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caterina.boscolo.meneguolo@cern.ch

Calculation of the allowed aperture for a gas storage cell in IP8

C. Boscolo Meneguolo, R. Bruce, M. Ferro-Luzzi,
M. Giovannozzi, S. Redaelli

Keywords:

Summary

In the framework of the Physics Beyond Collider studies, a working group was created in order to study some specific proposals to perform fixed-target physics experiments at the Large Hadron Collider. Among these proposals, the possibility has been described of installing an internal gas target, injecting unpolarized or polarized gas inside a storage cell (SC) located around the beam, close to the LHCb detector. In this work, the minimum acceptable radius for such a storage cell has been calculated in order to ensure safe operational conditions. An acceptable value is found to be between 3.0 mm and 3.5 mm depending on the SC longitudinal distance from the interaction point (IP) 8, taking into account various beam and optical configurations.

1 Introduction

Among the opportunities explored by Physics Beyond Collider study group [1, 2], some proposals are under study to perform fixed-target experiments at the Large Hadron Collider [3]. These include experiments performed with bent-crystal setups for beam splitting, solid internal targets, and unpolarized or polarized gaseous targets [4, 5, 6, 7, 8, 9]. In particular, a rich program is being explored involving the LHCb detector, exploiting its forward geometry and the pre-existent gas-injection system SMOG [10, 11, 12].

Future upgrades foresee the possibility of installing targets with both unpolarized and polarized gases, thanks to the installation of an open-ended cylindrical storage cell (SC) around the beam. According to the SC technology (described in [13]), the gas is injected at the center of the cell and flows longitudinally through it assuming a triangle-shaped density with a maximum at the center. This particular configuration allows to reach a considerable target thickness, still maintaining an acceptable vacuum pressure in the beam pipe.

The insertion of elements such as a SC inside the vacuum pipe and close to the beam requires extreme care from many points of view. In particular, the aperture of every element all around the accelerator ring has to be protected by the collimation system in order to guarantee safe operation. As a consequence, a minimum acceptable aperture has to be respected in the design of every element to be installed in the LHC.

The purpose of this note is to study the minimum safe radius for a SC to be inserted inside the vacuum pipe in proximity of IP8 for the HL-LHC machine at 7 TeV. The safe aperture is calculated as a function of the maximum longitudinal distance reached by the cell with respect to IP8. Different experimental configurations and scenarios are taken into account in the calculation of the final minimum radius.

2 Configuration assumptions and SC radius calculation

The experimental configuration at LHCb is set in order to let the experiment work at a constant luminosity, which is leveled throughout every fill. This affects the calculation of the minimum safe SC aperture through the separation used for the leveling. The variables to take into account for such a calculation are the value of β^*, the parallel beam separation and the presence of both an external crossing angle and the internal spectrometer angle.

The cell is supposed to be retractable, in such a way that it would be placed at a transverse position centered around the actual beam position once the beams are colliding and stable beam conditions are achieved. Otherwise, the calculation would be dominated by constraints imposed during particular stages of the fill cycle, such as, injection. The calculation will thus focus only on the scenario with colliding beams.

Furthermore, we do not consider any mechanical or alignment tolerances on the SC itself. In this section, we calculate instead the minimum allowed transverse aperture, including such tolerances. This means that the design aperture of the object has to be larger than the values given here.

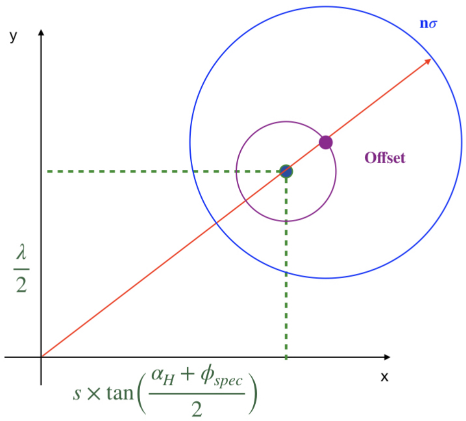
It has to be recalled that around IP8 the LHCb VErtex LOcator (VELO) detector is installed. The VELO's extent is asymmetric on the two sides of the IP, the downstream edge (according to B1 reference system) being further from the IP than the upstream one. The aperture of the VELO was studied in detail and approved [14]. This allows to consider any object to be installed upstream IP8 within the mirror projection of VELO's downstream edge as safe, as long as its aperture is larger than the VELO's, including all tolerances.

