystals and goniometers remain the same introduced above and available layout locations have been identified [10]. The need for such a further upgrade will be established at the beginning of Run 3 following the operational experience with the 4-crystal system.

4. Acknowledgements

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