LHC MACHINE PROTECTION

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Abstract

The protection of the LHC equipment against beam-induced destruction is given by passive and active components. For the fast losses a passive system consisting of collimators, absorbers and masks is used. For the others an active system consists of beam loss monitors, a beam interlock system and the beam dump. The LHC protection requirements are different to other accelerators. The differences are mainly due to its energy, its stored beam intensity and its dimension. At the LHC top energy the beam intensity is about 3 orders of magnitude above the destruction limit of the superconducting magnet coils and 11 orders above their fast loss quench limit. These extreme conditions require a very reliable damage protection and quench prevention with a high mean time between failures. The numerous amounts of loss locations require an appropriate amount of detectors. In such a fail safe system the false dump probability has to be kept low to keep a high operation efficiency. A balance was found between a reliable protection and operational efficiency. The main protection systems and beam instrumentation aspects of the measurement systems will be discussed.

DESTRUCTION POTENTIAL

The destruction potential of the LHC is illustrated by test measurements done in the SPS. The beam prepared for the injection into the LHC has been directed onto a stack of cupper and steel plates (see Fig. 1). The beam with a

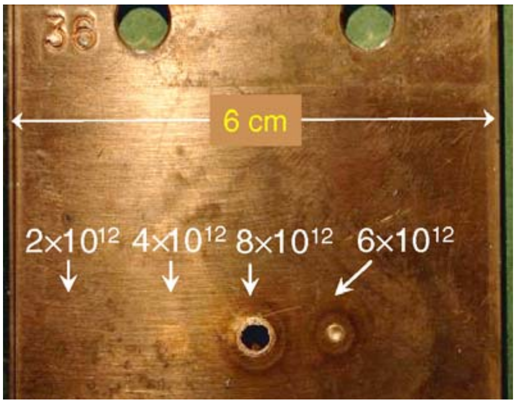

Figure 1: Destruction test of a Cu target in the SPS with a LHC beam.

size of σ_x=1.1, σ_y=0.6 mm and intensities of several 10^{12} protons at 450 GeV damaged clearly the cupper plates at a penetration depth where the maximum energy is deposited. The steel plates were not damaged [1]. The safe intensity of 2 10^{12} represents only 0.6 % of the total intensity of 3 10^{14} at the LHC injection energy.

To illustrate the destruction potential of the LHC beam at top energy of 7 TeV a simulation of the material phase transition in the longitudinal penetration channel is shown in Fig. 2.

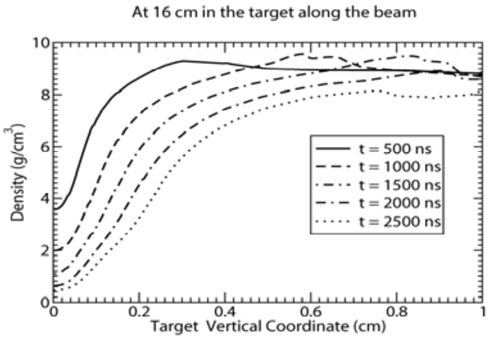

Figure 2: Density change of a Cu target material during the impact of 100 LHC bunches (bunch train duration 2500ns) with an intensity of 1.1 10^{11} proton per bunch at 7 TeV.

The energy deposited in the material leads to an increase of temperature, followed by a pressure increase which causes a shockwave leading to a reduction of the density. The following bunches would interact with less material where the density is reduced and will penetrate even further. It is expected that the whole LHC beam would penetrate over 10 m through the material if impacting [2].

Beam induced destruction of equipment is one reason for not being operational for an accelerator. Beam induced heating at the superconducting coils of the LHC magnets will cause a loss of their low resistance already at much lower levels as destruction of equipment. In case of a failure the tail of the beam will impact at the inner wall of the vacuum chamber and a secondary particle shower is depositing its energy in the vacuum chamber and in the surrounding coil (see Fig. 3). The lines of constant energy density show an decrease of the energy density in radial direction. The energy deposition is not leading to the largest temperature increase near to the vacuum chamber, because a He cooling channel is in between of the vacuum chamber and the coil which transports heat to the heat bath region for steady state losses (> 1 s). The quench location is near to the boarder between the inner and outer coil, where the heat flow is minimal (see Fig. 3, bottom) [3].

