MACHINE PROTECTION SYSTEM RESEARCH AND DEVELOPMENT FOR THE FERMILAB PIP-II PROTON LINAC*

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Abstract

The Fermilab Proton Improvement Plan (PIP-II) includes a high intensity proton linac being designed to support a world-leading physics program at Fermilab. Initially it will provide high intensity beams for Fermilab's neutrino program with a future extension to other applications requiring an upgrade to CW linac operation (e.g. muon experiments). The machine is conceived to be 2 mA CW, 800 MeV H- linac capable of working initially in a pulse (0.54 ms, 20 Hz) mode for injection into the existing Booster. The planned upgrade to CW operation implies that the total beam current and damage potential will be greater than in any present HEP hadron linac. To mitigate the primary technical risk and challenges associated with PIP-II, an integrated system test for the PIP-II front-end technology is being developed. As part of the R&D a robust Machine Protection System (MPS) is being designed and tested. This paper describes the progress and challenges associated with the MPS.

Introduction

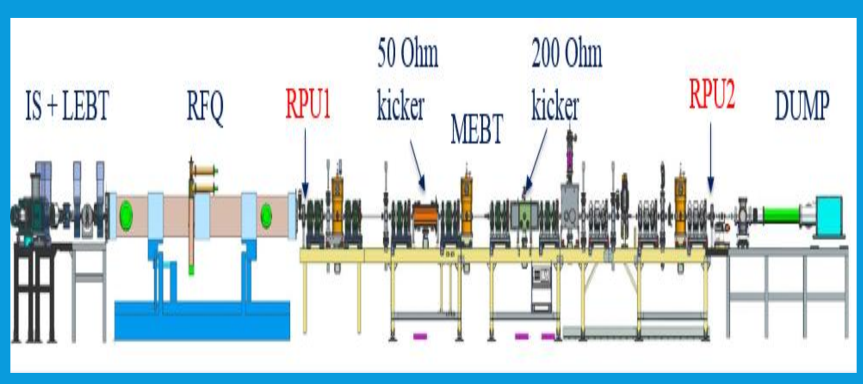

Figure 1 : Machine Layout of PIP II Facility

PIP-II is being designed and constructed to be a CW-compatible, pulsed H- SRF linac. It is an essential part of the planned program of upgrades to the existing Fermilab accelerator injection complex. To mitigate some risk and to validate the concept of the front-end associated with the PIP-II machine, a test accelerator is under construction. The test machine is known as the PIP-II Injector Test (PIP2IT) [2]. It includes a 10 mA DC, 30 keV H- ion source, a 2 m-long Low Energy Beam Transport (LEBT), a 2.1 MeV CW RFQ, along with a Medium Energy Beam Transport (MEBT) that feeds the first of 2 cryomodules. This increases the beam energy to about 25 MeV. A high Energy Beam Transport section (HEBT) takes the beam to a dump. The length of beam pulses in the machine is dictated by a chopper located between the last two solenoids in the LEBT. The chopper can provide 1 µsec - 16 msec pulses with a frequency that ranges from single shots to 60 Hz. The ion source, LEBT, RFQ, and initial version of the MEBT have been built, installed, and commissioned. Part of the ongoing R&D program associated with this setup includes the development and integration of a Machine Protection System into the complex capable of protecting the machine from beam induced damage while monitoring the chopper operation. An upgrade to quasi-CW operation is planned as a future mode of operation for the machine to deliver beam simultaneously to multiple users. This planned upgrade to CW operation implies that the total beam current and damage potential will be greater than in any present HEP hadron linac

