LHC POWERING ISSUES – REVIEW OF BEAM DUMPS*

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Abstract

Following the near catastrophic quench event in September 2008, the LHC magnets have seen their magnetic field strength reduced to a maximum safe value, limiting the LHC's beam energy. Since then, the challenge of establishing the causes of such an event and ensuring that it is not likely to reoccur has been of paramount priority. The main topic of this paper is to discuss the significant powering issues and causes of beam dumps over the last three years of operation, correlating individual system statistics, year-to-year, with intermittent system changes/upgrades.

To complement this, predictions of the systems most likely to cause issues whilst operating at higher energies will be discussed, as well as a brief look at past 'near-miss' events, their causes, and plans for prevention of future reoccurrence.

INTRODUCTION

What is a Powering 'Issue'?

For the purpose of this paper a powering issue is defined as follows:

- An unintended powering system event which hinders global operation, resulting in either physical system damage or a loss to availability.

Powering Systems

With regards to machine protection of the LHC, a 'powering system' can be defined as a system responsible for the electrical powering and/or monitoring of magnet circuits. Each of these powering systems has an independent ability to trigger a power abort (i.e. magnet current discharge) and/or 'beam dump' if certain thresholds, implemented for machine protection purposes, are exceeded [1].

BEAM DUMP REVIEW

All data used in the study was extracted from the LHC's Logging System; the Post Mortem Database [2].

It was concluded that an in depth analysis of the most prevalent powering systems, and a direct comparison of the most stable years of operation (2011-2012), would be the most conducive. Systems analysed in study: Power Converters (PCs); Powering/Warm Interlock Controllers (PIC/WIC); Fast Magnet Current Monitor (FMCM); and the Quench Protection System (QPS). The results and analysis of the study are as follows.

Power Converters

Statistics of beam dumps due to either powering failures or discharge requests of the PCs shows a global improvement from 2011 to 2012, during all stages of beam operation (Fig. 1). This confirms that all improvements to software, firmware and voltage/current regulation that occurred during this period were making a difference, given the increase in operation energy from 3.5 to 4 TeV [3].
Note: Majority of dumps are in stable beam mode. This is explained by the fact that an average powering cycle spends > 70% of its time in this mode.

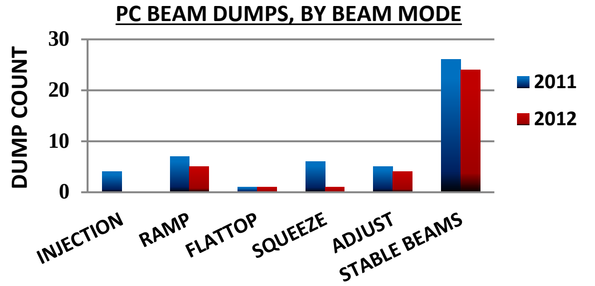

Figure 1: Comparison of Power Converter triggered beam dumps by beam mode, 2011 to 2012

A study looking at beam dumps by circuit type throughout 2012 found a large portion of triggers were caused by 600 A circuits. More interestingly, however, was the significant number of beam dumps caused by the Inner Triplets Systems; far greater than expected. Results can be found in Fig. 2.
Note: The peak of 60 A circuit triggers is explained by the large number of circuits relative to others circuit types.

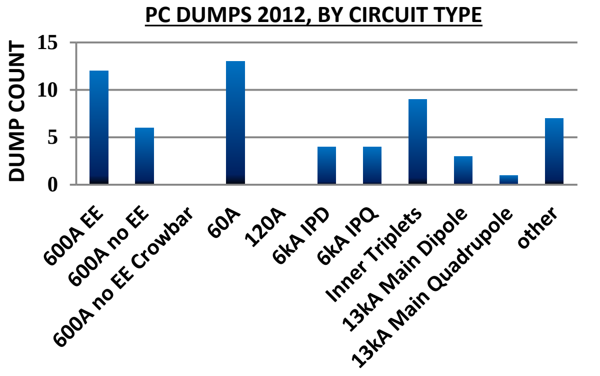

Figure 2: Power Converter triggered beam dumps by circuit type throughout 2012.