2.1 Minimum radius calculation

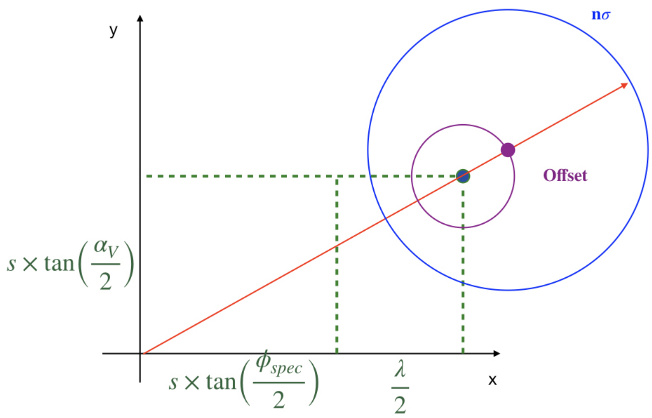
In order to calculate the minimum safe radius for the SC, we consider the transverse plane at an arbitrary s-position upstream of IP8 (according to Beam 1 reference system), and we calculate the maximum extent of the beam envelope at this location as shown in Fig. 1. This sets an inner limit on the aperture of the SC.

The standard crossing configuration assumed at IP8 is given by a horizontal external crossing angle to be summed to the horizontal spectrometer angle, which can be set to have either positive or negative polarity determining the sign. In such a configuration, the two beams are given a parallel separation in the vertical plane to level the luminosity, according to the β^* value and the total crossing angle (see Fig. 1a).

Another possible crossing configuration foresees a rotation of the crossing plane to be performed at every fill during the ramp and squeeze sequence, in order to have a vertical external crossing angle and an horizontal parallel beam separation. Since the spectrometer field remains constant, the internal angle contribution is to be added to the horizontal separation (see Fig. 1b).



(a) Horizontal crossing



(b) Vertical crossing

Figure 1: Schematic drawings of the beam in the transverse plane, explaining how to calculate the maximum extent of the beam envelope at an arbitrary s-location upstream of IP8, considering the geometric configuration, the orbit drifts (offset) and the beam envelope (nσ).

Thus, a first contribution to the aperture calculation is given by the transverse offset of the beam at s, which is given for the two different crossing scenarios by:

$$\begin{aligned} R^{\mathrm{H}} =& \sqrt{s^2 \tan^2\left(\frac{\alpha_{\mathrm{H}} + \phi_{\mathrm{spec}}}{2}\right) + \left(\frac{\lambda}{2}\right)^2} \\ R^{\mathrm{V}} =& \sqrt{\left[s \tan\left(\frac{\phi_{\mathrm{spec}}}{2}\right) + \frac{\lambda}{2}\right]^2 + s^2 \tan^2\left(\frac{\alpha_{\mathrm{V}}}{2}\right)} \end{aligned} \tag{1}$$

where s is the maximum distance from IP8 reached by the furthest storage cell edge, $\alpha_{\mathrm{H(V)}}$ is the horizontal (vertical) external crossing angle, ϕ_{spec} is the spectrometer angle, and $\lambda/2$ is the half parallel separation between the two beams needed for luminosity levelling by separation.

To this nominal offset, a shift given by the expected orbit drift during the physics fill has to be added. The estimate of this offset depends on whether the cell is foreseen to be re-aligned at every fill or not. If this is not the case, the orbit drifts over time are expected to be larger. An offset of 100 μm is assumed for the case of fill-by-fill alignment, while for the second case a pessimistic $\sim$ 2 mm offset is considered, as for the aperture calculations in any HL-LHC element at top energy [15].

