BNL-98531-2012-CP

The high-current ERL at BNL

I. Ben-Zvi

Presented at the 26th Linear Accelerator Conference (LINAC12)
Tel-Aviv, Israel
September 9-14, 2012

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of Science

THE HIGH-CURRENT ERL AT BNL*

I. Ben-Zvi[#], BNL, Upton NY, USA

Abstract

The electron hadron collider eRHIC will collide polarized or non-polarized electrons with a current of 50 mA and energy in the range of 5 GeV to 30 GeV with hadron beams, including heavy ions or polarized light ions of the RHIC storage ring. The electron beam will be generated in an Energy Recovery Linac (ERL) contained inside the RHIC tunnel, comprising six passes through two linac sections of about 2.5 GeV each. The electron ERL poses many challenges in term of a high-current high-polarization electron gun, HOM damping in the linac, crab cavities, harmonic cavities and beam stability. Three R&D projects are underway to provide experience with the eRHIC ERL components. A prototype high-current ERL is under commissioning to test performance at up to 300 mA of the ERL. A prototype polarized-electron gun based on funneling of 20 separate cathodes, providing 3.5 nC per bunch, is under construction and a Coherent electron Cooling (CeC) proof-of-principle experiment is under construction.

INTRODUCTION

RHIC, the Relativistic Heavy Ion Collider at Brookhaven Lab, found it first: a "perfect" liquid of strongly interacting quarks and gluons — a quark-gluon plasma (QGP) — produced by slamming heavy ions together at close to the speed of light. The fact that the QGP produced in these particle smashups was a liquid and not the expected gas, and that it flowed like a nearly frictionless fluid, took the physics world by surprise. Similarly, searches for the source of "missing" proton spin at RHIC have opened a deeper mystery: So far, it's nowhere to be found. To probe these and other puzzles, nuclear physicists would like to build a new machine: an electron-ion collider (EIC) designed to probe structures with extreme precision, at the scale of 10^{-15} meters, both protons and heavy ions to reveal their inner secrets.

The use of an Energy Recovery Linac (ERL) for the electron accelerator of eRHIC was suggested [1] as means to achieve high-luminosity, outstanding polarization and convenient upgradability features. Given a hadron machine design, a linac-ring configuration allows a 10- to 50-fold higher luminosity than an optimized ring-ring design. ERLs combine the advantages of linear accelerators, like beam quality, immunity to resonances, high degree of polarization and beam disruption with those of storage rings, such as high beam power and stability.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE
[#]benzvi@bnl.gov

A polarized electron beam with an energy up to 30 GeV would collide with a number of ion species accelerated in the existing RHIC accelerator complex, from polarized protons with a top energy of 250 GeV to fully-stripped uranium ions with energies up to 100 GeV/u covering a C.M. energy range from 45 to 175 GeV for polarized e-p, and from 32 to 110 GeV for electron heavy-ion-collisions. Using the present significant margin of the RHIC superconducting magnets the maximum beam energy could be increased by 10 or more percent.

The eRHIC design is based on using one of the two RHIC hadron rings and a multi-pass ERL. Using an ERL as the electron accelerator assures high luminosity in the range of 10^{33}~10^{34}cm^{2}s^{-1}. Locating the ERL inside the RHIC tunnel allows for significant cost savings and natural staging: the energy can be increased from the initial 5 - 10 GeV of the first stage to the final 30 GeV by incrementally adding additional accelerating cavities to the two main linacs. eRHIC will be able to provide electron-hadron collisions in up to three interaction regions. [2]

Polarized electrons will be generated in a high-current 20 photocathode funneling electron gun. The ion beams of the RHIC component will be cooled by a novel Coherent electron Cooling (CeC) system. The machine will heavily rely on SRF technology for production and acceleration of electrons, cooling of hadron beams and realizing crab crossing collision scheme.

In this paper we will describe the layout of the multi-pass eRHIC electron ERL, and describe R&D projects carried out in the Accelerator R&D Division of the BNL Collider-Accelerator Department (C-AD) towards the realization of eRHIC, including the polarized electron source, the SRF cavities (5-cell accelerating cavities, crab cavities), the R&D high-current ERL and the CeC Proof-of Principle (PoP) experiment.