Figure 2 : PXIE Facility

Protection System Overview

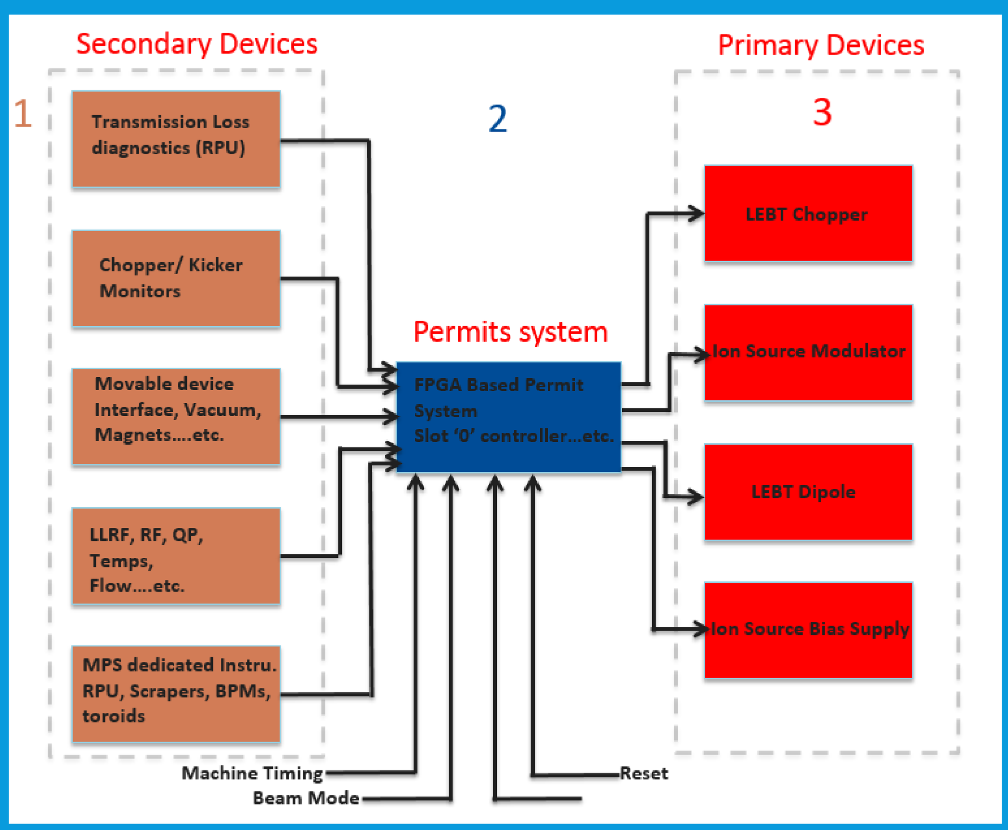

Figure 3 : MPS Overview

The PIP-II MPS will comprise of a logic system that takes in signals from various sub-systems and drives permits to beam enabling devices. These devices interacting with the MPS will be divided into primary and secondary categories based on how critical they are to mitigating beam damage as illustrated in Figure 3. Primary devices are main actuators for beam and should guarantee that, when they function properly, no dramatic damage can be caused by the beam even if protection through secondary devices fail. Both categories include sensing and beam-inhibiting devices. The primary beam-inhibiting devices are located at the Ion Source and in the LEBT section. They will include the LEBT chopper, the LEBT dipole, the Ion Source modulator and the Ion Source bias power supply. The secondary beam inhibiting devices are those devices whose malfunctioning will not create dramatic damage; either because the effects can be detected and mitigated by the primary devices, or because the inclusion of the device into the MPS is for the protection of the device itself (e.g. insertion devices). The secondary devices further decrease the probability of damage and possible irradiation of components. The list of secondary devices includes: the system providing the beam request sequence from the accelerator complex, status signals from the Linac subsystems, e.g. RF amplifiers, magnet power supplies, quench detection system, cryogenic system, LCW, the control system etc. In addition, these also include malfunctioning subsystems which can affect the beam delivery (e.g. RF amplifier) thereby dropping the Linac beam permit

