CONCEPTUAL DESIGN OF LEReC FAST MACHINE PROTECTION SYSTEM*

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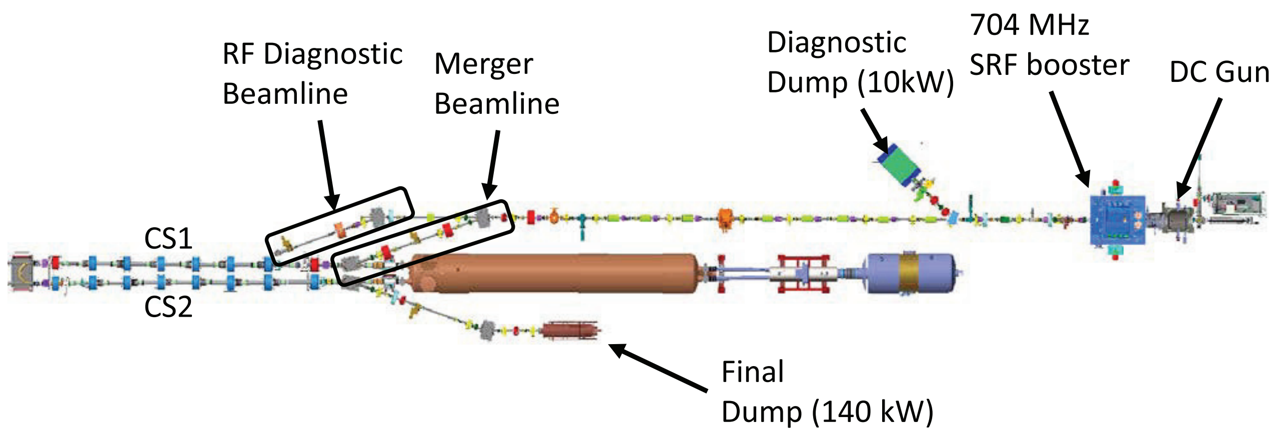

Figure 1: LEReC layout.

Abstract

The low energy RHIC Electron Cooling (LEReC) accelerator will be running with electron beams of up to 110 kW power with CW operation at 704 MHz. Although electron energies are relatively low (< 2.6 MeV), at several locations along the LEReC beamline, where the electron beam has small (about 250 um) RMS radius design size, it can potentially hit the vacuum chamber with a large incident angle. The accelerator must be protected against such a catastrophic scenario by a dedicated machine protection system (MPS). Such an MPS shall be capable of interrupting the beam within a few tens of microseconds. In this paper we describe the current conceptual design of the LEReC MPS.

LEREC LAYOUT AND PARAMETERS

The LEReC accelerator [1] consists of the 400 keV DC photo-gun followed by the 1.6-2.4 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.

We are planning to start the gun commissioning in the winter of 2017 with the short beamline that does not include the SRF Booster and ends at 10 kW beam dump.

The LEReC beam train consists of 9 MHz macro-bunches. Each macro-bunch 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.

Also, as an alternative to our nominal operational mode with continuous train of 9 MHz macro-bunches, we will have the capability to run a continuous wave (CW) of 704 MHz bunches.

Table 1: LEReC Beam Modes

Beam modes	Goals
Low Current Mode (**LCM**) Q_b=30-130 pC; N_b = 30; N_{mb} = 1; T = 1 s	Optics commissioning: beam trajectory, beam envelope, rough RF setting, emittance measurement
RF Studies Mode (**RFSM**) Q_b=130 pC; N_b = 10,15,20,25,30; Δt ≤ 250 us; T = 1 s - 10 s	RF fine-tuning. Study beam longitudinal dynamics.
Transitional Mode 1 (**TM1**) Q_b=130 pC; N_b = 30; Δt ≤ 1000 ms; T = 1 s	Gradual transition from LCM to HCM with nominal Q_b.
Transitional Mode 2 (**TM2**) Q_b=30 - 130 pC; N_b = 30;	Alternative to TM1
High Current Mode (**HCM**) Q_b=130 pC;	Get to the design parameters
CW mode (**CWM**) Q_b=50 pC; 704 MHz CW	Alternative to HCM

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

In the coming gun test we are going to utilize the LCM, TM2, HCM and CWM. TM2, HCM and CWM will be used with a reduced beam charge suitable for the 10 kW dump.

