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Crystal Collimation Cleaning Measurements with Proton Beams in LHC

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Summary

During this MD, performed on July 29$^{\text{th}}$, 2016, bent silicon crystal were tested with proton beams for a possible usage of crystal-assisted collimation. Tests were performed at both injection energy and flat top using horizontal and vertical crystal. Loss maps with crystals at 6.5 TeV were measured.

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 for both proton and ion beams [1, 2, 3]. The main goals of beam tests in 2016 with those devices are to compare the crystal collimation cleaning performances to the actual collimation system cleaning at 6.5 TeV, and to assess the reliability of the goniometers in dynamical operation phases like the energy 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 per plane. A setup has been conceived that uses only existing secondary collimators as absorbers for the channeled beam [4]. The scope of those MD is to demonstrate that channeling can be achieved and that a good collimation cleaning can be produced with a reduced set - ideally with one - secondary collimator.

In this note, the beam setup and machine configuration for the tests carried out in MD1 of 2016 are presented. This MD was devoted to measuring for the first time the crystal-collimation cleaning performance at 6.5 TeV. Also, tests of vertical crystals at top energy were carried out for the first time. Those tests could not be carried in 2015 due to lack of time. Some initial conclusions are then drawn.

2 Beam Setup

The MD was performed using several low-intensity bunches both at injection and flat top energy, with the standard 2016 optics. The transverse dumper (ADT) was used to excite selected bunches by applying a transverse 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 were used at flat top energy: excitations of individual bunches allowed several measurements in one single cycle to 6.5 TeV. To have enough losses for the time needed to complete crystal and collimator scans (see below), the ADT window was actually enlarged to act on three consecutive bunches. A specific filling scheme was prepared with groups of three pilots separated by 2 μs from each other, and each group separated by 3.5 μs from the following. The overall LHC availability during those studies was good. All the scheduled measurements were performed.

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) setup for crystal–based system: crystal as primary collimator, and several TCSGs open;

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

4) transverse scan of the channeled beam with a secondary collimator;

5) cleaning measurements through loss maps of a reduced collimation system based on a crystal in channeling position and different sets of secondary collimators.

The first step is performed in a similar way as a standard collimator jaw alignment and is not presented in detail. In the following section, the results of measurements (3), (4) are presented for both energies. Cleaning measurements (5) were performed for the first time.

3 Measurements

3.1 Injection Energy Checks

The first operation of the MD was to repeat a minimal set of measurements for the horizontal and vertical crystals at injection energy. Angular scans are performed by changing the crystal angle while monitoring beam losses immediately downstream of the crystals, following the detailed procedure described in [2]. The reason for this procedure was to check the angular reproducibility of the goniometer after several months and several updates to the control system. It is also important to assess channeling orientations to optimize the setup at top

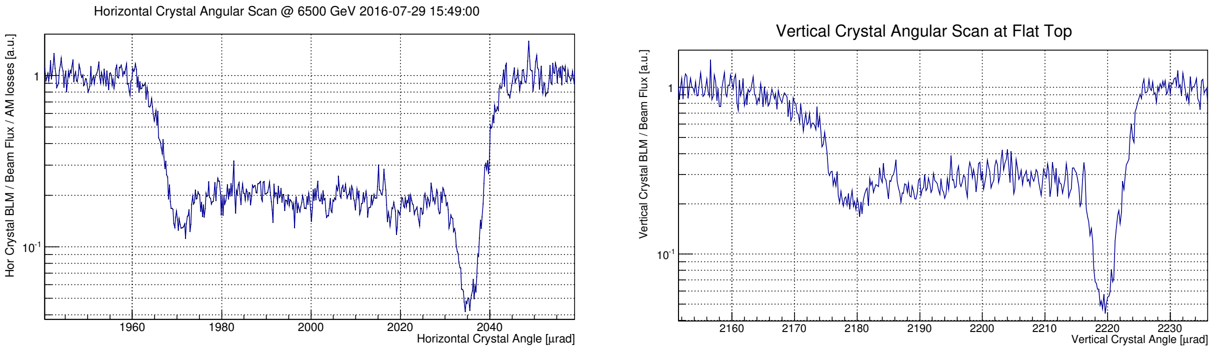

Figure 1: Horizontal (Left) and Vertical (Right) crystal angular scans at top energy. Losses normalized to the beam flux as a function of the goniometer angle.

energy. Both vertical and horizontal crystals were tested. Angular scans were performed to reestablish the channeling orientation angle with the procedure described in [1].

