One primary collimator with optional crystal feature, tested with beam

EuCARD, Collaboration (EuCARD)

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Abstract:

The WP8 of EuCARD aims at the design of more advanced materials and collimator concepts for high beam power in particle accelerators like LHC and FAIR. Deliverable 8.3.1 concerned the production and the validation by beam tests of an advanced collimator prototype to improve various aspects of the LHC collimation system, such as the accuracy of the collimator jaw alignment to the circulating beam, the duration of collimator setup time and the overall halo cleaning performance. A collimator prototype was built and installed in the SPS for beam tests in the running period between 2010 and 2012. Crystal collimation aspects were dealt with in a dedicated SPS experiment, which also profited from EuCARD contributions.
ONE PRIMARY COLLIMATOR WITH OPTIONAL CRYSTAL FEATURE, TESTED WITH BEAM

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1. EXECUTIVE SUMMARY

A collimator prototype with embedded beam position monitors (BPMs) was built and installed in the SPS for detailed beam tests performed over several machine studies between 2010 and 2012, with coasting beams representative of the LHC conditions. The beam tests provided a crucial validation of this design concept. The results of the SPS collimator experiments were published at the international HB2012 workshop in September 2012. Following the excellent results achieved, which fully validated the design concept, it was decided to adopt this BPM-design for an upgrade of the LHC collimation system that will be implemented during the long shutdown in 2013-2014. In total, 18 collimators will be replaced by the new design.

This prototype did not include crystal collimation features as it was decided to address this topic by dedicated SPS beam tests within the UA9 collaboration, using a crystal collimation apparatus that has been operational since 2009. EuCARD contributed to UA9 with funds for personnel and for the construction of a goniometer. The possibility to test crystal channeling at the LHC is presently under investigation as an outcome of the promising SPS results.

2. INTRODUCTION

Handling large stored energies in the LHC superconducting environment requires a powerful and complex collimation system that consists of about 100 movable collimators installed along the 27 km long LHC ring and its transfer lines. The first years of beam operation with high beam intensities have shown that the collimation system might limit the LHC performance in various ways. One of the main concerns is the cleaning efficiency of beam halo particles with superconducting magnets operating closer to their ultimate currents. On the other hand, other aspects such as the operational flexibility to change machine configurations and the accuracy of collimator setup are also important to maximize the time available for physics production and the peak luminosity performance. The collimation setup time was always considered a concern for a large and distributed LHC collimation system.

EuCARD addressed several of these issues as part of the WP8 study. A proposed solution to improve the collimation setup time relies on a collimator design that integrates beam position monitors (BPMs) into the movable collimator jaws. Four BPM buttons allow measuring the beam position at the upstream and downstream collimator jaw locations and the tilt angle of the jaws with respect to the beam orbit along the collimator. One can rapidly and precisely centre the collimator on the local beam orbit by equalizing the signal of the BPMs. This method provides a non-invasive and loss-free setup, as opposed to standard methods that rely on intercepting the beam halo with the bulk jaw material and measuring beam losses. Such an innovative concept called however for thorough beam testing before large scale deployment at the LHC.

The construction of a collimator prototype and the testing with beam at the SPS was carried out within the WP8 mandate. This provided the required validation for this new collimator design and laid the foundation on an important collimation system upgrade. Even though the BPM collimator concept can be applied to any collimator type (primary, secondary, tertiary collimators), it has been decided to first use this feature for tertiary collimators that protect the LHC experimental insertions, where the machine configuration is often changed to fulfil the experiment requirements and where it is more important to tightly control the orbit.
3. VALIDATION BY BEAM TEST OF PROPOSED DESIGN

EXPERIMENTAL VERIFICATION FOR A COLLIMATOR WITH IN-JAW BEAM POSITION MONITORS


Abstract

At present the beam based alignment of the LHC collimators is performed by touching the beam halo with the two jaws of each device. This method requires dedicated fills at low intensities that are done infrequently because the procedure is time consuming. This limits the operational flexibility in particular in the case of changes of optics and orbit configuration in the experimental regions. The system performance relies on the machine reproducibility and regular loss maps to validate the settings. To overcome these limitations and to allow a continuous monitoring of the beam position at the collimators, a design with in-jaw beam position monitors was proposed and successfully tested with a mock-up collimator in the CERN-SPS. Extensive beam experiments allowed to determine the achievable accuracy of the jaw alignment for single and multi-turn operation. In this paper the results of these experiments are discussed. The measured alignment accuracy is compared to the accuracies achieved with the present collimators in the LHC.