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Powering Interlock Controllers

The PIC results show a significant improvement during 2011 to 2012, having caused no spurious beam dumps since October 2011 (Fig. 3). In previous years, several trips occurred with nearly all being caused by Single Event Upsets (SEUs). The improvements were due to a successful Radiation to Electronics (R2E) mitigation relocation of systems in UJ14, UJ16 and UJ56 during Christmas shutdown in 2011 [4].

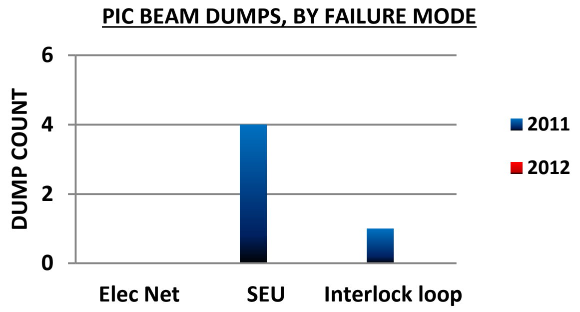

Figure 3: Comparison of beam dumps triggers by PIC by failure mode, 2011 to 2012. Elec Net – Electrical network fault, SEU – Single Event Upset.

The WIC results again show significant improvement from 2011 to 2012, particularly in beam dumps triggered due to electrical perturbations in the main electrical network (Fig. 4). However, unlike the PIC, no specific campaign or project was carried out to mitigate these effects and this may still be an issue in the future.

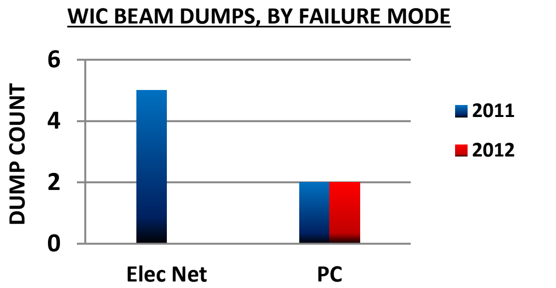

Figure 4: Comparison of beam dumps triggered by WIC by failure mode, 2011 to 2012. Elec Net – Electrical network fault, PC – Powering Converter failure.

Fast Magnet Current Monitor

In reviewing the FMCM the most significant results presented themselves when looking at all trips of specific individual circuits. Fig. 5 shows all FMCM trips since stable LHC operation began in 2009. Notably, the RD1 and RD34 circuits stand out as clear outliers.

Note: The graph shown includes all FMCM trips; when a beam dump is triggered due to electrical network issues, several monitors may trip simultaneously, resulting in large trip count. To quantify, the total beam dumps triggered by FMCM recorded was 78.

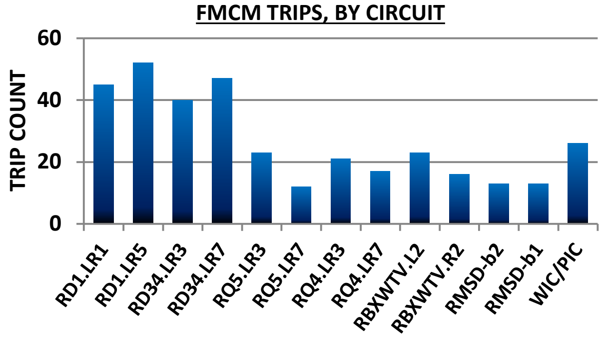

Figure 5: All FMCM Trips by specific circuit since 2009

Further investigation found that this is likely due to the fact that the RD1 and RD34 circuits are powered directly from the 18 kV grid instead of the more stable 400 V line like the RQ4 and RQ5 [5]. This drastically increases the circuit sensitivity to electrical network perturbations (Fig. 6). There are plans to design and implement an improved regulation characteristic for the thyristors of PCs that are connected directly to the 18 kV grid in attempt to reduce sensitivity [6].

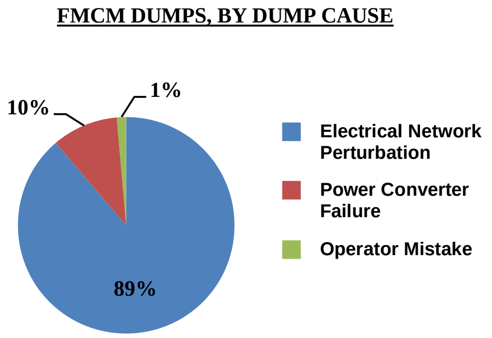

Figure 6: Pie Chart showing 89% of FMCM trips were due to electrical network issues.

