MACHINE PROTECTION ISSUES AND SOLUTIONS FOR LINEAR ACCELERATOR COMPLEXES

M. Jonker, H. Schmickler, R. Schmidt, D. Schulte, CERN, 1211 Genève 23, Switzerland
M. Ross, SLAC, Menlo Park, CA 94025-7015, USA

Abstract

The workshop "Machine Protection focusing on Linear Accelerator Complexes" was held from 6-8 June 2012 at CERN. This workshop brought together experts working on machine protection systems for accelerator facilities with high brilliance or large stored beam energies, with the main focus on linear accelerators and their injectors. An overview of the machine protection systems for several accelerators was given. Beam loss mechanisms and their detection were discussed. Mitigation of failures and protection systems were presented. This paper summarises the workshop and reviews the current state of the art in machine protection systems.

WORKSHOP OBJECTIVES

Machine protection has become a major concern in the design stages of the high power linear accelerators now under construction or being planned (e.g. high intensity protons linacs, XFEL, electron positron colliders). Due to the increased beam power the need for a dependable machine protection system becomes imperative. For this reason we organized this workshop on machine protection with a main focus on Linear Accelerator Complexes.

The objective of this workshop was to bring together for the first time experts on machine protection from various origins and disciplines, and to exchange experience and ideas for machine protection systems. The workshop was organized at CERN and could profit from the recent experience of the LHC collider, an accelerator where the need for a machine protection system was taken into account already during the design phase.

WORKSHOP ORGANISATION

The workshop was attended by 60 participants with a significant number from outside CERN.

Over 30 presentations were made in 6 half day sessions leaving ample time for discussion. The workshop sessions focused on the following topics:

Introduction: The session assessed the objectives for machine protection and reviewed existing solutions and challenges faced by future installations.

Beam loss mechanisms: The experience with beam loss mechanisms in existing installations and the outlook for future accelerator complexes were reviewed.

Failure detection: The session addressed the detection of failures that may lead to uncontrolled beams.

Failure mitigation: The session discussed various failure specific mitigations strategies.

Operational aspects: The session was dedicated to the operational aspects of machine protection (e.g. commissioning, intensity ramp, availability) and to risk management (risk assessment and management tools).

Summing up and closing: These five sessions were followed by a workshop summary session.

It is not in the scope of this paper to make a thorough report of these presentations. Here we highlight key issues and identify new trends and recommendations.

MACHINE PROTECTION

The purpose of machine protection is to protect the accelerator equipment from beam induced damage.

We did not consider equipment protection from other threats, (e.g. overheating of a power supply, protection of super conducting magnets). However, beam induced quenches and the effect of a magnet quench on the beam should be evaluated in the scope of machine protection.

Machine protection must not be confounded with personnel protection. Personnel protection is more stringent and need to fulfil legal requirements while the applied approach and solutions are often more basic.

Machine protection is not limited to the interlock system and its control and surveillance software. There are many more elements within the scope of machine protection ranging from failure studies to spares policies. The following list is non-exhaustive:

1. The passive protection devices (collimators and masks) to limit the damage caused by unmanageable failures.
2. The active beam-abort systems to dispose of any present beam upon detection of instabilities, including beam observation instrumentation, abort kicker-magnets, beam dumps and other beam inhibit systems.
3. A beam interlock system to inhibit the beam in case of equipment failures.
4. A strategy to limit the rate with which magnetic fields and device positions can change.
5. A post cycle beam and equipment quality assessment system to inhibit the next cycle when performance parameters are outside predefined limits.
6. A beam-stop restart system: i.e. an intensity ramp sequence that provides an appropriate protection depending on the machine mode and state.
7. A version control and parameter change authorization system.
8. A fault recording, analysis and playback system.
9. The written procedures to introduce changes in the parameters that control the machine protection system.
10. A set of test procedures to thoroughly test the components of the machine protection system after each change in the system.

11. A spares policy to reduce the loss of operational availability caused by unavoidable beam damage to equipment.

RISK NORMALIZATION

The damage potential of a system is given by the total amount of energy that can be released before the system can safely dispose of its energy and shut down the plant. Figure 1 shows that the beams of various accelerators contain enough stored energy to melt between 1 gr and 1 ton of copper. The vertical scales show the charge density of these beams, a measure how easily the beam can damage various materials on direct impact.

The stored beam energy information can be misleading as it does not account for the sensitivity of the equipment. The Fermi@Elletra accelerator in Trieste, presented at the workshop, is an example were very modest beam power of a few Watts still poses a concern due to the high sensitivity of the permanent magnets to beam loss induced radiation.

