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STATUS OF THE BNL LEReC MACHINE PROTECTION SYSTEM*

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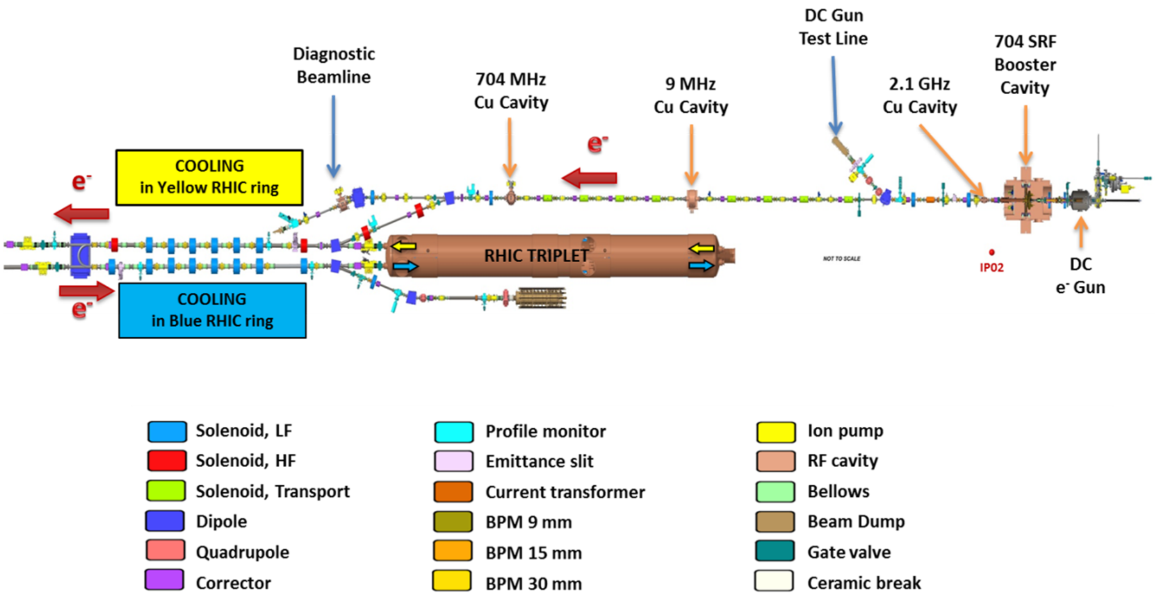

Figure 1: LEReC layout.

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 under the worst case scenario the missteered electron beam can damage the vacuum chamber and in-vacuum components within 40 us. Hence, the LEReC requires a dedicated fast machine protection system (MPS). The LEReC MPS has been designed and built and currently is under commissioning. In this paper we describe the most recent developments with the LEReC MPS.

LEREC LAYOUT AND PARAMETERS

The LEReC accelerator [1] consists of the 400 kV DC photo-gun followed by the 1.2-2.2 MV SRF Booster, the transport line and the merger that brings the beam to the two cooling sections (CS1 and CS2) followed by the 140 kW dump. The LEReC also includes two dedicated diagnostic beamlines: the low-power beamline capable of accepting 15 kW beam (DC Gun Test Line) 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 40 ps. The charge per bunch (Q_b) can be as high as 200 pC.

The LEReC can 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.

The nominal LEReC beam parameters pertinent to the MPS design are summarized in Table 1.

Table 1: LEReC Beam Parameters.

Kinetic Energy, MeV	1.6	2	2.6
Electron bunch (704 MHz) charge, pC	130	170	200
Bunches per macro-bunch (9 MHz)	30	30	24-30
Charge per macro-bunch, nC	4	5	5-6
Average current, mA	35	46	44-55
Average power, kW	56	93	114-142

In addition to the 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).

There are also several additional beam modes required for accelerator commissioning, study and transition to operational conditions. All these modes of operation comprise the MPS beam modes.

