# INSTRUMENTATION FOR THE PROPOSED LOW ENERGY RHIC ELECTRON COOLING PROJECT WITH ENERGY RECOVERY*

D. M. Gassner #, A. Fedotov, R. Hulsart, D. Kayran, V. Litvinenko, R. Michnoff, T. Miller, M. Minty, I. Pinayev, M. Wilinski, BNL, Upton, NY 11973, USA

*Abstract*

There is a strong interest in running RHIC at low ion beam energies of 7.7-20 GeV/nucleon [1]; this is much lower than the typical operations with 100 GeV/nucleon. The primary motivation for this effort is to explore the existence and location of the critical point on the QCD phase diagram. Electron cooling can increase the average integrated luminosity and increase the length of the stored lifetime. A cooling system is being designed that will provide a 30 – 50 mA electron beam with adequate quality and an energy range of 1.6 – 5 MeV. The cooling facility is planned to be inside the RHIC tunnel. The injector will include a 704 MHz SRF gun, a 704 MHz 5-cell SRF cavity followed by a normal conducting 2.1 GHz cavity. Electrons from the injector will be transported to the Yellow RHIC ring to allow electron-ion co-propagation for ~20 m, then a 180 degree U-turn electron transport so the same electron beam can similarly cool the Blue ion beam. After the cooling process with electron beam energies of 1.6 to 2 MeV, the electrons will be transported directly to a dump. When cooling with higher energy electrons between 2 and 5 MeV, after the cooling process, they will be routed through the acceleration cavity again to allow energy recovery and less power deposited in the dump. Special consideration is given to ensure overlap of electron and ion beams in the cooling section and achieving the requirements needed for cooling. The instrumentation systems described will include current transformers, beam position monitors, profile monitors, an emittance slit station, recombination and beam loss monitors.

## INTRODUCTION

The Low Energy RHIC electron Cooling (LEReC) project is presently in its design stage and scheduled to begin commissioning components in 2017, with operations planned for 2018-19. The electron and ion parameters are shown in Table 1 and 2. This will be the first bunched beam electron cooler and the first electron cooler in a collider. The goal is to achieve an efficient cooling system for Au+Au collision beams at 7.7, 11.5 and 20 GeV/u in the center of mass corresponding to electron energies of 1.6, 2.7 and 5.0 MeV. An effective cooling process would allow us to cool the beams beyond their natural emittances and also to either overcome or to significantly mitigate limitations caused by intrabeam scattering and other effects. It also would provide for longer and more efficient stores, which would result in significantly higher integrated luminosity.

Cooling of ion and hadron beams at low energy is also of critical importance for the productivity of present and future Nuclear Physics Colliders, such as RHIC, eRHIC and ELIC.

Table 1: Electron Beam Parameters

| Electron Parameters | |
|---|---|
| Electron Beam Energy | 1.6-5 MeV |
| Electron Bunch Charge | 100-300 pC |
| Electron Average Current | 30-50 mA |
| RMS Norm Emittance | ≤ 2.5 mm mrad |
| Bunch Rep Rate | 704 MHz |
| Bunch Train Rate | 9.1 MHz |
| RMS Energy Spread | $\leq 5 \times 10^{-4}$ |
| RMS Bunch Length | 100 ps |
| RMS Trans beam size | 2-4 mm |
| Max power with ER | 100 kW |

Table 2: RHIC Ion Beam Parameters

| Ions with gamma = 4.1 | |
|---|---|
| Particles per Bunch | $0.75 \times 10^{9}$ |
| Peak Current | 240mA |
| RMS Norm Emittance | 2.5 mm mrad |
| Rep Rate | 75.9 kHz |
| RMS Energy Spread | $\leq 5 \times 10^{-4}$ |
| RMS Bunch Length | 3.2m |
| RMS Trans beam size | 4.3 mm |
| Space charge tune shift | 0.02 |

