FINAL LAYOUT AND EXPECTED CLEANING FOR THE FIRST CRYSTAL-ASSISTED COLLIMATION TEST AT THE LHC*

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Abstract

The installation in the CERN Large Hadron Collider (LHC) of two crystals in the horizontal and vertical planes was accomplished during the present LHC long shutdown (LS1) for crystal collimation studies. An appropriate layout was designed to demonstrate the principle feasibility of crystal collimation at the LHC. Extensive simulation campaigns were made to evaluate different crystal positions and parameters, in order to ensure that the main goals of these first feasibility tests in the LHC are within reach. In this paper, the final layout is presented. An overview of the considerations behind the design choices and the crystal parameters is given, and the expected performance of the system is discussed.

INTRODUCTION

Promising results were achieved during the last four years of tests of crystal-assisted collimation in the CERN Super Proton Synchrotron (SPS), in the framework of the UA9 Collaboration [1–4], demonstrating the principle feasibility of such technology. However, before relying on this system for the much more complex and challenging LHC upgrade, experimental tests with LHC beams are considered mandatory. First preliminary tests are foreseen after the machine commissioning in 2015, where the main questions to be addressed are, among others:

- Can crystal-assisted collimation improve the present, already very good, cleaning system?
- Can crystal-assisted collimation ensure stable performance in any machine configuration[1]?
- Is crystal collimation compatible with safe operations in any beam condition?
- Do crystal properties, observed so far at lower beam energies, scale to the LHC energy as expected?

The definition of the final layout and crystal parameters has been achieved through extensive simulation campaigns performed with the collimation version of `SixTrack` [5, 6], where a routine simulating the interaction of protons with bent crystals is implemented [7, 8]. This paper follows initial layout studies [9, 10] where several crystal layout provided adequate cleaning, as expected for this technology that enable concentrating losses in single absorbers. In this paper, the final layout as installed is presented. This design is optimized to the outcome of the first tests that will be limited to low-intensity runs at the highest beam energy available after the startup in 2015. It is noted that a complete interlock strategy is under study, however what is needed to ensure the system safety during stable physics run is already in place. Moreover, the system will be completely transparent during normal operations, thanks to a movable segment of beam pipe included in the goniometer design, which masks the crystal and will be retracted only during dedicated beam tests.

FINAL LAYOUT

Two crystals in the horizontal and vertical planes of the LHC Beam 1, in the betatron collimation insertion (IR7), have been installed in April 2014. The main constraints for the design of a layout that could address the items mentioned in the previous Section were to have a minimum impact on the present collimation layout and infrastructure with a safe strategy to absorb the channeled and extracted halo.

The final layout relies on the installation of two new devices only, i.e. two goniometers for horizontal and vertical crystals, and on the use of existing secondary collimators (TCSG) to intercept the channeled beams. The horizontal layout consists of a goniometer slot TECGH.4L7.B1 at s = 19919.24 m from IP1, and the TCSG.B4L7.B1 and TCSG.6R7.B1 used as absorbers at any energy and only at top energy, respectively. The vertical one consists of a goniometer slot TECGV.6L7.B1 at s = 19843.82 m from IP1, and the TCSG.D4L7.B1 as absorber at any energy. The three horizontal and two vertical massive absorbers[2] (TCLA) at the end of the collimation chain will be always in place.

The LHC Beam Loss Monitoring (BLM) system features one ionization chamber at each collimator and several ones at each lattice magnet, in particular at the critical loss locations in the IR7 Dispersion Suppressor[3] (DS). The BLM system will be used for the first measurements of crystal-assisted collimation efficiency. Additional diamond BLMs are also installed to enable 2 ns acquisitions of losses at the crystals.

Moreover, space reservations for future system upgrades are made, such as the installation of Cherenkov detectors in primary LHC vacuum, useful to characterize the extracted halo. A complete lists of interventions is given in [11].