THE PROTECTION SYSTEM

Figure 4 shows a classification of the beam losses according to their duration. For the very fast losses (< 4 turns, 356 us) only passive components can protect the equipment. At LHC over 100 collimators and absorbers are foreseen for installation. The BLM system is the main active system to prevent magnet damage from

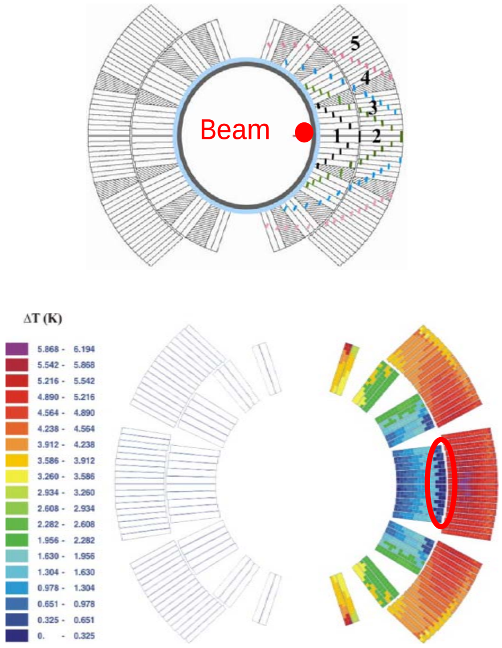

Figure 3: Top: Cross section of the superconducting coil of a LHC dipole magnet. The beam impact location and the lines of constant energy density are indicated. Bottom: Simulation of the temperature margin for the steady state (> 1 s) quench scenario. The quench location is in the midplane between the inner and outer coil (see ellipse).

all possible multi-turn losses. It is the only for short and intense particle losses, while at medium and longer los durations it is assisted by the quench protection system and the cryogenic system. Quench prevention is only ensured by the BLM system.

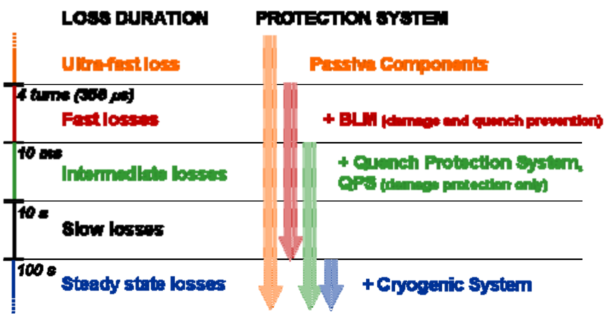

Figure 4: Classification of beam losses according to their duration and the applicable (passive, active) protection systems for the different loss classes.

Collimators and absorbers

The function of the collimators and absorbers is the protection of equipment against fast losses and to concentrate the steady state losses at locations, where the secondary shower particles do not lead to quenches of superconducting coils. For the capture of the steady state losses the collimators and absorbers are installed at two locations, for betatron and momentum cleaning. The fast loss protection is also done by placing collimators near to the insertion magnets or near to magnets in the injection and dump region of the LHC.

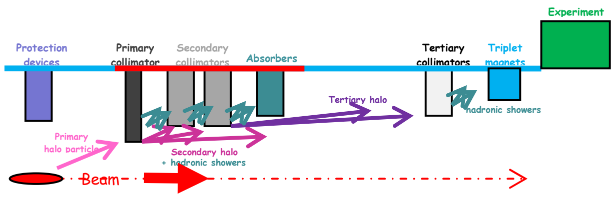

Figure 5: Sketch of the multi-turn LHC collimation system.

The setup for the multi-turn, 3 stage collimation system can be seen in Fig. 5. The beam hallo is intercepted at the collimator closest to the beam (primary). In the primary collimator most of the protons undergo multiple coulomb scattering and some of them will be caught by the secondary collimators, on average after some hundred turns. Protons which undergo also in the secondary multiple coulomb scattering will be caught by the tertiary collimator. The distribution of such losses

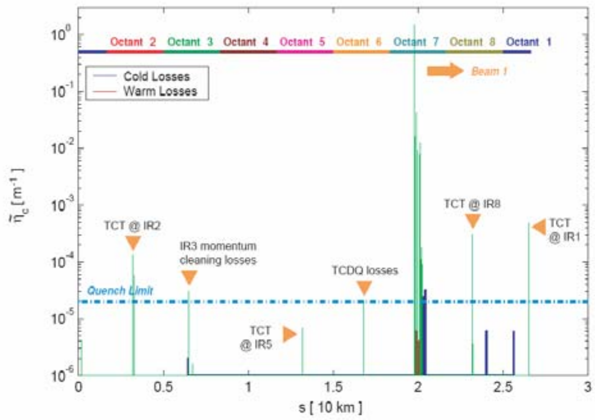

Figure 6: Distribution of the losses along the ring circumference.

along the circumference of the ring is shown in Fig. 6 [4]. The protons are mainly intercepted at the primary (TCP) und secondary (TCS) collimators at the collimation region in octant 7. Losses appear behind the collimator on the normal conducting magnets (green) and further down stream on superconducting magnets (blue). Decreasing losses (beam direction left to right) can also been seen at the tertiary collimators (TCT) in octant 8, 1, 2 and 5.

