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The Aperture and Layout of the LHC Extraction Septa and TCDS Diluter with an Enlarged MSDC Vacuum Chamber

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Summary

The LHC beam dumping system must safely abort the LHC beams over the whole energy range, under all realistically possible fault conditions. These include normal operation, failure of machine elements and also abnormal performance of subsystems of the beam dumping system itself. To avoid unnecessary irradiation and even equipment damage, the MSD extraction septa must provide sufficient aperture both for the circulating and extracted beams. In order to satisfy this requirement, a modified (enlarged) vacuum chamber design will be used for the limiting MSDC septa. The analysis of the available apertures is presented, with emphasis on the dependence on the local orbit and beam emittance.

1. Introduction

The concept of the LHC beam dumping system is to fast-extract the beam in a loss-free way from each ring of the collider and to transport it to an external dump, positioned sufficiently far away to allow for appropriate beam dilution in order not to overheat the absorber material. A loss-free extraction requires a particle-free gap in the circulating beam, during which the field of the extraction kicker can rise to its nominal value.

The layout of the system under construction is shown in Figure 1. It will be installed in straight section 6 and comprises for each ring 15 extraction kicker magnets MKD (3 μs rise time, 0.27 mrad overall horizontal deflection angle, 25 m overall length), 15 steel septum magnets MSD of three types MSDA, MSDB and MSDC (2.4 mrad overall vertical deflection angle, 72 m overall length), 10 modules of two types of dilution kicker magnets (22 m overall length), and finally the beam dump proper comprising the carbon TDE core and associated steel and concrete shielding (4 x 3.5 x 12.4 m^3 overall dimensions, weight about 1000 tons). This latter is situated in a cavern at 630 m from the dilution kickers and 750 m from the centre of the septum magnets. The TCDS and TCDQ elements are diluters upstream of the MSD and Q4 respectively, designed to protect machine elements from an unsynchronised beam abort.

The apertures of the MSD septa and TCDS diluter are critical for the circulating and extracted beams. With the present design of the extraction channel equipment, the nominal requirements for the circulating LHC beam aperture cannot be met [2,3]. In the following a solution to this problem is described which involves a modification to the vacuum chamber design of the five MSDC magnets per ring, which provides sufficient aperture for the circulating LHC beam as well as for the extracted beam under the present set of assumptions and parameters. Ring 1 only is described; the results for ring 2 are virtually identical.

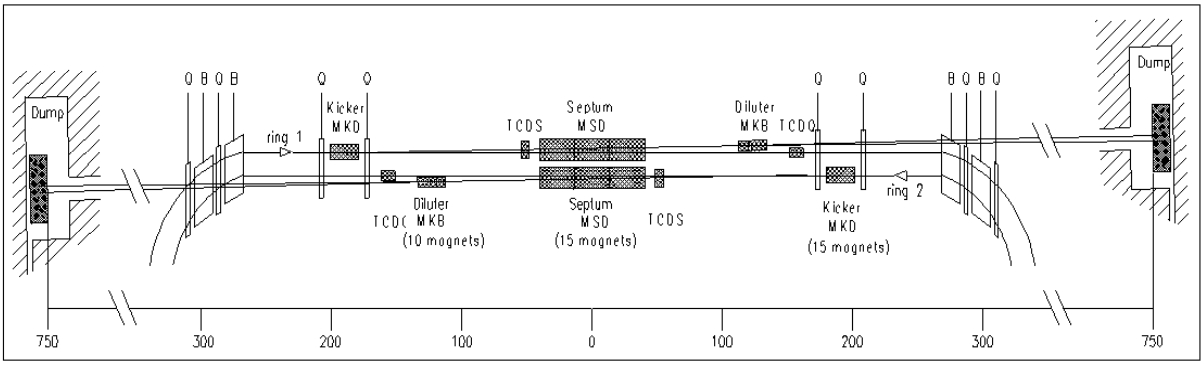

Figure 1. Schematic layout of beam dumping system elements around LHC point 6.

2. Assumed failure cases and parameters

2.1. Unsynchronised beam dump

An internal beam dumping system failure with potentially destructive consequences is the firing of the extraction kickers out of synchronisation with the beam gap [4], which can arise in several ways. In such case the beam would be swept over the machine aperture, and part of it would hit the MSD septum and vacuum chamber, and the coils of the first quadrupole downstream of the septum (the superconducting Q4), causing serious damage. To avoid this, the protective elements TCDS and TCDQ will be placed upstream of the septum and in front of Q4 [5], respectively.

2.2. Missing MKD module

The other main internal beam dumping system failure mode which is considered in this analysis is the 'missing module' case, where only 14 out of the 15 MKD modules fire correctly. The deflection of the extracted beam is reduced accordingly, which becomes a limiting case for the large emittance beam at injection.

2.3. Off normal LHC operating conditions

The beam dumping system must be able to accept LHC beams with well-controlled parameters (e.g. during a planned abort at the end of a physics run) and also beams with off-normal parameters (e.g. as arising from an equipment failure or beam instability), plus variations imposed by optical effects (e.g. beta-beating, tuning range). The relevant worst-case beam characteristics to be expected at point 6 arising from off-normal operating conditions have been agreed [4] and are given in table 1 for the various LHC beams considered. For the expected rate of local orbit change the present worst-case failure has been identified as the D1 trip [6], which determines the level at which the beam position must be interlocked to allow safe extraction [7].

