WORST CASE BEAM INCIDENT CAUSES AND PROTECTION

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Abstract

The failure events which can occur with the fastest timescales in the LHC are mainly associated with the injection and extraction processes. The possible worst case failure events are catalogued and the protection layers in place to prevent the failure or mitigate the consequences are described. Particular attention is paid to the beam dump system kickers, the energy tracking system, the injection kickers and the aperture/tune kickers. The requirements for the positioning of the dedicated absorbers with respect to the aperture will be recalled, and the implications for the setting-up and operational stability critically examined.

Introduction

Beam related failures leading to serious accelerator component damage (incidents, in the parlance of our times) are of particular concern at the LHC, and have been the subject of many analyses; e.g. [1-5]. The LHC machine protection system is designed to prevent such failures, either by generating an interlock to dump the beam before beam loss can occur, or by the use of beam intercepting protection devices [6-8] to ameliorate the consequences in the event of fast failures from kickers.

This paper focuses on some of the combinations of failures which could lead to worst case beam incidents. These incidents are normally not considered as being credible in terms of probability of occurrence during the lifetime of the LHC, but past experience has shown that no machine protection system is perfect. It is therefore hoped that scrutiny of the contributing factors and consequences may lead to the identification of some weaker areas in the machine protection strategy or implementation, which could help further reduce the risk of such incidents arising.

A selection of worst case beam incidents is presented, with a description of the contributing factors and the protection measures in place. The expected scope and scale of the consequences for each incident are described.

The LHC machine protection system is complex with many contributing systems and components, Fig. 1. No systematic catalogue of protection element failure combinations exists. In general the possible contributing factors have been well analysed for single failures, by the individual systems designers, with extensive work on reducing the causes [9-11]. For multiple failures across the different systems, there is less analysis, with only the most obvious ones covered.

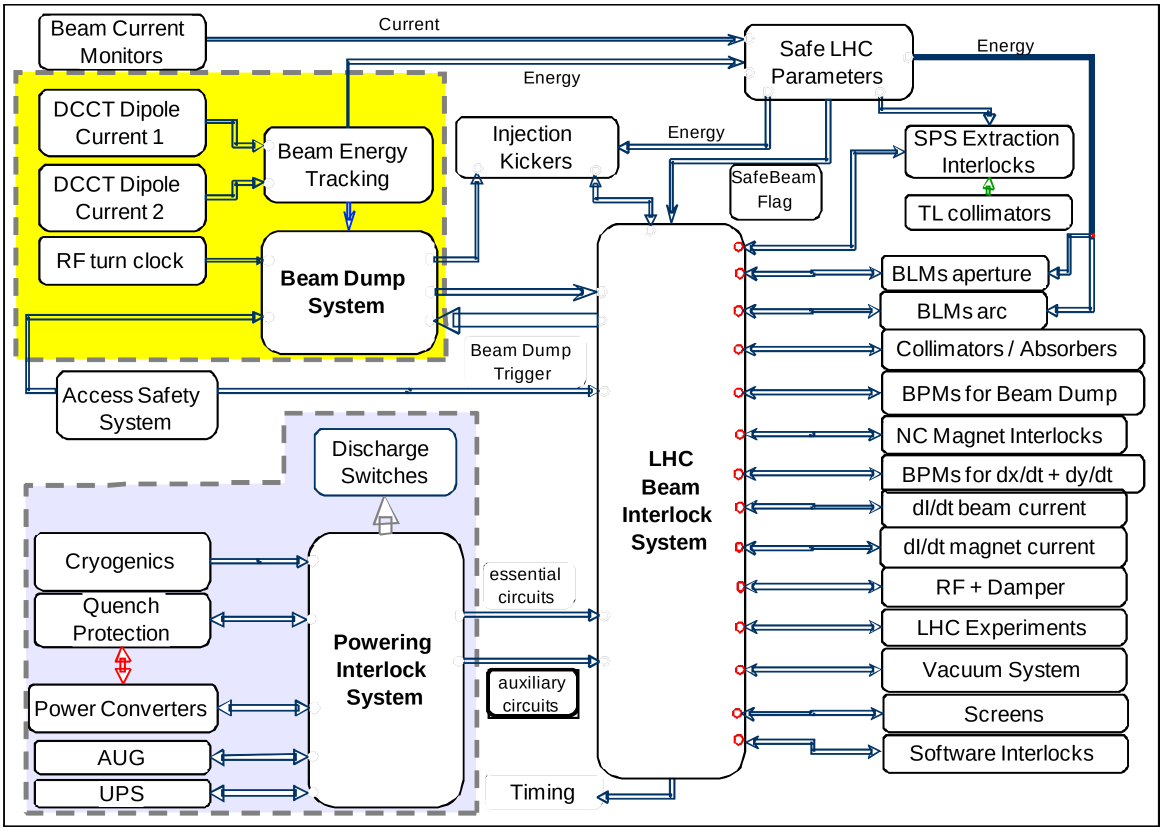

Figure 1: Schematic of the LHC machine protection system, with beam dump and energy tracking parts in yellow, quench protection and magnet powering interlocks in blue.