Quench Protection System

The QPS of the LHC, protecting more than 8,000 magnets, is one of the most complex protections systems ever made [7]. Naturally this lends itself to having a high probability of being the cause of an unintended beam dump, especially if the individual system thresholds are too conservative.

Looking at beam dumps triggered by the QPS, by circuit type, showed quite drastic changes in beam dump triggers when comparing 2011 to 2012 (Fig. 7). The most significant being a reduction in dumps due to particularly problematic 600 A Energy Extraction (EE) circuits. This reduction was due to the continuous improvement of thresholds for the RQTD-F circuits both during and since the Christmas shutdown in January 2012; RQTD-F circuits are particularly sensitive to action of the tune feedback system [8]. There are also plans for R2E mitigation via radiation hardening of protection electronics of 600 A circuits in several sectors (all UJ underground regions) during LS1 which is likely to further reduce the number of spurious triggers [9]. In contrast, however, an important increase in beam dumps caused by the 6 kA IPQs is also seen. This may be due to a scaling effect of SEUs with the increase of beam energy from 3.5 to 4 TeV, though this is not likely to be the sole cause of the increase. Further study into the matter is called for.

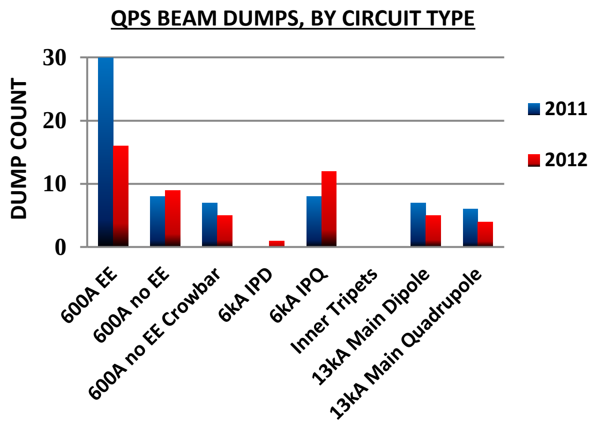

Figure 7: Comparison of beam dumps triggered by QPS by circuit type, 2011 to 2012

It is also of note that the 13 kA main dipole and quadrupole circuits have a notable reduction of beam dump triggers since 2011 but still have a high number of dump triggering when comparing with the number of circuits (e.g. LHC has only 8 13 kA dipole circuits [10]). However, the protection system of these circuits is of much higher complexity, containing significantly more QPS detection boards, naturally increasing the probability of false triggers. Fig. 8 shows this significance quite clearly; almost one trip for every two circuits.

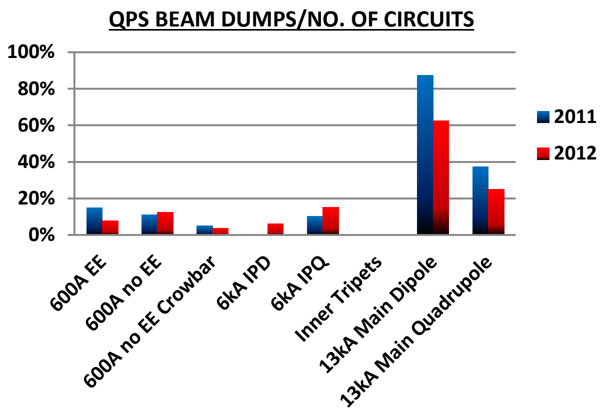

Figure 8: QPS triggered beam dumps in relation to the number of circuits of each type.

Looking at false dump triggers of the QPS by beam mode showed a significant reduction during the squeeze from 2011 to 2012 which correlates to the aforementioned reduction in beam dumps caused by fine tuning RQTD-F thresholds. Fig. 9 also shows a small increase in dumps during stable beam mode. As prior-mentioned, dumps are more likely to occur during this mode of operation throughout the beam cycle as it is the longest in time by a significant margin. The increase from 2011 to 2012 can likely be explained by the overall time spend in stable beam mode increasing by approximately 15%. It is, however, thought that beam instabilities (e.g. landau effects) which have been commonplace throughout 4 TeV operation, will have had a minor influence [11].

