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SIMULATION OF HEAVY-ION BEAM LOSSES WITH CRYSTAL COLLIMATION*

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Abstract

With the higher stored energy envisioned for future heavy-ion runs in the LHC and the challenging fragmentation aspect of heavy-ion beams due to interaction with collimator material, the need arises for even more performing collimation systems. One promising solution is crystal channeling, which is used in the HL-LHC baseline and starts with Run III for heavy-ion collimation. To investigate an optimal configuration for the collimation system, a well-tested simulation setup is required. This work shows the simulations of channeling and other coherent effects in the SixTrack-FLUKA Coupling simulation framework and compares simulated loss patterns with data from previous beam tests.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN collides both proton and heavy-ion beams. Due to the high stored beam energies, beam losses could cause quenches of superconducting elements or even damage. In particular, to keep control of the continuous beam losses during operation due to diffusive effects, instabilities, collisions and other mechanisms that deviate particles from the nominal orbit, a multi-stage collimation system has been put into place [2–5], with the main betatron collimation system installed in the LHC insertion region 7 (IR7). Previous studies showed that the cleaning inefficiency is about two orders of magnitude worse for Pb ions than for protons [6–8]. Hence, heavy-ion collimation is more critical, even if the planned stored beam energy is about a factor 30 smaller than for protons.

To improve the ion collimation performance facing the imminent HL-LHC upgrades [9–11], where the stored beam energy will be increased from about 13 MJ to 20 MJ, an increase of a factor of three in cleaning efficiency would be needed. For this, the so-called crystal collimation [12, 13] will be used starting from 2022. This method exploits the electromagnetic potential in the crystalline structure of a bent silicon crystal to guide the incoming particles. This mechanism is called crystal channeling [14, 15] and it occurs when particles enter the crystal with an incident angle below the so-called critical angle [13]. For channeled particles a bent crystal acts as an ideal septum by deflecting channeled particles onto a downstream absorber [16] with an equivalent field strength of hundreds of Tesla, while circulating particles passing close to it are not affected.

After numerous studies, four strip crystal collimators have been installed in the LHC, one per beam per plane. The specifications of the crystals are shown in [17, 18].

Crystal collimation has been demonstrated to work also for protons with low-intensity beams [19]. However, the present standard collimators cannot be used as absorbers with LHC's high-intensity proton beams, which is why this technique is presently not considered for operational use.

Simulations are crucial in understanding, mitigating and optimizing critical collimation losses. Previously, a complete simulation framework for heavy-ion collimation using crystals including standard interactions with other collimators and a precise 6D tracking did not exist, thus heavy-ion crystal collimation could not be studied systematically. This paper presents an extension of the existing simulation framework for standard ion collimation studies to include crystals, as well as benchmarks and simulation results on proton and heavy-ion crystal collimation including full coverage of multi-turn effects.

SIMULATION FRAMEWORK

The newly built simulation framework relies on the existing SixTrack-FLUKA coupling [20–22], which is the standard tool for simulating ion collimation [7, 23]. This package provides a framework for active information exchange between SixTrack [24] and FLUKA [25–28]. SixTrack is a 6D symplectic particle tracking code, whereas FLUKA is a general-purpose Monte Carlo code. SixTrack is used for the tracking in the magnetic lattice, while FLUKA simulates the particle-matter interactions in collimators [20, 21].

A crystal routine has been developed and been recently integrated in FLUKA [29–31]. Building on that, the SixTrack-FLUKA coupling has been updated to include crystal collimators, carrying a special flag and several crystal-specific parameters in the inputs to activate the crystal physics routine. Geometry models of the LHC crystals which follow closely the real curved geometries have been implemented. Auxiliary components such as the holders have not been implemented, as they are much smaller than conventional collimator supporting systems and their contribution is likely small for tracking purposes since particles are not expected to impact on them. The properties of the crystal lattice have been defined according to the most recent X-ray and hadronic

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measurements of LHC crystals [18, 32]. The channeling orientation of the crystal with respect to the beam is precisely calculated and implemented, and it can be customized for each simulation case. Finally, crystal-specific output files have been added.

