MACHINE PROTECTION STRATEGIES FOR HIGH POWER ACCELERATORS*

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Abstract

The Machine Protection System Requirements for a number of accelerators have been reviewed. The specific requirements vary depending on the type of machine, beam power, pulse length, etc. Some system concepts are common to a number of accelerators and these systems will be discussed. The Machine Protection System (MPS) must protect beam apertures and insertable devices from damage, minimize radiation produced by the beam (ALARA) for hands on maintenance, and shut down the beam when beam-on-target parameters drift outside specifications. MPS systems should be used as an Accelerator diagnostic. MPS can trigger data acquisition when a fault occurs, and start post mortem applications automatically. Tight integration with timing and other systems allows automatic recovery from beam faults.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy

INTRODUCTION

Machine protection systems have evolved from simple interlock systems to complex systems combining slow interlocks, fast interlocks to inhibit beam or trigger abort sequences, and sequences for automatically returning the accelerator to normal operation. MPS has to be fully integrated with global timing systems, adjacent MPS systems, beam diagnostics systems, RF systems, Control Systems, and others. Additionally, most new systems involve post mortem analysis to help sift through Gigabytes of data and pinpoint the cause of a failure or cause of drifting beam optics. High availability requirements, over 95% for SNS, dictate automation of recovery processes after an MPS fault.

In this paper we will discuss the role of MPS in:

1. Protecting the Machine
2. Protecting the Beam
3. Providing the Evidence
4. High Power Target protection; and
5. Assisting operations

PROTECT THE MACHINE

New accelerator facilities will have unprecedented beam power and beam power densities. The challenges presented depend on accelerator type, particle type, peak currents, maximum beam energy, etc. Spallation sources run loss-limited with high peak and average current on target. Linear colliders have very high current densities where a single errant pulse can cause considerable damage. Large hadron colliders have large stored energies in both beam and superconducting systems, both of which can damage beamline components and superconducting magnets. X-ray machines can damage the vacuum system by slight misalignments in wigglers, etc.

SNS will run in a loss-limited mode. Uncontrolled beam loss specifications are less than 1 W/m, or 10^{-4}. Collimation systems are designed to intercept beam in the linac where high losses are expected, or for halo cleaning. The total uncontrolled beam loss [2] in the SNS accumulator ring is compared with several other high current rings in Table 1. Some rings show large losses, but the injection rates are slow so the losses are allowable. At PSR the 0.3 % becomes significant due to the high-energy injection and 20 Hz operation. The beam loss goal for the SNS ring is very low at 0.01% but this is required for hands-on maintenance and availability reasons.

Table 1. Comparison of several rings, energies, peak currents, and beam loss.
(1) Accumulator rings, others are Rapid Cycling Synchrotrons
(2) Septum injection. Others are foil.

Machine	Einj	Eext	# Turns	Typ Ppp	Loss (%)
ISIS	70	800	300	1.6e13	10
PSR (1)	800	800	2300	3.1e13	0.3
KEK-PSB	40	500	50	2.0e12	10
FNAL-B	400	8000	15	2.0e12	30
AGS-B	200	1900	200	1.5e13	28
IPNS	50	450	140	3.0e12	17
CERN-PSB (2)	50	1400	15per ring	1.0e13	50
SNS (1)	1000	1000	1060	1.5e14	0.01

Neutron sources such as SNS, ISIS, and LANSCE use H^- sources to produce high-accumulated beam currents to strike a target in a short amount of time. SNS for instance accelerates 1060 turns at peak currents up to 38 ma. The H^- ions are stripped as they are injected into the accumulator ring, building up to 50 Amps peak. Extraction kickers are fired in the beam gap to steer the proton beam down the extraction line to a liquid mercury target to produce neutrons through spallation.

Linear colliders require very small beam size and high peak current to meet luminosity requirements. A single errant pulse will cause component damage if extracted from the damping ring. Recovery from faults requires the system to drop back in state and use pilot pulses. The systems have to measure pilot beams with sufficient accuracy, stability, and resolution for feedback systems to work properly. Pulse-to-pulse monitoring of beam parameters requires control system latencies much less than the beam repetition rate. Collimator design is critical to intercept the high power pulsed beam [3]. Use of the control system to monitor the properties of the beam pulse-to-pulse implies the control system is a "pulsed" control system.

