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STATE-OF-THE-ART AND FUTURE CHALLENGES FOR MACHINE PROTECTION SYSTEMS

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Abstract

Current frontier accelerators explore regimes of increasing power and stored energy, with beam energies spanning more than three orders of magnitude from the GeV to the TeV scale. In many cases the high beam power has to cohabit with superconducting equipment in the form of magnets or RF cavities requiring careful control of losses and of halos to mitigate quenches. Despite their large diversity in physics goals and operation modes, all facilities depend on their Machine Protection Systems (MPS) for safe and efficient running. This presentation will aim to give an overview of current MPS and on how the MPS act on or control the beams. Lessons from the LHC and other accelerators show that ever tighter monitoring of accelerator equipment and of beam parameters is required in the future. Such new monitoring systems must not only be very accurate but also be extremely reliable to minimize false alarms. Novel MPS ideas and concepts for linear colliders, high intensity hadron accelerators and to other high power accelerators will be presented.

INTRODUCTION

Each accelerator consists of numerous components, and many of them must be protected when they are powered. *Equipment protection* can be defined *as the collection of measures that protect the accelerator components when they are powered* even before beam is present. Superconducting magnets or cavities for example may quench with and without beam. The beam contributes an additional damage potential to a subset of accelerator components that are exposed to the beam or to its effects like synchrotron radiation. *Machine protection* can be defined *as the collection of measures that protect an accelerator from beam induced damage*. It must be noted here that this definition is not universal, sometimes equipment protection is included in machine protection.

Protection is required when there is some *risk* which is associated to an incident. We define risk as

$$\text{Risk} = \text{incident probability} \times \text{consequences} \qquad (1)$$

where the consequence may be for example loss of money, accelerator downtime or radiation doses to personnel. For beams we are interested in the cause and the probability of an uncontrolled beam loss affecting the equipment. In safety system the designer is usually basing his design on a matrix of occurrence frequency and consequences to define protection requirements (what in personal protection is called the SIL level). MPS designers work on the reduction of the probability, using for example design changes (slow down failures), equipment and beam parameter interlocking, and fail-safe design. The designers also mitigate the consequences, for example through machine layout and optics optimization, passive protection (collimators, absorbers, dumps) and equipment design (fast exchange).

Damage Potential of Beams

The damage potential of a beam depends on a number of factors, including

- Particle momentum and type (protons, ions, electrons or photons),
- Stored energy and/or beam power,
- Beam size (energy density),
- Time structure of beam (bunch trains etc).

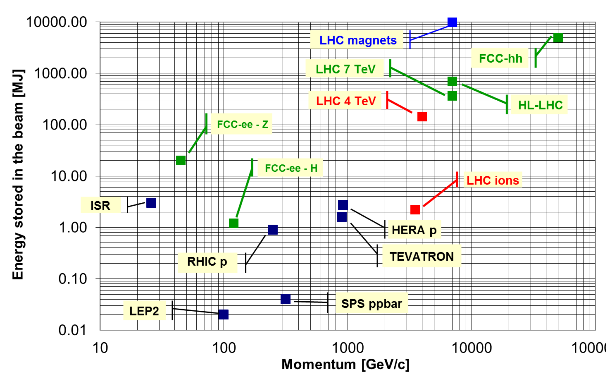

Figure 1: Stored energy versus beam momentum for colliders. The LHC holds the current record with 140 MJ stores at 4 TeV. The nominal LHC stored energy is 360 MJ at 7 TeV.

Different accelerators (colliders, linacs, hadron and electron machines) cannot be easily be compared directly. Figure 1 compares the stored energy of hadron colliders. SPS, RHIC (protons), HERA and TEVATRON operate(d) with stored energies of 1-3 MJ, while the LHC holds the record of 140 MJ, for a design of 360 MJ [1, 2]. The High Luminosity (HL-LHC) upgrade will push the LHC stored energy to 700 MJ. With an energy of 1 MJ it is possible to heat and melt 1.5 kg of Copper, 1 MJ corresponds also roughly to 0.25 kg of TNT. A similar scale for high power hadron accelerators is shown in Fig. 2. Planned projects like ESS [3] and IFMIF [4] aim for powers of 5-10 MW while existing facilities like SNS [5] and PSI operate just above 1 MW.