DESIGN CONSIDERATIONS OF THE PROTECTION SYSTEM

For the design of a safety system, in addition to the standard specifications, like dynamic range, resolution and response time, also a value for the “Mean Time

Between Failures" (MTBF) is needed to quantify the level of the protection. The estimate of the MTBF value was based in the case of CERN's LHC on the SIL (Safety Integrity Level) approach [6]. Other approaches like "As Low As Reasonably Practicable" (ALARP) are also often used.

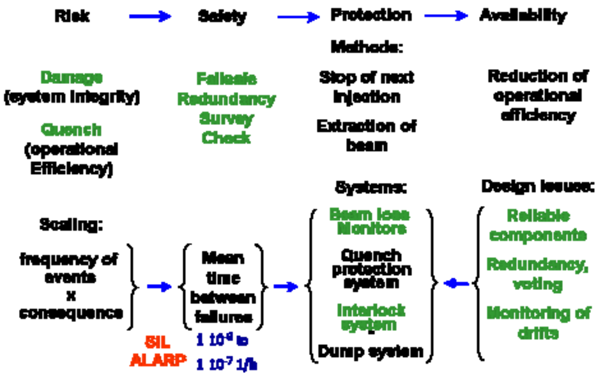

Figure 7: Schematic of the LHC protection system design approach (items in green are discussed in this paper).

For both approaches the MTBF value is estimated by the calculation of the risk of damage and the resulting down time of the equipment [5]. In the case of a failure in the safety system itself, it will fall in a failsafe state with the consequence of making the protected system unavailable.

The design considerations of a beam loss monitor system and others for machine protection are schematically shown in Fig. 7. In the first row the above discussed key words are listed. A risk requires a safety system which provides protection but it also reduces the availability of the protected system. In the risk column the consequences (damage and quench) of a non nominal operation (beam loss) are listed. A further consequence for both is the increase of the downtime of the accelerator. The risk is scaling with the consequences of the proton loss event and its frequency. From the risk the MTBF value is deduced. This main design criterion for the safety system is listed in the safety column as well as the means (failsafe, redundancy, survey, check) to reach the envisaged MTBF value. In the protection column the methods of protection are listed (stop of next injection and extraction of beam) for a one path particle guiding system (linac, transfer line) and for a multi path system (storage ring). The safety system is consisting of a beam loss measurement system, an interlock system and a beam dump system. If superconducting magnets are used, some protection could also be provided by the quench protection system. The availability column lists the means used in the design of the safety system to decrease the number of transitions of the system into the failsafe state. The effect of the components added to the system to increase the MTBF value results in a reduction of the availability of the system. This negative consequence of the safety increasing elements are partially compensated by the choice of reliable components, by redundancy voting and the monitoring of drifts of the safety system parameters (see Fig. 7, fourth column). The key words listed in green will be discussed below.

Risk Examples: Stored Energy in the Beam

The damage potential at CERN's LHC is over two orders of magnitude higher than at all other existing

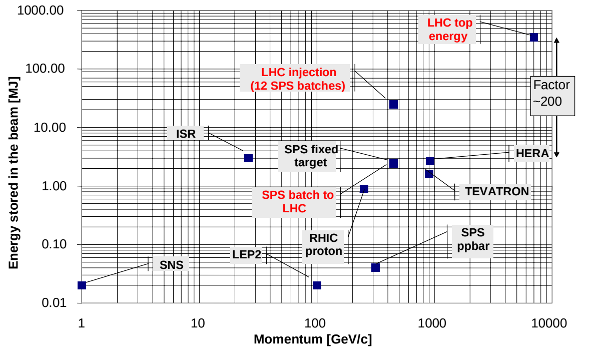

Figure 8: Comparison of the stored beam energy of different high energy physics accelerators as function of the beam momentum.

accelerators (see Fig. 8), since the stored beam energy given by the product of the single particle energy and intensity is largest at LHC. The consequence of a dangerous proton loss event was "illustrated" by an accidental loss at Fermi labs Tevatron (200 times lower stored beam energy as at LHC) where the proton beam was lost in a duration of a few revolutions melting some components. The loss was initiated by a moveable measurement instrument. The number of such moveable objects at LHC is also an order of magnitude higher than at Tevatron. This example may indicate the risk associated with the operation of LHC like beams leading to downtimes of months or even years.

