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Reliability Considerations on the LHC Beam Loss Monitors System

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Abstract. The increase of beam energy and beam intensity, together with the use of super conducting magnets, opens new failure scenarios and brings new criticalities for the whole accelerator protection system. For the LHC beam loss protection system, the failure rate and the availability requirements have been evaluated using the Safety Integrity Level (SIL) approach [1]. A downtime cost evaluation is used as input for the SIL approach. The most critical systems, which contribute to the final SIL value, are the dump system, the interlock system, the beam loss monitors system, and the energy monitor system. The Beam Loss Monitors System (BLMS) is critical for short and intense particles losses at 7 TeV and assisted by the Beam Current Decay System at 450 GeV. At medium and higher loss time it is assisted by other systems, such as the quench protection system and the cryogenic system. For BLMS, hardware and software have been evaluated in detail. The reliability input figures have been collected using historical data from the SPS, using temperature and radiation damage experimental data as well as using standard databases. All the data has been processed by reliability software (Isograph). The analysis spaces from the components data to the system configuration.

INTRODUCTION

The Large Hadron Collider (LHC) is the next CERN particle accelerator that will try to penetrate further into the matter structure, accelerating protons up to 7 TeV. The innovative characteristic is the wide scale use of superconducting magnets to reach fields closed to 9 Tesla so as to bend the high energy particles beam. The superconducting technology involves different challenges, mainly addressed to generate and maintain the magnets in the superconductive state. One of the critical applications is the Machine Protection System, which intends to avoid machine damages caused by the heating following a beam loss.

In previous work [1] we have introduced the general LHC approach to prevent these events with the utilization of different systems. In this work we will report the current situation, underling the progress and the current challenges.

LHC SYSTEM: MAIN ACTORS

In the LHC the safe philosophy will be: whenever there will be a dangerous proton loss, we extract the beam from the machine. The first line safety systems are: the Beam Loss Monitors System (BLMS), which detects the dangerous loss and inhibits a beam permit through the Beam Interlock System (BIS), so that the LHC Beam Dump System (LBDS) can extract the beams from the machine in a safe way. This extracts the beam in function of the beam energy signal given by the Beam Energy Meter (BEM). These 4 main systems are assisted by other second line systems that additionally protect the machine but with slower time constants: a first line system has to act for 100μs intense losses as well for 100s low losses; on the other hand, the second line systems react after 10 ms of time, so they cannot help against the fast losses. Recently it has been accepted to extend the Beam Current Monitor System capability to assist the Beam Loss Monitors System in the protection against the fast losses. Currently there are also ideas to extend the Beam Position Monitor to protect the machine also for the fast losses, but they are still not well defined. Due to the fact that the effectiveness of these options is still under study, we will develop our dependability considerations independently from these systems.

Nevertheless, several systems can generate dumps but not exclusively for the machine protection aim. From the operational systems to the safety ones we can have almost 20 systems that can request for a dump, as show in Fig 1.

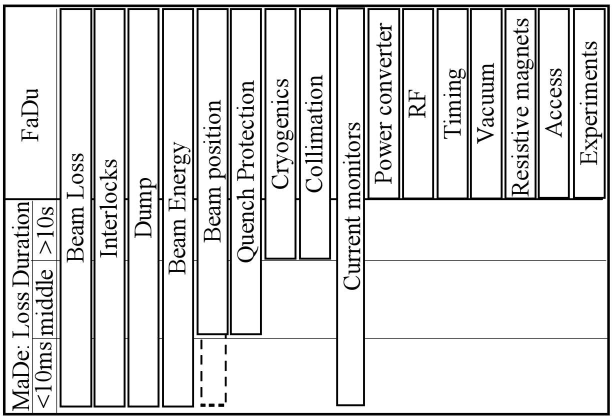

FIGURE 1. Main LHC systems connected to the Beam Interlock System and that can generate a FaDu and their effectiveness in term of machine protection.

If we assume that safety failure rates, calculated in [1], have to be equally shared between the different systems, we should guarantee a failure rate, with the Malfunction Approach defined in [2], less than 6 10^{-7} for a Magnet Destruction (MaDe) and less than 3.8 10^{-4} for a False Dump (FaDu). The equal distribution of the failure rates could be mainly unrealistic for the FaDu event, due to the fact that some of these systems, like Access, have historically really high reliability performances. Recently it has been proposed to introduce a mask system into the Interlocks Systems to reduce the number of false dump: not critical element dump requests will be ignored to not bring detriment to the overall machine operation time

BLMS FOR MAGNET PROTECTION

As reported in [3] and calculated in [4], Beam loss Monitor System have to protect the superconducting quadrupoles against losses of different duration and intensity. The quadrupole locations have been chosen because they are expected to be more loss sensible due to the larger beam dimensions and the limits in physical aperture.