In the context of events in 2008, worst case incidents are tentatively defined here as those cases which have the potential to stop the LHC for more than 6 months. This could be as a result of depositing a damaging beam into:

- many arc magnets simultaneously;
- many collimators;
- a continuous cryostat interconnect;
- A DFB;
- several injection or extraction kickers;
- several RF cavities;
- an experimental beam pipe or detector;
- a triplet magnet;

Some serious indirect beam-provoked damage might also be possible, such as the large loss of vacuum plus contamination of RF cavities, injection kickers or an experiment, the beam-induced quench in busbar cable etc.

A thorough analysis should evaluate combined failures up to some arbitrary order (2, 3, …?), from all the systems such as beam dump, BIS, SIS, BLMs, QPS, PIC, WIC, injections, collimators, operators, powering, etc. Assuming that each of these ~20 systems has a handful (~5) of 'functional failure' modes, the numerology of the analysis problem soon becomes intractable: there are maybe 10^2 single failures to consider, 10^4 double failures, 10^6 triple failures and so on. This precludes a systematic analysis; in the following a representative selection of the types of worst case incident are described. In the light of the 2008 incident in 34 in which the LHC machine was extensively damaged by a helium release after an electrical arc on the busbar between two main dipoles, it should also be noted that the collateral damage may significantly exceed the direct beam induced damage, and that this should be evaluated as part of any serious risk analysis.

INCIDENTS DURING BEAM ABORT

Failures leading to beam loss during beam abort are a particular concern. No interlock can protect against failures which happen during fast extraction in a single turn of the 7 TeV full intensity beam, and the stored LHC beam energy is up to 360 MJ.

Extraction kicker erratic plus failure of retriggering system

A combination of an erratic trigger of one of the 15 extraction kickers plus a failure of the retriggering system for the remaining 14 magnets would deflect the entire beam at between 12.1 and 17.8 sigma at 7 TeV, Fig. 2. A synchronous dump trigger would be generated by the BETs system about 5 turns later, but the beam impacts the TCDQ and about 35% of the horizontal collimators on first turn, and 85% of the horizontal collimators within two turns, assuming the collimators are consumed piecewise in the process. The huge beam losses and quenches would also trigger a dump via the BIS within 2-3 turns.

For beam 2 the TCTs and triplets are more exposed (for beam 1 there is an extra 5m of graphite and 3 m tungsten from the IR7 beam cleaning collimators. The elements downstream of the collimators could be damaged from secondary showers.

The extent of the damage cannot be predicted analytically, and numerical simulations would need to take account of mass transport timescales, since the beam modifies the target material on timescales short compared to the 86 μs beam length. This gap in our knowledge of the process involved is common to many of the cases discussed and will be discussed in more detail later in a later section.

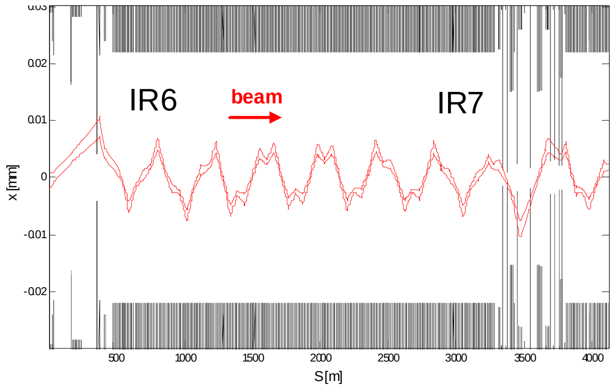

Figure 2. Beam trajectory from IR6 to IR7 for MKD erratic without retrigger.

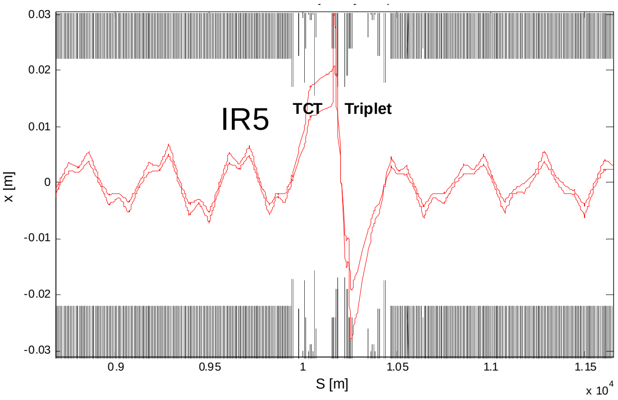

Figure 3. Beam trajectory through IR1 for MKD erratic without retrigger.

The protection against this failure relies on i) the inherently low erratic trigger rate of the GTO solid state switches (fewer than 1 per year across the 15 generators) and ii) the large redundancy and fault tolerance of the retriggering system, which is monitored after every dump to check that there are no blind failures or gradual degradations.

