OPERATIONAL PERFORMANCE OF THE LHC COLLIMATION

S. Redaelli*, R.W. Assmann, R. Bruce, A. Rossi, D. Wollmann, CERN, Geneva, Switzerland

Abstract

The collimation system of the CERN Large Hadron Collider (LHC) is the most advanced cleaning system built for accelerators. It consists of 98 two-sided and 2 one-sided movable collimators of various designs and materials, for a total of 396 degrees of freedom (2 motors per collimator jaw), that provide a multi-stage cleaning of beam halo as well as a crucial role for the LHC machine protection. Collimators can be moved with functions of time to guarantee the optimum settings during energy ramp and betatron squeeze. The system has been commissioned with proton beams for the 3.5 TeV LHC runs and has ensured a safe operation, providing a close to nominal cleaning performance in the initial LHC operational phases. In this paper, the system performance achieved in the early LHC commissioning in the 3 MJ stored energy regime is presented.

INTRODUCTION

The collimation system of the Large Hadron Collider (LHC) has been designed to fulfill the high energy challenge of 362 MJ stored beam energy. A complex and distributed system is needed to achieve the required cleaning performance and to ensure the passive machine protection [1]. The system saw the first exciting beam commissioning in 2009 and has become fully operational in 2010. In this paper, the preliminary analysis of the collimator performance achieved with the operation in the 2–3 MJ regime is presented. After a brief recapitulation of the system layout, the strategy for the collimator setting calculation is presented and the concept of beam-based parameters is introduced. The cleaning performance achieved at 3.5 TeV is then presented and some conclusions are drawn.

LHC COLLIMATION SYSTEM LAYOUT

The LHC collimation system layout is given in a companion paper [1]. An illustrative scheme with the collimator locations around the ring, taken from [2], is given in Fig. 1. Hundred movable collimators with different roles are installed (Table 1). The back-bone of the system is provided by two warm interaction regions (IRs): the momentum (IR3) and betatron (IR7) cleaning IRs, with 28 collimators per beam. Robust primary (TCP) and secondary (TCSG) collimators made of a Carbon fiber composite (CFC) define the momentum and betatron cuts for the beam halo. Additional high-Z material absorbers (TCLA) protect the superconducting magnets downstream of the warm insertions. In the experiment interaction regions (IR1/2/5/8),

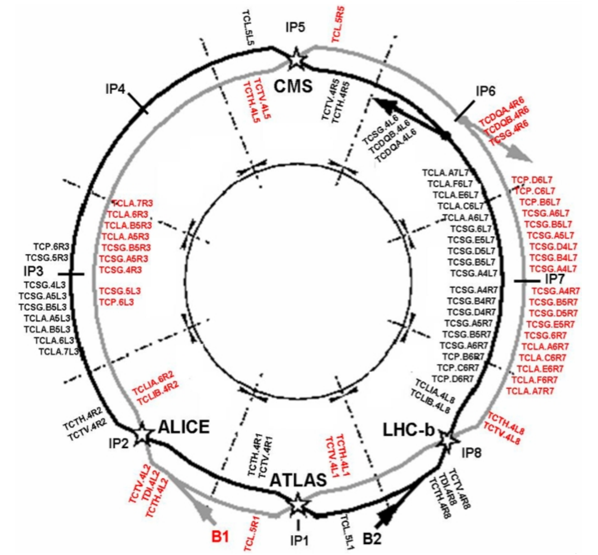

Figure 1: LHC layout with collimator locations [2].

Table 1: List of Movable LHC Collimators

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics debris absor.	TCL	H	4	Cu
Dump protection	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. (ring)	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

local protection is provided by 16 tertiary (TCT) collimators and by 4 physics debris absorbers (IR1 and IR5 only). Injection and dump protection elements are installed in IR2, IR8 and IR6. Various passive absorbers and masks are also available for dedicated local protections (not discussed here).

The collimators are installed in a variety of azimuthal orientations (see Fig. 2) and materials (CFC, Cu, W). Robust TCP and TCSG collimators sit at about 6 and 7 sigmas from the circulating beams (minimum full gap at 3.5 TeV is 3 mm, see the IR7 case in Fig. 3). Higher-Z collimators, more efficient to catch electromagnetic showers but also more fragile against beam losses, have typical settings above 10 sigmas.