To compare the importance of machine protection systems of various accelerators and, more important, the individual failure scenario that each machine protection system has to protect for, we propose to normalise the risk with the available resources of the accelerator complex.

In essence, risk is expressed in statistical terms as the expectation value of the impact caused by a given failure scenario:

$$Risk = Impact \times Frequency$$

There are two types of impacts: cost of damage repair and operational downtime. These impacts can be normalized by the yearly available financial resources and the yearly scheduled operational time. As such the risks terms are expressed as the fraction of the available resources.

By normalizing the risks, we can prioritize the need for risk mitigation independent of the actual impact of the failure. Furthermore it indicates where risk reduction pays off: i.e. where the achieved risk reduction is larger than the required investment expressed as a fraction of the available resources.

Yet, great care must be given to risk terms coming from low frequency high impact failure modes as those risks are particularly difficult to estimate. The frequency can be underestimated (e.g. not considering aging, human errors, unanticipated configuration changes or coincidences with other failure modes). The impact can be underestimated by ignoring knock-on effects (e.g. as the worst case potential knock-on effect: lab closure due to lost confidence by the resource providers).

BEAM LOSS SCENARIO

In evaluating failure scenarios, the mechanisms for beam losses play a key role and needs to be studied first. The beam loss mechanisms to be taken into account are:

Operational beam losses: These are the inherent quasi continuous losses that form the loss background. Although not the primary concern of failure studies, the accumulated effect of induced radiation may contribute to long term failure of machine components. Moreover, when the radiation fields are very high, this background may pose a problem to the electronics located in the accelerator environment.

Sources of operational losses are, depending on the accelerator, dark current, un-captured beam, satellite bunches, beam gas induced parasitic beam halo and beam collision debris.

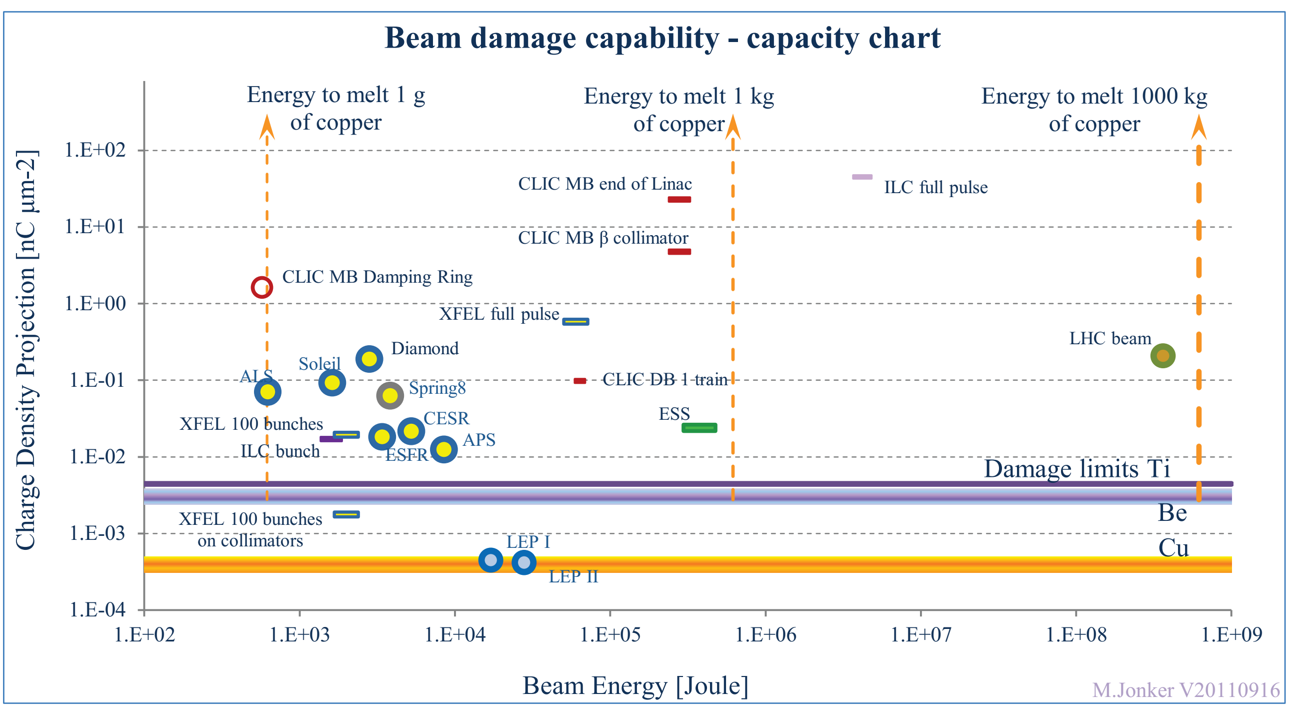

Figure 1: The charge density projection (a measure of the capability for a beam to cause damage) versus the total beam energy (a measure for the amount of damage the beam can cause) of existing and projected accelerators.