Table 1. Assumed LHC beam characteristics.

Beam	**Max ε_n**		**Total Orbit mm**	**Beta beat**	**Total p+**
	450 GeV [μm]	**7 TeV [μm]**		**[%]**	**10^{14}**
Commission (C)	6.0	12.0	±4	42	0.3
First Years (F)	6.0	12.0	±4	42	0.8
Nominal (N)	7.5	15.0	±4	42	3.1
Ultimate (U)	7.5	15.0	±4	42	5.3

3. Aperture for circulating beam

3.1. Aperture definitions

From [8] the aperture for the circulating beam is defined in terms of n1, where for the normal machine the specification to be met is n1 ≥ 7.0. For the conventional magnets in the warm insertions, this specification has been relaxed somewhat to n1 ≥ 6.5. A factor 1.17 has also been introduced into the β values to allow for possible variations caused by adjusting the LHC tune [9].

Note that, in order to correctly calculate apertures at the extreme locations, the Twiss parameter values are calculated at the ends of the vacuum chambers, and not (as is the case for the published LHC optics) at the magnetic extremities of the elements.

3.2. Aperture limit at TCDS

The TCDS limits the aperture in the horizontal plane only. Following the definitions in [8], the position of the TCDS can be expressed as:

$$x_{TCDS} = 1.22 k_\beta \sigma_x^{TCDS} n_1 + co_x + \delta_x^{TCDS} + k_\beta \delta_p D_x^{TCDS}$$

where:

k_β = beta beating factor,
σ_x = horizontal beam size (sigma),
co_x = maximum horizontal closed orbit excursion,
δ_x = sum of mechanical and alignment tolerances,
δ_p = momentum spread in beam,
D_x = dispersion (including parasitic dispersion).

3.3. Aperture limit at MSDC

The vacuum chamber of the MSDC magnets is also an aperture limit for the circulating beam, by a combination of horizontal and vertical beam sizes and offsets. The aperture of the vacuum chamber is also a function of the chamber radius. The position of the inside edge of the vacuum chamber with respect to the circulating beam axis can be expressed as:

$$x_{MSDC} = \mathrm{r_c} + \sqrt{r_c^2 - (co_y + k_\beta \delta_p D_y^{MSDC} + 0.7 k_\beta n_1 \sigma_y^{MSDC})^2} \\ - co_x - k_\beta \delta_p D_x^{MSDC} - 1.22 k_\beta n_1 \sigma_x^{MSDC}$$

where:

r_c = radius of clear aperture of vacuum chamber.

3.4. Shielding criteria

The MSD chambers are required to be shielded by the TCDS in the event of an unsynchronised MKD pre-trigger. It is possible to derive the analytical relation between the TCDS position, closed orbit, beam size and MSDC vacuum chamber position in order for this shielding condition to be met. We use the transformation to normalized horizontal phase space coordinates:

$$\begin{bmatrix} \bar{x} \\ \bar{x}' \end{bmatrix} = \sqrt{\frac{\beta_n}{\beta(s)}} \cdot \begin{bmatrix} 1 & 0 \\ \alpha(s) & \beta(s) \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}.$$

By choosing $\beta_n = 1$, we have:

$$\bar{x} = \frac{x}{\sqrt{\beta(s)}}.$$

Figure 2 shows the kicked beam, the extreme particle having an angle $\bar{k}'_0$ which grazes the TCDS and the MSDC chamber, where:

$\overline{co}_x$ = maximum orbit excursion at MKD centre,

$\bar{r} = N\sqrt{\varepsilon_x}$ normalised beam size ($N \times$ sigma) for which the shielding criteria is valid,

$\bar{\boldsymbol{x}}_{TCDS}$ = normalized minimum position of TCDS,

$\bar{x}_{MSD}$ = normalized position of MSDC chamber,

μ_1 = phase advance between MKD centre and TCDS entrance,

μ_2 = phase advance between MKD centre and MSDC.

