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Channeling efficiency reduction in high dose neutron irradiated silicon crystals for high energy and high intensity beam collimation and extraction

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2021 JINST 16 P08015

Abstract: The channeling process in bent silicon crystals are used since '70s to manipulate beams of high energy particles. During the last decade, several studies and experiments carried out by the UA9 Collaboration at CERN demonstrated the possibility to use bent crystals for beam collimation, extraction, focusing and splitting in particle accelerators. These crystals are subject to deterioration due to the interaction of the particles with the crystal lattice, degrading the beam steering performance. For this reason, robustness tests are crucial to estimate their reliability and operational lifetime. A $\sim$ 8% of reduction in channeling efficiency on crystals irradiated with $2.5 \cdot 10^{21}/\mathrm{cm}^2$ thermal neutrons was measured and reported in this manuscript. Extrapolations to possible operational scenarios in high energy accelerators are also discussed.

Keywords: Accelerator Applications; Accelerator Subsystems and Technologies

2021 JINST 16 P08015

Contents

1 Introduction

Coherent interactions of charged particles in bent monocrystalline crystals are used for several beam steering applications such as collimation, extraction, focusing and splitting. The main process used to deflect particles using bent crystals is the channeling one: high-energy charged particles entering in the crystal with small angles with respect to the bent lattice planes can be canalized between two neighboring planes acquiring a deflection which is equal to the geometrical bending of the crystal. Channeling is possible within a critical angle $\theta_c = (2U_o/pv)^{1/2}$ around the lattice plane orientation, where U_o is the depth of the planar potential well, p and v are the particle momentum and velocity [1].

The development of this technology began in the late ′70s and was studied and applied in several accelerator complexes around the world. In particular, in the last decade, the UA9 experiment at CERN (European Organization for Nuclear Research) strongly improved this technology, obtaining very promising results for the LHC (Large Hadron Collider) collimation [2] and the SPS slow extraction [3, 4], beam splitting and focusing [5]. Monocrystalline silicon is widely used for these purposes because of the lattice quality reached nowadays at a relatively low cost. For all these and future applications, such as in the High Luminosity Large Hadron Collider (HL-LHC) and the Future Circular Collider (FCC), it is important to study the crystal robustness during accelerator operations. In fact, high fluxes of high energy particles produce crystal lattice damage that affect the channeling performance. Channeling efficiency can be mainly affected by three different kinds of lattice defects: point-like defects (impurities, interstitials, vacancies), linear dislocations and mosaicity. At high energies, a large number of atoms along the channeling planes are involved in one oscillation of the channeled particle, consequently the point-like defects effect is the least important. Conversely, linear dislocations could decrease the channeling efficiency. Finally, the particle angular dispersion due to mosaicity of monoscrystalline and pure silicon crystals is much smaller than the channeling acceptance angle until tens of TeV, so it does not affect channeling performance in this energy range [6].

Thus, several tests have been performed over time to evaluate their operational life. In 1992, a first study was performed at the U-70 IHEP accelerator where a crystal was irradiated with

2021 JINST 16 P08015

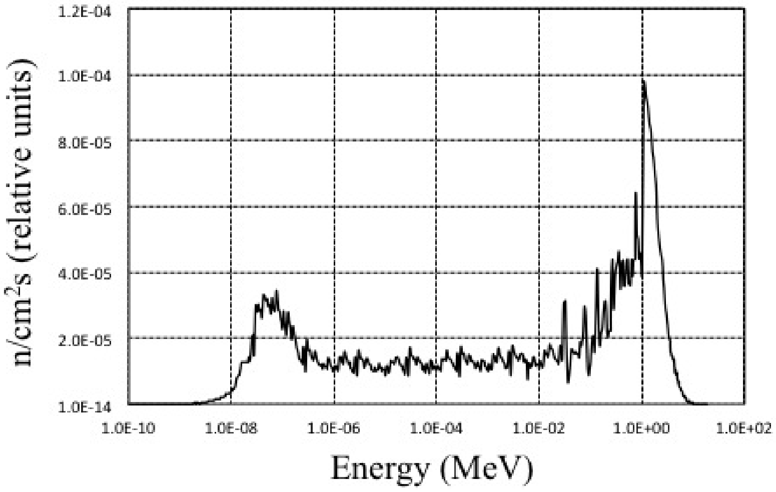

Figure 1. Energy spectrum of neutrons that have irradiated the nine crystal samples at the SCK-CEN BR2 neutron reactor.