INTRODUCTION

To intercept unavoidable losses of particles from the beam halo into the superconducting magnets the LHC has a powerful collimation system with 44 moveable collimators per beam [1, 2, 3]. The beam-based alignment of the LHC collimators is performed by touching the beam halo with the two jaws of each device and recording beam losses with the beam loss monitor (BLM) installed at the device [4]. This requires dedicated fills at low intensities that are done infrequently because the procedure is time consuming [5]. The introduction of a semi-automatic set-up procedure and constant improvements in the algorithms allowed to significantly reduce the set-up time in 2011 and 2012 compared to the first manual set-up in 2010 [6, 7]. To guarantee the validity of the set-up and therefore a sufficient cleaning, strict requirements for long term orbit stability have to be fulfilled.

To overcome these limitations a new collimator design with in-jaw beam position monitors was proposed and preliminary beam tests were successfully carried out with a mock-up collimator in the CERN-SPS [8, 9]. A sketch of the mock-up jaw with the BPM buttons in the beginning (upstream) and end (downstream) of the jaw is depicted in

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Figure 1: A view of a single jaw and cross-sections of the mock-up collimator with in-jaw BPM buttons [10].

Figure 2: View of the BPM button in the taper at the beginning of the jaw during laboratory measurement of the button position [9].

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Figure 1. Figure 2 shows one BPM button in the upstream taper of the jaw during laboratory measurements. A BPM-based alignment, where it is not necessary to touch the beam with the collimator jaws, would allow a fast and non-destructive beam-based collimator set-up, which would reduce the need for special fills with intensity constraints. In addition it would allow to continuously monitor the beam offsets in the collimators with a much better resolution than currently possible with the standard LHC BPMs, as the distance between buttons and beam would be much smaller and there would be no need for interpolating the orbit from the closest BPMs. The collimators could follow orbit drifts without overhead and give, therefore, more flexibility for local orbit changes, which are regularly required around the experimental insertions. Furthermore, the margins between collimator families could possibly be reduced, which would eventually allow smaller beam sizes at the experimental IPs, which means an increased luminosity.

Because of the promising results of the first beam tests in the SPS, presented in [8], an advanced mechanical design and a production prototype have been developed at CERN [11]. The first collimators with in-jaw beam position monitors will be installed in the period 2013-2014, when the LHC will not be operating because of upgrades and maintenance, into the experimental regions starting
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Figure 3: Simulation conditions for beam sweeps along the X axis for different jaw distances.

with ATLAS and CMS. These will replace the current tertiary collimators (TCTs). In addition the two secondary collimators (one per beam) installed in the dump region (IR6) will be replaced by collimators with jaw-integrated BPM buttons. Later also the TCTs around ALICE and LHCb will be replaced.

RESPONSE OF IN-JAW BPM BUTTONS

The CST Particle Studio Suite has been successfully used to simulate BPMs embedded into collimator jaws. Through EM simulation the jaw BPMs were characterized and studied for non-linearities of horizontal beam position dependence to the distance between jaws [10]. The particle beam was modelled by a single Gaussian-type bunch ($\sigma = 75$ mm) of $1.7 \times 10^{-16}$ C, corresponding to the nominal intensity of a LHC bunch ($1.1 \times 10^{11}$ p). The collimator model, shown in Figure 1, consists of two copper jaw blocks (84 mm x 1194 mm). The 50 mm homogeneous extrusions at both ends are needed to guarantee a smooth transition to the beam pipe. Graphite ($\rho = 13 \mu$m) was used as insert material on the jaw surfaces facing the beam. The four stainless steel (316L) pick-up buttons (diameter 10.3 mm), were placed at the jaw extremities 10 mm below the graphite surface [9]. The sensitivity of the embedded BPM signals was studied by simulating beam position sweeps in the hor. and ver. planes for several jaw distances and bunch lengths. For each jaw distance a set of 5 beam locations on the x axis was simulated (see Figure 3). All simulated beam positions were normalized to the button distance.

A slope parameter was introduced, which is a linear conversion coefficient between measured ($x_{meas}$) and actual simulated beam position ($x_{act}$) and is calculated as:

$$slope = \frac{x_{meas}}{x_{act}}$$

This quantity defines the mapping between the actual beam position and the measured position obtained from the BPM signals. Its values, calculated during the horizontal beam sweep simulations, are plotted in Figure 4. It can be seen that the slope value changes little for small button distances. However, even for the extreme case of the fully open jaws, the changes are $\leq 30$ %.

