WEAKNESSES OF THE LHC MACHINE PROTECTION SYSTEM

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ABSTRACT

This report tries to solve an unsolvable problem: To foresee problems or incidents in the operation of the LHC that are not covered by the machine protection or beam interlock systems. It is evident that this task is not easy to fulfil but nevertheless what still can be done is to scrutinise the logic of the LHC machine protection system and to compare its structure with “unexpected” incidents that occurred in other large storage rings. Going through the history of these rings and mainly profiting from discussions with the experts, this contribution summarises events that are normally not published in conference reports, sometimes they are not even mentioned in internal papers. By the definition of the subject this reflection cannot be complete but there is hope that it will enlighten topics and failure scenarios that are worth to be considered in the LHC operation.

GENERAL CONSIDERATIONS

The considerations presented here are based on discussions with colleagues from the LHC operation group, the machine physicists, and machine protection group. But last and not least on experience that could be gained at other machines like the TEVATRON, RHIC or the electron proton collider HERA.

They represent therefore a personal - sometimes even subjective view and our definition of what a machine protection system (MPS) should do or avoid is a bit wider and more general than the pure word would suggest.

A MPS should in any case protect the machine and its experiments from damage in case of hardware or software failures of one of its components. But it should also avoid or even inhibit scenarios and situations that per se can lead to dangerous incidents. Therefore a well established MPS has to be embedded carefully into the context of the machine operation and control system.

We strongly assume that a pure hardware failure like a trip in a magnet power converter will be recognised by the MPS. And we further assume that all the connections and channels of the MPS that would in such a case trigger the beam abort system are carefully checked. Our concern here is more subtle and we do not consider the cabling connections between the different hardware modules of the MPS as a weakness.

But in a system as large and complex as the LHC machine [1], exotic situations can occur and special errors might happen that were unforeseen. Profiting from the experience made at other machines we can get a first impression about procedures that can be performed in a storage ring, that were not inhibited by the MPS and that still lead to unhealthy situations in the operation of the machine. It will be well understood by the reader that in these special cases that can be considered as practical applications of Murphy’s law we do not mention names nor references [2].

Procedures and events that should be avoided: *„Injecting beam too early, ie. during the machine cycle (beam tranfer was not inhibited), or too late (the machine was arleady on the accleration ramp), or into a filled bucket trying to accumulate proton bunch intensities (which turned out to be difficult), accelerating beam without the adequate correction tables (resulting in a wonderful quench), loosing the beam due to failures in injection kickers, spontaneaous firing of kickers, tune jumps due to mis-tracking of quadrupoles, driving collimators too close to the beam, using forward spectrometers as primary collimators, driving the beam into head tail instabilities due to ambitious chromaticity correction, injection and even storage of beam in a machine whose sextupole magnets are powered with systematically the wrong polarity, correcting the orbit according to BPM signals that are systematically inter changed, provoking quenches by driving the beam to the vacuum chamber wall due to wrong BPM polarity or BPMs that are off, injecting beam in a machine whose vacuum valves are closed (but indicated as open etc“*.

To point it out clear enough: each of these examples lead sooner or later to an unexpected beam loss or quench and in none of these cases the installed machine protection system did expect a problem.

Fig 1 shows as an example the number of the alarms (i.e. beam dumps initialised by the MPS) which were triggered by the beam loss monitor system (BLM) at the super conducting HERA proton ring. Presented are data that correspond to the run years 1995-1997.

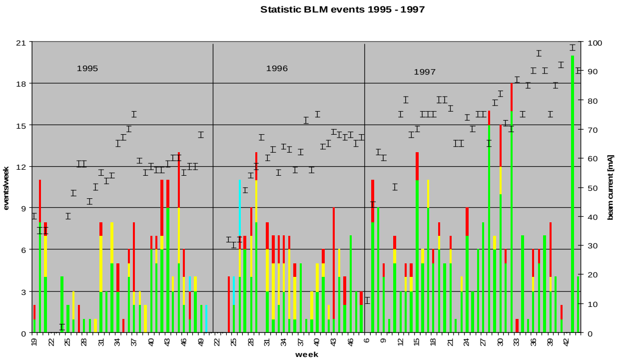

Figure 1: Number of beam loss and quench events triggered by the HERA MPS system per week

The black markers show the beam current stored in the machine. The green histogram bars indicate the number of beam loss alarms that were detected, yellow colour corresponds to very fast losses (faster than the 5ms repetition time of the BLM system: these events typically lead to beam induced quenches). Finally the red bars show the number of quenches. Each histogram bar corresponds to the number of events per week.