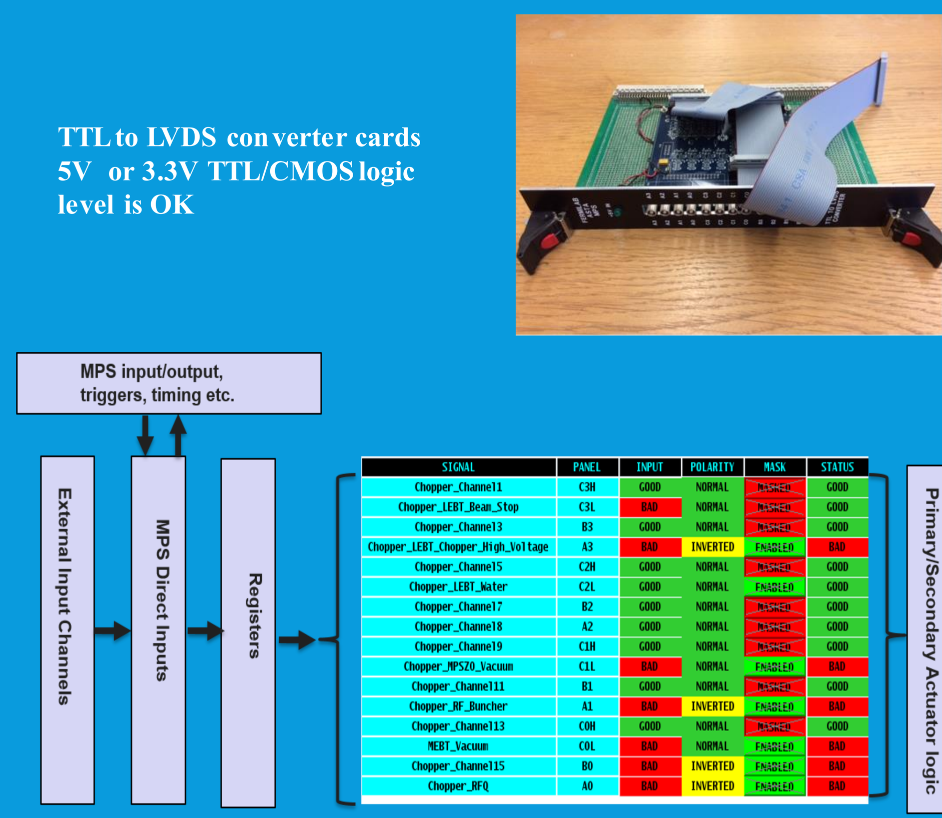

Figure 4 : Main MPS System setup

Ring Pickup Transmission Loss

A critical, primary device and component of the MPS is the Ring Pickup Unit (RPU). The ring pickup is similar to a single button BPM and will utilize rectifying electronics to generate a measure of the PIP-II beam pulse. These units are strategically placed both upstream and downstream and serve to measure the beam pulse width and the beam intensity. Two of these units in conjunction with a Faraday cup placed at the dump are used to measure the transmission loss across the PIP2IT machine. The readback from these units are routed through amplifiers and digitized. The result is sent to PPC5500 sitting in a VME crate. This processor utilizes these measurements and calculate the percent loss between any two units. This loss value is compared to user defined loss thresholds and a permit is removed if the measured losses exceed these limits. The loss protection system is capable of detecting losses of the order of 2 percent.

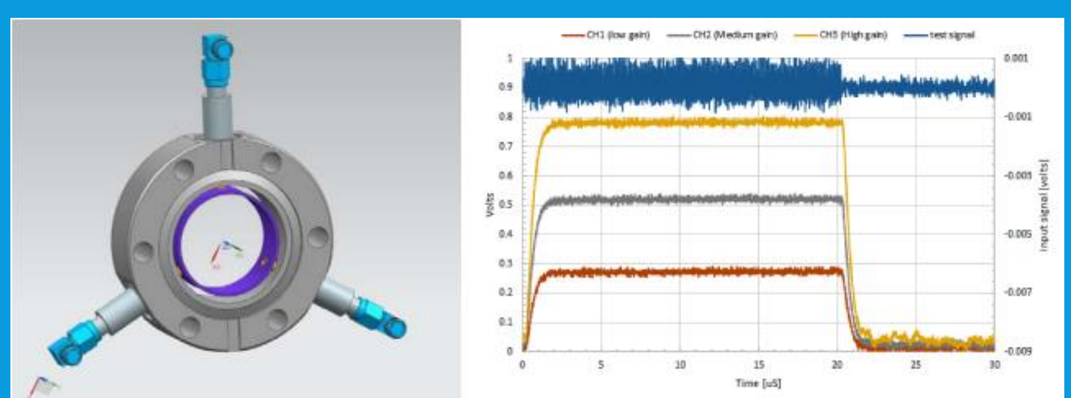

Figure 5 : Ring Pickup Loss Protection

Main Permit Board

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 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).