The horizontal correction factor is non-linear with respect to the jaw gap, but the behaviour of real collimator BPM signals for various jaw gaps can be predicted through simulation. This leads to the conclusion, that the horizontal non-linearity correction factor - in the form of a cross-term polynomial - for the whole jaw motion range can be derived from slope values for several jaw gaps by building an inverse fit to the slope surface shown in Figure 4.

The simulation results were confirmed with corresponding beam measurements performed with the mock-up collimator installed in the CERN-SPS. Despite the presence of several imperfections in the experiment’s conditions, a good agreement between simulation and measurement is observed (see Figure 5).

RESULTS OF BEAM MEASUREMENTS WITH MULTI-TURN BPM ELECTRONICS

The experiments with the mock-up collimator were performed in the CERN-SPS with stored beam at 120 GeV. The beam intensities were usually just below $1 \times 10^{11}$ protons, stored in one bunch. During the measurements presented below, the in-jaw BPMs were connected to the prototype of a high resolution diode-based orbit measurement system, which was developed at CERN for this application. This system is optimized for multi-turn applications. From measurements with BPMs installed in the LHC the achievable resolution with this system was estimated to be well below 1 $\mu$m [12].

Measurements with Primary and Secondary Protons Impacting on the Jaw

One major possible obstacle for the use of collimators with jaw-integrated BPM buttons could be a disturbance of the BPM signals due to particles impacting on the jaw.
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Figure 6: Beam offset measured with the upstream (blue) and downstream (red) BPMs in the mock-up collimator versus the gap of an upstream SPS collimator. The sharp increase of the BPM signal variation for smaller SPS collimator gaps is due to non-linearities in the BPM electronics at low beam intensities. The major part of the beam was already scattered away at that time.

Therefore several full beam scramplings with the maximum jaw movement speed of \(2 \text{ mm/s}\) have been performed with the mock-up collimator. No disturbances of the BPM signals by primary protons impacting on the jaws have been observed with beam intensities up to \(\sim 1.15 \times 10^{11}\) protons, i.e. a nominal LHC bunch. The BPM buttons, positioned in the taper at the beginning and end of the jaws, are retracted by 10.6 mm with respect to the jaw surface. From the above results this retraction seems to be sufficient to avoid the impact of protons in the buttons.

To measure the possible impact of secondary protons on the BPM signals, an upstream SPS collimator was used to scrape the beam. The created secondary halo was then intercepted by the mock-up collimator, which was kept at a constant gap of 21 mm. Figure 6 shows the beam offset in the BPM mock-up measured with the upstream (blue) and downstream (red) BPM button pairs versus the gap of the upstream SPS collimator. Up to a SPS collimator gap of 3.5 mm the variation in the BPM signal was \(\leq 35 \mu\text{m}\) which is below the expected accuracy of the experimental setup (\(\sim 50 \mu\text{m}\)). The sharp increase of the variation for smaller SPS collimator gaps is due to non-linearities in the BPM electronics at low beam intensities. The major part of the beam was already scraped away at that time.

**Measurements with a Four Corrector Closed Orbit Bump**

To compare the accuracy of the BPM-based alignment method with the currently used BLM-based method a four corrector closed orbit bump was created at the mock-up collimator. The amplitude of this bump was changed in steps of 1 mm starting with an initial beam offset of 0.4025 mm. Figure 7 shows changes of the beam offset during the measurement in 13 steps. The orbit offset at the collimator given by the bump (black line) is compared to the beam offsets measured with the in-jaw BPMs (red circles) and the BLM-based alignment method (blue crosses).

Figure 7: Comparison of the orbit offset at the collimator given by the bump (black line) and the beam offsets measured with the in-jaw BPMs (red circles) and the BLM-based alignment method (blue crosses).

The correlation between the bump settings and the beam centres measured with the jaw-integrated BPMs (red) and the BLM based method (blue) are depicted in Figure 8. The discrepancy between settings and achieved orbit offset was estimated to about 10% of the movement increment.

Figure 8: Correlation between measured beam centres (BPMs - red, BLM based method - blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment.

The deviations between measured and set beam offsets are dominated by this uncertainty. Figure 9 shows the correlation between beam offsets measured with the BLM-based method and the jaw-integrated BPMs (blue diamonds). The linear fit of the measurement data (blue line) and the coefficients of the fit polynomial emphasize the good agreement between both methods. Note that the BPMs allow an alignment within a couple of seconds, whereas the BLM-based method takes several minutes.