Hadron colliders have very high stored energy in the beam and the superconducting magnets, 13 GJ per sector for the LHC [4]. Beam losses can cause damage due to radiation and thermal effects. The stored energy in the beam is high enough to damage any component in the ring if the beam is not cleanly aborted. Beam abort systems must dump the beam before the beam trajectory changes and inhibit beam until the quench completes and the magnetic field is restored. Recovery from beam dumps can take a couple of hours. Recovery from magnet system quenches can take several times longer. Light sources also have high currents and small beams. Besides damage from the beam, upwards of 10 kW in the x-ray beam can damage the vacuum chambers. Beam diagnostics are thus required to monitor the e+/- beam position and X-ray beam. At the APS for instance, beam position monitors average 32 turns of beam position data on a turn-by-turn basis and will abort the beam in 300 usec by disabling ring RF if measurements indicate beam position errors.

Fast Machine Protection Inputs

Beam Diagnostics are the main input to fast MPS systems. Beam loss monitors detect beam loss that can cause radiation and thermal damage to equipment in the beam line tunnels. Component damage depends on the beam energy, beam current, and current density.

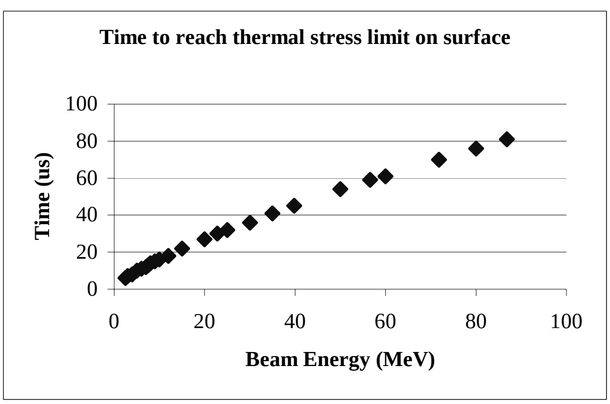

Figure 2. Time to reach the thermal stress limit in copper verses beam energy.

For SNS, damage will occur faster at lower energies [5]. Figure 2 shows the time to reach the thermal stress limit for copper assuming $\sigma_x = \sigma_y = 0.2$ cm, I = 36 ma, J = 62 J/gm (energy density). The time to reach the thermal stress limit at the bragg peak is quicker, however the peak energy deposition depth is dependant on beam energy and quickly goes beyond the thickness of the copper walls.

For low energy beams, differential current measurements are desired for fast beam loss detection [6]. A system using toroidal transformers was designed for the Tesla Test facility to provide a fast beam shutoff when the average loss exceeds 0.8 μa over the nominal 64 μa nominal machine current.

CW accelerators such as CEBAF [7] use beam current monitors for beam loss detection and beam current limits. The current monitoring system provides three functions:

1. Fault if beam loss exceeds loss limit.
2. Fault if current exceeds limit for an experimental hall.
3. Fault if current exceeds beam off threshold for multi end station operation.

The 2nd generation machine protection Beam Current Monitor / Accounting system was designed specifically for machine protection.

At higher beam energies, beam loss monitors are preferred. There are many publications available [8] on the topic of beam loss monitors. MPS systems typically receive faults from peak loss (within a pulse), integrated loss for a pulse, or integrated loss over many injection cycles or turns. Machines such as SNS, ISIS and TTF run loss-limited and need to keep losses below 10^{-4} for hands on maintenance. Superconducting accelerators such as the LHC will be affected by beam loss at a fraction of 10^{-8} of the beam [9]. Systems like the LHC use loss monitors for protection of the beam as well as protection of the machine. A beam dump due to a quench takes much longer to recover from than a beam abort due to increased losses.

Beam Position Monitors (BPM) are crucial for MPS systems in storage rings and linear colliders. Storage rings average beam position over a number of turns to determine if the closed orbit is exceeding some threshold. Beam abort is initiated to protect ring components from damage, or vacuum systems from damage due to mis-steered X-ray beams. In new collider designs, a pilot beam is used to verify beam optics for full power beam. The beam position monitors must have sufficient sensitivity to monitor these low intensity beams to accurately predict if the high power beam will be accelerated without damaging beam line components.