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* Research supported by EU FP7 HiLumi LHC - Grant Agreement 284404

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[1] injection, ramp, squeeze, etc.

[2] 1 m of Tungsten.

[3] Limiting region for the whole LHC, in terms of particle loss.

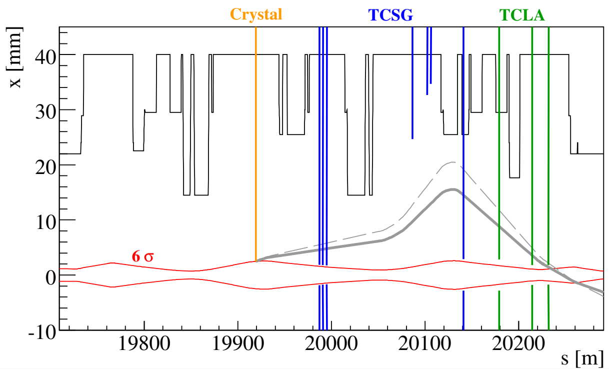

Figure 1: Horizontal layout for crystal-assisted collimation in the LHC-IR7 Beam 1, at 7 TeV. Orange line: crystal aperture (6 σ), blue lines: projection on the plane of interest of the secondary aperture (7 σ for selected TCSG, retracted otherwise) , green lines: projection on the plane of interest of the absorbers aperture (10 σ). Only the external side of the machine is resported: the aperture model (shown in black) is simmetric, as standard two-sided collimators, only the crystal is single-sided. Two configurations are possible: (1) at top energy using only the last TCSG in place (TCSG.6R7), (2) at any energy with four TCSG in place. The solid gray line is the trajectory followed by the channeled halo particles, i.e. a kick of 50 μrad is acquired, while the dashed one shows the maximum kick allowed if the configuaration (1) is used, i.e. 65 μrad.

CRYSTAL COLLIMATION CONFIGURATIONS

Ideally, a crystal-based system requires one single absorber that catches the channeled halo particles. This is not possible for the proposed layouts that use a 1 m long Carbon TCSG. In order to improve the cleaning compared to the present system, additional absorbers must be utilized during the beam tests, as shown in Figs. 1 and 2. For the vertical case, a TCLA collimator is available at 180 degrees phase advance from TCSG, used as vertical absorber. This setup can be used at any energy for bending angles above 50 μrad. For the horizontal case, there is no optimum TCLA location to catch the debris from the TCSG absorbers. The best cleaning performance is obtained by closing four TCSG and all horizontal TCLAs (green bars in Fig. 1). Different TCSGs might be used at injection and at top energy. The top energy case sets a maximum value of bending angle of 65 μrad in order to avoid hitting the magnet aperture[4] before intercepting the TCSG.6R7 (Fig. 1). These layout considerations were taken into account for the crystal parameter study discussed below, as they set limits for the bending angles.

CRYSTAL PARAMETERS DEFINITION

The crystal parameters should be chosen to ensure: I) best cleaning performance in the IR7 DS; II) safe margins for IR7 magnet aperture; III) large impacts parameter of extracted halo on the absorber, IV) usability both at 450 GeV and 7 TeV.

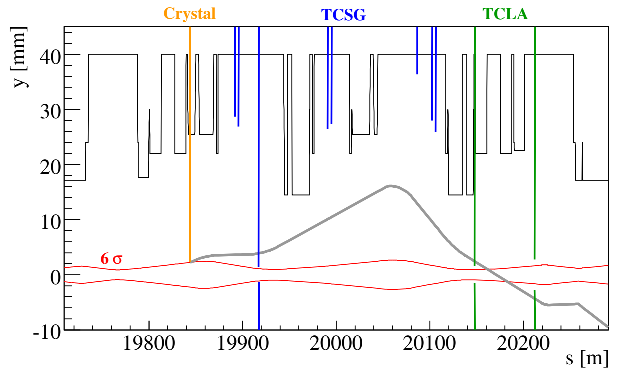

Figure 2: Same notation as in Fig. 1, but for the vertical plane.