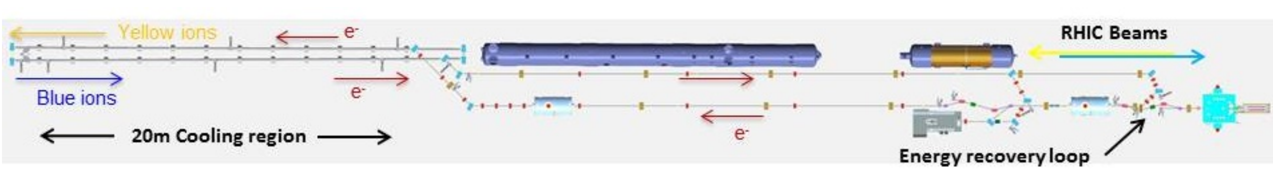


Figure 1: LEReC beam line layout for electron cooling with energy recovery. The Blue and Yellow adjacent 20 m ion cooling beam lines shown at left are located in a RHIC region without superconducting magnets.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Brookhaven National Laboratory under Contract No. DE-AC02-98CH10886.
# gassner@bnl.gov

ISBN 978-3-95450-141-0

### *Electron Guns and Bunch Patterns*

We are moving forward with two electron gun alternatives to ensure a reliable source is available for the LEReC project. We are planning to purchase a copy of the latest design 500 kV DC electron gun [2] from Cornell as a backup plan if the BNL ERL 704 MHz SCRF gun [3] does not meet the LEReC schedule or beam requirements. If the DC gun is chosen as the electron source, one option is to use the cavity of the SCRF gun as a booster.

An example of co-propagating electron-ion bunch patterns during the cooling process with 4.1 gamma ions are shown in Figs. 2 and 3. For the highest ion energy of 10.7 gamma we can place 18 electron bunches on a single ion bunch.

### *Electron Beam Path for Cooling*

The LEReC project is planned to be carried out in two phases. The first phase will use 1.6-2MeV electrons to cool 7.7-9.1 GeV gold ions. The electron beam path for this phase will be from the gun through a 5-cell SCRF Linac and 2.1 GHz cavity, and then ~20 m of beam transport to the RHIC beam line, cool both RHIC beams, and then back to a dump.

The instrumentation proposed for the original LEReC design without energy recovery can be found in this reference [4]. It has recently been decided to use many of the BNL R&D Energy Recovery Linac (ERL) [5] components in the LEReC project for a variety of reasons primarily driven by equipment cost savings.

During phase 2 scheduled for the following year, the plan is to modify the upstream beam lines to include two zig-zag emittance compensation regions, and install an additional beam transport to allow energy recovery and therefore reduced power deposited in the dump. This configuration is shown in Figs. 1 and 4.

### *Electron Beam Merging and Splitting*

There will be two zig-zag emittance compensation beam transports in injection portion of the LEReC facility when the energy recovery upgrade is installed. They are located upstream and downstream of the SCRF 5-cell 704 MHz cavity as shown in Fig. 4. Both zig-zags are similar, they each utilize four dipoles.

The main function of the merger upstream of the Linac is to combine two beams with different energies to allow

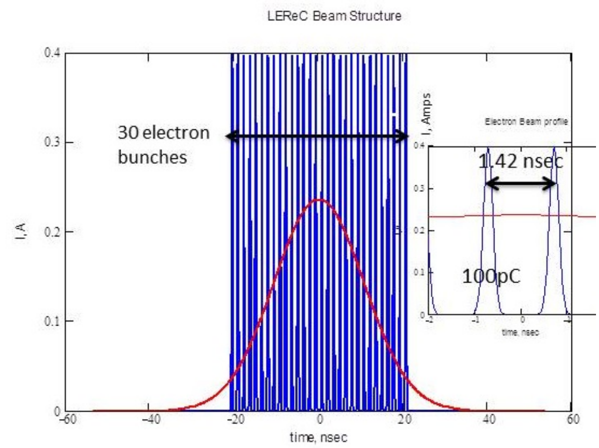


Figure 2: Thirty electrons bunches (blue, 1.42 ns apart) overlap a single ion bunch (red). Example for ion long bunches with 9 MHz RHIC RF at gamma = 4.1.