TCDQ/TCSG out plus asynchronous beam dump

If an asynchronous dump occurs the TCDQ system must intercept the beam swept across the LHC aperture [12]. At 450 GeV, simulations show that the fixed 2 m Fe TCDQM protects the LHC arc for a well-centred beam.

Even with the TCDQM removed the losses in the arc are at a low level, with most of the bam deposited on the cleaning collimators, Figs. 4 and 5.

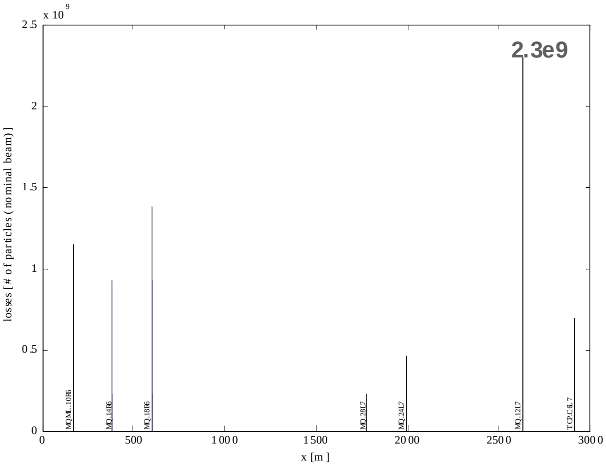

Figure 4. Losses in arc 67 for 450 GeV asynchronous dump with TCDQ retracted and TCDQM removed. The losses are well below the assumed damage limit.

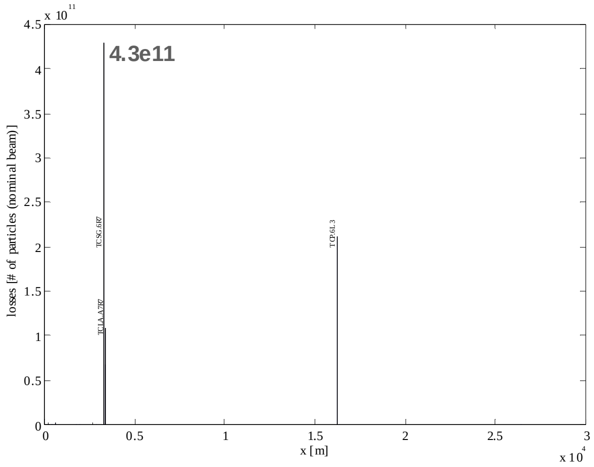

Figure 5. Losses at collimators in IR7 for 450 GeV asynchronous dump with TCDQ retracted and TCDQM removed.

At 7 TeV with 0.5m β*, beam 2 impacts the IR 5 TCTs with about 5e11 p+, which is at least an order of magnitude *above* the expected damage limit. Again IR1 is better protected with the intervening IR7. An error in the TCT positioning would expose the triplets, which could then damage several of the Q1, Q2 or Q3.

There are many concerns about protection against this scenario, since the TCTs are controlled and interlocked in common with TCDQ/TCSG, which means that there is scope for hidden common mode failures. In addition do the TCTs fully protect triplets even if well-positioned, or will the swept beam of a few μs length penetrate?

The precision on the beam position/collimator jaw specified to 0.5 σ, the feasibility of which remains to be demonstrated.

Finally, a similar effect to an asynchronous dump is produced at each dump if the abort gap is filled, which highlights the need for effective abort gap cleaning and monitoring.

The mechanisms to prevent this failure are i) the low inherent erratic trigger rate ii) the PLL locking the extraction kicker timing to the RF revolution frequency signal iii) the abort gap cleaning system iv) the TCDQ interlocking, both HW and SW and v) the SW interlocking of the beam position at the TCDQ.

There is concern that these measures are not sufficiently safe given the serious consequences of a failure, and improvements should be studied in 2009. The position interlocking of the TCDQ system should be critically reviewed.

Two or more missing MKD kickers

If two or more MKD kickers fail to trigger, the beam will be insufficiently deflected into the TCDS protection device (6m C/Ti/Fe), Fig. 6, and the MSD vacuum chambers [13]. If the TCDS is penetrated, damage could occur to MSDB and MSDC chambers, and the MSDC yokes, Fig. 7.

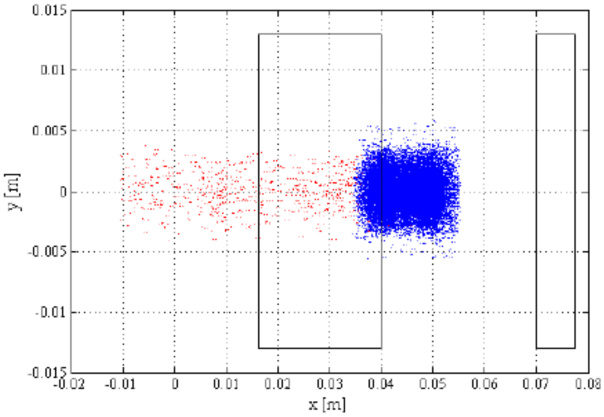

Figure 6. 450 GeV beam on TCDS block for two missing MKD kickers.