All in all the MPS system had to handle about 6 severe beam loss alarms per week on average and maximum values of more than 15 alarms had been observed [3]. A heavy load for a system than in each of these cases has to prevent damage of machine components. Considering for a moment only hardware related problems, the statistics of these events indicate that in general the source of the problems is wide spread: Experience shows that after some years of operation, single groups of hardware that dominate the error statistics, are rare. Peaks in the failure distribution will tell the machine coordinators to react and improve the situation. Therefore, in a machine that is well understood, one obtains in general a failure statistics that is more or less equally distributed over the different hardware groups, as presented e.g. in Fig 2. For different hardware components, the time needed due to fault & repair is indicated in per cent of the overall failure time for the HERA run year 2005. Considering the effect that large groups of hardware components (e.g. power converters) will have a higher probability to cause beam losses, the fault time is more or less equally distributed. In other words, the problems causing beam losses or beam induced quenches arise from practically any hardware component in the machine: vacuum, power converters, rf systems, and even the high energy detectors.

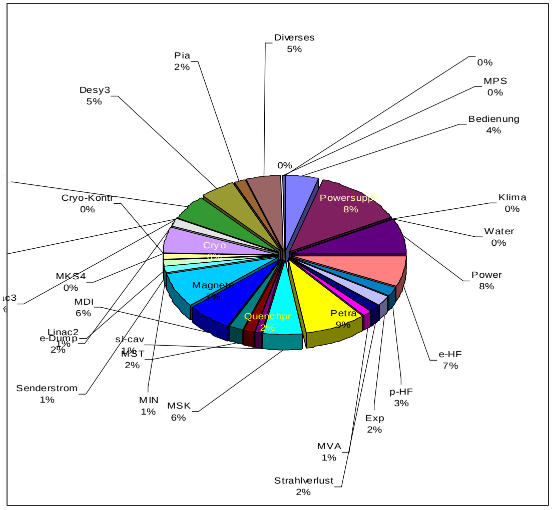

Figure 2: Hardware failures in HERA: statistics of the run year 2005. The graph shows the time loss due to failure and repair in per cent for the corresponding hardware components that caused the beam loss.

A trivial but important statement therefore can be drawn immediately: Considering pure hardware related failures, weaknesses in the MPS can be only avoided if

* the relevant MPS hardware components of the machine protection system are robust,

* the software is checked to react under all realistic circumstances

*and finally - considering the large variety of possible failure scenarios - the system is redundant, i.e. it does not rely on a single subcomponent like BLM's or the quench protection. It is also evident, that it will be more difficult to generate and check the software and to establish the redundancy of the system than to take care for the installation of robust hardware modules.

Concentrating for a moment on the beam loss monitor system (BLM) and taking into account the experience that we could gain at the HERA storage ring, we will outline some crucial points and try to trigger further contemplation about the philosophy of the LHC machine protection system.

Beam losses in general develop over a large number of turns and as the shower debris is propagating through the machine over long distances these events are observable at a number of BLM monitors. Fig 3 gives an example of such an event: A failure of a quadrupole power converter lead to errors in the beam optics, increasing the transverse beam size, and affecting the orbit and the tune of the machine of the machine.