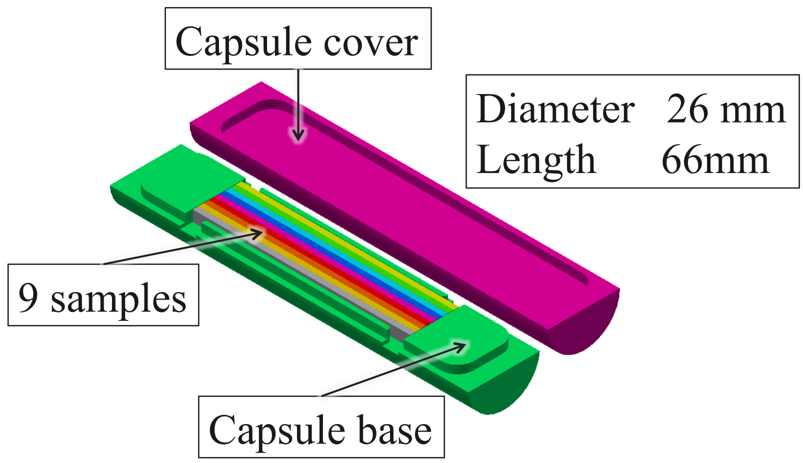

Figure 2. Drawing of the nine silicon crystal samples inserted in the irradiation capsule.

10^{19} protons/cm^2 at 70 GeV/c without showing measurable efficiency degradation [7]. In 1994 at BNL, a tiny reduction in low energy channeling capability for a crystal exposed to $4 \cdot 10^{20}$ protons/cm^2 at 28 GeV/c was observed [8]. In 1996 at CERN, in the context of the NA48 experiment, a crystal irradiated with $2.4 \cdot 10^{20}$ protons/cm^2 at 450 GeV/c showed a decrease in channeling efficiency [9].

With the objective of higher machine luminosity, recent rapid progress in accelerator technology enabled significant improvements in beam intensity. At the same time the crystal technology has assumed an increasingly important role, opening new questions on the crystal robustness. For this reason, UA9 and CERN management, decided to expose nine samples of silicon crystals to $2.5 \cdot 10^{21}$ neutrons/cm^2 with the energy spectrum in figure 1 in the SCK-CEN BR2 reactor in Belgium. A diagram and photograph of the crystal samples and irradiation capsule are shown in figure 2 and figure 3, respectively. Their channeling efficiency before and after the irradiation has been measured and compared.

Figure 3. Photograph of the nine silicon crystal samples wrapped in an aluminum protection foil (in the centre) ready to be closed in the irradiation capsule (up and down).

Table 1. Crystal parameters: dimensions (L_X, L_Y, L_Z), the range of bending angle (θ) and the range of channeling efficiency before irradiation (within $\theta_c/2$).

L_X [mm]	L_Y [mm]	L_Z [mm]	θ [μrad]	Eff. [%]
1.00 ± 0.02	40.0 ± 0.1	2.00 ± 0.02	43–135 ± 1	69–66 ± 2

2 Experimental measurements

These measurements have been performed at the H8 SPS extraction line using 180 GeV/c secondary hadron beam (~ 70% protons and ~ 30% positive pions) and with the following parameters: $\sigma_x \simeq 1.6$ mm, $\sigma_y \simeq 2$ mm, $\sigma_{\theta_x} \simeq 31$ μrad, $\sigma_{\theta_y} \simeq 44$ μrad. The UA9 experimental apparatus used in H8 to measure crystal angle and channeling efficiency is based on a high angular resolution telescope, able to reconstruct incoming and outgoing particle single tracks with respect to the crystal position on a lever arm of 10 m. For 180 GeV/c hadrons this resolution is 12.3 μrad and it is mainly due to multiple scattering in the sensor layers [10, 11]. A very precise angular actuator with a ~ 1 μrad of repeatability is used to orient the crystal in channeling. The nine crystal samples are all identical in terms of material and dimensions, only the bending angle is slightly different to cover the bending angle range used in accelerator operations. Their characteristics are reported in table 1 and have been chosen to be as similar as possible to those of crystals used for LHC and SPS applications [2–4] and following the irradiation capsule constraints at the same time.

