WHAT COULD STOP US AND WHEN

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Abstract

The LHC magnet system, as any other electrical machine, could suffer from electromechanical faults that may reduce operability, decrease performance, or, in the worst case, require an intervention and time-consuming exchange of components. Radiation-induced degradation of the mechanical properties of the insulating materials will increase the fault rate. In this report we consider the origins of faults, and attempt a quantitative estimate of the lifetime of the most critical components, the triplet and the resistive magnets around the collimator region.

INTRODUCTION

After the successful operation of the LHC during the period of run I, and the consolidation that will be completed in 2014, a vital question in preparation to long-term exploitation of the accelerator is to understand the limits of the lifetime of the overall technical installation, and especially of the superconducting and normal conducting magnets.

The concept of lifetime, and specific indicators such as the Mean Time Between Failures (MTBF), are a part of well-established engineering practice for components produced in series and operated over sufficiently long time to accumulate relevant statistics and allow analysis such as Weibull plots. Unfortunately, this is not the case for a large part of the magnetic system of the LHC, and especially for the superconducting magnets. These are in several cases first-of-kin productions, barely beyond the prototyping stage (e.g. inner triplet), or the accumulated statistics on failure rate and failure consequence is not appropriate to allow for a meaningful extrapolation (e.g. MB and MQ). An estimate, as attempted here, must hence be based on a one-by-one analysis of the most critical situations identified, and forcibly requires some guesswork.

In this report we recall the most common magnet failure modes, with special accent to superconducting magnets. We then recall the non-conformities and faults experienced in the LHC magnet system, and the limits to radiation dose on its various elements, and especially on the IR triplet and the magnets in vicinity of the collimator regions. These elements are taken as a basis for an extrapolation of the lifetime of the magnets, and a forecast, to the best of the accumulated knowledge, on when LHC operation may be interrupted by a magnet fault requiring a lengthy magnet exchange. This analysis does not cover the LHC injector chain, and is limited to hardware failures, i.e. does not consider performance limitations that are either expected (e.g. maximum energy from practical limits on magnet training, or cooling capacity in the inner triplet) or may be found when re-commissioning the machine after the LS1.

SUPERCONDUCTING MAGNETS FAILURE MODES

A number of papers have been dedicated to the analysis of the reasons for failures of superconducting magnet systems. References [1-3] provide a good summary and basis for statistics. A much-simplified overview of the catalogs reported in the references quoted is given in Fig. 1. In essence, the causes of highest incidence are insulation and mechanical failures, accounting for about 50 % of all recorded failures. It is interesting to note that under-performing superconductor, possibly the most difficult technology of the magnet, is rarely an issue (less than 20 % of recorded failures).

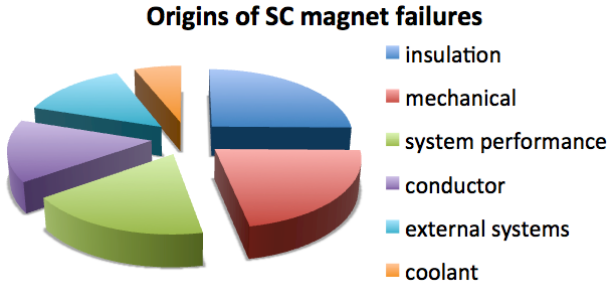

Figure 1. Distribution of failure modes, as recorded on various types of superconducting magnets systems, compiled from data in [2]

In the perspective of the above summary, we can compile the following list of potential trigger mechanisms for mechanical and electrical failures of the LHC magnets:

- Mechanical loading and fatigue on coil, structure, busses. These are associated with magnet powering, where the number of cycles during the machine lifetime is $O(10^4)$ per magnet, and thermal cycles, which are expected to be a few for the whole LHC;
- Singular events and associated thermal and electrical stress. These are essentially natural quenches, typically expected to be of the O(10) per magnet, as well as quenches induced by heater firing, with a somewhat larger total number of events in the range of O(100) per magnet, including commissioning and diagnostics;
- Radiation and associated degradation of mechanical and electrical strength. Doses in the range of O(10) MGy, as expected on the magnets in the triplet region of the LHC P1 and P5, and in the collimator regions of the LHC P3 and P7, are known to affect adversely insulators. We will discuss later these figures, in more detail.

