CRYSTAL-ASSISTED COLLIMATION EXPERIMENT FROM THE SPS TO THE LHC*

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Abstract

UA9 was operated in the CERN-SPS for more than six years in view of investigating halo collimation assisted by bent crystals. Silicon crystals 2 mm long, with bending angles of about 150 μrad, are used as primary collimators. The crystal collimation process is obtained through channeling with high efficiency, showing a steady reduction of almost one order of magnitude of the loss rate at the onset of the channeling process. This result holds both for protons and for lead-ions. The corresponding loss map in the accelerator ring is accordingly reduced. These observations strongly support the expectation of UA9 Collaboration that the coherent deflection of the beam halo by a bent crystal should enhance the collimation efficiency also in LHC. After a concise description of some results collected in the SPS which are useful to the LHC scenario, ongoing simulations strictly linked to the design of the crystals insertion in the LHC [4] are discussed.

INTRODUCTION

In the last six years of SPS runs, the UA9 Collaboration achieved a good understanding and control on the properties of a minimal collimation system based on a bent crystal as primary deflector and a massive absorber intercepting the channeled and extracted halo. Tests performed at 120 GeV and 270 GeV, with various machine conditions (unbunched, single bunch, multi-bunches with 50 and 25 ns spacing), are reported in [1, 2]. The UA9 setup in the SPS is described in [3]. The present goal is to test crystal collimation in LHC, using the layout in [4] that should allow performance similar to those obtained in the SPS. Hereafter, we shortly discuss the criteria on which the crystal-collimation layout is based, the simulations to predict its performance and their validation strategy and the evaluation of loss maps that represent the key observable for the collimation quality.

SYSTEM LAYOUT AND CHANNELING STABILITY

Ideal conditions for crystal collimation in the horizontal plane, require $\beta'_x \sim 0$ and $D_x \sim 0$ at the crystal location and a phase advance of $\Delta\phi \sim \frac{\pi}{2}$ between the crystal and the absorber. The above conditions imply, respectively: angular alignment of the crystal independent from the distance of the channeled halo particles from the beam centre, impact parameter on the crystal independent from the Δp/p of the halo particles, highest displacement of the deflected halo on the secondary collimator. Implementing them approximately in the SPS layout of UA9 leaded to very positive results, in which the crystal orientation for the maximal halo extraction was very reproducible at all energies. The possible operational use of crystal collimation in the LHC requires an optimal halo extraction for different machine configurations (injection, ramp, squeeze, etc) even if the layout is not ideal and in particular if the crystal is installed in a location with $\beta' \neq 0$, as proposed in [4]. We could test in UA9 the consequences of having $\beta' \neq 0$ by performing various angular scans with the crystal at different amplitude from the SPS beam centre. The result is shown in Fig. 1, where the theoretical beam divergence x' is plotted as a function of the crystal distance from the beam centre x (blue), together with the trend of the angular orientation of the crystal to achieve the extraction mode (red). The optimal crystal orientation follows very closely the inclination of the emittance ellipses of the halo particle intercepting the crystal. The error bars of the blue and red dots reflect the known imperfection of the crystal orientation mechanism.

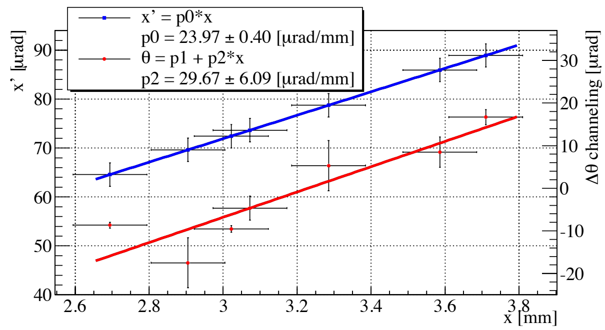

Figure 1: Theoretical beam divergence (left scale, blue line) as a function of the crystal distance from the closed orbit (x), and measured channeling orientation from a reference angle (right scale, red line).

ONGOING SIMULATIONS

In order to benchmark the simulations for LHC, tracking studies are ongoing in view of reproducing the results of the SPS tests. They are based on an extended version of the SixTrack code that contains a routine reproducing the different interactions in a bent crystal [5]. The ultimate goal is to reproduce the loss pattern seen in the SPS for different crystal orientations and beam conditions. Such a result is still in progress and will be widely discussed in one of the next UA9 publication (in preparation).

