EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 916

Protection of the LHC against Unsynchronised Beam Aborts

B. Goddard, R. Assmann, E. Carlier, J. Uythoven, J. Wenninger, W. Weterings
CERN, Geneva, Switzerland

Abstract

An unsynchronised beam abort in the LHC could damage downstream accelerator components, in particular the extraction septum magnets, the experimental low-beta triplet magnet apertures and the tertiary collimators. Although the LHC beam dumping system includes design features to minimise their frequency, such unsynchronised aborts cannot be excluded. A system of protection devices comprising fixed and moveable diluters and collimators will protect the downstream LHC aperture from the misdirected bunches in case of such a failure. The sources of unsynchronised aborts are described, together with the requirements and design of the protection devices and their expected performance. The accompanying operational requirements and envisaged solutions are discussed, in particular the problem of ensuring the local orbit at the protection devices.

Presented at
EPAC'06, Edinburgh, UK,
June 26-30, 2006

CERN,
CH-1211 Geneva 23,
Switzerland
Geneva, June 2006

PROTECTION OF THE LHC AGAINST UNSYNCHRONISED BEAM ABORTS

B.Goddard, R.Assmann, E.Carlier, J.Uythoven, J.Wenninger, W.Weterings,
CERN, Geneva, Switzerland.

Abstract

An unsynchronised beam abort in the LHC could damage downstream accelerator components, in particular the extraction septum magnets, the experimental low-beta triplet magnet apertures and the tertiary collimators. Although the LHC beam dumping system includes design features to minimise their frequency, such unsynchronised aborts cannot be excluded. A system of protection devices comprising fixed and moveable diluters and collimators will protect the downstream LHC aperture from the mis-directed bunches in case of such a failure. The sources of unsynchronised aborts are described, together with the requirements and design of the protection devices and their expected performance. The accompanying operational requirements and envisaged solutions are discussed, in particular the problem of ensuring the local orbit at the protection devices.

INTRODUCTION

The LHC beam dump system uses an extraction kicker system MKD to deflect the beam horizontally into a set of Lambertson septa MSD. The beam is then painted by the MKB dilution kickers onto the graphite TDE blocks.

Each MKD system consists of 15 modules, and the total nominal deflection is 0.285 mrad. The MKD system deflection (measured waveforms) is shown in Fig. 1. The LHC filling pattern contains batches of 72 consecutive bunches at 25 ns spacing. The particle-free abort gap is 3.0 μs, corresponding to 0.5 σ – 100% MKD deflection.

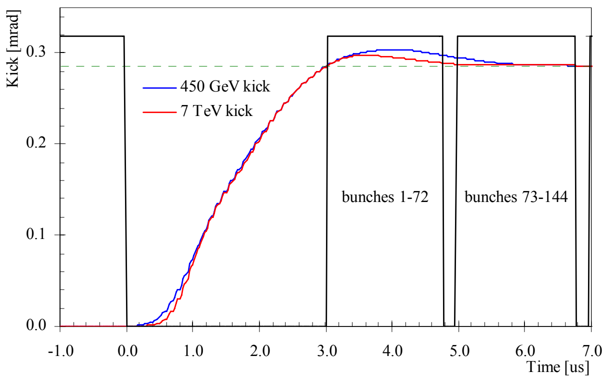

Figure 1. MKD system kick waveform in abort gap.

SOURCES OF ABNORMAL ABORTS

The LHC beam dump system has been designed to minimise the number of unsynchronised aborts. Correct functioning relies on simultaneous triggering of all 15 kicker magnet generators, with the correct phase with respect to the abort gap. The synchronisation is provided by the revolution frequency from the RF system: the overall tolerance on the timing jitter is 50 ns. Due to differences between individual generators and magnets, and in the response of the generator switches with energy, the triggering and main generator voltages will be non-linear functions of beam energy, supplied by look-up tables in the system EPROMs.

The kicker system is complex and there are several failures which can lead to unsynchronised firing. The frequency of such failures is difficult to predict, but it is assumed that a rate of one per year is possible, in broad agreement with experience at other hadron accelerators.

Synchronisation and rise time errors

In the absence of an RF synchronisation pulse, at the next turn the dump systems generates a trigger synchronised to an internal PLL locked to the RF revolution frequency, with a maximum error of 20 ns.

If the voltage tracking of the power trigger fails, the system rise time could be up to 150 ns too slow.