As show in Fig. 2, there is also a strong dependence with the energy and with the loss duration, that brings to a dynamics of 9 orders of magnitude. Note that the Fig. 2 has been calculated for the dipole magnet. Better definition of the levels for the quadrupoles is still on going.

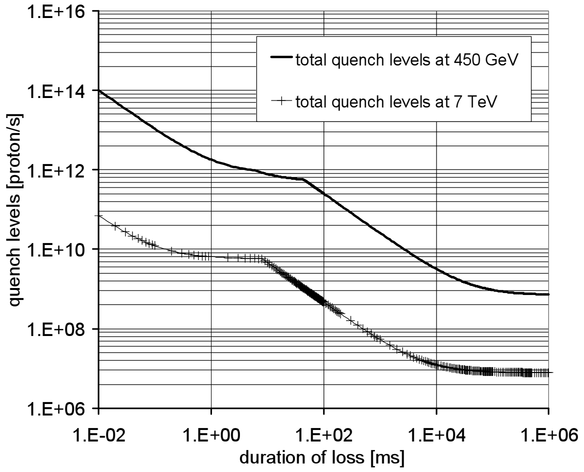

FIGURE 2. Calculated quench level for LHC dipole.

The BLMS, see the sketch in Fig. 3, is mainly constituted by Ionization Chambers (ICs) around the quadrupole magnets in the LHC tunnel. There will be 6 ICs per quadrupole, in different locations, to cover all the quadrupole, as calculated in [5].These chambers send a current, which ranges from 1 pA to 1 mA, to a Current to Frequency Converter which digitizes the current into pulses. These pulses are then counted by the digital part of the front end electronic. The digital part, hosted in a FPGA, multiplex 8 different channels (2 spares) and several status bits; it doubles the signal and sends it to the surface through 2 optical lines. At the surface the signals are checked and compared, to avoid transmission error, de-multiplexed and then compared with the threshold levels corresponding with the current beam energy. The measured signal, that arrives every 40 μs, is then averaged over different time windows to compare it with the other threshold levels [6]. In case of dangerous loss, the surface electronic inhibits a beam permit signal that is collected by a combiner card in the same VME crate. That combiner card generates two dump requests via a Beam Interlock User Interface.

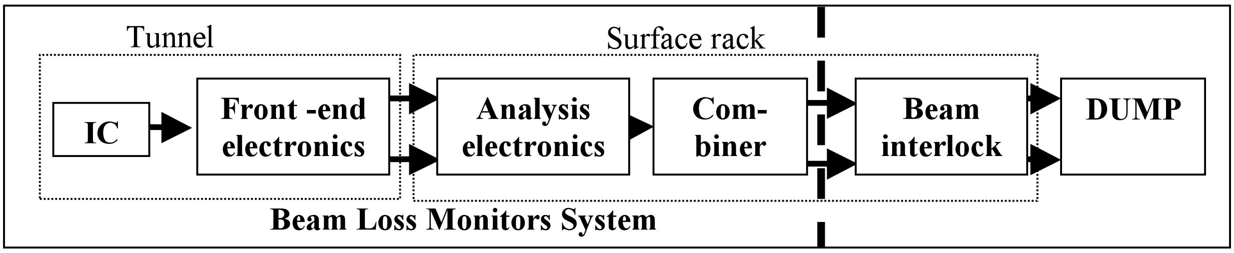

FIGURE 3. Sketch of the Beam Loss Monitors Systems layout.

RELIABILITY DATA COLLECTION

The failure rates of the different components are calculated using the Military Handbook 217F [7]. The general inputs are: expected ambient temperature of 10°C into the tunnel and 30° at the surface, fixed ground environment (a factor of 2 in the failure rate) for the tunnel, benign ground for the surface (factor 0.5); the average time to substitute a failed unit is 1 hours. Then all the usual component failure rates are evaluated with the military standard. For unusual components we have evaluated the failure rate using historical data from similar components. For example, for the Ionization Chambers we have 140 LHC like chambers installed in SPS which have been operational for 30 years without changing in the chamber sensitivity. It is a general procedure that the upper $\alpha\cdot 100\%$ confidence level of failure rate for a test of t_{tot} hours over N component and F fails after t_i hours is given by

$$comulative\_time = \sum_{i=1}^{F} t_i + (N-F)\cdot t_{tot} \tag{1}$$

$$\lambda = \frac{\chi^2\left(1-\alpha, 2\cdot(F+1)\right)}{2\cdot(F+1)\cdot comulative\_time} \tag{2}$$

For IC, we have a failure rate of 2.5 10^{-8}/h. Table 7 summarize some significant figures.