Risk Examples: Quench Levels and is Dependencies

The proton loss initiated quench of magnets is depending on the loss duration and on the beam energy. A

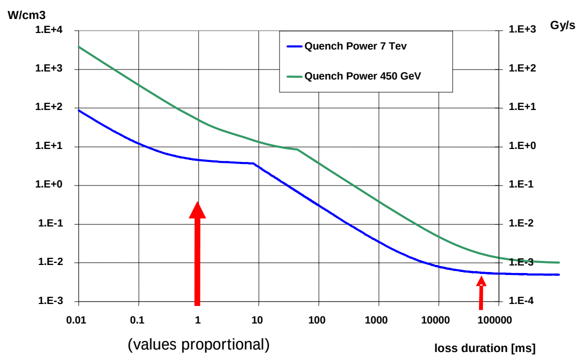

Figure 9: LHC bending magnet quench level curves as function of the loss duration.

quench of a magnet will create a downtime in the order of several hours in the case of LHC. To make the operation more efficient the beam could be dumped and a new store prepared. Figure 9 shows the expected loss dependence as function of the loss duration. The two curves indicate the levels for the injection and top energy of LHC. The two arrows indicate loss durations where the quench level of LHC are compared with levels at other storage rings (instant losses, steady state, see Table 1) [7][8]. It can be seen that the expected quench levels at LHC are lowest, resulting also in advanced requirements for the quench level detection.

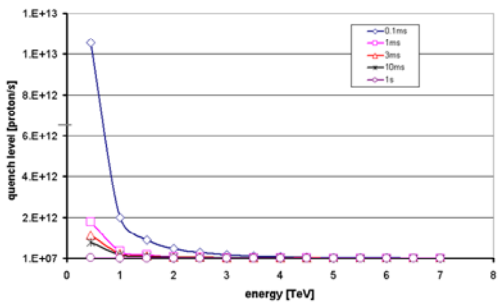

Figure 10: LHC bending magnet quench level curves as function of the beam energy. The parameterisation is for different loss durations.

The energy dependence of the quench levels is already seen in Fig. 9, their dependency as function of energy is shown in Fig. 10. The quench levels decrease rapidly with the particle energy leading to the requirement that the quench level thresholds need to be decreased during the energy ramp accordingly.

Table 1: Instant and steady state loss duration quench levels for different accelerators.

instant (0.01 - 10 ms)	J/cm^3
Tevatron	4.5E-03
RHIC	1.8E-02
LHC	8.7E-04
HERA	2.1 - 6.6E-03

steady state	W/cm^3
Tevatron	7.5E-02
RHIC	7.5E-02
LHC	5.3E-03

Safety Means

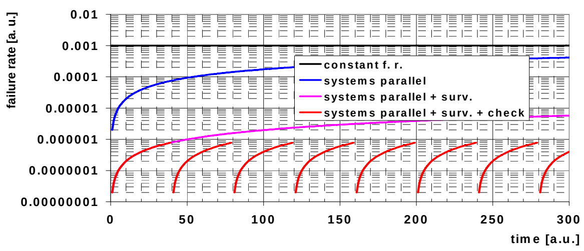

Figure 11: Calculation of the failure rates ranging from a simple system to redundant systems with surveillance and checks functionality.

The risk of damage could be reduced by safety means, which are incorporated in the safety system (see Fig. 7, second column). The most common safety feature of a system is the incorporation of the failsafe mechanism. In case of a failure of the safety system this system falls into a state where the protection is insured. If the system is doubled, redundancy is added, which will reduce the MTBF significantly for short time periods, but tends to reach the same value of the MTBF for long periods (see Fig. 11, failure rate = 1/MTBF) [10]. The use of a redundant and surveyed system will decrease the MTBF value for all durations compared to the simple redundant system. An even better result could be reached when a parallel system is not only surveyed but also its functionally is tested during the operation. This procedure will allow to assume that the status of the system after the test is identical to the status of the system as new. The frequency of the test will therefore determine the MTBF value.

Beam Dump Request Distribution

The beam loss measurement system is part of the equipment protection system. The protection as foreseen for LHC is schematically shown in Fig. 12 [10]. The number of beam dump request, which reaches the dump system over the machine interlock, is to 60 % operator initiated (inspired distribution by HERA [8]). The remaining dump requests are to 30 % caused by beam loss initiated dumps and to 10 % by various other reasons. The beam initiated requests are equally subdivided in losses with durations below 10 ms and above [7]. The short losses can only be detected by the beam loss system. The long losses can be detected in addition with the quench protection system (QPS, PIC). In this case two independent systems are available for the detection.