Equipment failure induced beam losses: losses leading to major damage of the accelerator components.

Transient beam losses: related to changing environment i.e. temperature drift, ground motion, UFOs* and others.

The session reviewed software tools and methods to simulate beam behaviour and beam loss for various failure modes. A presentation on the first measurement of induced beam kicks caused by breakdown in CLIC RF structures was of particular relevance to forecast the effect of these transient beam losses in CLIC.

FAILURE DETECTION

Detection and acting before a failure leads to damage is the most effective measure. Whilst largely used in circular accelerators, beam quality detection is not always applicable for a real-time beam abort system in linear accelerators. The observation of beam quality, however, is still very useful to detect upcoming instabilities and the information is fundamental for a beam permit system. Experience from the LHC transfer line and injection beam permit system gave a good example of the quality checks that can be implemented in linear accelerators.

Various beam diagnostics instruments were presented with emphasis on instrumentation for beam loss detection. Of particular interest were the scintillating fibre detectors which may provide an economic solution for large beam loss observation systems (e.g. for the CLIC drive-beam decelerators).

FAILURE MITIGATION

The basic principle of failure mitigation is to reduce either the frequency or the impact of a failure.

Equipment reliability has a direct impact on the failure frequency. Two presentations, on a kicker pulsing circuit and on a fault-tolerant magnet powering configuration were examples to reduce the frequency of critical equipment failures. It is worth noting that in both cases the solution also contributes to higher system availability.

A beam interlock system that stops the beam when equipment errors are detected or when the beam parameters are outside defined limits will reduce the frequency of dangerous beam failures. Such system relies on an efficient detection, decision and beam abort system.

For '*in-flight*' failures†, one has to rely entirely on passive protection such as masks and collimators. Due to the high brilliance of the beams the collimation systems are often on (or above) the edge of damage level in case of beam failures. Various ideas for improvements were presented during this session: alternative collimator design, nonlinear collimation optics as well as the use of novel material.

An important aspect to reduce the impact in case of damage is the spares policy. Although not explicitly discussed during this session, these points were addressed in the case of collimator spare surface, or in the build-in hot spares of the powering configurations.

IMPLEMENTATION AND OPERATION

The implementation and operation of the machine protection system is key to its success and performance.

The presentation on the operational experience in the SLC showed a case where the machine protection actions were actually a contributing factor to the unstable operation: Stopping beam operation provoked thermal oscillations not properly corrected for, which would subsequently induce new beam instabilities later in time.

Hence, the recovery from a beam stoppage should be considered carefully. Two presentations addressed this issue, one on the recovery of RF breakdowns, and a second on beam intensity ramp up procedures.

Also presented at this session were two tools, one to categorize and evaluate the risks in order to prioritize the mitigation and a second tool to evaluate machine availability. Both tools have similar goals, i.e. both tools have to catalogue failure scenarios, their frequency and impact whilst taking into account possible redundancies in the system and knock-on effects.

The complexity of a system certainly plays a large role in its reliability. This point already came up during various discussions at the workshop. It was further expanded in a dedicated presentation which stressed that the implementation of a machine protection system must follow an overall system approach, e.g. it is incorrect to oversimplify the interlock system at the price of creating extra complexity that is hidden in less controlled components elsewhere in the system.

CONCLUSIONS

Machine protection (MP) plays a crucial role in future high power linear accelerators and poses many new challenges, e.g. robust collimator designs; large scale beam loss detection systems; intensity ramp-up whilst following beam performance and environmental changes; improving equipment reliability and managing system complexity. Some challenges will be addressed through R&D programs, whilst others will need learning in realistic machine environments.

The workshop has shown that MP must be an integral part of the accelerator design stage and include well-planned and engineered instrumentation. Such instrumentation is crucial to understand the dynamics of the machine and will allow the MP to evolve in parallel with the commissioning of the machine at increasing stored beam energies.

The workshop allowed a fruitful exchange of experience and was highly valued by the participants. It is foreseen to repeat the workshop in two or three year. More details will be made available on the workshop website [1] or can be obtained by contacting the authors.

REFERENCES

[1] Conference web site and presentations repository: http://indico.cern.ch/conferenceDisplay.py?confId=185561

* Unidentified Falling Objects: dust particles observed in LHC beam.
† Failures occurring during beam passage.