* Stefano.Redaelli@cern.ch

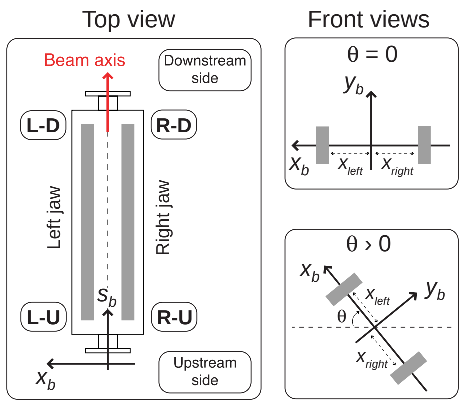

Figure 2: Schematic layout of an LHC collimator. Each jaw is moved with two independent stepping motors. Six linear variable differential transformers (LVDTs) measure the jaw corner positions and the collimator gaps at each jaw extremity. Four resolvers monitor the motor steps for a fully redundant position survey [3].

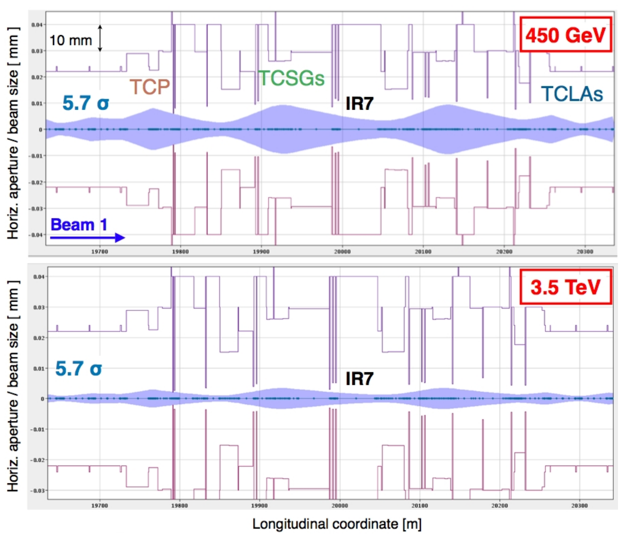

Figure 3: Horizontal aperture, collimator jaw positions (vertical bars) and 5.7 σ beam envelope at injection (top) and 3.5 TeV (bottom) in the betatron cleaning (IR7) from the LHC on-line model application [4].

With the exception of two one-sided TCDQ protection elements, each collimator has two jaws that are moved by 4 independent stepping motors, for adjustments of jaw positions and angles. The performance of the collimator control system is presented in [3, 5]. Note that a special feature of the control system is that the stepping motors can be driven through arbitrary functions of time. This is used to move the collimators synchronously to other accelerator systems like power converters and RF and to ensure optimum collimator settings during critical machine phases such as the energy ramp and the betatron squeeze.

COLLIMATOR SETTINGS

Collimator Setting Calculations

Collimator half-gap values, h, are expressed in units of the local *effective* beam size in the collimation plane, σ_{coll}:

$$\sigma_{\mathrm{coll}} = \sqrt{\sigma_x^2 \cos(\theta_{\mathrm{coll}})^2 + \sigma_y^2 \sin(\theta_{\mathrm{coll}})^2},$$

where $\sigma_i = \sqrt{\beta_i \epsilon_i / \gamma}$ $(i = x, y)$ are the beam sizes in the horizontal and vertical planes (ϵ_i are the beam emittance is both planes, β_i are the beta functions, γ the relativistic factor) and θ_{coll} is the collimator angle (e.g., $\theta_{\mathrm{coll}} = \pi/2$ for the vertical plane, see Fig. 2). The collimator half gaps are calculated as $h = n_\sigma \times \sigma_{\mathrm{coll}}$. For example, in IR7 at 450 GeV, $n_\sigma = 5.7$ for TCPs and $n_\sigma = 6.7$ for TCSGs. The collimator jaw positions are typically set symmetrically around the beam position, x_{beam}, as

$$\mathrm{jaw} = x_{\mathrm{beam}} \pm n_\sigma \times \sigma_{\mathrm{coll}}.$$

These simple analytical expressions are not adequate to optimize the collimator settings in all machine configurations. More generic expressions, based on linear scalings of the parameters involved, have been implemented in various mathematical packages that generate motor settings as a function of time for the collimator control system.

