16th Int. Conf. on Accelerator and Large Experimental Control Systems ICALEPCS2017, Barcelona, Spain JACoW Publishing
ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA110

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

A. Warner#, L. Carmichael, N. Liu, R. Neswold, A. Saewert, B. Harrison, J. Wu
Fermilab, Batavia, IL 60510, U.S. A

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 [1]. 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

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 (Figure 1) 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.

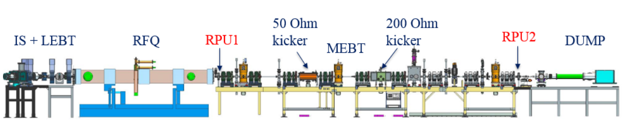

Figure 1: Schematic of PIP2IT facility.

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.

The MPS will ultimately be integrated as part of the entire Fermilab complex MPS responsible for protection of equipment in PIP-II and associated downstream machines from beam induced damage and excessive radiation damage. The system will therefore be integrated with legacy hardware and systems already operational and specific in scope. This integration process with the existing capabilities of the Fermilab facilities is part of the challenge associated with the design (see Figure 2). Since the main goal of the MPS is to protect the machines from beam induced damage; the system must inhibit the beam in case of excessive beam loss, equipment failures, or operator request. While achieving that objective, the system must also provide the ability to operate in a fail-safe manner with high availability. It must also manage beam intensity and permit limits as well as provide linac beam status to the accelerator complex control system.

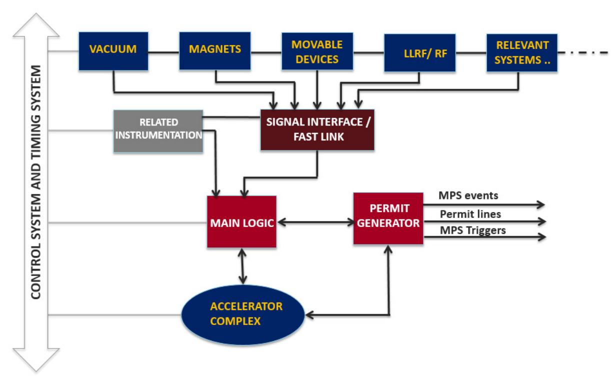

Figure 2: MPS integrated overview diagram.

The design will consider the redundant implementation of critical MPS components where possible to reduce probability of costly damage and corresponding downtime.

MPS PRIMARY DEVICES AND PERMITS

The PIP-II MPS will comprise of a logic system that

*Operated by Fermi Research Alliance, LLC, under Contract No. DE-AC0207CH11359 with the United States Department of Energy
#warner@fnal.gov

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA110

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.

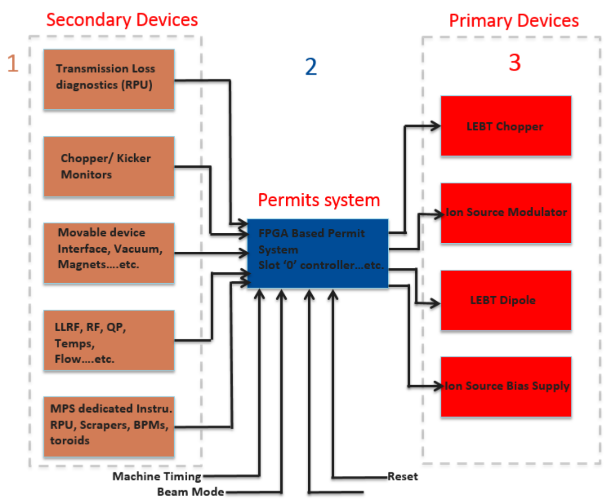

Figure 3: Primary and secondary device diagram.

The Primary devices shall not be masked for normal operations. However, there will be situations, such as MPS commissioning, when masking some of these devices will likely be required. In such cases, one can only mask these devices after receiving permission from the machine leader, MPS coordinator, and Operations Department, a form of administrative configuration control. Special instrumentation and diagnostics specifically developed for MPS use are included as primary devices. These will include a beam transmission loss system which compares beam current at various locations along the linac as well as permit signals from users indicating their readiness to receive beam from the PIP-II linac.

MPS SECONDARY DEVICES

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 devices 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 sensing 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. Devices and systems that are beam loss indicators (like radiation monitors, current signals induced on scrapers by the beam), vacuum gauges, valves and positions of insertion devices will also be capable to inhibit the beam. Examples of beam-inhibiting secondary devices are the MEBT chopper, switching magnets, separators, and beam stops that can prevent the beam entering an alarmed area.