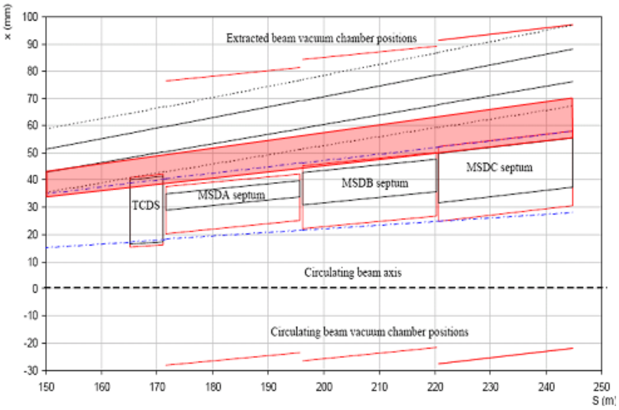

Figure 7. 450 GeV beam impacting TCDS block and downstream septum vacuum chambers and yokes.

Further downstream the next aperture restrictions are the TD vacuum line at the Q4 and Q5 cryo jumpers and the MKB kicker magnets. There is therefore a lot of sensitive equipment in this region but not very much stopping power. A sacrificial absorber has been considered in the TD line after MSD, but the design would need a much better knowledge on beam penetration depth and the ways in which the target materials fail, through both experiment and simulation.

The precautions against this failure are essentially the design reliability of the MKD generator switches and the redundancy in the design, including two switches per generator each capable of carrying the full current, and fully redundant triggering systems. Reliability calculations have shown [14] that the expected design failure rate conforms to SIL4, which means fewer than one failure expected in 10^6 years of operation.

Energy tracking failure

A failure of the energy tracking system BETS used to distribute the correct energies to the MKD could have very serious consequences [15]. If the beam is at 7 TeV but is kicked with e.g. 450 GeV strength, the case looks very much like the "erratic plus missing retrigger" above, except that the beam dump will not fire after 3-5 turns – all the beam will be lost in the LHC machine aperture. Another serious case is the inverse, kicking the 450 GeV beam with 7 TeV strengths, Fig. 8. In this case the angle is so large that the kicker magnets themselves are damaged, with two magnet yokes and five ceramic chambers likely to be damaged, together with Q4 and possibly the downstream TCDQM. Again the extent of the primary and collateral damage depends critically on the penetration of the beam into matter. The 450 GeV regime is clearly accessible with the SPS, and the proposed HiRadMat facility would be a very useful way to extend the experimental knowledge in this domain, and to benchmark the few simulations which have been made.

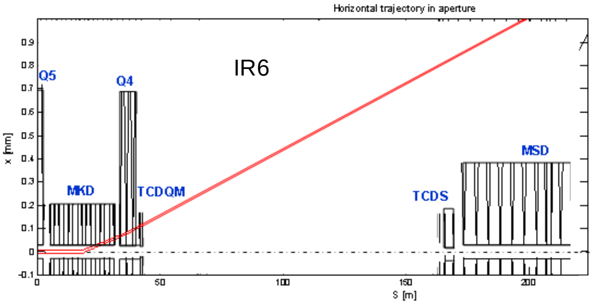

Figure 8. 450 GeV beam kicked with 7 TeV MKD strength, through MKD magnets and into Q4.

The BETS is designed with redundancy and failsafe logic to avoid such eventualities – the protection rests on the acquisition and comparison of four separate DCCT currents for the LHC energy, with two acting as a reference and two as an interlock signal. The energy ramp functions are contained in lookup tables separate to the interlock lookup tables. Both tables can only be changed by a local reprogramming of the FPGA, and the values are check explicitly before each fill. Again the system has been analysed and found to meet SIL4 [14]. A weakness here is the difficulty to extensively test the BETS, since this requires almost the full LHC machine in machine checkout mode and the current cycling of all the sectors concerned.

INCIDENTS DURING INJECTION

Injection also presents particular dangers, with an injected beam energy of over 2 MJ and fast kickers. A series of active and passive protection measures are taken [2], and as for extraction it requires a combination of failures to pose a risk to the machine.

Injection kicker doesn't trigger plus TDI and TCDD out

The failure of the injection kicker to fire gives an error of 0.8 mrad for the injected beam. If the TDI and TCDD are retracted, the beam impacts at about 37 mm vertically at the D1 entrance, and at about 40 mm at the exit, Fig. 8. These are exactly at the cold bore and coil radius, respectively. The D1 vacuum chamber and possibly the cold bore are likely to be damaged by direct beam loss, and the D1 coil by the secondary shower. This case would be fairly straightforward to analyse with e.g. FLUKA to determine the extent of the damage.

