THE MACHINE PROTECTION SYSTEM FOR FERMI@ELETTRA

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Abstract

FERMI@Elettra is a linac-driven free-electron laser currently under construction at the synchrotron radiation facility Elettra in Trieste, Italy. In order to prevent damage to accelerator components, an active machine protection system (MPS) monitors beam losses along the linac and, if necessary, inhibits the beam production in the injector. Special attention is paid to the protection of permanent undulator magnets from demagnetization by the excessive absorption of radiation. This paper discusses the system architecture and gives an overview of the major diagnostic subsystems: A beam loss position monitor based on the detection of Cherenkov light induced in quartz fibers, an array of discrete ionization chambers, and a system for differential charge loss measurements. The dose deposition in the undulator magnets will be monitored with electronic RadFET dosimeters.

INTRODUCTION

FERMI@Elettra is a fourth generation light source currently under construction at Sincrotrone Trieste. As illustrated in Fig. 1, the main components of the accelerator are a photocathode RF gun, 16 accelerating S-band sections, an X-band structure for phase space linearization, two magnetic chicanes for bunch compression, and two separate undulator sections with 7 and 10 undulators, respectively. The linac design foresees the extraction of electron bunches with a maximum charge of 1 nC at a rate of 50 Hz and the acceleration to a final energy of 1.2 GeV [1].

The maximum power carried by the beam amounts to about 60 W. While this hardly poses a direct threat to beamline components, considerable amounts of radiation can be released when a part of the electron beam strikes the vacuum chamber. Elevated radiation doses are especially undesirable in the undulator sections where they can lead to a partial demagnetization of the permanent magnets with a detrimental effect on the free-electron laser process.

To avoid beam-induced damage, Fermi will be protected by an active machine protection system (MPS) that can disable the extraction of charge in the photoinjector when necessary. In addition to the monitoring of components like dipole magnets and screens, the planned MPS will detect beam losses in the undulator section with three independent systems, two of them based on beam loss monitors (BLMs). The dose deposited in the undulator magnets will be measured with a system of RadFET solid-state dosimeters.

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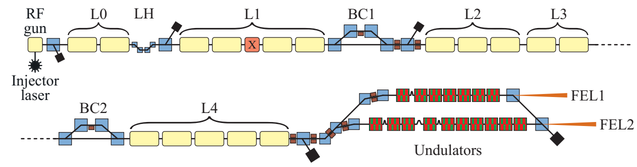

Figure 1: Overview of the FERMI@Elettra accelerator. Accelerating S-band structures are shown in yellow, main dipole magnets in blue, collimators in dark brown, undulators in red/green.

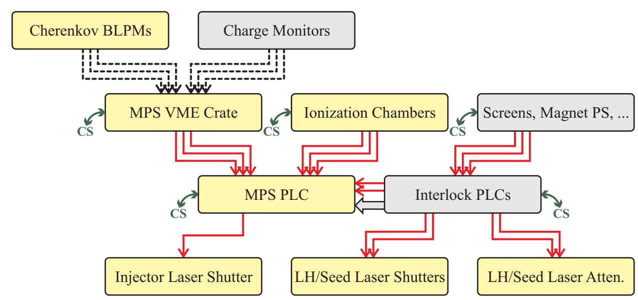

Figure 2: Overview of MPS subsystems. Digital alarm signals are marked by solid red lines, analog signals by dotted black lines. Connections to the control system are indicated by “CS”.

SYSTEM OVERVIEW

As shown in Fig. 2, the machine protection system consists of several subsystems with specific functionalities. The main interlock logic is implemented in a programmable logic controller, the MPS PLC. It receives digital alarm signals from a number of ionization chamber BLMs and from a separate unit, the MPS VME crate. This unit comprises a CPU with realtime software as well as ADCs and digital I/O boards connected via the VME64x bus. It monitors beam losses using differential charge measurements and with a Cherenkov beam loss position monitor (BLPM) system. The MPS PLC also receives information on the status of devices like screens and magnet power supplies from the separate linac and undulator interlock PLCs which are equipped with distributed inputs along the accelerator.

The only actuator of the MPS PLC is a mechanical shutter in the beam path of the injector laser. A future extension might enable the PLC to reduce the repetition rate of the electron beam by means of a pulse picker in the injector laser beamline. If operational experience should reveal significant dark current losses, the system can be easily adapted to disable the feed of RF power to single acceleration sections.