Each crystal is bent by an aluminum holder that imparts an anticlastic deformation to it along the (110) plane direction [12], which is identical for all samples (figure 4). The number of dislocations in the silicon used to produce the crystals, therefore before the irradiation with neutrons, is far below

2021 JINST 16 P08015

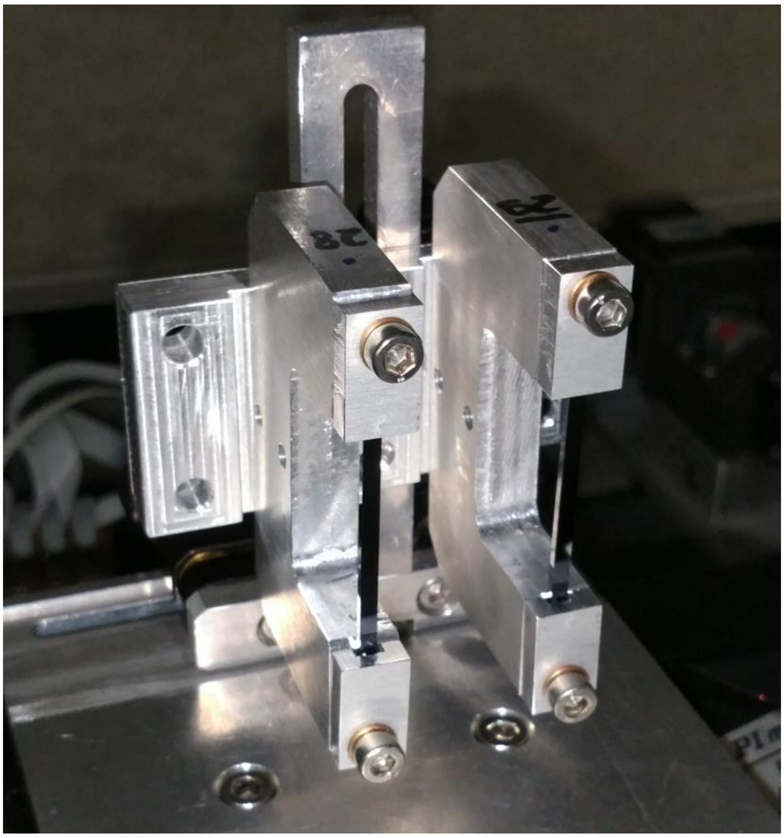

Figure 4. Photograph of two of the nine crystal samples mounted on the bending holder, ready to be tested at the H8 SPS extraction line.

$1/\text{cm}^2$, as certified by the manufacturer and usual for high energy and high intensity accelerator physics applications.

The crystals were first characterised at the H8 line, then were irradiated without the holders, mainly to avoid unrealistic effects on the holder itself. Indeed, it is not irradiated with such high dose during accelerator operations. Finally, they were mounted and bent again before the second characterisation at the H8 line. As a consequence, the bending angle before and after the irradiation is not exactly the same. Anyway, the critical bending radius R_c, above which particles can no longer be trapped between crystalline planes, is ~ 31.6 cm for 180 GeV positive particles channeled along (110) planes in silicon crystals [1]. For both the measurements, before and after the irradiation, the bending radius of the crystals varies between 15.5 m and 46.5 m. Thus, in all cases, the crystals were between 49 and 147 times above the critical radius. In this range the channeling efficiency variation due to the crystal curvature is negligible and within the error bars [6, 13].

The measurements of the channeling efficiency for each sample before and after irradiation are reported in figure 5. The mean efficiency reduction measured is $\sim 8\%$, going from $\sim 67\%$ to $\sim 59\%$ (a relative reduction of $\sim 12\%$). Following a conservative approach, the crystal efficiency has been computed dividing the number of channeled particles by the number of entering ones within $\theta_c/2$. All the measurements have been performed in the same experimental conditions and following the same procedures.