3.2 Flat top energy measurements

The results of the angular scans of vertical crystal are shown in Fig. 1. These measurements were recorded with the collimator settings listed in Table 1. Losses recorded at 1 Hz, normalized to the bunch by bunch flux, and to the steady losses measurement with crystals in amorphous orientation, are used to produce this plot. The beam flux is calculated by fitting with a 3rd order polynomial function the slope in the beam current. The vertical crystal was tested for the first time at top energy, due to lack of time in 2015 tests. It was found that in channeling losses are reduced with respect to amorphous orientation by factors 26 and 23 for horizontal and vertical crystals, respectively.

Collimator IR7	Standard [σ]	Horizontal scan [σ]	Vertical scan [σ]
TCP	5.5	7.5	7.5
TCPCV	Out	Out	5.5
TCPCH	Out	5.5	7.5
TCSG	7.5	7.5	7.5
TCLA	11.0	11.0	11.0

Table 1: IR7 Collimators positions (in σ units) during flat top standard operation and crystals scan operation.

3.3 Absorber Linear Scan

As for injection energy tests, in order to characterize the properties of the channeled beam one can make a transverse scan with secondary collimators located downstream of the crystal. When the crystal is oriented at its optimum angle for channeling the halo has its maximum distance from the beam envelope. A scan can then be performed with the secondary collimators TCSG.B4L7 and TCSG.D4L7 for horizontal and vertical crystal respectively. During

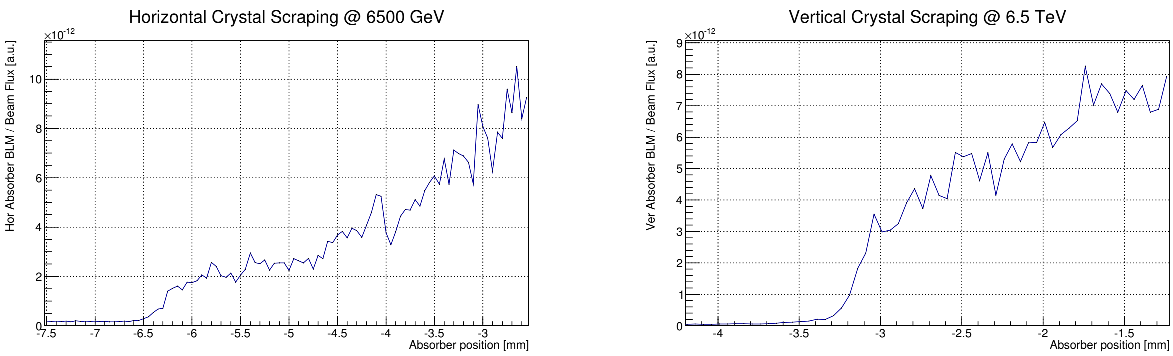

Figure 2: Horizontal (Left) and Vertical (Right) crystal channeled beam scrapings. Losses normalized to the beam intensity as a function of the absorber linear position.

these measurements, all the collimators located upstream of the secondary collimator used for the scan were opened to at least 7.5 σ. Inward and/or outward scans are performed by spanning the range in transverse amplitude between the primary beam envelope, defined by the crystal position and apertures where the collimator jaw does not intercept the channeled beam anymore. In this condition the channeled halo is intercepted by downstream collimators. The measurement is given in Figs. 2, where the losses recorded downstream of the secondary collimator used for the scan are given as a function of the collimator jaw position.

4 Cleaning measurements

Loss maps were measured both in horizontal and vertical planes of beam 1, for standard and crystal–based collimation system settings. Crystal collimation only uses a sub–set of the secondary collimators, that are all used compared in the standard system.

