IS THERE A LIMITATION TO THE STORED BEAM ENERGY FOR 2011 AND BEYOND?

R. Schmidt, CERN, Geneva, Switzerland

Abstract

The machine protection systems have been designed to ultimately operate with beams of a stored energy of 360 MJ. This presentation will address if there is an intermediate limit and what upgrades are required to permit operation with 360 MJ. A failure in one of the protection systems (BLM, BIC, LBDS, …) could have catastrophic consequences for LHC. Considering the operational experience, the most critical failure modes are reviewed, their probability is estimated and methods for mitigation are discussed. Ideas for reducing the risk include additional interlocks (DIDT interlock, abort gap cleaning/monitoring, fast BLMs, additional BPMs as HW interlock, aperture measurements,…), operational procedures and upgrades of hardware systems. There are also examples when the beams should NOT be dumped immediately.

LIMITATION TO THE STORED BEAM ENERGY?

For the run in 2011 and 2012 there should be no limitation for the stored energy with 75 ns or 50 ns filling schemes.

• Beam Interlock System: no dependence on the stored beam energy
• Beam Dumping System: No dependence on stored beam energy, but on energy [1]
• Beam Loss Monitors: No dependence on stored beam energy, but on energy [1]
• Beam Absorbers and Collimators: dependence on stored beam energy for the TCDQ that needs an upgrade for operation with nominal beam and 7 TeV. Assuming operating at 3.5…4.0 TeV with up to 900 bunches there should be no limitation. The exact limit is being assessed and an upgrade is being studied.

SAFE FOR THE FUTURE?

In the following the question is addressed if operation is expected to be safe in the long run and what improvement are recommended. The most critical mechanisms for failures are considered, and the risks at injection and with stored beam are analysed, for the principle protection systems: Beam Dumping Systems, Beam Interlock System, Safe Machine Parameter Systems, Injection Systems, Beam Loss Monitor System and Collimators / Beam Absorbers. Failures in other systems are not discussed here (SIS, FMCM, PIC, WIC, QPS, …).

FAILURE SCENARIOS

There are only very few mechanisms for single turn failures where the beam is deflected into the aperture within a single turn. This can happen at injection energy:

• the beam is not correctly injected
• the circulating beam is deflected because of a failure in the injection kickers system

This can also happen after start of the energy ramp:

• the injection kicker might fire
• there could be a failure when dumping the beams

There are no other known failure mechanisms that would lead to a single turn failure.

For multi turn failures many mechanisms cause a loss of beam. There is a lot of experience from 2010. The machine protection was designed with the fastest failures anticipated after a trip of a power converter for normal conducting magnets (typically D1). Such trips are detected with the FMCM (Fast Magnet Current Change Monitor) that worked very well in 2011. Another mechanism for fast beam losses was not predicted: UFOs lead to a loss of a small part of the beam within <1ms – 10ms [2]. It is assumed that these losses are caused by small particles inside the beam pipe.

RISKS

At 7 TeV with nominal beam parameters the energy stored in the beam is 360 MJ, and at 450 GeV about 28 MJ. Other parameters important for the assessment of damage is beam emittance and bunch pattern (although less relevant for major damage). The repair of damage after a serious failure will take a few days to many months. It cannot be excluded that there is damage beyond (reasonable) repair.

Occasional magnet quenches should be avoided, but are normally not considered as a major risk for LHC. However, before the interconnections of main magnets are consolidated, quenches at collision energy are critical. A quench close to a splice with insufficient copper stabilisation could lead to a thermal runaway, and an opening of the splice.

Failures of machine protection systems have been addressed several times [3,4,5]. Here a fresh look is presented, in light of the experience gained during 2009 and 2010 and new tools and simulation results.

INJECTION FAILURES

The duration of an injection kicker pulse is such to deflect maximum one batch with 288 bunches. The maximum number of injected bunches is 288. The energy of one batch (288 bunches) injected into LHC with
nominal beam parameters is 3 MJ. With 3 MJ, damage beyond repair is unlikely. This is shown with data from a SPS failure during extraction at 450 GeV on 25th of October 2004: the septum magnet power supply tripped during high intensity extraction. This caused damage of the beam pipe and a quadrupole magnet, when extracting one full nominal batch $3 \times 10^{13}$ (grazing incidence). This was very annoying, but not catastrophic. In LHC such incident would be more serious if this happens in superconducting section, but not lead to damage beyond repair.

However, after such incident the availability of spares could be an issue, depending on what is damaged by beam impact. Two questions:
- What are the most likely failure scenarios?
- If equipment is damaged, do we have spares?