The relation between the MPS beam mode and allowed destinations of the beam will be discussed in the following sections.

The LEReC MPS beam modes and their use are summarized in Table 2.

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Table 2: LEReC MPS 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 – 5 s; $Q_b \leq 200$ 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 cooling sections.
CW Mode (CWM) 704 MHz CW; $Q_b = 95 – 120$ pC	Alternative to HCM.

MPS OVERVIEW

MPS Parameters

The LEReC MPS [2, 3] is designed to protect the machine from 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 3.

Table 3: Main MPS Parameters

Parameter	**Symbol**	**Value**
Reaction time	t_{react}	40 us
Tolerable routine losses	I_{loss}	1 uA
Current threshold for ultimate 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 kept in some reasonable range and that some magnet power supply currents are kept at operational values.

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. For beam studies the LCM is the same as 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 at the gun exit to measure the beam current and to determine what beam and equipment manipulations are allowed at the moment. Two other devices supplementing the FCT are a dedicated fast photodiode (PD) measuring the laser intensity and the readback on the position of the half-wave plate (HWP) in a laser trailer. The switching between the pulsed and CW modes is produced by introducing the HWP in the path of the laser and if HWP is in CW mode position then the MPS assumes the HCM.

To monitor the beam trajectory the MPS relies on a few beam position monitors (BPMs) located along the beamline. The BPMs are equipped with fast electronics providing a few microseconds response.

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

The ion gauges (IG) measuring the vacuum are also an 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.

The MPS monitors the on/off status and the phase/amplitude settings of the LEReC RF cavities and the cryogenic system temperature.

Finally, the MPS monitors several magnet power supplies (PS) as well as the gun HVPS.

In the case of a trip condition, the MPS interlocks the laser by removing the voltage from the Pockels Cell (PC) and by closing the mechanical shutter.

MPS Logic

The schematic of the MPS logic is presented in Fig. 2.

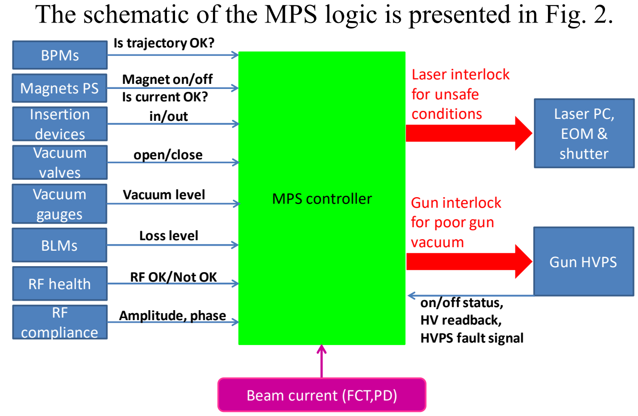

Figure 2: Schematic of LEReC MPS.

The MPS assesses the surface that 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). Operations with beam in each particular MM is only allowed below a certain current level.

The actual beam current is independently determined from both the FCT and the PD measurements. The MPS compares the measured beam current to the allowed current level and if the measured current exceeds the limit set for the present MM, then the MPS interlocks the laser.

Other causes for the MPS to trip the machine above a certain current level are the BPM readings, RF phase and amplitude readings or magnet PS readings being outside of the allowed range.

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

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RECENT MPS EXPERIENCE

MPS Commissioning

The prototype MPS was successfully commissioned and operated during the LEReC gun test performed from April – August of 2017 [5]. The gun test included studying a 400 keV beam produced by the gun and transporting it to the DC Gun Test Line. Based on the results of the LEReC gun test, the full MPS was devised and implemented for the 2018 LEReC commissioning run.

The commissioning procedure of the full LEReC MPS consisted of 3 main steps:

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 current levels of interest below the current measured by the FCT, created all possible beam faults and observed the expected machine trips.