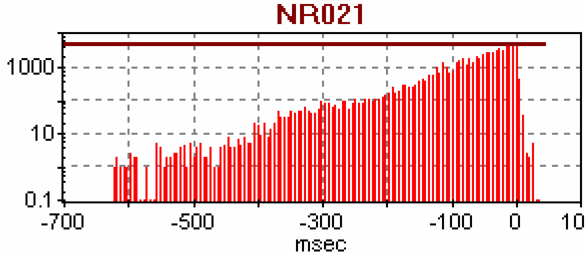

Figure 3:Beam loss monitor counts measured in case of a quadrupole failure in HERA. The horizontal line indicates the trigger level for the beam abort system.

The beam losses that were observed are recorded (in the case of the HERA BLM system) with a frequency of 200 Hz. The figure shows the increasing beam loss rate (counts registered by the BLM diode system) as measured within the 5 ms repetition rate during such an event. The horizontal line represents the threshold that, passed by the actual counting rate, would trigger a beam dump. The majority of the beam losses in case of hardware failures as well as in the case of operational errors will look like the example in Fig 3 and a slowly increasing loss pattern is obtained. In general losses will be observed in several locations in the ring, see Fig 4, where the expected instantaneous loss rates for the LHC (including seccondary particles) are plotted as a function of the BLM location in the machine [4].

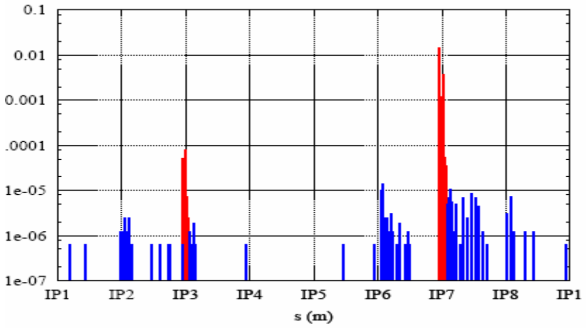

Figure 4: Expected beam loss rates for the LHC as a function of the position in the ring.

Much more critical are fast losses that can occur in case of errors in critical hardware components. Such devices as the power converters of strong dipoles or mini beta quadrupoles that have a strong impact on the beam lead in case of failures to very fast beam loss rates and could in the case of HERA induce quenches within a fraction of the 5ms repetition rate for the BLM system (see Fig 5).

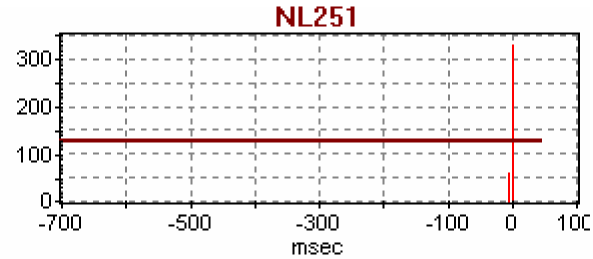

Figure 5: Fast beam losses observed in HERA: In case of failure of critical magnets fast losses were observed that caused several beam induced quenches.

Consequently redundant systems were installed to improve the situation: The MPS was completed by a fast magnet current monitor (FMCM) to detect magnet problems directly and a beam current monitor had been installed to initiate a beam abort in case of fast decay of the stored proton beam: a device that in case of problems can react within 1 turn and trigger a beam abort [5,6].

No beam induced quench had been observed in since then.

REDUNDANCY OF MPS

In the context of weaknesses of the MPS of HERA the conclusion has to be drawn that the system was not redundant and in case of the special situation that occurred (failure of magnets that were unexpectedly critical for the beam stability) the only existing component of the MPS, namely the beam loss monitors could not react in an adequate manner.

Similar considerations have been made for the LHC [4]. Different failure scenarios have been studied and based on particle tracking calculations the typical loss time for the beam has been deduced. Summarising the large amount of information that is provided for the LHC, the most prominent failure scenarios lead to beam loss rates in the order of milli seconds:

quench in sc. arc dipoles: τ_{loss} =20-30ms. The losses occur slowly enough and the BLM system can react in time to abort the beeam.

quench in sc. arc quadrupoles: τ_{loss}=200ms. Both systems, BLM and QPS react in time.

failure of nc quadrupoles: This represents a severe problem: the time to detect the beam losses is about τ_{det} = 6ms, but damage of machine components is expected already after τ_{damage}=6.4ms, leaving only a small safety margin for the machine protection system.

failure of nc. dipole: in this case the damage level is reached after only τ_{damage}=2ms.