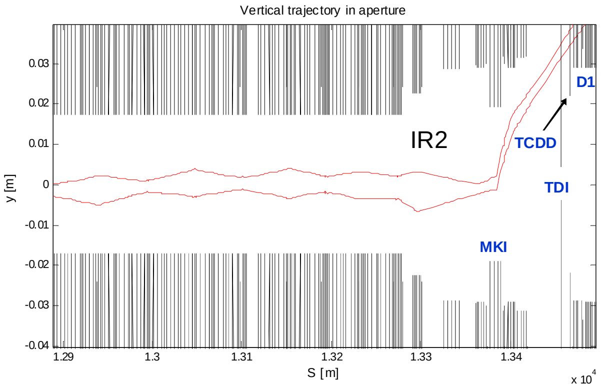

Figure 8. 450 GeV beam impacting IR2 D1, for MKI kicker not firing and TDI/TCDD retracted.

Failure of the MKI kickers to trigger can happen from many sources – a timing error, a triggering error, an injection inhibit from another interlock, etc The protection against this incident is therefore essentially the interlocking of the TDI position, since even with the TCDD in place the damage to this mask may already result in damage to D1 and collateral damage elsewhere, for example vacuum in the MKI. As for the TCDQ, the TDI interlocking should be critically reviewed. Also the possibility of fast vacuum valves around the MKI should be re-examined.

Injecting with dipole corrector field wrong

An injection of a high intensity beam with a wrong dipole corrector setting could immediately produce bam loss and damage, as analysed extensively for the experimental regions [4]. The beam could impact the experimental beam pipes in IR2 and IR8, Fig. 10, or could impact in an arc, possibly with many grazing incidence impacts. In the arc any cold-bore damage might leak He into the beam vacuum, where the collateral effects could be important. Also the cold mass could be linked with the interconnect via the beam pipe. For the injection regions safe limits of ~100 µrad on corrector dipoles and ~3% on D1/D2 currents have been derived, which are surveyed by a SW interlock process in the SIS.

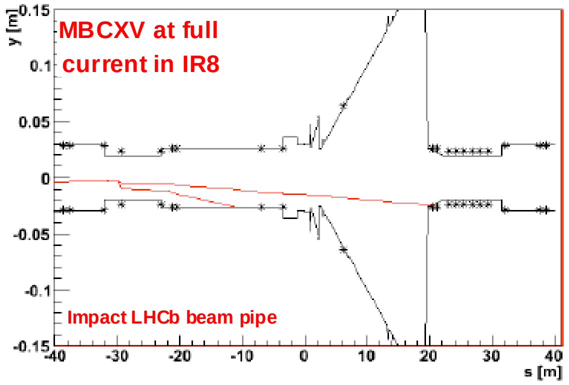

Figure 9. 450 GeV beam trajectories impacting LHCb experimental vacuum chamber for dipole corrector MBCXV error (courtesy R.Appleby).

This type of failure is a worrying cases because of the relatively weak protection and the large number of sources. The mechanism to prevent injection of a high intensity beam relies on the Beam Presence Flag, which is generated from a normal BCT. There are also many hundreds of unsurveyed magnet circuits which could deflect the beam onto the aperture. The possibility should be investigated of adding a HW surveillance of magnet currents, as is already the case for the SPS and the LHC transfer lines.

INCIDENTS WITH CIRCULATING BEAM

The incidents which can happen with circulating beam are in general over longer timescales than those with extraction or injection, but can still lead to severe consequences. The causes are different types of powering failures, including power supply trips, quenches, mains interruptions etc.

Fast powering failures

The effects of powering failures of separate magnet families has been extensively simulated [3]. The infamous warm D1 is recognised as the worst case at both 450 GeV and 7 TeV. If the collimators in their correct positions, the beam moves and the following timescales have been calculated with respect to the initial trip, Fig. 10:

- ~10 turns for beam to reach jaws
- ~25 turns to start quenching downstream magnets
- ~30 turns to reach collimator damage level

For other failures (including quenches) the time between first loss and damage is greater than ~100 turns. Grouped powering failures have been checked and are dominated by the fastest individual family

It is clear that correct BLM thresholds and correct collimator positions are critical to prevent damage following such a failure – extra protection systems FMCM have been added to ~20 circuits in the LHC and its transfer lines, but the redundancy between the detection systems for these fast cases is limited to just the BLMs and these FMCMs.

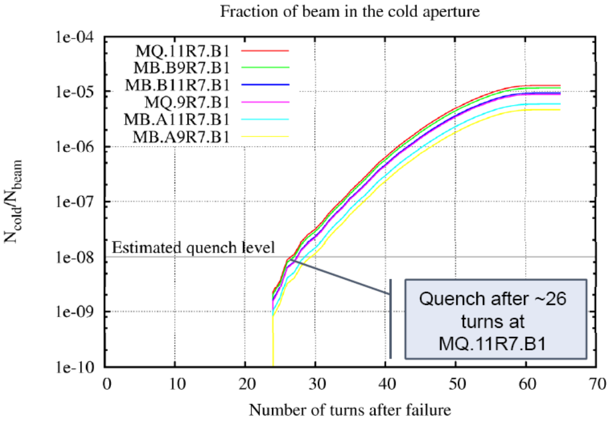

Figure 10. Beamlosses in quadrupoles after warm D1 trip (courtesy A.Gomez Alonso).