As a third contribution, one should consider the beam size along the SC. The cell is assumed to be located inside a drift, and the maximum σ value seen by the SC is reached at the furthest edge of the cell for the IP. As for any aperture calculation in the LHC, it is assumed that the β-function can be up to 20% larger than its nominal value [15]. The effective β-functions used for the aperture calculations, $\tilde{\beta}$ is thus

$$\tilde{\beta}(s) = 1.2 \times \beta(s) \tag{2}$$

The optics correction achieved so far in the LHC is generally very good, in particular at the collision points, where 20% might seem overly pessimistic at a first glance. However, one effect that could alter the effective β-function is that its minimum value, which should ideally be located at the IP, is known to be possibly subject to a shift from -30 cm to +30 cm from IP8 position, as well as to a β-beating effect. To verify the assumption that 20% β-beat covers all cases, $\tilde{\beta}$ was compared to the very pessimistic scenario of a -30 cm waist displacement combined with a β^* 5% reduction effect. It was verified that the $\beta(s)$ calculated in this latter scenario is well below $\tilde{\beta}(s)$ for the nominal value of $\beta^* = 3.0$ m, and at $\beta^* = 1.5$ m they are about the same. The worst case is found for the very pushed $\beta^* = 0.5$ m: in this case the $\beta(s)$ exceeds our assumption within a limited s-range by a variable factor, with the maximum being $\beta/\tilde{\beta} = 1.53$ at $\sim$40 cm from the IP, where the aperture is anyway very large. For $s > 2$ m from the IP, the difference between the two is less than about 15%, and for $s > 4.2$ m, $\tilde{\beta}(s) > \beta(s)$. The waist shift thus gives a larger effective β-function only for the most pushed scenario and only close to the IP.

The beam size σ as a function of s was calculated as

$$\sigma_{x,y}(s) = \sqrt{\varepsilon\left(\tilde{\beta^*_{x,y}} + \frac{s^2}{\tilde{\beta^{*2}_{x,y}}}\right)}, \tag{3}$$

$$\sigma = \max\{\sigma_x, \sigma_y\}, \tag{4}$$

where ε is the geometric beam emittance and $\tilde{\beta^*_{x,y}}$ are the values of β^* for x and y coordinate, scaled as explained.

In particular, for elements installed inside the LHC beam aperture at positions without local protection, a minimum safe aperture of 19.4σ is required for the HL-LHC reference emittance of 2.5 μm, as explained in Ref. [16]. We thus demand that the radius of the SC should stay outside this envelope when added to the central orbit value.

In the hypothesis that the cell would not be aligned at every fill, the contribution from dispersion, as well as the parasitic dispersion from the arc, should also be accounted for [15]. Because of the small β-function, this contribution is anyway negligible with respect to the $\sim$ 2 mm orbit offset and gives a negligible addition to the beam size.

Thus, the sum of the contributions listed above gives the minimum aperture, which can be summarized as follows:

$$R_{\mathrm{t}}^{\mathrm{H,V}} = R^{\mathrm{H,V}} + \mathrm{offset} + \mathrm{n}\sigma \ , \tag{5}$$

$$R_{\mathrm{min}} = \max\{R_{\mathrm{t}}^{\mathrm{H}}, R_{\mathrm{t}}^{\mathrm{V}}\} \ . \tag{6}$$

with $R^{\mathrm{H,V}}$ given by (1), according to the crossing configuration.

2.2 Luminosity leveling and parameters assumed

In order to calculate λ in Eq. (1), we must estimate the separation needed to maintain the target luminosity, which we assume to be 0.2×10^{34} cm^{-2}s^{-1} for the LHCb experiment [17]. The luminosity at the interaction point depends on the beam size (σ_x and σ_y), the parallel separation (λ) and the crossing angle (Φ). For the calculation of λ, we only consider the luminosity reduction due the crossing angle in the crossing plane, discarding any contribution of crossing angles in the separation plane. This assumption is pessimistic: indeed, any further crossing would have the effect of reducing the final luminosity, and hence the needed parallel separation.

Therefore, the following equation was assumed for the luminosity, which is solved for λ:

$$L_{LHCb} = \frac{kN_b^2 f}{4\pi\sigma_x\sigma_y} \exp\Big(-\frac{\lambda^2}{4\sigma_x^2}\Big)\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma}\tan\Phi\right)^2}} \tag{7}$$

where $k = 2572$ is the number of colliding bunches at IP8, f is the revolution frequency, $N_b = 2.2 \times 10^{11}$ is the number of particles per bunch, $\sigma_s = 9.0 \times 10^{-2}$ m is the bunch length. All these parameters are taken from HL-LHC version 1.3 in Ref. [17], and we assume a 20% beta-beating, which could occur in both directoins.