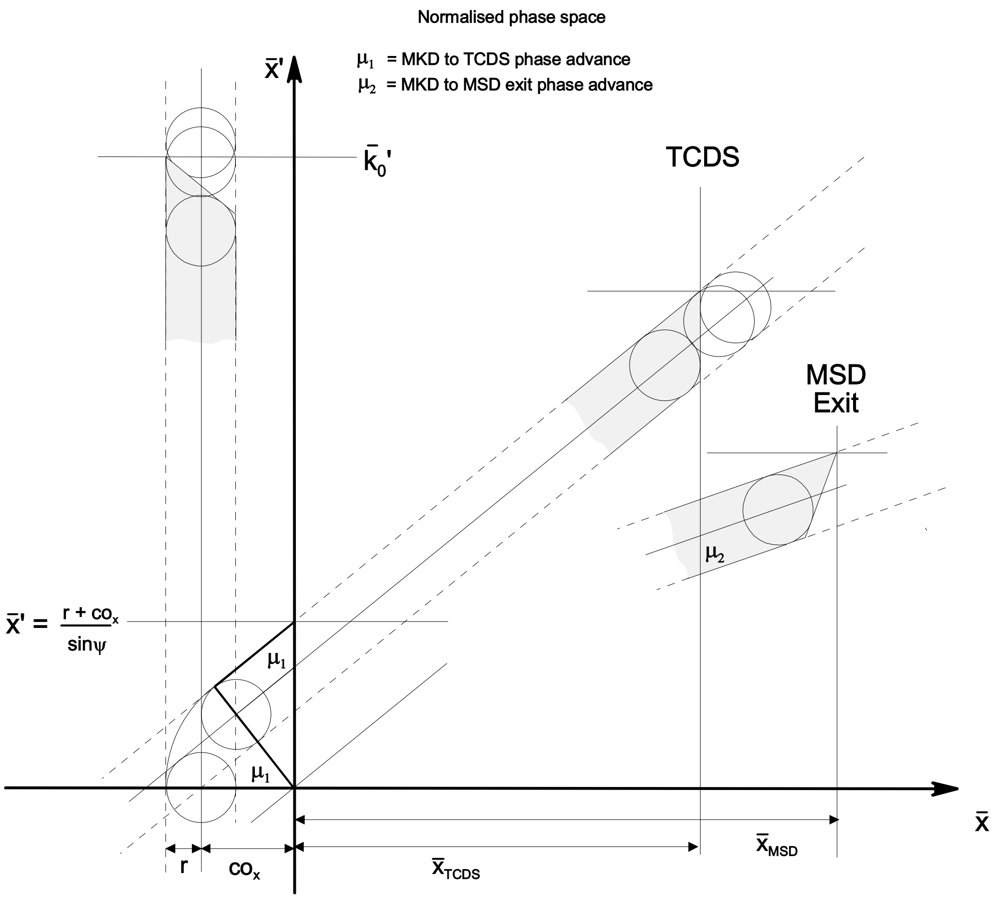

Figure 2. Normalised phase space diagram showing particles grazing TCDS and MSDC vacuum chamber.

From figure 2, it is evident that:

$$\bar{k}'_0 = \frac{\bar{x}_{TCDS}}{\sin\mu_1} + \frac{\overline{co}_x + \bar{r}}{\tan\mu_1} = \frac{\bar{x}_{MSD}}{\sin\mu_2} + \frac{\overline{co}_x + \bar{r}}{\tan\mu_2}$$

Therefore the shielding condition is met if:

$$\bar{x}_{MSD} = \bar{k}'_0 \sin\mu_2 - \left(\overline{co}_x + \bar{r}\right)\cos\mu_2$$

$$= \left(\frac{\bar{x}_{TCDS}}{\sin\mu_1} + \frac{\overline{co}_x + \bar{r}}{\tan\mu_1}\right)\sin\mu_2 - \left(\overline{co}_x + \bar{r}\right)\cos\mu_2$$

Rearranging and using the relation:

$$\sin\alpha\cos\beta - \cos\alpha\sin\beta = \sin(\alpha - \beta)$$

gives:

$$\bar{x}_{MSD} = a\cdot\bar{r} + a\cdot\overline{co}_x + b\cdot\bar{x}_{TCDS}$$

where:

$$a = \frac{\sin(\mu_2 - \mu_1)}{\sin\mu_1}, \quad b = \frac{\sin\mu_2}{\sin\mu_1}.$$

Transforming back into real co-ordinates, and including the mechanical and alignment tolerance δ_x^{TCDS} for the TCDS position, gives:

$$x_{MSD} = N\cdot a\cdot\sigma_{\mathrm{x}}^{\mathrm{MSD}} + a\cdot co_x\sqrt{\beta_x^{MSD}/\beta_x^{MKD}} + b\cdot\sqrt{\beta_x^{MSD}/\beta_x^{TCDS}}\,(x_{TCDS} + \delta_x^{TCDS}).$$

3.5. TCDS and MSDC layouts

The layout of the various points of the TCDS and MSDC vacuum chamber, figure 3, are thus fully defined according to these extreme trajectories. The maximum aperture for the overall system (considering the circulating plus extracted beam) is obtained when the TCDS is positioned as close as possible to the circulating beam axis. Assuming mechanical and alignment tolerances δx = ±1mm for the TCDS, with a ±4 mm orbit, the nominal TCDS position (upstream) is set to +16.3 mm, which corresponds to an acceptable n1 of 6.50. The plot of available aperture versus orbit at the TCDS is shown in figure 4.