2021 JINST 16 P08015

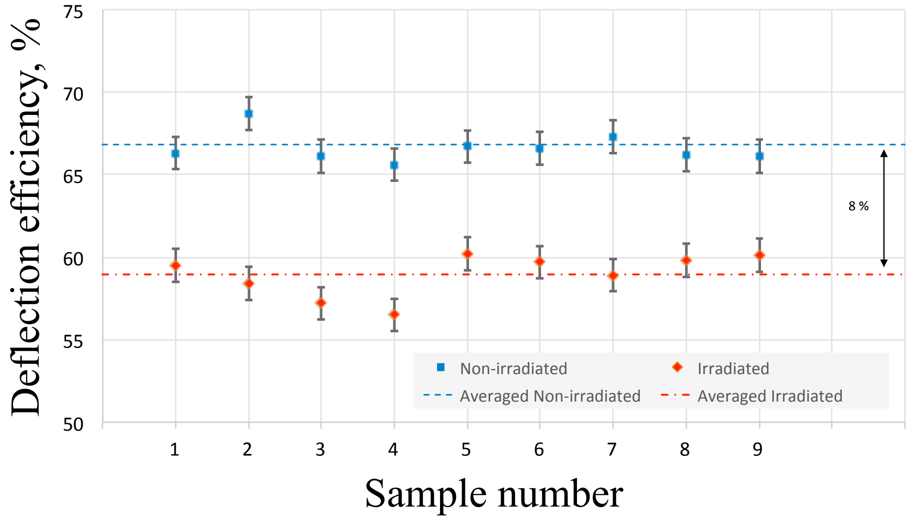

Figure 5. Channeling efficiencies of the nine crystal samples measured using the 180 GeV/c positive hadron beam before (blue square) and after (red diamond) neutron irradiation. The mean efficiency reduction is about ∼ 8%.

3 Extrapolations to irradiation with different particles and energies

To estimate the real crystal robustness in a high-energy proton accelerator, it is important to rescale the effect produced on the crystal by neutrons of the SCK-CEN reactor to the case of protons and heavy ions at different energies. For protons, the two representative energies chosen are 6.5 TeV, the LHC maximum energy, and 400 GeV/c, the SPS extraction energy towards the North Area. For the same reason, fully stripped lead (Pb) nuclei at 6.5Z TeV and 400Z GeV/c, where $Z = 82$ is the ion charge, have been chosen.

The parameter used for this rescaling is the number of Displacements Per Atom (DPA) produced during the irradiation, directly related to the total number of defects (or Frenkel pairs) by the formula:

$$DPA = \frac{1}{\rho}\Sigma_i N_i N_i^F \tag{3.1}$$

where ρ is the atomic density, N_i are the number of particles per interaction channel i, N_i^F the number of Frenkel pairs per channel.

Dislocations, which mainly degrade the channeling efficiency at high energy, are a combination of Frenkel pairs during and after the irradiation, as a consequence of their dynamics in the crystal volume. It is not possible to foreseen in a deterministic way the final status of crystal dislocations after the irradiation, but statistically the same number and distribution of Frenkel pairs will generate the same average density of dislocations in the crystal. This is well demonstrated also by the fact that the nine samples irradiated in the same way show almost exactly the same channeling efficiency reduction (8%).

Using the FLUKA Monte Carlo simulation tool [14, 15] it was possible to compute the number of DPA produced in the crystal by the real neutron energy spectrum, 400 GeV/c protons, 6.5 TeV

Table 2. FLUKA DPA simulations in a silicon crystal sample. From the left: type and energy of primary particles hitting the crystal, number of DPA per primary particle and fluence equivalent to the real neutron irradiation at SCK-CEN.

