

COMMISSIONING AND DESIGN OF THE MACHINE PROTECTION SYSTEM FOR FERMILAB'S FAST FACILITY*

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Abstract

The Fermilab Accelerator Science and Technology (FAST) Facility will provide an electron beam with up to 3000 bunches per macro-pulse, 5Hz repetition rate and 300 MeV beam energy. The completed machine will be capable of sustaining an average electron beam power of close to 15kW at the bunch charge of 3.2nC. A robust Machine Protection System (MPS) capable of interrupting the beam within a macro-pulse and that interfaces well with new and existing controls system infrastructure has been developed to mitigate and analyze faults related to this relatively high damage potential. This paper describes the component layers of the MPS system, including a FPGA-based Permit Generator and Laser Pulse Controller, the Beam Loss Monitoring system design as well as the controls and related work done to date.

INTRODUCTION

The FAST Facility comprises an electron injector based on the Advanced Superconducting Test Accelerator (ASTA)[1], a radio frequency quadrupole (RFQ) based proton injector and the Integrable Optics Test Accelerator (IOTA) storage ring. The electron beam is produced by a 1.3 GHz RF photo-injector and then accelerated to ~50 MeV by two 1.3 GHz SRF cryomodules, each containing a single 9-cell cavity. The beam will then be injected into the linear accelerator which consists of a 12-m long, 1.3 GHz 8-cavity superconducting cryomodule (CM2). This is a Tesla type III+ cryomodule[2] driven by a 5 MW klystron. The electron beam energy gain will be approximately 300 MeV at this stage.

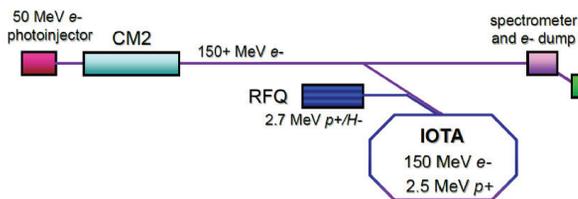


Figure 1: Schematic of FAST Facility.

The facility is also being expanded to accommodate further advanced accelerator research and development with the installation of a 2.5 MeV proton/H- RFQ accelerator. This accelerator starts with a 50 kV, 40 mA proton (or H-ion) source coupled to a pulsed 325 MHz RFQ to 2.5 MeV with a 1ms pulse duration for injecting into IOTA. This ring is 39 meters in circumference and will also be capable of storing electrons from 50 MeV to

150 MeV in energy. Figure 1 shows the placement of the ring in the FAST facility layout.

The Machine protection System (MPS) is being developed in stages that are commensurate with the commissioning goals for FAST. The primary objectives from the MPS point of view are to mitigate beam induced damage to the machine components and to provide a comprehensive over-view of the entire accelerator based on the input status of all the relevant subsystems [3].

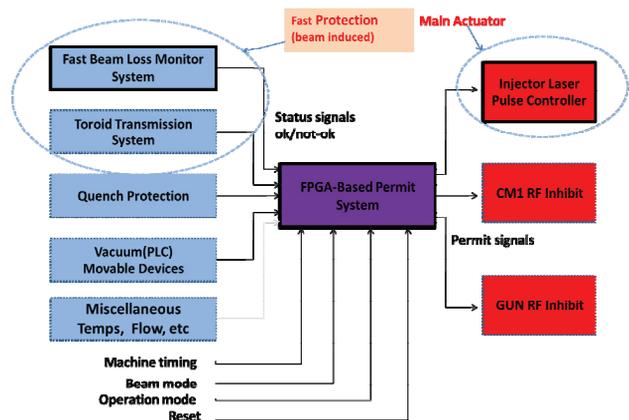


Figure 2: MPS Overview.

Figure 2 illustrates the overall MPS design which is divided into 3 layers; a sensor layer to collect sub-system status, a process layer that utilizes the status to generate the permits and an actuator layer to receive the permits and inhibit the beam. The initial stage of this development involved the design of the Laser Pulse Controller (LPC).