Slow powering failures

Slow powering failures encompasses trips, quenches or loading the wrong settings for one or many magnets, for instance ramping down the main dipoles for one sector to injection settings or ramping down the whole machine without dumping first (a similar type of incident in the SPS in 2008 destroyed a main dipole). For these cases the BLMs will trigger a dump when the beam reaches the collimators – but if the collimators are retracted on in incorrect positions, then these cases become more dangerous, since it is not clear that the dump request can be generated quickly enough to protect the aperture. Even more dangerous is the case that the BLM thresholds are wrong – here many collimators could be destroyed before a dump is triggered. The redundancy provided by the PIC is limited, since the reaction time after a magnet quench is about 150 turns, during which time the beam loss rate at the aperture may be high enough to cause damage.

In addition the near beam detectors are a particular concern due to their proximity - TOTEM is at 10 σ, and the VELO at 5 mm from the beam axis. This has been studied extensively for 450 GeV and 7 TeV for TOTEM and LHCb VELO, for failures of linear magnetic elements, and again the conclusion is that the protection relies critically on the collimator positions and the BLM thresholds. Local closed orbit bumps at detectors were identified as posing a danger – orbit monitoring and interlocks were added as a result.

For all the slow (and indeed the fast) powering failures it is clear that the protection relies on correct positioning of primary and secondary collimators and correct BLM thresholds. The machine protection functionality of the collimators has to be critically examined, since this has not been a primary design factor. The methods of collimator positioning interlocking should be reviewed, and in addition the methods of BLM threshold management critically examined. Finally, simulations could be made with collimators retracted, e.g. MB quench and finding whether the dump is triggered quickly enough to protect the machine aperture.

INCIDENT OF DUMP NOT TRIGGERED

The worst worst case incident in the LHC is that the beam interlock system does not forward the interlock signal to the dump system, or that the dump system does not react when this signal is received. If the dump was a programmed one, i.e. requested by the operators without any other fault condition, the beam will still be circulating, and the question arises as to the best course of action. Possibilities are:

- Call the BIS and LBDS experts to diagnose and repair the fault;
- Cut the RF Revolution Frequency to LBDS, to try to provoke a synchronous dump;
- Force an access system door to produce an asynchronous dump trigger;
- Start blowing beam up slowly with tune kicker, or transverse damper, to scrape slowly on the collimators;
- Scrape beam slowly away by moving collimators in, while staying below quench limit.

No detailed analysis has gone into this scenario - we should at least agree and maintain a procedure for the CCC.

If the dump fails to fire after an interlock condition, the beam will probably be lost very quickly afterwards, before any chance of human intervention. The question of how much of LHC machine will also be gone depends on the failure – damage may be limited to a few collimators, if losses at the TCDQ provoke a dump from the direct BLM, or many collimators may be consumed, or many collimators and many downstream SC magnets may be destroyed. Again, no quantitative studies have been made of this eventuality. However, some experience has been gained from other laboratories – the Tevatron experienced something like this, where the BLM signals were totally masked out. The damage was two lost collimators and three corrector magnets, for 1.5 MJ beam energy.

The beam interlock system and beam dump designs are centred around preventing this eventuality – nevertheless, a re-examination of the critical interface between the systems should be made, together with laboratory testing of the frequency transmission and error rates.

PENETRATION DEPTHS OF 450 GEV AND 7 TEV BEAMS

The penetration of high energy beams into matter is not easy to estimate, as the beam modifies the material properties on timescales of beam passage and drills into target. Simplistic energy balance estimates. give 100s of metres in Cu or Fe, but the huge scattering from dense target will blow up the primary beam size and the reality is not expected to be so pessimistic. With the 350 MJ 86 μs long beam, one cannot assume that processes are ‘adiabatic’, and to quantify these effects needs coupled nuclear – thermo-mechanical simulations, which are extremely difficult to implement. Some preliminary work has been done [16] coupling FLUKA output in a 2D hydrodynamic code, which found a factor 10 density reduction after 2.5 μs. Extrapolation to a full beam give penetrations of 10 - 40 m of Cu, Fig. 11, which means primary damage could be limited to 3-4 SC magnets. Similar estimates have shown that about 10 m of graphite will stop the full 7 TeV beam [17], which of interest for the beam dump core. It seems essential to better understand these processes to better estimate the direct and collateral damage expected.

