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The Consequences of Abnormal Beam Dump Actions on the LHC Collimation System

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Summary

The consequences of abnormal LHC beam dump actions on the collimation system are evaluated. We consider both an asynchronous beam dump, where all 15 kicker modules fire together, and the pre-firing of one kicker module, followed by the firing of the remainder. The frequency of such failures is difficult to predict. It is assumed that they will happen at least once per year. Using the measured kicker field waveform, the expected beam impact on the collimators is calculated. It is shown that a total of 20 nominal LHC bunches can impact on a single collimator jaw, within a transverse area of about 1 mm (full width) $\times$ 200 μm (rms). Due to the uneven horizontal distribution a peak impact of about 6 nominal bunches can occur in the first 200 μm from the edge of the collimator jaw. The design of a collimation system able to withstand such an impact appears difficult.[1]

1 Introduction

The LHC collimation system is designed to protect the machine from regular and irregular beam losses. The LHC Beam Cleaning Study Group [1] has recently been set up to study all aspects of this system. A recent LHC project note [2] gave preliminary specifications for the expected beam impact at the collimators, including simple estimates for LHC dump failures. Here, we present a more detailed investigation of this problem, incorporating the detailed waveform of the kicker magnets. Studies are presented for nominal bunch spacing (25 ns), nominal bunch intensity (1.1×10^{11}), nominal emittance (0.5 nm at 7 TeV), and LHC optics V 6.4. We consider a circulating beam at 7 TeV. The most serious problems for collimator survival are to be met at high energy. As a conservative assumption the primary collimators are put to a collimation depth of 5 σ. This is below the nominal collimation depth of 6 σ and provides some margin for operational collimator adjustments.

[1] This is an internal CERN publication and does not necessarily reflect the views of the LHC project management.

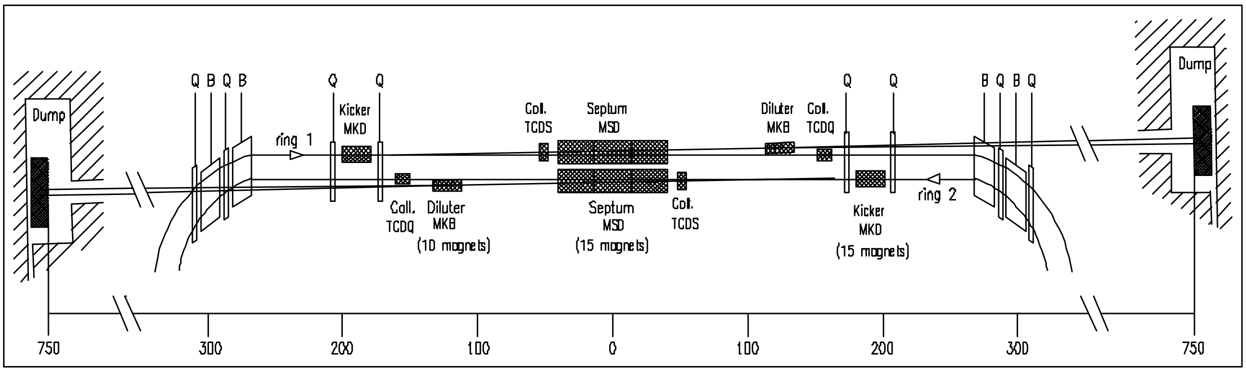

Figure 1: Basic layout of the beam dump systems for the two LHC beams. The MKD kicker deflects the LHC beam into the extraction channel in the septum MSD. The extracted beam is diluted by the MKB kickers and finally dumped in specially excavated beam dump caverns. The TCDS and TCDQ absorbers [4, 5] provide protection for the septum MSD and the downstream super-conducting magnets respectively.

2 The LHC dump kicker

In the LHC each beam has its own extraction line. The beam is extracted by an initial deflection from the dump kickers MKD [3]. The basic layout of the beam dump system is illustrated in Figure 1 for both beams. Each MKD kicker consists of 15 separate modules which are located next to each other in IR6, extending over about 26 m. The locations and horizontal beta functions at the 15 modules of beam 1 are displayed in Figure 2. Note that we use LHC optics V 6.4 which contains the latest arrangement of the LHC dump system.

