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OPERATIONAL EXPERIENCE WITH MACHINE PROTECTION SYSTEM FOR HIGH CURRENT, HIGH BRIGHTNESS ACCELERATOR *

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Abstract

The Low Energy RHIC Electron Cooler (LEReC), the world's first electron cooler utilizing an RF electron accelerator, was designed to operate with 1.6 - 2.6 MeV electron beams of up to 140 kW beam power. The LEReC successfully worked through RHIC Runs 2019 - 2021, substantially increasing RHIC luminosity, and has been routinely used for various studies since then. A dedicated, highly configurable Machine Protection System (MPS) is a critical part of the LEReC. This paper summarizes our experience with operating the LEReC MPS.

INTRODUCTION

The Low Energy RHIC Electron Cooler [1-4] is the first electron cooler based on RF acceleration of electron bunches. LEReC utilizes a non-magnetized electron beam and provides the cooling of colliding ions with the same e-beam in both RHIC rings. LEReC was commissioned in 2019, was successfully used in RHIC operations in 2020 (at $\gamma = 4.9$) and in 2021 (at $\gamma = 4.1$), and has been routinely used for various studies since then.

Electron bunches in LEReC are produced by a 375 keV photo-gun. In operations the CW electron beam consists of 9 MHz macrobunches, each containing 30-36 704 MHz electron bunches. Each ion bunch passing through the LEReC cooling section (CS) is overlapped with one electron macrobunch. In studies LEReC is also operated with uninterrupted 704 MHz CW beam.

The LEReC gun is followed by the SRF Booster, which accelerates the beam to 1.6-2 MeV. The transport beamline and the merger bring the beam to the cooling section in the Yellow RHIC ring, and then through the 180° bending magnet to the CS in the Blue RHIC ring, where electrons and Au^{79} ions are co-traveling with the same velocity. Finally, the extraction beamline sends electrons to the high-power beam dump.

Besides the high-power dump, there are two additional destinations for the beam. One is a gun diagnostic beamline, equipped with 25 kW beam dump. The other destination is a RF-diagnostic beamline equipped with a deflecting cavity, a mirrorless profile monitor and a mini dump accepting up to 10 W of beam power. This beamline is used for optimizing the e-bunch parameters in a longitudinal phase space and for fine-tuning of the LEReC RF system.

The LEReC layout is schematically shown in Fig. 1.

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By design LEReC can produce up to 85 mA current of electron beam with <2 μm emittance, and can operate at a maximum power of 140 kW. A robust, highly configurable Machine Protection System (MPS) with fast reaction time is a critically important part of LEReC.

MPS OVERVIEW

The LEReC MPS [5-7] is designed to protect the machine from damage caused by the loss of electron beam. The MPS parameters were derived from considering tolerable beam losses under various failure scenarios.

LEReC Beam Modes and MPS Levels

We devised four MPS levels. Each level defines what beam operations are allowed, what beam destinations are permitted, and what signals are monitored. The relations of MPS levels to various modes of LEReC beam operation are listed below:

- The MPS Level 1 corresponds to LEReC pulsed beam mode, in which trains of electron macrobunches are emitted with 1 Hz rate. The maximum allowed current in that mode is 40 nA. The beam can be sent to any LEReC beamline. It is allowed to intercept beam with profile monitors and emittance measurement slits in this mode.
- The Level 2 was designed to deliver long trains of macrobunches to the RF-diagnostic beamline. While the beam is allowed to be sent to any destination, the beam intercepting devices can not be operated in this mode.
- In Level 3 the LEReC is operating in CW mode, which corresponds to either 9 MHz, 704 MHz or 75 kHz current (75 kHz is RHIC revolution frequency, this mode was used for initial cooling setup). In Level 3 the beam power must be below 25 kW and the two possible destinations for the beam are the injection beamline dump or the high-power dump.
- The Level 4 is reserved for sending beam with average power of up to 140 kW to the high-power dump.

There is an additional Level/Mode, called the "Laser Alignment Mode", which is used to align the high-power laser on the gun cathode with the gun power supply being turned off.

MPS Signals

The MPS relies on numerous diagnostic systems [8].

The MPS utilizes the fast current transformer (FCT) located at the gun exit to measure the beam current and to determine the MPS Level.

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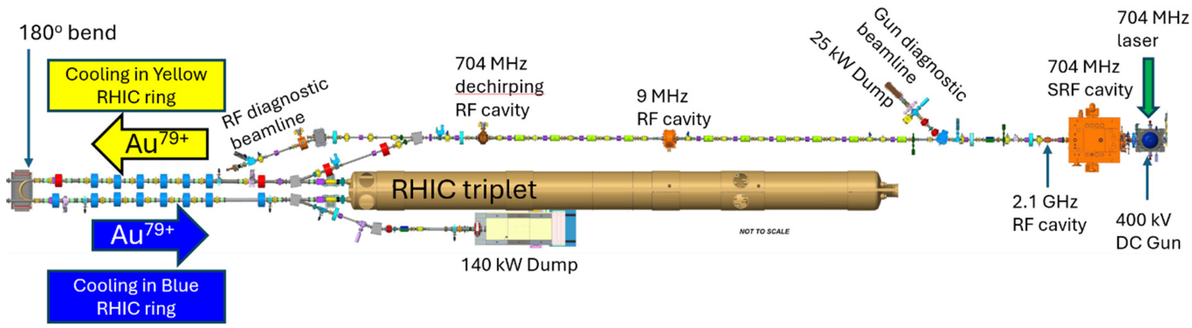

Figure 1: The LEReC layout.

