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Crystal Collimation During the LHC Energy Ramp

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Summary

During this MD, performed on October the 30$^{\text{th}}$, 2016, bent silicon crystals and their goniometers were tested with proton beams for a possible usage of crystal-assisted collimation during the LHC energy ramp. Tests were performed using horizontal and vertical crystal. Loss maps with both crystals were measured during the ramp. The goal was to assess if channeling conditions could be maintained continuously during a dynamic change of machine condition.

1 Introduction

During LS1, two bent crystals for beam collimation studies were installed in IR7, on two goniometers on beam 1. In 2015 the two crystals were tested, and channeling was successfully observed [1, 2]. The main goals of beam tests in 2016 are to compare crystal collimation to the present collimation system cleaning at 6.5 TeV, and to assess the reliability of the goniometer device in dynamical operation phases like the energy ramp. Cleaning performances were measured during the first MD of 2016 [3] while this MD was dedicated to testing the continuous channeling of beam halo during the ramp.

The crystal collimation concept relies on the usage of bent crystals that can channel halo particles at large angles of up to tens of μrad. As opposed to the standard LHC multi-stage collimation, where amorphous primary collimators scatter halo particles at $\sim \mu$rad angles onto several secondary collimators, crystal primaries could send halo particles in one single absorber. A setup has been conceived that uses only existing secondary collimators as absorbers for the channeled beam [6]. In order to use crystal collimation during operation, the possibility to keep the crystal in the channeling condition during dynamics phases like the energy ramp and the betatron squeeze needs to be assessed. This is challenging because the critical angle θ_c (above which channeling regime is lost) scales as the inverse of the square root of the energy, and its value for 6.5 TeV protons for a silicon crystal is 2.5 μrad. To take the LHC from injection energy (450 GeV) to the collision energy (6.5 TeV), a special ramp function has been developed to increase safely the strength of the superconductive magnets in the LHC [5]. Standard collimators are able to follow the natural reduction of the beam size during the energy ramp [4], the adiabatic damping. Along with beam size also the beam divergence reduces, therefore the impact angle of beam halo particles on the crystal changes whit the beam energy. To use crystal collimation during the energy ramp the goniometer orientation needs to change as well as the linear transverse position.

The goal of this MD is to demonstrate that the goniometers are able to keep the crystal in channeling for the whole energy ramp. In this note, the beam setup and machine configuration for the tests are presented. In particular, the description of the functions generated for the goniometers, the alignments operation, and the loss maps measured during the energy ramp are presented. Some initial conclusions are then drawn.

2 Beam Setup

The MD was performed with several low-intensity bunches at both injection and flat top energy, with standard optics. The transverse dumper (ADT) was used to excite the beam with white noise, as in standard collimation loss maps, to achieve controlled primary beam losses on crystals and/or collimators. This was the reason why several low-intensity bunches have been accelerated to flat top energy. They were excited individually during the ramp to verify the channeling conditions.

The overall LHC availability during those studies was good and two energy ramps were performed. All the scheduled measurements were executeded.

The measurements involved the following main activities:

1) beam-based alignment of the crystal with respect to the beam orbit and transverse positioning as primary collimator;

2) angular scan for the determination of the channeling condition;

3) ramp function generation for both crystals and for both stages;

4) energy ramp performed with crystals as primary collimators in channeling orientation, and loss maps measured at different energies.

The first step is performed in a similar way as a standard collimator jaw alignment and is not presented in detail. The first ramp test was performed knowing only the alignment condition (transverse position and channeling orientation) at injection energy. Hence, step (1) and (2) were repeated, once the ramp was completed, to verify that the last points of the functions were the actual transverse alignment and the best channeling orientation at flat top. In the second ramp the beam–based parameters were fixed at both injection and flat top energy refine the goniometers ramp functions. Function generation and results from measurements (4) are presented in the following section.

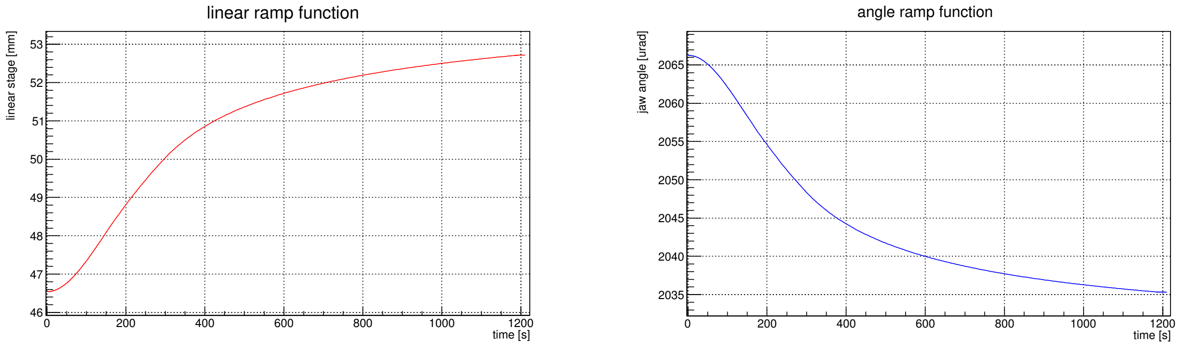

Figure 1: Horizontal crystal ramp functions. Left. Linear stage function. Right. Rotational stage function.