Prefire of dump kicker switch (erratic aborts)

In the event of a pre-fire of one kicker switch, a hard-wired system triggers all remaining 14 generators. This erratic abort produces the most severe beam load profile at low amplitudes [1], Fig. 2, depending on the re-triggering delay, now 700 ns for energies ≥3 TeV. To minimise the failure frequency, the 30 kV dump kicker switches use solid-state Fast High Current Thyristors FHCTs [2], rather than thyratrons, as FHCTs are less prone to spontaneous firing. 600 FHCTs are used, with the voltage drop surveyed to avoid that an undetected short circuit in one wafer over-stresses the remainder.

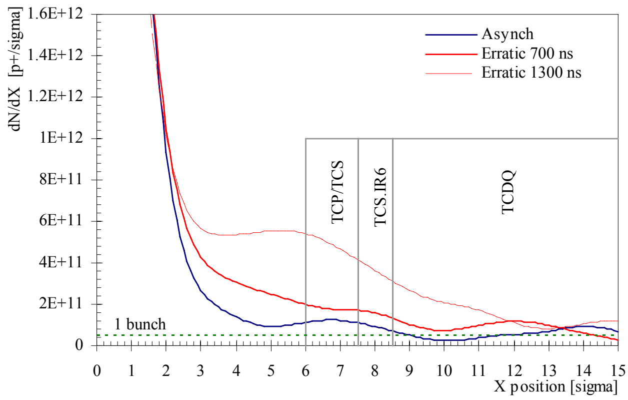

Figure 2. Transverse proton density as a function of amplitude for asynchronous and erratic aborts (using measured 7 TeV waveforms from 15 magnets).

Asynchronous aborts

An additional trigger is sent to the switches with a one-turn delay after reception of the trigger from the interlock system, in case both Triggering and Synchronisation units fail. This would produce the nominal kicker waveform, asynchronous with the abort gap, Fig. 2.

Accidentally-filled abort gap

The abort gap could also contain beam injected with the wrong phase, or uncaptured drifting beam, which would be swept across the aperture during a normal dump.

BEAM INTERCEPTING DEVICES

The LHC machine has been designed with intercepting devices to protect from unsynchronised aborts. The TCDS [3] protects the MSD septa. The TCDQ [4] and TCS.IR6 protect the Q4 magnet and the general LHC aperture. Additionally, the primary and secondary collimators TCP/TCS [5] are designed to withstand beam impact from an unsynchronised abort [1].

Table 1 shows the assumed settings and calculated beam loads for these devices, for the asynchronous and 700 ns erratic cases (the impact profiles on the collimators depend on the settings and optics, so the total in the interval 5.0 – 7.5 σ is quoted).

Table 1. 7 TeV settings and loads for protection devices.

	Setting σ	Total p+ [bunches]		Max. Density $[10^{11}$ p+/σ]	
		async	erratic	asynch	erratic
TCP/TCS	5.0	2.4	4.3	1.2	2.5
TCS.IR6	7.5	0.8	1.4	1.1	1.7
TCDQ	8.5	15.1	17.3	0.9	1.3
TCDS	58.8	27.8	28.4	0.6	0.6

TCDS diluter

The TCDS is a 6.0 m long fixed block upstream of the MSD septum, with a graded composition of graphite, high- and low-density carbon composite and titanium, for optimum absorbing power and robustness. The severe beam loading on this object makes this a difficult engineering challenge: conceptual and mechanical designs have been the subject of extensive FLUKA and finite element dynamic stress simulations [6].

TCDQ diluter and TCS.IR6 collimator

The TCDQ is a 6.0 m long mobile single-sided graphite block, installed about 15 m upstream of the super-conducting lattice quadrupole Q4. The TCS.IR6 collimator follows, with two 1.2 m long carbon composite jaws. The position of the TCDQ/TCS.IR6 with respect to the LHC orbit must be maintained to within about 0.5 σ, otherwise the protection of the LHC aperture will not be ensured – the TCDQ/TCS.IR6 jaws must be closed between 450 GeV and 7 TeV, by approximately 12 mm per side. With the tight positioning required to protect the LHC aperture, the secondary halo load on this system is a cause for concern for LHC performance [7].