ELECTROMECHANICAL FAILURES

We consider under this chapter failures such as insulation degradation or shorts induced by mechanical or thermal stress, movements, electrical stress, loss of continuity on vital diagnostics, or degraded continuity (splice resistance) in the electrical circuit.

As mentioned earlier, the statistics on failure modes in the LHC is extremely limited, and, if we try to put it in the framework of a Failure Mode and Effect Analysis (FMEA) the LHC may still be in the "infant mortality" regime of the bathtub curve describing failure rate vs. time. On the other hand, with the energy limitation or Run I, electromagnetic loads have only reached a third of those expected at nominal operation. Finally, it is difficult to provide a strict definition of a failure of electromechanical nature in an LHC cryomagnet. Indeed, many electrical failures may simply lead to a degraded performance (e.g. loss of a corrector magnet), which may be accepted, mitigated or completely compensated.

In spite of the above caveats, we decided to use the present statistics on electrical non-conformities, which provides a record of all faults of electro-mechanical origin, to attempt an extrapolation of the rate of occurrence of such events for the duration of the LHC lifetime, essentially computing a Mean Time Between Failure (MTBF) for the instrumented cryomagnet. By assuming that this rate is identical on all magnet types, we can use this extrapolation to evaluate the probability of a failure of electromechanical origin in any circuit. It should be understood that one such failure does not necessarily entail the complete loss of performance. It is however the experience in LS1 that one such event will eventually call for a maintenance operation at the level of the cold mass, or a magnet exchange, during a technical stop or shutdown period. As we will discuss later, depending on the magnet in question, this may entail long times for the warm-up, radiation cooling and operation that will impact on the integrated luminosity delivered by the LHC.

At the moment of the analysis reported in [4], and excluding the September 2008 incident and consequences, a total of 35 non-conformities (NC's) of electromechanical nature were initiated since the beginning of the commissioning of the LHC. Limiting to the cold part of the cryomagnets, 12 were known before the beginning of the electrical quality assurance (ELQA) campaign performed at the beginning of LS1, and 7 additional were discovered during the ELQA campaign. This has led to the exchange of 21 cryomagnets since the beginning of hardware commissioning, 1 in 2007 (suspect of developing inter-turn short), 2 in 2008 (high internal splice resistance), and 18 in 2013 (various issues of excessive internal splice resistance, quench heater performance and insulation, coil insulation).

If we consider each of these NC as a failure. resulting in the exchange of a cryomagnet assembly, we can determine a failure rate (normalized to the total population of cryomagnets, i.e. approximately 1700), and estimate the MTBF. The standard technique to produce stable extrapolations is to fit the failure rate in a Weibull plot, and use the parameters of the fit to compute the normalized failure rate and MTBF of the cryomagnet assembly. Applying one such process we obtain a MTBF in the range of 400 to 500 years, a first guess to be taken cautiously in the light of the various qualifying remarks made earlier.

This MTBF estimate translates in approximately 3 to 4 cryomagnet electrical NC's per year of operation, and at least 10 to 15 magnets exchanges every long shutdown. In particular, the probability of electrical failure of one of the triplet magnets within the next 10 years of operation is 3 %, i.e. 1 magnet. We recall here that while a magnet exchange in the arc is possible within 3 months, for the IR quadrupoles a magnet exchange requires removal of the DFBX and triplet up to the magnet to be exchanged, an operation that may require as long as 1 year.

RADIATION INDUCED FAILURES

This chapter covers electrical and mechanical failures that can be induced by degraded mechanical and dielectric properties, mainly in the coil insulation. A subtle point of radiation degradation is that failure may be gradual, and very localized in space (e.g. reduction of the crack threshold for resins), causing e.g. premature quenches and de-training. At this stage, however, this is only a conjecture, without supporting experimental or evidence.

In accordance to the measurements and projection reported in [6], and the analyses performed in [7] and [8], the hot spots in the LHC will be in the triplet region of P1 and P5, and in the magnets around the collimator region of P7.