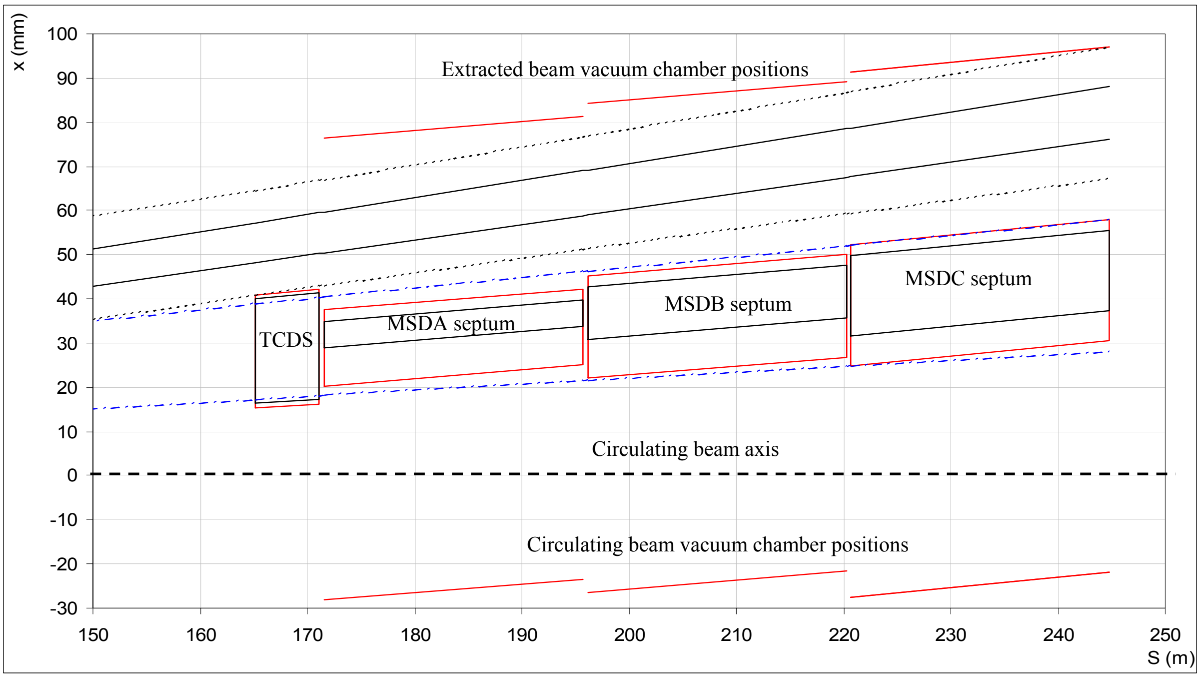

Figure 3. Layout of TCDS and MSD vacuum septa and chambers. Note that the MSDA and B magnets are equipped with chambers of 48.4 mm diameter clear aperture (all tolerances included) and the MSDC magnets with larger aperture chambers of 52.4 mm diameter clear aperture.

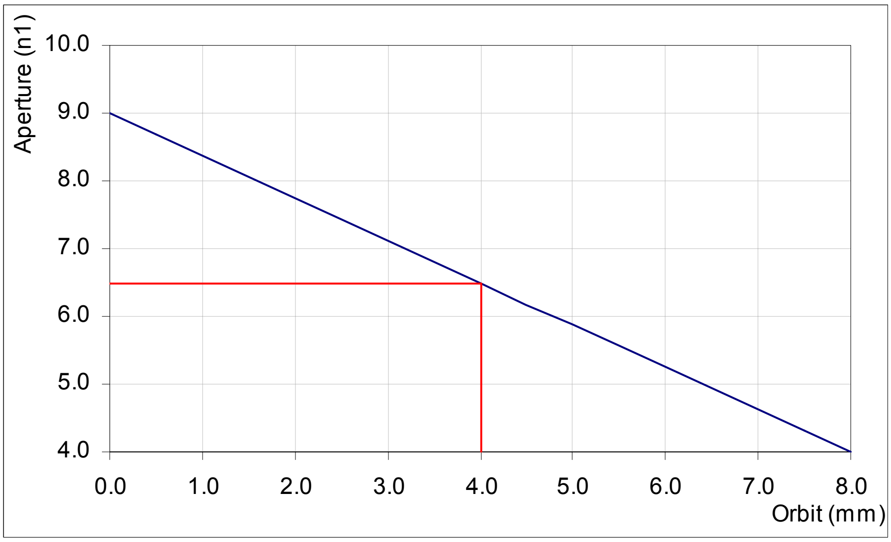

Figure 4. Aperture at TCDS for circulating beam as a function of local horizontal closed orbit excursion.

The position of the MSDC vacuum chamber is determined by the criteria mentioned above for shielding by the TCDS in the event of an asynchronous dump, and by the need to provide enough aperture for the circulating beam. Setting the condition that the chamber should be shielded to $N \geq 2\,\sigma$ at 450 GeV/c (which corresponds to $> 7\,\sigma$ at 7 TeV), and assuming a clear vacuum chamber aperture of radius 26.2mm [10] we arrive from the shielding criteria at a minimum outside position for the chamber of +24.9 mm for the <u>upstream</u> end.

The total width of the MSDC septum is 27.3 mm, which includes the 18 mm iron septum, plus the vacuum chambers and mechanical tolerances for both circulating and extracted beams. This fixes the position of the clear aperture of the vacuum chamber in the extracted beam channel at the upstream end of the MSDC1 at +52.2 mm.

This position then defines the width of the TCDS, since it must shield to N sigma or better the chamber of the extracted beam at this position. From similar considerations to those explained previously, it can be shown that the position of the TCDS outside edge is given by:

$$x_{TCDS} = \frac{\left(x_{MSDC} + N \cdot a \cdot \sigma_{\mathrm{x}}^{\mathrm{MSDC}} + a \cdot co_x \sqrt{\beta_x^{MSDC} / \beta_x^{MKD}}\right)}{b \cdot \sqrt{\beta_x^{MSDC} / \beta_x^{TCDS}}} + \delta_x^{TCDS} \quad .$$

The outer edge of the TCDS at the upstream end is then at 39.9 mm. For the downstream end, the block is aligned along the trajectory of the extreme 2 σ particles which grazes the TCDS and the MSDC. The TCDS width is then fixed at 23.6 and 24.1 mm for the upstream and downstream ends, respectively.