3 Energy ramp functions

Standard collimators are able to follow the adiabatic dump of the LHC beam during the energy ramp. The functions used to operate collimators during the ramp [4] are based on an interpolation of the LHC energy ramp function [5]. Crystal devices can be compared to a single side collimator during beam based alignment. Standard collimator ramp functions [4] were adapted to generate new functions for a single side device with a rotational stage. The linear stage function for the crystal device is $x(t) = x_c - n(t) \times \sigma(t)$, where $n(t)$ and $\sigma(t)$ are the evolution of the settings and beam size as a function of time. Linear interpolation of $n(t)$ and $\sigma(t)$ are used:

$$x(t) = x_c - \left[n_{\text{inj}} + \frac{n_{\text{ft}} - n_{\text{inj}}}{\gamma_{\text{ft}} - \gamma_{\text{inj}}}\left(\gamma(t) - \gamma_{\text{inj}}\right)\right] \times \left[\tilde{\sigma}_{\text{inj}} + \frac{\tilde{\sigma}_{\text{ft}} - \tilde{\sigma}_{\text{inj}}}{\gamma_{\text{ft}} - \gamma_{\text{inj}}}\left(\gamma(t) - \gamma_{\text{inj}}\right)\right] \frac{1}{\sqrt{\gamma(t)}}, \tag{1}$$

where n is the chosen setting in units of sigma, $\tilde{\sigma} = \sqrt{\beta \epsilon_n}$ is the normalized beam size (β is the optics function of the lattice and ϵ_n the normalized emittance), γ is the relativistic parameter, and x_c is the beam position at goniometer location. The linear stage function is generated by interpolating the beam-based parameters (transverse alignment) found at injection (inj) and top (ft) energy. For the goniometer angle the same approach is used:

$$x'(t) = x'_{\text{CH}} + \left[n_{\text{inj}} + \frac{n_{\text{ft}} - n_{\text{inj}}}{\gamma_{\text{ft}} - \gamma_{\text{inj}}}\left(\gamma(t) - \gamma_{\text{inj}}\right)\right] \times \left[\tilde{\sigma'}_{\text{inj}} + \frac{\tilde{\sigma'}_{\text{ft}} - \tilde{\sigma'}_{\text{inj}}}{\gamma_{\text{ft}} - \gamma_{\text{inj}}}\left(\gamma(t) - \gamma_{\text{inj}}\right)\right] \frac{1}{\sqrt{\gamma(t)}}, \tag{2}$$

where $\tilde{\sigma}_{\prime} = -\alpha\sqrt{\epsilon_n/\beta}$ is the normalized beam divergence.

Script were prepared to generate updated functions by using beam–based parameters during the MD. In Fig. 1 the points generated in Eq. 1 (Left) and Eq. 2 (Right) are shown.

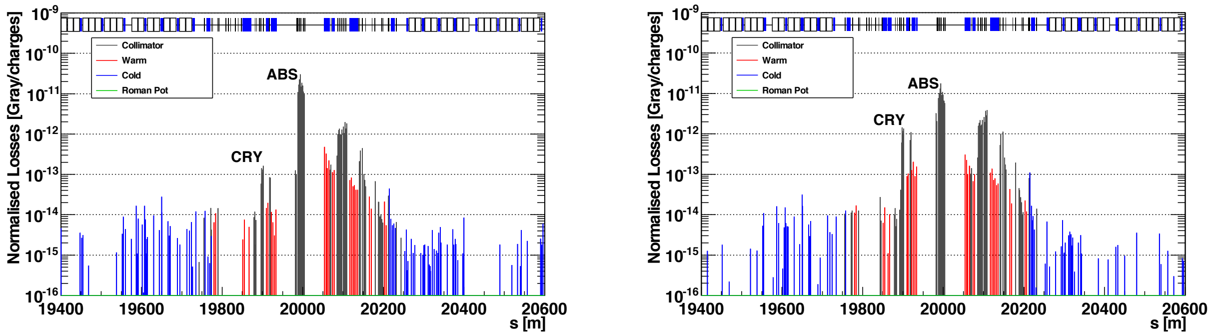

Figure 2: Loss pattern in IR7 during horizontal angular scan when the crystal is oriented in channeling (Left) and in amorphous (Right). Losses are normalized to the beam flux. Crystal (CRY) and the collimator used as absorber (ABS) are shown on the plots.