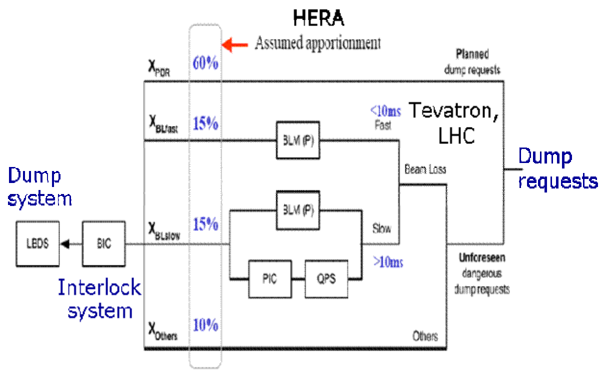

Figure 12: Dump request distribution and the employment of the beam loss system.

THE BEAM LOSS ACQUISITION SYSTEM

The electrical signals of the ionisation chamber and secondary emission detectors are digitized with a current to frequency converter and these pulses are counted over a period of 40 us (see Fig. 13). The counter value is transmitted every 40 us to the surface analysis electronics using a high speed optical link (with a cyclic redundancy check). The signal treatment and transmission chain is doubled after the current to frequency conversion to meet the required failure rate probability. The surface electronics calculates the integrated loss values and compares them to a table of loss duration and beam energy depended threshold values. Warning information is transmitted by a software protocol. The beam abort signals are transmitted to the beam dump kicker magnets using the LHC beam interlock system (LBIS). The beam energy information is received over a dedicated link. Details to the readout system can be found in [11-16].

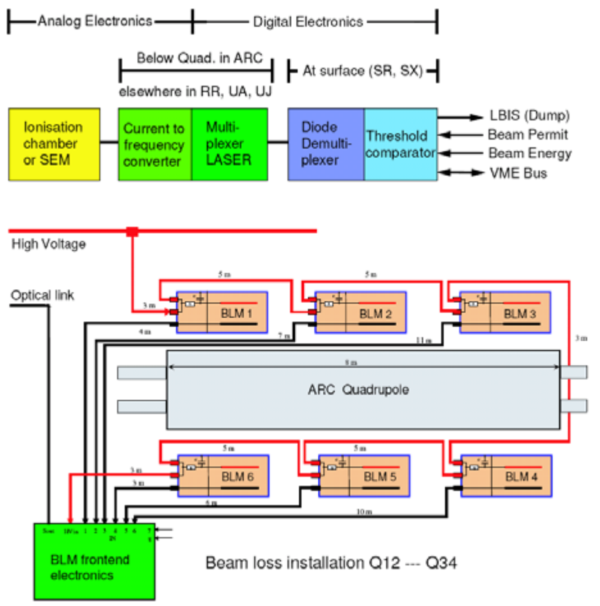

Figure 13: Schematic view of the signal transmission chain and the BLM installation at one arc quadrupole magnet. The beam permit and beam energy treatment is in this schematic simplified.

The analog electronics is located below the quadrupole magnets in the arc. For all detectors of the dispersion suppressor and the long straight sections the electronics is located in side tunnels to the LHC. All components of the tunnel electronics are radiation certified to 500 Gray. The dose expected at the electronics locations is about 20 Gray per year. No single event effect was observed during these tests. The temperature stability of the circuit was tested from 15 to 50 degrees Celsius. The analog signal transmission cables have a length of a few meters in the LHC arcs and up to 500 m in the long straight sections. This part of the transmission is subject to the injection of electromagnetic crosstalk and noise.

The BLM system will drive an online event display and write extensive online logging (at a rate of 1 Hz) and post mortem data (up to 2000 turns plus averages of up to 10 minutes) to a database for offline analysis (see paragraph below).

System Tests

The testing procedures are described in [17]. They have been defined in order to achieve the required reliability and availability of the system. The functionality of all components will be tested before installation. Thereafter, there are three different inspection frequencies: tests after

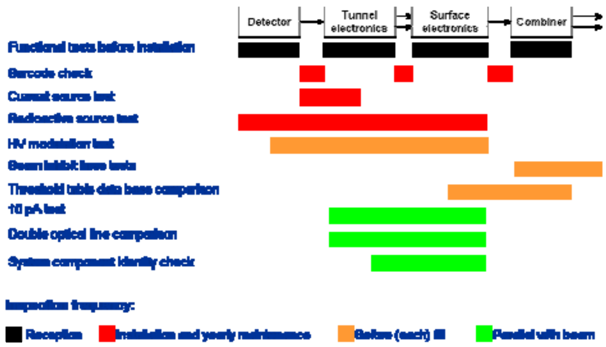

Figure 14: Schematic of test for the LHC beam loss system.

installation and during yearly maintenance, test before each fill and tests which take place with beam, in parallel to the data taking. Figure 14 lists the most important tests and their frequency. The availability of all electronics channels is constantly monitored and radiation dose induced drifts in the electronic channels are corrected (up to a maximum level, which corresponds to 10% of the lowest beam abort threshold value). The availability of all detectors, the acquisitions chain and the generation and communication of the beam abort signal is verified for each channel before each injection into the LHC. The composition of the chamber gas is the only component in the BLM system which is not remotely monitored. The properties of the chamber gas are sufficiently close to the ones of air at ambient pressure (i.e. inside a detector which has developed a leak) not to compromise the precision of the BLM system, but sufficiently different to detect a leak during the scheduled annual test of all the chambers with a radioactive source. Environmental tests have taken place during the design of the tunnel electronics.