We calculate λ for various scenarios (presented in Sec. 2.3). In each scenario, the β^* and crossing angle are usually fixed. Thus, the half parallel separation was derived from (7), for the beginning of the fill where the largest separation is needed to obtain the target luminosity. The obtained values of λ can then be used to calculate the minimum radius with (5).

2.3 Considered scenarios

The calculation was performed for several scenarios, all characterized by different configuration assumptions. In Table 1 we show the main parameters assumed for the scenarios being studied: the values of β^*, the external half crossing angle $\alpha/2$ (either horizontal or vertical), the internal half spectrometer angle $\phi_{spec}/2$ (which is always considered with negative polarity in order to obtain the most pessimistic total horizontal angle, which gives the most pessimistic aperture), and the half parallel separation $\lambda/2$ (which was calculated for every case in order to obtain the desired operational luminosity, a part from β^*-leveling cases and Van der Meer scans).

The following particular features were assumed for different scenarios:

- *Baseline runs* where all parameters were set to the nominal listed in Ref. [17] for stable beam in HL-LHC.
- *H (V) pushed* scenario presents nominal values for horizontal (vertical) crossing angle and lower values for $\beta^* = 1.5$ m;
- *H (V) very pushed* scenario considers more pushed values of $\beta^* = 1.0$ ($\beta^* = 0.5$-1.0) and larger external crossing angles;
- *Ion runs* are considered assuming a very pushed $\beta^* = 0.5$ m;

	SCENARIOS								
	Base-line	**H pushed**	**H very pushed**	**V pushed**	**V very pushed**	**ion runs**	**Van der Meer**	**H β^*-leveling**	**V β^*-leveling**
β^*_x **[m]**	3.0	1.5	1.0	1.5	0.5	0.5	30.0	12.5	13.5
β^*_y **[m]**	3.0	1.5	1.0	1.5	1.0	0.5	30.0	12.5	13.5
half ext. $\alpha_H/2$ [μrad]	-250.0	-250.0	-320.0			-250.0	-300.0	-250.0	
half ext. $\alpha_V/2$ [μrad]				-200.0	-250.0				-200.0
half int. $\phi_{spec}/2$ (H) [μrad]	-135.0	-135.0	-135.0	-135.0	-135.0	-135.0	-135.0	-135.0	-135.0
half total H angle [μrad]	-385.0	-385.0	-455.0	-135.0	-135.0	-385.0	-435.0	-385.0	-135.0
half parallel separation $\lambda/2$ [mm]	0.038	0.032	0.027	0.035	0.022	0.042	0.72	0.0	0.0

Table 1: Configuration parameters assumed for the scenarios considered.

- *Van der Meer scan* runs are foreseen and we assume that they will be performed with up to $\beta^* = 30.0$ m, half external crossing angle of -300.0 μrad and half parallel separation up to 6.6σ;
- β^**-leveling runs* consist in performing the luminosity leveling by regulating β^*, while nominal external crossing angle (either horizontal or vertical) and no parallel separation are set. The value of β^* was calculated to this purpose from Eq. (7);

It should be noted that the very pushed scenario, as well as the ion scenario, are possibly not realistic given the known constraints of the optics design and aperture at the time of writing. However, these scenarios are studied anyway as limiting cases, in order to stay on the pessimistic side and take into account any possible future improvements.

3 Results

In Fig. 2 the minimum SC radius calculated for the horizontal crossing, pushed scenario, is shown (red solid line), together with the three partial contributions explained in Section 2.1. It should be noted that increasing values in the abscissa of the plot correspond to moving further upstream from IP8 (in Beam 1 reference system), thus to decreasing s-coordinate along LHC circumference.

The radius is plotted in the longitudinal range from 0 to 5.25 m from IP8. The upper limit was chosen because it is the location of the first spectrometer bump compensator. The maximum extent of VELO detector is plotted as well for comparison. As can be seen, the dominant contribution comes from the beam envelope, which is followed by the nominal orbit.

