THE ERL HIGH-ENERGY COOLER FOR RHIC*

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Abstract

Electron cooling [1] entered a new era with the July 2005 cooling of the Tevatron recycler ring [2] at Fermilab, using γ=9.5. Considering that the cooling rate decreases as faster than γ^2 and the electron energy forces higher electron currents, new acceleration techniques, high-energy electron cooling presents special challenges to the accelerator scientists and engineers. For example, electron cooling of RHIC at collisions requires electron beam energy up to about 54 MeV at an average current of between 50 to 100 mA and a particularly bright electron beam. The accelerator chosen to generate this electron beam is a superconducting Energy Recovery Linac (ERL) with a superconducting RF gun with a laser-photocathode.

INTRODUCTION

The successes of the first years at RHIC make it clear that there are outstanding physics opportunities to be pursued at RHIC over the next decade. They may be summarized in terms of four fundamental questions:

1. What are the phases of QCD matter?
2. What is the wave function of the proton?
3. What is the wave function of a heavy nucleus?
4. What is the nature of non-equilibrium processes in a fundamental theory?

To exploit these opportunities, the RHIC detectors will require upgraded capabilities, and RHIC will require a luminosity upgrade. In addition to various improvements, electron cooling is considered to be the main ingredient toward this luminosity upgrade.

Research towards high-energy electron cooling of RHIC is in its 5th year at BNL, starting with a design provided by the Budker Institute [3]. The design evolved during the past 5 years. The present design will use classical (non-magnetized) electron cooling. The luminosity upgrade of RHIC calls for electron cooling of various stored ion beams, such as 100 GeV/A gold ions at collision energies. High energy cooling of a collider in operation at γ~100 presents many challenges to the design of the cooler. The cooling is slowed down by the high-energy such that an accurate estimate of the cooling times requires a detailed calculation of the cooling process, which takes place simultaneously with various diffusive mechanisms. This task becomes even more challenging when the cooling is performed directly at a collision energy which puts special demands on the description of the beam distribution function under cooling.

The design of an electron cooler must take into account both electron beam dynamics issues as well as the electron cooling physics. The necessary electron energy of 54 MeV is clearly out of reach for DC accelerator system of any kind. The high energy also necessitates a bunched beam, with a high electron bunch charge, low emittance and small energy spread. The Collider-Accelerator Department adopted the Energy Recovery Linac (ERL) for generating the high-current, high-energy and high-quality electron beam. The RHIC electron cooler ERL will use four Superconducting RF (SRF) 5-cell cavities, designed to operate at ampere-class average currents with high bunch charges. The electron source will be a superconducting, 705.75 MHz laser-photocathode RF gun, followed up by a superconducting Energy Recovery Linac (ERL). An R&D ERL is under construction to demonstrate the ERL at the unprecedented average current of 0.5 amperes. Beam dynamics performance and luminosity enhancement are described for the case of magnetized and non-magnetized electron cooling of RHIC.

THE LAYOUT OF THE RHIC COOLER

The electron cooler, seen in Figure 1, will be located at the 2 o'clock IR of RHIC, which will be modified to accommodate the cooler.

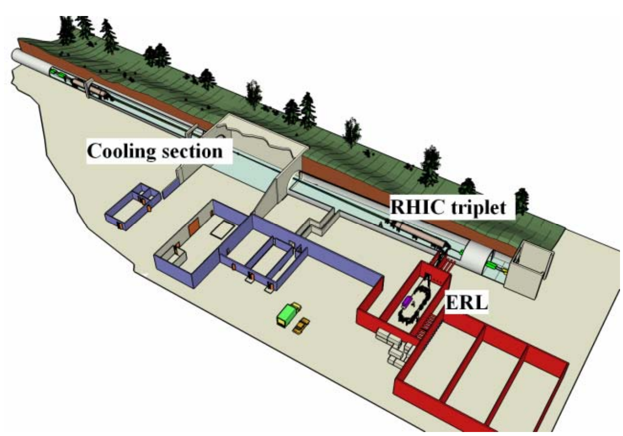

Figure 1: Layout of the RHIC high-energy electron cooler.

RHIC Modifications

There are various solutions to the adaptation of the RHIC lattice to accommodate an electron cooler. section with a large beta function and large cooling section length. The plans for the modification of RHIC [4] allow a generous ~110 meters dispersion free space for the cooling section and large, nearly constant beta functions of up to 800 meters in the cooling section.

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Energy Recovery Linac

A single Energy Recovery Linac (ERL) will be used to cool both independent RHIC rings [5]. The schematic layout of the two-pass ERL is shown in Figure 2.