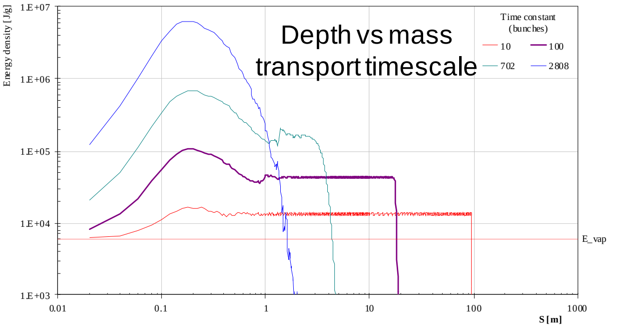

Figure 11. Estimates of penetration depth of 7 TeV beam into Cu, for different mass transport timescales.

PREVENTION, PROTECTION AND MITIGATION

General considerations

The LHC machine protection system is based on analyses of expected failures and their consequences. A great deal of work has been done between about 2003 and 2008 on the protection against beam incidents for the experiments, for injection, for circulating beam and for the LHC dump [1-8]. However, it is clear that the analysis has not been systematic in the sense that all failures and possible combinations have been exhaustively catalogued and analysed; instead a more intuitive approach based on experience has been generally applied. An attempt to systematically catalogue failures and combinations thereof should be made, in order to at least demonstrate that the most dangerous cases have all been accounted for.

The prevention of dangerous failures is a major part of the machine protection strategy and relies on the equipment design and operational procedures. An example is the fault-tolerance of the dump system main generators, where two parallel switches are used to meet the required reliability. Clearly the achieved reliability will be adversely affected by factors such as design errors, blind failures and common-cause failures, which are not taken into account in reliability analyses.

The active protection against failures relies on an active surveillance from different types of monitor, Fig. 1, and the interlock system, to detect and react to dangerous faults in time. The typical reaction time of a few ms allows most failures to be safely dealt with. The combination of collimator and BLM systems are assumed to be sufficient to catch a large variety of failures which come under the heading of "powering failures". For the LHC there is the explicitly stated assumption that the redundancy between detection systems greatly improves coverage; however, this assumption has not been fully demonstrated by quantitative analysis.

For the fastest failures, mitigation is essential, using fixed and movable devices to intercept mis-steered beams where interlocking not possible. The most dangerous systems for the machine are the mobile protection devices TDI and TCDQ, where the jaws must be positioned with high accuracy with respect to the beam – and the beam must be kept stable at these locations to the same tolerances.

Multiple failures

A functional failure in a critical system could lead to a worst case beam incident – there is only one energy tracking system, one interlock system and one beam dump system. These systems have been extensively analysed and the single failures have been taken into account in the design using fault tolerance and redundancy. Reliability studies have shown that the present designs meet the requirements in terms of the SIL levels, and technical audits of these systems have also been made which gave positive feedback on the critical subsystem design.

If multiple failures inside or across systems are considered, many worst case incidents are possible, as the above examples make clear. Overall, the faith in the LHC machine protection strategy is based on the assumption of redundancy, both in the need for multiple systems to fail simultaneously, and in the assumption that several monitoring systems will generate interlocks to dump the beam. The assumption is therefore that *"the chance of (failure A) + (failure B) happening is very small"*. Without a full quantitative analysis, there is therefore the clear danger of using the fallacious Argument of Personal Incredularity, such that our belief in the infallibility of the system rests on the argument that *"I personally find it very hard to believe that these things could all fail at once. I therefore assume that they cannot all fail at once"*. Past experience has shown that such conjunctions do occur, for example in 2008 in LHC, where a failure of the beam interlocking of a vacuum valve occurred as a result of 5 separate faults. For these multiple failures, the increased complexity makes the failure modes much more difficult to analyse and understand, and the interdependencies between the LHC systems mean that we have to worry about common single causes for multiple failures, for example the collimator position interlocks and the BLM thresholds are "controlled" by the energy value distributed over the Safe LHC Parameters system, which gives scope for common failure modes on two different systems.

It should also be borne in mind that the more often that we test (stress) the machine protection system, the more failures there will be. This means that, even if we believe the machine protection to be infallible, we should still make every effort to avoid stressing it, by well adapted procedures and sequencing, to avoid situations where operator error can make a single failure dangerous. A good example here is the possibility of ramping down the LHC energy with beam still in the machine – this should be avoided, even though we believe we are protected against it.

CONCLUSIONS

With the present LHC machine protection system we believe that we are well protected against the many possible worst case beam incidents. This belief may be somewhat hubristic, since to date, loopholes in machine protection systems have always occurred, and have been closed only after a beam incident has occurred. The SPS in recent years provides several examples where individual magnets and septa have been destroyed - although clearly many more such incidents have been avoided over the same time period. For the LHC there is clearly the possibility that an oversight in the conception or error in implementation, or even a combination of failures could lead to an incident where the beam damages equipment.

It is presently difficult to pronounce on expected scale of damage; the direct and secondary consequences of these incidents must be better quantified but this requires a much better knowledge of the way in which 7 TeV (and 450 GeV) beams on 100 μs timescales penetrate into matter. Such knowledge has a direct impact on prevention and mitigation 'weighting', the spares policy, procedures, etc.

