LEReC INSTRUMENTATION DESIGN & CONSTRUCTION *

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Abstract

The Relativisitc Heavy Ion Collider (RHIC) at BNL will collide ions with low center-of-mass energies of 7.7 – 20 GeV/nucleon, much lower than 100 GeV per nucleon. The primary motivation is to explore the existence of the critical point on the QCD phase diagram. An electron accelerator is being constructed to provide Low Energy RHIC electron Cooling (LEReC) [1] to cool both the blue & yellow RHIC ion beams by co-propagating a 10 – 50 mA electron beam of 1.6 – 2.6 MeV. This cooling facility will include a 400 keV DC gun, SRF booster cavity and a beam transport with multiple phase adjusting RF cavities to bring the electron beam to one ring to allow electron-ion co-propagation for ~20 m, then through a 180° U-turn electron transport so that the same electron beam can cool the other counter-rotating ion beam, and finally to a beam dump. The injector commissioning is planned to start in early 2017 and full LEReC commissioning planned to start in early 2018. The instrumentation systems that will be described include current transformers, BPMs, profile monitors, multi-slit and single slit scanning emittance stations, time-of-flight and magnetic energy measurements, and beam halo and loss monitors.

INTRODUCTION

Full operation of LEReC is planned for 2019-20 with cooling of the RHIC ion beams using bunched electron beams of 1.6 – 2.6 MeV [1, 2]. With delivery of a 750 keV DC gun from Cornell University [3] (planned for operation at 400 keV) in October of this year, the injection section is being installed to support commissioning of the gun, followed by installation of the rest of the machine in the summer of 2017. The electron beam has a nested pulse structure [4], where 80 ps bunches at 704 MHz are grouped in macrobunches and positioned to overlap with the 9.1 MHz RHIC ion beam. The macro bunch size varies 30 – 24 bunches and its maximum charge varies 130 – 200 pC (incl. 30% margin) depending on the range of ion bunch length. The machine layout is shown in Fig. 1.

ELECTRON BEAM INSTRUMENTATION

The parameters measured in each section of the machine layout are quantified in Table 1. Details of each instrument type are elaborated on below.

Gun Instrumentation

In support of HV conditioning of the DC gun, a 24-bit ADC board measuring the voltage across a 350 Ω shunt resistor in series with the HVPS and the cathode and sits at the cathode potential in the SF_6 tank. It is powered via a "power over fiber" link [5]. Cathode current is reported during HV conditioning where the current is kept below 100 μA. The gun has a floating anode biased positive to < 1kV to provide ion collection between the gun and booster. A Keithley 6514 electrometer will monitor the anode current.

Table 1: Parameters Measured in Each Machine Section

Tt-Total; **Inj**-Injection; **Tr**-Transport; **Mg**-Merger; **Dia**-Diagnostic; **Cl**-Cooling; **Ex**-Extraction

Tt	Measure	Inj	Tr	Mg	Dia	Cl	Ex
13	Profile	3	1	1	1	6	1
4	Charge	2			1		1
7	Current	4			1		2
41	Position	8	9	2	2	17	3
1	Halo	1					
3	Emittance	1				2	
2	Δp/p			1		1	
1	Energy					1	
1	Long. Φ Sp				1		
15	Beam Loss	4	3	1		5	2

Profile Monitors

Beam profile monitors (PM) employ YAG:Ce crystals and optics for 50-μm resolution. All 13 PMs have low impedance vacuum chambers [6]. YAG:Ce crystals are 100 μm thick with 100 nm Al coatings. All but one PM have 45° polished Cu or SS mirrors that can withstand a single full-power macrobunch @ 1Hz. The PM in the diagnostic section will have a mirrorless design to withstand 250 μs long trains. Tilted lens optics will correct for depth-of-field limitations associated with its 45° YAG crystal. All PM's are pneumatically driven and use GigE digital cameras.

