MACHINE PROTECTION SYSTEMS AND THEIR IMPACT ON BEAM AVAILABILITY AND ACCELERATOR RELIABILITY

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Abstract

Over the last decades, the complexity and performance levels of machine protection have developed. The level of reliability and availability analysis prior to operation differs between facilities, just as the pragmatic changes of the machine protection during operation. This paper studies the experience and development of machine protection for some of the state of the art proton and ion accelerators, and how it relates to reducing damage to and downtime of the machine. The findings are discussed and categorized, with emphasis on proton accelerators. The paper is concluded with some recommendations for a future high power linear proton accelerator.

INTRODUCTION

As the users of previous generations of research accelerators were mainly the actual developers, only the accelerator physicists themselves were concerned by the lack of protection. However, as the concept of user facilities was incorporated in the 70s, research in other fields became dependent on the accelerators performing as designed [1,2]. With this came higher demands on the machines to be more reliable and available [3]. However, even up to today, though the concepts of reliability and availability are targeted at an early stage, the main goal is still to push the beam parameters beyond existing limits. Once this goal is fulfilled, the machine reliability and beam availability receive more attention.

Because of the very high beam powers and energies in current and future accelerators [3–7], the risk of beam-induced damage is significant. In as little as a few microseconds, the energy from a deposited beam could lead to permanent damage or melting of the equipment [8]. For dealing with this, efficient protection systems need to be implemented together with appropriate monitoring. The beam interlock systems (BIS), receiving beam permit signals from the monitors, play a central role in these protection systems. The BIS creates an overall beam permit signal, which defines if beam operation will be continued or inhibited. For hazards not directly related to beam-induced damage, more sophisticated and flexible local protection systems could be implemented, which act between the monitors or sensors and the beam interlock system.

This paper looks into current state of the art proton and ion accelerator facilities and discusses their machine protection (MP) based on analysis prior to operation, pragmatic changes of the MP, and other measures of improvement.

RELIABILITY AND AVAILABILITY

Two figures to measure the performance of a system are reliability and availability, and this paper uses the following definitions [9].

Reliability is the probability of fulfilling the major design function (MDF) of the system, continuously and without interruptions, for a predefined period of time – for example one hour or one day. Mathematically, reliability is defined as $R(t) = e^{-\lambda t}$, where λ is the failure rate and t the predefined time period.

Availability is the probability to find the machine fulfilling its MDF, when it is claimed to be in operation. Mathematically, and after an extended period of operation (years), the availability can be calculated as $A(t) = 1 - MTBF/(MTBF + MDT)$, where $MTBF$ is mean time between failures and MDT is the mean downtime.

For user facilities especially, where the users are dependent on the accelerator operating as it should, those two figures of merit account to a large extent for the user satisfaction of the facility, and the aim for MP should be to have those numbers optimized.

STORAGE RINGS AND LINACS

The typical solution for MP to avoid beam-induced damage is to stop beam operation. Synchrotrons, such as the Large Hadron Collider (LHC), have the entire beam stored in its storage ring. The only option for protection in case of a hazardous fault is to extract and dump the beam, and then restart the injection and acceleration process [10]. This generally leads to low availability numbers, as much of the operational time is needed to inject and accelerate the beam up to nominal energy [11]. Therefore, the MP reliability has to be very high in order to avoid false dumping procedures.

Linacs, such as the superconducting linac at the Spallation Neutron Source (SNS), tend to aim for high average power, meaning a constant delivery of beam pulses without major interruptions. The advantage of such pulsed machines is, if an error occurs, the ability to 'skip' individual or groups of pulses or run in a degraded mode, e.g. at lower beam current or lower repetition rates. When the problem has been resolved, operation can continue as before. For this reason, high-power linacs tend to achieve higher beam availabilities than high-energy proton and ion storage rings. However, putting this simple idea into practice needs an advanced strategy for MP.

Comparing the two types of machines gives that storage rings tend to have a stronger connection between accelerator reliability and beam availability, due to the inevitable downtime associated with each beam dump.

For linacs, on the other hand, accelerator reliability and beam availability are less intertwined in that there is no required downtime for each beam stop, which puts higher pressure on fast beam recovery after a fault. It goes without saying, however, that both types need to aim for high accelerator reliability figures for satisfactory operation.