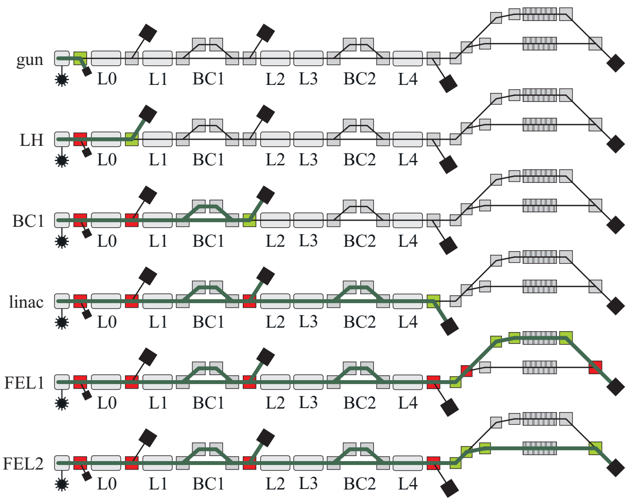

Figure 3: Beam paths corresponding to various operation modes. The MPS monitors the power supplies of the highlighted dipole magnets.

To protect diagnostic screens from damage, the interlock PLCs autonomously handle interlocks for the powerful laserheater (LH) and seed laser systems. Their actuators comprise a mechanical shutter and an insertable optical attenuator for each laser system.

MPS INTERLOCK LOGIC

The core functionality of the machine protection system is implemented in the MPS PLC. It fulfills three main tasks:

- It determines an *operation mode* for the accelerator from the status of the main dipole magnet power supplies. As long as the setup of the accelerator does not match a valid operation mode, the production of electron bunches in the photoinjector is inhibited.
- It monitors the status of screen movers and inhibits the beam production as long as any screen is in an unsafe position.
- It monitors several digital alarm signals from beam loss monitors and other sources. When an alarm is detected, beam production is inhibited and must be restarted manually.

Operation Modes

An operation mode is an abstraction of a valid beam path through the accelerator, i.e. a beam path on which the electrons can safely be guided to a beam dump. As illustrated in Fig. 3, six operation modes are defined. The PLC can uniquely identify each operation mode by the state of the main dipole magnet power supplies. As a basic safety measure, if the prerequisites for none of the predefined operation modes are fulfilled, beam production is inhibited. The operation mode also serves as an input to other parts of the interlock logic.

In the initial setup, the MPS checks only whether the power supplies are switched on or off. A monitoring of the actual magnet current is possible at a later stage.

Screen Interlocks

Fermi is equipped with multiscreen installations consisting of a movable support carrying various types of screens. Based on the status of several position switches and on the current operation mode, the MPS blocks the injector laser while the support is moving or when specific targets are inserted. The main purpose of this interlock is to prevent unnecessary radiation spills in the accelerator tunnel. To prevent the transport of beam with degraded emittance up to the undulator section, the use of many screens in the linac is prohibited while the accelerator is in FEL-1 or FEL-2 mode.

The MPS also protects several screens in the undulator sections from damage by the FEL radiation itself. For this, the injector laser is blocked while the undulator gaps are closed and one of the screens is in an unsafe position.

Several screens also need to be protected from the powerful laserheater and seed laser beams that copropagate with the electron bunches inside the vacuum chamber. The two laser systems are therefore equipped with shutters and insertable attenuators which are controlled by independent interlock PLCs. When fluorescent or optical transition radiation screens are inserted, the laser beams are automatically attenuated to facilitate the transverse alignment of the overlap with the electron beam without causing damage to screens or CCD cameras.

MPS Alarms

In case of hazardous conditions that require an intervention by the operators, the MPS PLC can raise an *MPS alarm*. In this case, the beam production is stopped by blocking the injector laser. To unblock the laser again, the operators are required to acknowledge the alarm via the control system.

The PLC collects about 60 digital alarm signals from its subsystems, mainly from beam loss monitors. An alarm signal on any of these lines immediately triggers an MPS alarm unless the signal is masked. Separate programmable masks exists for each operation mode, which allows to adapt the MPS behavior to the needs of daily machine operation in a very flexible way. The total response time of the MPS to critical alarm signals is expected to be below 20 ms.