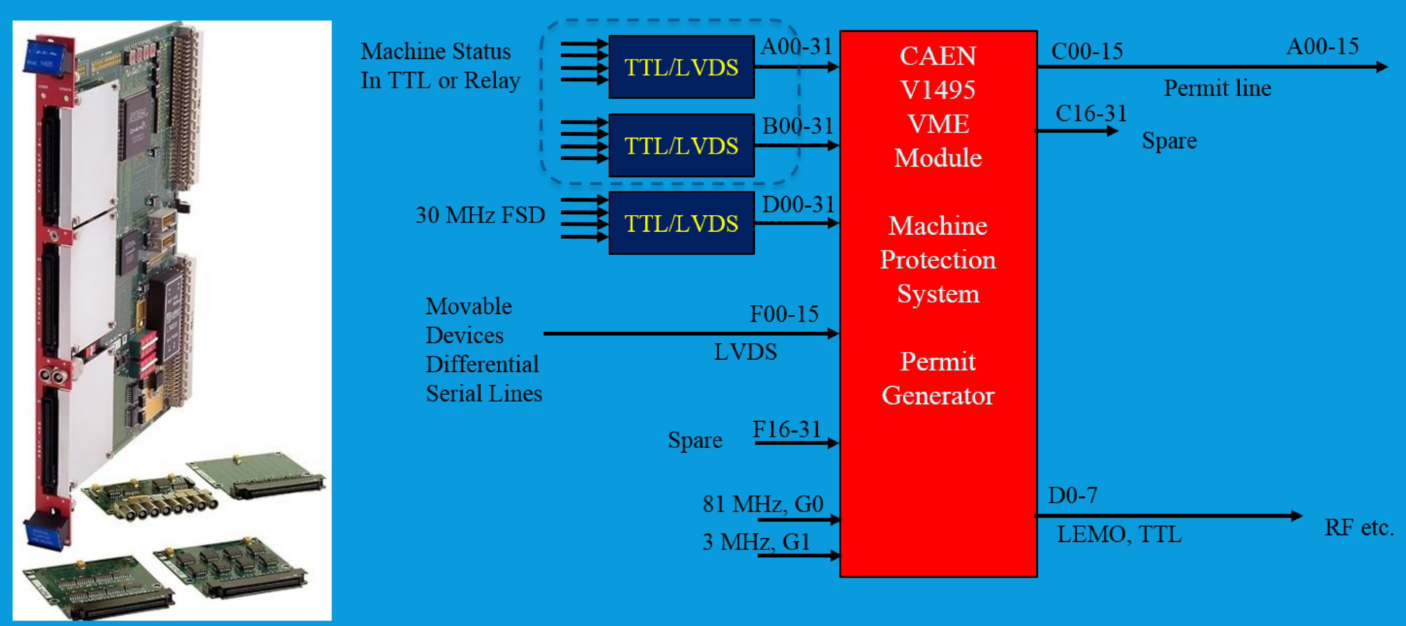

Figure 6 : MPS FPGA Block Diagram

Electrode Protection

Electronics designed to monitor both the MEBT kicker electrodes and machine scraper currents will provide fast comparative analysis of beam-induced current signals. It is planned to provide both digital and analog integration methods for monitoring excessive beam loss of these devices. Figure 7 is a schematic diagram of the integration process that will be implemented. The integration criterion will be based on the characteristic time constant required to prevent damage to a given device. Ideally the total interruption time interval will limit the beam power to which the given device can be exposed below its damage potential limits. The MEBT kickers have electronically isolated electrodes on both sides of the kickers. Loss measurement at these electrodes can serve as a good measure of potential beam damage to the kickers