Figure 9: Correlation between beam offsets measured with the BLM-based method and the jaw-integrated BPMs. The linear fit of the measurement data (blue line) and the coefficients of the fit polynomial emphasize the good agreement between both methods.

Figure 10 depicts the differences between the centres measured by the BPM and BLM-based methods (red circles), the differences between the bump set values and the
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Figure 9: Correlation between beam offsets measured with the BLM based method and the jaw-integrated BPMs (blue diamonds). The blue line shows the linear fit of the measurement data.

centres measured by the BPMs (blue crosses), and by the BLM-based alignment (black diamonds). The deviations between the set and measured values for the beam offset can be found in the interval $[-50 \mu m, +140 \mu m]$ as indicated by the dashed black lines. The deviations between BPM and BLM method were within $[-50 \mu m, +63 \mu m]$ or between the red dotted lines.

The data indicate that the orbit drifted within the first 30 mins of the measurement, i.e. between step one and four, by $\sim 100 \mu m$, in addition to closed orbit bump. The end of this orbit drift is indicated by the magenta dashed line. Excluding the data points before the end of this orbit drift (left of the magenta line), the deviations between the set and measured beam offset were $\leq 40 \mu m$. i.e. the black diamonds and blue crosses can be found between the upper red dotted line and the upper black dashed line. The differences between beam offsets measured by the BPM and the BLM method were $\leq 25 \mu m$, i.e. the red circles lie on or between the green dotted lines. Thereby does the $50 \mu m$ step size of the collimator jaw movement during the BLM-based alignment define the maximal error of this method. Thus, the deviation between the BPM and BLM-based alignments is dominated by this.

RESULTS OF TURN-BY-TURN MEASUREMENTS WITH THE LHC BPM ELECTRONICS

The use of collimators with in-jaw BPM buttons may also be interesting in the transfer lines between the SPS and the LHC. As this would be a single pass application the shot-by-shot or respectively the turn-by-turn reproducibility of the measured beam offset is the figure of merit.

The measurements presented below were performed with a standard LHC BPM electronics connected to the in-jaw BPM buttons in single pass operation. The beam offset in the collimator was recorded in every turn for a total number of 300 turns before the jaws were moved again.

Figure 10: Differences between bump settings and beam offsets measured with the in-jaw BPMs (blue crosses) respectively the BLM-based method (black diamonds). The differences of measured beam offsets between the BPM and BLM based method are shown as red circles. The vertical purple line indicates the end of an additional external orbit drift during the first 30 mins of the measurement. The horizontal dotted green lines indicate the maximum deviation between the beam offsets measured with the BPMs and the BLM-based methods, if the data during the orbit drift are not included.

Collimator Scans with Constant Gap

To measure the turn-by-turn reproducibility of the BPM signals for different beam offsets at constant gap the two collimator jaws were scanned in parallel across the gap. This measurement performed at four gap widths: 14.75, 17.35, 20.35, and 24.75 mm.

Figure 11 shows the rms of the beam offsets for turn-by-turn measurements during parallel scans with the jaws at gaps of 17.35 mm (upper) and 24.75 mm (lower). For the scan at a gap of 17.35 mm the rms stays around 65 $\mu m$ during the whole measurement. At a gap of 24.75 mm the rms decreases with increasing beam offset. This effect may be explained by the non-linearity of the BPM buttons for big beam offsets. The non-linearity of the buttons has not been taken into account here. The maximum rms of the measured beam offsets versus the collimator gap size is plotted in Figure 12. As expected the rms increases with increasing gap, i.e. with longer distance between buttons and beam. The rms stays below $90 \mu m$ even for gaps as large as 24.75 mm.

CONCLUSION

Collimators with in-jaw BPMs promise a drastically reduced set-up time of the LHC collimation system - a few seconds per collimator compared to currently several minutes - and less strict requirements for the long-term orbit stability. Furthermore they allow to continuously monitor beam offsets at the collimators and therefore improve the passive machine protection. They would allow tighter col-
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Figure 11: RMS of the beam offsets for turn-by-turn measurements (300 turns) during collimator scans at gaps of 17.35 mm (upper) and 24.75 mm (lower) for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator.

Figure 12: Measured maximum RMS of the beam offset versus collimator gap for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator.

