UPDATE ON BEAM FAILURE SCENARIOS

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Abstract

At the time the LHC machine protection system was designed a number of standard failures scenarios have been taken into account, like the D1 warm dipole failure and the asynchronous beam dump. This paper will analyse if these failures did take place and if the protection system worked as expected. An iteration is made to see if the failure catalogue needs to be extended, based on the past operational experience and on the 2015 beam parameters and whether we need to adapt the machine protection system to possible new failure scenarios.

INTRODUCTION

The LHC machine protection system needs to protect the machine from damage by the beam. Ideally it has to protect against any possible failure scenario. Different critical failure scenarios, which are either difficult to protect against or would cause a large damage, have been taking into account for the design of the machine protection system. This paper lists the standard failure scenarios, checks if they did occur, if the protection system worked as expected and whether a change of the machine protection system is required for specific failure scenarios. This paper also discusses failures that did occur but were not foreseen and failures for which the machine protection system reacted differently than expected.

It is worth mentioning that the splice failure, which occurred in 2008, was not part of the failure catalogue. The first reason being that it is a non-beam related failure mode. Only beam related failure modes are treated in this paper. The second reason being that, although people were aware of the splice quench possibility, they were not fully aware of the risk of a quench in a bad splice, i.e. not only did they underestimate the frequency of the failure, they also underestimated the large impact caused by collateral damage. This shows the importance of having correct estimates of failure rates and failure impacts.

THE BIG THREE

The Big Three failure scenarios were defined before the first operation of the LHC [1]. They are described and analysed below.

Injection kicker flashover

This is a single turn, fast failure. An electrical break-down or flash-over in an injection kicker magnet can affect the injected beam (with too little but also too much deflection), or the stored beam. In all cases the beam is to be absorbed by the injection absorber TDI. In case a large number of bunches is affected, a quench of the magnets downstream of the TDI is expected.

This fault occurred several times. In the case of grazing beam incidence on the TDI, downstream magnets quenched as expected. In one occasion, part of the ALICE detector was affected by the sprayed beam and a short circuit of a magnet corrector circuit occurred at the moment of beam impact. However, the short circuit could not be explained considering the power deposition.

On all the occasions a kicker magnet break down occurred, the protection system functioned as expected and the beam was absorbed by the TDI. For this reason no real changes of the protection system against this failure mode is foreseen. However, the importance of the correct positioning of the TDI has been demonstrated. Additional difficulties with the TDI occurred due to deformation of the jaws caused by beam induced heating. The following actions were or will be taken:

- During operation the TDI was moved to ‘parking’ position as quickly as possible to limit the beam induced heating.
- During LS1 the TDI will receive a reinforced beam screen and a general maintenance of the moving parts is foreseen.
- During LS1 a Beam Energy Tracking System (BETS) will be installed as additional interlock on the TDI position.
- During LS2 a complete overhaul of the TDI will take place.

Asynchronous beam dump

This failure is also a single turn failure which occurs when the firing of the extraction kicker magnets MKD is not synchronised with the abort gap. The expected scenario for this to happen was a pre-firing of one of the 15 extraction kicker magnet, followed by the re-triggering of the other 14 magnets.

This failure mode did happen, although not the way it was expected, possibly helped by the fact of running at lower than nominal beam energies. One asynchronous beam was caused by a Trigger Fan Out problem [2].

The protection worked as expected, as the TCDQ absorber was in the correct position. Changes to the beam dumping system are foreseen during LS1: the Trigger Synchronisation Unit (TSU) will be modified, including the powering. A strong dependency on the TSU was revealed and a redundant triggering of the beam dumping system from the BIS, not requiring the TSU, will be implemented during LS1 [2].

Normal conducting D1 failures

This failure is a multi-turn failure. The D1 dipole magnets in points 1 and 5 are normal magnets, having short time constants in case of failures, and are located at a position with a large beta-value. Following a D1 trip 10^9

lost protons (detection limit) can be expected after about 15 turns while the level of 10^{12} lost protons (damage limit) is reached after about 25 turns. Hence, the beam will need to be dumped between 15 to 25 turns [3]. Because of the criticality of this failure the D1 power converters have been equipped with Fast Magnet Current change Monitoring (FMCMs) to dump the beam when any perturbation of the D1 current is detected.

This failure mode occurred as part of general power perturbations, resulting in power converter trips. The beams were always cleanly dumped, triggered by the FMCM, before any significant change of the D1 current or the orbit could be measured. No losses on the BLMs were measured before the beam dump. Sometimes the FMCM protection is too sensitive as it occurred that the FMCM dumped the beam due to a real power perturbation, but no power converter trip took place.

The changes foreseen during LS1 are to relax the thresholds of the FMCM dumping the beam [4].

OTHER FORESEEN FAILURE MODES

Fast kicker systems

The fast tune and aperture measurement kickers MKQ/MKA, the AC-dipole and the transverse feedback system were considered potentially dangerous. The operation of the MKA and AC-dipole was limited to safe beam only and controlled by additional keys in the CCC. No dangerous beam loss related to any of these systems occurred.

Beam hitting the cold aperture

The beam never hit the cold aperture during normal operation. No beam induced quenches of magnets occurred besides those caused by the breakdown of the injection kicker magnets as mentioned above. The limits imposed on collimation, defined as the required cleaning efficiency, turned out not to be an issue.

The beam dumping system does not dump

Luckily enough this never occurred. However, a procedure [5] was put in place on what to do if ever this would happen. The procedure consists of:

- Force the opening of the BIS loop by using various client inputs.
- Generate an internal fault of the LBDS, which should result in an internal beam dump request.
- Scrape away the beam with the collimators in point 7, using the ADT as excitation.

