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STATUS OF THE BNL LEReC MACHINE PROTECTION SYSTEM*

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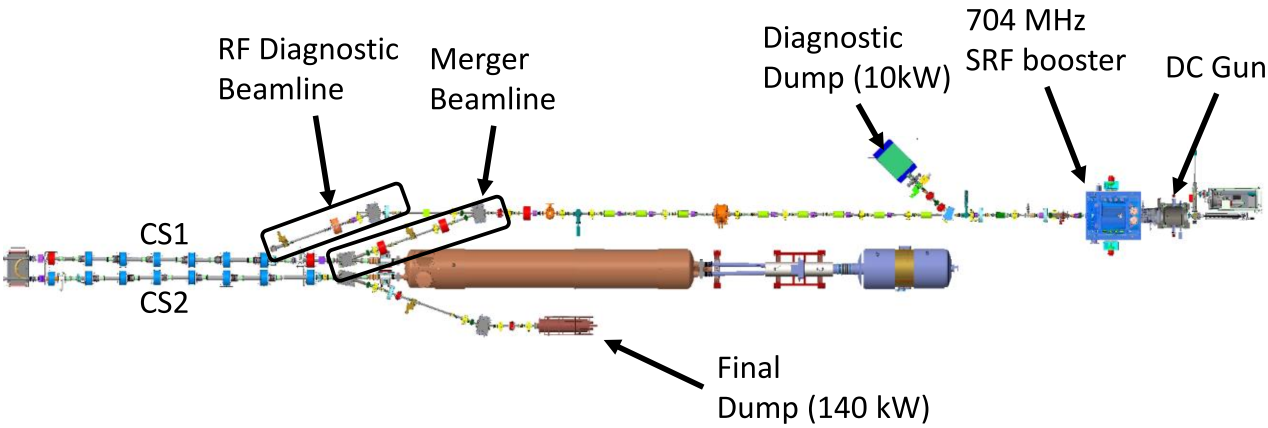

Figure 1: LEReC layout.

Abstract

The low energy RHIC Electron Cooler (LEReC) will be operating with 1.6-2.6 MeV electron beams having up to 140 kW power. It was determined that the missteered electron beam can damage the vacuum chamber and in-vacuum components within 40 us. We protect our accelerator against such a catastrophic scenario by a dedicated machine protection system (MPS). In this paper we describe the current status of the LEReC MPS design. We share our recent experience in commissioning and operation of the scaled down MPS used for the LEReC gun test beamline and discuss the status of the MPS designed for the commissioning of the full LEReC facility planned for next year.

LEREC LAYOUT AND PARAMETERS

The LEReC accelerator [1] consists of the 400 keV DC photo-gun followed by the 1.2-2.2 MeV SRF Booster, the transport line, the merger that brings the beam to the two cooling sections (CS1 and CS2) and the cooling sections followed by the 140 kW dump. The LEReC also includes two dedicated diagnostic beamlines: the low-power beamline capable of accepting 10 kW beam and the RF diagnostic beamline.

The LEReC layout is schematically shown in Fig. 1.

The LEReC beam train consists of 9 MHz macro-bunches. Each macro-bunch (MB) consists of N_b=30 bunches repeated with 704 MHz frequency. The length of each bunch at the cathode is 80 ps. The charge per bunch (Q_b) can be as high as 200 pC.

We will have the ability to work with macro-bunch trains of various length (Δt), various number of macro-bunches per train (N_{mb}), and various time delay (T) between the trains.

In addition to baseline operational modes listed in Table 1 the LEReC might also be operated with CW 704 MHz beam of 85 mA (at 1.6 MeV) and 68 mA (at 2 MeV).

The LEReC beam modes and their use are summarized in Table 1.