Part.	E [GeV/c]	DPA [p.p.p.]	ϕ_{eq} [1/cm^2]
n	Spectrum	$5.7 \cdot 10^{-20}$	$2.5 \cdot 10^{21}$
p	400	$5.8 \cdot 10^{-20}$	$2.4 \cdot 10^{21}$
p	$6.5 \cdot 10^3$	$6.2 \cdot 10^{-20}$	$2.3 \cdot 10^{21}$
Pb	$400 \cdot Z$	$4.7 \cdot 10^{-17}$	$3.0 \cdot 10^{18}$
Pb	$6.5 \cdot 10^3 \cdot Z$	$4.8 \cdot 10^{-17}$	$2.9 \cdot 10^{18}$

protons, 400Z GeV/c Pb ions and 6.5Z TeV Pb ions respectively. In this way it is possible to scale the neutron fluence (ϕ) to the equivalent fluence (ϕ_{eq}) for all the different beams steered by the crystal during LHC or SPS operations. The different ϕ_{eq} are reported in table 2.

The Energy Displacement Threshold used in simulations for silicon is 25 eV, but in the literature it varies from 20 eV to 40 eV. This affects the DPA and the ϕ_{eq} estimation by $\sim$ 10%. The statistical error is negligible in comparison.

These extrapolations are based on the two following reasonable assumptions. The first is that the stresses induced by the crystal holder are negligible at this level of bending and thus irradiate an unbent or a bent crystal is equivalent in terms of DPA production and dynamics in the crystal. By simple analytical or finite elements simulations of silicon crystal bent with an anticlastic curvature of 139 µm (the maximum reached in this study) is evident that such stresses are not critical for density variation and mechanical tensions inside the crystal [12]. Nevertheless, crystals were kept bent for several months after irradiation, allowing any defects to evolve under stress before performing the efficiency tests with 180 GeV hadrons.

4 Crystal operational lifetime estimations

To indicate the practical consequences of these results, an estimate of the crystal lifetime for some relevant accelerator applications follows. The ϕ_{eq} can be used to estimate for how many years a crystal can be used, for example, as a primary collimator in the LHC for protons and Pb ions, before reducing its single-pass channeling efficiency by $\sim$ 8%. Defining the crystal lifetime (l) as:

$$l = \frac{\phi_{eq} S}{p_{cry}(1 - \varepsilon_{CH})} \tag{4.1}$$

where p_{cry} is the number of impacting protons on a surface S of the crystal, and $(1 - \varepsilon_{CH})$ is the fraction of protons that are not channeled even after repeated passages through the crystal in a circular machine (i.e. ε_{CH} in the multi-turn channeling efficiency). Here we assume that the protons deflected due to channeling do not cause damage to the crystal lattice.

A uniformly irradiated surface S can be evaluated taking the average impact parameter of 0.3 µm [16] and one beam sigma of about 150 µm [17] in the collimation and transverse planes, respectively, as first approximation. The measured multi-turn channeling efficiency for crystals in the LHC is of $\varepsilon_{CH} \sim 85\%$ [18]. The impacting protons are given by:

$$p_{cry} = \frac{p_{coll}}{2N_{cry}} \tag{4.2}$$

where p_{coll} is the number of protons handled in one year by the collimation system, which is in the range of 1–5 × 10^{15} p/year depending on the LHC working point [19]; $\frac{1}{2}$ is the sharing of the losses between the horizontal and vertical planes [20], while $N_{\text{cry}} = 2$ is the number of crystals per plane. Thus, a reduction of ∼ 8 % in single-pass channeling efficiency is expected after 5.5 to 27.5 years of operations. A similar lifetime is expected if used with 6.5 Z TeV Pb ion beams. The decrease of about a factor 10^3 in ϕ_{eq} is compensated by a factor 10^{-3} in stored beam intensity [21, 22].

Concerning extraction applications, one of the most promising is the use of a bent crystal to shadow the SPS electrostatic septa during the slow extraction by deflecting particles that would impinging on it, thus reducing the losses and increasing the extraction efficiency. This technique has been recently successfully proved at the SPS [23]. An estimation of the crystal lifetime can be simply obtained considering that the number of 400 GeV/c protons extracted from the SPS in 2018 was 1.23 × 10^{19}, that only the 5 % of them would cross the crystal on an impact surface of (0.8 x 0.9) mm^2 [24]. Taking into account a channeling efficiency of 65 %, the crystal loses the ∼ 8% of efficiency in ∼ 82 years.

