# THE DESIGN AND IMPLEMENTATION OF THE MACHINE PROTECTION SYSTEM FOR THE FERMILAB ELECTRON COOLING FACILITY *

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## Abstract

The Fermilab Recycler ring employs an electron cooler to store and cool 8.9-GeV antiprotons. The cooler is based on a 4.3-MV, 0.1-A, DC electrostatic accelerator for which current losses have to remain low ($\sim 10^{-5}$) in order to operate reliably. The Machine Protection System (MPS) has been designed to interrupt the beam in a matter of 1-2 μs when losses higher than a safe limit are detected, either in the accelerator itself or in the beam lines. This paper highlights the various diagnostics, electronics and logic that the MPS relies upon to successfully ensure that no damage be sustained to the cooler or the Recycler ring.

## INTRODUCTION

Stable operations of a 4.3 MeV Pelletron (an electrostatic accelerator) with a 100 mA DC electron beam has lead to the successful demonstration of electron cooling of 8 GeV anti-protons in the Recycler ring [1][2]. The electron beam is transported to interact with the anti-proton beam in a common 20-meter long straight section (i.e. cooling section) after which electrons are separated from the antiprotons and recaptured at the high voltage terminal of the machine; there the beam is dumped in the collector at the energy of 3 kV. Losses during this energy recovery process are kept below, ~ 10 μA. Increased beam loss during this process can lead to a reduction of the terminal voltage and, in turn, an interruption in re-circulation. In severe cases the terminal voltage of the machine can be discharged to near zero in a microsecond, releasing ~3 kJ of stored energy. This so-called full discharge results in an increased vacuum pressure of the accelerating tubes, it can damaged electronics in the terminal and may degrade the electric strength of the tubes [3]. In addition a sustained current loss in a single location could melt and drill a hole in the vacuum chamber. At the R&D stage of the project encountering these types of scenarios indicated a need for an elaborate protection scheme. Twice the electron beam drilled a hole in the vacuum chamber. As a result we limited the current available to DC losses to ~20 μA so that the timescale for melting the beam pipe is of the order of several seconds, in which case the loss monitor system mentioned below insures that the electron beam can be turned off in less than 1 second.

To mitigate these effects fast protection circuitry has been developed at the terminal level as part of a Machine Protection System (MPS) which closes the gun in 1 μs if the terminal voltage decreases because of higher losses. The MPS consists of two interconnected parts: a permit system and a crash recovery system. The permit system monitors several critical machine- and subsystem-related alarms as well as the loss monitors for the entire beam-line. The crash recovery system is a slower, higher-level application which regulates the beam given the status of a range of machine parameters. Figure 1 shows a simplified flow diagram of the whole system.

## PROTECTION SYSTEM OVERVIEW

The main hardware components of the protection system comprise: (1) the electron gun's modulator and fast circuitry in the terminal along with its fiber optically connected interface module located at ground level, (2) the beam permit box and (3) an Internet Rack Monitor (IRM) processor which is capable of interfacing up to 64 analog channels with digitization of all 64 channels done by the hardware at 1 kHz.
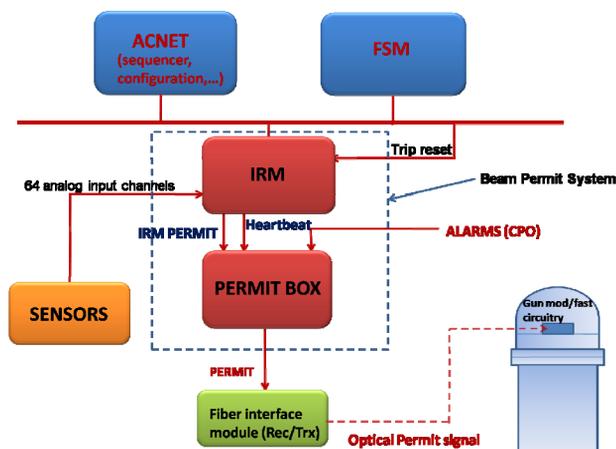


Figure 1: Protection system diagram.