An important result already achieved is the estimate of the spot-size of the channeled and extracted halo and its

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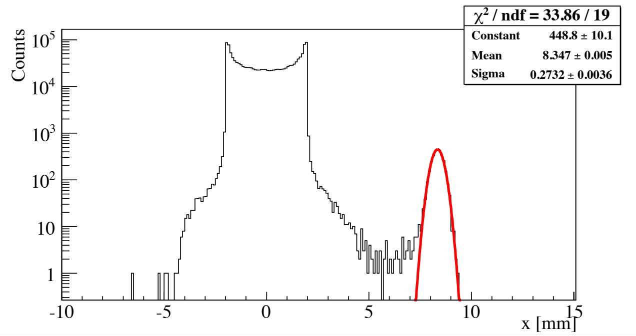

Figure 2: Simulated particles distribution at the Medipix location: beam core around 0, channeled and extracted beam around 8.4mm.

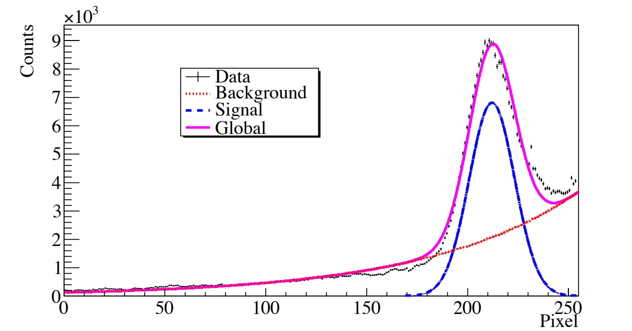

Figure 3: Horizontal projection of the experimental spot of the channeled and extracted beam, seen by the Medipix.

validation with the SPS data. This is a key information that should be used at a later stage to compute the energy deposition on the massive absorber and to predict safe beam conditions for its integrity during the LHC test.

In practice, SixTrack simulations have been carried out on the SPS optical model that includes the UA9 layout. A “screen” has been placed at the location of the first Roman Pot equipped with Medipix detectors [3], then parametric studies have been performed and the simulated distribution of the extracted halo has been compared with the experimental data. The parametric studies consisted in the variation of the generated halo, in order to change the impacting distribution on the crystal from an average impact parameter of $\sim$10μm, up to $\sim$150μm. This allowed us to evaluate the number of crystalline planes used in the extraction process. The main result of these studies is that the dimension and the divergence of the channeled and extracted beam is essentially independent from the portion of crystal that intercepts the halo particles. The simulated distribution of the extracted halo at the Medipix ”screen” does not change by varying the number of crystalline planes used and fits well the experimental distribution seen by the Medipix itself. The extracted halo spot-size can be thus calculated using only optics considerations. SPS simulations have been made only in the horizontal plane. An example of the simulated particles distribution at the Medipix location is shown in Fig. 2. The extracted beam has been fitted with a gaussian. Using the theoretical equation reported in [4], the expected mean is of 8.4 mm. Taking into account the spread due to the critical channeling angle the minimum and maximum displacement of the extracted particles are 8.1 mm and 8.8 mm respectively, giving a width of the spot of $\sim$700μm. In Fig. 3 the horizontal projection of the experimental spot seen by the Medipix is shown. The spot due to the channeled particles has been fitted with a gaussian, while the background due to the interaction of the circulating particles with the Roman Pot border and the dead layer of Medipix is fitted with an exponential function. The gaussian fit gives a width of the extracted beam of $\sim$12 pixels, i.e. of 12x55 μm = 600 μm, in excellent agreement with the simulation result.

LOSS MAPS

In the UA9, the measurement of the loss rate during the experimental tests is based on various detectors. Close to the UA9 devices that interact with the beam, the detectors are mainly plastic scintillators and ionisation chambers specifically designed for the LHC Beam Loss Monitor (BLM) system. In the rest of the SPS ring, the detection of the loss rate relies on the original SPS BLM system [3]. During the years, the number the detectors has been largely increased and their position optimized. In particular, detectors have been added at increasing distances from the region were the crystal are installed. One of the most effective upgrades has been the installation of supplementary detectors in the first dispersion suppressor downstream the experimental installation. This area is critical because of the high value assumed by the dispersion function. Particles that have lost momentum during the interaction with the collimation system (i.e. off-momentum particles) are subjected to a large lateral displacement and are likely to be lost in this region. According to theoretical considerations, the crystal-based collimation system should reduce the probability of producing off-momentum particles with respect to a system based on amorphous primary deflectors. Hence, the measurement of the loss rate in the dispersion suppressor provides an important characterization of the crystal-based collimation system.