**CRITICAL FAILURES**

The criticality of the different systems is addressed by considering the most likely serious failures and consequences.
- Most critical are failures of the Beam Dumping Systems and Beam Interlock System that could lead in the worst case to damage of LHC equipment and experiments beyond repair.
- Failures of the Injection Systems, the Beam Loss Monitor System, the Safe Machine Parameter System, Collimation and Beam Absorbers for injection and beam dump protection could lead to damage that requires repair for many month (damage similar to the 19/9/2008 accident).
- For other collimators, failures would most likely lead to damage that take days to a few weeks to repair.
- Systems like SIS and FMCM: failures critical in combination with other failures are critical and could lead to serious damage.

**DETECTING FAILURES WITH CIRCULATING BEAM**

The detection of failures and dumping the circulating beams worked very well during the past year(s). The detection of beam losses with BLMs showed high level of redundancy. In general, after beam loss, several BLMs trigger a beam dump and protection does not rely on the correct operation of a single BLM. Very fast failures (UFs) were detected in time and beam losses remained below quench limit. There was no accidental quench with circulating beams.

Failures in the electrical distribution were efficiently detected by Fast Magnet Current Change monitors (FMCM). In case of a failure the beams were always dumped before the beam was affected.

In some cases failures other monitors detected the failure before any beam loss occurred (e.g. BPMs, …).

**SERIOUS FAILURE IN A PROTECTION SYSTEM**

**Beam Loss Monitor System**

A complete failure of the BLM system is very unlikely but not impossible, since the correct functioning relies on complex programming in FPGA and all monitors having the same code.

The thresholds for BLMs could be too high, e.g. due to a wrong transmission of the energy or due to a major problem in the threshold tables. This is not expected to be catastrophic, since many thresholds are independent of energy, for other thresholds the change with energy is not very large. Still, all efforts should be done set the thresholds correctly.

In all cases when the beam was dumped by BLMs, beam losses are also visible at the primary collimators in IR7 (TCP) and/or at the secondary collimators in IR (TCSG). If the beam would not be dumped and losses would further increase, the threshold of these monitors would be exceeded.

If the beam loss monitor would not detect the failure, beam losses would quench a magnet and the QPS would dump the beam via the Powering Interlocks (PIC) and Beam Interlocks (BIC). This takes about 10 ms and would dump the beam in time for most failures, but not all.

**Beam Interlock System**

The most serious failure mode is if the system does not transmit the beam dump request to the beam dumping system (despite two/four fold redundancy). Beam would be lost due to orbit movement at collimators, possibly destroying the entire collimation system and leading to massive magnet quenches. It cannot be excluded that the LHC would be damaged beyond repair. The mitigation for such failure is to trigger the beam dump using a link to the beam dumping system that does not use the Beam Interlock System.

**Mitigation**

It is proposed to commission the already installed “direct BLMs” in IR6. These beam loss monitors are installed close to TCDQ / TCSG and have a direct link to the Beam Dumping System. From 2009 data, it should be possible to derive the thresholds.

The interface between Beam Interlock System and Beam Dumping System is highly critical. A redundant triggering of kicker magnets by the Beam Interlock System via an additional channel is considered. The signal would enter into the retriggering branch of the TSU unit and result in an asynchronous beam dump. Such signal must be delayed in order to ensure that the normal trigger comes first.

The time between the interlock generated by the Beam Interlock System and the beam dump should be measured with high accuracy.

Fast Beam Current change Monitor will become operational during this year. Such monitors were used successfully for many years during HERA operation. In
case the beam loss monitors do not detect significant loss of beam, these monitors would trigger a beam dump.

### BEAM DUMP KICKER FAILURES

**Beam Dump Kicker not firing**

In Chamonix 2009 B. Goddard addressed two questions [6]:

"What do we do if the dump doesn’t react to a programmed request?" In the case of a dump requested by operation, there is still time to react, and it is suggested to work out a procedure for operation what to do in some case.

“If dump fails to fire after an interlock, beam will probably already be long gone. How much of LHC machine will also be gone?” Depending on the stored beam energy, massive damage is expected.

With the operational experience, progress in simulation work and the future tests at HiRadMat it should be possible to address this problem quantitatively. The simulation studies require the coupling of programs such as FLUKA (for calculating the energy deposition into material) and BIG2 (or possibly ANSYS-AUTODYN) to calculate the hydrodynamic response of the target, as already done in the past [7]. Code validation experiments at HiRadMat (interaction of SPS beam with targets, such as collimators) are planned.