Machine operation and commissioning can continue without beam diagnostics however MPS function could be compromised. Systems that will be used for MPS should be designed with those goals from the beginning. Beam diagnostics for machine protection should be designed with some or all of the following system requirements, dependant on machine:

- Fail Safe Design, detects internal faults, cable connection status, power supply faults, etc.
- Remote self test and calibration capability, interpulse test functions (Force a fault between pulses)
- Controlled access to threshold settings
- Heartbeat from timing system
- Machine / beam mode aware
- Circular buffers, waveforms on demand
- Pulse-to-pulse or turn-by-turn (Deterministic)

As stated before, SNS will accumulate 1060 turns in the ring before extraction. There is a 250 nsec gap in the beam to allow the kicker system to ramp to full power. Any beam in the gap will be uncontrolled loss in the ring and extraction line. The goal is to keep the gap clean to less than $1x10^{-4}$ of the injected current. With up to 50 amps circulating, this is a measurement range of greater than $1x10^{6}$. Several methods are being investigated. A beam-in-gap kicker will kick beam onto a collimator monitored by a fast loss monitor. A new technique used to monitor low currents for beam-in-gap measurements is the laser profile monitor, Figure 3 [10]. Electrons are measured on a collector after being deflected by a small dipole magnet.

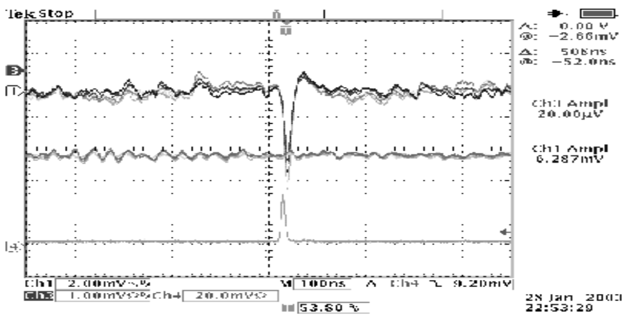

Figure 3. Beam-in-Gap measurement made by a fast laser pulse. The measurement above show about 60 ua of beam measured in the beam tail. Improvements in the amplifier design should bring the resolution below the 10^{-4} level.

Types of Machine Protection

A survey of several accelerators of different types show the following types of Machine Protection Systems (not all accelerators have all the systems) are implemented or are being designed. The names vary depending on the facility. Larger accelerators have several MPS systems, one per machine section. These need to be integrated with each other and other systems at a high level.

1. Average Machine Protection
2. Fast Protect
3. Beam Accounting
4. Maximum Allowable Intrapulse Difference (MAID) (and prepulse)

Average Machine Protection

The Average Machine Protection uses slow inputs from vacuum systems, power supply systems, etc for slow interlock inputs. Faults due to these inputs will cause damage due to mis-steering, defocusing, or intercepting the beam and the beam is inhibited until the fault is cleared. Systems will either mask these types of inputs from beam lines not in use using a Machine Mode indication, or the various beam lines are a subsystem in themselves, and are summed in a master MPS system. Some facilities allow masking of these under special circumstances, such as machine commissioning, BPM studies, beam-based alignment, etc. Other facilities hard code these inputs into PLC logic, FPGA logic or software and require repairs before the machine can be brought on line.

Fast Protect Systems

Fast Protect systems fall into three categories, turning off the beam as soon as possible, prohibiting beam from being injected to the next part of the accelerator or aborting the beam from a storage / accumulator ring. For long pulse accelerators, the mechanism is turning off the source. Electron storage rings may turn off the ring RF, allowing the beam to coast inward to collimators in the ring as the beam loses energy due to synchrotron radiation. Large hadron accelerators use fast, high reliable kicker systems to kick the beam out of the ring to a beam dump designed to handle the high power in the beam. Linear colliders must prevent an errant pulse from being launched into the accelerator, as an errant beam will cause damage and there is no way to prevent damage once the pulse is injected, because the monitoring signal can not catch up to the beam and abort systems.