The RFSM and TM1 will be required for the complete LEReC commissioning planned for 2018 and will require laser R&D.

MPS REACTION TIME

In this paper we discuss the fast part of the LEReC MPS, which is designed to protect the machine from the damage caused by the loss of electron beam.

The RMS transverse beam size throughout the accelerator is larger than 1 mm with the exception of three locations in the merger line. In the two merger bends and in the middle of the merger line the beam is focused to 250 um RMS radius.

The design electron beam energy is 1.6 MeV, 2.0 MeV and 2.6 MeV, while our initial gun test will be performed with just 400 keV. The RF system can support electrons of up to 3 MeV energy.

The vacuum chamber in each of our bending magnets is of Y shape. Hence, the missteered beam can hit the vacuum chamber crotch at a normal incident angle.

The beam missteering with magnets is a slow process that does not define the MPS reaction time. On the other hand, the beam missteering due to the jump in the RF phase can happen in a few microseconds. Yet, a significant jump in energy will change beam focusing and, most importantly, the beam energy simply cannot get high enough for the beam to hit the "crotch" in the bending magnet vacuum chamber at 90^{o} angle. Therefore, the worst case scenario of ultra-focused beam hitting a vacuum chamber at a normal incident angle cannot be realized.

It follows from the geometry of the chamber that the beam with 250 um RMS radius (*R*) can be deposited on the vacuum chamber at the maximum grazing angle (α) of 35 mrad.

We estimate the temperature increase of the stainless steel vacuum chamber of width (*w*) in time *t* as:

$$\Delta T = \frac{Pt \sin\alpha}{C_s w \rho 2\pi R^2} \qquad (1)$$

Where C_s and ρ are respectively the specific heat capacity and density of stainless steel, and *P* is the beam power.

The stainless steel temperature to yield is 170 ^{o}C. Applying (1) to the failure happening for the worst parameters taken for the beam with *R*=250 um we obtain the time to yield of 37 us. If we apply (1) to the (highly improbable) case of the beam with *R*=1 mm deposited on the vacuum chamber at a normal incident angle we obtain the time to yield of 21 us.

Thus, building a substantial safety margin into our system we require the MPS reaction time to be 20 us.

The estimates performed with (1) were double-checked and confirmed by ANSYS simulations.

LOW CURRENT MODE

It is essential for successful machine commissioning that in the LCM the MPS allows any beam steering as well as complete loss of the beam.

In the LCM the beam can be deposited on the vacuum chamber, the YAG profile monitor equipped with the copper mirror inclined at 45^{o} with respect to the beam direction, the emittance slit, the vacuum valve or the beam scraper.

To estimate the thermal effect of the beam loss in the LCM we apply (1) to the case of the beam with the timing pattern specified for the LCM (Table 1) and with *R*=0.25 mm deposited on a stainless steel surface with a normal incident angle and to the case of the beam with *R*=1 mm deposited on the copper surface at 45^{o} angle. The results of such calculations are presented in Fig. 2.

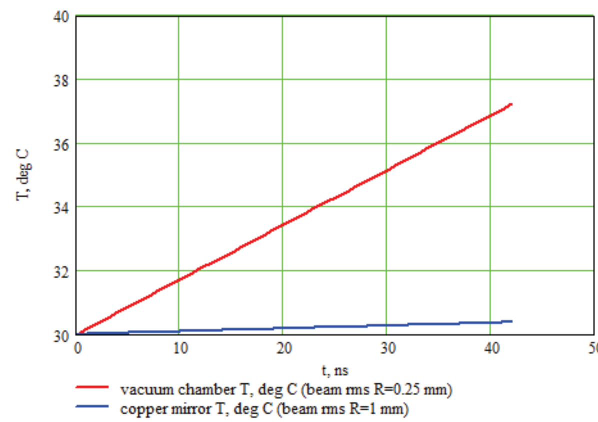

Figure 2: Red trace shows the effect of 42 ns long macro-bunch with *R*=0.25 mm and Q_b=130 pC hitting the stainless steel surface at a normal incident angle. The blue trace shows the thermal effect on the copper mirror intercepting 42 ns long macro-bunch with R=1 mm and Q_b=130 pC at 45^{o} angle.