Table 1: LEReC Beam Modes

Beam Modes	Goals
Low Current Mode (LCM) $N_b = 30$; $N_{mb} = 1$; $T = 1$ s $Q_b = 30 – 200$ pC	Optics commissioning; Rough RF settings; Emittance measurement
RF Studies Mode (RFSM) $N_b = 10,15,20,25,30$; $\Delta t \leq 250$ us; $T = 1$s – 5s; $Q_b \leq 200$ pC	RF fine-tuning. Study beam longitudinal phase space.
Transition Mode (TM) $N_b = 30$; $\Delta t = T$; $Q_b \leq 200$pC	Transition from LCM to HCM with gradual adjustment of Q_b.
High current Mode (HCM) $N_b = 30$; $\Delta t = T$; $Q_b = 130 – 200$ pC	Getting nominal e-beam parameters in the CS.
CW Mode (CWM) 704 MHz CW; $Q_b = 95 – 120$ pC	Alternative to HCM.

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MPS OVERVIEW

MPS Parameters

The LEReC MPS [2, 3] is designed to protect the machine from the damage caused by the loss of electron beam.

We determined the MPS parameters from the studies of tolerable beam losses under various failure scenarios. The main MPS parameters are shown in Table 2.

Table 2: Main MPS Parameters

Parameter	Symbol	Value
Reaction time	t_{react}	40 us
Tolerable routine losses	I_{loss}	1 uA
Current threshold for ultimately safe operation mode (USOM)	I_{USOM}	40 nA

The MPS reaction time was derived under assumption that beam optics studies are performed in LCM only and that in HCM the beam trajectory is locked in some reasonable range and that some magnet power supply currents are locked at operational value.

We assume that the eventual setting for tolerable loss threshold will be found experimentally while I_{loss}=1 uA is an initial setting. The beam current used in such studies must not exceed 600 uA.

In the USOM any operations with the electron beam are allowed. Apparently the LCM is the USOM.

MPS Related Diagnostics

The MPS relies on the numerous LEReC beam diagnostic systems [4].

The MPS utilizes the fast current transformer (FCT) located close to the gun exit to measure the beam current and to determine what beam and equipment manipulations are allowed at the moment. Another device that is planned as a supplement to the FCT is a dedicated photodiode (PD) located at the exit of the laser room.

The output of the LEReC FCT is the measure of the instantaneous beam current while for the MPS purposes we require the instantaneous measurement of an average beam current. To achieve this goal we measure the total charge accumulated in the moving window of 1 s length. This charge defines our current levels for the MPS.

To monitor the beam trajectory the MPS relies on a number of beam position monitors (BPMs) located along the beamline. The BPMs are equipped with fast electronics capable of providing the response within 12 us.

A number of photomultipliers retrofitted with a few feet long optical fibre are planned to be used as beam loss monitors (BLMs) that determine the routine beam losses.

The ion gauges (IG) measuring the vacuum are also the integral part of the MPS. The gun IG plays a special role in machine protection – the MPS is required to trip the gun high voltage power supply (HVPS) when the gun IG readings exceed the predefined limit.

Finally, the MPS is monitoring a number of magnet power supplies (PS) as well as the gun HVPS.

MPS-Laser Interface

The sequence of the laser devices used to shape the pulse trains in the time domain is schematically shown in Fig. 2.

The CW train of laser pulses coming out of the oscillator is chopped into the 9 MHz macro-pulses by the pulse picker - an electro-optic modulator (EOM) with a fast (~1 ns) rise/fall time.

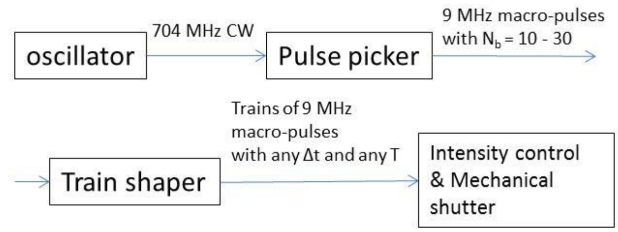

Figure 2: Laser pulse shaping scheme.

The train shaper is a Pockels cell (PC) followed by a half-wave plate (HWP). Depending on the HWP angle the PC either passes the laser pulses through or blocks the laser when the voltage is applied. The first polarization is used to create the trains of macro-bunches of particular length with some repetition rate. The second polarization is used in CWM.

The Intensity Controller consists of the EOM for intensity stabilization and the HWP for intensity limitation. The EOM is used to cut a few percent of laser intensity to smooth the intensity variation. The remotely controlled HWP is used to set the required laser intensity.