Redundancy voting

The redundancy voting procedure allows to increase the availability of a system. An example is the cyclic redundancy check (CRC) comparison of a redundant transmitted signal (see Fig. **Error! Reference source not found.**15). The CRC is calculated at the transmitter side and again at the receiver side for each link. For each link the CRCs are compared separately. In addition the CRC of both transmission links, which are calculated at the receiver side, are compared. In case that the comparison of the CRCs of one link is negative, the data of the other link are chosen independently of the result of the CRC comparisons of both links. The result of the comparison of both links allows to identify the location of the error in the data stream [15].

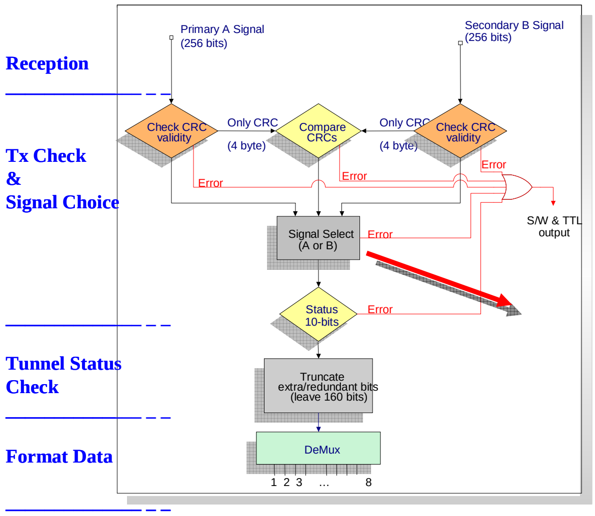

Figure 15: Schematic drawing of the redundant signal transmission comparison for the LHC design.

SOFTWARE AND DATABASE STRUCTURE

The LHC beam loss system consists of 4000 electronic channels. Each channel has threshold settings and can be connected to the interlock and dump system. The thresholds are stored in 2 dimensional tables. 12 values are needed for the integration intervals and another 32 values are needed to cover the beam energy variations. In total 384 values are needed per channel and for the whole system 1.5 10^6 values are used. The clients of the system request measurement data which are integrated over different durations or/and triggered by different events. E. g. the collimation system will be supplied with measurements which are integrated over 2.5 ms lasting for 80 ms triggered by every movement of a collimator.