The non-linear beam response of the in-jaw BPM buttons depending on the gap width has been simulated and compared to measurements with beam. Despite the presence of several imperfections in the experiment conditions, a good agreement between simulation and measurement was observed. Experiments with a mock-up collimator in the CERN-SPS have shown an excellent agreement between the novel BPM and the state of the art BLM-based collimator alignment method, which was better than 25 μm. So far no disturbances in the BPM signals due to primary or secondary particles impacting on the collimator jaws have been observed. The accuracy of in-jaw BPM buttons in single pass operation has been measured for the first time. The rms of the measured beam offsets stayed below 90 μm even for gaps as large as 24.75 mm. Taking into account the results of laboratory measurements, tests in the LHC and the LHC collimation set-up experience it can be concluded that the accuracy of BPM based collimator set-up will be better than the current state of the art BLM-based method. Furthermore, the measurements showed that the accuracy of in-jaw BPMs in single pass operation is sufficient for the application in the transfer lines of the LHC.

REFERENCES

4. SUMMARY OF RECENT SPS CRYSTAL COLLIMATION TESTS

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

Walter Scandale, Daniele Mirarchi, Stefano Redaelli, CERN, Geneva, Switzerland for the UA9 Collaboration

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 [3] are discussed.

INTRODUCTION

In the last four years of operation in the SPS, 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 present goal is to apply crystal collimation to LHC and to prepare the likely future tests after the Long Shutdown (LS1). The optimal layout for crystal collimation tests in LHC is described in [3]. Such a layout should allow performance similar to those obtained in the SPS, presented here below. A complete description of the UA9 experimental apparatus in the SPS can be found in [4].

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 $\Delta \phi$ on the halo particles, highest displacement of the deflected halo on the secondary collimator. Implementing them approximately in the SPS layout of UA9 lead 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 [3]. 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 $\chi'$ 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.

ONGOING SIMULATIONS

In the next two subsections are introduced some ongoing studies in order to reproduce the SPS data. As example of validation of the code used a comparison of the experimental and simulated spot of the extracted beam on a pixel detector is presented, which involves also key extrapolations for the LHC layout design. Then experimental evidences are shown in view of supporting what asserted in [3].

Validation

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

SixTrack code that contains a routine reproducing the different interactions in a bent crystal [5]. The ultimate goal will be to reproduce the loss pattern seen in the SPS for different crystal orientations (that will be main subject of the next UA9 publication). Other important results have been already achieved, in particular, in view of estimating the spot-size of the channeled and extracted halo and the energy deposition on the massive absorber. The UA9 layout has been implemented in the SPS optics, for which SixTrack simulations have been carried out. A “screen” has been placed at the location of the first Roman Pot equipped with Medipix detectors [4], 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 ~10 mm, up to ~150 mm. 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 [3], the expected mean is at 8.4 mm. Taking into account the spread due to the critical channeling angle the minimum and maximum displacement of the extracted particles are 8.05 mm and 8.76 mm respectively, giving a width of the spot of ~700 µm. In Fig. 3 it is shown the horizontal projection of the experimental spot seen by the Medipix, in which 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 ~12 pixels, i.e. of 12x35 µm = 660 µm, in excellent agreement with the simulation results. These results are being extrapolated to LHC in order to check that the absorber can tolerate the energy released without any damage for each component of the present LHC collimation system.

Loss Maps

In the UA9 layout various type of detectors [4] for the measurements of the losses generated during the collimation tests are present. In the SPS sextant where the UA9 components sit, the loss detection is mainly based on plastic scintillators and Beam Loss Monitor (BLM) designed for the LHC. For the far losses along the whole ring the SPS-BLM system is used. Year by year the losses measurement system of UA9 has been modified and improved, and detectors have been installed also far from the crystals. One of the most useful insertion has been to install supplementary detectors in the first high dispersive area downstream the crystal. The main motivation of this addition is the fact that theoretically a collimation system in which the primary stage is a bent crystal in channeling orientation, would create much less off-momentum particles with respect to a collimation system in which the primary stage is made of an amorphous material. Hence an area with a high value of dispersion is the best candidate to study the off-momentum population. An example of the losses seen by the BLM close to the crystal during an angular scan is shown in Fig. 4. Here are clearly visible the different interactions type can be experienced by a particle traversing a crystal: a flat top is present during the amorphous orientation of the crystal (indicated by AM in green), a dip indicating the channeling orientation since now the particles are traveling in a quite empty space (indicated by CH in orange), and a plateau when the crystal is in the volume reflection orientation (indicated by VR in purple). The reduction factor of the inelastic interaction is given by the ratio between the losses in the amorphous orientation with respect to the losses in the channeling orientation, and the relative error given by error propagation. On the other hand
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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