The Prosilica GT1600 camera with iris control is being investigated for use with P-Iris type lenses for remote control of iris settings to help cope with wide macrobunch intensities during commissioning. All PM's have LED illumination and optical features next to and in the same plane as the YAG crystal to assist in focusing of the optics. A 450 nm laser is included to test the response and focus of the YAG crystal by simulated beam scintillation. Two of the PM's in the cooling section are hybrid devices [6] with a horizontal-plane BPM integrated into the chamber.

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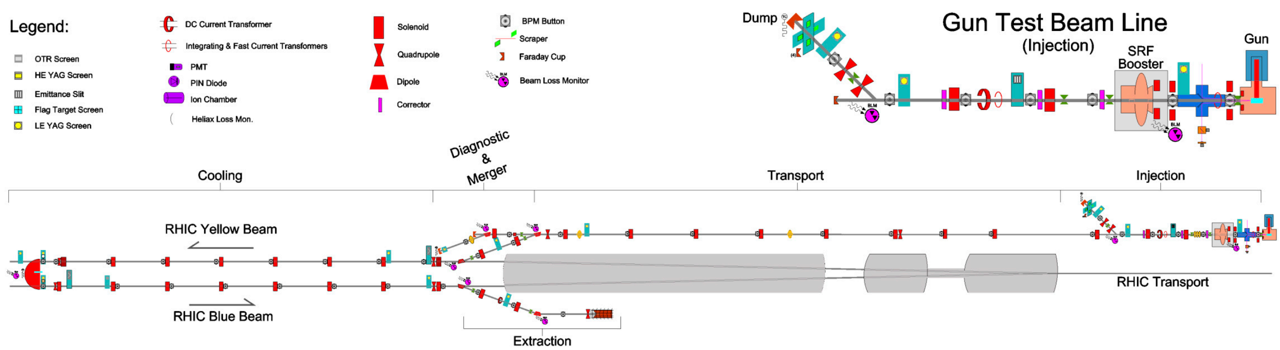

Figure 1: Layout of LEReC electron accelerator showing the five sections. An enlarged view of the injection section as it will be set up during the Gun Test is shown on the right.

Charge and Current

Beam charge is measured by one in-flange integrating current transformer (ICT), Bergoz model ICT-CF6-60.4, in the injection section, and by the three Faraday cups in the electrically isolated beam dumps, in the injection section spur, diagnostic section and extraction section. Beam current is measured by four Fast Current transformers (FCT), Bergoz model FCT-CF6.75"-96.0-UHV-ARB, one at the beginning of the injection line and one upstream of each beam dump. The FCTs are tuned to a narrow band at 704 MHz with a Q = 5 and a 5V/A ratio. Signals from the above mentioned devices are all digitized by FMC164 daughter cards with 16-bit 250 MS/s ADCs supported by a Zynq-7000 FPGA on a ZC706 board by Xilinx.

The first FCT in the injection section is used by the MPS to trip if the beam current exceeds the limit of the current specified by the auto-detected machine mode, based on beam destination [7]. The subsequent three FCTs, upstream of each beam dump (Injection, Diagnostic, and Extraction) are used by the MPS to trip on beam loss by differential current measurements along trajectories toward each beam dump.

Additionally, two DC current transformers (DCCT), Bergoz model NPCT-S-115, will differentially measure low level losses, between the Injection and extraction sections, to detect small losses causing slow heating of the beam line. Under development, recent tests suggest resolutions of 1 – 5 µA with 63 kHz sampling and 1 second averaging.

Due to the low rigidity of the 1.6 MeV electron beam, all ceramic surfaces will be shielded to avoid charge build-up that can deflect the beam. A cylindrical shield attached at one end was made for both the ICT and DCCTs. The FCTs are being ordered with Bergoz's ARB option that hides the ceramic behind a 3-mm gap between opposing flange faces extending beneath the ceramic from both sides.