A few changes to the crystal routine itself have been triggered by this work, e.g. fixes to simulate high-energy particles accurately [25].

PROTON BENCHMARK RESULTS

To benchmark the new implementation, we start with protons, since the results can be compared against a multitude of experimental data and a different, independent crystal routine for protons that only exists in the standard version of SixTrack [12, 13]. Detailed information on the physics and benchmark of the routine can be found in [33–38]. We first study LHC measurements taken in 2018 at 6.5 TeV [39], using a 4 mm crystal of ~65 μrad bending angle as primary collimator. The collimation cleaning efficiency was assessed by observing the beam loss pattern around the ring during provoked losses (so-called loss maps). Around 4000 beam loss monitors (BLMs) placed around the LHC [40, 41] were used to measure local losses. Measured loss maps shown are normalized to the sum of all recorded values.

We compare simulated and measured loss maps for the horizontal plane of Beam 1 at 6.5 TeV (2018 configuration). Simulated loss maps are normalized by the total energy lost around the ring and by the element length (so-called cleaning inefficiency, η) [4]. The initial distribution is a pencil beam with 60×10^6 protons impacting at 1 μm from the edge of the crystal. A detailed description of the measurement performed on the 12$^{\text{th}}$ of September 2018, along with the optical setup and collimation configurations can be found in [32, 39].

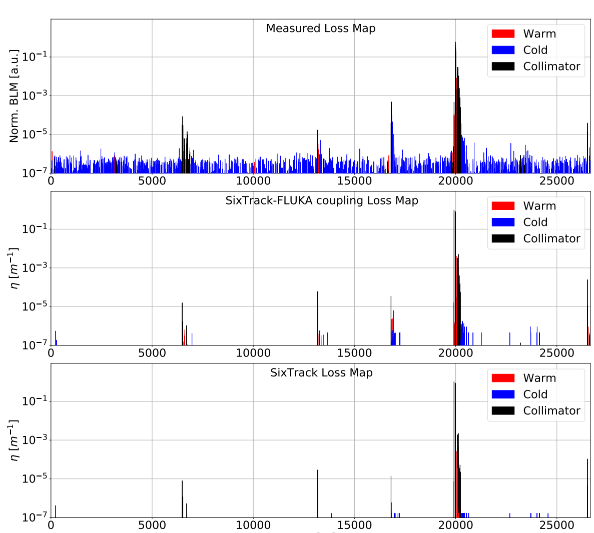

Figure 1: Measured (top), SixTrack-FLUKA coupling simulated (middle) and SixTrack simulated (bottom) loss map for 2018 proton run at 6.5 TeV.

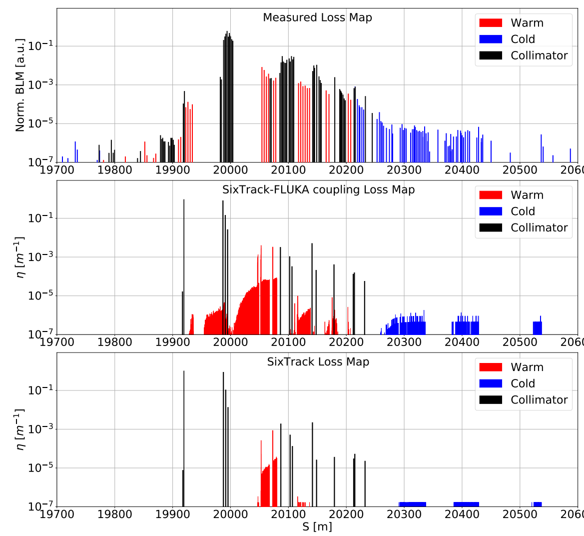

Figure 2: Measured (top), SixTrack-FLUKA coupling simulated (middle) and SixTrack simulated (bottom) loss map around IR7 for 2018 proton run at 6.5 TeV.