an example of the losses seen by the BLM in the high dispersive area, during the same angular scan, is shown in Fig. 5. It is clearly visible here the same behavior of the losses as at the crystal location, and the different physics regimes ongoing are visible as well. It demonstrates that a crystal in channeling orientation creates much less off-momentum particles with respect to an amorphous primary stage, and the reduction is about of the same order. This justifies why for the LHC case so much attention is paid to evaluate the reduction of the losses in the Disperion Suppressor [3] when a crystal in channeling orientation is used instead of a standard primary collimator.

Moreover, during the last year it has been possible to observe the behavior of the losses along the whole SPS ring for different crystal orientation, using a full machine (288 bunches) with a very high circulating intensity ($3.3 \times 10^{13}$ p), which creates enough losses to be above the sensibility of the SPS-BLM system. Complete loss maps have been collected, which will be published soon. An example of losses seen by an SPS-BLM far from the crystal is shown in Fig. 6. A visible reduction of the losses has been measured along the whole SPS ring, while the crystal is placed in channeling orientation with respect to an amorphous one. This justifies why for the LHC is expected a general reduction of the losses induced by the collimation system along the whole LHC ring, which is why in [3] has been paid particular attention at the peaks on the losses which are created by particles coming from the primary collimation stage. This good results is promising for the LHC. It should however be noted that this improvement around the ring at the SPS is more easily visible because the amorphous crystal is not followed by a collimation system (higher background losses). At the LHC, where a very efficient cleaning mechanism is in place, it might be more difficult to see improvements around the ring.

CONCLUSIONS

It has been shown here how the expertise acquired in the UA9 framework is helping the setting up of the first crystal assisted collimation tests in the LHC. They go from the theoretical considerations behind an optimal experimental layout useful to estimate possible improvements with respect to a standard amorphous collimation, up to the interesting observables which could be used to quantify such possible improvements. Passing through the estimation of the main characteristics of the channelled and extracted beam useful to establish the requirements for its massive absorber.

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REFERENCES

5. CONCLUSIONS

Prototyping and beam testing of advanced collimator designs have been a core activity of the EuCARD WP8. The construction of a collimator with integrated BPMs and his thorough testing with the SPS beams provided crucial input for an important upgrade of the LHC collimation system that is taking place now, in the long shutdown after the first LHC running period. The concept of integrated BPMs is now considered a key feature of every upgrade of collimators, including the transfer lines. Even if the concept was first conceived for the primary collimators, it can be applied to every collimator type. Following the operational experience in the first LHC run, it has been decided to equip first the tertiary collimators in the experiment insertion regions, and some secondary collimators in the LHC dump region. This upgrade will improve the operational flexibility of the LHC and allow higher luminosities given the possibility to achieve smaller $\beta^*$ values in the high luminosity experiments. Details of the layout changes are given in these Engineering Change Requests that have recently been approved:

https://edms.cern.ch/document/1251162/1.0
https://edms.cern.ch/document/1251173/1.0

It should be noted that the deliverables were from the start split by application (LHC versus FAIR). Even though the work of both institutes profited from common meetings and discussions, the respective publications were done separately. The collimation paper attached to this report (Section 4) concerns the beam tests for the CERN collimator design with participation by CERN people only. Similarly, results of FAIR collimator tests were reported. A common final publication including ColMat partners is being considered.

EuCARD contributed also to the successful UA9 crystal collimation experiment at the SPS, which has achieved promising results in 2012. A dedicated experiment apparatus, separated from the one dedicated to the BPM-collimator design, was preferred to address in detail crystal collimation aspects. In addition to the construction of a precision goniometer to control the crystal angle with respect to the beam, which was built in 2010, EuCARD funded manpower resources that participated to the successful completion of the 2012 UA9 beam tests at the SPS. These tests were focused (1) on the demonstration of the reduction of losses in dispersive areas when the crystal is oriented in channeling configuration as opposed to its amorphous orientation; (2) on the assessment of losses around the SPS ring for high beam loss rates. Both attempts were successful, as reported in the attached publication submitted to the IPAC13 conference. These findings strengthened the expectation that crystals might be used in principle as primary collimators at the LHC to reduce the dispersive losses that presently limit the cleaning performance of the LHC collimation system.