Development of a Machine Protection System for the Superconducting Beam Test Facility at Fermilab *

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Abstract

The Fermilab's Superconducting RF Beam Test Facility currently under construction will produce electron beams capable of damaging the acceleration structures and the beam line vacuum chambers in the event of an aberrant accelerator pulse. The accelerator is being designed with the capability to operate with up to 3000 bunches per macro-pulse, 5Hz repetition rate and 1.5 GeV beam energy. It will be able to sustain an average beam power of 72 KW at the bunch charge of 3.2 nC. Operation at full intensity will deposit enough energy in niobium material to approach the melting point of 2500 C. In the early phase with only 3 cryomodules installed the facility will be capable of generating electron beam energies of 810 MeV and an average beam power that approaches 40 KW. In either case a robust Machine Protection System (MPS) is required to mitigate effects due to such large damage potentials. This paper will describe the MPS system being developed, the system requirements and the controls issues under consideration.

Introduction

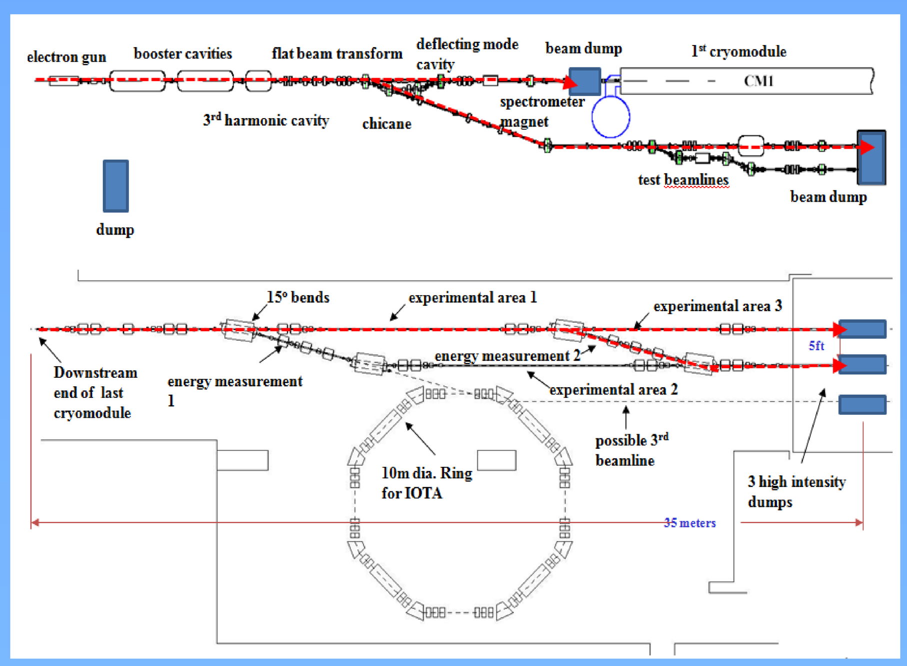


Figure 1 : Machine Layout of SRF Test Beam Facility

The beam at Fermilab's New Superconducting RF Beam Test Facility [1], when operational, will need systems to protect critical components from beam induced damages such as beam pipe collision and excessive beam losses. The MPS must therefore identify hazardous conditions and then take the appropriate action before damage is caused. Since the loss of a full bunch train can result in significant damage, the MPS must be able to interrupt the beam within a macro-pulse and keep the number of bunches below the damage potential once the protection system reacts; the goal is to keep the number of bunches on the order of 3-6 bunches. With the high possible bunch frequency of 3 MHz this necessitates a reaction time in the range of 1-2 μs with cable delay included for the 134 metre long machine. The MPS will use the status of critical sub-systems and losses measured by a fast Beam Loss Monitor (BLM) system, using scintillators and photomultiplier tubes (PMT) to identify potential faults. Once a fault is observed, the MPS can then stop or reduce beam intensity by removing the permit from different beam actuators, including the laser pulse controller.