It is obvious that the effect of complete beam loss in the LCM is well within the range of elastic deformation of both stainless steel and copper. We do not expect any fatigue failure from such a small thermo-mechanical stress.

We conclude that the LCM is ultimately a safe operation mode that does not require any control of beam trajectory or beam losses.

POSSIBLE FAILURE SCENARIOS

We consider the following possible machine failures:

1. Beam lost inside the gun.
2. There is a possible laser failure that will result in the train of electron bunches having the same average beam power but carrying a charge per bunch which differs from the design one. These wrong-charge bunches will be not focused properly and will get lost at the entrance of the SRF Booster.

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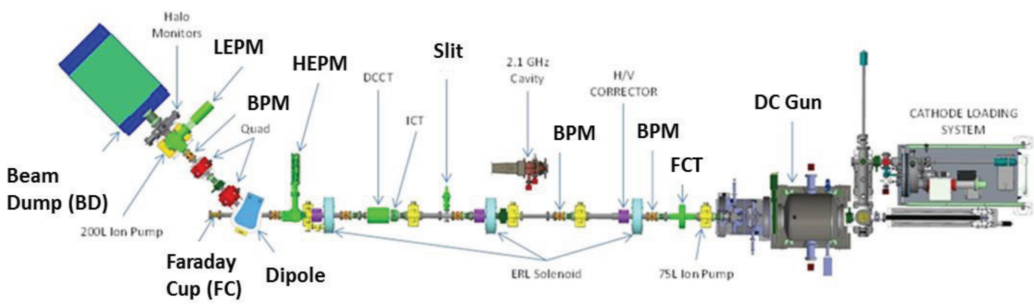


Figure 3: Layout of LEReC gun test.

3. Beam having a wrong power is lost on the insertion device, dump or vacuum chamber.

We shall exclude the possibility of beam losses inside the gun. To do so we will initially use administrative controls, which will require an operator to start commissioning with minimally observable charge and current to establish good beam trajectory out of the gun prior to increasing beam charge. After the beam trajectory out of the gun is established, the MPS will be monitoring the settings of the anode corrector current and of the laser input mirrors position.

After detailed studies of the possible beam losses in the SRF Booster due to the laser failure described above we concluded that the planned Booster quench protection is adequate enough to guarantee that no damage is done to the SRF system. Therefore the MPS will rely on the quench detection signal to shut down the accelerator in a timely fashion.

Finally, we plan both proactive and reactive responses from the MPS to protect accelerator against the failure described in item 3.

The scheme of proactive protection involves automatic detection of the present beam power and of the surface, which the beam is supposed to hit. It also includes continuously monitoring the readings of a number of beam position monitors (BPMs) and tripping the accelerator in case the beam trajectory goes outside of the allowed range.

The reactive part of machine protection will rely on detecting the beam losses exceeding allowed threshold. We plan to install a number of beam loss monitors (BLMs) in the strategic locations and also to detect losses from the differential readings of the fast current transformers (FCTs) located downstream of the gun and upstream of each of the beam dumps [2].

Thus, the MPS will rely on BPM, FCT and BLM readings. We expect the FCT and BLM reaction times to be within a few microseconds range. The BPM readings are updated every 12 us.

MPS LOGIC

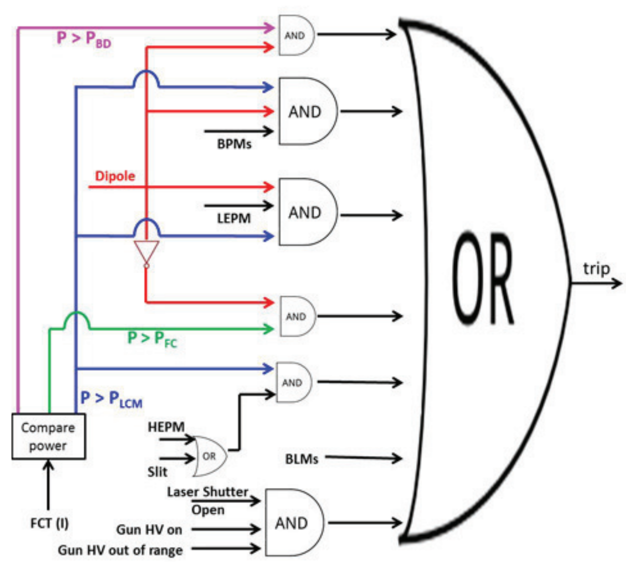
The MPS determines the surface, which the beam is supposed to hit, from the settings of the dipoles and from what insertion devices are inserted into the beamline. These inputs to the MPS are called qualifiers.