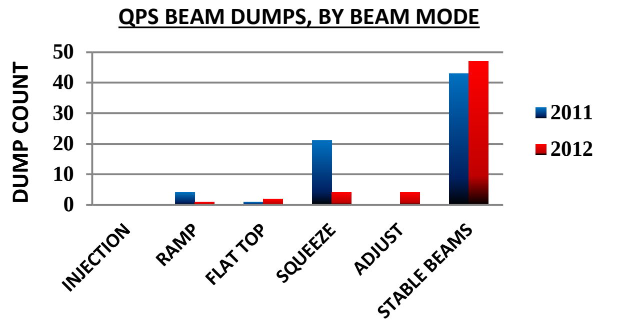

Figure 9: Comparison of beam dumps triggered by QPS by beam mode, 2011 to 2012

Single Event Upsets (SEUs) are becoming more prevalent as the LHC's performance and inherent radiation emissions increases, particularly for systems consisting of thousands of electronic circuits. SEUs are commonly understood as radiation effects that interfere with electronics at a component level which may results in system degradation, eventually resulting in a beam dump. Fig. 10 shows the proportion of QPS beam dumps caused by SEUs. It is clear that in high radiation areas, such as those surrounding the experiments (especially ATLAS and CMS) or beam cleaning regions (collimators), SEUs pose significant issues. The probability of such events occurring is likely to scale with LHC operation energy. Studies to further mitigate SEUs effects remain necessary.

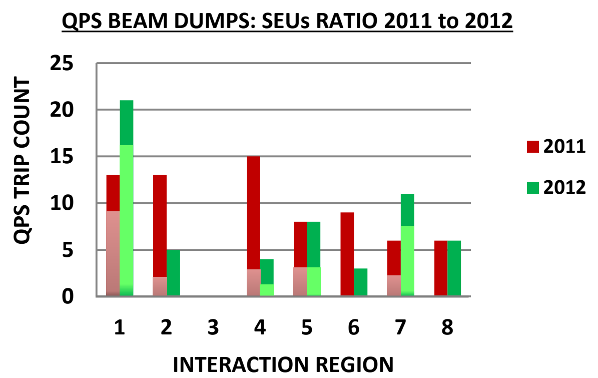

Figure 10: Comparison of QPS SEU dumps to total dumps in all regions 2011-2012. Note: Pale section represent number of dumps caused by SEUs.

As expected, the percentage of SEU/other dump is high in IR1 (ATLAS) and IR5 (CMS); IR1, being much greater than IR5 as only one side of the LHC electronics near CMS lies within a high radiation zone, roughly halving the probability. Furthermore, there is also a notable margin of reduction in other dumps at IR4, which can be again explained by the tuning of RQTD-F circuit thresholds. More interestingly, however, is the significant proportion of SEU dumps at IR7. This is likely due the radiation scattering from the beam cleaning collimators in this region, but it was deemed higher than expected and a closer look at individual circuits statistics surrounding IR7 was called for, see Fig.11 below.

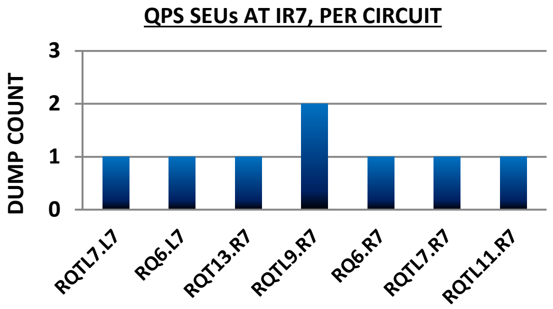

Figure 11: QPS beam dumps due to SEUs at IR7

First thing to note is that there is no specific circuit causing a majority of faults and the SEUs are essentially random. As prior-mentioned, the probability is likely to increase as radiation increases at nominal energy. To make matters worse there are no R2E mitigation relocation plans for LS1 and this issue may continue. However, all the circuits that have tripped so far are 600 A circuits, and all 600 A circuits are being improved and redesigned with radiation hardening in mind. Hopefully this will mitigate some of the effects as scattering due to collimation is likely to scale quite considerably with energy.