In the triplet magnets at P1 and P5, the most critical locations are projected at the IP side of the Q2, and in the MCBX orbit corrector located at the non-IP side of the Q3. The expected dose [7] by LS3 (for an integrated luminosity of 300 fb-1), taking into account a relatively comfortable but realistic 50 % uncertainty, is in the range of 18 to 40 MGy in the worst location of the Q2, and in the range of 13 to 30 MGy in the MCBX. For the magnets around the collimators at P7 [8], and specifically in the D3/D4 (MBW) and Q4/Q5 (MQW), the expected dose, based on dosimetry and simulations, is more than a factor two higher, i.e. from 80 to 90 MGy.

The above dose levels are high. Although it is not possible to provide a deterministic estimate of the failure, which depends much on the local details of material quality, quantity and geometry, values in the range of 20 to 50 MGy are typical for onset of brittle fracture and significant loss of mechanical properties for thermosetting resins, such as those used in the triplet magnets [9-12]. To give useful comparative values, after an irradiation to 20 MGy the bonding strength of the epoxies used in the G11 spacers of the quadrupoles, or to glue the layers of the MCBX, is reduced to 20 % of the value before irradiation. Fracture strength of insulators

degrades to 50 % of the value before irradiation, after 20 MGy (G11) to 50 MGy (polyimide). These values suggest that the triplet magnets may experience a failure, possibly initiated by a gradual performance degradation (premature quenches), at a dose level expected for a total integrated luminosity of 300 fb-1. These are values consistent with the initial specification and analysis of the magnet design as described in [13] that was giving a triplet lifetime of 7 years of continuous operation.

Two different resins are used in the normal conducting coils of the magnets around the collimators [8]. While the MBW resin, especially thanks to the presence of fibers, is expected to maintain a significant strength up to a dose in the range of 70 MGy, the conventional resin used in the MQW may no withstand doses in excess of 50 MGy. This is especially true for filler and spacer pieces, whose failure may result in undesirable movements during powering, and induce further electrical faults. In both cases, we see that the expected radiation resistance limits fall short of the projected irradiation dose. It is for this reason that partial protective measures are proposed already during LS1 [14]. A plan has been proposed for LS2 and LS3 to modify this region of the LHC allowing efficient and rapid maintenance (see later), prepare radiation hard spares, and modify the layout to introduce redundancy.

MATTERS OF PERSONNEL DOSE

Reference [6] gives an analysis of the ambient dose measurements performed during LS1, and the extrapolation to the conditions expected at the time of an LS3. The results indicate that the ambient dose in the zone of the normal conducting magnets next to the collimators region may reach values in the range of 1 mSv/h after 6 months cool-down time (obviously higher ambient doses will be registered close to the collimators themselves). The zone of the triplet magnets at P1 and P5 have less severe conditions, with values around 0.1 mSv/h after a 4 months cool-down time.

At the time of LS3, these zones will be classified as limited stay area, requiring at least ALARA level II preparation of interventions. To date, none of these regions is ready for rapid, partially automated maintenance that would allow for distant operation (e.g. from a nearby shielded area). It is hence urgent to envisage scenarios for the disconnection of the magnets, to prepare for the period after LS2 when radiation levels will increased significantly with respect to the present, rather bland situation. At the same time, it is important that spares and upgrades are designed taking into account considerations of dose limitations during magnet installation and removal.

CONCLUSIONS

On the time scale of LS3, and provided the integrated luminosity scales as projected, we should expect aging-related electromechanical and/or radiation induced failures in the triplet magnets (most critical are the Q2 and MCBX) at Points 1 and 5. This projection is coherent with the expected lifetime of the triplet, as defined by the magnet design and construction. By that time, a magnet exchange in the triplet may require a time of the order of 1 year (4 to 6 months cooling time, 6 to 8 months of work, with a scenario that requires to be defined to satisfy the dose limitations and the ALARA principles).

Magnet faults in the collimation region of Point 7, which may be induced by the relatively high level of coil irradiation, can be avoided by a number of protective actions. Partial protection is on-going on the most exposed MBW and MQW, to be continued during LS2 and complemented by radiation-hard spare coils.

It is also clear that selected area of the LHC (triplet, collimators) need to be prepared so that later interventions are possible (repairs, consolidation) in a reasonable time and personnel exposure. This consideration also applies to design of spare components and upgrades, where focus should be on radiation hardness, redundancy and maintainability.

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