## Gun Modulator and Fast Circuitry

The Gun Modulator is located inside the deck enclosure which is inside of the Pelletron terminal. Its output drives the "control electrode" of the electron gun located in the terminal at the top of the accelerating column. The modulator is used to control the beam generated by the electron gun for either cooling antiprotons in the Recycler (DC beam) or for machine diagnostic purposes (Pulsed beam). In the same way the voltage on the grid of a triode tube defines the tube current, the voltage on the control electrode defines the gun current (i.e. electron beam current). Depending on the desired operating mode when producing the electron beam, the modulator either adds an AC voltage to the DC voltage of the control

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electrode (provided by a separate power supply), or it delivers high voltage pulses to the control electrode. The modulator also serves the function of shutting the gun off rapidly (~1 μs) when the permit signal is removed. In particular, this fast protection circuitry was developed for the case of fast terminal voltage drops due to beam current losses, thus reducing the risk of full discharges [3]. In addition the modulator guarantees that the gun remains clamped off until after the gun's anode supply is totally powered off in the case of a sudden power loss at the terminal while the beam is still on. It was also painstakingly designed to remain protected during high voltage breakdowns of the machine; since the control electrode is known to sustain damaging energy when the machine breaks down the modulator must reliably survive these events. The modulator is actually composed of two separate modules that communicate with each other; the modulator chassis in the Pelletron deck enclosure as mentioned above, and the interface module at ground level. The single purpose of the interface module on the ground is to relay information back and forth between the chassis in the terminal and the control system frontend at ground. The two modules are connected to each other via a number of fiber optic cables.

*Beam Permit Box*

A variety of operating parameters are monitored at ground level by the beam permit box which issues a permit signal that is transmitted over a dedicated fiber to the modulator in the terminal. This beam permit box forms the hardware interface between the IRM and the interface module at ground level. Additional inputs are provided to the box that allows the sequencer or a manual switch located in the control room to disable beam.

The beam permit box has a fast comparator for monitoring the so-called CPO (capacitive pick off) monitor. The CPO is a device that measures voltage changes at the terminal and depending on the magnitude of the voltage drop and its time derivative, the permit may be removed, inducing a trip. The CPO has a 16nsec rise time and 19 msec fall time and a positive output for a discharge spark. The typical trip level is a 10 kV change on the terminal as measured by the CPO monitor at about 50 kV/V. A CPO signal exceeding the trip level will latch a trip condition and take away the Permit in about 9nsec. A DAC in the IRM provides an analogue trip level. The smallest usable trip level is about 1 kV. A setting larger than 150 kV may never trip. The trip level is accurate to about +/-0.5 kV. The change in voltage must be fast compared to the 50usec AC coupling time constant used in the circuitry. In addition to the Beam Permit, outputs from the beam permit box include a buffered copy of the CPO signal for monitoring in the control room as well as a slightly filtered copy for an ADC channel in the IRM.
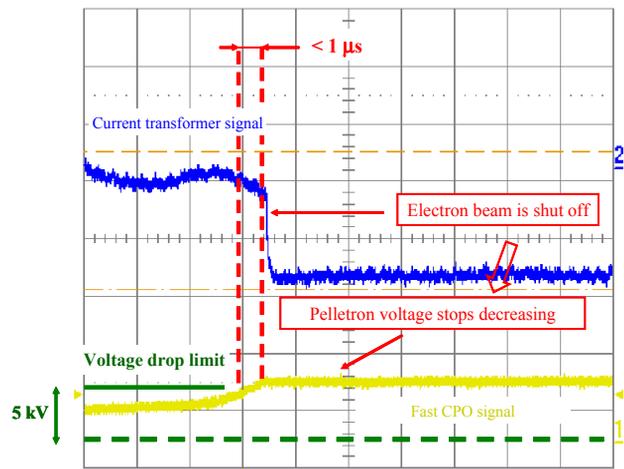


Figure 2: Oscillograms of a recirculation interruption. The yellow trace is the terminal voltage, and the blue trace is the cathode current.

*IRM Permit System*

The IRM digitizes and monitors 22 loss monitor channels distributed along the entire beam-line along with the CPO signal. Upper and lower threshold limits for each channel that is monitored by this system is downloaded via the control system. A local subroutine then scans each input channel against its limits. Based on the status of the inputs the system provides the permit box with an 'IRM permit' input. It is worth noting that the hardware automatically stores its results into a 64K circular buffer that has room for 512 sets of data which translates into 512 ms of data saved per channel. The local application which operates at 15 Hz runs on the system and supplies an interrupt routine that the underlying system code invokes from the digitizer interrupt; this occurs at the end of the digitization process over an 800 μs period. The interrupt code is invoked when the latest set of 1 kHz data has been stored into the buffer. The system then passes to the interrupt code an indication of where this latest data set is stored within the circular buffer. Since continued execution of the interrupt routine is so important, a heartbeat output line is provided that is driven by the kilohertz interrupt routine logic. It is driven high at the start of the interrupt routine execution and driven low at the end, about 100 μs later, if the maximum of 64 channels is being scanned. Its minimum time can be about 6–10 μs if the first channel reading is out of limits. If the permit box fails to see this heartbeat activity, it assumes there is no active interrupt monitoring going on, a heartbeat trip condition will be latched and the permit will not be issued.