LASER PULSE CONTROLLER

The LPC is designed to be the primary actuator for beam inhibits. Its main function is to provide a gate to the gun laser system via the Pockels cells with a width that corresponds to the total number of 3 MHz pulses allowed without crossing the programmable threshold for losses. The maximum width of the gate is 1 ms which would accommodate a maximum of 3000 bunches. It is designed to inhibit the system within the 1ms macro-pulse window. The response time of the system has been demonstrated to be $\ll 1$ microsecond corresponding to less than 3 bunches in the machine. The LPC also provides a number of timing channels to the accelerator complex including a pulse which corresponds with the arrival of the first bunch; so-called first bunch trigger. This is an adjustable trigger delay with < 40 ps of jitter and tuneable to steps of

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100ps. The laser itself operates continuously at 3 MHz with 200 fs of intrinsic jitter. The LPC is built on a VME platform with a fully programmable general purpose FPGA board. It has inputs for the requested beam modes (intensity limits) defined by the logic layer of the MPS, the operational modes (which defines the beam paths in the machine), the MPS permit signal, the 3 MHz machine timing, and a macro-pulse trigger. It also has ability to control a mechanical shutter used to block laser light from reaching the cathode when it's necessary.

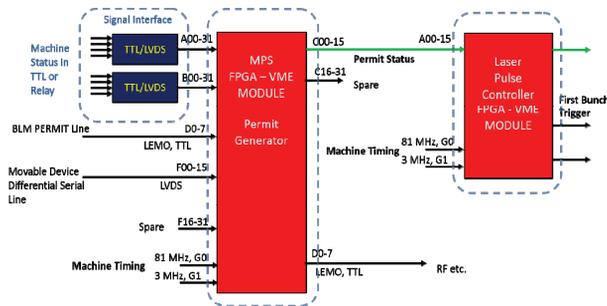


Figure 3: MPS FPGA block diagram.

MPS MAIN PERMIT SYSTEM

The main MPS permit generator board is the central component of the system that serves to collect status (OK/Not-OK) information from the various machine subsystems. The information is used in conjunction with user input such as operational mode and beam mode requests to generate a permit condition. The subsystems interface with the system through several modules that are designed to maintain signal integrity and provide noise immunity by converting input signals to Low Voltage differential signal levels (LVDS).

The permit system is built on a general purpose FPGA board designed to take advantage of its expandability and customizability. The boards can be programmed “on the fly” via VME without any external hardware tools and without disconnecting the boards from the system, and without resetting the system or turning off the crate. A flash memory on the boards stores the programming file.

The boards have been organized into functional blocks to accommodate various input signal types. Machine status signals in slow TTL or relay contact logic levels from vacuum PLCs etc. are converted into LVDS format and sent to ports “A” and “B”. Movable device status is encoded onto a serial differential link and fed into half of port “F” and beam loss monitor status, which is critical for fast protection is fed into “D” port via a 30 MHz carrier pulse train. Output signals to the LPC are received via port “C” and several other TTL output signals are provided via the port “D” for RF inhibits and test monitoring via oscilloscope. In addition to this, several ports allow for future expansion. Individual subsystem and channels can be masked directly at the hardware level or via configuration control software based on modes.

BEAM LOSS MONITOR SYSTEM

The beam loss monitors (BLMs) are the primary protection devices against fast losses and are designed to protect the machine by inhibiting the beam or limiting the beam intensity in response to losses above damage threshold levels. In addition, the same loss monitor signals are also used for beam tuning and diagnostics. The monitors are made of plastic scintillator material coupled to photo-multiplier tubes (PMTs). They deliver a measurement of beam and dark current losses to the control system as well as generate a fast alarm signal when the beam losses exceed user-defined thresholds. The time resolution of the loss measurement provides the ability to distinguish single bunches within each macro pulse. This is achieved at the sampling frequency of 3 MHz (the bunching frequency of the machine) with a repetition rate of 5 Hz. Including cable delays; the interruption signals from the system are generated within 1µs after the loss has occurred during commissioning to the 50 MeV beam dump. Since dark current and beam can only be produced during the RF pulse of the gun and the acceleration modules, it is sufficient to monitor a time window slightly longer than 1 ms per macro-pulse interval; however for alarm generation, continuous monitoring was done to minimize the dependency on time.

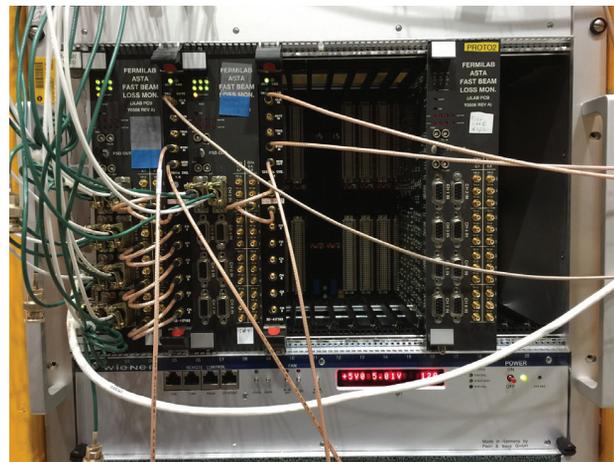


Figure 4: BLM Boards.