In standard collimation loss maps, cleaning inefficiency is measured by normalizing all the monitors (BLM) to the losses recorded at the highest BLM close to the primary collimators. This value is proportional to the number of halo particles intercepted by the collimation system, hence the losses in the dispersion suppressor region (DS) of IR7 give a direct measurement of collimation inefficiency. Channeling however suppress nuclear interaction, so losses at the crystal are small and they are maximum at the secondary collimator used as absorber. It is not possible to compare the two system by using the same normalization of the BLM signal used for the standard system.

For a direct comparison of absolute losses, we therefore use a different normalization. Each BLM signal in Gy/s is normalized by the flux of primary beam losses in p/s calculated from the bunch–by–bunch beam current measurements. The leakage factor is defined as the highest normalized loss value observed in IR7-DS during a loss map.

Standard collimation loss maps were measured as reference to compare the two systems. For the crystal system, different arrangements of the TCSGs downstream of the crystal were tested. In Table 2 the different settings used are presented. The leakage ratios found in IR7-DS, on two different cold magnets position, and on momentum cleaning primary collimator (TCP IR3), are presented in Table 3.

In the horizontal plane, we observed an improvement of standard collimation below the

Collimator	Standard [σ]	Horizontal [σ]					Vertical [σ]		
Configuration	Reference	1	2	3	4	5	1	2	3*
TCP.D6L7	5.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCP.C6L7	5.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCP.B6L7	5.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCSG.A6L7	7.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCPCV.A6L7	Out	Out	Out	Out	Out	Out	5.5	5.5	5.5
TCSG.B5L7	7.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCSG.A5L7	7.5	7.5	7.5	7.5	7.5	7.5	Out	Out	Out
TCSG.D4L7	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
TCPCH.A4L7	Out	5.5	5.5	5.5	5.5	5.5	Out	Out	Out
TCSG.B4L7	7.5	7.5	7.5	7.5	7.5	Out	7.5	Out	7.5
TCSG.A4L7	7.5	7.5	7.5	Out	Out	Out	7.5	Out	7.5
TCSG.A4R7	7.5	7.5	7.5	Out	Out	Out	7.5	Out	7.5
TCSG.B5R7	7.5	7.5	Out	Out	Out	Out	7.5	Out	7.5
TCSG.D5R7	7.5	7.5	Out	Out	Out	Out	7.5	Out	7.5
TCSG.E5R7	7.5	7.5	Out	Out	Out	Out	7.5	Out	7.5
TCSG.6R7	7.5	7.5	7.5	7.5	7.5	7.5	7.5	Out	7.5
TCLA.A6R7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
TCLA.B6R7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
TCLA.C6R7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
TCLA.D6R7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
TCLA.A7R7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0

Table 2: IR7 Collimators positions (in σ units) during flat top Loss Maps measurements.

2016 operational performance. In particular, what appears to be the effect of showers coming from TCLAs is affecting the region Q7. If we look at the Q8 region the max improvement is a factor 3. It is also observable how reducing the set of TCSGs is affecting the crystal collimation performances. Simulations of loss maps with this settings are in progress to assess the hypothesis made before. For vertical crystal, an improvement by a factor 9.17 is observed in IR7-DS, with a reduction of losses on IR3 TCP by a factor 14.13. When a reduced set of TCSGs is used the system shows the same behavior observed for horizontal case: with limited or no improvement of the cleaning. Also, a loss map with vertical crystal in amorphous orientation was measured; it is possible to observe the differences in the loss pattern. ADD REFERENCE TO FIGURE. In particular, the monitors at crystal and at the absorber position (TCSG.D4L7 in this case) show a quantitative behavior. When in channeling losses at crystal position are about 2 order of magnitude lower than at the absorber, when in amorphous they are about 1 order of magnitude less.