The beam deflection from a single MKD kicker module is shown in Figure 3 as a function of time. The waveform was measured in a prototype magnet. The absolute value is scaled to the nominal total deflection of 0.0177 mrad per module, corresponding to the presently assumed total deflection of 0.265 mrad.

3 Dump failure modes considered

For a correct beam dump action the 15 modules must all be fired at the same time (tolerance on timing jitter below 15 ns) and be synchronous with the 3 μs beam abort gap. In addition, the kicker module settings must track the beam energy.

Two failure modes are considered: first a simultaneous triggering of all 15 kicker modules, asynchronous with the beam abort gap ("asynchronous"), and second a random pre-trigger of one kicker module, followed a short time after by the simultaneous re-triggering of the remaining 14 modules ("erratic"). The frequency of such failures is difficult to predict. It is assumed that they will happen at least once per year. This estimate is in agreement with the experience at other modern accelerators. In the following we discuss these failure modes.

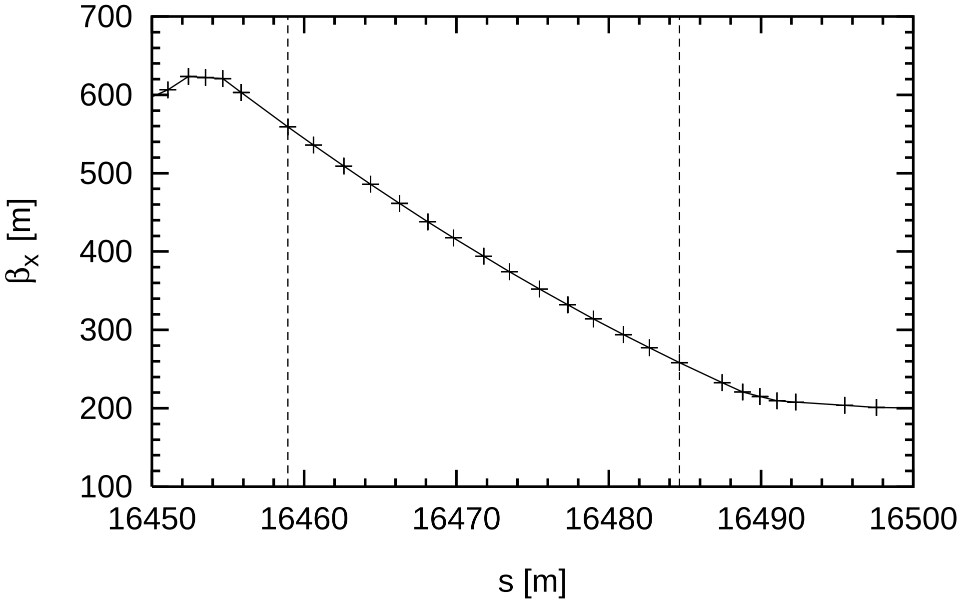

Figure 2: The beam 1 horizontal beta function in the region of the MKD modules versus longitudinal position s (LHC optics V 6.4). The two vertical lines indicate the centers of the first and last of the 15 MKD modules.