The half-gap function versus energy is expressed as

$$h(\gamma) = n_\sigma(\gamma) \times \sigma_{\mathrm{coll}}(\gamma),$$

where $\gamma = \gamma(t)$. During the energy ramp, we assume for simplicity that n_σ and the beam size $\sqrt{\epsilon\beta}$ scale linearly with γ. We do not have stopping points at intermediate energies and hence no beam-based setup is available. A linear interpolation between the beam-based parameters at injection and flat-top yields:

$$\begin{aligned} h(\gamma) &= \left[n_{\sigma,0} + \frac{n_{\sigma,1} - n_{\sigma,0}}{\gamma_1 - \gamma_0}(\gamma - \gamma_0) \right] \times \\ &\times \frac{1}{\sqrt{\gamma}} \left[\frac{\sqrt{\epsilon_1 \beta_1} - \sqrt{\epsilon_0 \beta_0}}{\gamma_1 - \gamma_0}(\gamma - \gamma_0) \right]. \end{aligned}$$

The indexes “0” and “1” indicate injection and top-energy parameters, or the parameters at the beginning and at the end of the squeeze. The beam centre is also expressed as a linear function of γ to give the jaw position as

$$\mathrm{jaw}(\gamma) = \left[x_{\mathrm{beam},0} + \frac{x_{\mathrm{beam},1} - x_{\mathrm{beam},0}}{\gamma_1 - \gamma_0}(\gamma - \gamma_0) \right] \pm h(\gamma).$$

The same formalism is used to compute the limit functions for each collimator motor axis (4) and gap (2) [5]. A total of 28 functions per collimators are generated for each machine condition. More complex functional dependences could easily be implemented but this first linear approach proved to provide good performance.

Note that the beam size $\sigma_{\mathrm{coll}} = \sigma_{\mathrm{coll}}(\gamma)$ is also a function of the optics and therefore it changes, for the tertiary collimators in the experimental regions, during the betatron

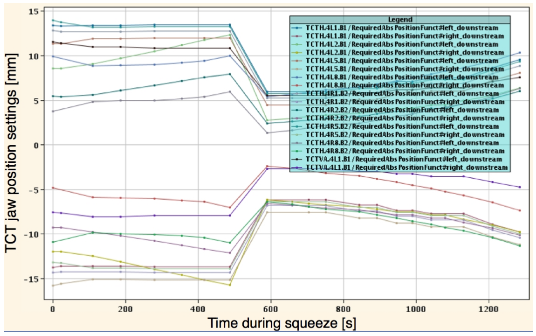

Figure 4: Settings generated for the TCT jaws in all IRs during the squeeze, taking into account (1) the settings of Table 2, (2) the beam-based orbit positions and (3) the beam size variation during the change of optics.

squeeze that is carried out at constant energy [6]. During the squeeze, linear piece-wise functions are used to interpolate x_{beam} settings, following the different crossing angle and beam separation configurations (see next section). An example of squeeze settings for the TCT collimators in all IRs, which take into account variation of beam centre, optics and n_σ settings, is given in Fig. 4.

Optimized Collimator Settings

Nominal collimator settings for optimum performance are established in detail [2] but impose tight tolerances on the stability of machine parameters such as orbit and optics. Following initial ideas in [7], a set of relaxed settings is adopted, where increased collimator retractions at top energy allow operating the machine with larger operational margins. The collimator settings for each LHC configuration are listed in Table 2 for all collimators types and for each machine phase. Note in particular a 5 sigma margin between the TCTs in all IRs and the dump protection elements (it would be below 1 sigma with the nominal settings). Relaxed settings are only possible with a reduced β^* operation, hence the limit to 3.5 m adopted so far [6].

