PARAMETRIC STUDY OF A TWO-STAGE BETATRON COLLIMATION FOR THE PS2

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Abstract

Beam losses are a major limiting factor in the performance of any high intensity synchrotron. For the new CERN Proton Synchrotron 2 (PS2), an overall low loss design has been adopted. However, it is unavoidable that due to different processes a certain fraction of particles leave the beam core populating the so-called beam halo. A collimation system removes in a controlled way all particles outside the prescribed betatron and momentum acceptances. This article presents a two-stage betatron collimation design as an optical device for different long straight section layouts. Parametric studies for the different main design parameters are presented and their influence in the expected cleaning efficiency of the system is analyzed and compared to the accepted thresholds of admissible losses.

INTRODUCTION

Optics design of collimation systems has been extensively treated in previous works [1, 2, 3], and codes (e.g. DJ [4]) were developed in order to minimize the escaping halo between different stages of a collimation system. The relative phase advance between the different collimation stages is pointed out in all cases as a key parameter to maximize the cleaning efficiency. Nevertheless, in small and medium size accelerators space constraints are tight, preventing an optimal collimation system design. The new racetrack CERN PS2 will feature a two-stage betatron collimation system in one of the two long straight sections with fixed optics. In this article the main relevant optics parameters of a betatron collimation system are discussed and evaluated to optimize the cleaning efficiency in the PS2.

OPTICS MODEL OF A COLLIMATION SYSTEM

A collimation system is intended to absorb particles outside defined limits (so-called beam halo) before they reach the magnets, damaging and radioactivating them. The most common way to do that is to place blocks of certain materials as the closest element to the beam to intend to absorb these particles in a controlled way. However, it is unavoidable that a certain fraction of this halo will be outscattered back to the vacuum chamber after losing energy and with an increased divergence. For this reason a second stage located at a certain retraction from the first is needed to trap these scattered particles. A two stage betatron collimation system is designed for the PS2 where the primaries act as pure scatterers increasing the divergence of the particle, and thus the probability of being absorbed in the secondaries. For the present study, each collimator is composed by two parallel movable straight jaws.

The collimation process and the main optics parameters involved can be summarized in the following points.

- Due to different diffusion processes [5], particles leave the beam core drifting towards larger amplitudes with a certain diffusion velocity (v_{diff}). The collimators define the minimum transverse acceptance seen by the beam during along the ring (Fig. 1). Assuming a slow diffusion process [2], particles will impact first tangentially to the collimator jaws (red dots in Fig. 1). Additional collimators at different azimuthal angles could be added to assure the same acceptance in any radial direction.

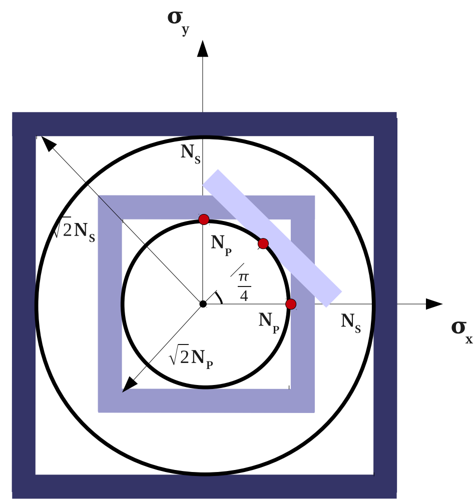

Figure 1: Transverse view of a two stage collimation system in number of betatronic sigmas (with $\sigma = \sqrt{\beta\epsilon}$). The half aperture of primary collimators in both planes is $N_P\,\sigma$ and $N_S\,\sigma$ for the secondaries. In a slow diffusion process the beam halo particles will impact first tangentially to the jaw, i.e. in its middle point.

- At a certain excursion the particle finally hits the primary collimator and gets scattered to larger amplitudes. Depending on the particle's divergence at the jaw collimation, the impact would be at the front or along the edge. In both cases it is possible to define an impact parameter (d) as in Fig. 2.
- For systems where primaries are meant to be only scatterers, the length (l_P) should be adjusted to provide enough divergence to reach the secondaries with the fewer number of passages through them, while assuring the own survival of the scrapers.