Figure 1 compares measured and simulated loss maps. Black, red and blue bars represent the losses on the collimators, warm sections and superconducting (cold) sections respectively. Above the measurement noise level, a good qualitative agreement of the measured loss pattern with the SixTrack-FLUKA coupling can be observed. However, a detailed quantitative comparison is not possible here since the simulations show lost particles and the measurements show the energy deposition at the BLMs from the induced shower. The particle shower propagation to the BLMs is more pronounced in the warm regions, explaining these higher measurement values. Both, losses on IR7 cold magnets and on the collimators show good agreement, except for a slight underestimation of the simulation compared to data for the collimator cluster around s = 20100 m, which may be due to upstream showers. Additionally, the high bar in simulation at s = 19919.5 m in Fig. 2 representing the crystal cannot be directly compared to the measured data, as the simulation is normalized to the length of the crystal, which is two orders of magnitude shorter than the other collimators.

The SixTrack-FLUKA coupling shows also an excellent agreement with the SixTrack standalone routine (Figs. 1 and 2), where it should be noted that SixTrack has a higher energy cut and hence gives less warm losses around s = 20150 m.

So-called angular scans are performed to assess the scattering out of the crystal for various crystal orientations. The crystal is rotated with respect to the incoming beam, and the BLM signal close to the crystal is recorded as a function of angle. The absorption at different orientation angles is then normalized by the amorphous absorption. The scan ranges over angles where the crystal is in the orientation for channeling, volume reflection, or amorphous scattering, giving rise to variations in the rate of inelastic interactions

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at the crystal, and hence also the local BLM signal [13]. The measurement is described in [39].

The simulation results from the SixTrack-FLUKA coupling are compared both to measured data and SixTrack simulations in Fig. 3. A reasonable agreement among the

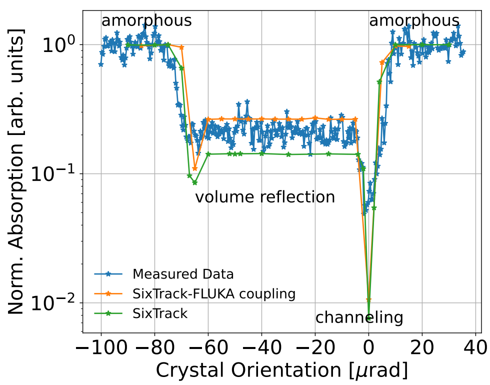

Figure 3: Angular scan of a 65 μrad crystal for measured data (blue), SixTrack-FLUKA coupling (orange) and SixTrack alone (green) [32, 39].

three sets of data is seen, especially concerning the sharp minimum, which corresponds to the situation where the crystal is in channeling orientation, where the inelastic interactions are reduced to the minimum. The discrepancy with respect to the measured data can in part be explained by imperfections that are not considered in simulation and that the simulated inelastic nuclear interactions are not directly comparable to BLM signals. However, in the middle volume reflection section, approximately from -70 μrad to -10 μrad there seem to be an underestimation by SixTrack and an overestimation by the SixTrack-FLUKA coupling. This discrepancy, not seen in previously studies [19], which may originate from using an ideal model of the collimation system, is under further investigations.

ION BENCHMARK RESULTS

A similar comparison to measured loss maps from 2018 with crystals as primary collimators has been carried out for Pb ions at 6.37 Z TeV. More information about the measurement done on the 27$^{\text{th}}$ of November 2018, the optical setup and collimation system settings can be found in [32, 42]. In the SixTrack-FLUKA coupling, an initial distribution of 6×10^6 $^{208}\text{Pb}^{82+}$ ions was simulated.

The measured and simulated loss maps are shown in Figs. 4 and 5. When excluding the background noise, the simulated loss pattern reflects well what is seen from the measured BLM signals including the losses in insertion region 3 (around s = 7000 m). The zoom of IR7 in Fig. 5 shows that the highest three clusters in the superconducting region around s = 20300 m, s = 20400 m and s = 20530 m in the measured data plot are reproduced up to the same order of magnitude in simulation. Sudden spikes such as the one around s = 400 m are due to the aperture treatment

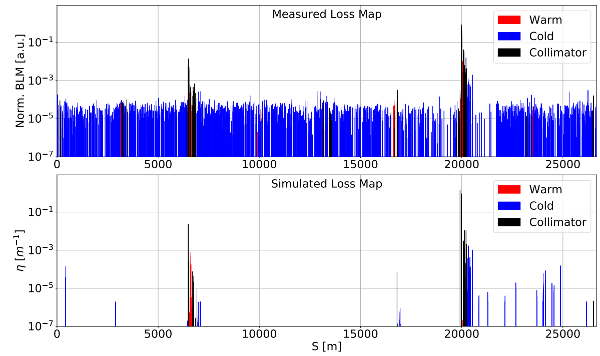

Figure 4: Measured (top) and simulated (bottom) loss map for 2018 Pb run at 6.37Z TeV.