During the trips the MPS is blocking the laser beam to the photocathode by removing the high voltage from both the PC and the intensity control EOM and by closing the mechanical shutter.

MPS Logic

The overall MPS schematic is presented in Fig. 3.

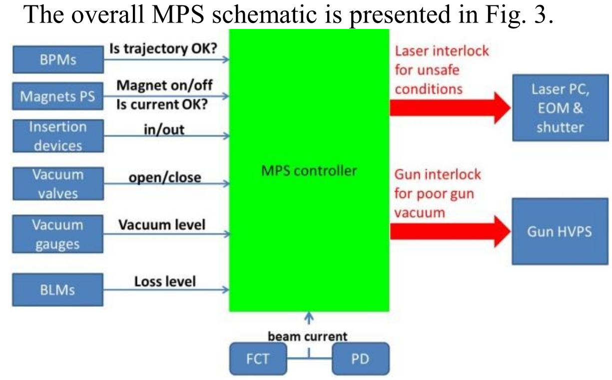

Figure 3: Schematic of LEReC MPS.

The MPS assesses the surface, which the beam is hitting, from the settings of the dipoles and from what insertion devices are inserted into the beamline. These inputs to the MPS are called “qualifiers” and the surface hit by the beam defines the “machine mode” (MM). The operation in each particular MM is allowed below certain current level only.

The actual beam current is calculated from the FCT and the PD readings. The MPS compares the measured beam current to the allowed current level and if the measured

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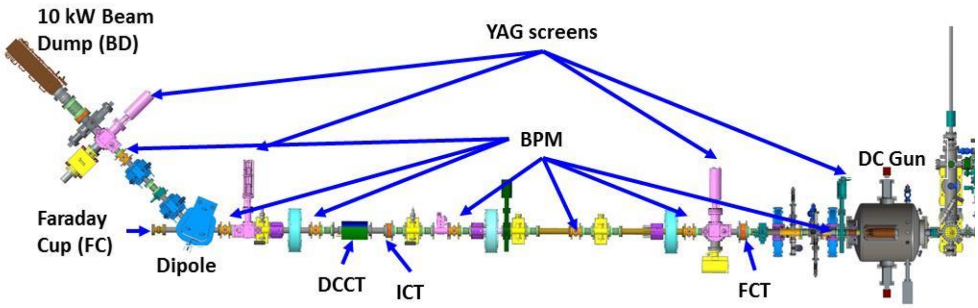

Figure 4: Layout of LEReC gun test.

current exceeds the limit set for the present MM then the MPS interlocks the laser.

Another cause for the MPS to trip the machine above certain current level is the BPM readings or magnet PS readings outside of the allowed range.

Finally, above certain current level the MPS trips the beam if the loss measured by the BLMs is above the I_{loss}.

The MPS allows two additional modes of operation: the "isolation mode" and the "laser alignment mode". In the isolation mode the laser shutter is closed so that the gun and the laser conditioning can be performed independently. The qualifier for this mode is the status of the laser shutter. In the laser alignment mode the gun high voltage (HV) is turned off, so that the laser can be aligned on the cathode. The status of the gun HV is the qualifier for this mode.

MPS EXPERIENCE IN GUN TEST

In April –August of 2017 we performed the LEReC gun test with the gun diagnostic beamline (Fig. 4). The beam energy in this test was 300 - 400 kV with the maximum allowed beam power of 10 kW.

Since the diagnostic beamline included all (with the exception of the RF cavities) essential building blocks of the full LEReC, it was a perfect test bench for the scaled down LEReC MPS.

This MPS has 3 current levels. At the first 40 nA level (I_{USOM}) any beam manipulations as well as inserting any insertion devices is allowed. Faraday Cup (FC) level of up to 50 nA is reserved for sending the beam straight to the flange FC. The beam dump (BD) level is set to 25 mA and corresponds to the maximum beam current allowed on the BD.

The setting of the dipole magnet and the position of insertion devices define the MMs for the gun test MPS.

The rest of the MPS logic is not different from the full scale LEReC logic described above.