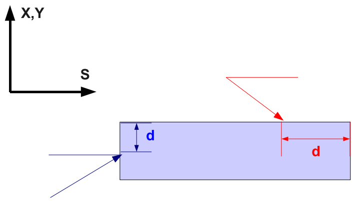

Figure 2: Sketch of different definitions of the impact parameter (d) for different optics at the location of the jaw. For positive divergences particles will impact along the edge of the jaw and for negative in the front end. According to [6], the impact parameter grows linearly with halo transverse diffusion velocity.

- The relative phase advance (μ) between successive collimation stages has been pointed out by many studies as one of the main design parameter of a collimation system. It was proved [2] that for a given retraction between primaries and secondaries the escaping halo in the collimated plane is minimized (considering one dimensional scattering) for a certain betatronic phase advance given by,

$$\mu_{\mathrm{S},1} = \cos^{-1}\left(\frac{N_{\mathrm{P}}}{N_{\mathrm{S}}}\right), \qquad \mu_{\mathrm{S},2} = \pi - \mu_{\mathrm{P}}, \tag{1}$$

with $\mathrm{N_P}$ and $\mathrm{N_S}$. A second secondary at $\mu_{\mathrm{S},2}$ is needed to trap particles scattered with negative divergence (Fig. 3).

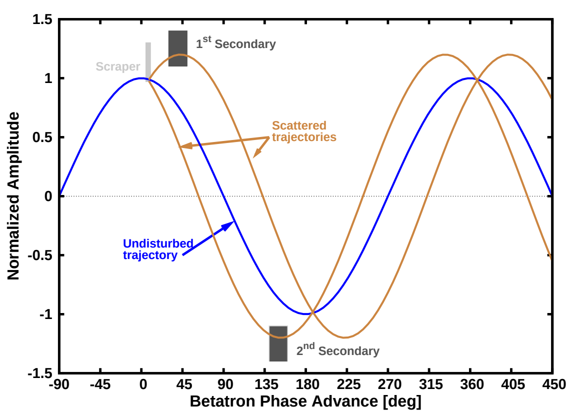

Figure 3: Sketch of particle trajectories after traversing the scraper considering scattering only in the collimation plane. Two sets of secondaries are required to optimize the absorption efficiency.

- The scattering process is isotropic, meaning that the particle is deflected as well in the plane orthogonal to the collimation process. The emittance growth in each plane due to a increased divergence is related with the β function at that location by,

$$\epsilon_{\mathrm{x,y}} = \epsilon_{0,\mathrm{x,y}} + \beta_{\mathrm{P,x,y}}\theta^2, \tag{2}$$

where ϵ_0 is the emittance before scattering, β_{P} is the betatronic function at the scatterer location and θ the kick received by the particle. A detailed study of optimal phase advances for scattering in different azimuthal directions is presented in [2]. In these cases the phase advances are fixed independently of the ratio between apertures so, of not application to any given optics. To minimize the effect of orthogonal scattering, locations with similar β functions in both planes should be aimed for.

- Finally, in order to evaluate the performance of a collimation system a reasonable estimation of the beam halo population and beam power to be absorbed by the collimators is needed.

PS2 LATTICE

As a high intensity machine PS2 is following a low loss design (e.g. the negative momentum lattice prevents from transition crossing losses). In this respect a two stage betatron collimation system is designed to prevent uncontrolled losses from beam halo formation. The integration of PS2 in the CERN acceleration complex suggests a racetrack lattice, to perform injection and extraction in the same long straight section (LSS). RF cavities (upstream) and the collimation system (downstream) will be placed in the opposite LSS.

Two main layouts for the straight section have been considered during the PS2 lattice design process. A 145 m long LSS with a middle triplet [7] and more recently a 108 m long LSS with a middle doublet [8]. Table 1 shows main parameters for collimation design in each case.