**Other risks during beam abort**

One of the failure modes that should not lead to any damage is an asynchronous beam dump with high intensity beams. There are several conditions required for a correct beam dump, in order of importance:

- The Beam dump kickers must deflect the beam with the correct angle. This is the most serious failure.
- The TCDQ / TCS absorbers must be at the correct position and beam must be centred between TCS jaws.
- Large orbit bumps around the LHC must be avoided.

- Other collimators must be at the correct position. Most bunches will hit the TCDQ. Although this absorber was designed for such impact, a procedure should be developed to validate the integrity of this object. The correct position of the TCDQ / TCS assembly with respect to the orbit is of the utmost importance for LHC machine protection.

  The closer the TCDQ is to the beam orbit, the better for protection in case of serious failure, but also for asynchronous beam dumps. The control of the horizontal beam position in the TCDQ / TCS is very important. However, the TCDQ should not violate the collimation hierarchy for keeping the required cleaning efficiency.

  Can The CDQ / TCSG absorbers move closer to the beam? A test is suggested. An interlock of the TCDQ position with respect to the beam using a solution based on hardware and the BETS (energy information) is proposed.

**Beam dump kicker deflects beam with wrong angle**

A deflection of the beam by a small angle is most dangerous (deflection by 5-10 \( \sigma \)), since the deflected beam can affect equipment in the entire machine. It could lead damage of the collimation system and to damage of other equipment.

Such wrong deflection could be due to a failure of the energy tracking system, e.g. the beam is deflected with a strength corresponding to 450 GeV, instead of, say, to 3.5 TeV or 7 TeV.

Another failure mode is a fault of the retriggering system and only one kicker magnet fires. An improved automatic test system is under development.

The TCDQ / TCSG absorbers could help to mitigate the consequences in case of such serious failures of the beam dumping system. In a future upgrade of the TCDQ the robustness of this absorber might be increased.

**Massive beam impact**

In the worst case, all bunches would be deflected into equipment. The challenge is to calculate the impact of 2808 bunches as function of time. During the impact, the material vaporises. Simulation results show that a 7 TeV nominal beam would tunnel through 25-30 m of copper. In the case of a graphite target, most of particles would be stopped by a graphite absorber of about 10 m length. The validation of the codes is planned with an impact experiment at HiRadMat.

### OTHER SHOWSTOPPERS FOR HIGH STORED BEAM ENERGY?

When increasing the stored beam energy there are several effects to be watched out for:

- Single event upsets
- EMC effects might appear with more bunches / other bunch patterns
- UFOs: it might be required to increase the thresholds of the beam loss monitors and this could
increase the number of quenches. A compromise has to be found since a quench has a (small) risk of triggering a thermal runaway of a high current splice and lead to rupture.

- Beam instabilities: how fast can the beam become unstable? Is the phase coverage by collimators for losses that happen in a few turns sufficient? For the time being, there is no indication that we must worry…

Reviews on machine protection were very useful. From past reviews in general the recommendations were followed, sometime later than recommended by the reviewers. Later this year another review might be organised.

**PROPOSALS**

1. Mitigation of serious failure modes of BLM and BIC: direct BLM to be connected to Beam Dumping System using BLMs close to TCSG in IR6. This can be done soon. Later, possibly BLMs close to TCP in IR7 could be linked directly to the beam dump in the future.
2. Fast Beam Current Change Monitor should be made operational soon.
3. Mitigation of serious failures of Beam Dumping System: write procedure for CCC, what to do if an operators requests a beam dump, and it does not work.
4. A redundant triggering interface between BIC and LBDS should be considered.
5. TCDQ / TCS positioning to be improved (e.g. energy tracking).
6. Buttons to measure the beam position should be directly installed in beam absorbers would increase the level of protection, ensuring that the beam is always centred. The TCSG and TDI are prime candidates to be equipped with buttons.
7. The TCDQ consolidation should takes into account studies of beam tunnelling simulations (can the TCDQ stop the full beam with minimum consequences?)
8. Study consequences of catastrophic failures with simulation programs (MAD, SIXTRACK, FLUKA, AUTODYN).
9. Do we have sufficient pares for possible damage due to the most likely failure modes?
10. It possible, software interlocks should move towards hardware interlocks.
11. Injection: make sure that TDI is at the correct position.

**ACKNOWLEDGMENTS**

Thanks to many colleagues for discussions: J.Blanco, E.Carlier, B.Dehning, B.Goddard, R.Jones, N.Tahir, J.Wenninger, M.Zerlauth and others.

**REFERENCES**

[2] M.Sapinski et al., Is the BLM system ready to go to higher intensities? Chamonix 2011 Workshop on LHC Performance, CERN, Geneva, Switzerland