MPS Reaction Time

To measure the MPS reaction time: the BPM signal, the fault signal from BPM controller to the MPS, the MPS trip signal to the laser and the MPS PD signal were monitored on the scope. The fault condition was created at the monitored BPM and the reaction time was measured by observing the delay between the fault registered by the BPM and the disappearance of the signal on the fast photodiode.

The example of such a measurement is shown in Fig. 3.

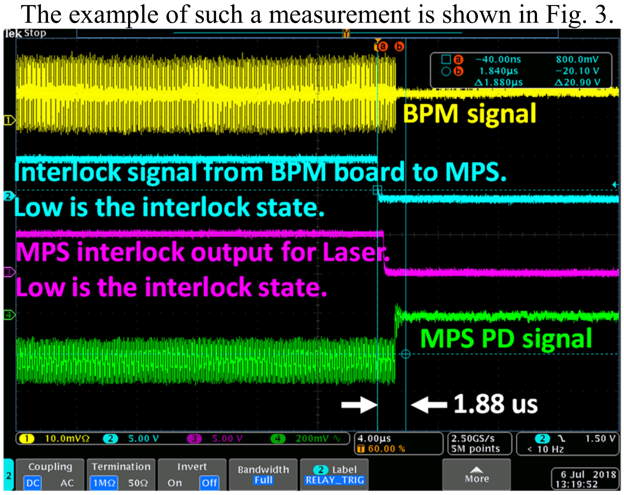

Figure 3: Measurement of the MPS reaction time.

As it can be seen from the presented plot the MPS controller response time is 500 ns (blue trace to purple trace). The overall MPS reaction time, or the time from an interlock to 'no-beam' condition, is within 2 µs. A generous 3µs of processing and cable delay time can be added to this result. Hence, the overall MPS reaction time is 5 µs, which is an order of magnitude less than the required 40 µs.

Adjusting MPS Diagnostic Configuration

The majority of the MPS related diagnostic devices were commissioned and integrated into the prototype MPS during the LEReC gun test. Nonetheless, during this year's run we discovered that some configuration changes were required for proper MPS operation.

The FCT, which is customized by Bergoz to optimize its sensitivity at 704 MHz was affected by the RF noise produced by the nearby SRF Booster. While it was not a problem for CW operation, in the pulsed mode the noise was interpreted as real beam current and caused multiple erroneous trips. Better shielding of RF connections helped somewhat with the noise problem but eventually, to completely eliminate this issue, we had to bypass the FCT amplifier, increase the FCT noise threshold and recalibrate the FCT.

Another example, before enabling the BLMs in the MPS we had to reduce the BLM gains. Although their new settings allowed the BLMs to be utilized for monitoring the losses in CW mode, the reduced sensitivity made them much less useful for fine-tuning of the beam transfer efficiency. Presently we are considering having two configurations for the BLMs. One for monitoring the losses during CW operations and another for optimising beam transfer in preparation to run CW.

LEReC Commissioning

Successful implementation and utilization of the MPS allowed us to operate the LEReC with the desired beam parameters required for 2018 accelerator commissioning.

Figure 4 shows the example of the recent CW run of the LEReC.

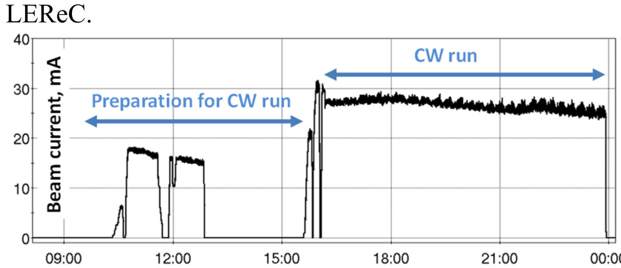

Figure 4: Eight-hour long LEReC CW run.

CONCLUSION

We described the current status of the Machine Protection System for the Low Energy RHIC Electron Cooling accelerator. The MPS was successfully commissioned and utilized in the 2018 LEReC commissioning run. Presently we are preparing our accelerator for commissioning of the first-ever bunched electron cooling during 2019 RHIC run.

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