The front-end signal processing boards used are based on electronics designed by Jefferson Lab for their 12 GeV loss monitor system upgrade [4]. These BLM boards have been modified to meet the specific machine requirement at FAST. The main design change was to process the amplified signals from these boards using faster 125 MHz digitizer boards. The signals are further processed by an on-board FPGA to provide the require threshold levels and protection system shut-down signals.

USER INTERFACE

The user interface is a critical component of the MPS. It provides operators with the tools necessary to find the source of detected trips and provides the following functionality:

- Trip visualization
- Configuration and control
- Post-mortem analysis

A web page, as shown in Figure 5, serves as the entry point to the user interface. This page provides a global view of the permit system, a list of all pertinent applications and has a global log of all critical MPS messages. Trip visualization is provided through several Synoptic displays (Figure 6) which allow users to view the overall trip status and then to drill down to a specific trip.

Configuration control is provided through several Java applications. FAST Facility operators use these applications to select desired beam and operational modes, setup subsystem status masks and set BLM limits. Post-mortem analysis is essential to recovering from a trip. Detected trips are cached on the main MPS board. A background process (Finite State Machine) timestamps all trips and saves them into a repository. A Java application is used to display the logged trip history.

Commissioning was accomplished by manually setting the subsystem status masks and BLM threshold limits. In further runs, as operational knowledge is obtained, the goal is to create a mapping between the modes, masks and BLM limits so that mode changes would allow the correct masks and BLM limits to be automatically downloaded to the permit system.

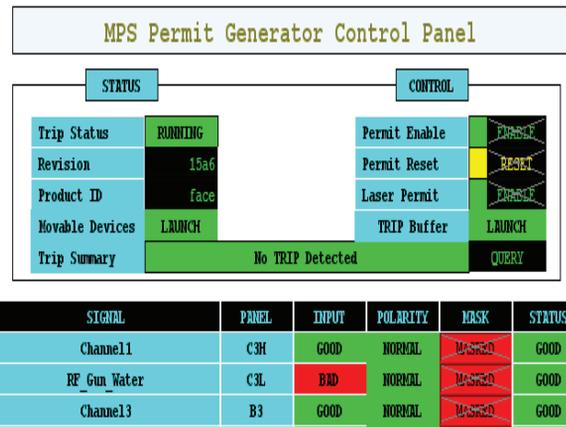


Figure 6: Configuration/Control.

CONCLUSION

The main components for the FAST Machine Protection System have been successfully commissioned. Commissioning began with successfully delivering 20 MeV beam to the low energy 50MeV dump for this first stage. The reaction time of the system is less than 1 us. The loss monitor system is sensitive to losses < 10 pC/bunch. The LPC meets the jitter specifications for tuning and controlling the number of bunches and bunch spacing. The main permit board was successfully interfaced to the control system. Trip visualization, configuration control and post-mortem analysis applications have been successfully developed. For the next phase of commissioning, the system will be expanded to protect the machine from 150MeV injection into IOTA.

REFERENCES

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- [2] M. Church, *et al.* "Status and plans for an SRF test facility at Fermilab", SRF'11, Chicago, August 2011, MOPO006; <http://www.JACoW.org>.
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The screenshot shows the MPS Web Portal interface. On the left is a navigation menu with categories: APPLICATIONS, Visualization (MPS Viewer, Trip History, Register History), Configuration/Control (Mode Control, BLM Limits), and Synoptic (Viewer, Builder). The main content area is divided into three panels: PERMIT SYSTEM (showing BLM, MOVABLE, VACUUM, MAGNETS, PLC, MODES, MPS, TRIP, GUN, CHILL), MONITORING SYSTEM (with Trip Logger, Register Logger, and Check List buttons), and STATUS (showing Beam Mode: Low Intensity, Operational Mode: Gun - Offense - Dump 1, and Trip Summary: No TRIP Detected). At the bottom is the MPS LOG table.

Date	Severity	Source	Message
5/27/15 9:30:14 AM	SEVERE	Trip Logger	Trip Detected on Channel 2
5/27/15 9:30:55 AM	MODERATE	Register Logger	Permit System Was RESET

Figure 5: MPS Web Portal.