The superconducting RF (SRF) Gun (1) produces 5 nC 4.7 MeV electron beam. The beam goes through the injection channel (2) comes into SC RF Linac (3) to be accelerated first time up to 30 MeV. The 30 MeV beam makes two achromatic 180 degrees bends (4, 4') and come back in to the linac (3) second time to get acceleration to 54.5 MeV. The 54.5 is transported to the RHIC (5) for cooling ion beam in both rings (see VII). The used 54.5 MeV electron beam is returning back (6) into the linac (3) in decelerated phase. After first deceleration to 30 MeV beam goes through two 180 degrees achromatic bends (4,4') again. In the last time passing through the linac beam gives back rest of the energy to cavities and goes to beam dump (7) having injection energy 4.7 MeV.

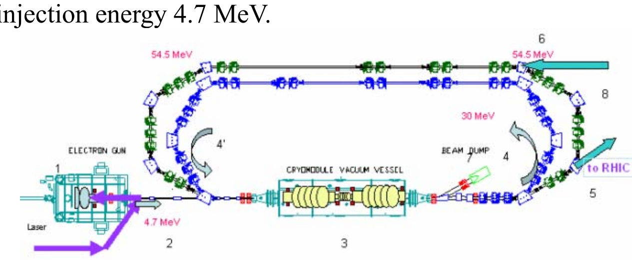

Figure 2: Energy Recovery Linac. (1) SRF gun. (2) Injection merger line. (3) SRF linac. (4,4') 180° achromatic turns. (5,6) Transport lines to and from RHIC. (7) Ejection line and beam dump. (8) Beam line for independent ERL operation.

The decelerating beams deposit into the SRF linac the same amount of energy as taken by the accelerating beams. Therefore, the RF power required to operate the SRF linac is very low and is at few 10's of watts level. A higher RF power or a reactive-power stabilization system will be used to maintain stability against microphonics and energy recovery mismatch.

The electron beam parameters are given in Table 1.

Table 1: Main electron beam parameters

Parameter	**Value**	**Units**
RF frequency	703.75	MHz
Bunch frequency	9.38	MHz
Bunch charge	5	Nano Coulombs
Gun kinetic energy	4.7	MeV
Linac kinetic energy	54.34	MeV
Normalized rms emittance	~3	µm
Momentum spread, rms	$1.8 \cdot 10^{-4}$	-
Bunch length, rms	7.8	mm

The emittance depends on the bunch distribution generated by the laser. In Table 1 we assume a uniform – uniform distribution, or "beer-can" distribution.

Beam Transport from ERL to RHIC and Return

The studies of the degradation in the electron beam performance after one pass through a cooling section shows that the emittance growth is less than 1 % [6]. The electron beam performances are still good enough to reuse such beam for cooling of other ring ion beam. To keep the cooling parameters the same the electron beam should be well matched between two rings.

Some of the considerations for the transport of the beams everywhere in the cooler are: The influence of transverse wake-fields of misaligned beams in the complete transport system must be avoided (due to resistive wall and other impedances). Space charge defocusing in the cooling section must be counteracted by distributed short, weakly focusing solenoids (~10 m spacing, focal length ~ 1km). The effects of non-uniform density profile on the defocusing needs to be studied. One must consider electron and ion trapping by both electron and ions and the related space charge effects

A study of the influence of bunch-to-bunch charge and position variations in e-beam on the emittance of the hadron beam needs to be done. Effect of arbitrary field errors along the cooling section on cooling requires studies. Study of the sensitivity to errors due to PS ripple, hysteresis effects, hadron bunch charge variation, etc. on matching of electron beam into the cooling sections (especially on the second pass).

The schematic layout of the two rings matcher is shown on Figure 3, and the turn-around point of the electron beam is shown in Figure 4. The region there a matching section could be installed is limited by the size of the RHIC tunnel and necessity to bypass the RHIC superconducting triplet. At the present design, the electron travel time from the center of the yellow ring to the center of the blue ring is 4 bunch spacing.

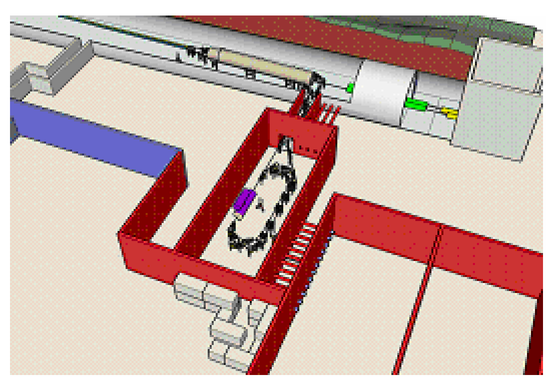

Figure 3: Energy Recovery Linac to cooling section.