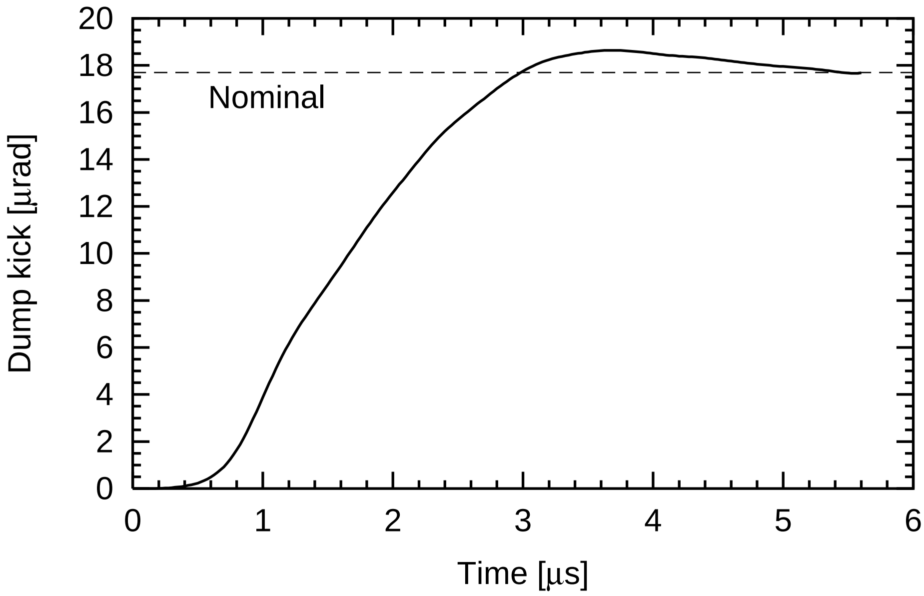

Figure 3: The measured nominal LHC dump kick per module versus time. The dashed line indicates the nominal asymptotic kick.

Origin	450 GeV		7 TeV	
	ΔT [ns]	T_{sum} [ns]	ΔT [ns]	T_{sum} [ns]
Erratic switch No. 1	0	0	0	0
Re-triggering pick-up 10 V signal	400	400	200	200
Cable delay	180	580	180	380
Trigger unit delay	120	700	120	500
Cable delay + transformer delay	100	800	100	600
Turn delay GTO stack	400	1200	400	1000
Operational margin	300	1500	300	1300

Table 1: Overview on the re-triggering delay as specified and measured. An operational margin of 300 ns was included in order to account for the limited experimental evidence and for possible deviations under LHC operational conditions. Measured total delays are consistent with the above values.

3.1 Asynchronous dump

In an asynchronous beam dump the dump is triggered out of synchronization with the LHC dump gap. In all other aspects the dump functions normally, i.e. all 15 kickers are synchronized, however the kicker rise time can be fully experienced by the LHC beam. For the following studies we assume that the rise time is indeed fully missing the dump gap.

3.2 Pre-firing of a single dump module (erratic)

The dump system consists of 15 separate modules and a single module can spontaneously self-trigger. This pre-firing of one module is almost certainly out of synchronization with the dump gap. The system is designed such that the other 14 modules ”re-trigger” with the shortest possible delay such that the nominal dump kick is established as soon as possible. In particular one can not wait with the re-triggering for the dump gap. The kick from a single module would deflect almost all LHC beam into the extraction elements.

The re-triggering time was an important aspect of the system design. Its main components are summarized in Table 1. In this note we assume a nominal re-triggering delay of 1.3 μs at top energy. The MKD induced beam deflection for a pre-firing of a single dump module is shown in Figure 4 for this nominal re-triggering time.

4 Loss impact on collimators

The downstream effect of the beam deflection θ^i_{MKD} from the MKD kicker modules is obtained in normalized units (number of σ_x) as:

$$\tilde{x} = \frac{x}{\sigma_x} = \sum_{i=1}^{15} \sqrt{\frac{\beta^i_{MKD}}{\epsilon_x}} \cdot \sin(\Delta\psi^i_x) \cdot \theta^i_{MKD} \tag{1}$$

We note that the downstream effect of the MKD deflection in normalized units only depends on the horizontal β-function at the MKD kickers, the horizontal emittance ϵ_x, the horizontal phase ad-

