

RECURRING SOURCES OF PREMATURE BEAM DUMPS

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Abstract

While the fraction of premature beam dumps has considerably decreased during the 2016 run in favour of programmed end of fill dumps, still 1 out of 2 beam aborts are non-programmed. The root causes of these are primarily equipment failures as well as UFOs and electrical perturbations. In this contribution we will analyse the premature beam dumps observed in 2016, with an emphasis on identifying recurring failures. An outlook on the planned mitigation strategies for the main contributors to the failure statistics will conclude this paper.

PREMATURE BEAM DUMPS IN 2016

During 2016 operation, 175 fills (out of a total of 762 fills) were brought into Stable Beams for physics production. 84 of these fills were deliberately aborted by the operators, while 86 of the fills were prematurely aborted by the protection systems [1] (not including an additional 9 fills which were aborted due to suspected radiation to electronics effects, which are discussed in [2]). Figure 2 illustrates the distribution of the 86 premature beam dumps on the various root causes. While the majority of equipment systems only exhibit a few premature dumps, 3 main contributors can easily be identified, namely beam losses (primarily due to UFOs), power converter failures and electrical perturbations. These main categories will be analysed in detail in the subsequent sections.

For systems with less than 6 beam dumps, little or no correlation can be found amongst the causes of the premature aborts, and the failure rate appears consistent with the complexity of the respective system. A few noteworthy issues are:

- Out of the 4 premature beam dumps allocated to the collimation system, 3 were traced to drifts of LVDTs on different collimators (used for position measurements and interlocking). As such drifts are typically developing over longer periods in time, a continuous and more proactive way of detecting larger drifts e.g. from Logging Data could be envisaged.
- Half of the 6 premature dumps from the quench detection system (QPS) are due to glitches on the current reading sensors of 600A corrector circuits (used for the inductive compensation of voltage signals). The suspected cause is a non-optimal shielding of the signal cabling which will be improved during the upcoming EYETS.
- Two natural training quenches were observed in the main quadrupole magnet MQ.22L8 on 21st of May,

respective 3rd of June 2016. This happened during a period of beams duration often above 20 h, and a possible explanation could be the development of a different current sharing in the strands when operating for extended periods at nominal current. No additional training quench was however observed during the second part of the year.

- Dynamic effects of heat load to the cryogenic system during injection and beam dump were very well mitigated in 2016 thanks to the implemented feed-forward in the cryogenic controls system. Only two occasions where cryo-maintain was lost in stable beams were observed, both of which occurred in the long straight section right of IR5 (powering subsector LR5) [3].

As depicted in Figure 1, the duration in stable beams until the occurrence of premature dumps does not show any unexpected correlation, and approaches the expected exponential decay for failures randomly distributed over time. It can be noted however that failures linked to higher beam intensities or the operational cycle (such as RF, collimator position interlocks) tend to occur early on during the fill, while magnet powering failures and quenches typically occurred at the end of longer fills.

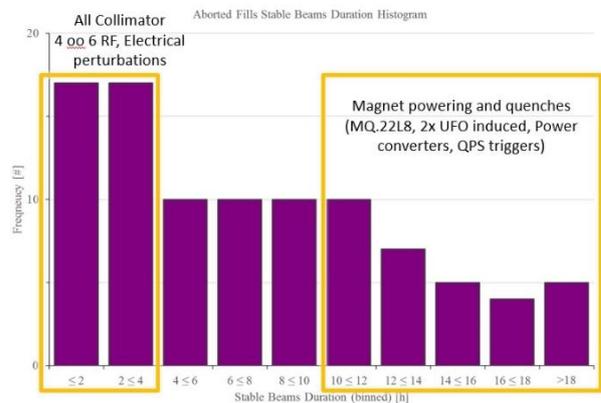


Figure 1: Duration in stable beams for premature beam dumps

It should be noted that the above statistics is slightly biased, as after the introduction of the bunch compression and merging scheme (BCMS) and the reduction of the crossing angle in the high luminosity experiments ATLAS and CMS, the optimal fill length for programmed dumps was first reduced to around 15, and later 10-12 hours which will impact the above distribution for bins >10 hours.