To add redundancy to the system, a readback of a position of a half-wave plate (HWP) in a laser trailer is used to define whether LEReC is operating in CW mode. The switching between the pulsed and CW modes is done by introducing the HWP in the path of the laser, and if HWP is in CW mode position and the laser shutter is open then the MPS sets itself to Level 3.

The fast response to the MPS is provided by beam position monitors (BPMs) and by beam loss monitors (BLMs). The BLMs are photomultipliers retrofitted with a few feet long scintillating fibre. The BLMs cover the whole expanse of the LEReC beamlines. The overall MPS reaction time was measured to be <5 µs [7]. This well satisfies LEReC requirements [6].

The MPS monitors on/off status and phase/amplitude settings of the LEReC RF cavities, temperature sensors at the beam dumps entrances, beam dumps water temperature and water flow, power supply currents of bending magnets and of several strategically important focusing lenses, the status and current readings of the gun power supply, and the ion gauges (IGs) measuring the vacuum. The gun IG plays a special role – the MPS trips the gun high voltage power supply (HVPS) if the gun IG readings exceed the predefined limit.

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

MPS Logic

The MPS logic is designed to allow operators working with the machine without worrying about inadvertently creating potentially unsafe conditions.

The proper beam energy is guaranteed by monitoring the gun voltage and RF cavities voltage and phase readings. Respectively, the beam power at a particular energy is defined by the beam current, which is monitored by the FCT. Finally, the beam destination is determined by checking which bending magnets are turned on or off and by making sure that the current readbacks on the bends are within the set thresholds.

The FCT current limits for Level switching along with thresholds for RF and gun parameters and bending magnets currents are set by an MPS specialist prior to starting LEReC in each new configurational setup.

Such an approach completely automates the machine protection during any possible scenario of running LEReC, while keeping MPS highly configurable, and allowing for a wide variety of studies being performed with LEReC.

A schematic of the MPS logic is shown in Fig. 2.

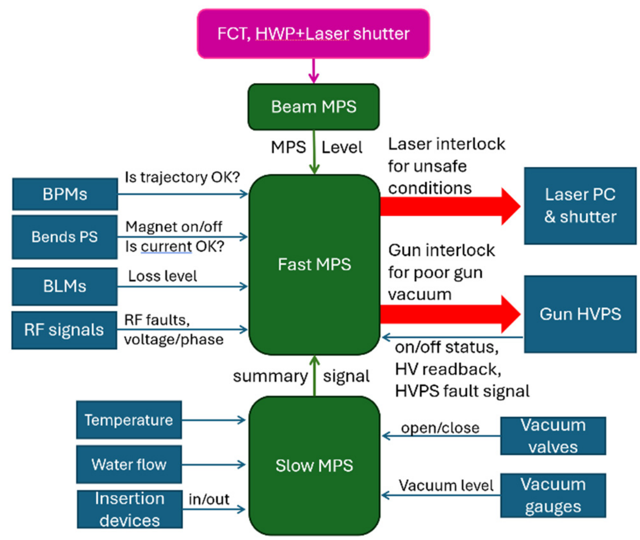

Figure 2: Schematic of LEReC MPS.

MPS OPERATIONAL EXPERIENCE

Administering MPS

A prototype of the MPS was developed for 2017 LEReC run dedicated to gun commissioning. The run included 7 m beamline to the diagnostic dump and was done without the SRF cavity. Yet, the MPS prototype had all main features of the final system.

MPS for the full LEReC was developed and commissioned in 2018 as a part of accelerator commissioning. In 2019 MPS was operated with some minor modifications (as compared to 2018) during commissioning of electron cooling. From 2019 to the present time, MPS stayed unchanged except for an addition/removal of a few new/obsolete devices.

At the start of each LEReC run a thorough check of MPS is performed, first without and then with the beam. Since MPS involves every aspect of LEReC operations, the MPS checks also serve as a dry run and a start-up of the accelerator.

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In RHIC control system the MPS is represented by several applications for reconfiguring the system. Which are reserved for MPS specialists, and by an additional application designed for interaction of operators with MPS (see Fig. 3).