An example of the loss rate measured by the BLM closer to the crystal is shown in Fig. 4. During the measurement, the crystal was slowly rotated. The loss rate is reported in the plot as a function of the orientation of the crystal, in order to show its variation due to the onset of different type of interactions in the crystals. In the intervals between 1700 μrad and 1900 μrad and between 2400 μrad and 2600 μrad the crystal is in ”amorphous” orientation (AM in the plot), meaning that the crystalline planes are not parallel to the impinging particles. These regions are characterized by flat tops in the loss rate profile. A dip centered at about 2050 μrad corresponds to a good alignment of the crystalline planes with respect to incoming particles. In this condition, the ”channeling” interaction (CH in the plot) is dominant. Finally, from 2150 μrad to 2300 μrad, a plateau

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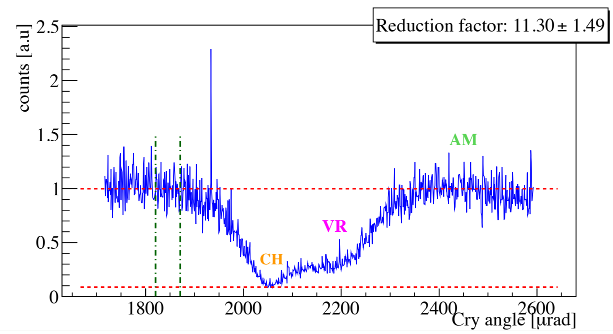

Figure 4: Example of the losses seen by the BLM close to the crystal during an angular scan.

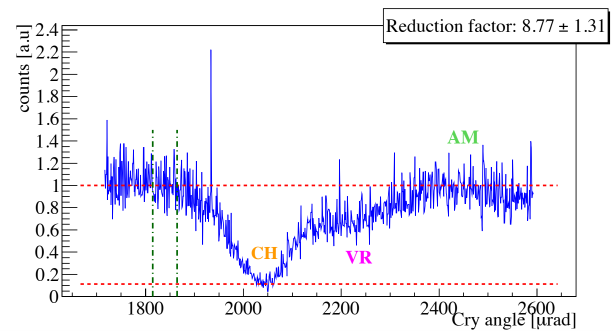

Figure 5: Example of the losses seen by the BLM in the high dispersive area during an angular scan.

with reduced loss rate is observed due to the "volume reflection" interaction. For this orientation, the trajectory of the particles traversing the volume of the crystal eventually became tangent to the bent crystalline planes. When this happens, the particle is reflected by the planes. Analyzing this plot, a "reduction factor" can be defined by considering the ratio between the loss rate in amorphous and in channeling orientation. This number allows to estimate the reduced cross section for inelastic interactions in the crystal correctly oriented. The loss rate measured by the BLM in the dispersion suppressor during the same angular scan is shown in Fig. 5. The shape of the two plots is extremely well correlated. This repeated observation demonstrates experimentally that the loss rate due to off-momentum particles is reduced when using a crystalline primary deflector with respect to an amorphous primary deflector of the same length and material. Preliminary simulated results indicate that a similar reduction holds also when using a standard LHC collimator as primary deflector. Furthermore, the same observation should be valid for a crystal-assisted collimation system installed in the LHC. More details are reported in [4].

During the last year of data taking, the loss rate profile for different crystal orientation has been observed along the whole SPS ring and a complete set of results will be published soon. In order to register a significant loss rate in the entire SPS BLM system, a very high circulating in-

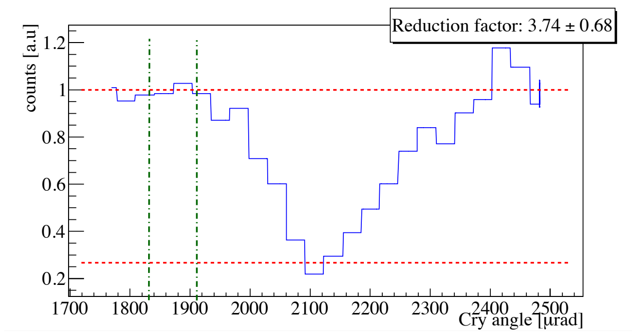

Figure 6: Example of the losses seen by an SPS-BLM in the sextant 4 (BLM 420), during an angular scan with a crystal placed in the sextant 5.

tensity was used (3.3×10^{13} particles distributed in 288 bunches). An example of the loss rate registered by one of the BLM in a region far from the UA9 installation is shown in Fig. 6. Also in this case the loss rate is reported as a function of the crystal orientation and a clear reduction of the signal is visible for the orientation that allows for the channeling interaction. Numerical simulations of a crystal-assisted collimation system operated in the LHC predict similar results, as discussed in [4]. It should be noted, however, that the loss rate reduction measured by UA9 in SPS (and extrapolated to LHC) is based on a collimation system composed of a single primary deflector and a single secondary absorber. The loss rate reduction when using a crystal-assisted collimation system based on the full LHC secondary collimation chain may be less keen.

CONCLUSIONS

The expertise acquired in the UA9 framework has been of an invaluable help in defining the first crystal assisted collimation tests for LHC. The UA9 layout has bees extended to LHC, just by taking into account and re-using as much as possible the specific features of the LHC collimation system. Simulation tools have been validated with the experimental results of UA9. Finally, specific hot point, such as the energy deposition in the secondary collimators and the beam loss distribution far from the collimation area should be better predicted and mastered thank to the informations gathered in the SPS.

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