The largest incident that happened in an accelerator was the September 2008 LHC incident that did not involve beam [6]. A defective magnet interconnect resulted in an electrical arc that provoked a helium pressure wave damaging 600 m of LHC machine and polluting the beam vacuum over more than 2 km. In total 53 magnets had to be repaired.

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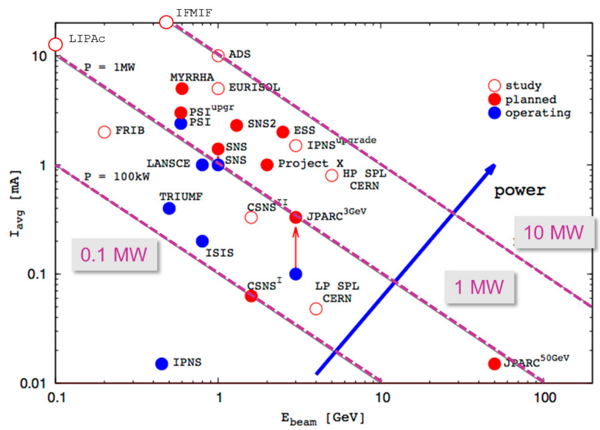

Figure 2: Average beam power for existing and planned high intensity hadron machines (courtesy M. Lindroos).

It is important to note here that damage to accelerator components does not always require MWs and MJs. Low energy beams can deposit energy very locally due to a very high dE/dx and they are surprisingly damaging. Recently a thin (0.2 mm) bellow was damaged by a 3 MeV and 10 W average power proton beam at CERN's LINAC4. Very low loss levels may also lead to permanent damage of undulators in FELs [7]. The problem of "Errant Beam" at SNS is another example where low energy beams that are outside the normal operation envelope can become a problem [5]. The beam intensity losses are well below "classical damage" level. But errant beam loss in SC linacs leads to accumulating damage and degradation of SC linac cavity performance over time. At SNS most issues were traced to room temperature linac faults, with very fast RF failures due to vacuum problems [8].

MPS DESIGN

The design of a modern MPS should be guided by the principle of the 3 P's:

- **Protect the machine**, the highest priority is to avoid damage of the accelerator.
- **Protect the beam**, complex protection systems may reduce the accelerator availability, an aspect that must be taken into account at the design phase. Typical availability target are: 99% for light sources, 95% for spallation sources like SNS [5], ESS, while the LHC so far reached a modest 35% [9].
- **Provide the evidence**, clear (post-mortem) diagnostics must be provided when the protection systems stop operation or when something goes wrong (failure, damage, but also near misses).

A modern MPS is not just limited to the design of fast interlocks!

Accelerator protection can be split into a number of functions. First of all one should aim to avoid or minimize failures by design. Since this is not always possible, as a first protection layer should detect a failure at the equipment level as early as possible. A second protection layer should detect the consequences of the failure on beam parameters (orbit, tune, losses etc). In case the two protection layers are not applicable or cannot protect all failure cases, passive protection by collimators and absorbers provides a third line of defence [1]. More than one system may provide protection within each layer.

The protection strategy can be very different for circulating beams and for beam transfer and linacs. For circulating beams the impact of a failure on the beam usually develops progressively (even if the time scales can cover many orders of magnitude) which provides room for reaction by the MPS. The notable exception are kicker magnet failures (for injection or beam dump) that lead to failures similar to beam transfers [1]. For linacs and beam transfer it is usually not possible to stop the beam if it is produced or if the transfer is initiated. Incorrect element settings can be fatal, requiring mitigation by active and passive protection, use of low intensity probe beams before sending high intensity trains [10,11]. At the LHC for example, despite storing up to 140 MJ, not a single SC magnet was quenched with circulating beam even though the quench threshold of the magnets is around few tens of mJ at 4 TeV [2]. But many magnets were quenched during injection, mainly due to expected injection kicker failures (7 events in 2012). The beam energy of up to 2 MJ is safely absorbed in injection dump blocks, but the shower leakage quenches magnets over a distance of 1 km as shown in Fig. 3.