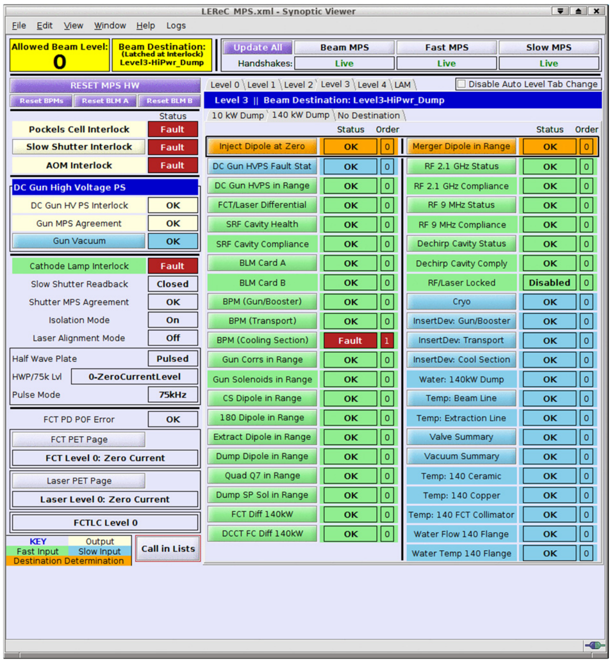

Figure 3: LEReC MPS application for control system. The application shows that the MPS trip happened due to an incorrect trajectory in the cooling section.

MPS Configurability

An architecture of LEReC MPS provides possibility to configure the system for support of operations in a new experimental setup. As an example, we consider LEReC run of 2024 dedicated to high current studies.

It was decided to use the injection beamline for these studies, so that LEReC could run in parallel to RHIC program. Since, the injection dump can accept 25 kW of beam power only, we had to work with the beam at a significantly reduced energy. As a result, the gun voltage was reduced to 300 kV from its usual 375 kV setting. The SRF cavity voltage was reduced from 1375 kV to 150 kV, and the 3rd harmonic cavity (which runs counter-phase to the SRF) was set to 40 kV, as compared to its usual 150 kV settings. The resulting beam energy was 410 kV, which was allowing us to run up to 60 mA to the injection dump.

The MPS window for proper current of the bending magnet directing beam to the injection dump line was readjusted along with the windows for RF voltages and phases.

Finally, the current threshold for MPS Level 3 was adjusted to 62 mA, to allow stable 60 mA operation.

This reconfiguration of MPS allowed us to successfully perform the studies, achieving the planned current (Fig. 4)

Some Finds and Lessons

In the first year, we discovered that there was a CW current background in a pulsed mode, substantial enough to destroy the beam profile monitor located at the gun exit.

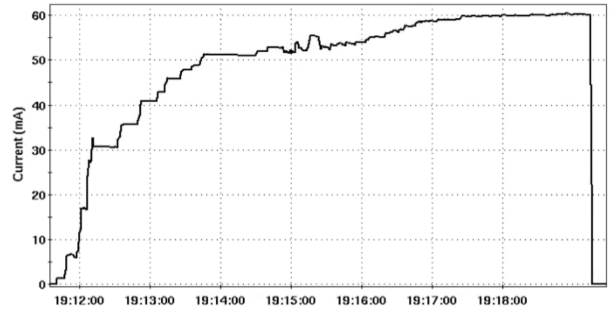

Figure 4: Results of LEReC high current studies in 2024.

The source of the problem was tracked to a low intensity CW laser "leaking" to the cathode, due to HWP not being exactly at 90° w.r.t. laser polarization. The problem was fixed by changing the CW/pulsed switch logic, so that the HWP inserted in the laser pathway corresponds to CW mode while retracted HWP corresponds to pulsed mode. This change made that part of the system fail-safe.

Another early MPS event was caused by allowing untrained personnel to make configuration changes. This resulted in misidentification of a CW beam destination and caused destruction of a vacuum valve. After that, only the MPS specialists were allowed to make system adjustments. Additionally, the MPS started monitoring the vacuum in all LEReC beamlines independent of assumed beam destination.

Beam loss monitors upgrade was the main modification of MPS-related equipment.

From the start and through the 2019 run, BLM photomultipliers were retrofitted with 1 mm diameter scintillating plastic optical fibre (POF). Then, it was noticed that an increased current in CW mode has caused ~17 % darkening in some of the fibres.

An undoped quartz fibre was tested and found to have a response of 85 % of that of the POF, which can be compensated for with increased bias voltage. Thus, a 1.5 mm quartz fibre in armoured sheath with SMA terminations was ordered in 16 lengths of 3 - 13 m and used to replace the POF covering the entire 100 m of the LEReC beamlines. The quartz fibre has been successfully used since 2020 without any degradation in strength of the signal.

CONCLUSION

LEReC MPS is a robust, highly configurable system with an overall response time less than 5 µs, which has been reliably protecting a high-current, high-brightness electron accelerator since the 2017 commissioning run.

We described our experience with LEReC MPS, including examples of utilizing its configurability for facilitating LEReC studies in unusual setups, and lessons that we learned over the years of operations.

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