LAYOUT OF THE ACCELERATOR

eRHIC General Layout

Figure 1 presents a layout of the collider with locations of various systems in the existing RHIC tunnel. The injection system consists of an electron gun, 10 MeV SRF injector linac (with no energy recovery) and 600-MeV single-pass SRF ERL. Two 2.45 GeV SRF linacs in combination with six passes make the main ERL. In addition to the main SRF linacs, eRHIC will have energy loss and energy spread compensation linacs (not shown in the figure). The CeC accelerator will consist of a low frequency SRF gun and buncher and a 136 MeV ERL. Finally, there will be SRF crab cavities for both hadrons and electrons (not shown in figure). The lattice provides separation of the electron orbits to individual arcs in the arcs, similar combiners to bring the orbits on the axis of the linac sections and bypasses for the interaction points.

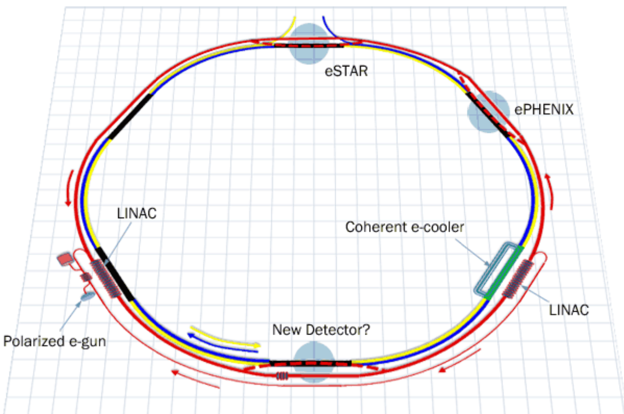

Figure 1: A schematic of the design for adding an electron ring (red), and possible future detector, to RHIC to create eRHIC, which would be the world's first electron-ion collider (EIC).

eRHIC Lattice

The lattice of recirculation passes is based on a low-emittance near-isochronous cell, which allows a flexible tuning R56 parameter and has a large dipole filling factor to minimize synchrotron radiation. The four splitters/mergers provide the transition between the beam line in the linacs and six vertically arranged recirculation passes in the arcs. The by-pass lines around the experimental detectors are provided for all recirculation passes except the top energy pass. The electron and proton bunch frequencies at different proton energies are matched by a combination of path length variation of the electrons and the electron RF harmonic. More details on the electron optics can be found in [3].

One potential weakness of the ERL is transverse beam break-up (BBU) instability that could severely limit the available beam current. Strong damping of HOMs has been the method of choice for suppressing BBU instabilities. A new method of suppressing BBU by many orders of magnitude has been recently proposed [4,5]. This method uses the chromaticity of the transverse motion, a naturally occurring effect, to dephase the transverse instability.

SRF Systems

The rather extensive SRF systems of eRHIC are described in detail by Belomestnykh [6,7]. These include ERL cavities at 704 MHz, low frequency injector cavities at 112 MHz, energy loss and energy spread compensation cavities at 1408 MHz, and crab cavities at a number of harmonics – 225 MHz, 450 MHz, 676 MHz and 1013 MHz. In this paper I will concentrate on the main linac cavities and the ERLs. The ERLs do not include any quadrupole magnets, still providing reasonably low beta-functions in the linacs. SRF linacs for the three ERLs (main ERL, 600-MeV pre-accelerator, and CeC) will utilize the same 704-MHz linac technology with minor modifications. Some parameters of these linacs are presented in Table 1. Two main ERL linacs will be located in the IP2 and IP10 straight sections, where their lengths are limited to 200 m for each linac. Parameters of the main linacs are listed in Table 1. The energy of the main ERL will be increased from 5 GeV in Phase I to 30 GeV in stages by adding cryomodules to the main linacs until they occupy all allotted space. Due to limitation on the beam loss power, the beam current will be lowered at energies above 20 GeV to keep the synchrotron radiation power loss below 10 MW.

Table 1: Parameters of the 704-MHz SRF linacs

Parameter	Main	Pre-acc.	CeC	injector
E gain [MeV]	2450	590	136	10
Current [mA]	50	50	70	50
Length [m]	200	60	19	5.2
No. of cavities	120	30	8	2
E_{acc} [MV/m]	19.2	18.5	15.1	4.7

eRHIC Main Accelerator Cavities at 704 MHz

A five-cell 703.8-MHz superconducting cavity for high-current applications (Figure 2) is under development at BNL and Stony Brook University [8,9,10]. This cavity has been designed as a universal high-current cavity with respect to damping yet with optimized shunt impedance and low surface electric fields, suitable for proton acceleration as well as electron ERL service.

The cavity has an optimized shape that supports strong damping of higher order modes (HOMs), which is accomplished via six antenna-type couplers attached to the large diameter beam pipes. The prototype copper cavity and niobium cavity were engineered and constructed by Advanced Energy Systems, Inc. (AES) and the niobium cavity is shown in Figure 3. Each cavity will be housed in an individual cryomodule. A series of such basic cryomodules will form one long cryomodule with 1-meter long transitions to room temperature at the ends.