4 Measurements

4.1 Injection Energy Checks

The first operation of the MD was to establish a first set of beam-based parameters for the horizontal and vertical crystals at the injection energy of 450 GeV. Transverse alignment was performed with respect to the primary collimators at 5.5 σ. Quick angular scans were performed to check the channeling orientation of the goniometer and update the functions for the control system, for both crystals.

4.2 First Ramp Attempt

After the generation of the ramp functions for both horizontal and vertical goniometers, both crystals were aligned at 5.5 σ and oriented in the optimal channeling orientation. For this first ramp, the values at flat top energy where not fixed, and has been left as free parameters. The LHC energy ramp and the functions for the goniometers were launched at the same time. In Table 1 the chosen settings for crystal collimation ramp are presented and compared with collimator settings in IR7 during a standard energy ramp. Loss Maps were measured with losses induced by the ADT, every ∼500 GeV. The procedure for continuous

Collimator IR7	Standard Ramp [σ]	Horizontal Ramp [σ]	Vertical Ramp [σ]
TCP	5.7 to 5.5	Out	Out
TCSG upstream	10.0 to 7.5	Out	Out
TCPCV	Out	–	5.5 to 5.5
TCPCH	Out	5.5 to 5.5	–
TCSG downstream	10.0 to 7.5	10.0 to 7.5	10.0 to 7.5
TCLA	14.0 to 11.0	14.0 to 11.0	14.0 to 11.0

Table 1: IR7 Collimator settings (in σ units) at injection and at flat top during standard ramp and crystals collimation ramp.

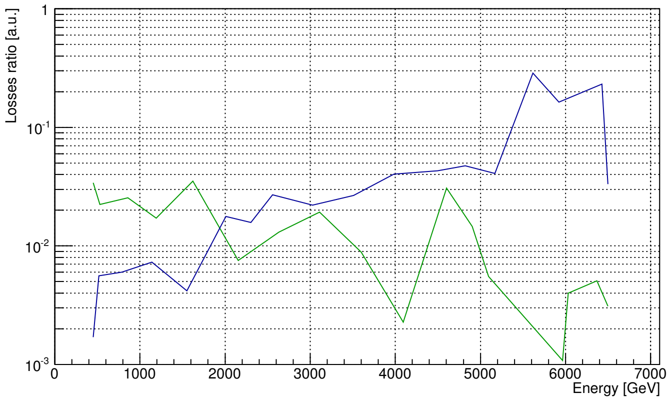

Figure 3: Ratio of losses recorded at crystal and absorber as a function of energy during the first ramp. Both horizontal (blue box and solid line) and vertical (green circle and solid line) crystals are presented.

loss maps during the ramp was established in the commissioning phase.

As observed during the first MD of 2016 when crystal collimation is in place a specific loss pattern is observed in IR7. In particular, when in channeling losses at crystal position are lower due to the reduction of nuclear interaction [7], while losses at the first collimator used as absorber increase (when the channeled halo hit the jaw). The two loss pattern are shown in Fig. 2 for horizontal crystal case. The ratio of the measurements of two monitors at crystal and at absorber is used as an empirical figure of merit to identify channeling conditions. For horizontal crystal, TCSG.B4L7.B1 is used as the first absorber and its monitor is used, for vertical crystal TCSG.D4L7.B1 is used. For each case, a ratio above 10^{-2} indicates the lost of channeling orientation. In Fig. 3 the ratios for horizontal and vertical crystals are presented. In the horizontal plane, channeling was lost at about 2 TeV, around one-third of the energy ramp, while vertical crystal was controlled until the end of the ramp. This was however a good results, considering that flat top values, were left as free parameters, evolving as the theoretical function predicts.

4.3 Flat Top Energy Checks

Beam-based alignment checks were performed to confirm the linear position and the best orientation angle for channeling at 6.5 TeV, at the end of the first ramp. New values were found for horizontal crystal and used to generate new ramp functions, fixing the arriving points.

4.4 Second Ramp Attempt

During the recovery time (ramp down and the new injection) the new functions were generated and deployed to the horizontal goniometer. In Fig. 4 the goniometer stages movements (and the RMS over a 10 Hz acquisition) are shown. The rotational stage vibrations (Fig. 4 Right) are well below the $\pm\theta_c$(E) acceptance for channeling orientation.