BEAM LOSS MONITORING

The Fermi MPS uses three independent methods for the detection of beam losses: A differential charge measurement with toroidal charge monitors, Cherenkov beam loss position monitors (BLPMs), and ionization chamber BLMs. The differential charge measurement is the only MPS subsystem monitoring the global beam loss along the

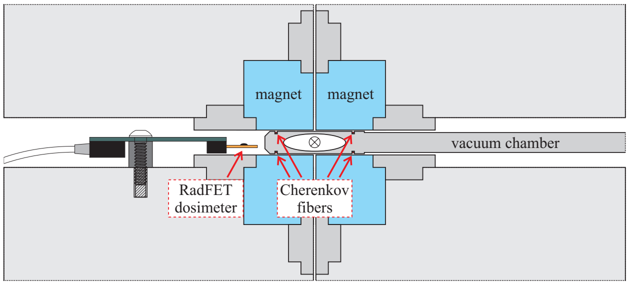

Figure 4: Cross section of an FEL-1 undulator with closed gap. The positions of the four Cherenkov fibers and of a RadFET dosimeter are indicated.

accelerator. In contrast, the Cherenkov BLPMs and ionization chambers are used only to monitor local beam losses in the undulator sections.

As a pure diagnostic instrument without connection to the MPS, some critical points along the Fermi linac are also equipped with inexpensive PIN diode BLMs [2].

Cherenkov Fiber BLPMs

Four Cherenkov beam loss position monitors [3, 4] will be installed along each FEL electron beam line. Each BLPM consists of an optical fiber, a frontend for the detection of Cherenkov light generated by particles traversing the fiber, and a test pulser.

A custom quartz fiber with high OH content is used to obtain sufficient radiation hardness. The fiber core has a diameter of 300 µm. It is surrounded by a step-index silica cladding, a polyimide buffer, and a protective nylon jacket of 330, 370, and 850 µm diameter, respectively. Four fibers per undulator string are placed in parallel grooves on the surface of the undulator vacuum chambers as shown in Fig. 4. Each fiber has a total length of 100 m.

The frontend uses Hamamatsu S10362-11-050U multi-pixel photon counters (MPPC, [5]) for the detection of the Cherenkov light. A custom electronics package adjusts the bias voltage in dependence of the MPPC temperature in order to maintain a constant detector gain. Because the arrival time of a light pulse with respect to the bunch trigger is a measure of the longitudinal position of the beam loss, the MPPC signal is sampled by a fast 12-bit ADC with 250 Msamples/s. The resulting longitudinal resolution is about 50 cm.

To ensure the integrity of the fiber and of the readout chain, a LED-based test pulser at the far end of the fiber injects 100 ns long light pulses of a well-defined amplitude after the passage of the bunch. If these pulses are not detected by the frontend, the BLPM is considered defective.

A single-channel prototype of the MPPC frontend has been successfully used to measure beam losses in the laser-heater section. The final version with eight channels is currently in production.

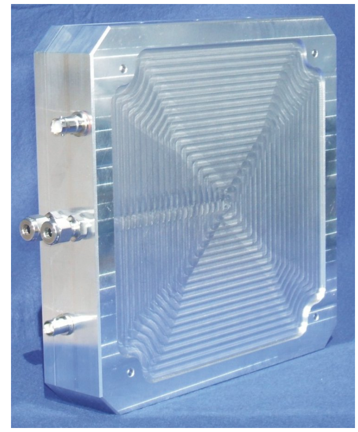

Figure 5: Photo of the ionization chamber.

Ionization Chamber Beam Loss Monitors

For the measurement of the momentary radiation dose rate along the undulator beam lines, about 20 ionization chambers will be used as beam loss monitors.

Each ionization chamber consists of three plane electrodes mounted inside an aluminum enclosure containing a gas volume of 1.3 l (Fig. 5). A high voltage of up to 1000 V is applied between two outer electrodes and a central, grounded one. Additional guard electrodes reduce leakage currents and increase the homogeneity of the electric field. The chamber has a gas inlet and an outlet to facilitate a change of the contained gas. In the final installation, the chambers will be connected in a daisy chain and purged with a small constant flux of nitrogen at atmospheric pressure.