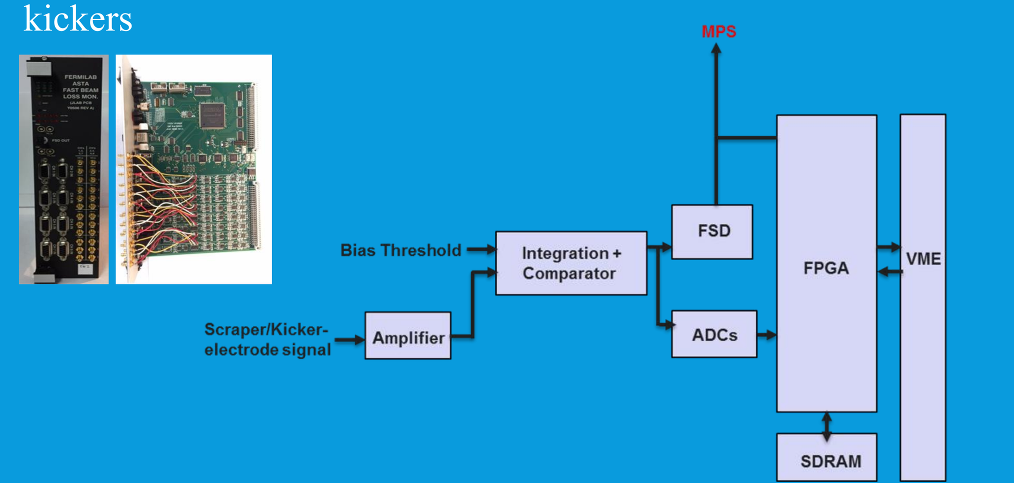

Figure 7 : Electrode Loss Protection

User Interface

Trip visualization and configuration control is provided through several Synoptic displays. These displays allow the user to setup limits and drill down to the tripped channel.

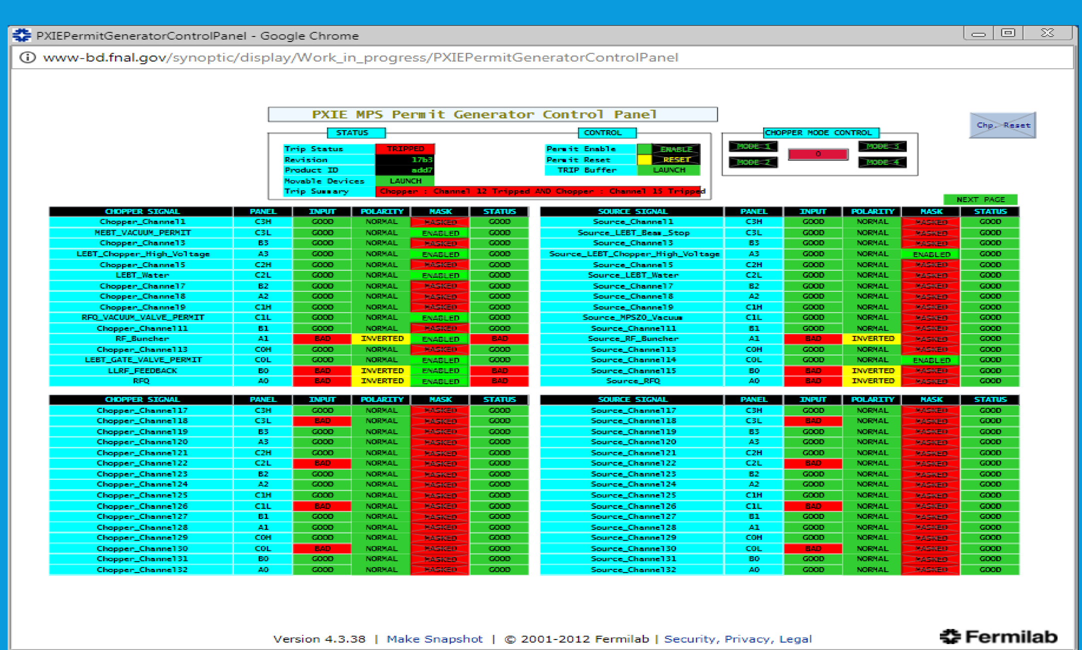

Figure 8 : Trip Visualization

A Synoptic page provides a global view of the trip status of a machine. Additionally, several autonomous tasks keep track of system messages, logs trips detected and track changes to crucial FPGA registers.