Table 1: Main Parameter of the LSS Versions Considered for the PS2 Lattice

Parameter	Doublet	Triplet
Length [m]	107.9	145.0
$\beta_{\mathrm{x,y,prim}}$ [m]	(21.4,41.2)	(18.1,48.4)
$\alpha_{\mathrm{x,y,prim}}$ [-]	(0,0)	(-0.6,2.3)
$\Delta\mu_{\mathrm{coll,x,y}}$ [deg]	(124,100)	(198,144)
$\mathrm{N_P}$ [σ]	2.5	3.5
$\mathrm{N_S}$ [σ]	3.0	4.0
$\mu_{\mathrm{opt,x,y}}$ [deg]	(29,151)	(31,149)

High brightness machines tend to enlarge the beam sizes to avoid collective effects. This leads to small ratio between machine acceptance and beam size. At PS2 a combination of ($\mathrm{N_P}$,$\mathrm{N_S}$)=(3.5,4.0) was considered for the triplet option, and a revised ($\mathrm{N_P}$,$\mathrm{N_S}$)=(2.5,3.0) for the new doublet. As quoted in Table 1 a reduction in the aperture of primaries and secondaries of 1 σ does not change the theoretical optimal phase advances required. However, the shortening of the LSS reduces the phase advance available not meeting the theoretical requirements.

The transverse shape of the vacuum chamber for different PS2 elements is defined as a superellipse [9] with coefficient $n = 3$.

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1, \tag{3}$$

with a and b the semi-diameters for each element. The large acceptance in all azimuthal angles of this particular shape prevents from needing to add tilted collimators.

Table 2 presents phase advance and half apertures for the each LSS configuration. According to [3] an additional set of collimators can be added at 90° to improve efficiency.

Table 2: Collimator Parameter List for the Triplet Variant (upper half) and the Doublet (lower half)

Collimator	Angle [rad]	$\phi_\mathbf{x}$ [deg]	$\phi_\mathbf{y}$ [deg]	N$_\sigma$ [-]
TCP.H.1	0	0	0.0	3.5
TCP.V.1	$\frac{\pi}{2}$	0	0.0	3.5
TCS.H.1	0	29	34	4.0
TCS.V.1	$\frac{\pi}{2}$	27	29	4.0
TCS.H.90	0	90	52	4.0
TCS.V.90	$\frac{\pi}{2}$	118	90	4.0
TCS.H.2	0	148	110	4.0
TCS.V.2	$\frac{\pi}{2}$	200	133	4.0
TCP.H.1	0	0	0	2.5
TCP.V.1	$\frac{\pi}{2}$	0	0	2.5
TCS.H.1	0	29	14	3.0
TCS.V.1	$\frac{\pi}{2}$	38	29	3.0
TCS.H.90	0	100	72	3.0
TCS.V.90	$\frac{\pi}{2}$	104	73	3.0
TCS.H.2	0	119	90	3.0
TCS.V.2	$\frac{\pi}{2}$	123	95	3.0

PS2 COLLIMATION SYSTEM OPTIMISATION

State-of-art of collimation tools used for LHC and RHIC studies [10] are adapted and used for PS2 simulations. The scattering routines are revised and updated for the PS2 energy range (E_{kinetic}=1-50 GeV). Benchmarking of these tools were done during CERN PS Continuous Transfer extraction were beam loss pattern measured by the BLMs were successfully reproduced [11]. Beam halo formation in a space charge dominated beam simulations for PS2 [12] are still ongoing, so for the present studies a slow diffusion process is considered, varying the average impact parameter (pencil distribution) to simulate different v_{diff}.

The aperture of the collimators and relative retraction between the different stages set the optimal phase advances for the secondaries. Next, the length of the scatterer is optimized to reach the secondaries in the fewer number of turns to minimize the power deposited in the scraper. At first approximation for thin scatterers ($l_{\text{scatt}} \ll \lambda_I$), the scatterer length can be approximated considering only Multiple Coulomb Scattering (MCS). From [13] for the MCS there is a Gaussian approximation for the central 98% of the projected angular distribution with a width give by [13],

$$\theta(s) = \frac{13.6\text{MeV}}{\beta_{\text{rel}} cp}\sqrt{\frac{x}{\chi_0}}\left(1 + 0.038 \ln\frac{x}{\chi_0}\right), \quad (4)$$

where p, $\beta_{\text{rel}} c$ are the momentum, velocity, and x/χ_0 is the thickness of the scattering medium in radiation lengths. The theoretical lengths to reach the secondaries for copper and tungsten are presented in Table 3 for the different LSS variants.

Table 3: Theoretical Scraper Length to Reach Secondaries for a Single Passage Assuming Only Multiple Coulomb Scattering

Material	$L_{\text{Doub,x,S}}$ [m]	$L_{\text{Trip,x,S}}$ [m]	$L_{\text{Doub,y,S}}$ [m]	$L_{\text{Trip,y,S}}$ [m]
C	0.006	0.01	0.0008	0.003
W	0.0001	0.0002	0.00004	0.00005

The results presented next, if not stated contrary, are for tungsten for both, primary and secondaries, and for the triplet variant of the LSS.