Parameter	ILC RF unit test	range
bunch charge	3.2 nC	0.05 nC to >20 nC
bunch spacing	333 nsec	<12 nsec to 0.1 sec
bunch train length	1 msec	1 bunch to 1 msec
bunch train repetition rate	5 Hz	0.1 Hz to 5 Hz
norm. transverse emittance	~10 mm	~1 mm to ~50 mm
RMS bunch length	1 ps	100 fs to 20 ps
peak bunch current	3 kA	10 kA
injection energy	40 MeV	5 MeV to 50 MeV
high energy	810 MeV	40 MeV to 1500 MeV

Table 1: Beam Parameters

Protection System Overview

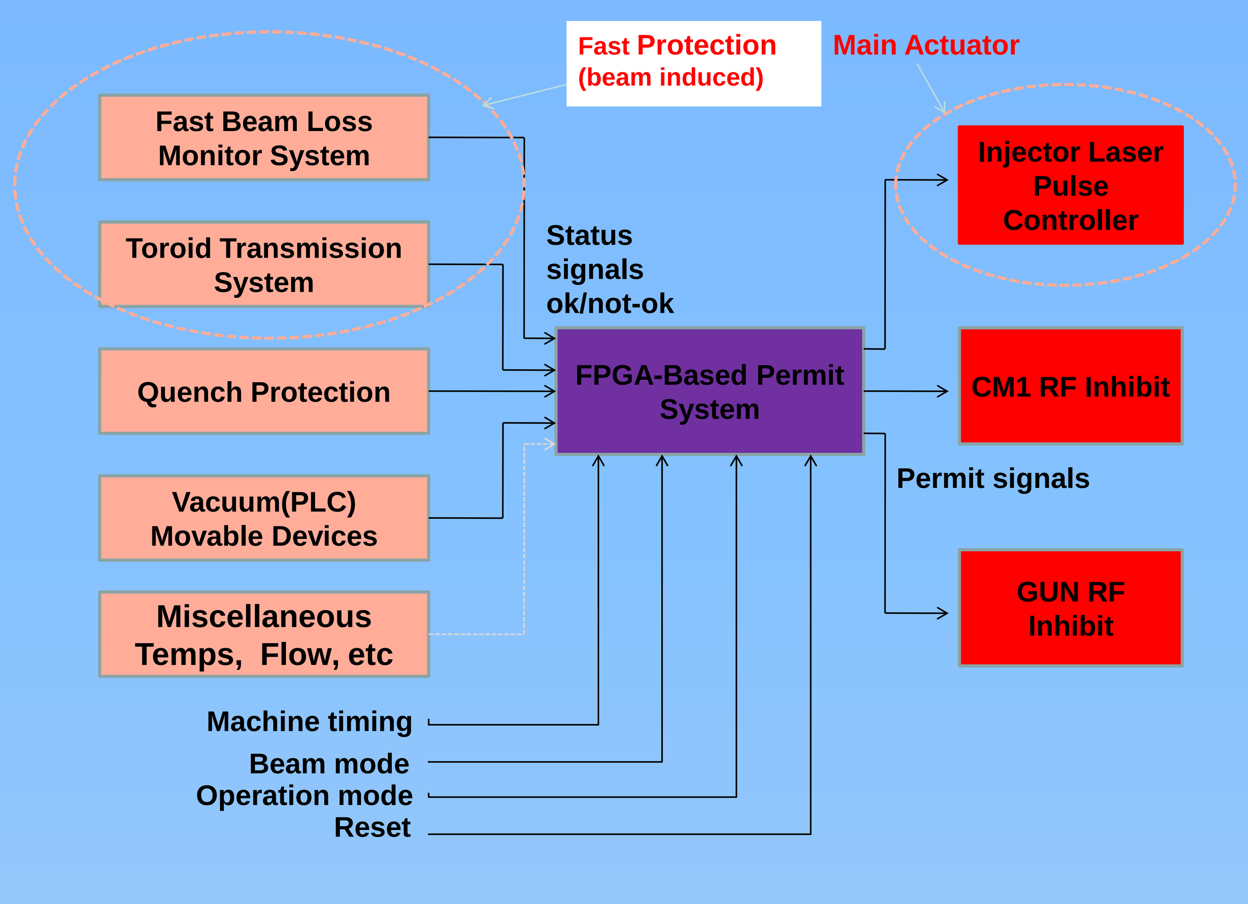
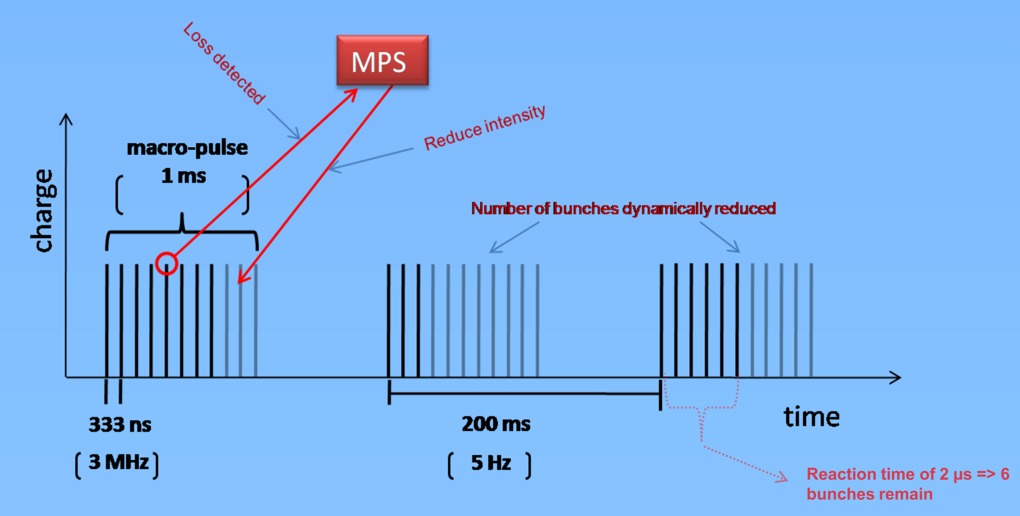