Depending on the qualifiers MPS determines what beam power is allowed for the present machine settings.

The actual beam power is calculated from the current readings of the FCT and from the assumed beam energy.

Next, the MPS compares the measured beam power to the allowed one and if the measured power exceeds the allowed limit then the MPS trips the machine. Another cause for the MPS to trip the machine above certain power limit is the BPM readings outside of the allowed range.

Finally, the MPS always monitors the BLM readings and in case the losses are above the predefined limit the MPS trips the accelerator.



	0	1
Dipole	Off	On
BPMs	In range	Not in range
LEPM	Out	In
HEPM	Out	In
Slit	Out	In
BLMs	Losses are below limit	Losses are above limit

Figure 4: MPS Logic for the LEReC gun test.

To clarify the described concepts we will consider the MPS logic for the simple beamline that will be commissioned during LEReC gun test (Fig. 3).

The logic of the MPS for the gun test is schematically shown in Fig. 4.

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The LEReC gun test beamline consists of the DC gun and the transport line to the beam dump (BD) which includes a single dipole magnet. If the dipole is turned on then the beam is transferred to the BD, if the dipole is turned off then the beam is transported to the Faraday cup (FC). Both the BD and the FC have the beam power levels (P_{BD} and P_{FC}) that they can accept.

The energy of the beam in the gun test is defined by the gun only and is expected to be 400 keV. Therefore, beam power is completely defined by the current as read by the FCT.

The insertion devices in the gun test beam line include the emittance measurement slit and the high energy profile monitor (HEPM) installed upstream of the dipole as well as the low energy profile monitor installed downstream of the dipole (LEPM). The insertion devices can accept the LCM beam. If the beam power exceeds the power of the low current mode beam (P_{LCM}) then the MPS trips the machine.

The MPS monitors beam trajectory in the BPMs upstream and downstream of the dipole for beam power $P>P_{LCM}$.

Finally, we have two additional operation modes, the "isolation mode" and "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 TO LASER INTERFACE

The MPS trips the accelerator by shutting down the laser beam to the photocathode.

The sequence of the laser devices used to shape the pulse trains in the time domain is schematically shown in Fig. 5.

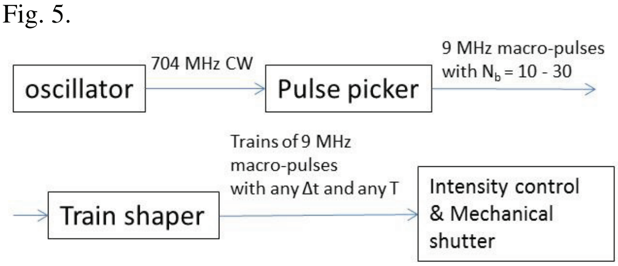

Figure 5: Laser pulse shaping scheme.

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. Since the pulse picker has to be fine-tuned for the high extinction ratio it must be physically by-passed to switch to the CWM. Hence, it cannot be used by the MPS.

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 PC can withstand the high voltage only for 5% of its switching period. Therefore, in the CWM it can be used by the MPS only in combination with the fast mechanical shutter. That is, when a trip condition is detected the MPS will apply a voltage to the PC for 50 ms, which is enough time to close the shutter (shutter closing time is a few milliseconds).

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.

The EOM can be used to shut down the laser since its "0 Voltage" state corresponds to zero laser output. The alignment of the EOM can get as bad as 2 % after it was exercised several times. Thus we expect that about 2 % of the nominal laser intensity will be reaching the cathode until the mechanical laser shutter is completely closed.

We plan to use both the PC and the intensity control EOM together with the mechanical shutter to block the laser beam to the photocathode.

CONCLUSION

We discussed the conceptual design of the fast Machine Protection System for the Low Energy RHIC Electron Cooling accelerator.

The MPS is designed to protect the insertion devices, the vacuum chamber and the beam dumps from excessive deposit of the electron beam.

The MPS will detect any possible fault condition and will shut down the electron beam within 20 us by inhibiting the laser beam to the photocathode.

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