The downstream end of the MSDC extracted beam chamber is aligned along the trajectory of the extreme 2 σ particle which grazes the TCDS.

These considerations then fix completely the geometry of these critical elements, and also the positions of the vacuum chambers for the circulating and extracted beams. The MSDA and MSDB vacuum chambers are aligned so as to balence the clearance on both circulating and extracted beam sides between the aforementioned grazing trajectories.

All nominal element positions are shown below in table 2 for reference – note that these refer to the nominal TCDS position and the nominal position of the MSDC iron septum. The limits of the clear aperture of the TCDS and vacuum chambers, after accounting for chamber widths and all tolerances (including mechanical and survey), are given in table 3 for completeness.

Table 2. Positions of nominal physical elements for TCDS and MSD septa.

	S [m]	x (inside) [mm]	x (outside) [mm]
	Nominal physical element positions		
TCDS upstream	165.10	16.3	39.9
TCDS downstream	171.10	17.2	41.3
MSDA septum upstream	171.60	29.0	35.0
MSDA septum downstream	195.70	33.8	39.8
MSDB septum upstream	196.15	30.8	42.8
MSDB septum downstream	220.25	35.6	47.6
MSDC septum upstream	220.70	31.7	49.7
MSDC septum downstream	244.80	37.4	55.4

Table 3. Positions of clear aperture limits (including tolerances) for TCDS and MSD septa.

	S [m]	x (inside) [mm]	x (outside) [mm]
	Clear aperture limits		
TCDS upstream	165.10	15.3	40.9
TCDS downstream	171.10	16.2	42.3
MSDA circulating upstream	171.60	-28.2	20.2
MSDA circulating downstream	195.70	-23.4	25.0
MSDB circulating upstream	196.15	-26.4	22.0
MSDB circulating downstream	220.25	-21.6	26.8
MSDC circulating upstream	220.70	-27.5	24.9
MSDC circulating downstream	244.80	-21.8	30.6
MSDA extracted upstream	171.60	37.5	76.5
MSDA extracted downstream	195.70	42.3	81.3
MSDB extracted upstream	196.15	45.3	84.3
MSDB extracted downstream	220.25	50.1	89.1
MSDC extracted upstream	220.70	52.2	91.2
MSDC extracted downstream	244.80	58.0	96.9

This layout provides a comfortable aperture for the circulating beam at the MSDC as seen from figure 5 below, where for an orbit excursion of 4 mm (in both horizontal and vertical planes) the aperture remains above n1 = 7.

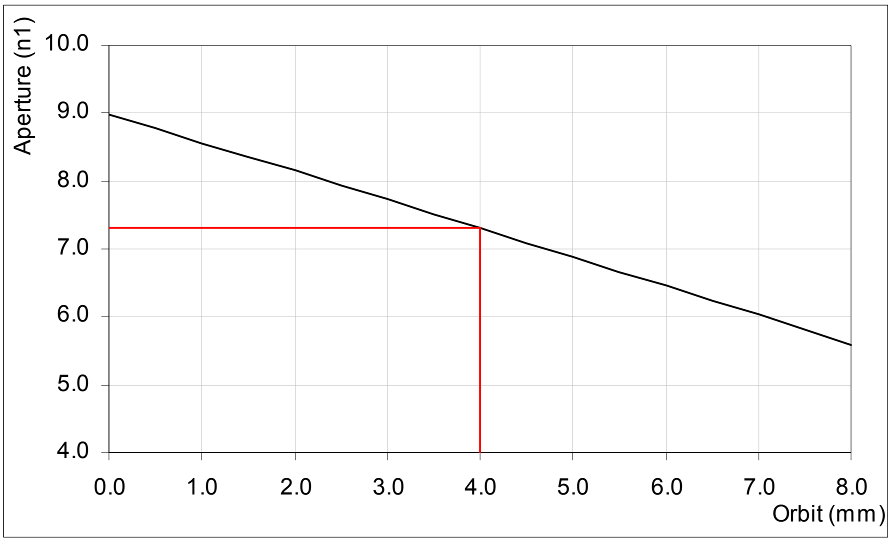

Figure 5. Aperture at MSDC5 vacuum chamber for circulating beam as a function of local horizontal closed orbit excursion (4 mm vertical orbit assumed).

4. Aperture for extracted beam

With the layout of the extraction elements fixed, for the extracted beam aperture calculation the total overshoot of the MKD kicker waveform is taken to be 10% [11].

4.1. Nominal case - 15/15 MKD

The extracted beam is centred in the septum gap for the nominal case (so for the 14/15 missing MKD module failure the beam approaches the TCDS). The same kick, 0.269 mrad, is imposed from 450 GeV to 7 TeV beam energy, which eases setting up, post-mortem and energy-tracking. The available aperture at 450 GeV and 7 TeV as a function of orbit is shown in figures 6 and 7. Assuming that for ‘loss free’ extraction an aperture of 4 sigma is sufficient at 450 GeV, and 6 σ at 7 TeV, the orbit should stay within about ±4 mm and ±7.3 mm, respectively.

The apertures during beam abort are ‘comfortable’ (5.6/22 sigma at 450 GeV/7 TeV respectively) if the orbit stays within ±2 mm and all 15 MKD modules trigger correctly.