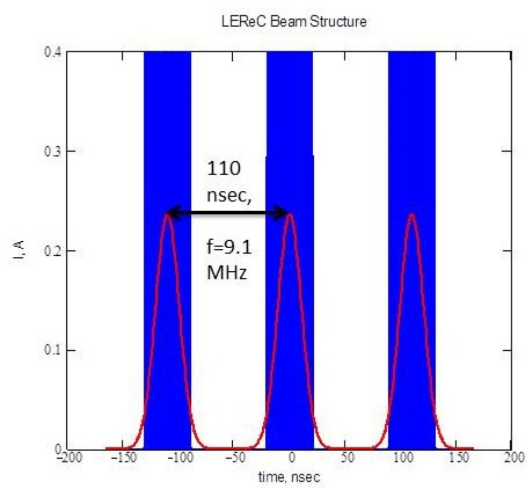


Figure 3: Electron bunches (blue) overlap ion bunches (red) spaced 110ns apart utilizing the 9 MHz RHIC RF.

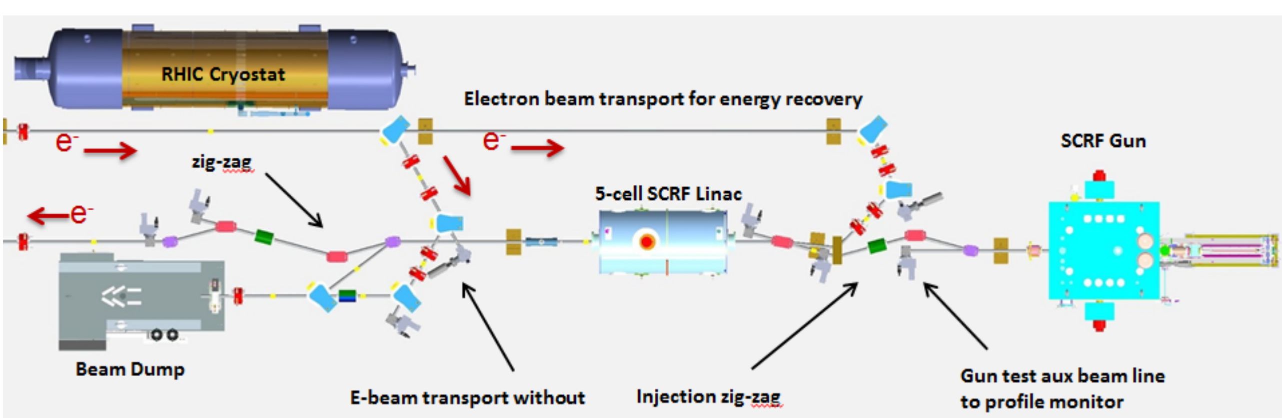


Figure 4: LEReC beam line detailed layout showing additional beam transport and two zig-zag matching sections that allow recirculation through the Linac for energy recovery when cooling with 2 to 5 MeV electrons.



ISBN 978-3-95450-141-0

energy recovery, and conversely the main function of the separator downstream of the Linac is to extract the low energy beam and steer it towards the dump and allow the higher energy beam to continue while maintaining its emittance. The zig-zag for existing ERL configuration was proposed to preserve the emittance of the low-energy high-charge electron beam [6].

Since each beam has an energy spread a single dipole would not only separate the high and low energy beam but also introduce a transverse growth of emittance, proportional to the initial energy spread. By matching the "dispersion function" to be zero after the merge this is avoided.

The combination of low energies (less than 10 MeV) and high bunch charge is another effect that blows up the emittance. The space charge forces repel particles from each other. Hence, the particles in the head of the bunch gain energy, while the particles at the tail of the bunch lose energy. If an electron changes energy inside the bump then the dispersion matching is disrupted. However, by adding a second bump in the opposite direction the disruption in the first bump is cancelled in the second bump. A zig-zag is the compact form of two bumps.