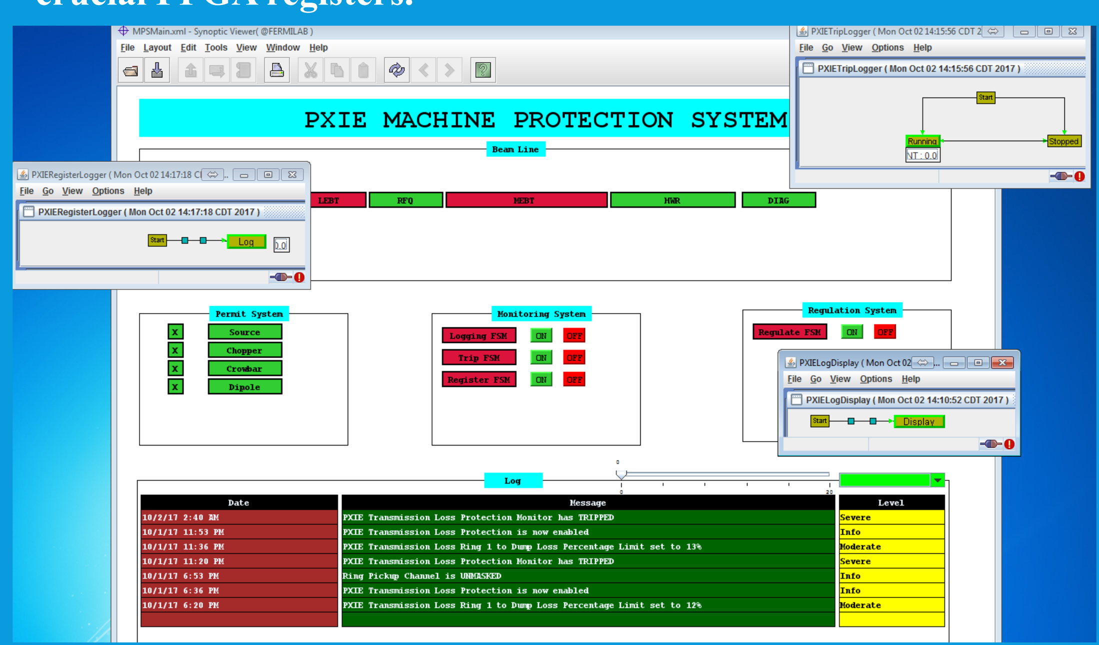

Figure 9 : MPS Global View

The transmission loss system has a distinct interface which displays loss status, provides configuration control and logs the last trip detected..

Figure 10 : Transmission Loss Protection Interface

Summary

A MPS for the PIP-II machine is being developed at the PIP2IT test facility. In addition to studying various schemes to protect the machine in the LEBT and MEBT where the damage potential is at its minimum, several diagnostics and signal processing techniques are being implemented. These diagnostics and techniques are a part of the R&D required to address several challenges associated with low energy beam loss in the warm sections of the machine prior to injection to cryomodules. Its critical components include a Permit system capable of monitoring critical channels and removing the permit within several microseconds and a transmission loss system which can detect transmission losses and react with 250 microseconds. An electrode protection Scheme is also under development. The MPS has also been successfully integrated into the control system and configuration control, trip visualization and post mortem analysis tools are being added.

References

[1] PIP-II Conceptual Design Report, 2017, http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=113
[2] P. F. Derwent et al., "PIP-II Injector Test: challenges and status", presented at LINAC'16, East Lansing, MI, USA, September 2016, WE1A01, unpublished