Figure 2 : MPS Overview

The simplified overview block diagram of the proposed MPS is shown in Figure 2. The MPS has connections to several external devices and sub-systems. The top layer comprises signal providers such as fast beam loss monitors, RF signals, quench protection, toroid transmission, vacuum, magnet power supplies and more. All devices or subsystems that are determined to be pertinent to protecting the machine or necessary for machine configuration are included here. The state of the machine is determined from this comprehensive overview of the inputs and allowable operational modes are determined based on this information by the middle logic layer. The main goals for the MPS system as a whole are:

- Provide precise protection of all critical components by first determining the fault severity (high, intermediate, etc) and then taking the appropriate action to avoid damage.
- Allow for high availability by ensuring that the maximum requested beam intensity is allowed for the detected fault severity.
- Monitor MPS components and perform periodic self-checks in order to ensure robustness and a high level of reliability.
- Provide well-integrated, user-friendly tools for fault visualization, control and post-mortem analysis.



MPS should allow the machine to be up most of the time for user operations:
We could dynamically reduce the intensity by some factor based on the type of loss, where it occurs and no. of trips. Do this until we are below damage limits.

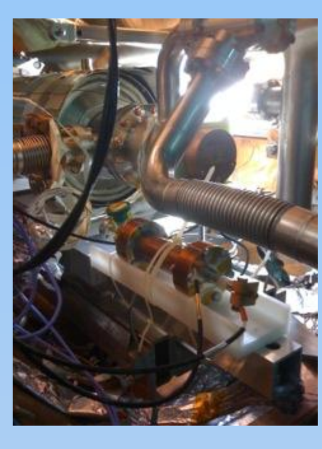
Fast Beam Loss Monitors

Several types of beam loss monitors (BLMs) will be used for the detection of electromagnetic showers. The fast protection system is being designed to interrupt the beam within a macro-pulse and will rely heavily on the ability to detect and react to losses within a few nanoseconds; for this reason the primary loss monitors for fast protection are made of plastic scintillator with photomultipliers attached and have already been designed, built and tested. Figure 3: shows some measurement results.