## ELECTRON BEAM DIAGNOSTICS

The electron beam diagnostics systems will provide measurements to:

- Commission the 704 MHz SCRF gun with a maximum energy of 2 MeV beam and commission the SCRF Linac.
- Ensure the beam transport of electron bunches without significant degradation of beam emittance and energy spread throughout the 1.6 to 5 MeV energy range.
- Ensure low transverse angular spread for the electron beam in the cooling section.
- Ensure that the quality of the beam is preserved through the entire beam transport and both cooling sections.

The preliminary distribution of the beam diagnostics is shown in Figs. 7 and 8.

### *Electron Beam Position Monitors*

As we are still in the early stages of the system design, the development of a detailed commissioning plan is still underway. There are 24 dual plane position monitor pick-up stations planned. We plan to reuse the 9 mm buttons from ERL and purchase additional 15 mm buttons from MPF Inc. These will be installed at key locations along the ~70 meter beam line. The proposed BPM locations and quantity may vary as the simulations and specifications evolve. We plan to use Libera Brilliance Single Pass [7] electronics from Instrumentation Technologies; these will also be repurposed from the ERL project. The allowable transverse error for a single pass of 100 pC bunch is 10 microns (angular resolution of one microradian with a cooling section length of 20 meters). The angle between the electron and ion beam should not be more than 50 microradians, this specification comes from the limitation of 50 microradian difference over the 2 m distance between cooling section solenoids, and it allows 100 microns transverse deflection. Averaging position data over multiple passes and increasing number of bunches will increase the measurement accuracy.

To measure the short electron bunch train position while it co-propagates with the long ion bunches, electronics with an input band-pass filter frequency of 500 MHz can be used so the signal from the ion bunches (3 m rms bunch length, 7.5 e8 ions) that have lower frequency components will be suppressed. These units will require lower band-pass filter frequency (10-100 MHz). The effect of the electron beam can be subtracted from the data from ion BPM receivers. Calibration can be done by running each beam independently. The electron-ion beam transverse alignment in the cooling section needs to be ~2% of the 5 mm electron beam sigma, or ~100 microns.

We plan to utilize new in-house designed VME based BPM electronics modules in the cooling region, these are presently under development. These modules are based on a Xilinx Zynq processor programmable logic array combination which allows for greater flexibility in designing custom processing algorithms for a variety of bunch frequencies and types. The present design incorporates 500 MHz and 707 MHz band pass RF filters in the analog input section which are suited for electron beam measurements. A different configuration also allows the use of a 39 MHz low pass filter instead for hadron beam measurements. A set of four A/D converters can be clocked at rates up to 400 MHz and provide four channels of measurement on each VME board which will correspond to each dual-plane BPM module. Each VME module has its own Ethernet connection to the network which allows direct access to data from standard Controls software tools. The first series of hardware boards have been received at BNL and are currently under testing and evaluation.

### *Electron Beam Transverse Profile Monitors*

Transverse beam profiles will be measured at a variety of pneumatically plunging stations using 0.1 X 30 mm YAG:Ce screens. Images from the YAG screens are transported through a mirror labyrinth to a GigE CCD camera in a local enclosed optics box.

A pair of specially designed YAG dipole profile monitors [8] will be provided in the zig-zag transport sections. This design is necessary due to tight space constraints. They will plunge into the beam path inside of the two 30º y-shaped dipole vacuum chambers as shown in Figs. 5 and 6. These instruments are presently being designed and fabricated by Radiabeam Technologies. Precise YAG screen positioning will be provided by a stepper motor actuated plunging mechanism, with a 4-inch stroke, that has a long YAG screen holder that extends into the dipole magnet chamber through an auxiliary port to intercept the electron beam. The beam can be imaged at different places on the crystal including the edge depending on the plunge depth. This can be useful for semi-destructive beam halo monitoring.