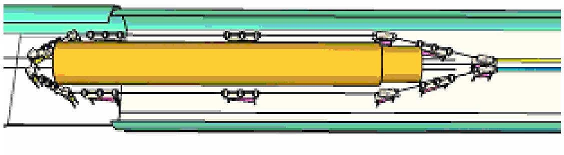

Figure 4: Turn-around point of the electron beam

NOVEL ERL COMPONENTS

The ERL of the RHIC II electron cooler must produce a high repetition rate of large bunch charges at a low emittance (see Table 1 above). This is an unprecedented performance which necessitated the development of a few new accelerator components that will be briefly described in this section.

SRF ERL Cavity

We developed a 5-cell ERL cavity [7,8] at 703.75 MHz. The cavity was designed as a "single-mode" cavity, in which all Higher Order Modes (HOMs) propagate to a HOM load through the large beam pipe. Measurements of the damped Q and R/Q of the HOMs and simulations show that the cavity is stable to over 2 amperes in a 54 MeV ERL. The cavity was built by AES and is undergoing chemistry at Jefferson Laboratory. Figure 5 shows the cavity at JLab after the first BCP.

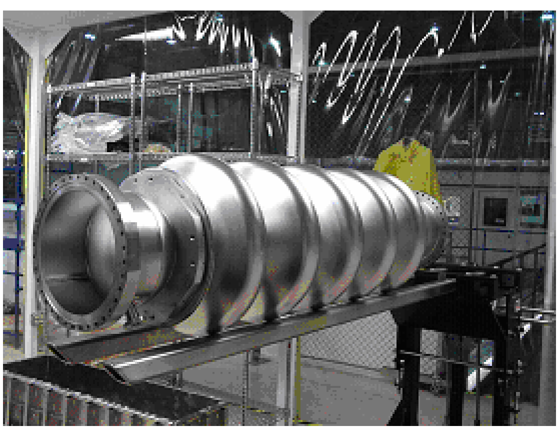

Figure 5. The ERL cavity following BCP at JLab.

Beam Merger

A problem in ERL is the merging of the low energy beam from the injector and the returning high-energy beam from the linac. The beams must be merged in order to be collinear with the linac axis. This requires bending of the low energy electron. This leads to emittance growth in the dispersive plane, particularly so with large bunch charge. Space-charge induced energy spread and the dipoles lead to effective correlated emittance growth.

This problem is resolved by the "Z-bend" merger [9]. This symmetric system, which satisfies all achromatic conditions and preserves the emittance of the low energy is shown in Figure 6. In addition, the weak focusing by the dipoles preserves laminar flow and thus is compatible with emittance compensation.

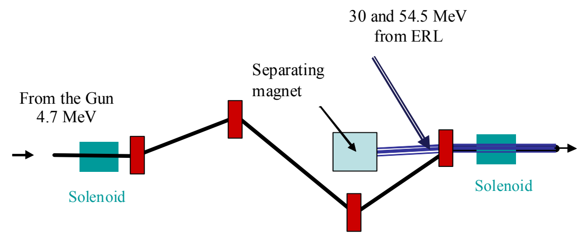

Figure 6. The "Z-bend" ERL beam merger.

Superconducting RF Gun

The production of a high bunch charge at low emittance requires a high RF electric field at the cathode and a relatively large bunch volume. These constraints can be best met with a superconducting RF (SRF) laser-photocathode electron gun. To operate in CW mode with 50 mA current and 4.7 MeV kinetic energy beam the gun should supply about 250 kW power to the beam. There are many different projects right now considering the use of SRF photo-injector. The first SRF gun developed with a successful insertion mechanism is the KFR Rossendorf gun [10]. The gun operated successfully and demonstrated a peak electric field of 22 MV/m over the cathode area. To test the performance of this high-charge SRF laser-photocathode gun we are developing in collaboration with AES a ½ cell SRF laser-photocathode gun, as shown in Figure 7.

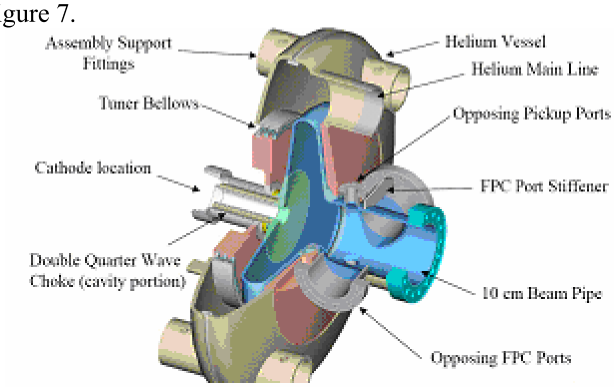

Figure 7. The SRF gun, it helium vessel and choke joint cathode insertion port. The high power fundamental power coupler (FPC) ports are also shown.