4.2. Missing MKD module failure case – 14/15 MKD

The worst missing MKD module is the MKD1; in this case the effective deflection at the TCDS is 91.96% of the total, and the beam therefore approaches the TCDS. The available apertures at 450 GeV and 7 TeV as a function of orbit are shown in figures 8 and 9. Here it is clear that, for even moderate orbit excursions, the TCDS will receive some beam in the event of an MKD missing, with the attendant risk of quenches in downstream superconducting magnets or of damage to the TCDS.

We conclude that a missing MKD case at low energy will produce losses on the TCDS for moderate orbit excursions. The consequences are discussed in the following chapter.

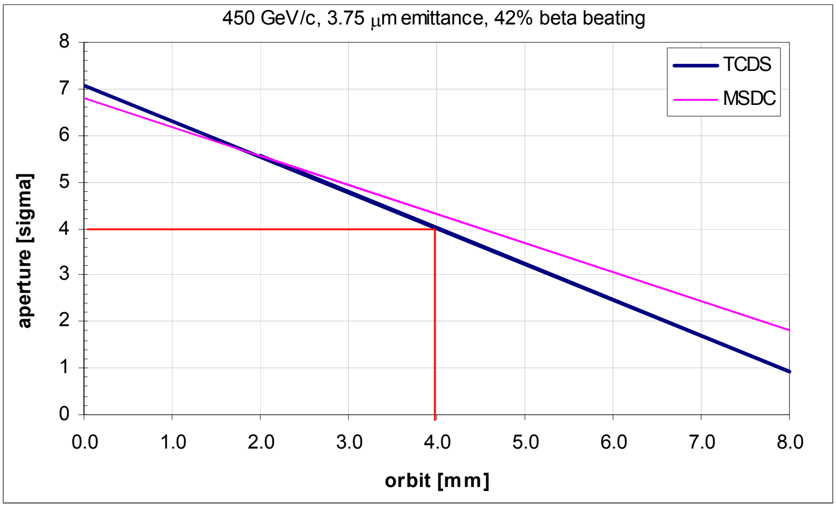

Figure 6. Aperture at 450 GeV for extracted beam as a function of the orbit in the nominal 15/15 MKD case.

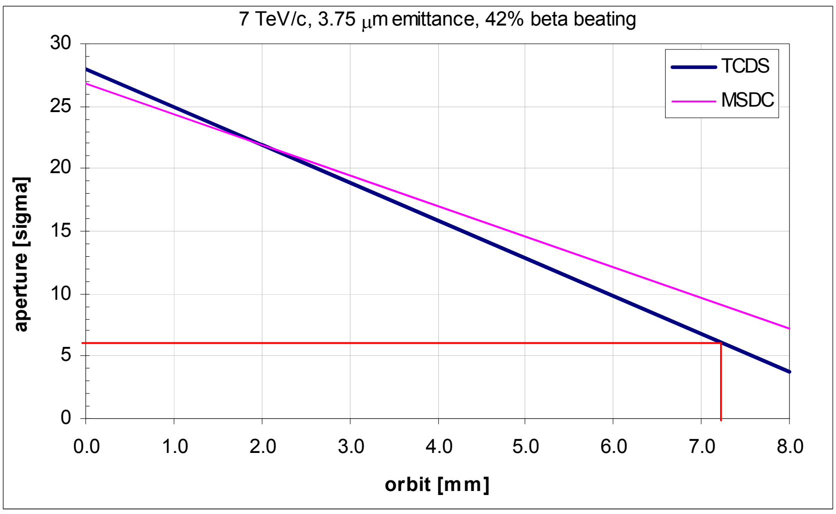

Figure 7. Aperture at 7 TeV for extracted beam as a function of the orbit in the nominal 15/15 MKD case.

5. Aperture with increased LHC emittance

In addition to the missing MKD module case described above, the dump channel must also accept off-normal LHC operating conditions, which manifest themselves in point 6 as fast orbit excursions and emittance increases. These events are likely to occur during the LHC lifetime (indeed dump actions will probably be correlated with unstable or off-normal beam conditions) and so the allowed range of parameters must not result in damage to the LHC, including the dumping system itself. Ideally these failures should also not result in any losses in the extraction channel; these criteria, however, should be evaluated with the likely occurrence rate of each failure mode or combination of failure modes. Finally, it should be noted that, although an increased emittance will result in a smaller aperture of the dump channel, the associated reduction in the energy density of the beam also reduces the risk of damage to the extraction elements.

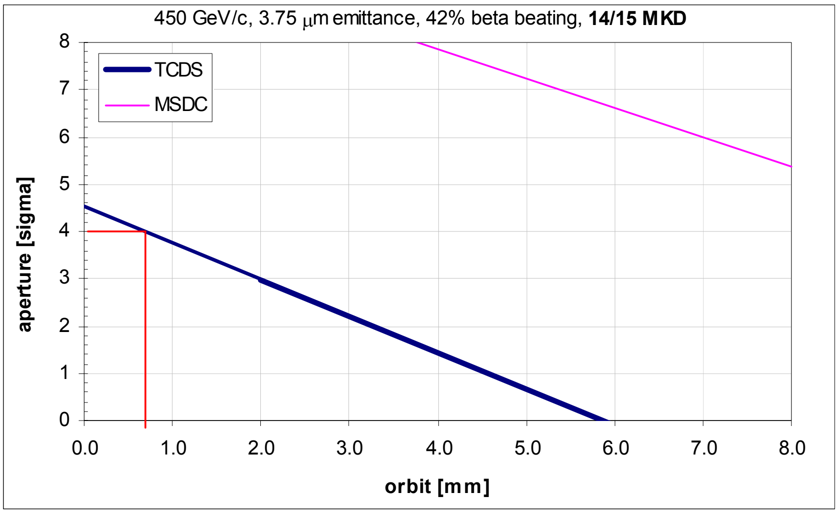

Figure 8. Aperture at 450 GeV for extracted beam as a function of the orbit in the 14/15 MKD case.