ISBN 978-3-95450-141-0

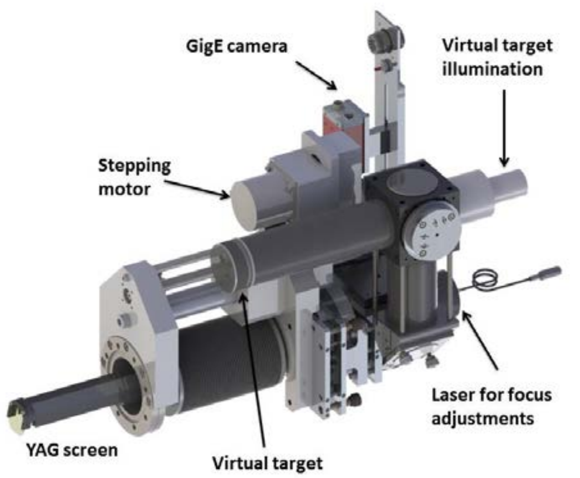


Figure 5: Dipole Profile Monitor assembly, drawing courtesy of Radiabeam Technologies.

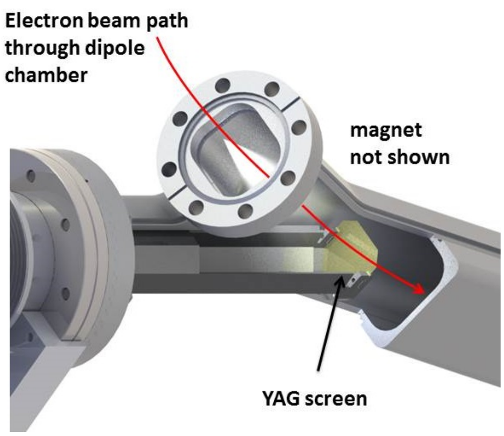


Figure 6: Dipole Profile Monitor shown with YAG screen inserted into the beam path, drawing courtesy of Radiabeam Technologies.

## *Electron Beam Emittance*

There are several techniques planned to measure beam emittance. The expected rms normalized emittance is 2.5 mm-mrad. Several emittance slit stations will be used to measure the electron beam emittance. The first station with be located just downstream of the gun to ensure the gun performance meets the requirements. The second station will be located just before the electron beam merges with the ion beam to ensure the emittance is adequate for cooling. These stations will be comprised a multi-position plunging tungsten mask with a slit pattern upstream of a YAG profile monitor. A calibration laser will be installed upstream of each slit mask to ensure the slits are properly aligned with the electron beam.

## *Electron Bunch Charge and Current*

Bunch-by-bunch and bunch train charge will be measured by a Bergoz [9] in-flange Integrating Current Transformer (ICT). Beam charge signals will be processed by standard BCM-IHR Integrate-Hold-Reset electronics feeding a beam-synch triggered digitizer. In order to increase the range of commissioning modes that

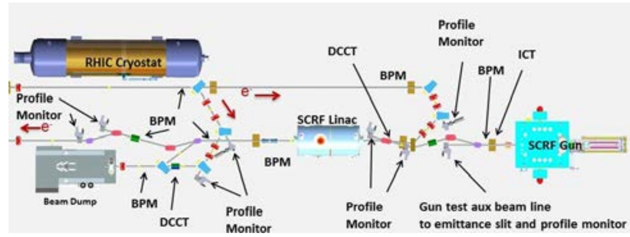


Figure 7: Electron beam diagnostics in the injection transport from the SCRF Gun to the 5-cell SRF Linac, and the transport to the beam dump after energy recovery.

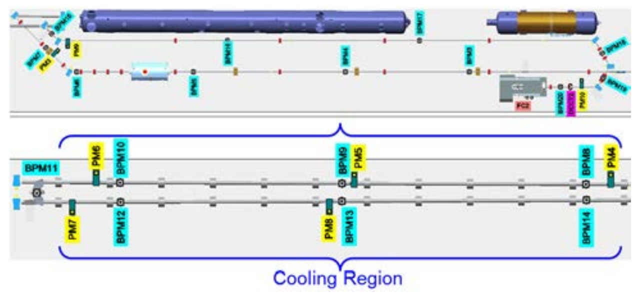


Figure 8: Top, BPMs (blue) and profile monitors (yellow) in the transport to and from the cooling region. Bottom, diagnostics are shown in the cooling and U-turn region.

this system will be compatible with, the 10 kHz measurement rate option was included. The ICT will be installed in the upstream portion of the electron transport near the gun.