RING PICKUP TRANSMISSION LOSS PROTECTION SYSTEM

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.

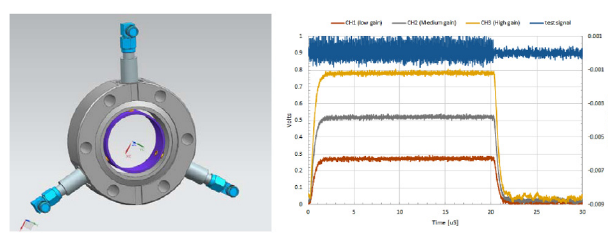

Figure 4: Ring pickup unit and response.

These units (Figure 4) 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 (Figure 5.). 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. The present scheme was developed to test the operational principles and runs at 4 KHz as a Front-end process. However, the final scheme is planned to be implemented in FPGA logic on Fermilab 125 MHz digitisers.

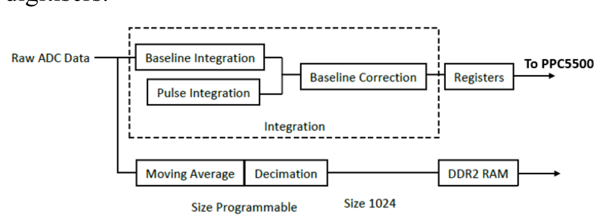

Figure 5: Ring pickup signal processing.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA110

ELECTRODE LOSS PROTECTION

Several ring pickups will be dedicated to monitor the LEBT chopper performance, monitor beam intensity and provide transmission loss information to the MPS. In addition, 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 6 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.

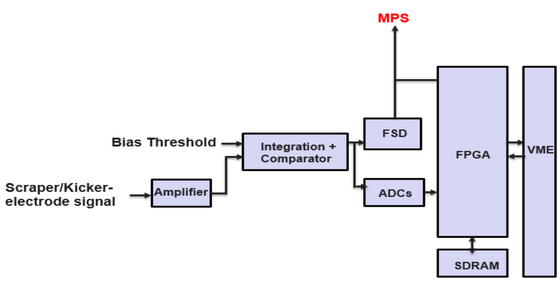

Figure 6: Electrode loss protection.

The protection scheme currently under development will compare the losses detected at these electrodes to some user defined thresholds. A 30 MHz (arbitrarily chosen) MPS permit signal will be pulled upon when losses exceeding the thresholds. Figure 6 provides a description.

MPS USER INTERFACE

The user interface is an essential component of the MPS. Once a trip is detected and the permit removed, it is necessary to able to drill down to find the source of this trip and then to be able to reconfigure your system to handle future trips.

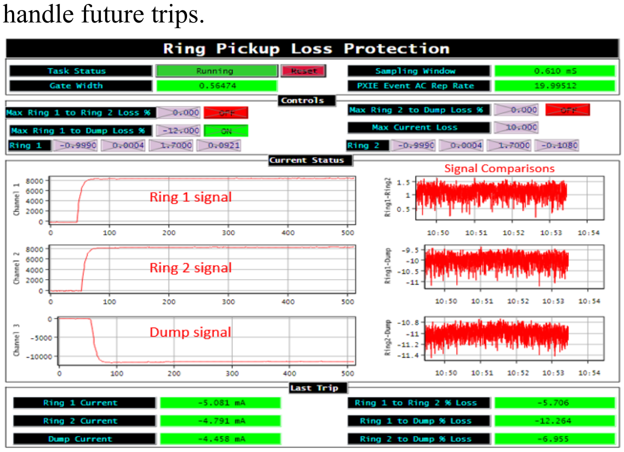

Figure 7: Transmission loss synoptic display.

This functionality can be termed trip visualization, post-mortem analysis and configuration control.

Synoptic pages are used as one of the main interfaces to the MPS. These pages provide operators with hierarchical system views which can be drilled down to find the source of a trip. Figure 7 illustrates the Synoptic page used to view the transmission losses measures by the RPU devices. Additionally, these pages provide one way of reconfiguring the protection systems. Constraints, like loss percentage, can be easily adjusted on these displays.

The MPS also utilizes several autonomous tasks (Finite State Machines) to monitor trips and changes in critical registers. This information is time stamped and logged and by generating causal relationships; it serves as a critical component of the post-mortem analysis.

CONCLUSION

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.