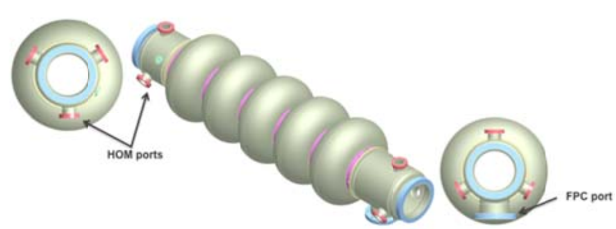

Figure 2: Schematic high-current 704 MHz SRF cavity.

Figure 3: Niobium five-cell 704 MHz SRF cavity.

THE R&D HIGH-CURRENT ERL

The plan for the high-current eRHIC ERL calls for six acceleration passes (and six deceleration passes) of 50 mA in a SRF linac structure. This is a lot of current through each cavity – equivalent to 600 mA. Thus an important part of our R&D program is building a high-brightness 300 mA Energy Recovery Linac (ERL) [11] (see Figure 4).

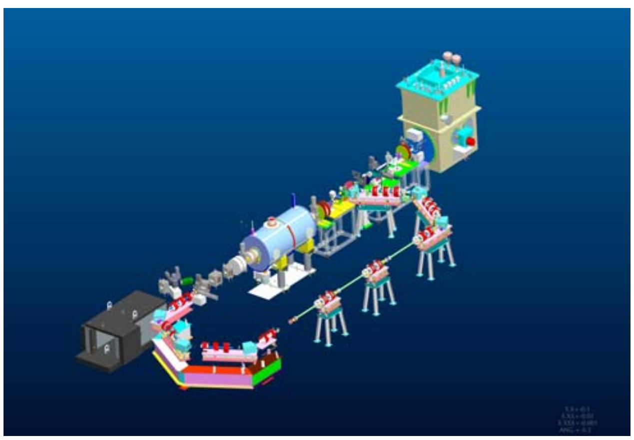

Figure 4: Schematic layout of the R&D Energy Recovery Linac at BNL. The electron gun is on the upper right side; the 5-cell accelerating cavity in the middle and the beam dump is on lower left.

The ERL is in final assembly stages, with commissioning of subsystems going on at present time. The objective of this ERL is to serve as a platform for R&D into high current ERL, in particular issues of halo generation and control, Higher-Order Mode (HOM) issues, coherent emissions for the beam and high-brightness, high-power beam generation and preservation.

BNL is developing several superconducting RF guns for different applications [12]. The first gun is based on a half-cell 1.3 GHz elliptical cavity, made by AES. This gun is used to study generation of polarized electrons from GaAs photocathodes. The second gun, made by Niowave Inc. is based on a quarter-wave resonator, operating at 112 MHz. This gun will be used for photocathode studies, including a diamond-amplified cathode, and to generate high charge, low repetition rate beam for the coherent electron cooling experiment. The third gun, shown in Figure 5, is a half-cell elliptical cavity operating at 704 MHz. It was engineered and constructed by AES and is designed to produce very high average current (up to 500 mA) electron beam at 2 MeV for the ERL prototype from a multi-alkali. This RF gun is equipped with a load-lock cathode delivery system. The accelerating unit of the ERL is a 704 MHz strongly HOM-damped 5-cell cavity built by AES. The AES built ERL ring has a highly flexible single-pass loop and a comprehensive system of beam instrumentation. At the time of writing of this manuscript, all elements of the ERL are in house and most are installed and surveyed to their exact positions. The first beam from the SRF gun is expected in December 2012, beam through the 5-cell cavity is anticipated in February 2012 and beam through the ERL loop in May 2013. We plan to study the performance of this unique machine: The high QE photocathodes and their load-lock delivery system, the SRF gun capable of 500 mA current at 2 MeV beam kinetic energy, the zig-zag beam merger, the highly damped 5-cell SRF accelerating cavity, and various advanced instrumentation elements.

Figure 5: The SRF Photocathode electron gun installed in the ERL vault, as seen from the cathode insertion side Notice the dual waveguide system of the fundamental power couplers.

Of particular interest are the high-current, low-emittance properties of the system, like coherent emissions, beam halo evolution and mitigation and emittance preservation. We plan to increase the current gradually from sub-mA to ampere-class in stages.