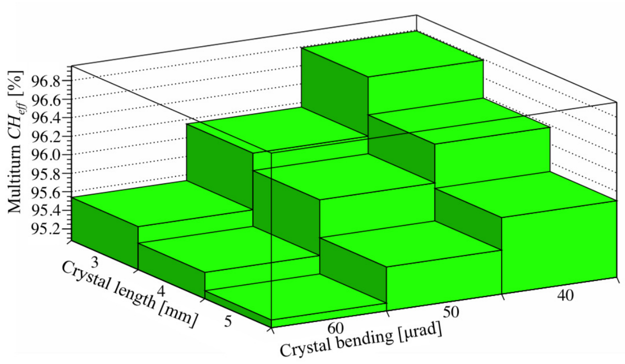

Figure 3: Multiturn channeling efficiency (CH_{eff}) for different combinations of crystal bendings and lengths probed.

Key parameters for crystals are the lenght (l) and bending angle (θ). Many combinations were probed, with driving considerations based on the oscillation period between crystalline planes (λ) and the critical bending radius (R_c). At 7 TeV they are estimated to be $\lambda \sim 250$ μm and $R_c \sim 16.8$ m.

Suitable bending radius $R = l/\theta$, are given by geometrical constraints. Combinations of l and θ have to ensure: $R > 3R_c$ for adequate crystal channeling performace ("long" crystals), low probability of inelastic interaction ("short" crystals), large impact parameter on the absorber ("large" θ) and safe margin from the IR7 magnet aperture of the extracted halo ("small" θ). Thus, the final sub-set of considered l and θ was 3, 4, 5 mm and 40, 50, 60 μrad, respectively.

To evaluate the influence of the crystal parameters on the system performance taking into account the multiturn process, key observables are: integrated losses in the IR7 DS, multiturn channeling effeciency, and nuclear interaction rate at the crystal. For the final sub-set of possible combinations of lengths and bendings introduced above, similar results were found. Taking as example what achieved with the layout (1) in Fig. 1, the integrated losses in the DS are in the range of $(\sim 3.4 \pm 0.4) \cdot 10^{-4}$. The nuclear interaction rate is found

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[4] It is related to the maximum closed orbit shift of 4 mm in IR7, hence a margin of 5 mm is taken.

Table 1: Main Features of the Crystals Installed in the LHC

Collimation plane	**Bending [μrad]**	**Length [mm]**	**Material**	**Bending planes**
Hor.	50	4	Si	110
Ver.	50	4	Si	111

in the range of $(\sim 0.49 \pm 0.09)\%$, while what achieved in terms of multiturn channeling efficiency is shown in Fig. 3.

Another key feature due to the multiturn effect is the maximum angular tilt for which a consistent fraction of the halo is still channeled, and beyond which crystals are seen as any standard amorphous collimator by the beam. This tilt is found to be ~ 5 μrad, which are slightly more than two critical channeling angles (θ_c) at 7 TeV, and it is caused by repeated passages through the crystal, with angles each time slightly modified by the previous passage. This effect translates in an additional deflection to the crystal bending itself during angular scans, which must be taken into account. Hence a margin of $\sim 4\theta_c$ (i.e. ~ 10 μrad) is considered.

All these considerations lead to the crystal parameters reported in Table 1. The main difference between installed crystals is the manifacturing technology: Strip and Quasi-Mosaic crystals are placed in the horizontal and vertical goniometers, respectively. This will allow to test its influence mainly on ions beam collimation.

EXPECTED PERFORMANCE

Extensive simulation campaigns were performed to ensure that the possible cleaning improvement achieved with the crystal-assisted system relative to the present one, could be visible in the low-intensity beam test. Nominal conditions, perfect crystal and machine were assumed in the simulations. Studies were based on a statistics $> 10^7$ intercepted protons, in order to evaluate losses of the order of 10^{-6}.