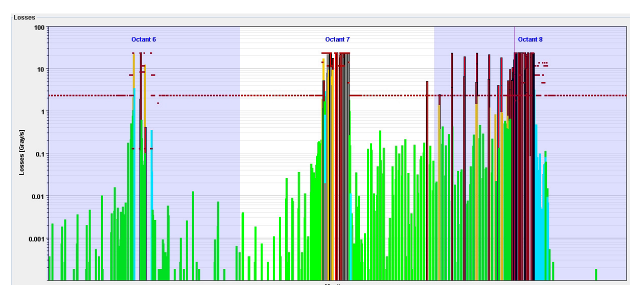

Figure 3: Beam losses during an injection failure at the LHC. The beam moves from right to left. The vertical scale is the beam loss, red bars indicate losses after dump threshold. Many loss monitors are saturated.

MATERIAL DAMAGE

An important aspect for collimators, absorbers, dumps and targets is the survival due to nominal or abnormal beam impacts. For high intensity and energy proton beams, the current material robustness limits are around 4 MJ. In the past decade a lot of effort was invested to better understand and simulate the interaction of high energy density beams with matter. In 2004 a controlled experiment was performed at the SPS with 450 GeV protons to validate damage threshold for the LHC beams. This experiment remains the reference for the definition of a "safe" beam at the LHC [12]. To improve test possibilities the HiRadMat beam line was build at

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the SPS at CERN as high radiation to materials test facility. Beams of 2-3 MJ with a duration of 7-8 μs (fast extraction) can be provided to test materials [13].

For high intensity beams made of long bunch trains, hydrodynamic tunneling significantly increases the damage range in a material. Leading bunches melt the material and create a plasma, the following bunches see less material and penetrate deeper into the material. This effect greatly enhances the damage potential of long bunch trains, leading for the nominal 360 MJ LHC beam to a penetration depth of around 20 m in carbon [14].

INSTRUMENTATION

Machine protection is based on many different beam instruments to monitor and interlock the beams, for example:

- Beam current transformers (BCT),
- Beam loss monitors (BLM) of various kinds,
- Beam position monitors (BPM),
- Synchrotron light to monitor abort gaps.

A general challenge for all beam instrumentation is to cope with an ever increasing dynamic range between safe commissioning beams and nominal beams. At LHC the difference spans more than 4 orders of magnitude in total intensity, and a factor 20 in bunch intensity. Despite such large differences the beam position measurement should not suffer intensity systematics due to bunch intensity and filling patterns.

To improve the sensitivity of BLMs for superconducting machines there is now a trend to move BLMs from the outside to the inside of the cryostats which reduces for example the shielding effect from iron yokes. A variety of BLMs (silicon, liquid helium, diamonds) are considered for the cryogenic environment [15]. First tests are foreseen in the LHC in 2015, and similar ideas are pursued at IFMIF for high sensitivity halo monitors [4].

The high sensitivity and speed of certain BLMs (diamond detectors, scintillators) make them useful beyond the protection as they provided bunch by bunch diagnostics. For example LHC uses CVD diamonds for bunch-by-bunch diagnostics [16], IFMIF plans to use CVD diamonds for micro-loss halo diagnostics and tuning, integrated into cryo-module as close as possible to the beam [4]. At XFEL and FLASH scintillators with photo-multipliers are/will be used for bunch-by-bunch diagnostics [17].

A particular problem is affecting the LHC: very fast and localized beam losses were observed as soon as the LHC intensity was increased in 2010. The beam losses were traced to dust particles falling into the beam and were nicknamed "UFOs" [16, 18]. In the injection kicker modules the UFOs were traced to Aluminum oxide particles. Each year roughly 20 beams were dumped at 3.5 and 4 TeV when beam losses due to UFOs exceeded BLM thresholds. The speed of UFOs is at the limit of the LHC MPS reaction time. Increased losses at 7 TeV may render UFOs a serious availability problem at the LHC.

For linacs high sensitivity BCTs play an important role, and for example the SNS errant beam issue was improvements with better vacuum conditions, improved diagnostics, fast differential beam current monitors (DBCMs) and a faster MPS response [8].

Equipment failures or incorrect settings changes remain a major concern for MPS. For fast magnet powering failures a dedicated fast interlocking device was developed for HERA and was adopted for SPS and LHC where it is now widely used to protect against failure in magnet circuits with very short time constants [20]. Another techniques is to limit the speed of changes for equipment and for active systems (ramp rates). Such limitations should be applied at the lowest level (hardware) is possible, as high level software limitations may be accidentally bypassed. As an example to avoid mistakes of the trajectory feedbacks at ILC/CLIC the shot-to-shot changes will be limited [10, 11].