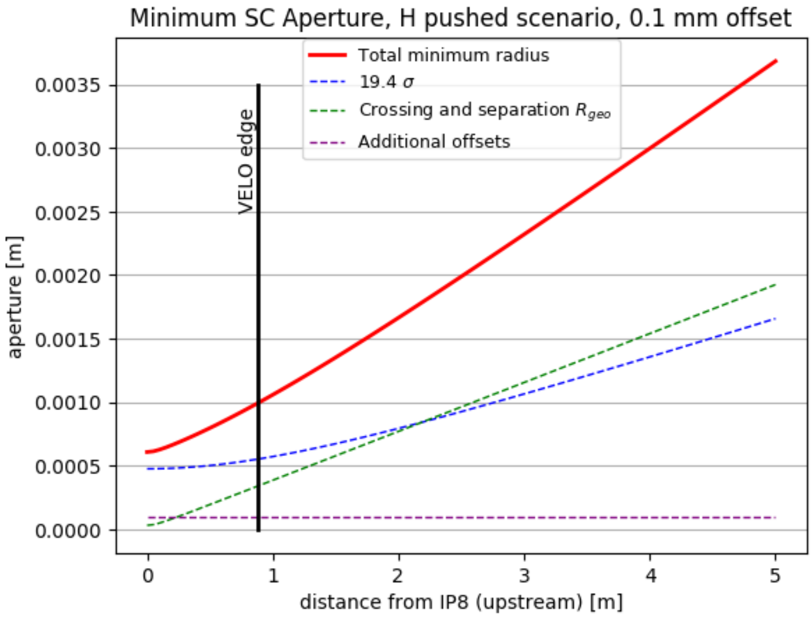


Figure 2: Minimum storage cell aperture for horizontal crossing, pushed scenario ($\beta^* = 1.5$ m). Dashed lines correspond to the contributions explained in Sec. 2.1. Solid red line is the sum of the other three. Black vertical line highlights VELO edge position. A 0.1 mm offset due to orbit drifts is assumed (SC aligned at every fill).

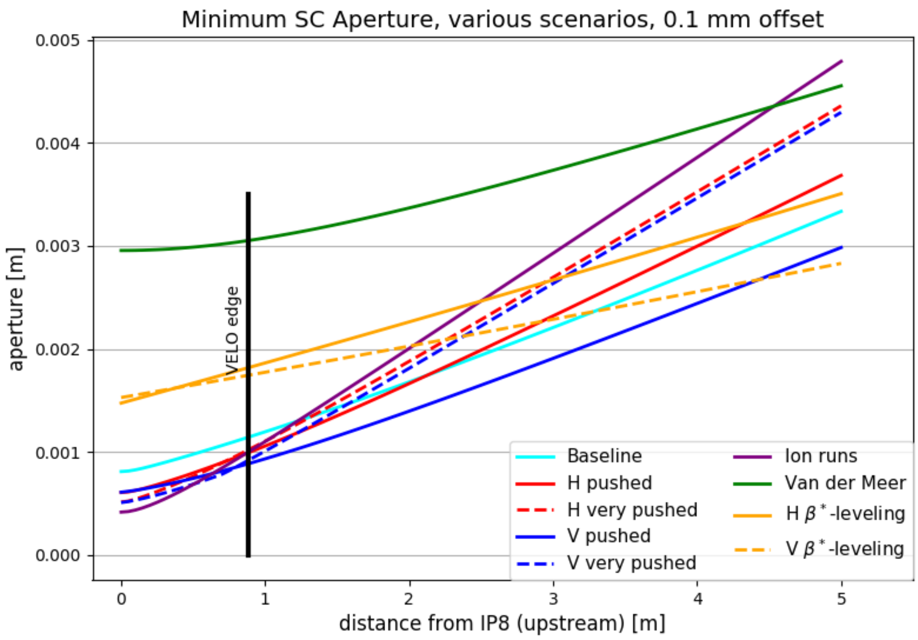


Figure 3: Minimum storage cell aperture for all scenarios. A 0.1 mm offset due to orbit drifts is assumed (SC aligned at every fill).