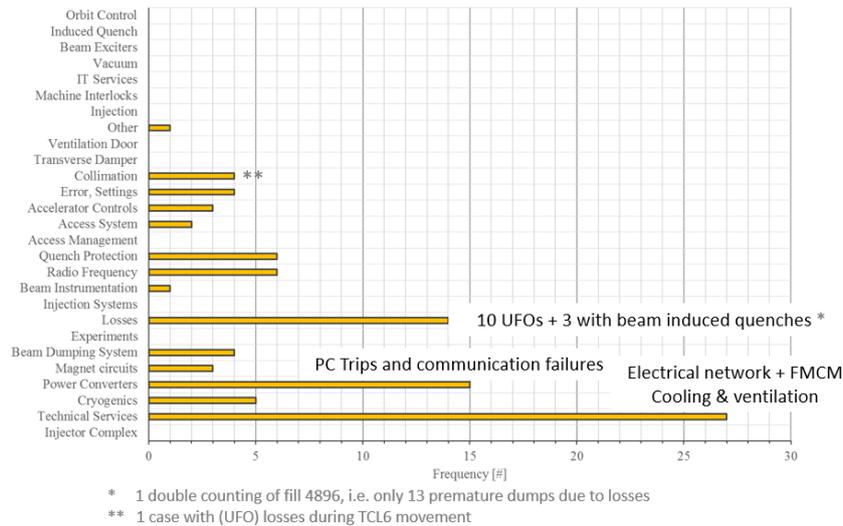


Figure 2: Distribution of root causes for premature beam dumps as observed in the operational year 2016

TECHNICAL SERVICES

Technical services were identified as the root cause for more than 30% of the premature beam dumps (27 out of a total of 86). This includes 4 dumps related to cooling and ventilation (a water infiltration in the power converter RQ4.L5B1 due to a hose badly crimped on RQT12.L5B1 converter located at the first floor, a failure of a water pump in IR2 as well as 2 interlocks due to low water flow in the water cooled DC cables of circuits RQX.R5 and RQ4.L5B2). The main contribution is given by 23 electrical perturbations which resulted in protective dumps by the Fast Magnet Current Change Monitors (FMCM). 9 of these electrical perturbations were large enough to affect as well other systems (such as power converters, RF, experimental magnets, cryogenics...) including the short circuit on the 66kV transformer caused by an animal. Hence a premature dump is unavoidable for these 9 cases.

In 13 cases of electrical perturbations however only 4 magnet circuits, namely RD1.LR1, RD1.LR5, RD34.LR3 and RD34.LR7 were affected. This singularity is due to the use of a power converter using thyristor bridges for direct conversion rather than IGBT switch-mode bridges with an intermediate DC energy storage link. In addition, these converters are connected to the 18kV grid (rather than the 400V grid), hence network perturbations entering CERNs 400kV grid are more visible at this higher voltage level.

Network perturbations typically provoke current oscillations with a peak amplitude of 0.5-1 A at the output of these thyristor based power converters, which in turn would result in a perturbation of the closed orbit in the order of 3-6 σ which is largely exceeding the allowed tolerances (in comparison the maximum excursion allowed at the TCTs of IR1 and IR5 for the nominal 2016 optics is in the order of 1 σ) [4].

While the peak amplitude of the current oscillation strongly depends on the timing, the affected phases and the network configuration at the time of the perturbation, the

circuit RD1.LR5 shows a much higher sensitivity to electrical perturbations as compared to the identical magnet powering circuit RD1.LR1. This can be explained by the different network topology of the 18kV grid, as the network of SR1 is a network node and as such much more robust against perturbations, while SR5 is fed through long distribution lines from the machine network of LHC P6).

This singularity of the magnet powering system was already identified several years ago. In conjunction with the power converter group a consolidation project has been launched to produce 4 new switched-mode power converters (850A/700V) to replace the original power converters for these 4 circuits during the EYETS of 2016/17. They have been designed to withstand voltage dips of $\pm 10\%$ continuously on all three phases, up to -20% on a single phase for 100ms or -15% on all 3 phases for 100ms without any impact on the output current (see as well EDMS Doc. Nr. 1451491). This will allow to mitigate the majority of protective dumps observed in 2016. A first power converter of this new SATURN family has already been successfully tested in building 287 and will soon be installed in the surface buildings of the LHC. By the end of the EYETS, all 4 power converters will have been exchanged, with the previously used power supply remaining in the SRs as hot standbys. In order to fully qualify the performance of the new power converter type in conjunction with the FMCMs it is highly recommended to perform dedicated tests with deliberate injections of perturbations in building 287 and/or to perform a longer term reliability run in at least one of the surface buildings during the commissioning period following the EYETS.