COLLIMATION AND HALO CLEANING

At the LHC it was demonstrated that a complex multi-stage cleaning (collimation) system with over 100 collimators can be operated efficiently and can provide excellent and reproducible performance, with cleaning efficiencies of in excess of 99.99% [21]. Alignment of the jaws is performed by touching the primary beam halo with each jaw in turn, and over three years the alignment speed was improved with automated algorithms from 20 to around 3 minutes per collimator [22]. The quality of the beam cleaning is checked at regular intervals with a low intensity bunch that is excited with the transverse damper to provoke losses at the collimators in a controlled fashion [23]. A similar simulation of an asynchronous dump is performed at the same time.

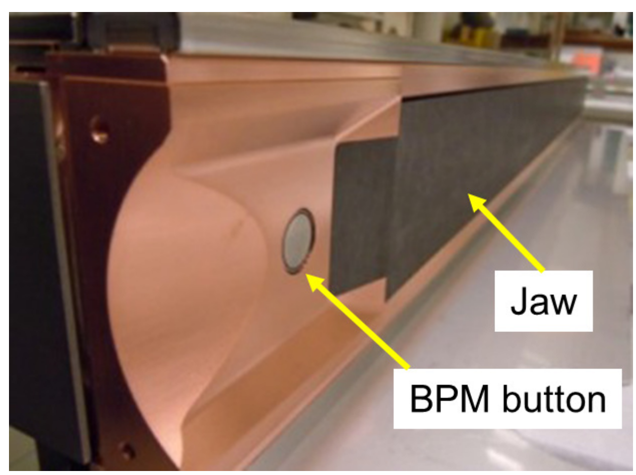

Figure 4: LHC collimator jaw with integrated BPM buttons.

Since setting up many collimators with loss signals remains very time consuming, Beam Position Monitor (BPMs) are directly integrated into the jaws for next generation LHC collimators [24], see Fig. 4. This provides direct monitoring of the beam position with respect to the jaw center for alignment, with setup times of less than one minute per collimator. The position measurement can also be used to interlock the beam position without need of interpolation from nearby

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BPMs. The first collimators with integrated BPMs will be used during LHC operation in 2015.

An alternative concept of a rotatable collimator is pursued as a possible solution to beam induced damage for the LHC upgrade [25]. Such a collimator provides 20 flat facets of Glidcop that can be exchanged after a beam impact. The impedance of the rotatable collimator is much lower than for standard LHC collimators made of carbon and tungsten which improves the beam stability and provides margin for higher beam intensities. Collimation by crystal channeling is another alternative, see for example [26], such devices do not provide passive protection in case of failures.

Halo control and monitoring are becoming increasingly critical issues for many accelerators. For the HL-LHC upgrade the LHC beam halo at a distance of 4-5σ from the core will store tens of MJ if current LHC observations are scaled [18]. A fast loss of the beam halo, for example by Crab Cavity failures, could lead to collimator damage on the time scales on few LHC revolutions. Halo cleaning techniques include tune modulation and electron lenses pioneered at the TEVATRON [27]. The e-lens provides a soft scrapper that does not suffer from material damage. It strength is tunable to adjust diffusion speeds. Such a lens is considered as an option for HL-LHC upgrade. For halo monitoring ring loss monitors (FRIB) and non-invasive halo monitoring from synchrotron light are considered. When the beam halo is depleted in a storage ring, protection by loss monitoring may however become more difficult due to faster onset of critical loss rates. This issue that deserves more analysis in the future.

AVAILABILITY

Besides peak beam performance a high availability is a key factor for modern machines. LHC [1], ILC [10], XFEL [17], SNS [5] etc are projects where availability was seen as an issue from the start, with many thousand inputs into the MPS. For the LHC a Failure Mode, Effects and Criticality Analysis (FMECA) was used to asses safety and availability of the main MPS components. In addition the system designs were reviewed by external consultants in the field of safety (car industry, air traffic etc). There is a lot to learn from the experience and the work principles used by such external partners. The LHC experience shows that the FMECA approach can provide reasonable estimates for availability, but it requires a significant effort and a systematic approach. A key benefit of a failure analysis, besides the estimates for failure rates are an in depth analysis of the system that sometimes reveals dangerous common mode failures [28].