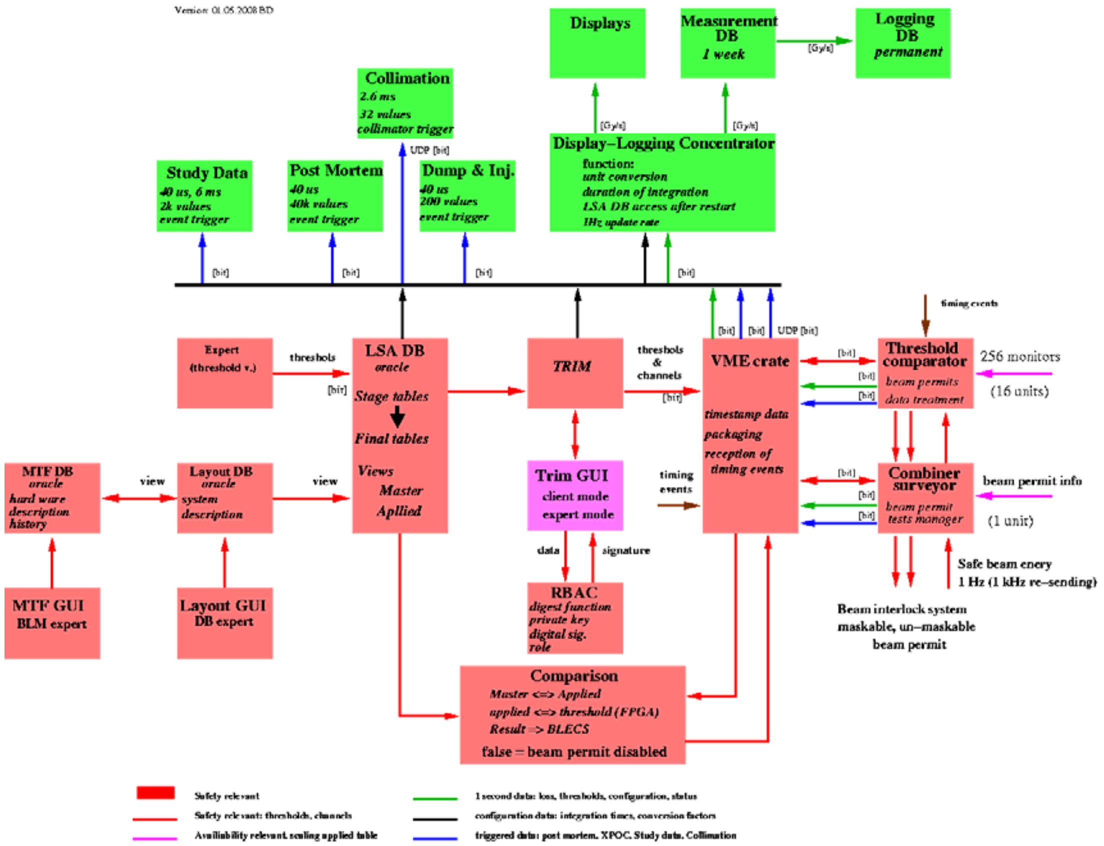

Figure 16: Schematic of the software structure for the LHC beam loss system. The green blocks are software entities which are not relevant for the safety of the system. The red blocks are safety critical.

The overview of the software layout is shown in Fig. 16. The safety critical parts (red) are strictly separated from the part which are not safety critical (green). The data streams are sent over the Ethernet to the different clients. The access to the single front-end VME crates by the clients is minimized by the usage of concentrators (e. g. display and logging concentrator, not all concentrators are shown).

The amount of threshold values and the request of having the threshold values frequently and safely changeable require a well defined setting management. The settings are stored in 3 databases, MTF, Layout and LSA (see on left side of Fig. 16). The MTF DB holds all the hardware data and its history. The layout DB holds the connectivity and channel assignments. The settings needed for the operation of the system are propagated to the LSA DB, where also the threshold values are stored. In the LSA DB the reference settings are stored and the front-ends are loaded from this DB. The loading is done with a trim interface, which allows a secure transmission of the settings to the front-end. In the front-end itself the settings are stored in the thresholds comparators (VME card), in the FPGA memories (see right site of Fig. 16). The safety is given by the comparison procedure between LSA DB and FPGA memories (see lower part of Fig. 16). A process is reading the LSA DB settings and the front-end memory values (FPGA memory) and writes back to the font-end the result of the comparison. If it is negative the combiner and survey module is taking away the beam permit.

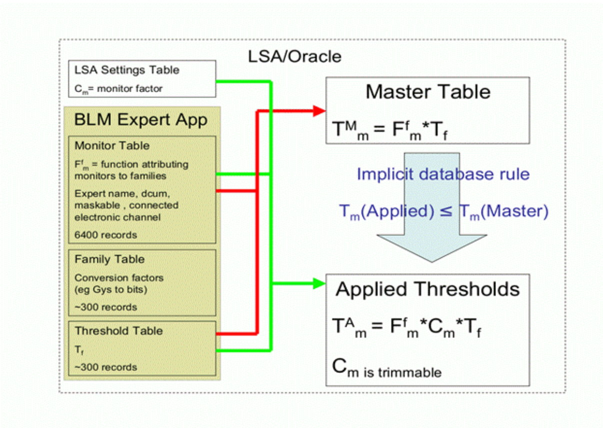

Figure 17: LSA database layout. Left side: the information of different tables are combined with views for the master table and the applied table.

The LSA data base layout is defined for safety reasons as shown in Fig. 16 and 17. The propagated layout DB settings are first stored in the stage tables as well as the threshold settings introduced by the expert GUI. After verification of the settings (history comparison) the settings are propagated to the final tables. In addition to this two level table system the information of the final tables is propagated to two views, the master table view and the applied table view. The threshold values of the master table should be always higher as the values of the applied table. The access to the applied table is also possible with the trim GUI (see Fig. 16 and Fig 17, factor Cm) to allow the scaling of the threshold values. The safety of this procedure is again given by a DB internal comparison of master table and applied table.

UNSAFETY OF THE BEAM LOSS SYSTEM AND THE FOLLOWING INTERLOCK SYSTEM

The discussed aim of the beam loss measurement system is the protection of the accelerator equipment to allow an efficient operation. If the detectors are located at the likely loss locations (this aspect is not discussed in this paper), the MTBF value of the beam loss system will indicate the provided safety.