Discussion

Downtime in operation of the LHC curtails invaluable time allocated to physics experiments, thus maximizing availability is worthy of study, time and resources.

Following the study, a clearer understanding of what are the main causes of unintended beam dumps is attained, making decisions for mitigation/machine upgrades easier with respect to maximizing availability. One of the major causes of downtime is clearly shown to be false triggering of the QPS, however, several other unexpected statistics came to the forefront (e.g. Triplet PCs trips, extent of FMCM RD1/34 issues, SEUs prevalence at IR7).

Beyond LS1

A major aspect of the study was to determine which systems are most likely to be the problematic when operating near nominal energies and whether or not there are plans to help minimize potential issues. The following is a brief summary of these systems:

- Circuits powered directly by 18 kV lines, even after implementing the planned filter improvements.
- There are several improvements planned for the QPS system, however, as SEUs are likely to scale with luminosity they likely to remain a problem. In particular with regard to the 6 kA IPQs, until the installation of more radiation tolerant electronics has occurred.
- PCs show steady improvement year-to-year, however the issues with the Triplets may worsen. Furthermore, for the operation of Achromatic Telescope Squeezing (ATS) Optics and improved damping of beam instabilities, several 600 A circuits will be stressed at their operation limits (beyond nominal design) [12]; potential issues may arise.

‘NEAR-MISS’ EVENTS

A ‘near-miss’ event can be defined as a system non-conformity which if, however unlikely, were to occur in a more critical context, would result in a ‘catastrophic’ event.

Prime example of a ‘catastrophic’ event

The LHC was originally designed to run at a nominal energy of 7 TeV, however, just after first operation began, on 19th September 2008 an entirely unforeseen quench event occurred in the main 13 kA dipole circuit, resulting in severe mechanical damage and a yearlong magnet replacement/repair campaign [13]. Details of event were as follows:

- ‘Catastrophic’ quench originating at an interconnect during ramp at 8.6 kA
- Large helium leak
- Extreme pressures developed causing severe structural damage
- 53 magnets needed to be replaced/repaired

To prevent such an event occurring again, a global campaign for the consolidation of all interconnects within a resistance threshold has been planned for LS1. Furthermore, since it is hypothetically possible for this event to occur in the bypass diode leads, a measurement protocol, Copper Stabilizer Continuity Measurement (CSCM) [14], was designed to test if the diode leads were able to carry nominal currents; a type test was carried out successfully in April 2013. Analysis of results is on-going.

Examples of past ‘near miss’ events

All detailed events have been extensively covered in other studies/publications; information can be found on EDMS.

- Event in RB.A34 2011
  - QPS failed to respond and to trigger the EE system on discharge request.
  - Prevention of future reoccurrence involved the introduction of a new commissioning phase to check specifically for this issue.
- Event in RQX.A23 2011
  - Continuous firing of the Inner Triplet System’s quench heaters without request.

- Prevention of future reoccurrence involved a firmware update of all relevant systems.

- Event in RCD.A12 Jan 2013
  - EE failed to open on direct request. This has occurred multiple times due to error initially going unnoticed.
  - Prevention of future reoccurrence involved a firmware update of all relevant systems.
- QPS failed to detect quench and to send discharge request
  - Prevention of future reoccurrence involved a system update and reset; update could have been scheduled prior to incident.

Reflection

'Near-miss' events, however worrying, give unique opportunities to witness, analyse and study the prevention of such errors. It is also important to point a common cause amongst both past, and recent, 'near-misses' as they were all a result of either human error or systems not being up-to-date. This in itself is a significant correlation and calls for more stringent system update protocols.

CONCLUSION

In summary, the study shows that a substantial amount of work is still necessary to improve the overall system protection, stability and availability. This is especially the case for failures caused by SEUs and network perturbations. Alongside the prevailing radiation and electrical network issues, almost all 'near-miss' and single non-conforming events studied were all due to either a lack of system software/firmware updates or human errors. This is not something to taken lightly, and certainly exhibits a need for a more meticulous standard of training/operation/ testing/commissioning and documentation.

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