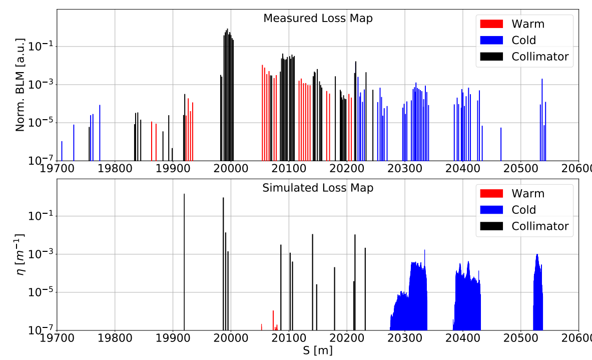

Figure 5: Measured (top) and simulated (bottom) loss map around IR7 for 2018 Pb run at 6.37 Z TeV.

in SixTrack and should not be attributed to crystal performance. Concerning the losses on the collimators, for heavy ions there is a small underestimation for the collimators around s = 20100 m as seen for protons. However, the same caveats apply as for protons on the short crystal length and that the simulation comparison does not include the shower development, which is particularly important for the BLMs at warm magnets and collimators in IR7. Such a comparison is discussed in [43].

CONCLUSION

The high energy stored in the Large Hadron Collider beam makes any beam losses potentially dangerous. These can be controlled with a multi-stage collimation system. In particular, compared to proton collimation, heavy-ion collimation has shown to be about two orders of magnitude less efficient. To improve the collimation efficiency in future heavy-ion runs, so-called crystal collimation is planned in the baseline.

A simulation framework for crystal collimation with ions was needed. Based on the existing tools in the SixTrack-FLUKA coupling, this paper presents the development of such a tool. The crystal collimator element has been inserted and other supplementary changes have been made. Simulations of loss maps with crystal collimation with both protons and, for the first time, heavy-ions, have been compared to past experimental data and for protons also with results from

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another simulation tool. Overall, a good agreement has been found, with remaining minor discrepancies currently being investigated.

REFERENCES

[1] O. S. Brüning *et al.*, "LHC design report v.1 : The LHC main ring," *CERN-2004-003-V1*, 2004.

[2] R.W. Assmann, "Collimators and Beam Absorbers for Cleaning and Machine Protection," *Proceedings of the LHC Project Workshop - Chamonix XIV, Chamonix, France*, p. 261, 2005.

[3] R.W. Assmann *et al.*, "The Final Collimation System for the LHC," *Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland*, p. 986, 2006.

[4] R. Bruce *et al.*, "Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 081 004, 8 2014, doi:10.1103/PhysRevSTAB.17.081004

[5] R. Bruce *et al.*, "Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics," *Nucl. Instrum. Methods Phys. Res. A*, vol. 848, pp. 19–30, 2017, doi:http://dx.doi.org/10.1016/j.nima.2016.12.039

[6] P. Hermes *et al.*, "Measured and simulated heavy-ion beam loss patterns at the CERN Large Hadron Collider," *Nucl. Instrum. Methods Phys. Res. A*, vol. 819, pp. 73–83, 2016, doi:http://dx.doi.org/10.1016/j.nima.2016.02.050

[7] N. Fuster-Martínez *et al.*, "Simulations of heavy-ion halo collimation at the cern large hadron collider: Benchmark with measurements and cleaning performance evaluation," *Phys. Rev. Accel. Beams*, vol. 23, p. 111 002, 11 2020, doi:10.1103/PhysRevAccelBeams.23.111002