## CRASH RECOVERY REGULATION

The gun current is regulated by a Java-based Finite State Machine (FSM) which reduces or switches off the gun current whenever a distinct set of fault conditions are detected and increases the current back to its nominal set point when normal conditions return. This regulation

process is an essential part of the Pelletron operation as it serves to anticipate critical faults, thus improving the overall efficiency of the operational aspects of electron cooling. The FSM provides the following functionalities:

1. Maintains (or recovers) the nominal electron beam current whenever drifts or unexpected changes occur.
2. Reduces the gun current as needed to compensate for soft fault conditions such as vacuum deterioration and slow (i.e. ~ seconds) HV drops.
3. Execute a consistent set of steps and checks whenever the machine needs to recover from a trip. It is particularly important when the trip is due to a large HV discharge.
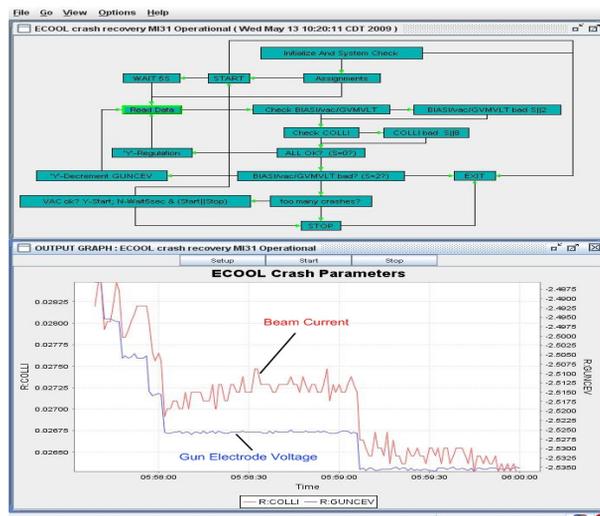


Figure 3: FSM Display. The plot shows the FSM regulating the gun control electrode voltage in order to reduce the beam current back to its nominal value.

The FSM class is imbedded in the Java-based Data Acquisition Engine (DAE) infrastructure that sits on top of the Fermilab accelerator control system (ACNET). The ACNET control system is a 3-tiered system that uses a connectionless User Datagram Protocol (UDP) to connect different machines. The DAE infrastructure refers to a client server model where Java clients use Remote Method Invocation (RMI) to communicate with the DAE servers that are tied directly to the ACNET control system. Each FSM operates in a thin client-server model where the FSM client starts jobs remotely on the server which is bundled with the DAE engines. The FSM server handles all communication with ACNET and all computations. Information such as state transitions and requested data is sent back to the client through RMI

## CONTROL SYSTEM INTEGRATION

An integral part of the MPS is the display and analysis of any detected faults. Faults that are detected by the permit systems are time-stamped by the IRM. A persistent FSM logs the data associated with a trip generated by the permit or regulation systems and stores the monitored

data in a database. A Java application provides an integrated, graphical display of faults detected by the permit and regulation systems. Figure 4 shows the application's main window where the beam line is schematically represented with all the monitored channels for which the stored data can be accessed (inserts in Fig. 4). Additionally, a display of the fault history along with the first fault in a fault sequence is illustrated.
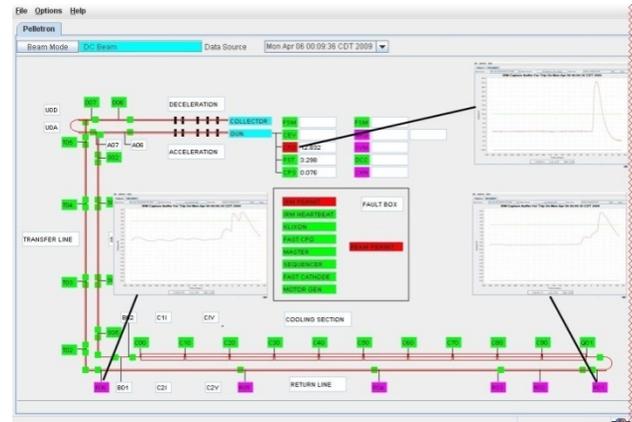


Figure 4: Fault System Display.

## SUMMARY

The machine protection system works well and is fully operational. The fast gun circuitry in conjunction with the beam permit box has successfully aided in reducing the frequency of full discharges to about one per year, thus increasing the cooler reliability. The Crash recovery FSM has proven to be very useful operationally as it significantly reduces manual interventions while running beam. It in turn increased the electron beam uptime, which is now close to 92% (except for occasional hardware failures). The FSM infrastructure has become an integral part of the Pelletron's machine protection scheme at various levels and helped in streamlining fault analyses. It not only captures operational knowledge in the regulation script, but also allows for the easy testing and implementation of additional scripts to improve operational efficiency.

## REFERENCES

[1] S. Nagaitsev et al., Phys. Rev. Lett. **96**, 044801 (2006).
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