There will be a pair of Bergoz NPCT DCCTs configured in differential mode, installed to measure the absolute beam current and transport efficiency, one near the injector and one near the dump. We plan to employ a similar system that is presently being designed for use at the BNL ERL [10].

The low and high power dumps will be electrically isolated to allow direct current measurements of the collected beam using current meters or gated integrators.

## *Electron Beam Loss Monitors*

Efficient beam transport needs to be maintained and protection against possible damage to the equipment needs to be provided in the electron beam transport and in the common sections. Photomultiplier tube (PMT) based loss monitors are a candidate to be the primary loss detector and will be installed at a variety of locations. The design of the detector and signal processing electronics [11] are based on ones developed at Jefferson Lab and used at CEBAF. At the LEReC facility we plan to use the Hamamatsu R11558 PMT in these loss detectors. Based on experience we will obtain at the ERL, we also plan use some long heliax cable detectors and RHIC style ion chambers.

## *Electron Beam Stability*

The stability requirement for bunch intensity variations is better than 7%. Shot-to-shot charge variations at this level can be monitored with an ICT and beam charge monitor electronics by Bergoz which has a dynamic range



ISBN 978-3-95450-141-0

over 800. The bunch phase jitter requirement can tolerate 100 ps which is comparable the 100 ps rms electron bunch length we are planning. We have measured the RHIC ion beam jitter to be less than 25 ps.

### *Ion Clearing*

The preliminary design included plans for ion clearing electrodes in the beam transport line every 5m. An alternative clearing method could be produced by simply making few microsecond clearing gap in electron bunch current. We will have a 100 ns gap between electron bunch trains, which may be enough to clear away unwanted ions. Future simulations will confirm the best strategy to use with the LEReC beam parameters to avoid the impact of ionized residual gas that is considered a source for instabilities in accelerators.

### *Energy Spread, Halo, and Bunch Length*

Simulations and tracking will be done to determine the best method and location to measure and collimate the beam halo. Early determinations show a preference to locating halo related instruments after the first bend.

By accelerating off-crest in the accelerating cavity and viewing the transverse beam profile images on a downstream YAG screen we will get information about the bunch length from the measured growth of the beam energy spread.

### *Electron-Ion Energy Match*

The diagnostics and method to match the electron energy to the ion energy has to be detailed. The strategy for synchronization between the bunches needs to be determined, an early estimate of accuracy/resolution of ~10 ps. We will need a transducer that can provide this level of accuracy, a BPM pick-up may be useful depending on the type chosen.

### *Beam Dump Diagnostics*

The 1 MW water cooled dump [12] constructed for the BNL Energy Recovery Linac project will be repurposed to absorb the 100 kW LEReC electron beam power. Typically a set of distributed dump vessel temperature sensors would be used to monitor and help avoid any concentrations of dumped beam power and damage. This dump is designed with a dual layered water cooling jacket to provide a forward and return cooling path making distributed spatial temperature monitoring impractical.

A variety of diagnostics will be provided upstream of the dump to monitor the incoming beam in addition to loss monitors around the dump vessel to measure the radiation distribution pattern from the dumped beam [13]. During dump commissioning and while operating at low power, x-rays will be detected by set of 7/8” heliax ion chambers that encage the dump both in circular and axial directions as shown in Fig. 9. When running higher power levels RHIC style ion chambers installed outside of the dump shielding layer will be used because the internal heliax ion chambers will likely saturate.