For the LHC a reliability working group predicted the rate of false dumps and the safety of the LHC MPS for 7 TeV operation. The predictions can now be compared with observations, even though the machine was only operated at 4 TeV. The observations are basically in line with predictions, but some failure modes do not match completely, in particular radiation to electronics affecting some large systems installed in the LHC tunnel was not included in the initial predictions [29]. After 4 years of operation a detailed analysis of the LHC Beam Dumping System (LBDS) failures was performed and compared to the failure model established before operation. The analysis confirmed that the LBDS meets the intended SIL3 safety standard [28].

OPERATION

For the MPS design it is important to consider commissioning, machine experiments, low intensity operation phases where some flexibility is needed and where there is need to relax or mask certain interlocks. This is typically done by the concept of accelerator mode or by the use of beam intensity and energy in the interlock logic. At the LHC a "setup beam flag", which is a function of energy and intensity, defines if certain interlocks may be masked or not [1, 2]. For Petra III, the intensity is used to automatically deactivate certain interlock channels [30]. Many MPS automatically take into account a number of predefined accelerator modes to reconfigure the interlocks, avoiding human errors [7].

Direct injection of an intense beam into a synchrotron or into a linac may be problematic and require excessive surveillance efforts. For this reason the concept of "witness" beam or bunch is being used in some places. At the LHC with nominal injection of 3 MJ the "beam presence" concept is used [1, 2]. Only a probe beam (typically 10^{10} protons) may be injected into an empty ring. Intense beam injection requires a minimum beam intensity to be circulating, which constitutes the best check that conditions are reasonable for high intensity injection. This principle avoids many catastrophic failure cases happening right on the first turn, before the MPS is able to react. CLIC and ILC foresee to use witness bunches (ahead of main train) or low intensity witness trains [11].

Pre-flight checks and validations (after stops, interventions, before filling) are important to asses the good state of the MPS. At the LHC all BLM are tested between two fills using a HV modulation to ensure signal and cable integrity, and the consistency of the dump threshold is checked with respect to a reference database [31].

When the MPS triggers a beam abort, post-mortem (PM) diagnostics must be provided to identify the root cause of the abort. With complex systems and many 1000 inputs, the analysis can be tedious, automatic analysis tools are needed to help the operator and the MPS expert. The LHC post-mortem event data has currently a size of 200 MB, and some automated analysis is provided to tag the event [32]. An automated PM analysis of beam aborts is available to PETRA III operators [33]. At the LHC the MPS is so critical that for every beam dump, automatic post operation checks (POCs) are performed based on the PM data [34]. The POC asses that all signals are correct, that there is no loss of redundancy and the system can be considered "as good as new". Machine operation is interrupted and an expert check is required if an automated POC fails.

Changes to MPS components (for example repairs) and to the MPS configuration (for machine experiments) can be

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a threat to the MPS safety. There is an important human factor in reporting and proper execution, and the larger the machine, the more complicated the tracking becomes due to the larger number of intervening persons. For the LHC a tracking system was developed for the (re-)commissioning of systems, including expert signatures and automated test analysis [35]. This system is very advanced for magnet commissioning, and it is planned to extend it to beam MPS.

OUTLOOK AND CONCLUSIONS

A project like the Future Hadron Collider [36] is designed to operate at beam energies of 50 TeV with stored energies of 7 GJ, 10 times larger than the LHC after the luminosity upgrade, see Fig. 1 label FCC-hh. The beams will be injected at 3 TeV, and already the injection process is entirely dominated by machine protection issues. Collimation will become more challenging due to the small scattering angles, and it is probable that multiple beam dumps will be required.

Requirements for high powers and large stored energy provide a steady flow of challenges for innovative MP concepts. We may soon reach limits of materials, new concepts may be required, for example sacrificial devices like the rotatable collimator. Due to the high powers even very small halo losses may lead to low term issues for SC cavities or undulators. Monitoring of beam properties and equipment pushes to ever tighter tolerances with large dynamic ranges required for the machine commissioning. And least but not last, availability is a key aspect of a modern MPS design.

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