THE CEC POP EXPERIMENT

An effective cooling of ion and hadron beams at energy of collision is of critical importance for the productivity of present and future Nuclear Physics Colliders, such as RHIC, eRHIC and ELIC. Such cooling would allow to cool beam beyond their natural emittances and also to either overcome or to significantly mitigate limitations caused by the hour-glass effect and the intra-beam scattering. It also would provide for longer and more efficient stores, which would result in significantly higher integrated luminosity. To efficiently cool the transverse and longitudinal emittances of high-energy proton and ion beams by an order of magnitude, the novel technique of Coherent electron Cooling (CeC) is being considered [13].

The CeC principle of operation is as follows: Initially the hadron beam that is being cooled enters a drift space called "modulator", where it overlaps an electron beam of the exact same average velocity. In the modulator each hadron induces a density modulation in the electron beam. The electron beam is then sent to an undulator, which serves as a high-gain FEL. The density modulation is amplified by the FEL to a desired extent. Then both hadron beam and electron beam are brought to an overlap, following a precise temporal delay, in another drift space called the "kicker". There the hadrons interact with the self-induced electric field of the electron beam and receive energy kicks toward their central energy. The process reduces the hadron's energy spread, i.e. cools the hadron beam. The longitudinal cooling can be shared to cool transversally. Simulations show cooling times of tens of minutes can be achieved for the high-energy proton beam of RHIC, an achievement that cannot be done with traditional stochastic- or electron- cooling techniques.

The eRHIC CeC system will use a small ERL, with 136 MeV energy to produce the 70 mA electron beam for the cooler. A proof-of-principle experiment at RHIC for the CeC technique is under preparation [14]. The electron accelerator for this experiment will use a 20 MeV SRF linac at 704 MHz, based on the cavity described above, and injected by a 112 MHz SRF electron gun [12] equipped with 500 MHz copper buncher cavities.

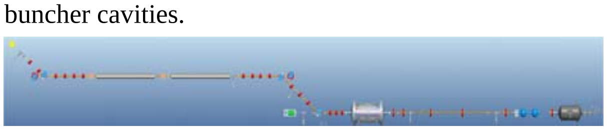

Figure 6: Layout of the Coherent electron Cooling POP experiment. See text for details.

Figure 6 shows the schematic layout of the Proof-of-Principle CeC experiment in RHIC. From right-to-left: 112 MHz SRF gun, normal conducting 500 MHz buncher cavities (blue), transport (solenoids in red), 704 MHz accelerating cavity, dog-leg, modulator section (focusing solenoid in red), FEL amplifier, kicker section (with focusing solenoids) then a bend to an electron beam dump.

THE POLARIZED GUN AND INJECTOR

Since the luminosity in a collider is proportional to the number of particles in each bunch, we want to increase the beam current, hence the bunch charge. When polarized electrons are required the gun performance is ultimately limited by the rapid aging of the cathodes caused by ion back-bombardment. The number of ions that are created in the gun and hit the cathode is proportional to the beam current and the vacuum pressure. A high beam current is therefore a direct cause of cathode aging. The approach we are taking at BNL is to multiplex a large number of cathodes in what is known technically as a funneling scheme. We call it the "Gatling gun" [15, 16], due to its similarity with a historical multiple barrels machine gun. The Gatling Gun R&D project aims to prove the concept of a DC gun with twenty separate cathodes. The beams from these cathodes are merged using a rotating magnetic field. We are carrying out R&D aimed at proving that the destruction caused by the back-scattered ions is reduced for each cathode by a factor of twenty. Each cathode will produce a pulse stream at a frequency of 700 kHz, controlled by a laser. The timing of firing the laser beams is such that each cathode is emitting with a delay relative to the previous one. The 20 cathodes combined thus produce a bunch stream at 14 MHz. As seen in Figure 7, the beams coming out of the cathodes pass through a hole in the anode, then a focusing solenoid, then a 30° fixed field bending-magnet. When the beams reach the central axis of the gun, they are bent onto the exit common path by a field, rotating at 700 kHz.

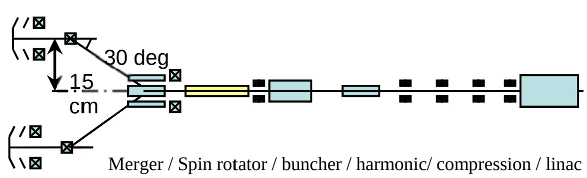

Figure 7: Schematic of the Gatling Gun injector

The funneling device [17] generates combined dipole and quadrupole-magnetic fields; the symmetries of fields are well preserved, and they can bend and focus the 200 keV beam by 30° with little emittance growth. Our simulations demonstrate that the radius of the good field (0.1%) region is more than 6 cm; the power losses in the coils (including the eddy-current effect) are about

600 W, and the power losses (viz., eddy current, hysteresis, and residual) are about 650 W.

Low frequency SRF structures will be used at the initial stages of acceleration/bunching in the 10 MeV main ERL injector and in the CeC injector.