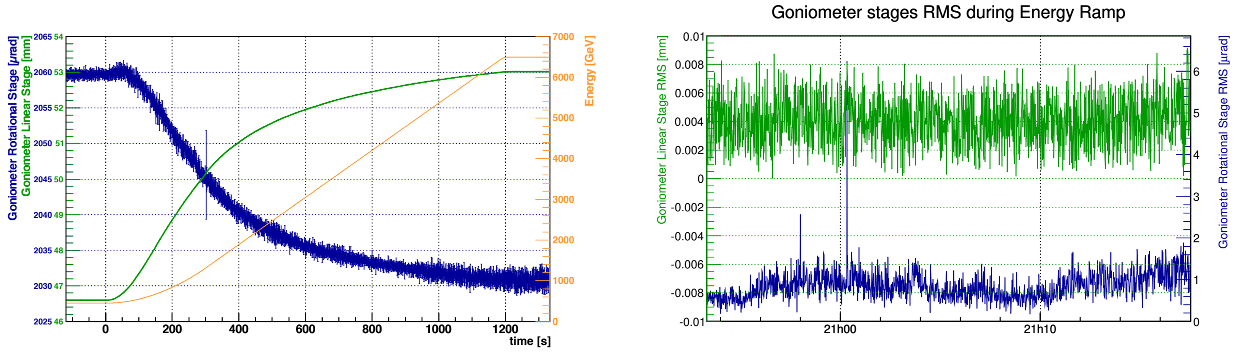

Figure 4: Left. Linear and rotational stages points during the energy ramp. Data are averaged over a second (raw data rate 10 Hz), also RMS is calculated and shown as error bars. Right. RMS for both linear and rotational stage during the second ramp.

Also, the ratio of losses recorded at crystal and absorber were under control, as well as the loss pattern, and is shown in Fig. 5.

5 Conclusions

The setup for crystal collimation tests in IR7 was tested to assess the stability of the goniometers during one of the dynamical phases of LHC, the energy ramp. For the first time channeling orientation was conserved during the ramp with protons. Evidence of channeling comes from the monitoring the loss pattern in IR7, and in general along the machine. An empirical measurement comes from monitoring local losses downstream of the crystals, which are suppressed in channeling compared to amorphous orientations, and local losses downstream of secondary collimators further downstream, which indicate the presence of a channeled halo separated from the beam core. A good stability, needed to accomplish the goals of this MD, was delivered by the goniometers, which are the first generation prototype

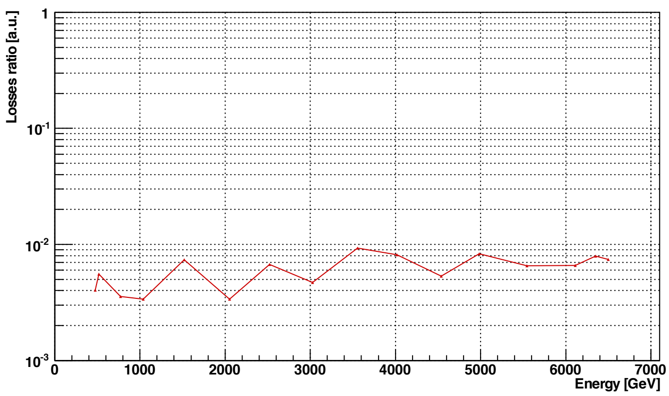

Figure 5: Ratio of losses recorded at crystal and absorber as a function of energy during the second ramp for the horizontal crystal.

of this kind of devices. The new generation, installed during 2017 winter shutdown, has been optimized and can reach a even higher accuracy with respect to the first generation.

6 Acknowledgements

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References

[1] R. Rossi et al., *Crystal Collimation with protons at injection energy*, MD Note, CERN-ACC-NOTE-2016-0035, 2016

[2] R. Rossi et al., *Crystal Collimation with protons at flat top energy*, MD Note, CERN-ACC-NOTE-2017-0021, 2017

[3] R. Rossi et al., *Crystal Collimation Cleaning Measurements with Proton Beams in LHC*, MD Note, CERN-ACC-Note-2018-0024-MD, 2018

[4] R. Bruce, R. W. Assmann, S. Redaelli, *Principles for generation of time-dependent collimator settings during the LHC cycle*, Proceedings of IPAC'11, San Sebastian, Spain, pp.3753-3755, 2011.

[5] O. Bruning et al., *LHC design report*, CERN-2004-003

[6] D. Mirarchi, *Crystal Collimation for LHC*, PhD Thesis, CERN-THESIS-2015-099, 2015

[7] W. Scandale et al., *Probability of inelastic nuclear interactions of high-energy protons in a bent crystal*, NIM B 268 2655-2659, 2010

[8] W. Scandale et al.,*Volume reflection dependence of 400 GeV/c protons on the bent crystal curvature*, Phys. Rev. Lett. 101 234801, 2008