[8] N. F. Martinez *et al.*, "Run 2 collimation overview," *Proceedings of the 9th LHC Operations Evian Workshop, Evian, France*, 2019, http://cds.cern.ch/record/2750291?ln=en

[9] I. B. Alonso *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN, 2020, doi:10.23731/CYRM-2020-0010

[10] R. Bruce *et al.*, "HL-LHC operational scenario for Pb-Pb and p-Pb operation," *CERN-ACC-2020-0011*, 2020, https://cds.cern.ch/record/2722753

[11] R. Bruce, M. Jebramcik, J. Jowett, T. Mertens, and M. Schaumann, "Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider," *Eur. Phys. J. Plus*, vol. 136, p. 745, 2021, doi:10.1140/epjp/s13360-021-01685-5

[12] V. Previtali, "Performance evaluation of a crystal-enhanced collimation system for the LHC," Presented on 07 Oct 2010, Ph.D. dissertation, EPFL, Lausanne, 2010, https://cds.cern.ch/record/1302274

[13] D. Mirarchi, "Crystal Collimation for LHC," Ph.D. dissertation, Imperial College, London, 2015, http://cds.cern.ch/record/2036210

[14] V. M. Biryukov, Y. A. Chesnokov, and V. I. Kotov, *Crystal channeling and its application at high-energy accelerators*. 1997.

[15] W. Scandale and A. M. Taratin, "Channeling and volume reflection of high-energy charged particles in short bent crystals. Crystal assisted collimation of the accelerator beam halo," *Phys. Rep.*, vol. 815, 1–107. 107 p, 2019, doi:10.1016/j.physrep.2019.04.003

[16] *Crystal channeling of ions on different TCSG materials*, presented at LHC Collimation Upgrade Specification Meeting, 2018.

[17] D. Mirarchi, G. Hall, S. Redaelli, and W. Scandale, "Design and implementation of a crystal collimation test stand at the large hadron collider," *The European Physical Journal C*, vol. 77, no. 6, p. 424, 2017, doi:10.1140/epjc/s10052-017-4985-4

[18] E. Matheson, S. A. Solis Paiva, and M. di Castro, *LHC Crystal Goniometers: Crystal X-Ray Measurements*, Presentation at the special LHC Collimation Upgrade Specification Meeting: Material and design readiness for LS2 productions, CERN, Geneva, Switzerland, 2017, https://indico.cern.ch/event/634704/

[19] R. Rossi, "Experimental Assessment of Crystal Collimation at the Large Hadron Collider," Presented 26 Jan 2018, 2017, https://cds.cern.ch/record/2644175

[20] A. Mereghetti *et al.*, "Sixtrack-FLUKA active coupling for the upgrade of the SPS scrapers," *Proceedings of the International Particle Accelerator Conference 2013, Shanghai, China*, p. 2657, 2013.

[21] P. Hermes *et al.*, "Simulation of Heavy-Ion Beam Losses with the SixTrack-FLUKA Active Coupling," *Proceedings of the International Particle Accelerator Conference 2016, Busan, Korea*, 2016, http://accelconf.web.cern.ch/AccelConf/ipac2016/papers/wepmw029.pdf

[22] *ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators: CERN, Geneva, Switzerland 30 Oct 2015. ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators*, CERN, 2018, doi:10.23732/CYRCP-2018-002

[23] P. Hermes, "Heavy-Ion Collimation at the Large Hadron Collider : Simulations and Measurements," Ph.D. dissertation, University of Munster, 2016.

[24] *Sixtrack web site*, http://sixtrack.web.cern.ch/SixTrack/.

[25] https://fluka.cern.

[26] G. Battistoni *et al.*, "Overview of the FLUKA code," *Annals Nucl. Energy*, vol. 82, pp. 10–18, 2015, doi:10.1016/j.anucene.2014.11.007

[27] C. Ahdida *et al.*, "New capabilities of the FLUKA multi-purpose code," *Frontiers in Physics*, vol. 9, 2022, doi:10.3389/fphy.2021.788253

[28] S. Roesler, R. Engel, and J. Ranft, "The Monte Carlo Event Generator DPMJET-III," *Proceedings of the Monte Carlo 2000 Conference, Lisbon, October 23-26 2000, Springer-Verlag Berlin*, pp. 1033–1038, 2001.