MPS Commissioning

The commissioning procedure of the scaled down LEReC MPS consisted of the 3 main blocks.

The integrated system test consisted of checking the interaction between the MPS controller, the MPS diagnostic subsystems, the laser, and the gun HVPS.

The second step was the MPS test without the beam. In that step we verified the logic of the MPS controller by emulating various fault conditions and observing the laser interlocks.

In the final step we commissioned the entire integrated LEReC MPS with electron beam. Working in the LCM we successively adjusted the FC and BD current levels to the level below the current measured by the FCT, created all possible beam faults and observed the expected machine trips.

The scaled down MPS was successfully commissioned with the aid of dedicated software that allowed us to communicate to the MPS controller and the MPS related diagnostic systems. The screenshot of the software GUI is shown in Fig. 5.

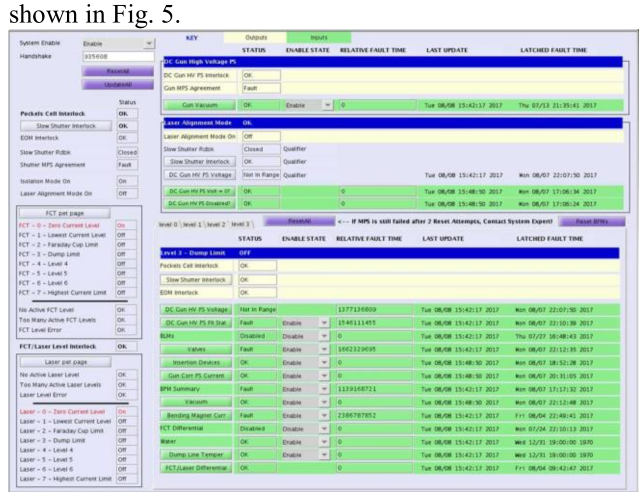

Figure 5: MPS software GUI.

Experience with MPS Diagnostics

We started beam operations in the LCM. The FCT immediately started detecting the e-beam and reporting respective beam current level to the MPS. Figure 6 shows raw FCT signal on the scope under typical operational conditions.

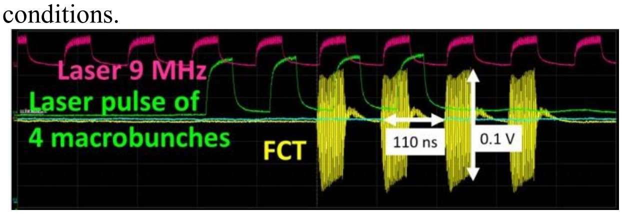

Figure 6: Raw FCT signal for the pulse of 4 MBs.

The FCT was pre-calibrated on the test bench with the pulse generator. The final calibration of the processed FCT signal was performed with the beam.

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We compared FCT readings to the readings of the FCs and the well-calibrated Integrated Current Transformer (ICT) for various electron charges per bunch and various numbers of MBs.

Figure 7 shows comparison of the calibrated FCT output to beam charge measured by the BD FC. Transport efficiency was set to 100% for this measurement.

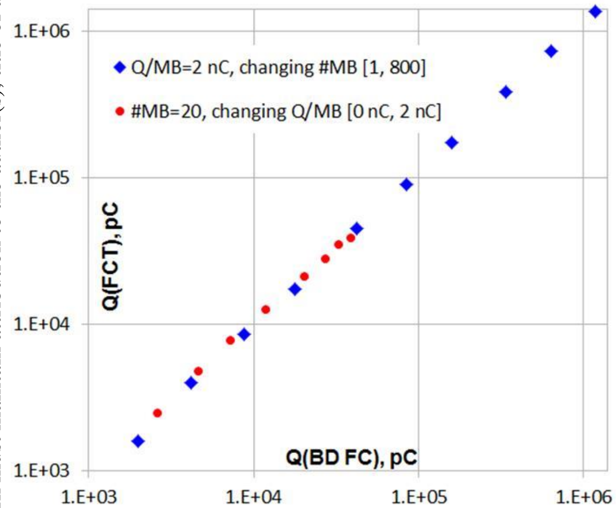

Figure 7: FCT vs BD FC for varying number of MBs at Q=2 nC/MB and for 20 MBs with varying Q/MB.