Each ionization chamber has a separate frontend electronics package. It is based on the readout electronics described in [6], featuring a microcontroller and a 20-bit ADC. Besides amplifying, integrating, and digitizing current pulses from the ionization chamber, the frontend also generates the necessary high voltage. Readout of data and control of all device funtions is possible via a standard Ethernet interface. The frontend also compares the digitized signal with a set of programmable thresholds and, if necessary, signalizes an alarm on a digital output connected to the MPS PLC.

With a nitrogen filling at standard atmospheric pressure, the sensitivity of the chamber in terms of generated charge per absorbed dose amounts to

$$S \approx 1.3\,\mathrm{l} \cdot 1.25\,\frac{\mathrm{g}}{\mathrm{l}} \cdot \frac{e}{35\,\mathrm{eV}} \approx 46\,\frac{\mu\mathrm{C}}{\mathrm{Gy}},$$

using the average energy of 35 eV for creating an electron-ion pair in nitrogen [7]. A first measurement with a prototype of the chamber in air has roughly confirmed this estimate, yielding a sensitivity of ∼40 µC/Gy. A leakage current of less than 200 fA at the maximum voltage of 1000 V has also been measured, the measurement being limited by noise. This allows to estimate a detection threshold of

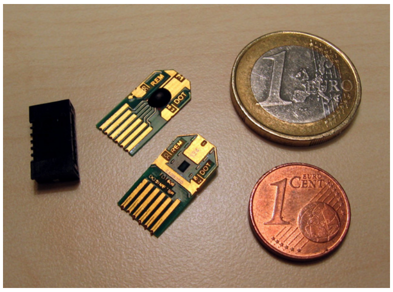

Figure 6: Photo of two RadFET boards and a suitable FPC socket.

less than 18 µGy/h. A more detailed characterization of the chamber is underway.

Differential Charge Measurements

Fermi is equipped with several bunch charge monitors based on the Bergoz integrating current transformer [8]. These monitors provide a voltage output proportional to the bunch charge. The preamplified signal from eight of these charge monitors in various places along the accelerator—behind the gun, in front of electron beam dumps, upstream and downstream of the undulator sections—is digitized by a single 16-bit ADC board. A realtime software checks the charge loss across various pairs of charge monitors and can raise alarm signals that are propagated to the MPS PLC, where they are interpreted according to the current operation mode. During the commissioning of the system, rather coarse charge loss thresholds of 25 % in the linac and 5 % in the undulator sections are foreseen.

UNDULATOR DOSIMETRY

The dose deposition in the sensitive undulator magnets will be monitored by four integrating, compact radiation-sensitive MOSFET dosimeters (RadFET, see e.g. [9]) per undulator. The devices are of the type RFT-300-CC10G1 produced by REM Oxford [10], have an oxide thickness of 300 nm, and allow the measurement of doses up to about 10 kGy without the application of a bias voltage during irradiation.

The dosimeters are mounted on the undulator support structure with the help of a small printed circuit board as depicted in Fig. 4. Simulations show that in typical beam loss scenarios the dose absorbed by the dosimeter is of comparable magnitude to the average dose absorbed by nearby magnets. Close to the front and back of the undulator, two RadFETs are fixed to the lower support, and two to the upper one. In this way, a rudimentary overview of the spatial dose distribution can be gathered.

The RadFETs are read out by a custom microprocessor-controlled reader unit that periodically drives the RadFETs with a constant current of 490 µA. The voltage needed to drive this current is digitized with a 24-bit ADC. Each unit has four channels and communicates via an ethernet interface.

Unlike the beam loss monitors, the dosimeters have a purely diagnostic function. Hence, no direct connection to the MPS is foreseen. However, the reader is equipped with an interlock output that can be freely controlled by the microcontroller code. The implementation of MPS alarms based on measured dose rates is therefore easily possible.

In the first test of a prototype of the reader unit, a RadFET has been irradiated in the bremsstrahlung-dominated radiation field of a 100 MeV electron beam impinging on a steel flange. The measured doses of up to 30 Gy are in excellent agreement with those measured with Gafchromic EBT2 film dosimeters. A more detailed characterization of the dosimetry system is in progress.

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