The procedure was tested without beam, but never needed during normal operation.

Power Cuts

Many power cuts happened and the beams were always cleanly dumped by the FMCM. As we seem to rely heavily on the FMCM it might be good to calculate the safety (SIL level) of the FMCM for the hardware and the acquisition chains.

Magnet Quenches

No quenches at top energy ever occurred, only quenches due to injection failures, as is already mentioned above. The circulating beam was always cleanly dumped.

Beam instabilities

Beam instabilities, mainly during the squeeze process or when bringing the beams into collision, have been the origin of beam dumps. In all cases the beam was cleanly dumped. In these cases the beam dumps were triggered by either the BLMs in the collimation regions or the Beam Position Monitoring System (BPMS) in point 6.

FAILURE MODES THAT WERE NOT FORESEEN

Injection errors

Injection errors took place. On one occasion the wrong beam from the SPS was extracted for injection into the LHC. The problem was traced back to injection timing settings in the SPS. Other injections errors took place related to the timing system.

Local orbit bumps

The orbit feedback has been producing local bumps in the orbit. Protection exists by the SIS and additional software being put in operation towards the end of the run. Knowledge of these systems should be wider spread.

Beam Induced Heating

Various LHC equipment has been affected by beam induced heating, leading to potentially dangerous situations:

The injection absorber TDI suffered from deformation and was blocked in its movement on several occasions. As the TDI is one of the most critical machine protection devices, alignment of the TDI was verified with beam at several occasions after experiencing positioning problems. The heating of the TDI also resulted in background problems of the ALICE detector.

One mirror of the synchrotron light monitors BSRT has been heating significantly and there was a risk that it would fall from its support into the beam aperture. Beam operation was stopped to remove the mirror.

The injection kickers MKI were heating significantly. If the kicker ferrites would reach a temperature above their Curie point during injection the beam would be badly injected. Great care was taken to monitor the MKI temperatures and on several occasions a significant cool-down time was required before injection could take place.

UFOs

Unidentified Falling Objects, or UFOs, have been leading to significant beam losses and clean beam dumps. UFOs took place especially at the injection kickers and the Roman Pots after movement of the pots. Large beam losses can potentially lead to quenches of magnets and the associated risks.

Abort Gap Population

At several occasions the beam abort gap was filled with particles due to RF problems. In some cases the RF failure was only detected by the increase of the abort gap population. The cleaning of the abort gap by the transverse damper was not fully automatic and could potentially have led to dangerous situations. After the removal of the synchrotron light monitor mirror of one beam (see above) the situation was even more dangerous as no direct measurement of the abort gap population by the BSRA was available during several weeks.

Long Range Beam-Beam Kick

During an MD in December 2012 one large intensity beam was intentionally dumped while the other was kept circulating. A 0.6 σ effect was measured on the orbit. This is a one turn kick and the effect is very fast. It can also affect the protection by collimation. Simulations for post LS1 are foreseen.

Radiation leading to many False Dumps

Many dumps were initiated by radiation effects on the electronics, e.g. the electronics of the QPS. Possible dangers are that these radiation effects could have (temporarily?) reduced the redundancy of machine protection or surveillance elements.

Unprotected QPS Circuits

During the powering tests at the end of Run I, it was discovered that some powering circuits were not protected by the QPS system. This was traced back to the reset procedures of the QPS and some known system faults.

WHAT WENT DIFFERENTLY

Beam Loss Monitors

Taking into account the complexity of the BLM system, it was initially expected that masking of some BLMs, to cope with hardware failures, would be occasionally required. The availability of the BLM system turned out to be excellent and masking of BLMs was extremely rare. The BLM system performed extremely well and provided a general and reliable safety net against failures which are not ‘too fast’.

At the start-up of the LHC it was foreseen to connect some ‘direct BLMs’ at point 6 directly to the beam dumping system, without passing via the Beam Interlock System. This was only done in 2012, later than originally foreseen. However, it never triggered a beam dump, as it should.

Systems not implemented

A Beam Position Change Monitor was initially foreseen. It should trigger a beam dump in the case of beam position changers faster than 1 mm/ms, not using any absolute reference. This system was never implemented. However, the BPMS system at point 6 has dumped the beam at several occasions, using an absolute beam position reference and considering individual bunches. This system provided the required interlock in case of beam instabilities.

The Beam Current Change Monitor, seen as an alternative to the measurement of losses by the BLMs, was never implemented. It is now foreseen to be commissioned at start-up in 2015.

BIS channels that never triggered

Many of the Beam Interlock Channels never triggered during beam operation. Their functionality has been checked at the beginning of Run I, but a periodic check of these channels could increase the machine safety.

CONCLUSIONS

The LHC Machine Protection System functioned properly during Run I of the LHC. No major damage to the machine occurred after 2008. The Big Three failures scenarios originally foreseen all occurred and changes are foreseen on all three systems affected for start-up in 2015:

- Changes to the injection absorber TDI.
- Changes to the LBDS / TSU powering and direct link between BIS and LBDS.
- Changes to the FMCM threshold (dumping too often).

As expected, some unexpected failure scenarios also occurred. They have been related with the timing system, beam induced heating, orbit bumps, UFOs, abort gap filling and the QPS system. Our protection against these failures needs to be improved, either by improvement of the equipment involved or by improving the surveillance of these systems.

As a global conclusion one can once again state that one has to stay vigilant against foreseen and unforeseen system faults. Each beam dump needs to be properly understood by looking at the Post Mortem data in detail before operation can be continued.

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