TABLE 1). Summary of the calculated failure rate.

Element	Failure rate λ [10^{-8} 1/h]			Inspection interval [h]	Notes
	Single	Not redundant	Redundant		
IC+cable+terminations	2.5	24		20	Experience SPS
Integrator	2.0			Continuous (40 μs)	Dose and fluence tested
Switch	8.7				
FPGA TX*	200	840	0.014		
Laser	510				
2 Optical connectors	20				
Optical fibre	20				
Photodiode	3.2				
FPGA RX*	70				

From the table we can see that the lasers are the weakest components: this is the reason why we have decided to double the optical line, with the improvements reported in the column “Redundant”. The FPGA figures, here, are overestimated with the MIL standard, experimental data will substitute them. The power supply is not considered here, because there are actions on going for their final layout definition. Due to the fact that there is a revaluation of the temperatures and the radiation levels, we still report that values, that could be more conservative than the final ones, on the other hand we are collecting good experimental life test values that strong improve the failure scenarios. Further dependability evaluations are on going.

In the previous table is also reported the inspection interval, this could be continuous, (that means an on line measurement of the functionalities), every operational dump, (roughly every 20 hours), or every year, (IC gas is checked during every shout down with a radioactive source). A frequent inspection interval decreases the probability to find the system not ready when required and so decrease the Magnet Destruction probability.

ANALYSIS

The entire system has been studied with commercial software (Isograph). A fault tree analysis has been performed, with particular attention to the unavailability of the system (the probability to find the system not ready to act), for the Magnet Destruction, and to the failure rate of the system for the False Dumps generation. The unavailability of a single BLMS channel, without power supply, is 4.9 10^{-7}/h and it is given for the 55% by failure of the IC, mainly for the reason that it is the least checked component. On the other hand the single channel failure rate is around 2.4 10^{-7}/h, 70% given by the switch systems into the CFC. Considering that we have 3200 channels in the system, we have a failure rate of 7.7 10^{-4}. The False Dump number is quite close to the maximum accepted by the Malfunction Approach, after the LHC systems apportionment. In this way BLMS generates, in 4000 operational hours per years, 3 false dumps. We are trying to reduce this figure, which is in any case not so worrying, by improving the switch electronics. Always for the False Dump event, it is foreseen, during the beam collision phase, to mask the arc detectors because they should be less significant in this phase respect the straight section detectors. With this action, the False Dump per year decrease, in first approximation, to 1. For the Magnet Destruction further considerations are required. The previously given figure is the unavailability (U_1) of a single channel. For the system, we have to consider the probability that the losses could be seen by just 1 or more channel. It is in fact common experience that a single dangerous loss could affect more than one location around the ring and so more than one channel that could detect the loss. So, if we define N_i to be the number of losses per year that occur in i locations and U_i to be the probability to have i unavailable channels, the system unavailability per year (U_s) is:

$$U_s = \sum U_i \cdot N_i \approx \sum U_1^{\,i} \cdot N_i \approx U_1 \cdot N_1 \qquad (3)$$

In fact, the probability that 2 channels (so distant to avoid common failure causes) fails at the same time is U_1^2, and so on for more channels. In the last step of Eq (3) we neglected the term higher than U_1, due to the fact that U_1 is <<1. So the question now is: how many losses, of the 100 initially foreseen, are affecting just one channel? If we suppose that N_1=100, we will lose in 4000 hours 0.2 magnets, the maximum MaDe per years. If N = N_1+N_2 = 5+95 we will decrease U_s to the FA requirements. To estimate what the loss distribution along the rings is and their correlation, a beam dynamics simulation project is required and it has already been lunched.

CONCLUSIONS

The IEC 61508 standard has been used as a guideline to estimate the failure rate of the Beam Loss Monitor System. Either for the main function failure, the Magnet Destruction, or the system induced failure, False Dump, our current design is on the border of the tolerated risk; further analysis are required to better estimate the LHC loss distribution and correlation. Improved electronics is also in the process of being developed.

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