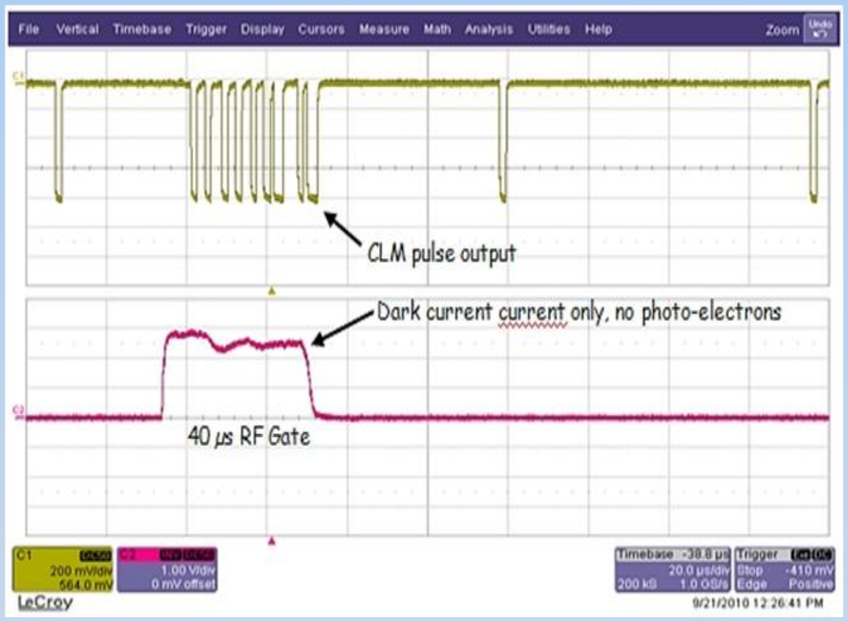
Figure 3 : FBLM Showing pulsed beam loss

EJ208 Scintillator properties	Value
Rise time	1.0 ns
Scintillator Brightness	76 p.e./ MeV
Wavelength of max emission	435 nm
Detector sensitivity	7.0 pC/Mev
Decay time	3.3 ns
Density	1.023 g/cc
Light attenuation length 1/e	210 cm
Number of electrons	3.37/cm³
	PMT Specifications
Rise time	3-5 ns
Gain (min)	2.7×10^5
Supply voltage (max)	2000 volts
Sensitivity	0.1 – 200 A/lm

Cryogenic Loss Monitors



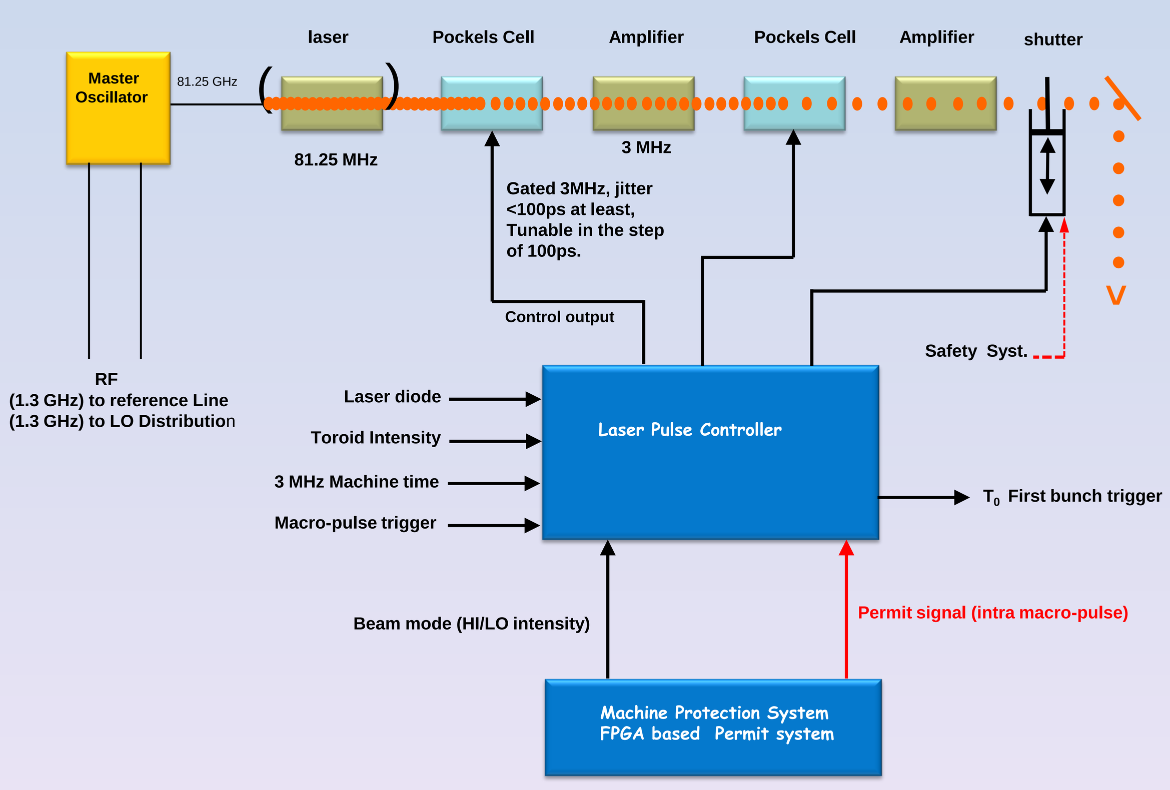
Although loss monitors are typically one of the main diagnostics for protecting the accelerator from beam induces damage. Most accelerator facilities do not cover the cold sections of the machine with loss monitors. To address these issues a Cryogenic Loss Monitor (CLM) ionization chamber capable of operation in the cold sections of a cryomodule has been developed and will be installed and tested [2]. The monitor electronics have been optimized to be sensitive to DC losses and the signals from these devices will be used to study and quantify dark current losses in particular, see figure 4. In order to increase the resolution bandwidth and the response time of the devices a new scheme which uses a Field Programmable Gate Array (FPGA) based Time-to-Digital converter (TDC) method is implemented [3] instead of a standard pulse counting method.