ARCHITECTURE OF MP

The general architecture for modern MP is a set of local protection systems and monitors that send beam permit signals into a BIS, which combines the different beam permits into a global beam permit, allowing for beam operation. There are strict, hardwired connections between critical equipment and the BIS, together with a software layer for performance optimization.

To achieve successful MP, a post-mortem system that collects data from the faults that cause a beam trip is essential, as well as methods for early fault detection. Within the scope of MP, surrounding features such as preventive maintenance procedures are also included [12].

CURRENT STATE OF THE ART FACILITIES

LHC

CERN is a research organization that has put time, money, and effort into studies and analyses on how to achieve high accelerator reliability and beam availability numbers for systems related to MP [10]. LHC (operative since 2009) has a daisy chain beam interlock system design that has been successful in its performance. It contains a combination of hardware and software interlocks feeding beam permit signals into the BIS.

The detailed design of the MP at LHC received much attention prior to setup [10,13]. Much effort and simulation studies were put together in order to design a robust and reliable BIS as well as critical input systems. This has led to very few false beam trips and the architecture has been the foundation of other machines, such as Linac 4 and the European Spallation Source (ESS). As LHC has been operational over the past years, new ideas and solutions have arisen and been implemented, but the basic concept stays the same.

One of the major MP issues for LHC is the need to push the limits of the hardware in order to reach nominal energies. Each small increase in beam energy implies a higher damage potential that needs to be considered. Even though rigorous analyses were carried out prior to commissioning, some problems arose that were not accounted for and were hard to foresee. One of these is the so-called unidentified falling objects (UFO) [14]. These objects, presumed to be dirt particles, obstruct the beam path and cause beam losses.

To keep track of and analyze beam trips, the LHC implemented an e-logbook where the cause for each beam dump is noted down in detail. However, some faults are not immediately understood and often an expert is needed for providing a detailed analysis and finding the root cause. This is time consuming and sometimes happens several weeks after the actual fault. For the restart of LHC in 2015, there is an upgraded and automatic version of the e-logbook, which is believed to improve the performance of the post-mortem analysis [15].

In 2005, there were substantiated predictions made on the failure rate of a number of MP-relevant systems for the LHC. These turned out to be very accurate [16], and have been used as goals to meet and guidelines on how reliable a system needs to be. Through better understanding, dedicated tests, and more detailed simulations during the operational period, it has been found that some of the BLM thresholds were initially set too conservatively and that damage or quenches did not occur at the beam loss levels that were predicted. With this information, the dedicated BLM thresholds were relaxed, the sensitivity to false beam dumps was lowered, and the reliability of the machine went up.

SNS

SNS is a high-power (1 MW) neutron spallation facility that started its operation in 2006. It is a collaboration of six labs, involved in and responsible for different components and systems. The operational start of SNS was not preceded by rigorous MP analyses, which became apparent in the first years of operation. However, many improvements have been made during the operational period and accelerator reliability and beam availability numbers have increased steadily [17].

SNS took much of their MP design from previous experience of other laboratories [5]. However, as SNS greatly surpassed previous similar facilities in terms of beam power, there were many complications in the first years of operation. Many of which were due to the collaborative approach of six different labs responsible for different areas in the construction, integration, and coordination of the machine [18].

The SNS MPS uses the concept of a pilot beam, which is a pulse of less than nominal power that checks that everything is in order before full-scale operation is continued after each beam drop [5]. In addition, there is a beam parameter check between each pulse during regular operation, which makes sure that the maximum inter-pulse difference (MAID) of the beam parameters is not above threshold [3]. In case of mismatched beam parameters, the next pulse is inhibited from being injected to the linac.

The SNS MPS has a post-mortem system that collects data when neutron production is on, but only automatically saves the beam trip if it lasts longer than three minutes. There has been an effort to implement an e-logbook for storing fault information, but since this is not automized at this stage and is dependent on operators manually entering the information, it is partially incomplete [19].