LHC collimators

The LHC collimation system in IRs 3 and 7 removes halo particles to prevent quenches of the superconducting magnets. Since it defines the LHC aperture, the collimation system together with the beam loss monitoring system has an important general role in machine protection. The experimental triplets are equipped with local tertiary collimators TCTs which have both a beam cleaning and protection role.

With the beam dump system located in IR6, the collimation system must also withstand bunches escaping the TCDQ system after an unsynchronised abort. To this end, the primary and secondary collimator jaws are made from robust carbon composite, designed to withstand the erratic failure. The tertiary collimator jaws, however, are made from tungsten, which would not survive the impact of a fraction of one bunch at 7 TeV.

DILUTER PERFORMANCE ISSUES

Real damage limits are difficult to estimate in a generic way, since the actual energy deposition depends strongly on the details of the impact, and the material response cannot simply be parameterised with macroscopic characteristics. No experimental data exist yet for 7 TeV, which means that overall the quoted numbers must be treated as indicative rather than hard design constraints.

The unsynchronised diluters and collimators must often serve a dual role, with local objects to be protected from the impacting proton beam and from the resulting secondary showers, and in addition with aperture limits far downstream to be protected from surviving primary protons. The analysis of the local protection relies on detailed case-by-case Monte-Carlo simulations of the energy deposition, using a detailed 3D geometry over many tens of meters. The energy deposition results can then be used as input for analytical or numerical mechanical stress analyses, where dynamic effects are often important in the sub-μs time domain considered. To evaluate the protection afforded to remote aperture limits, it is possible to make some analytical estimates based on scattering formulae, to calculate a new beam intensity and size, and hence to obtain a scaling of the expected energy deposition. Effective dilution factors are plotted in Fig. 3 for the TCDQ system elements.

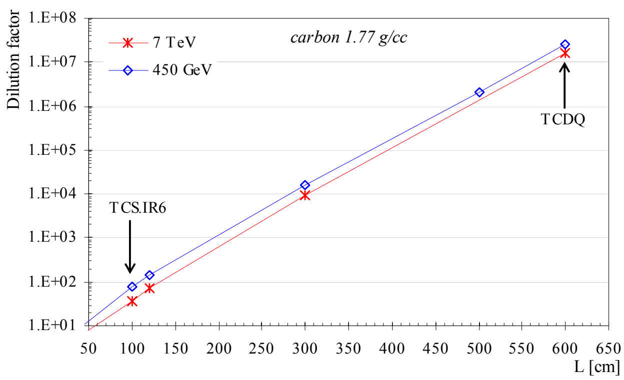

Figure 3. Dilution factor as function of carbon jaw length.

The 1.0 m long TCS.IR6 jaw reduces the energy deposition by a factor of about 35 at 7 TeV, through a combination of attenuation and emittance increase. This is of interest to evaluate the effects of retraction of the TCDQ with respect to the TCS.IR6 jaw on the beam density profile, Fig. 4. It indicates that the TCDQ may be retracted from the TCS.IR6 by about 0.5 σ, since in this case the maximum total p+ in the range 7.5 – 8.5 σ is about 5 % of a single bunch.

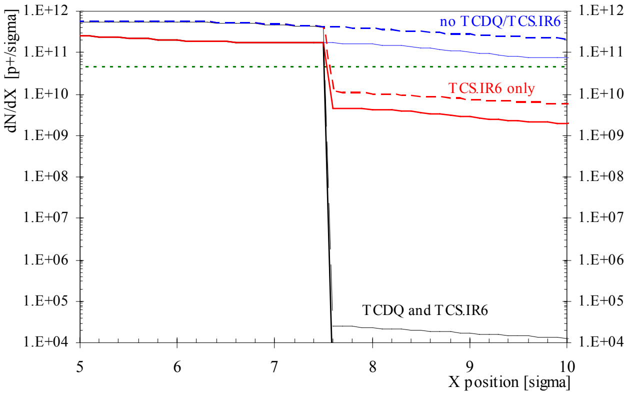

Figure 4. Effect of retracting TCDQ/TCS.IR6 jaws (solid represents 700 ns, dashed 1300 ns retriggering delay).