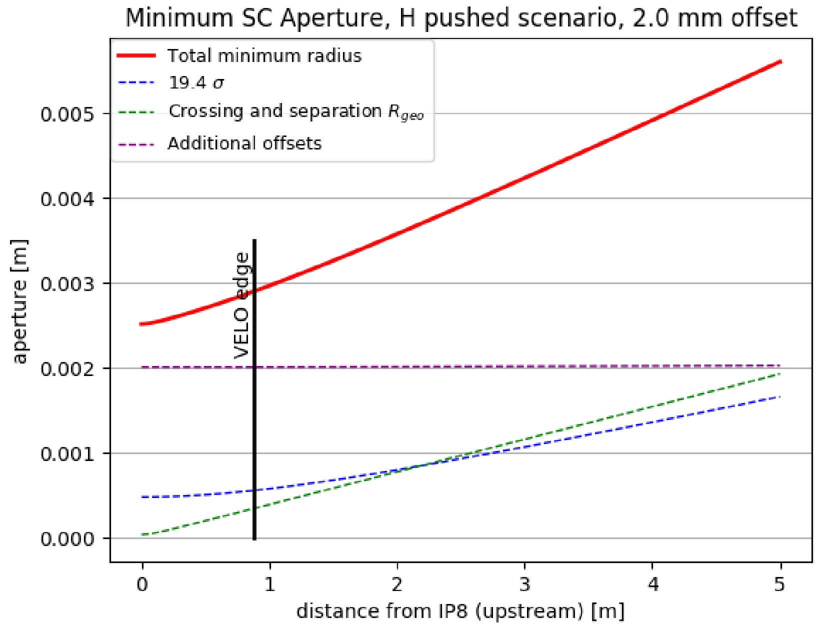


Figure 4: Minimum storage cell aperture for horizontal crossing, pushed scenario ($\beta^* = 1.5$ m). A 2.0 mm offset due to orbit drifts is assumed (SC not aligned at every fill).

Fig. 3 shows the minimum radius calculated for every scenario in Table 1, with all contributions summed. The Van der Meer scan dominates up to c.a. 4.5 m far from the IP, where it's overtaken by the ion runs scenario. These two limits impose a final safe radius of $R_{min} = 3.0 - 4.8$ mm. If Van der Meer scans and ion runs are discarded, then the minimum safe radius has a stronger dependence on the position and varies within the interval $R_{min} = 1.5 - 4.4$ mm.

Results are shown in Fig. 4 and 5 for the case where the SC is not aligned to the beam in every fill, imposing the pessimistic 2 mm offset, which largely dominates in the partial contributions (see Fig. 4). This configuration would impose a minimum radius of 5 to 6.7 mm, or $R_{min} = 3.5 - 6.3$ mm if Van der Meer scans and ion runs are discarded.

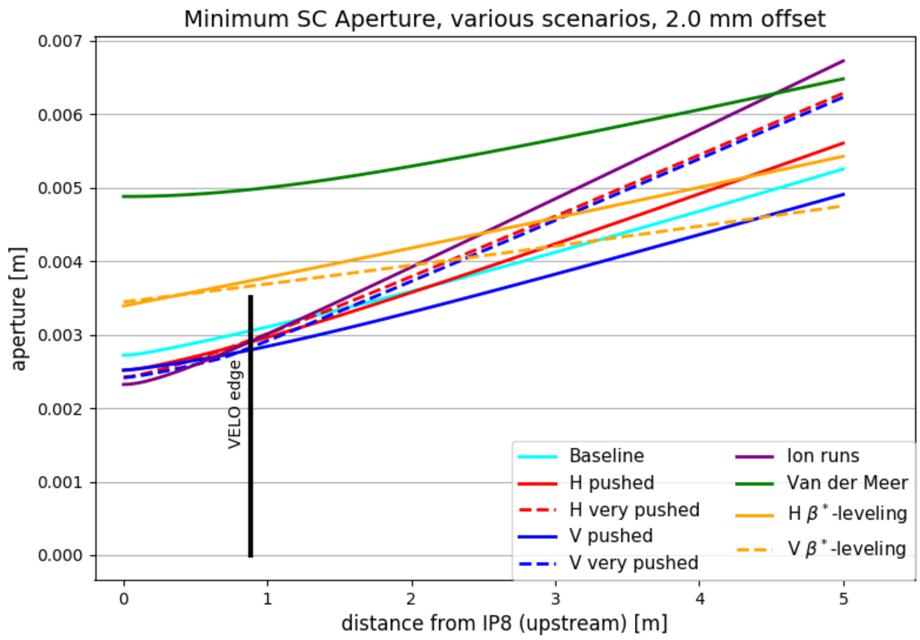


Figure 5: Minimum storage cell aperture for all scenarios. A 2.0 mm offset due to orbit drifts is assumed (SC not aligned at every fill).