3.5-nC bunches of polarized electrons will be produced at each cathode for each pulse. The bunches will be relatively long to alleviate space charge effects and will have to be shortened prior to injection into the 704 MHz SRF linac. This will be accomplished by velocity modulation in a 112 MHz quarter wave SRF buncher. A third harmonic single-cell elliptical SRF structure will be used for linearization. The buncher will operate at accelerating voltage of 1.3 MV and the third harmonica cavity – at 0.6 MV. The gun is in an advanced state of construction, as can be seen in Figure 8, showing the chamber accepting the fixed dipoles and the laser ports.

Figure 8: A component of the funneling polarized electron gun. Laser input ports are shown on top.

SUMMARY

The Accelerator R&D Division of the Collider-Accelerator Department at Brookhaven National Laboratory is carrying out R&D on eRHIC, a high-current, high-energy Energy Recovery Linac (ERL) designed for colliding 50 mA polarized electrons at an energy of 20 GeV with the beams of the Relativistic Heavy Ion Collider (RHIC). The R&D includes the design of the 6-pass ERL beam dynamics, accelerating cavities, crab cavities and other SRF devices. Three focused R&D efforts in this context include the construction, commissioning and testing of three major systems: A 20 MeV, 300 mA R&D ERL, a Proof-of-Principle (PoP) experiment in Coherent electron Cooling and a PoP experiment to demonstrate a funneling polarized electron gun, aimed at extending the current state-of-the-art 4 mA guns to as much as 20 times higher.

ACKNOWLEDGMENT

The various R&D projects described in this paper are the work of a very large number of colleagues at BNL in general, mostly in the Collider-Accelerator Department (C-AD) and in the Accelerator R&D Division of C-AD. The dedicated and expert work of these colleagues is gratefully acknowledged.

REFERENCES

[1] Ben-Zvi, I. Kewisch, J. Murphy and S. Peggs, “Accelerator Physics Issues in eRHIC”, Nuclear Instruments and Methods in Physics Research **A463**, 94 (2001).

[2] V. Ptitsyn, et al., “High Luminosity Electron-Hadron Collider eRHIC,” Proceedings of IPAC’2011, p. 3726.

[3] D. Trbojevic et al., “Recirculating Electron Linacs (REL) for LHeC and eRHIC”, IPAC’2011, p. 1099

[4] V.N. Litvinenko, “Chromaticity of the lattice and beam stability in energy recovery linacs”, Vladimir N. Litvinenko, Phys. Rev. ST Accel. Beams **15**, 074401

[5] V. N. Litvinenko, “Novel method of suppressing transverse beam-break-up instability in multi-turn energy recovery linacs”, in the proceedings of this conference.

[6] S. Belomestnykh, et al., “Superconducting RF Systems for eRHIC”, WEPPC109, Proceedings of IPAC’2012, page 2474.

[7] S. Belomestnykh, et al, Superconducting RF Linac for eRHIC”, in the proceedings of this conference.

[8] Wencan Xu, et al., “High current cavity design at BNL,” *Nucl. Instr. and Meth. A* **622** (2010) 17-20.

[9] Wencan Xu, et al., “High Current SRF Cavity Design for SPL and eRHIC,” PAC’2011, pp. 2589.

[10] Wencan Xu, et al., “Progress on the High-Current 704 MHz Superconducting RF Cavity at BNL,” WEPPC113, Proceedings of IPAC’2012, page 2486

[11] I. Ben-Zvi et al., “The Status of the BNL R&D ERL” ICFA Beam Dynamics News Letter # 58, 2012.

[12] S. Belomestnykh et al, “Developing of Superconducting RF Guns At BNL”, in the proceedings of this conference.

[13] V. N. Litvinenko, Y. S. Derbenev, Physical Review Letters 102, 114801 (2009).

[14] V.N. Litvinenko et al., “Proof-of-Principle Experiment for FEL-Based Coherent Electron Cooling”, Proceedings of PAC’2011, p. 2064

[15] V. N. Litvinenko, C-AD/AP/417 Note, (2011).

[16] X. Chang, et al., “A Multiple Cathode Gun Design for the eRHIC Polarized Electron Source,” Proceedings of PAC’2011, p. 1969.

[17] I. Ben-Zvi, et al, “Generating high-frequency, rotating magnetic fields with low harmonic content”, Physical Review ST-AB **14**, 092001 (2011)