Beam Position Monitor

Button-style BPMs (41 in total) are 4-button dual plane types, except for the two horizontal BPMs in the Hybrid PM's [6]. The strictest requirement for position monitoring is a 50-µm relative accuracy between the electron and ion beams in the cooling section where the angle between them of < 100 µrad is necessary for effective cooling.

Dual electronics modules share each cooling section BPM – one with a 700-MHz band-pass filter for electrons and one with a 39-MHz low-pass filter for ions. Custom VME-based V301 electronics modules [8] are being installed, for 2×17 cooling section BPMs, and 8 elsewhere.

The 39-MHz modules will measure both electrons and ions. In order to have an identical response to both the electron macro bunches (with a 704 MHz internal structure) and the ion bunches, the 9-MHz structure of both beams will be isolated with digital filters. Avoiding interference of the two beams' signals, the electron train will be measured in the ion beam abort gap and the ion beam measured one bunch per turn. The selected ion bunch will be sequenced through all buckets, with the corresponding electron bunch suppressed. With this sequenced electron bunch suppression, reduced cooling of each ion bunch will only be about 0.9% instead 100% for one bunch.

The V301 modules are being equipped with position alarms with 12-µs response times to trip the MPS. This will be one of the two primary lines of defense that the MPS [7] relies upon to turn off the electron beam.

Relative phase between modules will also be measured to determine beam energy during the 400 keV low energy test of the DC gun by resolving the time of flight between selected BPMs.

Libera Brilliance Single Pass electronics, repurposed from the ERL [9], will be used at 16 locations outside of the cooling sections. The 17 BPMs in the cooling section use 64 conical-style 28-mm buttons in 5-inch chambers, made by MPF [10]. The rest of the transport employs a mixture of 40 new 15-mm buttons made by MPF and 56 x 9-mm buttons (repurposed from the ERL).

Beam Halo Monitor

In order to measure the beam halo, a four-quadrant halo monitor will be installed at the end of the diagnostic spur in the injection section. Repurposed from the ERL, each of the four stepper-controlled 5mm-thick copper blades will be mounted to provide a minimum aperture of 40 mm. Each blade is 30 mm wide and can travel from 20 mm to 43 mm from beam center. The blades are isolated and connected to integrating amplifiers and are digitized with the same electronics as are used for the faraday cups.

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Emittance

Emittance measurements are planned in three locations to ensure normalized emittance < 2.5 µm. In the injection section, a dual multi-slit mask, 2.0 m upstream of a PM is pneumatically driven. Based on the expected beam size, divergence and energy, a 10-slit array was made with slits 150 µm wide, separated by 1.35 mm covering an area 12 x 15 mm. Two such arrays are placed orthogonally on one tungsten mask 1.50 mm thick for horizontal and vertical emittance measurements.

The mask design can accommodate measurements of three beam energies, 400 keV, 1.6 MeV, and 2.6 MeV. Simulations of emittance measurements with beam phase space distribution from Parmela calculations were performed to optimize the slit geometry and drift length from multi-slit to the profile monitor for the three energies. Measurement errors for the three energies of 0.15%, 23.5%, and 24.3% respectively were predicted [11, 12].

In the cooling section, two emittance slit scanners [6] being installed next year, have large 2-mm thick tungsten masks with orthogonal 150-µm wide slits that are stepper-driven at 45° for H+V measurements in one scan. Downstream PMs will take images at a 1 Hz rate while the masks scan at 0.5 mm/sec over a 30 mm spot to include all particles in the beam.

Energy Spread

The electron beam must have an energy spread of $\Delta p/p < 5\times10^{-4}$ for effective cooling of the ion beam. Thus $\Delta p/p$ is measured in two locations. The beam is temporarily focused to a minimum on a PM during the measurement. The first measurement is made at the mid point of the merger section. By comparing the beam sizes (σ_x, σ_y) on the screen, the difference $\Delta\sigma$ gives the dispersion due to the energy spread. The second measurement is made across the 180° dipole in the cooling section where three PM's are used [6]. The first PM will insert a slit 150 µm wide in a 1.5 mm thick tungsten mask to define the horizontal size (σ_x). A second PM down stream of the dipole will, with the dipole off, measure σ_{x1} at a distance (d_1). A third PM, at an equivalent distance (d_1) but along the path through the dipole, will measure σ_{x2} of the beam after the dipole. The resolution will be < 5% $\Delta p/p$.