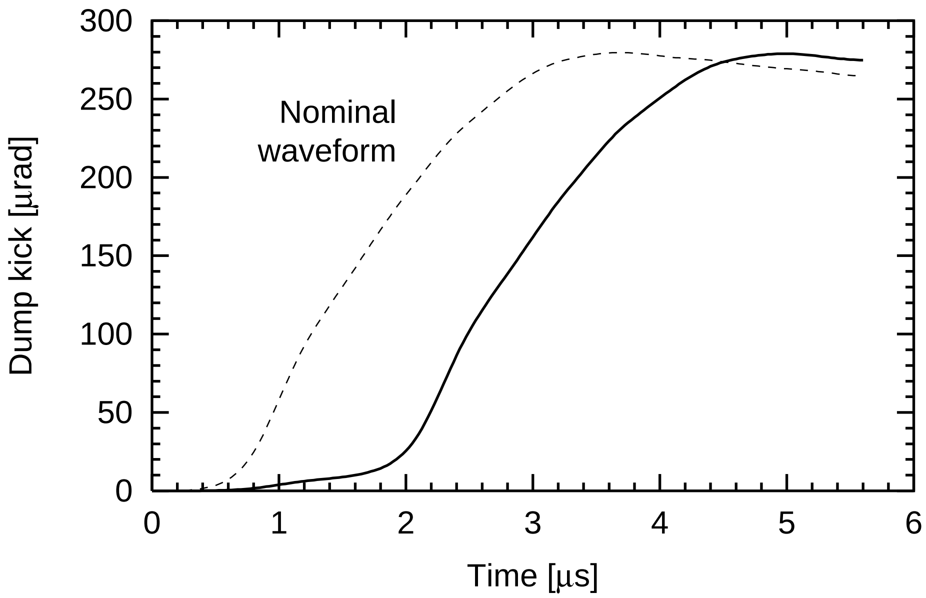

Figure 4: The total MKD deflection for a one module pre-fire and a re-triggering time of 1.3 μs (solid line). The dashed line shows the nominal waveform for a simultaneous firing of all 15 modules.

vance to the observation point, and the kick θ^i_{MKD}. In particular, the β-function at the observation point does not enter.

4.1 Requirements for LHC collimation system

Using Equation 1 we can then calculate the normalized downstream horizontal beam offset. Figure 5 shows the normalized horizontal beam offset versus time for a pre-fire of one MKD module and a re-triggering time of 1.3 μs. Note that the curves are sampled in steps of 25 ns so that each point corresponds to one LHC bunch. Two extreme cases (maximum and minimum beta) have been calculated.

The data from Figure 5 can be projected onto the axis of x offset, integrating over a few μs of time. We thus obtain the time-integrated horizontal distribution for the considered dump failure modes. The horizontal distribution for an asynchronous dump is shown in Figure 6. The case of a pre-fire of one dump module is shown in Figure 7 for a re-triggering time of 1.3 μs. We note that the case of a one module pre-trigger is much more severe than an asynchronous beam dump. The horizontal beam distribution on the collimator jaw is not flat but can be quite varied. This is an important observation because material damage depends more on the peak intensity deposited than on the integral. The peak impact occurs for MKD15 and is about 6 nominal LHC bunches in one σ_x, just close to the edge of the collimators.

In order to allow for sufficient operational tuning range in collimator settings we assume that the primary collimation depth can be as small as 5 σ_x. In addition, we require that the 9.5 m long TCDQ absorber [4, 5] just downstream of the MKD modules is protecting the aperture at 10 σ_x. The TCDQ will then not only safely protect the downstream super-conducting magnets against damage but will also limit the amount of beam that can impact on a collimator jaw. We note that

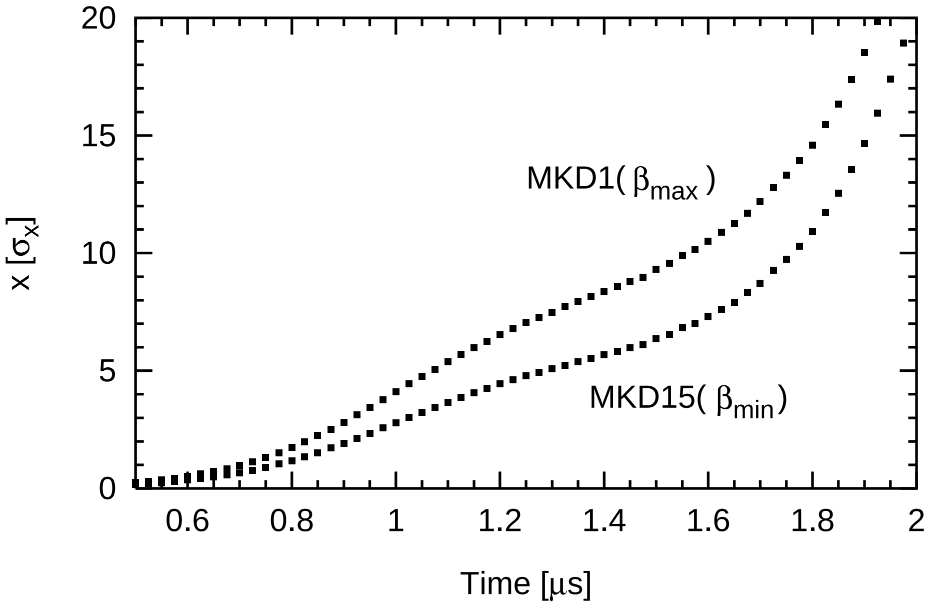

Figure 5: Normalized beam offset downstream of the MKD kickers versus time for a single module pre-trigger. The re-triggering time for the other 14 modules is taken to be 1.3 μs. The two curves refer to the modules with maximum and minimum horizontal beta functions. Each point corresponds to one LHC bunch.