4 Aperture calculation with MAD-X

As an alternative method to verify the safe aperture, the aperture module in MAD-X [18] was used to calculate the beam-stay-clear in the nominal HL-LHC optics v1.3 with β^* =3 m in IP8 at 7 TeV. A half external crossing angle of -250 μrad and the full spectrometer bump of -135 μrad were used, as well as a parallel separation of 38 μm for luminosity leveling, as detailed in Table 1.

In order to model the pipe of the storage cell, markers were installed every metre between IP8 and 5 m upstream. A circular aperture of 3.3 mm was assigned to the storage cell, since this was calculated to be the limiting safe aperture for the baseline scenario at s = 5 m (see Fig. 3). The beam tolerances from Ref. [16] were used, i.e. a normalized emittance of 2.5 μm, a 20% β-beat, a fractional momentum offset of 2×10^{-4}, and a relative parasitic dispersion of 0.1. In the assumption that the storage cell is aligned in every fill, the nominal 2 mm orbit tolerance was reduced to 0.1 mm. No mechanical tolerances were assigned to the storage cell, since the computed minimum radius given in this document applies to the value after the tolerances have been subtracted.

The resulting aperture in Fig. 6. As can be seen, the beam-stay-clear is still large close to IP8 and drops down to 19.2 σ at $s = -5$ m. This can be compared to the results of the analytic calculations in Fig. 3, which showed that the safe 19.4 σ is obtained at $s = -5$ m. The two calculations are thus consistent within 0.2 σ. The small difference is likely due to the slightly different treatment of the dispersive contribution.

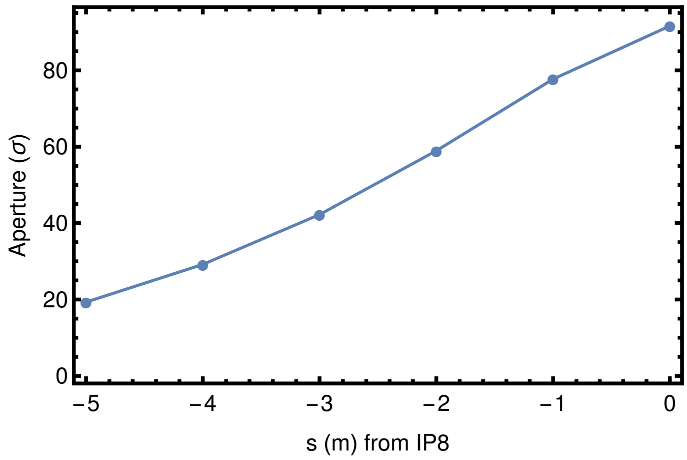


Figure 6: The available aperture upstream of IP8 as calculated with MAD-X for HL-LHC v1.3, assuming a normalized emittance of 2.5 μm, β^* =3 m, a horizontal half external crossing angle of -250 μrad, a -135 μrad horizontal spectrometer bump and a vertical parallel separation of 38 μm.

5 Conclusions

An analytic calculation of the minimum safe aperture for a storage cell upstream of IP8 has been presented and validated with MAD-X. The radius was calculated as a function of the distance of the furthest cell edge from the interaction point. Depending on the distance from IP8, a minimum radius between 3.0 mm and 4.8 mm is found, assuming that the storage cell is realigned in every fill so that it is never misaligned by more than 100 μm. The dominating limitation is given by the conditions during the Van der Meer scans and the vertical crossing configuration with very pushed β^* values.

This value gives the minimum aperture, after all tolerances on the storage cell itself have been subtracted, such as manufacturing and alignment tolerances. The design aperture of a storage cell should thus be correspondingly larger than this minimum acceptable radius.

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