SNS has two fast protect systems, Fast Protect Latched (FPL) and Fast Protect Auto Reset (FPAR). The hardware is the same; the FPGA logic is slightly different. Both have a maximum shutdown time of 20 usec, although it is faster closer to the source due to fewer IC propagation delays and shorter cable distances. There are two bypass mechanisms for the MPS hardware: software masks initiated by an operator (if enabled using hardware jumpers) and beam/machine mode masking through the timing system. Beam/machine modes are broadcast on the Real Time Data Link (RTDL) and will automatically bypass certain MPS inputs for diagnostic pulses to allow intrusive diagnostics to operate without operator intervention. The mode masks are downloaded during initialization, and verified periodically during operation. The beam/machine mode is encoded three ways in a 24-bit frame. There is an 8 bit CRC check of each frame. In addition, there is a 24-bit CRC frame for all RTDL frames broadcast in a cycle. The MPS hardware also uses the CYCLE_START event and the RTDL_VALID events for heartbeats indicating the timing system is healthy and stale modes are not used. The probability of detecting an erroneous mode broadcast on the RTDL using the two CRC checks, and encoding the data in three ways is better than 99.999994% [11].

Fast protect systems for linear colliders prevent errant beams from being launched into the accelerator. Once a pulse is launched, there is little to be done to protect the machine, except to design collimation systems to handle the beam. This is very difficult to impossible so some engineering is under way to design "sacrificial" collimator systems.

Beam Loss monitors at HERA often have the last chance to recognize a doomed beam and abort it safely before uncontrolled and possibly damaging losses occur.

Beam Accounting

Beam Current Accounting and Beam Loss Accounting are required for monitoring integrated losses and warning operations when loss limits are approached. Some systems will shut down the machine as the limits are reached. Beam loss and accounting are used to stop beam-induced radiation damage before it occurs. Some machines like CEBAF at JLAB have beam loss accounting to limit power to the various experimental halls. These limits are set by power limit requirements for the experimental devices (spectrometers) and the beam dumps in each experimental hall.

Beam Loss monitors and beam current monitors are used in these systems. Beam loss monitors can pinpoint the beam loss better than current monitors, but calibration for absolute losses is harder due to the particle types, equipment shielding the detector, etc. Beam current monitors can be calibrated to a high degree of accuracy [CEBAF, TTF], but they can also be "fooled" by opposite charged particles or beam spray after beam loss.

Maximum Allowable Interpulse Difference (MAID)

MAID was originally designed to monitor orbit stability using BPM's and abort the beam if the orbit starts drifting outside allowable limits. In this case it is a turn-by-turn difference rather than an interpulse difference. It was planned for the Tevatron [12] but not really used. Complexes such as PEPII are using the MAID principle.

MAID requires previous pulsed data to be verified from the accelerator physics point of view-- that is the data fits within an ellipse defined by the beam envelope in the accelerator. This applies to beam position monitors, beam loss monitors and device control monitors [13]. Just prior to injection all systems that can change the beam trajectory or beam energy are verified to be operational. This prepulse system gives a final beam permit signal to allow beam. Beam is also monitored in damping rings or injection systems that will abort errant beams before being injected.

For accelerators depending on MAID, any intermittent faults require the injected beam to be brought to a low power state in the injection sequence. In order for full beam to proceed, an automated sequence to bring the beam back on line should be initiated. These procedures require integration of a number of systems, MPS between injectors, damping rings and accelerators, timing system sequences, control system feedback loops, feed forward algorithms, and timing systems. The complexity speaks for itself.

PROTECT THE BEAM (AVAILABILITY)

Protecting the beam is a goal for all accelerators desiring high beam availability. SNS goals are >95% availability at full power for production beam. Beam down time is increased unnecessarily when MPS provides false trips, or input devices provide nuisance trips. The MTBF decreases as the number of MPS inputs increases. For instance, the MTBF for inputs to the LHC have to exceed 200 years to meet the goal of less than 1 trip per 2 weeks.

Experience at LANSCE and the PSR have determined that losses of 1 W/m will allow hands-on accelerator maintenance (~100mR/hr at 1 foot), with transverse losses primarily at quadrupoles where the beta-max occurs [14]. Meeting the ALARA limits for hands-on maintenance will increase machine availability by reducing the time to repair.

Software masking of inputs allows components in the down slope of a bathtub curve to be identified during the commissioning process and masked out to increase beam time. If the component or device is not deemed critical for steering and focusing, it can be masked during operation until a suitable time for repair occurs.

PROVIDE THE EVIDENCE

MPS Faults should post Abort or Fault events locally or globally through the timing system. Control system devices, beam diagnostics, and pulse systems use these triggers to freeze circular buffers and provide waveforms of the interrupted pulse. Post mortem analysis will identify first faults using timestamps from MPS input faults.