Especially the last case, the failure of a normal conducting dipole magnet, is worrying: The damage level for machine components is obtained after a time of only 2ms, or expressed in number of turns, after 25 turns (Fig 6).

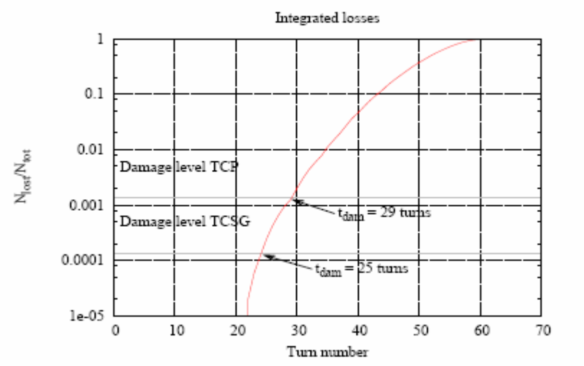

Figure 6: Development of beam losses of a large nc dipole magnet in LHC: The damage level for the machine is reached already after 25 turns.

It is questionable whether the time needed for detection of these errors and reaction of the signal and abort chain is short enough to prevent damage from machine components like magnets or electronics. And it is therefore strongly recommended to install in addition to the existing BLM monitors and the FMCM a redundant beam current monitor that can measure fast changes in the stored beam current.

MPS AND MACHINE OPERATION

As explained in the previous example, the major layout of most MPS systems is concentrated on the detection of beam losses or magnet quenches and they trigger the beam abort system to avoid damage of hardware components. More sophisticated MPS systems include control and survey of critical hardware components as power converters, rf systems etc, that in case of failure would lead to beam losses. Hardware errors can be detected and the beam can be aborted even before the first beam losses are observed; and hopefully much before the losses can reach the damage level of the machine. An excellent example is the FMCM that is installed at several components in the LHC to survey the current of critical power converters.

It is more than a purely philosophical question whether these considerations can and should be extended from pure hardware control to the general control system of the machine. In other words: How can the MPS be implemented into the control system and the operation of the machine. It is evident e.g. that the MPS will inhibit beam transfer if the LHC magnet currents have not reached their injection plateau. It is not so evident how this interference between MPS and control system can be extended to include general issues of the machine operation. Fig 7 illustrates this point for the HERA storage ring: For the run year 2007 the number of “events” is presented that lead to unscheduled beam losses. The majority of all beam losses (more than 85 events) is obtained due to procedures during beam operation. In this sense we consider it as a weakness of any MPS, if beyond the pure control of hardware components the control of machine operation and dedicated beam handling is not established equally well. A highly sophisticated interaction between MPS and beam operation is needed to minimise beam losses, quenches and in worst cases damage of the machine due to errors and mistakes during operation.

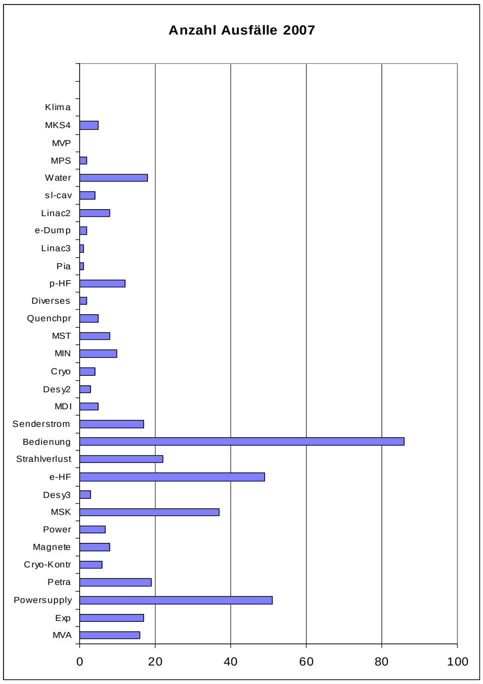

Figure 7 : HERA error statistics for the run year 2007: The histogram bars indicate the number of beam losses due to failure of different hardware components, including operational procedures.