Operational sequences are provided to smoothly run through the different setting sets. An example is given in Fig. 5, where the gaps of a selected sample of collimator is shown as a function of time during one fill (bottom graph). The current of the LHC dipoles and of a matching quadrupole indicate the different machine configurations (top). In this example,, tertiary collimators are moved with discrete steps.

Establishment of Beam-based Parameters

The collimation cleaning performance and the passive protection functionality rely on respecting *hierarchy* between collimators of different functional types, e.g. TCPs must act all the time as first aperture bottleneck and high-Z devices must remain in the shadow of robust collimators. The best performance is achieved by using a set of beam-based parameters for beam size and orbit position at each collimator. This is mandatory in order (1) to compensate

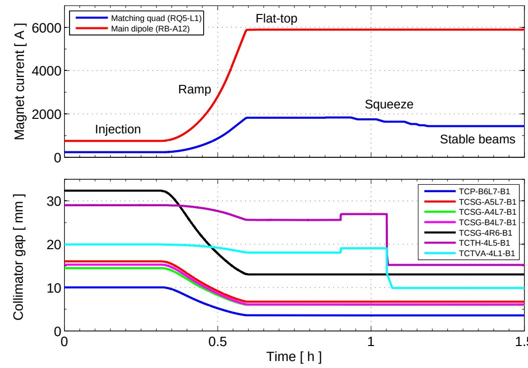

Figure 5: Operational cycle for a selected number of collimators. Measured magnet currents (top) and collimator gaps (bottom) versus time are given for a typical LHC fill.

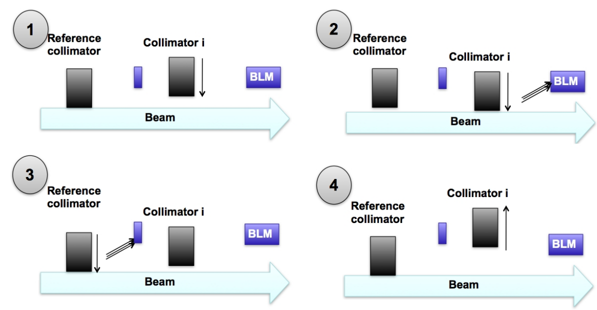

Figure 6: Scheme of the collimator setup procedure [8].

unknown offsets of the collimator alignment with respect to the nominal closed orbit, (2) to avoid systematics of the readings of beam position monitors and also (3) to take into account local errors of the beta functions.

The procedure for the determination of local beam size and orbit (Fig. 6) has been established [8] based on the experience gained with prototype beam tests at the SPS [9]. The beam halo is shaped with a reference collimators (1), typically a TCP, that is closed to a known half-gap of 3 to 5 sigmas. This reference halo is used to cross-align other collimators by moving their jaws in small steps of 5 μm to 20 μm until the halo is *touched*, with symmetric beam loss responses from left and right jaws (2). This gives the local orbit position. The reference collimator is then closed further (3) until it touches the halo again: this allows one to cross-calibrate the gaps of the two collimators. The average of initial and final gaps of the reference collimator in units n_σ gives the normalized gap of the other collimator. Finally, the latter is opened to its nominal settings (4).

The experience at the LHC showed that, at injection (larger gaps) the beam-based determination of σ_{coll} provides consistent collimation hierarchy. With smaller gaps at top energy, the procedure is more sensitive on gap measurement errors. As the LHC optics is well under control and essentially within the specification from cleaning requirements [10], the top energy settings are actually relying on the nominal beta functions and not on the beam-based values. The beam-based orbit is instead used in all cases.

Table 2: Main Beam Parameters and Collimator Settings for the Present LHC Run Configurations