POWER CONVERTERS

A total of 15 premature beam dumps had their root cause in one of the more than 1700 power converters powering the LHC magnets. Many of the mitigations deployed by the power converter group in previous YETS (consolidation of auxiliary power converters, revision of interlock/alarm

strategy for less critical failures...) have proven very successful and little to no correlated faults have been observed during 2016. Six of the failures are allocated to R2E effects, which predominantly occurred in 600A power converters located in radiation exposed areas such as the RRs around IR1 and IR5. Four failures were allocated to internal/external power converter failures (bad contacts, water fault and an external current lead over temperature), two failures to communication issues, two issues related to the orbit feedback and QPS settings and a last failure due to a spurious trigger in the interface with the magnet interlock system.

UFO'S AND MAGNET QUENCHES

Thanks to the beam conditioning that took place during the 2015 run, UFO occurrences and subsequent beam aborts and magnet quenches have (only) accounted for 13 premature dumps during the 2016 run. As depicted in Figure 3, UFO occurrences can be divided in 4 main categories:

- **Beam Losses:** Four of the premature dumps were triggered by beam losses, three of which in long straight sections and one in the arc of sector 23. The region of 5L1 to 6L1 in particular have shown increased UFO rates. Corrections of BLM thresholds were already applied during the year to further mitigate the impact of UFOs in the long-straight sections.
- **Beam Losses in Sector 12:** Following the suspicion of an inter-turn short of the main dipole magnet 31L2, the beam loss thresholds in sector 12 have been lowered by up to a factor 10 as one of the mitigation measures to avoid UFO induced quenches [5]. These lower thresholds were deployed in mid-August 2016 and caused 3 out of the 6 additional beam dumps following UFO losses since the change of thresholds.
- **Experiments:** Three premature beam aborts were caused by the Beam Condition Monitors (BCMs) of the main experiments, namely ALICE, CMS and LHCb, while little or no beam losses were observed on the close-by machine beam loss monitors. Further work is planned within the BLM threshold working group to increase the coherence of beam loss thresholds between the machine and the experiments.
- **Magnet Quenches (due to very fast UFOs):** Only three UFOs lead to sufficient losses to trigger a beam induced magnet quench during the 2016 run. It was noted that all 3 magnet quenches occurred during the initial 3 months of operation. Since July 2016, no UFO induced magnet quench was observed, indicating a potential conditioning effect of large and fast UFOs that could lead to subsequent magnet quenches.

In general, the strategy to increase the BLM thresholds in the arcs for 2016 to around 3 times of the expected quench limits has proven very efficient, allowing to

achieve a good trade-off between protective dumps due to losses and magnet induced quenches. The strategy might however have to be reviewed after longer shut-downs and/or partial warm-ups of the machine, where a deconditioning effect of the machine could be expected.

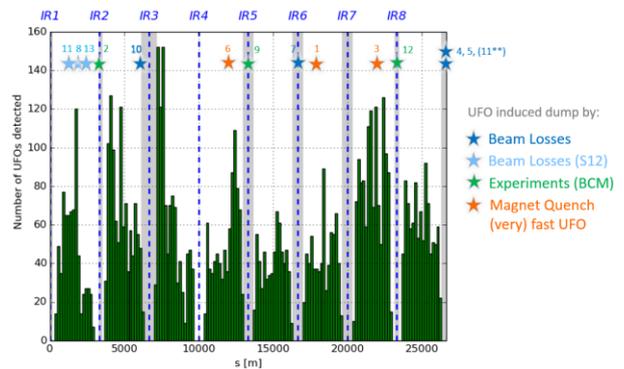


Figure 3: UFO's leading to premature beam dumps by subsequent losses during 2016 operation..

CONCLUSION AND OUTLOOK

The consolidation efforts by all equipment groups have very efficiently mitigated the recurrent failure modes observed prior to 2016 (R2E effects in quench protection system, weakness of auxiliary power supplies of 60-600A power supplies...). Little to no correlation could be identified in the remaining fault distribution for these systems, nevertheless several additional mitigations are planned for the EYETS. Three main fault categories remain to be addressed with the focus on the consolidation of the RD1 and RD34 power converter which will mitigate an additional 15% of the premature dumps observed in 2016. R2E remains a concern for power converters for the coming years. They are however expected to be mitigated with the deployment of FGClite (60A during EYETS, RRs during YETS 2017-18) and eventually a radiation tolerant and redundant 600A power converter type (LS2). Little gain is expected from further optimisations of BLM thresholds, especially following periods which might lead to a deconditioning of the machine.

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