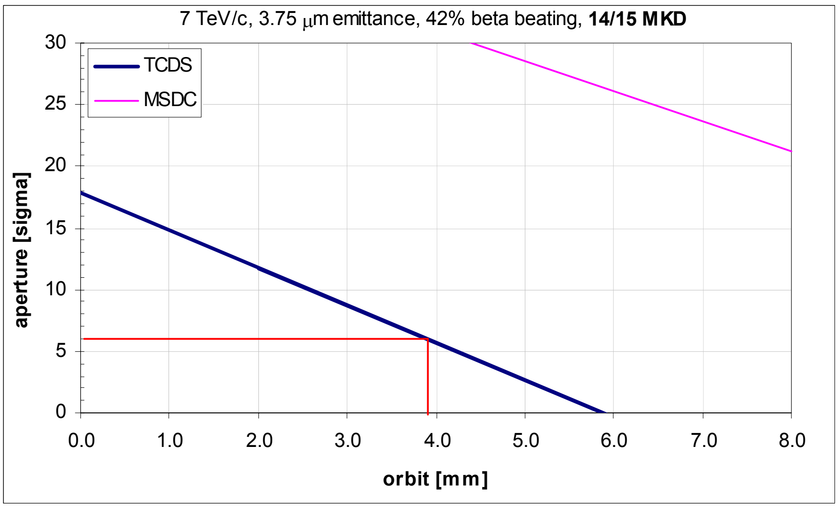

Figure 9. Aperture at 7 TeV for extracted beam as a function of the orbit in the 14/15 MKD case.

5.1. TCDS damage limits

For the various combinations of parameters described in table 1, for both the nominal and 14/15 MKD case, the aperture of the dump channel was evaluated and the resulting impacting number of protons on the TCDS calculated, under the somewhat pessimistic assumption of a non-truncated Gaussian beam distribution, and neglecting for the time being the diluting effect of the non-trapezoidal MKD kicker waveform [12].

The resulting figures were compared with safe limits for protons impacting the TCDS at 450 GeV and 7 TeV, which have been derived by scaling previous FLUKA results [13], assuming;

- 450 GeV: with nominal sigma, the estimated damage limit (protons per sigma) of the TCDS is about 330 x 10^{11} protons (this assumes a factor 2 safety margin);
- 7 TeV: the estimated damage limit (protons per sigma) of the TCDS is about 0.8 x 10^{11} protons (taking the same safety margin);
- For different emittances, the above figures are assumed to scale linearly with the horizontal beam size (i.e. the square root of the emittance);
- Any emittance increase is assumed to be in one plane only.

5.1.1. 15/15 MKD case

With 15/15 MKD firing, the results of the analysis for the different combinations of failures are summarised in table 3 for different beam types - Commissioning (C), First years (F), Nominal (N) and Ultimate (U). It is apparent from the table that, if the orbit excursion at extraction in point 6 is controlled to better than about ±7 mm, the TCDS (and also the MSD) should not be damaged for any of the considered beam parameters. However, losses may occur at low energy if the beam emittance is larger than nominal and the orbit is greater than ±2 mm.

Table 3. Clearance and orbit limits for TCDS damage threshold under different combinations of beam parameters for the 15/15 MKD case.

E	Beam	p+	limit p+	ε	Orbit limit mm	
[GeV]	type	e14	e11	[μm]	Loss	Damage
450	C	0.3	295	3.0	4.7	11.8
450	C	0.3	417	6.0	**2.8**	n/a
450	F	0.8	295	3.0	4.7	8.9
450	F	0.8	417	6.0	**2.8**	9.4
450	N	3.1	330	3.8	4.1	7.7
450	N	3.1	467	7.5	**2.0**	7.5
450	U	5.3	330	3.8	4.1	7.3
450	U	5.3	467	7.5	**2.0**	6.9
7000	C	0.3	0.7	3.0	7.6	8.5
7000	C	0.3	1.4	12.0	5.8	7.8
7000	F	0.8	0.7	3.0	7.6	8.5
7000	F	0.8	1.4	12.0	5.8	7.6
7000	N	3.1	0.8	3.8	7.4	8.2
7000	N	3.1	1.5	15.0	5.5	7.3
7000	U	5.3	0.8	3.8	7.4	8.1
7000	U	5.3	1.5	15.0	5.5	7.2

5.1.2. 14/15 MKD case

With 14/15 MKD modules triggering, the situation becomes much less comfortable, as shown in table 4. For this case, losses on the TCDS at 450 GeV for an MKD missing module seem inevitable. However, during the Commissioning and First years, the TCDS does not risk damage for orbit excursions up to about 5.6 mm. For nominal beams, the total orbit should be <3.9 mm to avoid damage to TCDS, if it is assumed that 4x nominal emittance at 7TeV can occur together with the 14/15 MKD failure case.