Plane	Configuration	Crystal Orientation	Leackage ratio Standard/Crystal		
			IR7-DS Q7	IR7-DS Q8	TCP IR3
H	1	CH	1.85	4.71	3.72
H	2	CH	1.60	4.21	3.34
H	3	CH	0.75	2.89	2.22
H	4	CH	0.18	1.20	2.47
H	5	CH	0.22	1.41	2.80
V	1	CH	9.17	–	14.13
V	2	CH	0.92	4.58	5.63
V	3	AM	0.49	–	0.47

Table 3: IR7 Collimators positions (in σ units) during flat top standard operation and crystals scan operation.

5 Conclusions

The setup for crystal collimation tests in IR7 was tested again to confirm the stability of the goniometers at injection energy and top energy. For the first time channeling was observed with vertical crystal, that is a Quasi–Mosaic crystal, with protons at 6.5 TeV. Channeling for horizontal crystal confirmed as in 2015. Evidence of channeling comes from the monitoring of local losses downstream of the crystals, which are suppressed in channeling compared to amorphous orientations, and from scans of secondary collimators further downstream, which indicate the presence of a well-defined channeled halo separated from the beam core. Those tests were preliminary carried out with both crystals at both energies, providing a comprehensive set of data for a full characterization of both crystals. The preliminary analysis indicates that a crystal–based system can improve, both in horizontal and vertical planes, the cleaning of present multi–stage system. In the best cases, improvement factors of DS losses of 4.7 (H) and 9.17 (V) could be achieved. It is important to note that this improvements can only be achieved if a large number of secondary collimators downstream of the crystal are used. If only one TCSG per plane is used, the performance of a crystal–based system is still good but not better than the present system. This is a feature of the present setup for low beam intensity tests, which uses only 1 m of CFC as primary absorber.

6 Acknowledgements

We would like to thank the OP crew for their assistance during the MD.

7 Appendix

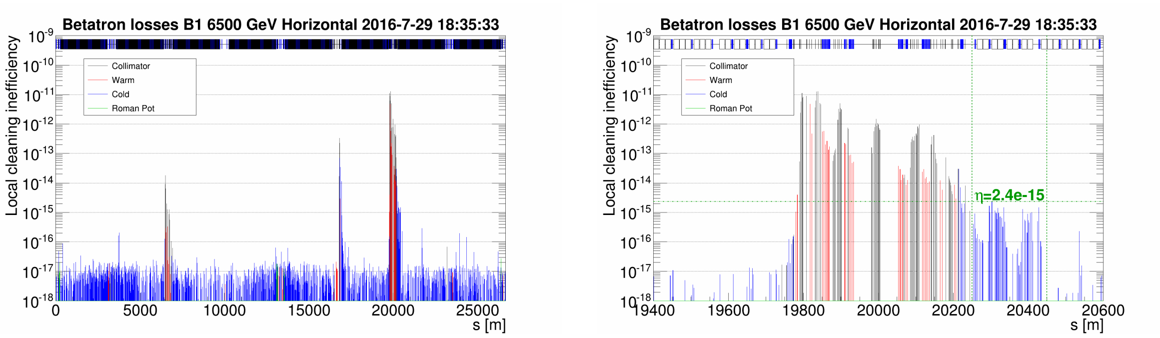

Figure 3: Horizontal standard loss maps. IR7 zoom is presented on the right.

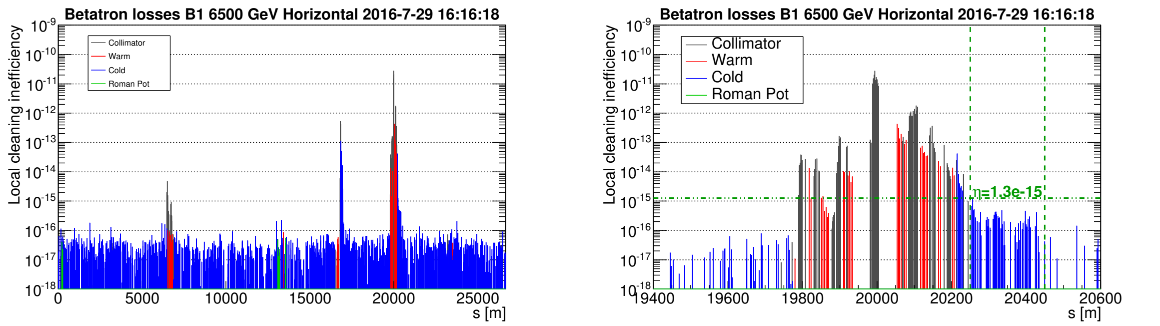

Figure 4: Horizontal crystal collimation loss maps. Settings 1 on Table 3. IR7 zoom is presented on the right.