Parameter	Symbol	Min	Typ.	Max	Comment
Mechanical					
He-volume	V		120 cm³		
Fill pressure	p		1.0 bar		absolute
Diameter			2.73 inch		without shroud
Length			11.2 inch		without shroud
Detector Operation					
HV			-95 V	-120 V	on chamber body
Sensitivity			1.9 pA / (Rad/hr)		calculated
			6.84 nC/Rad		calculated
Electronic I/O					
Ballast resistor	RB		1.0 MΩ		safety resistor
Supply voltage	Vdd	4.5 V	5.0 V	5.5 V	
Supply current	Idd		105 mA		
Charge per pulse	Qp		**2.286 pC**		
Frequency out	f		**0.831Hz / (Rad/hr)**		after offset of 100 Hz nominal
Offset current	Ioff		100 pA		
Offset current drift	dIoff/dT			10 pA/K	
Environmental					
Operating temperature	T	5K		350K	chamber only
Magnetic field				TBD	

Figure 4 : reaction of CLM to dark current losses

Laser Pulse Control



- Block the Pockels cell based pulse kickers as long as the MPS input is in an alarm state.
- Enforce the limit on the number of bunches as given by the currently selected beam mode.
- Close the laser shutter on request of the MPS. This may happen when there is no valid operational mode or when some combination of loss monitors exceed thresholds which trigger a dump condition.

One of the main actuators for the MPS is the injector laser pulse control. This will be the device that controls the number and the spacing of bunches in a macro-pulse by picking single laser pulses out of a train. This is achieved by manipulating the Pockels cell (voltage-controlled wave plates). This system is also the main actuator for beam inhibits issued by the MPS. It is envisioned that this would be a VME board with a fully programmable FPGA.

Controls System

The MPS will need server support for the various hardware systems to View, Configure and Diagnose the system. Already there are currently several servers under development for the beam loss monitor system and the laser pulse controller. These servers were implemented using the PowerPC 5500 series boards running VxWorks 6.4 and implementing the ACNET protocol. Some of the main requirements for these servers include:

- Time-stamping at a sub-microsecond resolution in order to allow for data correlation.
- Circular buffers that are logged using ACNET data loggers and thus provide a repository used for post-mortem analysis.

A control system that is well integrated with all MPS components, from the various front-ends to the high level applications, is critical to leveraging the full functionality of that control system.

Summary

Significant effort is underway towards developing a reliable MPS for this new facility. System integration and commission challenges lay ahead.

References

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[2] A. Warner and J. Wu, "Cryogenic loss monitors with FPGA signal processing", Fermilab preprint FERMILAB-PUB-11-467-AD
[3] J. Wu, et al. "ADC and TDC implemented using FPGA", IEEE Nuclear Science Symposium Conference Record 2007;1:281–286