Energy

Absolute energy of the electron beam is measured in two ways. A time-of-flight energy measurement at 400 keV will be made by the V301 BPM modules [8], during gun commissioning. The 180° dipole is used as a magnetic energy spectrometer [6] for beam energies of 1.6 – 2.6 MeV in conjunction with up and downstream BPMs. Accounting for various possible errors in measurements and in the magnet field, we expect to measure beam energy with an accuracy of 2.6×10^{-3} [13].

The magnetic field of the 180° dipole will be continuously monitored by an NMR probe, built by Caylar [14], installed in the gap. It will measure the average field (195 gauss for 1.6 MeV beam) at a 1-Hz rate. The probe is optimized for low field measurements of 180 – 325 gauss with an accuracy of 50 milligauss and a noise floor of < 20 milligauss. Needing only slow correction, the feedback from the NMR probe will simply modify the magnet power supply set-point via software in the control system.

Longitudinal Phase Space

For low $\Delta p/p$, short bunches of 80 ps are produced in the gun to mitigate the effect of the RF curvature in the LINAC and then chirped, stretched, linearized and de-chirped by the four cavities [15]. The energy chirp introduced in the 704-MHz SRF booster cavity stretches the bunch to mitigate effects of the high space charge. The chirp is then linearized by the 2.1-GHz warm cavity just downstream of the booster and then de-chirped by the 704-MHz warm cavity at the end of the transport section. Moreover, a 9-MHz warm cavity in the middle of the transport section compensates for periodic transient beam loading across the macro bunch. In order to achieve minimum beam energy-spread, each cavity must be tuned in amplitude and phase, in addition to the laser phase and DC gun voltage, resulting in 10 parameters to optimize. This necessitates the "Longitudinal Phase Monitor" (LPM) in the diagnostic section while tuning to optimizing the longitudinal phase space.

The LPM is comprised of a 704-MHz transverse mode deflecting cavity [16] located just after a 20° dipole and upstream of the mirrorless PM. The $\Delta p/p$ of the macro-bunch is displayed on the PM as the dipole expresses the $\Delta p/p$ as horizontal $\Delta\sigma_x$ and the deflecting cavity tilts the beam to express the beam's longitudinal axis onto the vertical axis. This gives an image of $\Delta p/p$ vs time (or length – z).

With a horizontal beam size σ_x = 250 µm and a dispersion of 1 m at the PM, a $\Delta p/p$ of 5×10^{-4} results in an increased σ_x = 560 µm. We require a $\Delta p/p$ resolution of 1×10^{-4} (1/5 of nominal) to properly tune the V and Φ of the RF cavities. This translates to a required resolution of the PM of 100 µm (met by the 50-µm design resolution.)

In order to measure RF field stability in the presence of beam loading transients, the profile must be taken after the cavities have stabilized. Thus this PM must withstand a macrobunch train length up to 250 µs [17]. As the Prosilica GT GigE digital camera has a 20ns trigger jitter [18], it will be gated to capture only the last 10 µs [19]. Once the RF system is properly tuned, its response to a single macro bunch will be equivalent to that of a long train. Thus, the PMs in the cooling section are designed to withstand single macro bunches at 1 Hz.