Considering the values in Table 3, different lengths of scatterers are scanned to find the optimal. The length traversed in the scatterer (and thus the kick received) is a function of the impact parameter. Figure 4 top, presents the length traversed in the scatterer during the first impact compared to the RMS value given by Eq. (4) (green line). For small impact parameters the particle is outscattered before traversing the complete length. For larger impact parameter the length traversed increases until a steady state where the particle traverses completely the scraper. The number of passages needed are then related with the length of the scraper and the impact parameter (Fig. 4 middle). Around $d \sim$3 10^{-7}, the multiple passage regime changes to a single passage one. Combining number of passages and length traversed (Fig. 4 bottom) it can be seen that there is transition regime centered around 10^{-7} m where there is a minimum in the total length traversed. This minimum is explained from the Monte Carlo nature of the scattering process, as in that region some particles can receive enough kick to reach the secondaries while others would need subsequent passages.

To evaluate the performance of the system the cleaning efficiency is calculated. The cleaning efficiency is defined as the ratio between particles absorbed by the collimators with respect to the initial complete beam halo. In Fig. 5 the cleaning efficiency is evaluated for an horizontal (top) and a vertical halo (bottom). Similarly to Fig. 4 a minimum is found around 10^{-7} m, as in this intermediate regime there will be particles which will not reach the secondaries in a single passage, however in a second passage they will traverse the complete length and being overkicked and lost. It is worthy to note that the efficiency increases with the length of the scatterer as the available acceptance allows to provide kicks larger than the theoretical minimum without compromising the efficiency. However the increased efficiency for larger lengths as well means a deeper minimum (up to 2% less) as the limit between single passage and overkicked is decreased.

In order to evaluate the effect of the orthogonal scattering, the absorptions of horizontal and vertical collimators

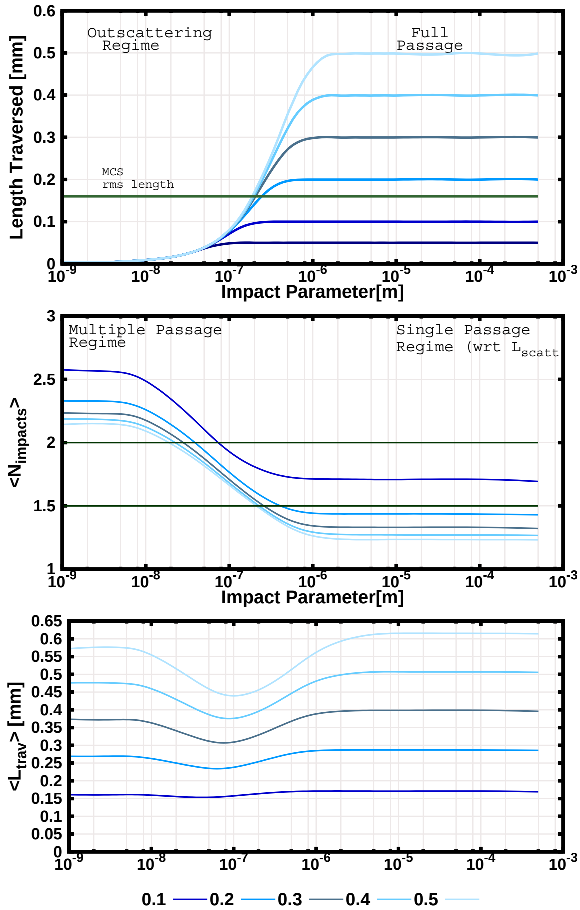

Figure 4: Top, average length traversed in the scatterer during the first passage at the primary. The green line denotes the equivalent length to receive the necessary kick to reach the secondaries. Middle, average number of passages needed to reach the secondaries or being lost. Bottom, average total length traversed in the primaries. In all three plots the results are scanned for different scatterer lengths and average impact parameters.

for a horizontal and vertical halo are shown in Fig. 6. The ratio between (β) functions at the location of the scatterer ($\beta_y \approx 2.5\beta_x$) together with the fact that kicks required to reach the secondaries are of same magnitude of the emittance, can cause losses in the vertical plane for an horizontal halo. As shown in Fig. 6 for a vertical halo (bottom), vertical collimators (right) absorb most of the halo (80%), while for an horizontal halo (top), due to the orthogonal contribution, the absorptions are equally distributed in both. This raises the concern that the beam loading in vertical collimators is 75% of the total.