In reality some extra margin is to be gained from the MKD waveform. Integrating over all bunches gains about 0.5 σ in clearance, since only relatively few bunches actually pass on the extreme trajectory.

Table 4. Clearance and orbit limits for TCDS damage threshold under different combinations of beam parameters for the 14/15 MKD case.

E [GeV]	Beam type	p+ e14	limit p+ e11	ε [μm]	Orbit limit mm Loss	Damage
450	C	0.3	295	3.0	**1.4**	8.5
450	C	0.3	417	6.0	**-0.6**	n/a
450	F	0.8	295	3.0	**1.4**	5.6
450	F	0.8	417	6.0	**-0.6**	6.1
450	N	3.1	330	3.8	**0.8**	4.4
450	N	3.1	467	7.5	**-1.4**	4.1
450	U	5.3	330	3.8	**0.8**	4.0
450	U	5.3	467	7.5	**-1.4**	**3.6**
7000	C	0.3	0.7	3.0	**4.3**	5.2
7000	C	0.3	1.4	12.0	**2.5**	4.5
7000	F	0.8	0.7	3.0	**4.3**	5.1
7000	F	0.8	1.4	12.0	**2.5**	4.3
7000	N	3.1	0.8	3.8	**4.0**	4.9
7000	N	3.1	1.5	15.0	**2.1**	**3.9**
7000	U	5.3	0.8	3.8	**4.0**	4.8
7000	U	5.3	1.5	15.0	**2.1**	**3.8**

5.2. Q4 quench level

The MARS simulations performed for point 6 [14] show that Q4 quenches can be expected for an impact of ~4 x 10^9 protons on the TCDS at 7 TeV, and for ~1.2 x 10^{11} protons at 450 GeV. To compare the different cases, the number of protons impacting on the TCDS were calculated for a dump abort, assuming a maximum orbit of 4 mm. The results were then compared with these quench limits and expressed as a factor (number of impacting protons divided by quench limit), table 5. Although the maximum expected number of protons and therefore the energy deposition is some factor of ~600 above the quench limit (assumed to be 0.5 mJ/g), this is still well below the damage limit which is some factor of 10^4 or even 10^5 higher.

Table 5. Ratio of impacting protons to scaled quench limit at TCDS for dump action with orbit at 4 mm.

E GeV	Beam type	p+ e14	ε um	σ mm	Q factor 15/15	14/15
450	C	0.3	3.0	1.0	0.0	**10**
450	C	0.3	6.0	1.4	0.1	**28**
450	F	0.8	3.0	1.0	0.0	**27**
450	F	0.8	6.0	1.4	0.4	**75**
450	N	3.1	3.8	1.1	0.1	**160**
450	N	3.1	7.5	1.5	**5**	**345**
450	U	5.3	3.8	1.1	0.1	**271**
450	U	5.3	7.5	1.5	**8**	**586**
7000	C	0.3	3.0	0.2	0.0	0.0
7000	C	0.3	12.0	0.5	0.0	**2**
7000	F	0.8	3.0	0.2	0.0	0.0
7000	F	0.8	12.0	0.5	0.0	**6**
7000	N	3.1	3.8	0.3	0.0	0.0
7000	N	3.1	15.0	0.6	0.0	**80**
7000	U	5.3	3.8	0.3	0.0	0.0
7000	U	5.3	15.0	0.6	0.0	**136**

From table 5, quenches seem likely at 450GeV when the emittance is larger than nominal and the orbit at 4 mm, which reinforces the importance of good orbit control in point 6. In addition, quenches seem inevitable at 450 GeV for the 14/15 MKD module failure case.

An investigation will be launched into whether this effect could be improved by the addition of simple fixed masks outside the vacuum chambers downstream of the MSD septa, since such additional protection could be easily installed if found to be necessary operationally.

6. Conclusions

The aperture limits of the dump channel have been quantified at different energies and under various realistic failure scenarios. The aperture of the dump channel is limited, especially for off-normal operating conditions of the dump system itself or of the LHC machine. However, the use of a larger aperture vacuum chamber in the MSDC magnets allows the nominal aperture specification for the circulating LHC beam to be met. At the same time an adequate aperture is provided for the extracted beam, which under the presently assumed range of fault conditions and machine parameters does not risk damage to the extraction equipment or LHC machine. The following points should be retained:

1. An increase in the diamteter of the MSDC vacuum chamber has been shown to be technically feasible within the present constraints from bakeout and tolerances [15];
2. Orbit control (feedback) will be needed in point 6 to ensure that the orbit stays below ±2 mm, in order to minimise the risk of quenches when the beam is dumped;
3. Operation during commissioning and ‘early years’ is not expected to be limited by the dump aperture;
4. For normal operation, with realistic failure cases, orbit excursions of up to ±4 mm should be tolerable without damage to any elements, up to nominal intensities;

5. Emittance increases of x2 / x4 will not result in equipment damage at 450GeV / 7TeV respectively, but may produce Q4 quenches at low energy for large orbit excursions;
6. The 14/15 MKD case will produce losses on the TCDS and Q4 quench but should not result in damage, again provided the orbit is held to better than ±4 mm;
7. Reliable interlocking to the local beam position at a level of ±4 mm in point 6 is absolutely necessary.

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