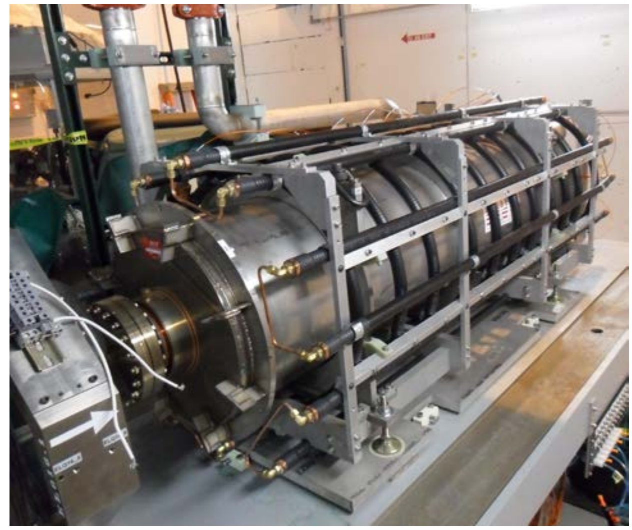

Figure 9: Electron beam dump shown with heliax cable ion chambers installed to monitor x-ray levels and ensure uniform distribution of the collected beam.

## RHIC ION BEAM DIAGNOSTICS

The primary diagnostics for monitoring of the cooling process will be the RHIC Wall Current Monitor [14] and Schottky monitors. A new wideband Schottky pick-up is being designed for improved monitoring of the longitudinal stochastic cooling characteristics that may also be useful for LEReC. The valuable experience gained using these instruments during the successful stochastic cooling commissioning and Coherent electron Cooling Proof of Principle [15] will be applied to the LEReC effort.

The existing RHIC DX BPMs will be used to center the $10^9$ ions per bunch, 2.5 mm-mrad rms norm emittance ion beam in the cooling regions. The RHIC closed loop orbit system will ensure ion beam position stability.

### *Recombination Measurement*

In order to measure the number of ions that have accumulated electrons while co-propagating with the electron bunches during the cooling process, a detector will be located near the place where simulations determine these ions with non-ideal charge state will be lost. This is most likely to be near the RHIC collimators. The detector planned is a scintillator coupled to a photomultiplier tube and signal processing electronics (counting) and/or pin diode loss monitors, both types can provide scalar data that can be logged versus time. A calculated estimate of the recombination rate is about 5 e6 ions/sec.

## ACKNOWLEDGMENTS

The authors would like to thank LEReC team for the concept development, simulations and support, J. Fite for engineering support, J. Kewisch for helpful discussions, Marcos Ruelas from Radiabeam, and S. Picataggio for the beam line drawings.

ISBN 978-3-95450-141-0

## REFERENCES

[1] A. Fedotov et al., “Bunched Beam Electron Cooler for Low-Energy RHIC Operation”, PAC2013, TUOAA1, http://jacow.org
[2] B. Dunham et al., “Performance of the Cornell High-Brightness, High-Power Electron Injector” IPAC2012, MOOAA01.
[3] D. Kayran et al., “First Test Results from SRF Photoinjector for the R&D ERL at BNL” IPAC2014, MOPRI064.
[4] D. Gassner et al., “Instrumentation for the Proposed Low Energy RHIC Electron Cooling Project”, IBIC 2013, TUPF24.
[5] D. Kayran et al., “Status of High Current R&D Energy Recovery Linac at BNL”, PAC2011, THP006.
[6] D. Kayran et al., “Merger System Optimization in BNL’s High Current R&D ERL” Proceeding of PAC 2007, THPAS097.
[7] http://www.i-tech.si/
[8] D. Gassner et al., “Status of the BNL ERL Instrumentation”, ERL2013, PS11
[9] http://www.bergoz.com/
[10] P. Cameron et al., “Differential Current Measurement in the BNL Energy Recovery Linac Test Facility”, Newport News, Virginia ERL2005.
[11] T. Allison et al., "New Beam Loss Monitor For 12GeV Upgrade”, ICALEPCS2009, WEP092.
[12] A. Hershcovitch “R&D ERL: Beam Dump”, PAC99, C-A/AP/#378 January 2010.
[13] T. Miller et al., “Instrumentation Designs for Beam Distribution Measurements in the ERL Beam Dump at BNL”, ERL2013, PS14, Sept 2013.
[14] P. Cameron et al., “The RHIC Wall Current Monitor System”, PAC1999, WEA116.
[15] D. Gassner et al., "Coherent Electron Cooling Proof of Principle Instrumentation Design”, BIW2012, WEAP01.



ISBN 978-3-95450-141-0