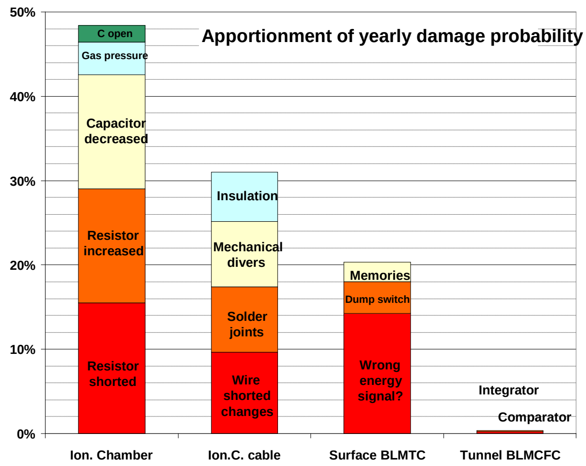

Figure 18. Relative probability of a system component being responsible for a damage to a LHC magnet in the case of a loss.

This value was calculated for the foreseen LHC beam loss system starting from the single component level and using tabulated or CERN measurements [5][17]. To identify the weakness of safety system components a relative comparison is shown in Figure 18. In the LHC design the ionisation chambers and their cabling contribute most to the unsafety of the system. Even with no damage in 30 years of the ion chamber operation (SPS ionisation chamber experience), systems which are redundant and frequently checked, contribute less to the unsafety. The availability of the system is decreased by false dumps. The components of the beam loss system which are most responsible for this dumps are located in the very front end of the signal treatment chain, which are not redundant. For the LHC design it is a discharge switch of an analogue integrator.

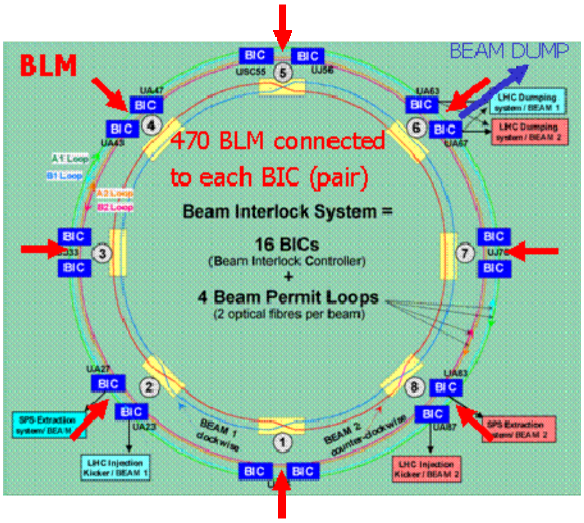

Figure 19: Schematic of the beam interlock system. Two redundant links for each beam link the client dump request to the beam dump system IR6.

The signal chain safety starting at the detectors of the beam loss system and including the interlock system has been addressed recently [18].

Table 2: Listing of the included elements in the safety analysis.

i	Component i	Number n_i
1	IC	3744
2	FEE	624
3	BEE	312
4	Combiner Card	24
5	VME crate	24
6	CIBU-S	8
7	BICbeam1	16
8	BICbeam2	16
	Total	4768

The layout of the beam interlock system [19] is shown in Fig. 19. For each beam two rings are used to transmit the beam permit signal to the LHC dump at IR 6. A 10 MHz signal can be interrupted by clients (e.g. the beam loss system) at each location of the beam interlock controllers (BIC). If the beam permit signal is taken away the beam dump kicker magnets are triggered and after a maximum delay of one turn (waiting time for dump gap in bunch structure) the beam is directed into the dump channel.

The components and the structure of the beam loss system and the beam interlock system have been modeled to estimate the damage risk and the false dump probability in an first step.

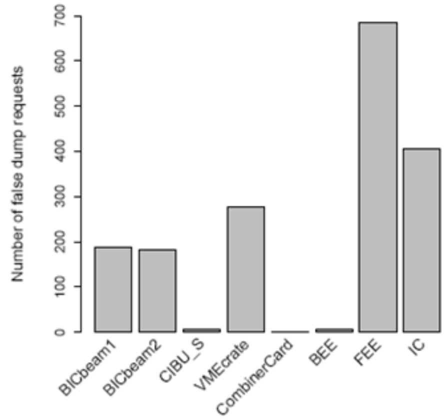

Figure 20: Distribution of contribution of the components to false dumps by triggering a false dump request.

The model predicts that the fraction of early ended missions triggered by beam loss event is 11.3 %. The false dumps due to a false dump request contribute to the mission end by a component failure with 1.7 %. The components which are most likely to create these false dump requests are components in the front-end electronics (FEE) and the ionisation chamber (IC) itself (see Fig. 20). The input data (failure rates of components) for this study are identical to the previous study. A new information given by this study is the contribution of the beam interlock system components to the false dump requests..

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