It has been suggested that an automatic reset of the linac in case of a fault would be able to keep some downtimes below one second. As of now, there is instead a division into the fast protect system between the latched system (FPL), needing manual intervention, and the auto reset system (FPAR), doing what the name suggests [5]. There is also a duality for setting the beam loss thresholds, where the integration time for beam losses is set in the hardware, and the trip point limits and masking capabilities are set in the software, being EPICS [20]. The system itself is flexible in terms of possibilities to add and delete sensors and to bypass the hardware configuration using software inputs. This has helped in the commissioning of the machine, but also adds more complexity and lack of robustness in the machine protection system.

Other Facilities: CEBAF, SLAC, HERA, and J-PARC

For the Continuous Electron Beam Accelerator Facility (CEBAF), just as for Linac Coherent Light Source-I (LCLS-I) and II, flexibility in the beam interlock system has been a priority [21–23]. This has been a key feature in order to allow for changes and additions to be made on the system. The flexibility of the LCLS MP (both I and II use the same setup) allows for running in degraded mode by lowering the repetition rate of the pulses, in order to keep beam availability numbers up even when a fault is detected. As soon the fault is recovered, the beam is ramped up to nominal power [24]. However, the flexibility in LCLS has also made the beam interlock system and its connecting devices a complex matter, where there are four different kinds of link nodes and many layers included in the communication between the central link processor and the devices – with the need for a special team to support and maintain this system.

Throughout the operational period of the Hadron Elektron Ring Anlage (HERA), availability increases were sought after and achieved through preventive maintenance and improved fault diagnostics. Special attention was paid towards the new technology in the accelerator itself, and the final result was that there were actually more problems with the conventional systems, something that was claimed to be underestimated in the design. The beam interlock system had very low flexibility, which caused a lot of trouble combined with the old controls software that was 'reused' for HERA [25,26].

J-PARC has a clear hierarchical structure of the MPS, where a software control system layer is implemented to try to avoid MP actions and excessive use of the actuation system, in order to keep a high reliability and availability [27]. Prior to operation, J-PARC made detailed reliability studies on e.g. the klystrons, and found exact figures on the number of component failures per year [28]. They also found proofs that these component failures tend to follow an increased rather than a constant failure rate distribution.

RECOMMENDATIONS FOR FUTURE MP DESIGNS

From the experience of current state of the art accelerator facilities, the involvement of too many labs in the construction and delivery of equipment tends to lead to complications in terms of responsibility and integration. SNS experienced much trouble in the start with failing systems that had to be exchanged [29]. However, there is a general experience among accelerator facilities that the first few years are much worse in terms of reliability and availability [11,26,29]. As child diseases are cured, thresholds are adjusted, and the operations team has learned from previous mistakes and gets to know the machine, the numbers tend to increase.

There is also a tendency for unexpected faults and beam losses to occur, which were not accounted for in the pre-operational analysis – especially when beam energy and beam power is increased unprecedentedly. Examples are the UFOs in LHC and the slow energy deposit at SNS. These problems had to be accounted for once higher energies and powers were reached, and it is recommended that new machines stay aware and observant of unexpected beam losses. On the other hand, as with the HERA experience, a too comfortable approach towards less advanced conventional systems may also be a danger and lead to unforeseen downtimes.

Discussions on machine downtime issues often lead to the topic of lacking redundancy as an overall flaw among accelerators. Adding redundancy is one of the most frequent approaches to deal with unstable or error-prone equipment, such as power supplies and RF equipment [10,15,30]. It is also suggested that a well thought-through alarm handling strategy is implemented, in order to increase the effectiveness of MP.

The number of MP inputs is in the region of several thousands. Naturally, many of these inputs might fail or send spurious signals. To deal with this, especially during commissioning, a masking method should be present to make operation possible, even with equipment firing erroneous signals [12].

CONCLUSIONS

The different ways of stopping beam operation for storage rings and linacs give different relations between accelerator reliability and beam availability, where storage rings have a closer connection between the two. It is found that rigorous analyses before commissioning of an accelerator is very beneficial to the accelerator reliability, and expert experience from other facilities can only be a first top-level prediction of the design.

Newer facilities have unprecedented beam powers and energies and the upcoming faults are difficult to foresee. This needs to be considered, and planning for redundancy at an early stage is crucial to have successful operation. It is also recommended to stay observant of unexpected problems, as higher beam powers are reached. This should be dealt with using a well-designed alarm handling system, and making good use of post-mortem analyses.

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