In this context immediately a third weakness of the LHC MPS has to be pointed out: its complexity. Fig 8 shows the different subsystems of the MPS and the information flow that in case of an alarm will trigger the beam abort system or inhibit special machine procedures. 140 subsystems are interacting with each other - some of them representing more than 1000 components like beam loss or beam position monitors [7].

It has not to be mentioned explicitly that such a sophisticated system needs systematic tests to check its logic, and that special procedures have to be established to test the availability of the different components and to mask false alarms in case of problems of the MPS hardware itself.

The weakness that has to be pointed out here is the need for book keeping and issue tracking in case of problems. As in any complex system there will be a need to disable false alarms and it has to be defined in advance how many masked alarms can be tolerated in the system. And if so, how the information will be passed to the operators and the control system of the LHC, and whether the responsibilities for masking false alarms are already defined clear enough.

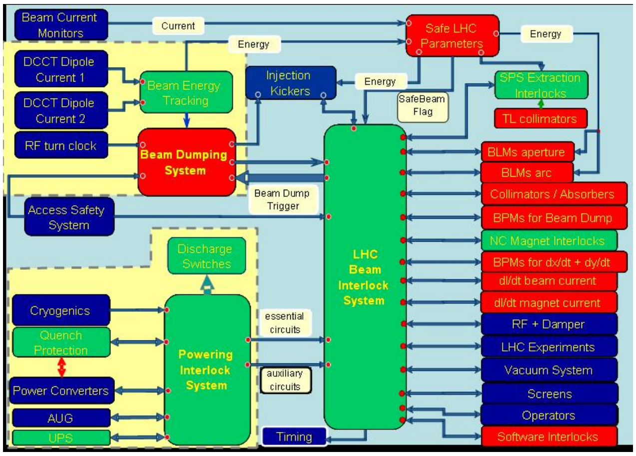

Figure 8: Schematic layout of the LHC machine protection system and its components

Last but not least the information flow from / to the four LHC experiments has to be mentioned. According to Fig. 8, the experiments have access to the LHC MPS and can - in case of problems - trigger a beam dump. The question that has to be discussed is whether the information flow in the opposite direction is equally well established and clear defined. In case of the detector magnets it is assumed that a system similar to that one of the machine magnets exists and a quench of a super conducting detector solenoid or a power converter problem at the detector dipoles or its compensators will be recognised. More complicated is e.g. the problem of movable detector components. Most prominent among them are the proton forward spectrometers that are installed inside the vacuum chambers and that are equipped with movable parts to approach the beam during luminosity operation. It is well known experience in several labs that failures of these systems can lead to severe damage of the detector parts and / or machine components. Again, as in the case of the general operation of the machine it has to be discussed whether and how the operation of critical detector devices can be embedded in the MPS of the accelerator.

RESUME

The MPS of the LHC collider represents an extremely complex and highly integrated system. A large number of hardware components from the machine and the experiments are combined and will in case of technical or operational problems trigger the beam interlock system to abort the two beams. It is far beyond the schedule of such a summary to critically check all technical subsystems. But based on the experience made at other machines and following suggestions from studies about the LHC error analysis the following résumé concerning possible weaknesses of the system might be drawn.

Plans for testing the MPS and its subsystems are already well established. Similar procedures for masking of false alarms or broken subcomponents are required and clear defined strategies for the corresponding book keeping are urgently needed. An advantage, but in this context also a disadvantage of the MPS system, has been mentioned: its complexity. And it has to be pointed out that a large amount of self discipline will be demanded from the machine operators and may be even more from the experts of the technical devices. Training and experience of the operations team is essential to handle unforeseen situations and to understand the logic of the MPS in these cases. On the technical side of the system the absolute need for redundancy is pointed out, i.e. the need of several independent components that are fast and reliable enough to handle exotic beam losses.

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