ORBIT CONTROL AT THE TCDQ

In the LHC, a global feedback system [8] will stabilise the orbit with an RMS of ≤500 µm, and to about 50 µm at the collimators. At the TCDQ, the requirement to stabilise the orbit with respect to the jaw to within ±0.5 σ imposes a stability of about ±200 µm at 7 TeV. The feedback system will use 528 BPMs per ring for horizontal and vertical beam position measurements. The real-time sampling frequency will be up to 25 Hz, and the BPM resolution below 5 µm for nominal intensity. The steering will be accomplished with ~280 mostly superconducting orbit correctors per beam and per plane, with an effective bandwidth of about 1 Hz. The orbit perturbations are expected to have frequencies below about 0.5 Hz, so that an effective global correction is possible at 10 Hz. Prototype tests in the SPS have demonstrated ≤10 µm orbit stability over a few hours [8]. A software interlock will survey the orbit at the TCDQ and compare it with the defined reference, at a frequency of about 1 Hz.

The orbit at the TCDQ will be hardware interlocked at ±4 mm, to protect the beam dump during extraction. During early LHC operation with $\beta^* \geq 2$ m, it will be possible to rely on this interlock and gap defined by the two TCS.IR6 jaws to effectively guarantee the protection of the TCTs and triplets for any orbit at the TCDQ.

ABORT GAP MONITOR AND CLEANING

The abort gap population from uncaptured beam or longitudinal diffusion processes is expected to be $\sim 3\times10^{10}$ and 3×10^{8} p+/100 ns at 450 GeV and 7 TeV, respectively [9]: higher populations could occasionally occur.

The 3.0 µs abort gap will be monitored using light from the synchrotron telescope and a dedicated gated photomultiplier system. One 100 ns sample can be taken each turn, with a complete measurement of the beam profile in the abort gap possible at ~10 Hz. The expected sensitivity levels are 4×10^{9} and 6×10^{6} p+/100 ns at 450 GeV and 7 TeV, respectively, corresponding to about 1 % and 0.001 % of the nominal bunch populations.

The abort gap may be cleaned [10] with the transverse damper, which can excite the beam by about 0.33 σ and 0.08 σ per turn at 450 GeV and 7 TeV, respectively. The excitation frequency may need to be varied to overcome the effects of the detuning at large amplitudes, and the 1 MHz damper bandwidth means that the cleaning will only be effective in the central 2 µs of the abort gap.

The abort gap monitoring and cleaning systems will provide important diagnostics and tools for improving operational efficiency, but at present it is not planned to connect the abort gap monitor to the beam interlock system: the signal will be rather used to produce an alarm. Clearly, if the positioning of the TCDQ system with respect to the beam proves to be very problematic, or if the abort gap population is significantly higher than expected, the monitoring and cleaning systems will also play an active role in machine protection.

CONCLUSIONS

The danger of unsynchronised beam aborts is recognised for the LHC, and the beam dump and collimation system have been designed accordingly, from the internal PLL in the synchronisation system to the FHCTs switches which intrinsically have low a pre-firing rate. Protection devices are designed to prevent damage to local elements in the extraction region, and a movable diluter system positioned close to the beam will intercept all bunches with amplitudes above 7.5 σ, protecting the arcs, tertiary collimators and triplet apertures. The primary and secondary collimators have been designed to withstand up to 20 bunches escaping this system. The tolerances on the TCDQ system positioning with respect to the beam are tight: some flexibility exists in the positioning of the TCDQ with respect to the TCS.IR6, and for the system settings in early LHC operational phases, but in general control of the orbit and the optics at these key protection devices will provide an interesting operational challenge.

REFERENCES

[1] R.Assmann, B.Goddard, E.Vossenberg, E.Weisse, CERN LHC project note 293, 2002.

[2] L.Ducimetière et al., LHC Project Report 260, 1999.

[3] B.Goddard, M.Sans, W.Weterings, Proc. EPAC'04, Lucerne, 2006.

[4] A.Presland, B.Goddard, W.Weterings., Proc. PAC'05, Knoxville, 2005.

[5] R.Assmann et al., Proc EPAC'04, Lucerne, 2004.

[6] B.Goddard, A.Presland, W.Weterings, Proc. EPAC'06, Edinburgh 2006.

[7] B.Goddard et al. Proc EPAC'06, Edinburgh 2006.

[8] R.Steinhagen et al. LHC Project Report 779, 2004.

[9] S.Fartoukh, B.Jeanneret, E.Shaposhnikova, Proc. EPAC'04, Lucerne, 2004.

[10] W.Höfle, Proc. EPAC'04, Lucerne, 2004.