Beam Loss Monitor

The machine has several vulnerable spots where a normal incident beam can breach the vacuum chamber in as little as 30 µs. This requires a comparable reaction of the MPS [7] with fast trip indicators. Thus, in addition to the beam position alarms, an array of fast beam loss detectors will be installed. This will consist of 16 PMT-based sensors, 8 RHIC style ion chamber sensors, and 8 PIN diode sensors all repurposed from the ERL [9]. The PMT sensors are based on a design used for the 12 GeV up-

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grade to CEBAF [20] at JLAB. The ion chambers are spares produced for the BLM system [21] in RHIC. The PIN diode detectors are model BLM “Beam Loss Monitors”, from Bergoz Instrumentation. These detectors will constitute eight groups of all three types distributed to each bending magnet and around the SRF booster. The remaining eight PMTs will be distributed along the transport and in the cooling section.

The PMT sensors were used in CEBAF at energies above 5 MeV. To increase their sensitivity to the 1.6 MeV beams in LEReC, scintillating fibers, 2 – 12 m long, will be coupled to the PMTs. The fibers are BCF-60 radiation hardened 1 mm diameter fibers by Saint Gobain [22]. The total length of fibers will cover the entire length of the LEReC machine.

The signals from the PMTs will be processed by VME based 8-channel FPGA electronics cards [23] purchased from JLAB. With a 1-μs fast shutdown output to the MPS, this PMT BLM card also has a log amplifier to provide 5 decades of dynamic response to aid in the commissioning of the machine with low beam power.

COOLING INSTRUMENTATION

Energy Matching

For successful e-beam cooling of the RHIC beam, the energies of the two beams must be matched with 10^{-4} accuracy. To start, the absolute e-beam energy must be set to an accuracy of better than 10^{-2} [13]. While the energy of the ion beam can be known to $<1\times10^{-4}$, the electron energy will be initially set to 5% by the RF voltage and then to 0.3% by the magnetic spectrometer. Yet finer e-beam energy will be attained by observing the recombination monitors where the rate will be maximized with further alignment and scanning of the RF phase. The final e-beam energy will be set by observing the Schottky spectrum while further adjusting the position and RF phase.

Recombination Monitor

As an indicator of proper alignment of the electron and ion beams for cooling, PIN diodes attached to rate counters will be installed in one of the cold arcs of RHIC to detect radiation from lost Au^{78+} ions from recombination. Energy matching of the electron and ion beams of at least 2% is required. Recombination will indicate an energy match of up to 0.1%. Recombined ions are lost in a local dispersion bump created in a special RHIC orbit with a deviation of 7σ in one of the arcs [24]. Recombination rates of better than 4 MHz are expected, less the attenuation due to the vacuum chamber and obscuring objects in the tunnel. A successful test was done during the RHIC 2016 run showing that lost ions can be detected outside the cryostat.

Schottky Monitor

Analyzing the Schottky spectrum from the RHIC wall current monitor (WCM), the evidence of cooling can be seen as was done at FermiLab in their recycler [2, 25]. The Schottky spectrum will be used as a probe to find the precise electron beam energy. The RHIC has a momentum acceptance aperture of $\Delta p/p = \pm4\times10^{-3}$. The RHIC beam will be debunched after injection to fill the aperture. Adding the copropagating electron beam will concentrate the ion beam energy at the electron beam energy, forming a peak in the Schottky spectrum from the WCM that will be off-center by $\Delta f/f = \eta\ \Delta p/p$. The electron energy will be iteratively adjusted accordingly by the RF voltage until the energies are matched to 1×10^{-4}. With the proper RF voltage setting found by this iterative process, the debunched ion beam will be dumped and a properly bunched ion beam reinjected so that the energies of the two beams will match and the peak will form in the Schottky spectrum on-center, indicating cooling of the ion beam.

STATUS AND CONCLUSION

The commissioning of the DC gun and test beam line are planned to run in parallel with the 2017 RHIC run. The gun will be delivered to BNL high voltage conditioning will be completed this fall. The entire gun test beam line will be installed and ready for pre-beam tests before the start of the upcoming RHIC run.

During the 2017 RHIC shutdown next summer, construction of the transport, merger and the diagnostic sections will be completed as well as the addition of the 180° dipole and instrumentation in the cooling section. Full operation of LEReC is planned for the 2019 RHIC run.

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