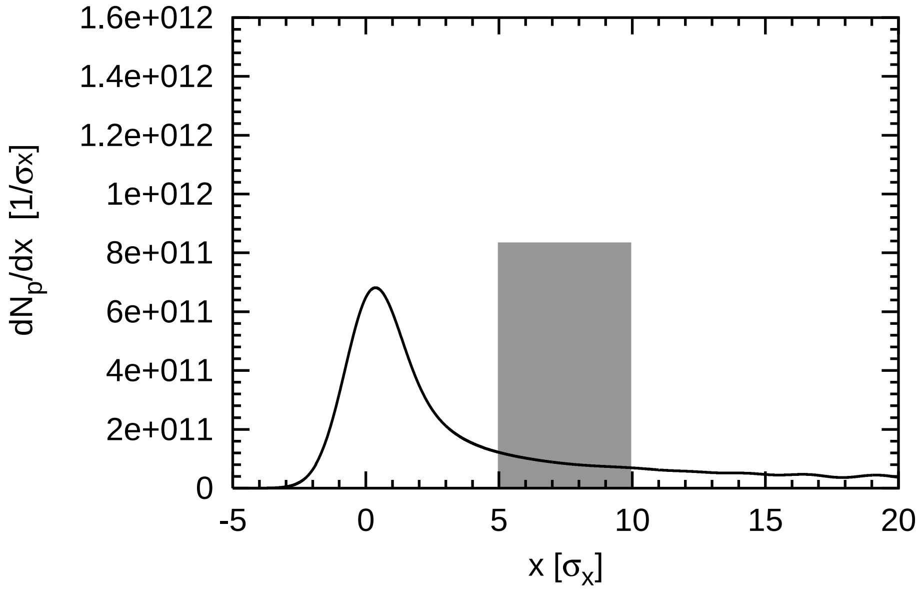

Figure 6: Time integrated horizontal distribution of LHC proton beam downstream of the MKD kickers and after an asynchronous beam dump. We can assume that all beam between 5 σ_x and 10 σ_x can impact on a primary collimator (shaded area). The vertical scale is set to cover the same range as in Figure 7.

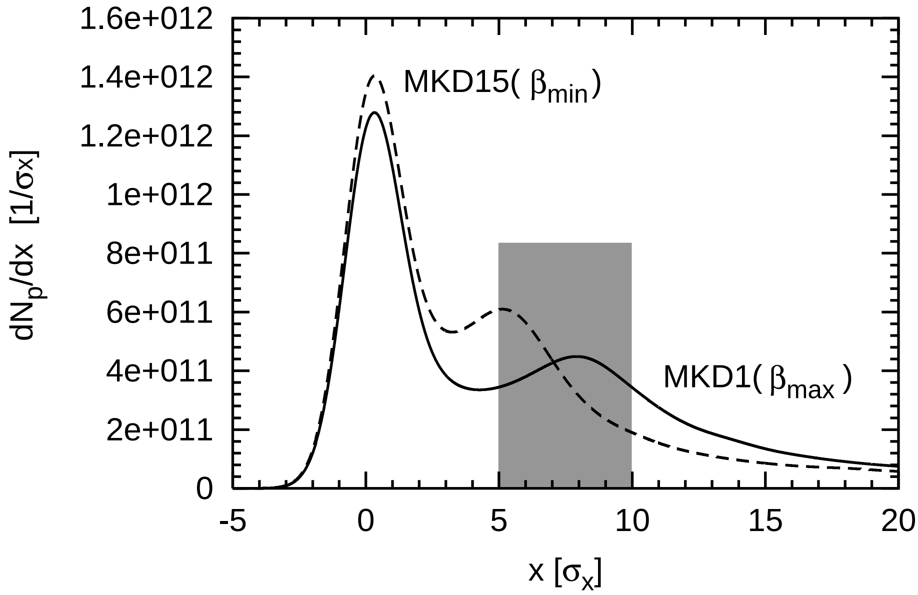

Figure 7: Time integrated horizontal distribution of LHC proton beam downstream of the MKD kickers and after a pre-fire of one kicker module (both for modules at maximum and minimum β-function). The 14 other modules are here assumed to re-trigger with a delay of 1.3 μs. We can assume that all beam between 5 σ_x and 10 σ_x can impact on a primary collimator (shaded area).