During commissioning we determined that due to the beam loading inside the gun and the slow HVPS regulation loop the only feasible way of switching to CW mode was increasing beam current from zero level. Since the FCT processing scheme doesn't detect any beam charge less than ~0.5 pC/bunch, we made a decision to always set the MPS to the high current level prior to switching to CW operations. Based on our experience we might make it a permanent automated feature of our MPS for 2018 run.

The BPMs proved to be an extremely useful part of the MPS. After commissioning BPMs both in the pulsed and in the CW modes they have been reliably interlocking the MPS whenever the beam trajectory was moved out of the allowed range. Noticeably, the BPMs were interlocking the MPS because of trajectory change along the train of macrobunches due to the beam loading in the gun. Figure 8 shows the readings of the BPM in dispersive region when beam loading is happening along the train of 50000 MBs and when the gun HVPS regulation loop is malfunctioning in CW mode. Such behaviour causes the respective BPM to trip the MPS when the position of any macrobunch is outside of the allowed range.

The vacuum gauges, readback of the magnets PS currents and readback of position of various insertion devices demonstrated proper and reliable interaction with the MPS during the whole 2017 run. Figure 9 gives an example of the LEReC trip in CW mode due to the BD vacuum exceeding the low limit set for low current operation.

While BLMs interaction with the MPS was fully commissioned and BLMs showed good sensitivity to the direct losses of the beam in pulsed mode, tests of BLMs in the CW mode were limited in time due to schedule pressure. The final integration of BLMs into the MPS will be performed during 2018 run.

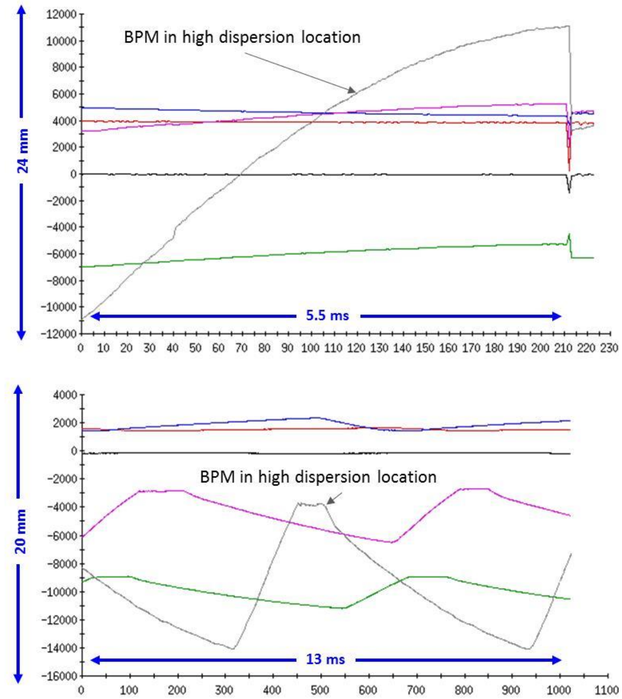

Figure 8: BPMs readings when the beam loading is happening along the train of 50000 MBs with 60 pC/MB (upper plot) and when the gun HVPS regulation loop is malfunctioning in CWM at 2.8 mA current (lower plot).

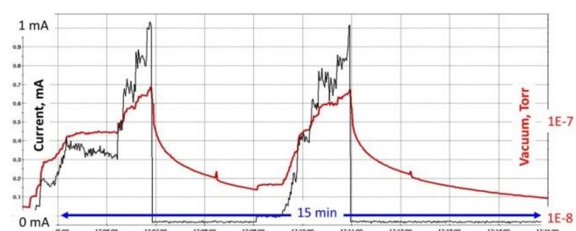

Figure 9: Two MPS vacuum trips during CW operations.

CONCLUSION

We described the design of the Machine Protection System for the Low Energy RHIC Electron Cooling accelerator.

The scaled down MPS was successfully commissioned and utilized in operation of the LEReC gun test.

Presently we are expanding the commissioned system to include all the components necessary for the commissioning of the full LEReC in 2018.

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