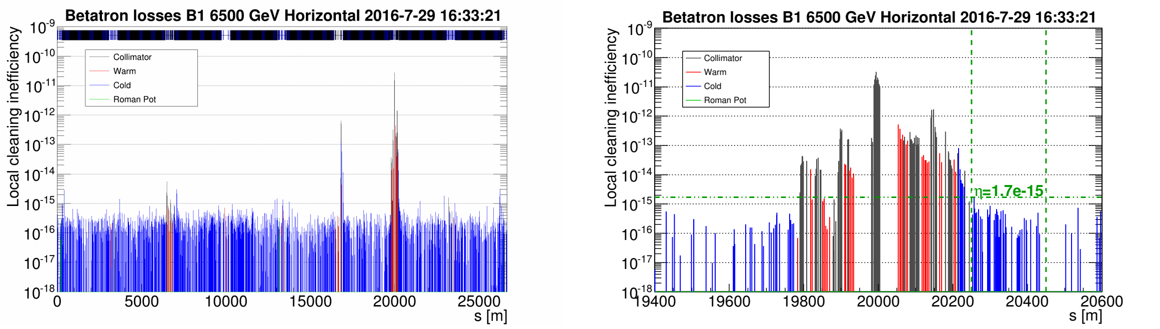

Figure 5: Horizontal crystal collimation loss maps. Settings 2 on Table 3. IR7 zoom is presented on the right.

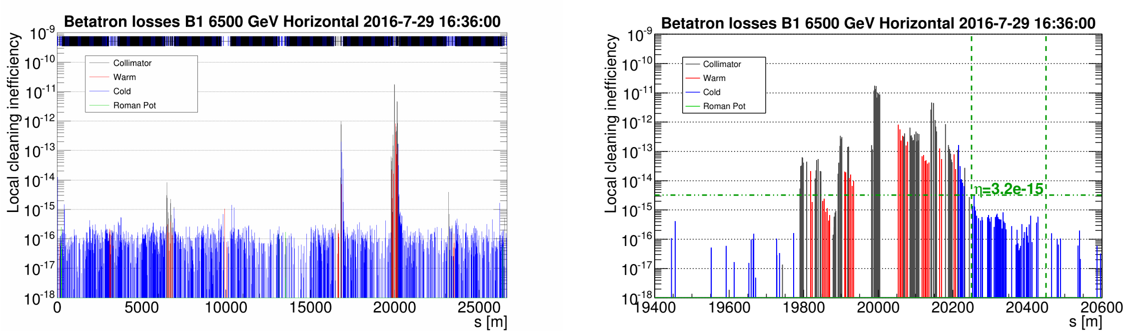

Figure 6: Horizontal crystal collimation loss maps. Settings 3 on Table 3. IR7 zoom is presented on the right.