These estimations have been made under the reasonable and conservative assumption that the channeling efficiency reduction due to irradiation for 180 GeV, 400 GeV and at 6.5 TeV charged particles is the same. For the case of the crystal extraction at 400 GeV, the extrapolation is completely reasonable (only a factor two in energy), for crystal collimation at 6.5 TeV the extrapolation is more delicate, but anyway conservative. In fact, it is true that the dechanneling length due to dislocations (linear defects) scales with $1/E^{1/2}$, but this effect is well compensated by the fact that the nuclear and electronic dechanneling length scales linearly with E. This taking in to account that a loss of 8% of efficiency at 180 GeV, due to defects production under irradiation, suggest a number of dislocations in the crystal no so high, of the order of 1/cm^2. Moreover, the influence on dechenneling of all the other kind of defects (point like, two dimensional, three dimensional, etc. . .) vanishes at high energy [6].

5 Conclusions

Concluding, a detailed study of bent silicon crystal robustness up to 2.5·10^{21} thermal neutron irradiation has been carried out, showing a reduction in the channeling efficiency of ∼ 8%. This is a new and important proof of their reliability also for application in high intensity machine such as SPS, LHC, HL-LHC and eventually FCC.

Recently, further tests to evaluate the robustness of silicon crystals in case of accidental fast irradiation during machine operations have been performed by UA9 at the CERN HiRadMat facility [25–27]. These crystals are of the same type used for LHC collimation and SPS extraction and they have been irradiated, bent by the same holder used for accelerator operations, with the same proton beam extracted from the SPS or used to fill the LHC (2.5 × 10^{13} 440 GeV/c protons, with a pulse length of 7.2 µs.). The experimental results show no evident changes in beam steering performance after the irradiation, strengthening the conclusions reported here. The same HiRadMat test on the irradiated samples studied in this manuscript is scheduled. It will provide a robustness test in case of accidental fast irradiation at the end of their operational lifetime. Then, a deeper investigation to evaluate the atomic structure damages after irradiation, for example using the RBS technique, are planned. The ultimate reliability test, already in progress, will be the performance study, at different energies, of high dose proton irradiated silicon crystals.

Acknowledgments

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References

[1] V.M. Biryukov, V.I. Kotov and Y.A. Chesnokov, *Steering of high-energy charged particle beams by bent single crystals*, *Phys. Usp.* **37** (1994) 937.

[2] W. Scandale et al., *Observation of channeling for 6500 GeV/ c protons in the crystal assisted collimation setup for LHC*, *Phys. Lett. B* **758** (2016) 129.

[3] W. Scandale, A.D. Kovalenko and A.M. Taratin, *Possibility of high efficient beam extraction from the CERN SPS with a bent crystal. Simulation results*, *Nucl. Instrum. Meth. A* **848** (2017) 166.

[4] M.A. Fraser et al., *Experimental results of crystal-assisted slow extraction at the SPS*, in *Proceeddings of the 8th International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 623–626 [arXiv:1707.05151].

[5] W. Scandale et al., *Observation of focusing of 400 GeV/c proton beam with the help of bent crystals*, *Phys. Lett. B* **733** (2014) 366

[6] V.M. Biryukov, Y.A. Chesnokov and V.I. Kotov, *Crystal channeling and its application at high-energy accelerators*, Springer Science & Business Media (2013).

[7] Y.A. Chesnokov et al., *Results on studying 70-GeV proton beam focusing by bent crystal*, in *Proceedings of the XV International Conference on High Energy Accelerators*, Hamburg, Germany, 20–24 July 1992, pp. 128–130.

[8] S.I. Baker, R.A. Carrigan, Jr., V.R. Cupps, II, J.S. Förster, W.M. Gibson and C.-R. Sun, *Effects on Channeling of Radiation Damage due to 28-GeV Protons*, *Nucl. Instrum. Meth. B* **90** (1994) 119.

[9] A. Baurichter et al., *Channeling of high-energy particles in bent crystals: Experiments at the CERN SPS*, *Nucl. Instrum. Meth. B* **164-165** (2000) 27.