Examples of complete loss map simulation, regarding cleaning performaces in the horizontal plane at 7 TeV for standard and crystal-assisted collimation (config. (2)) are shown in Fig. 4, top and bottom, respectively.

A summary of key configurations and observables during first experimental tests at top energy (main goal) is given in Table 2. The average level of expected losses in the DS, and its ratio with respect to standard collimation performance is reported. The last column shows the ratio with respect to what expected in the DS when crystals are in amorphous (AM) orientation. A significant improvement in cleaning efficiency is expected with respect to the present collimation system, which ranges around a factor ~ 10, for different layouts and configurations. The difference between the configurations (1) and (2) for the horizontal plane is given by the cut in angle performed by the selected TCSGs on particles scattered and not channeled by the crystal, and by the absortion efficiency of what emerges from those TCSGs. This effect is more prominent at injection energy due to the less effectiveness of the kicks given by the crystals, hence the complete chain of TCSGs might be used at this energy to ensure a better phase space coverage, in order to estimate the real enhancement could be given by the reduced probability of inelastic interactions in bent crystals also at this energy, which could be masked by features due to absorber inefficiency and not by the technology itself.

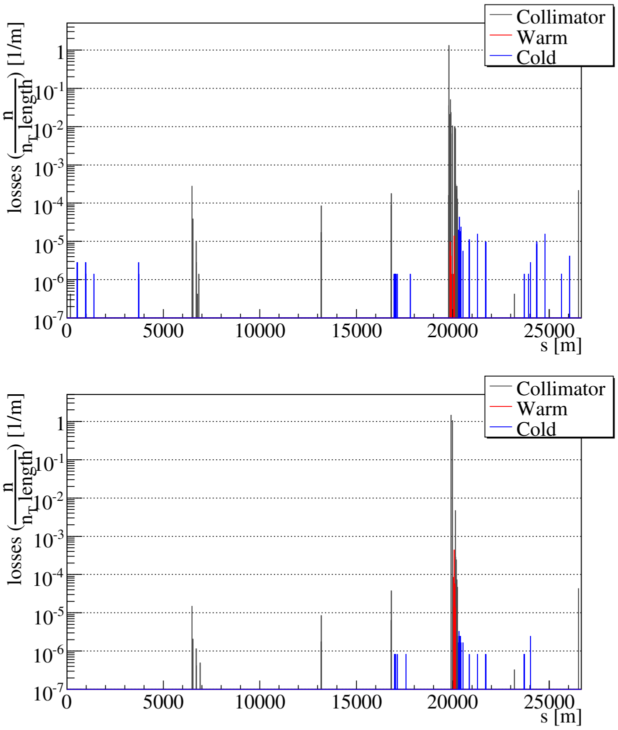

Figure 4: Horizontal loss map at 7 TeV for standard (top) and crystal-assisted collimation (bottom).

Table 2: Summary table of key configurations and observables for the first experimental tests at top energy, for the present system (Std.) and crystal-assisted collimation (CH).

Config.	**Plane**	**IR7-DS avr. losses**	**Ratio w.r.t. Std coll.**	**Ratio w.r.t. crystal in AM**
Std.	H	1.4e-5	1.0	(1) 3.4 - (2) 4.2
CH (1)	H	1.2e-6	11.7	39.2
CH (2)	H	1.8e-6	7.8	32.8
Std.	V	1.4e-5	1.0	3.5
CH	V	1.3e-6	10.8	37.7

CONCLUSION

An overview of the final layouts for first crystal-assisted collimation tests in the LHC, with expected performace and prepartory studies was given. Crystal bending and length were optimized to ensure tests in any machine configuration and provide $R > 4R_c$. Based on these promising results that show a better performance of the crystal-based collimation, we are confident that the proposed layout can ensure a successful set of tests for beam energies ranging from injection to top energy, in both planes, both with ions and protons.

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