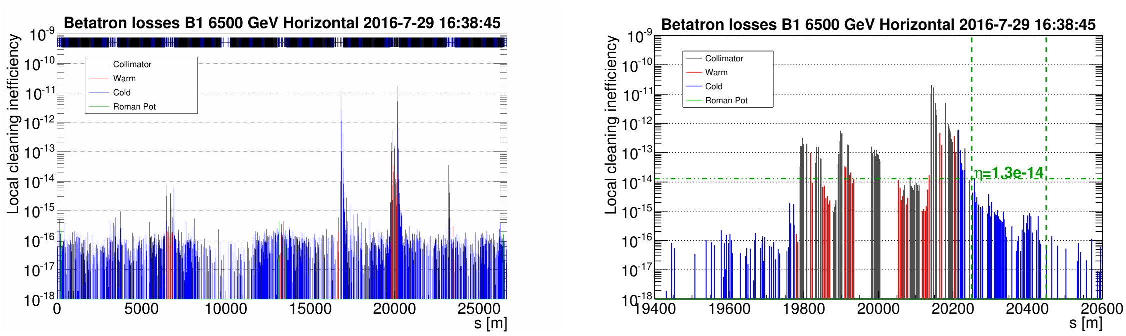

Figure 7: Horizontal crystal collimation loss maps. Settings 4 on Table 3. IR7 zoom is presented on the right.

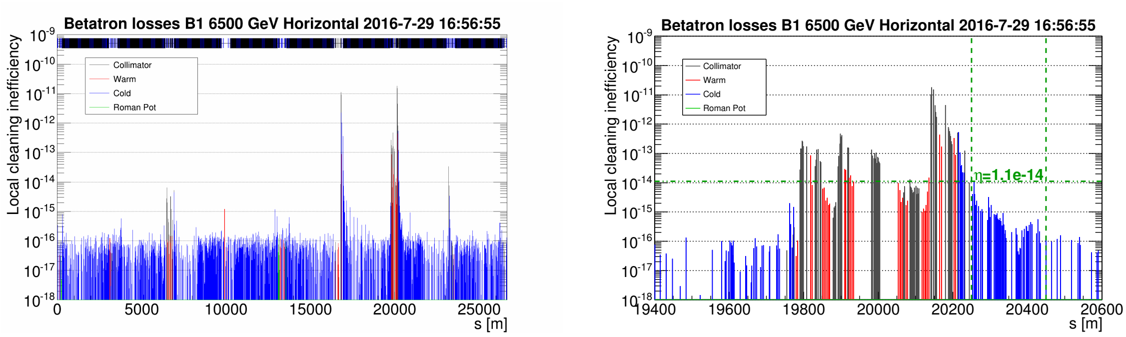

Figure 8: Horizontal crystal collimation loss maps. Settings 5 on Table 3. IR7 zoom is presented on the right.

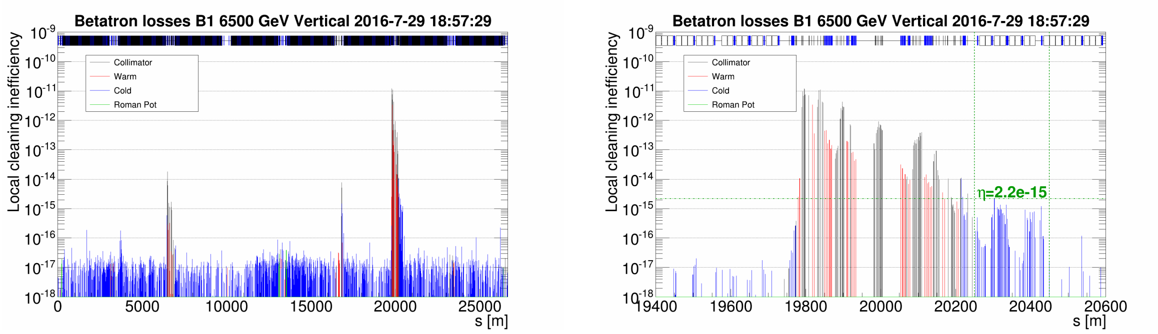

Figure 9: Vertical standard loss maps. IR7 zoom is presented on the right.