this requirement imposes tolerances on the optics and the orbit at the TCDQ that are more strict than foreseen, though not as strict as for the primary and secondary collimators. In particular we advocate controlling the horizontal orbit at the TCDQ to better than 1 σ_x (≈450 μm) in order to ensure efficient protection. The detailed procedure of setting and controlling the protection with the TCDQ requires further studies.

With the assumptions on collimation depth and TCDQ setting we can expect beam impact on the primary collimator in the range from 5 σ_x to 10 σ_x. Integrating the horizontal loss distributions over this range, we obtain the expected beam impact in number of protons. This has been calculated as a function of re-triggering time (note that a re-triggering time of zero corresponds to an asynchronous beam dump). The resulting beam loss versus re-triggering time is shown in Figure 8. We obtain an impact of about 4 LHC bunches for an asynchronous beam dump and of about 20 bunches for a single module pre-fire with a 1.3 μs re-triggering time.

4.2 Situation for LHC optics V 6.4

The actual beam impact on a given collimator will strongly depend on the details of the optics and the collimator arrangement. In general, we can write the minimum normalized beam offset $\tilde{x}_{min}$ that can still impact a collimator with collimation depth N_c and azimuthal orientation ϕ as:

$$\tilde{x}_{min} = N_c \cdot \frac{\sqrt{1 + \beta_x/\beta_y \tan^2(\phi)}}{\sin(\Delta\psi_x)} \tag{2}$$

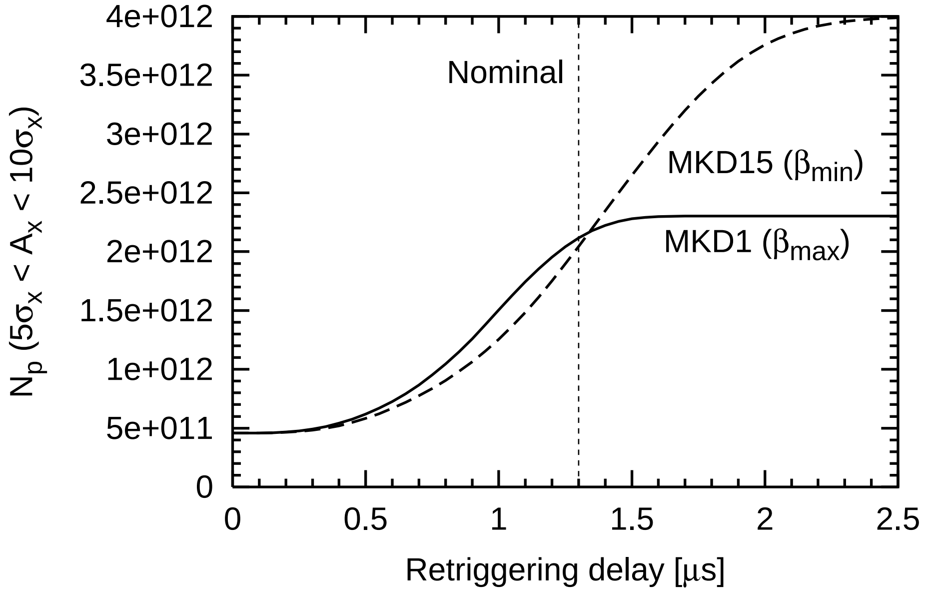

Figure 8: Expected maximum beam impact on the horizontal primary collimator in number of protons versus re-triggering time. Zero re-triggering time corresponds to an asynchronous beam dump. It is assumed that the primary collimation depth is 5 σ_x and that beam above 10 σ_x impacts on the TCDQ absorber.

	Beam 1		Beam 2	
Element	ψ_x [2π]	$\psi_x - N\pi$ [degree]	ψ_x [2π]	$\psi_x - N\pi$ [degree]
MKD kicker	0.	0.	0.	0.
TCDQ absorber	0.266	95.8	0.2653	95.5
Primary coll. (β-cleaning)	7.457	164.7	56.366	131.6

Table 2: Horizontal betatron phase advance between the dump kickers MKD (insertion 6) and the primary collimators in the betatron cleaning section (insertion 7), both for beam 1 and beam 2.