From an optic point of view, different materials for the scraper are translated into different kicks per unit length. On the other hand a larger scatterer would lead to a larger probability of nuclear interactions. Comparing the behavior of a copper and a tungsten scatterer, it is found that the efficiency profile presents again a minimum. The larger lengths required for lighter materials displaced the transition region from multiple to single passage towards larger

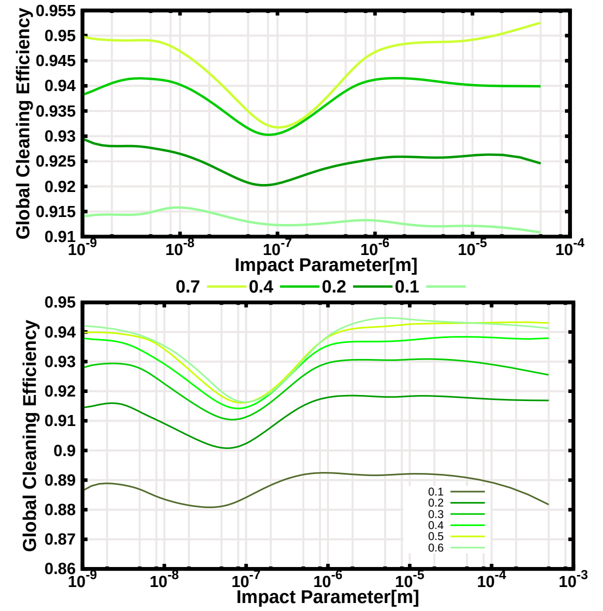

Figure 5: Cleaning efficiency of an extended collimation system (added 90° collimators) for the triplet variant of the LSS for a horizontal halo (top) and a vertical one (bottom).

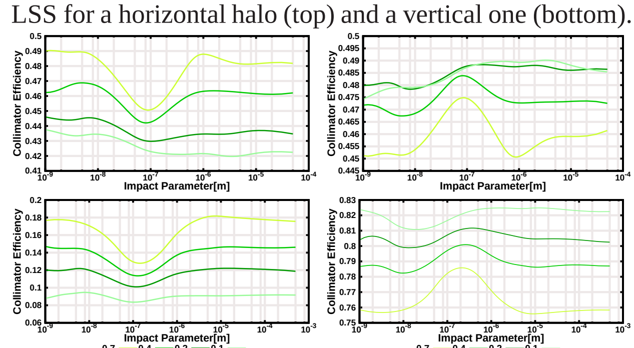

Figure 6: Cleaning efficiency for an horizontal halo (top) and a vertical one (bottom), distinguishing between in beam loadings in horizontal collimators (left) and vertical (right) for different scrapers' length and impact parameters. The larger orthogonal scattering in the vertical plane makes the vertical collimators absorb almost 50% of the scattered particles from the horizontal plane.

impact parameters ($\sim$6 10^{-6} m) as shown in Fig. 7.

The validation of the system is done against the common threshold of 1 W/m average losses along the machine. From CERN PS operation, the PS2 expected halo is $\sim$3% of the total beam intensity [14], with most of the losses observed to happen at the end of the first parabolic ramp at the beginning of the cycle ($E_{kinetic}$= 5 GeV). Considering the Fixed Target beam, this assumptions give P_{halo} =10 kW. For the global cleaning efficiencies calculated before the system is always below the 1 W/m limit (Fig. 8). A two stage system according to (1) fulfills as well the requirements, additional 90° improves almost by four units the efficiency. Future upgrades adding possible collimators in the remain space available could raise the efficiency up to 99% (Fig. 8 top). Looking now into the average loss power along the accelerator, the theoretical two stage system al-

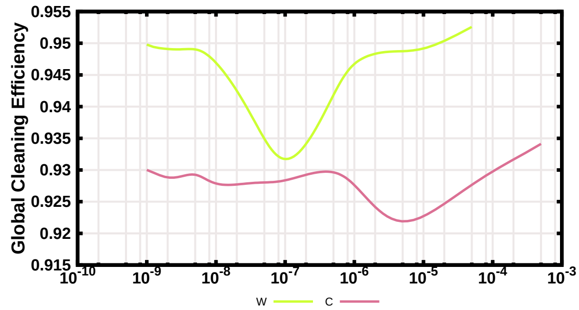

Figure 7: Top, cleaning efficiency comparison for scrapers' material Tungsten and Copper, with L_W= 0.7 mm and L_C=2 mm.