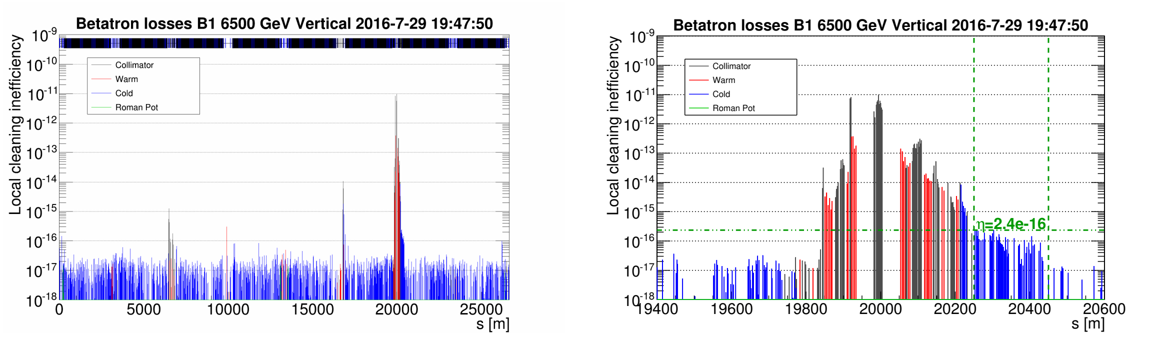

Figure 10: Vertical crystal collimation loss maps. Settings 1 on Table 3. IR7 zoom is presented on the right.

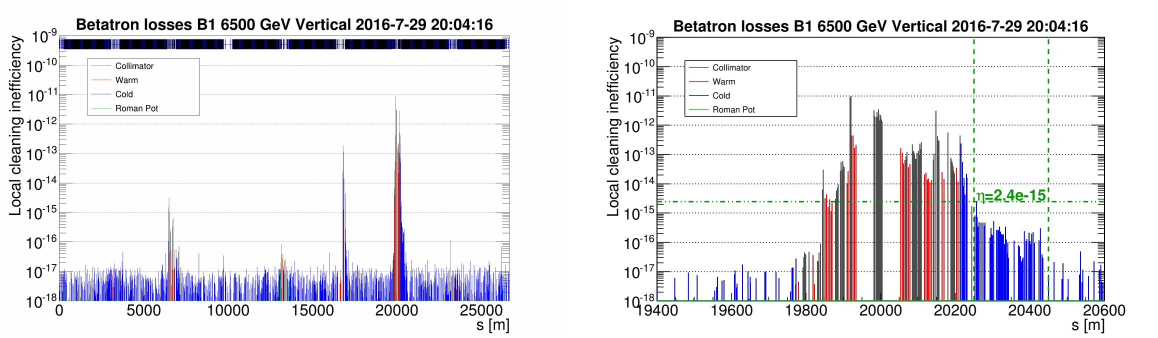

Figure 11: Vertical crystal collimation loss maps. Settings 2 on Table 3. IR7 zoom is presented on the right.

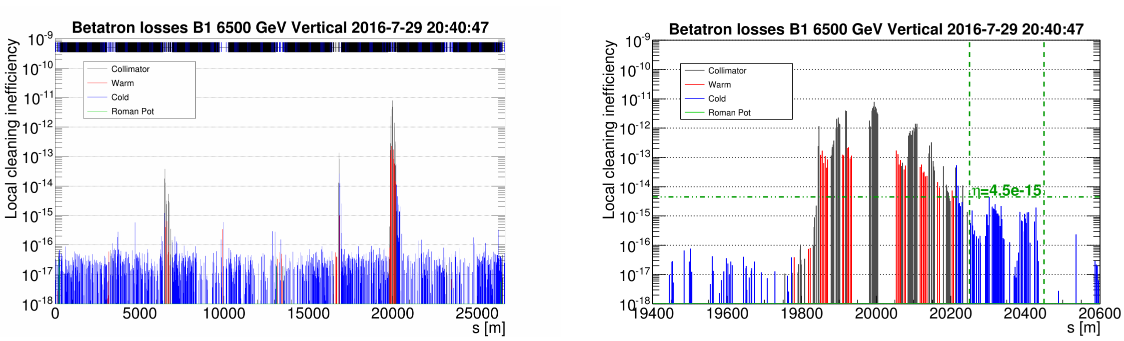

Figure 12: Vertical crystal collimation loss maps, crystal in amorphous orientation. Settings 3 on Table 3. IR7 zoom is presented on the right.

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