This relation is valid for round beam ($\epsilon_x = \epsilon_y$). Here, $\Delta\psi_x$ describes the phase advance between the kick (the MKD kickers) and the observation point, β_x and β_y are the horizontal and vertical beta functions at the observation point. In particular, for a primary horizontal collimator ($\phi = 0$) with $\Delta\psi_x = \pi/2 + m \cdot \pi$ and equal beta functions ($\beta_x = \beta_y$) we obtain $\tilde{x}_{min} = N_c$. All beam above the primary collimation depth (here $N_c = 5$) is hitting this collimator. This is the case we discussed for the basic collimator requirements.

The actual beam impact was computed for a MKD kick with the LHC optics V 6.4 and the present LHC collimation system layout. The phase advance conditions are summarized in Table 2 for the two beams. We consider beam 1 as the more extreme example. The primary and secondary collimation depths are set to 5 σ and 6 σ (this is a conservative assumption as the nominal primary collimation depth is 6 σ). It turns out that the actual LHC optics of beam 1 has the primary collimators at a multiple of π phase advance with respect to the MKD kick (this was also true for the LHC optics V 6.2). The primary collimators do therefore see no beam impact. The calculated beam impact for beam 1 is summarized in Table 3. Only beam between 7.8 and 10 σ is intercepted

Element	$\tilde{x}_{min}$	Impact range [σ_x]
TCDQ.4R6.B1	10.05	$>$ 10.05
TCS.C6L7.B1	8.90	8.90 - 10.05
TCS.B6L7.B1	8.80	8.80 - 8.90
TCS.B5L7.B1	7.87	7.87 - 8.80
TCS.A5L7.B1	7.78	7.78 - 7.87

Table 3: Beam impact in LHC optics V 6.4 (beam 1) for a beam disturbance originating at the MKD kickers. Note that the primary collimators sit at 5 σ and the secondary collimators at 6 σ. Nevertheless, due to the collimator orientations and betatron phase advances the beam is only intercepted above 7.8 σ_x. The situation is different for beam 2.

by four secondary collimators (horizontal and skew). The situation is substantially different for beam 2 where beam will be intercepted at the primary horizontal collimator from 6.7 to 10 σ_x.

5 Conclusion

The consequences of abnormal LHC beam dump actions on the collimation system have been evaluated, both for an asynchronous beam dump and the erratic pre-firing of one kicker module. The frequency of such failures is difficult to predict. It is assumed that they will happen at least once per year. As a conservative assumption the primary collimators were put to a collimation depth of 5 σ. This is below the nominal collimation depth of 6 σ and provides some margin for operational collimator adjustments.

Using the measured kicker rise time, the expected beam impact on the collimators was calculated. The maximum beam hitting a single collimator jaw was evaluated to be about 20 nominal LHC bunches. The impact of these bunches will occur in a small rectangular area of about 1 mm (full width) $\times$ 200 μm (rms width). The detailed distribution has been specified, showing that a peak impact of about 6 nominal bunches can occur in the first 200 μm from the edge of the collimator. The collimator jaws must be designed such that this beam impact can be tolerated, however, this appears to be difficult.

It was shown that the impact pattern depends significantly on the details of the optics and the arrangement of the collimators. In particular, for the nominal LHC V 6.4 optics the mis-kicked bunches of beam 1 will impact on four secondary collimators (horizontal and skew). These collimators capture beam from 7.8 to 10 σ_x (up to 8 bunches), even though they are set to 6 σ_x (with the primary collimators at 5 σ_x). The primary collimators are out of phase with the MKD generated kick, as it was also the case in LHC V 6.2. The situation is different for beam 2 where beam will be intercepted at the primary horizontal collimator from 6.7 to 10 σ_x. We note that a careful optimization of phase advance conditions between dump kickers and cleaning insertions can in principle relax the survival requirements for the LHC collimators. However, this route is not followed in order to maintain the existing operational flexibility in the LHC optics.

6 Acknowledgments

We wish to thank our colleagues in the LHC Beam Cleaning Study Group and the AP optics team for the discussions on this topic and the useful input to this work.

References

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