The cases considered demonstrate that it is too easy to additionally stress the machine protection (e.g. ramping down without a beam dump). To avoid such issues we must define dangerous scenarios and find ways to avoid them.

Another issue which the RBAC system may not help with is "Quis custodiet ipsos custodes?" – the danger of the experts who know how to override interlocks, and push outside defined envelope, e.g. in MD. It is clear that experts must follow the defined procedure, even if they wrote them themselves, and that formal commissioning of crucial machine protection systems is essential.

The commissioning of the different functionalities needs time in schedule – the energy tracking in September 2008 was given no time before the beam commissioning started – which is clearly not acceptable.

The positioning and interlocking of the TCDQ and TDI devices with respect to the beam relies on rather 'soft' concepts such as software interlocks, SMP energy via timing system, positioning and interlock functions generated online in the LSA control system etc., and must be critically reviewed. For the TCDQ, the possibility of adding the TCDQ position into the BETs and reducing the interlock BPM thresholds should be evaluated.

The collimator positioning and BLM thresholds are crucial for the many slow failures. The collimators are an important part of machine protection against failures, but again the positioning relies on rather 'soft' concepts like the TCDQ and TDI positioning. Again a critical review of the actual implementation should be made for the collimator positioning and the beam loss monitoring threshold management.

For the dump system the energy tracking and triggering systems are absolutely crucial and a formal acceptance testing with review processes should be implemented. The implementation of the connections between LBDS and BIS should be critically reviewed.

For the longer term, more fundamental changes can also be studied, such as locating a TCLA after TCDQM or even a warm Q4 to allow the TCDQ to be located closer to the beam and reduce the tolerances on the positioning. It would be useful to launch studies of sacrificial absorbers to mitigate the direct and collateral damage where applicable, such as in the dump line after the MSD septa.

RECOMMENDATIONS

- Catalogue the failures for the different protection systems and analyse at least double failures;
- Critically review the implementation of:
  - TCDQ, TDI and collimator positioning and interlocking;
  - BLM threshold management;
  - LBDS energy tracking and retriggering;
  - BIS to LBDS connection
- Investigate the precautions which can be made to avoid unnecessarily stressing the protection systems;
- Ensure that the RBAC roles and rules are correctly implemented;
- Allocate sufficient time during machine checkout and beam commissioning for the protection systems;
- Ensure all test and commissioning procedures are finished and approved;
- Study specific cases of beam impact into accelerator components;
- Study the penetration of ~100 μs long 7 TeV and 450 GeV beams into matter;
- Invest in a test facility like HiRadMat to make tests to benchmark penetration and damage studies;
- Consider longer term studies like warm Q4, sacrificial absorbers etc.

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REFERENCES

[1] R. Schmidt et al., Protection of the CERN Large Hadron Collider, New Journal of Physics, 97, NJP/230233/SPE, 2006.
[2] V.Kain, Machine Protection and Beam Quality during the LHC Injection Process, CERN-THESIS-2005-047.
[3] A.Gómez Alonso, Transverse Impact Distribution of the Beam Losses at the LHC Collimators in case of Magnet Failures, LHC-PROJECT-Report-1162, 2008.
[4] R.Appleby et al., in preparation.
[5] T.Kramer et al., Apertures in the LHC beam dump system and beam losses during beam abort, proc. EPAC 2008.
[6] B.Goddard et al., Protection of the LHC against Unsynchronised Beam Aborts, proc. EPAC 2006.
[7] A.Presland, B.Goddard, W.Weterings, The Performance of the New TCDQ System in the LHC Beam Dumping Region, proc. PAC 2005
[8] V.Kain et al., Protection Level During Extraction, Transfer and Injection into the LHC, proc PAC 2005.
[9] J.Uythoven et al., Results from the LHC beam dump reliability run, proc. EPAC 2008.
[10] E.Carlier et al., The LHC Beam Dumping System Trigger Synchronisation and Distribution System, CERN-AB-2006-007, 2006.
[11] E.Carlier et al., The Beam Energy Tracking System of the LHC Beam Dumping System, CERN-AB-2006-006-BT, 2006.
[12] B.Goddard, M.Sans and W.Weterings, The LHC beam dumping system protection elements TCDS and TCDQ, proc. EPAC 2004.
[13] B.Goddard et al., LHC Beam Dumping System: Extraction Channel Layout and Acceptance, proc PAC 2003.
[14] R.Filippini, Dependability analysis of a safety critical system : the LHC beam dumping system at CERN, CERN-THESIS-2006-054.
[15] B.Goddard et al., Possible Causes and Consequences of Serious Failures of the LHC Machine Protection System, LHC-Project-Report-755, 2006.
[16] N.Tahir et al., Impact of the 7 TeV/c Large Hadron Collider proton beam on a copper target, J. Appl. Phys. 97 (2005) 83532-1-8, 2005.
[17] N.Tahir et al, in preparation.