[29] P. Schoofs, "Monte Carlo Modeling of Crystal Channeling at High Energies," Presented 18 Mar 2014, Ph.D. dissertation, EPFL Lausanne, 2014, https://cds.cern.ch/record/1950908

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK018

[30] P. Schoofs, F. Cerutti, A. Ferrari, and G. Smirnov, "Monte carlo modeling of crystal channeling at high energies," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 309, pp. 115–119, 2013, The 5th International Conference "Channeling 2012", "Charged & Neutral Particles Channeling Phenomena" September 23-28,2012, Alghero (Sardinia), Italy, doi:https://doi.org/10.1016/j.nimb.2013.02.027

[31] P. Schoofs, F. Cerutti, A. Ferrari, and G. Smirnov, "Benchmark of the FLUKA model of crystal channeling against the ua9-h8 experiment," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 355, pp. 374–377, 2015, Proceedings of the 6th International Conference Channeling 2014:"Charged & Neutral Particles Channeling Phenomena" October 5-10, 2014, Capri, Italy, doi:https://doi.org/10.1016/j.nimb.2015.03.074

[32] M. D'Andrea, "Applications of crystal collimation to the cern large hadron collider (lhc) and its high luminosity upgrade project (hl-lhc)," PhD, 2021, http://cds.cern.ch/record/2758839

[33] D. Mirarchi, S. Redaelli, and W. Scandale, "Crystal implementation in SixTrack for proton beams," *CERN Yellow Reports: Conference Proceedings*, 18 p, 2018, doi:10.23732/CYRCP-2018-002.91

[34] D. Mirarchi, G. Hall, S. Redaelli, and W. Scandale, "A crystal routine for collimation studies in circular proton accelerators," *Nucl. Instrum. Methods Phys. Res., B*, vol. 355, 378–382. 5 p, 2015, doi:10.1016/j.nimb.2015.03.026

[35] W. Scandale *et al.*, "Study of inelastic nuclear interactions of 400 GeV/c protons in bent silicon crystals for beam steering purposes," *Eur. Phys. J. C*, vol. 78, 505. 8 p, 2018, doi:10.1140/epjc/s10052-018-5985-8

[36] W. Scandale *et al.*, "Observation of strong leakage reduction in crystal assisted collimation of the SPS beam," *Phys. Lett. B*, vol. 748, 451–454. 4 p, 2015, doi:10.1016/j.physletb.2015.07.040

[37] W. Scandale *et al.*, "Observation of channeling for 6500 GeV/ c protons in the crystal assisted collimation setup for LHC," *Phys. Lett. B*, vol. 758, 129–133. 5 p, 2016, doi:10.1016/j.physletb.2016.05.004

[38] D. Mirarchi *et al.*, "Reducing Beam-Related Background on Forward Physics Detectors Using Crystal Collimation at the Large Hadron Collider," *Phys. Rev. Applied*, vol. 14, 064066. 20 p, 2020, doi:10.1103/PhysRevApplied.14.064066

[39] M. D'Andrea *et al.*, "Operational Aspects of Crystal Collimation with Proton Beams," 2019, https://cds.cern.ch/record/2678780

[40] E. Holzer *et al.*, "Beam Loss Monitoring System for the LHC," *IEEE Nuclear Science Symposium Conference Record*, vol. 2, p. 1052, 2005, doi:10.1109/NSSMIC.2005.1596433

[41] E. B. Holzer *et al*, "Development, production and testing of 4500 beam loss monitors," *Proc. of the European Particle Accelerator Conf. 2008, Genoa, Italy*, p. 1134, 2008.

[42] M. D'Andrea *et al.*, "Crystal Collimation Tests with Pb Ion Beams," *CERN-ACC-NOTE-2019-0024*, 2019, https://cds.cern.ch/record/2678781

[43] J. Potoine *et al.*, "Power deposition studies for crystal-based heavy ion collimation in the LHC," *Proceedings of IPAC22, Bangkok, Thailand*, 2022.