Parameter	Unit	Plane	Type	Set 1	Set 2	Set 3	Set 4	Set 5
				Injection	Top energy	Crossing	Squeeze	Collision
Energy	[GeV]	n.a.	n.a.	450	3500	3500	3500	3500
β^* in IR1/5	[m]	n.a.	n.a.	11.0	11.0	11.0	3.5	3.5
β^* in IR2/8	[m]	n.a.	n.a.	10.0	10.0	10.0	3.5	3.5
Crossing angle IR1/5/8	[μrad]	n.a.	n.a.	170	170	100	100	100
Crossing angle IR2	[μrad]	n.a.	n.a.	170	170	110	110	110
Beam separation	[mm]	n.a.	n.a.	2.0	2.0	2.0	2.0	0.0
Primary cut IR7	[σ]	H,V,S	TCP	5.7	5.7	5.7	5.7	5.7
Secondary cut IR7	[σ]	H,V,S	TCSG	6.7	8.5	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H,V	TCLA	10.0	17.7	17.7	17.7	17.7
Primary cut IR3	[σ]	H	TCP	8.0	12.0	12.0	12.0	12.0
Secondary cut IR3	[σ]	H	TCSG	9.3	15.6	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H,V	TCLA	10.0	17.6	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H,V	TCT	13.0	35.0	35.0	15.0	15.0
Physics debris collimators	[σ]	H	TCL	out	out	out	out	out
Primary protection IR6	[σ]	H	TCSG	7.0	9.3	9.3	9.3	9.3
Secondary protection IR6	[σ]	H	TCDQ	8.0	10.6	10.6	10.6	10.6

Detailed comparison of the collimator beam-based parameters and of other beam measurements are ongoing.

As the collimator set-up procedure is time consuming (15-30 minutes per collimator) the present modus of operation was based on fixed collimator settings that are kept constant fill after fill. The machine is then corrected to the same reference orbit used for the collimator alignments in each machine configuration.

PERFORMANCE

The fill-to-fill reproducibility of the collimator positions is of a few microns. A typical example for one jaw of a TCP collimator is given in Fig. 7. This result confirm the findings of the hardware commissioning [5] in the real LHC accelerator environment with circulating beams and magnets powered. This is a key ingredient for the system performance because the collimator settings are kept the same

The collimator settings of each machine configuration are validated with dedicated loss maps studies that are used to determine the cleaning performance of the system and the collimation hierarchy (see also [8]). Artificially high loss rates are induced by driving transverse beam instabilities, e.g. by crossing the third-order resonance, or by changing the RF frequency. In these conditions, it is verified that (1) the hierarchy is respected, by checking that the relative loss rates at the different collimators are in agreement with the predictions or within tolerable levels and that (2) the leakage of losses to the other machine equipment, in particular the superconducting magnets, are as expected.

A vertical beam 1 loss map recorded at top energy with squeezed, colliding beams is given in Fig. 8. This was obtained by moving the beam across the vertical third order resonance. Beam losses recorded by about 4000 monitors around the ring [11] are plotted as a function of the longitudinal coordinate for the collimators (black), for cold elements (blue) and for warm ones (red). Losses are normalized with the peak loss at the primary collimator in IR7. It is clear that the primary loss location occurs at the TCP collimators in IR7 (see also details of IR7 region in Fig. 9). In this example, the maximum leakage to superconducting magnets, defined as the ratio between highest loss spike in a cold element and the TCP loss, is about 0.00018 for a cleaning efficiency of 99.982 %. This calculation based on the ratio of the beam loss monitor signals at the various elements is a preliminary estimate of the cleaning performance of the system. More detailed calculations must take into account the ratios of the deposited energy in different elements (studies are ongoing). An error analysis is also ongoing.

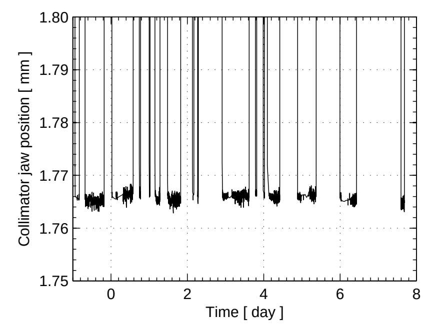

Figure 7: End-of-ramp settings for one TCP jaw as a function of time over 9 days. The fill-to-fill reproducibility with all the LHC equipment active is of a few μm, confirming the results of [5] in the real accelerator environment.