[10] M. Pesaresi, W. Ferguson, J. Fulcher, G. Hall, M. Raymond, M. Ryan et al., *Design and performance of a high rate, high angular resolution beam telescope used for crystal channeling studies*, 2011 *JINST* **6** P04006.

[11] K. Uchida et al., *Results from the CBC3 readout ASIC for CMS 2S-modules*, *Nucl. Instrum. Meth. A* **924** (2019) 175.

[12] A.G. Afonin, V.M. Biryukov, V.A. Gavrilushkin, V.N. Gres', B.A. Zelenov, V.I. Kotov et al., *First results of experiments on high-efficiency single-crystal extraction of protons from the u-70 accelerator*, *J. Exp. Theor. Phys. Lett.* **67** (1998) 781.

[13] E. Bagli, L. Bandiera, V. Guidi, A. Mazzolari, D. De Salvador, A. Berra et al., *Steering efficiency of a ultrarelativistic proton beam in a thin bent crystal*, *Eur. Phys. J. C* **74** (2014) 2740 [arXiv:1311.4674].

[14] T.T. Böhlen, F. Cerutti, M.P.W. Chin, A. Fassò, A. Ferrari, P.G. Ortega et al., *The FLUKA Code: Developments and Challenges for High Energy and Medical Applications*, *Nucl. Data Sheets* **120** (2014) 211.

[15] A. Ferrari et al., *Fluka: A multi-particle transport code*, Tech. Rep., CERN Yellow Reports: Monographs, CERN, Geneva, Switzerland (2005) [DOI: https://doi.org/10.5170/CERN-2005-010].

[16] G. Valentino, R. Assmann, R. Bruce, F. Burkart, S. Redaelli, B. Salvachua et al., *Beam Diffusion Measurements Using Collimator Scans in the LHC*, *Phys. Rev. ST Accel. Beams* **16** (2013) 021003.

[17] D. Mirarchi, G. Hall, S. Redaelli and W. Scandale, *Design and implementation of a crystal collimation test stand at the Large Hadron Collider*, *Eur. Phys. J. C* **77** (2017) 424.

[18] R. Rossi, *Experimental Assessment of Crystal Collimation at the Large Hadron Collider*, Ph.D. thesis, INFN & University Roma I, CERN-THESIS-2017-424, 2019.

[19] O. Stein et al., *Run 2 prompt dose distribution and evolution at the large hadron collider and implications for future accelerator operation*, in *Proceedings of the International Particle Accelerator Conference*, Melbourne, Australia, 19-24 May 2019, pp. 4013–4015.

[20] B. Salvachua et al., *Decomposition of beam losses at LHC*, in *Proceedings of the International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 88–91.

[21] B. Salvachua, *Overview of proton runs during run 2*, in *Proceedings of the LHC Beam Operations Workshop*, Evian Les Bains, France, 30 January–1 February 2019, pp. 7–14.

[22] J. Jowett, *Overview of ion runs during run 2*, in *Proceedings of the LHC Beam Operations Workshop*, Evian Les Bains, France, 30 January–1 February 2019, pp. 15–25.

[23] F. Velotti et al., *Reduction of resonant slow extraction losses with shadowing of septum wires by a bent crystal*, in *Proceedings of the International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 631–634.

[24] M.A. Fraser et al., *Demonstration of loss reduction using a thin bent crystal to shadow an electrostatic septum during resonant slow extraction*, in *Proceedings of the International Particle Accelerator Conference*, Melbourne, Australia, 19–24 May 2019, pp. 3399–3403.

[25] F. Harden, A. Bouvard, N. Charitonidis and Y. Kadi, *HiRadMat: A facility beyond the realms of materials testing*, *J. Phys. Conf. Ser.* **1350** (2019) 012162.

[26] A. Lechner, *Robustness Test of a Silicon Strip Crystal for Crystal-Assisted Collimation Studies in the LHC*, *Conf. Proc.* **C130512** (2013) THPFI059.

[27] W. Scandale et al., *Beam steering performance of bent silicon crystals irradiated with high-intensity and high-energy protons*, *Eur. Phys. J. C* **79** (2019) 933.

2021 JINST 16 P08015