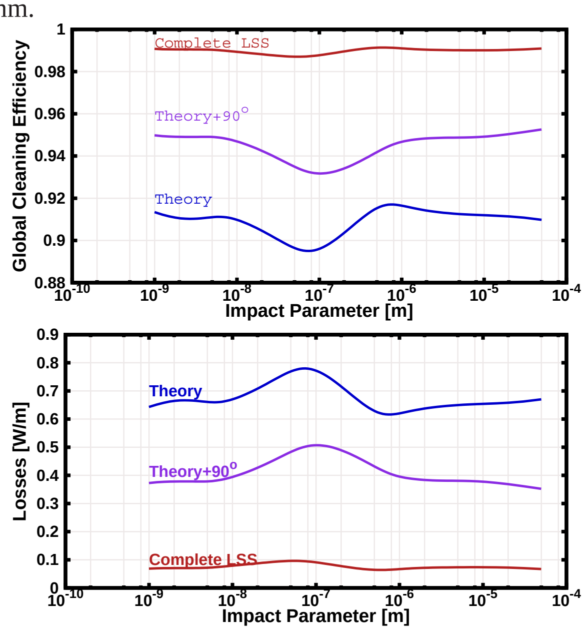

Figure 8: Global cleaning efficiency and distributed power along PS2 considering P_{halo} = 10 kW. Theoretical two stage collimation system (blue), extended case with additional collimators at 90° (purple) and ideal maximum filling filling with collimators the LSS. In both cases the limit of 1 W/m is not trespassed.

ready reduces uncontrolled losses to a reasonable ∼0.7 W/m, however if requested from radio protection group can be reduced to ∼0.1 W/m adding additional collimators.

The histogram of losses along the machine is depicted in Fig. 9 for the extended configuration. Expected hot regions are the second half of LSS2 where the collimation system is placed and the beginning of ARC1 where the 1 W/m limit is barely trespassed. The other sensitive regions as LSS1 (injection/extraction elements) and first half of LSS2 (RF cavities) remain clean. Further energy deposition studies with complete geometry and radio protection considerations are needed to complement the present studies.

Same simulations were carried out for the new LSS variant with the middle doublet with the configuration presented in Table 2. The average efficiency was found to be ∼95.5%, meaning 1 W/m, which again fulfills the requirements for average uncontrolled losses, both globally and locally.

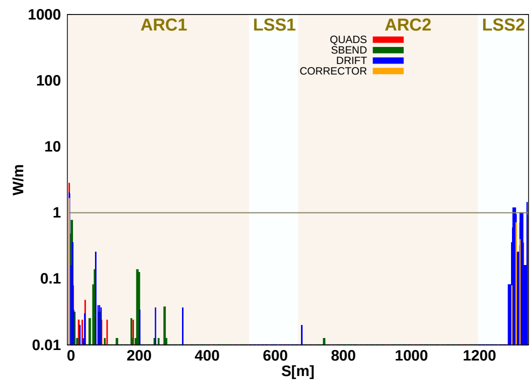

Figure 9: Local cleaning efficiency (losses in the collimators not depicted) for the extended configuration. The limit of 1 W/m is locally fulfilled except in the collimation region and first magnets in ARC1.

CONCLUSIONS

A two stage betatron collimation system is proposed for the new PS2. The expected performance is analyzed with respect to the main parameters involved in the collimation process. It has been shown that there exist a minimum in cleaning efficiency for a certain impact parameter. This minimum correspond to a intermediate regime between multiple and single passage through the scatterer, where due to the Monte Carlo nature of the process some particles will reach the secondaries, while others will be overkicked in second passages. The effect of the orthogonal scattering in the beam loading of the different collimators has been highlighted. The expected performance considering a reasonable beam halo power is under the threshold of 1 W/m for both layouts of the LSS.

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