Using a correlator tool, such as the XAL Correlator package developed by the AP group at SNS, faults can easily be captured and sorted by time (figure 4). Using the hierarchy provided, these faults can trigger capture of waveforms and slow data buffers depending on the location and type of the machine fault. This will help reduce data sorting from Gigabytes to Megabytes.

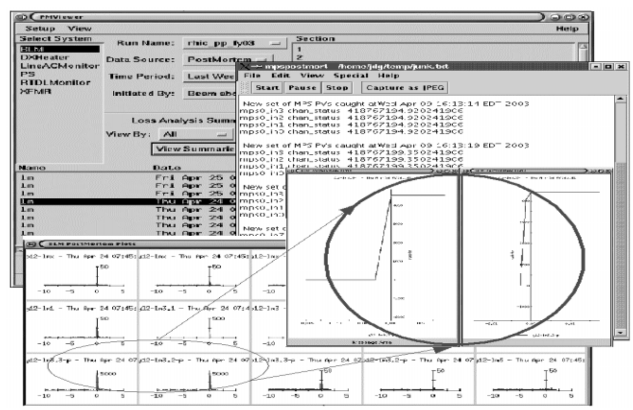

Figure 4. Typical Post Mortem displays for quick identification of MPS faults and root analysis. (RHIC Example)

The application will bring up the data post processed by:

Event	User Pulse	Sub System
Time Stamp	MPS Fault	Peak Loss
Timing Event	System	Data Excursion

Standard displays built into XAL include waterfall, XY correlator, 2d and 3d, Strip charts, phase space parameters, and difference from model, yesterdays beam, etc.

HIGH POWER TARGET PROTECTION

At SNS, the target requirements for errant pulses is less than 2 full power pulses for beam power within the nominal spot size (50% beam power outside of 200 mm x 70 mm) and for peak single pulse current density < 3.2×10^{16} protons/m^2.

Accelerator Physics fault studies have determined which quadrupoles could cause target parameters to be exceeded. In the majority of cases, large beam losses are predicted when the target parameters are exceeded [15]. Standard monitoring of RTBT beam line elements (On-Off), and loss monitor inputs provide a first level of defense. Redundant inputs are chosen from the AP studies where beam loss monitors and power supply status cannot monitor losses. These magnets are chosen for redundant input using current window monitoring for the power supply.

Accelerator physics models and commissioning results using wire scanners, harps, beam loss monitors, and beam position monitors define acceptable pulse-to-pulse windows for MAID. Control system performance needs to be verified for latency and Quality of Service (QoS). A single control system network should be sufficient but a second high QoS network can be added in the future if required.

OPERATIONS

The operator interface for MPS should make faults easy to locate, reset, and startup reset routines. During initial commissioning, faults are located manually or (preferably) using post mortem tools. As commissioning proceeds into operations, the fault discovery process is automated and operators note the number and type of fault in the logbooks.

Three types of interface screens are being implemented at SNS. A system overview screen shows the status of all MPS Machine Mode chains. An interlock view shows the MPS system where the chain is broken. Clicking down this screen path shown each MPS input and MPS chassis status from an MPS engineers point of view.

A machine-oriented view allows operations to link the fault to a location on the beam line. This allows device specific screens to pop up device status, cause of device fault, device reset functions, and MPS reset functions. Input masking is available at this level as well as the setting of chatter fault (N faults in M pulses) limits. A system status view is also offered showing MPS inputs by system and subsystem.

Each of these displays is highlighted in a fault condition. The operations group will eventually develop high-level screens to their taste. Other EPICS tools like the Alarm Handler also show MPS faults in a hierarchical manner.

CONCLUSIONS

Machine Protection is not just a system to shut off beam like an interlock chain. MPS needs to be tightly integrated with local MPS, global timing systems, global controls, beam diagnostics, and fast abort systems. Startup sequences can be very complex to automate bringing the beam online after an MPS fault Control systems used to provide pulse-to-pulse beam permit signals become a pulsed control system. Network infrastructures need to be provided to allow this functionality. Post mortem systems triggered by MPS will help operations recover from faults. Automatic recovery will further increase the availability of the machine. MPS should become a machine diagnostic tool, integrated with other systems to maximize availability and pinpoint failures for operations.

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