The cleaning achieved with loss maps in all planes and beams for the same conditions (squeezed, colliding beams), is summarized in Table 3. For betatron losses, the limiting location is always found in the magnets of the cold dispersion suppressor downstream of IR7. This is a predicted limitation of the collimation Phase I system that will be addressed by a system upgrade [1]. An example of hierarchy

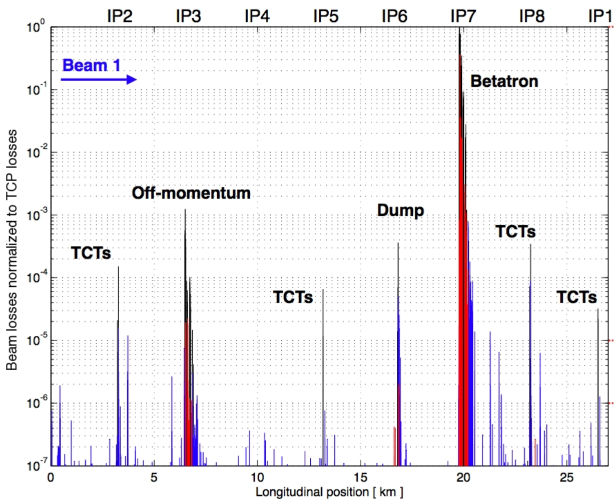

Figure 8: Vertical loss maps for beam 1 at 3.5 TeV with squeezed, colliding beams (setting set 5 of Table 2).

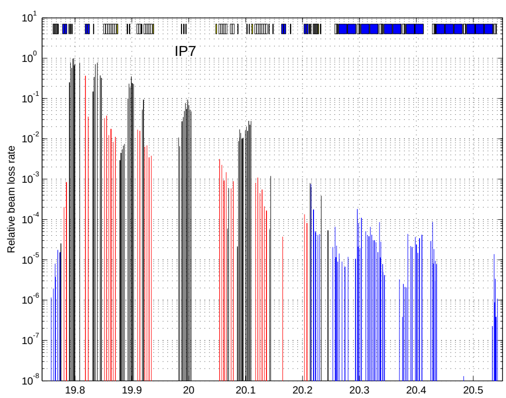

Figure 9: Zoom around IR7 of the loss map of Fig. 8.

and cleaning in IR3 during momentum losses is given in Fig. 9. The efficiency of the momentum cleaning is typically a factor 100 worst than the betatron cleaning.

CONCLUSIONS

The LHC collimation system has been successfully commissioned for the LHC proton LHC runs. The preliminary operational performance was presented. A complex handling of collimator settings is required to ensure optimum settings in each machine configuration. Tools have been developed to cope with this complexity. The results of the first commissioning experience are very encouraging. Cleaning efficiencies above 99.98 % are achieved. No beam-based quenches were experienced so far with total stored beam energies up to 3 MJ. The leakage of halo particles is peaked at the dispersion suppressors downstream of the betatron cleaning, in agreement with predictions, and this will represent a future limitation of the system. Based on these results achieved so far, the LHC is entering a new operation phase that is expected to carry the machine to stored energies of 25 MJ by the end of the 2010 run, with an ambitious luminosity goal of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The LHC collimation is ready for this challenge.

Table 3: Betatron Cleaning Efficiency at 3.5 TeV in Collision with all Interaction Points Squeezed to $\beta^* = 3.5$ m

Beam and plane	Leakage	Efficiency
B1 – horizontal	2.37E-04	99.976
B1 – vertical	1.79E-04	99.982
B2 – horizontal	3.86E-04	99.961
B2 – vertical	1.72E-04	99.983

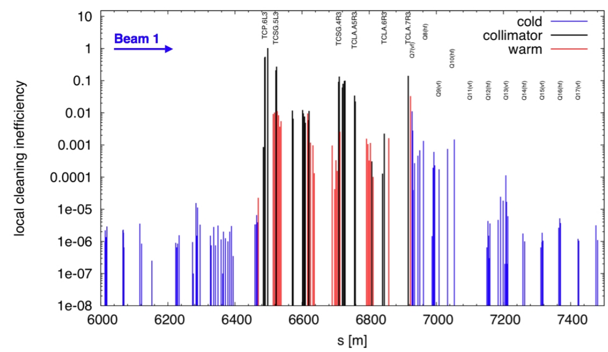

Figure 10: Momentum loss map for beam 1 at 3.5 TeV.

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