Diamond Amplified Photocathode

The production of CW 50 mA current with a long lifetime and low thermal emittance is a challenge. A new scheme combines a high Quantum Efficiency (QE) photocathode (CsK2Sb or similar) with a diamond window [11]. Electrons generated at a photocathode in the conventional way and accelerated to the diamond, which has a thin metal layer deposited facing the photocathode, by a few KeV. This generates a shower of secondary electrons and holes, using about 13 eV of primary energy per electron-hole pair. The electrons drift towards the gun face of the diamond by the gun's electric field and exit into the vacuum. This is made possible by a negative electron affinity surface thanks to hydrogenising the diamond. The advantages of this system are amplification of the QE of the photocathode by a factor of a few hundreds, isolation of the cathode from the gun environment (for long photocathode lifetime), isolation of the gun from the photocathode materials and a low thermal emittance due to the thermalization of the drifting electrons. In experiments we demonstrated so far a gain of up to 200 as well as emission into vacuum.

THEORY, SIMULATIONS AND EXPERIMENTS

A cooled RHIC is dominated by Intra-Beam Scattering (IBS), electron-ion recombination and beam disintegration in the IP.

IBS results in a luminosity loss due to emittance dilution, bunch length growth leading to particle loss from the bucket and loss of effective luminosity in the detector. Recombination is avoidable, but beam disintegration places a hard limit on the integrated luminosity per store.

The IBS theory was compared carefully to measurements [12] as can be seem in Figures 8 and 9.

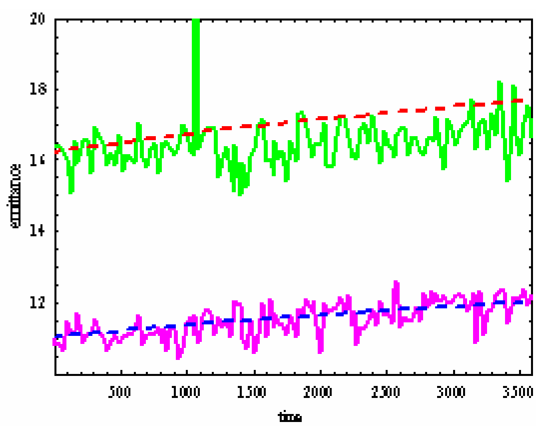

Figure 8. Growth of 95% normalized emittance [μm] for bunch with intensity $N=2.9\cdot10^9$ as a function of time in store. Upper curve is for the horizontal emittance. The dashed curves are Martini's model, the others measurement.

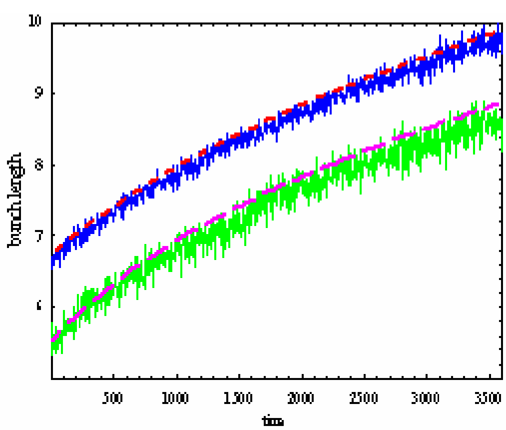

Figure 9. FWHM [ns] bunch length growth for bunch intensities of $N=2.9\cdot10^9$ (upper curve) and $1.4\cdot10^9$ (lower curve) as a function of time.

A detailed analytic treatment of IBS, which depends on individual particle amplitudes, was proposed by Burov [13], with an analytic formulation done for a "flattened" Gaussian distribution. Also, a simplified "core-tail" model, based on a different diffusion coefficients for beam core and tails was also proposed [14]. In addition, the standard IBS theory was reformulated for the rms growth rates of a bi-Gaussian distribution by Parzen [15].

We collaborate with JINR (Dubna) in the cooling dynamics simulations code BETACOOL [16], and with Tech-X corp. (Boulder, Colorado) in the friction force simulations from first principles code VORPAL [17]. In Figure 10 we compare the non-magnetized friction force from BETACOOL and VORPAL for an anisotropic electron distribution, with parallel velocity of 10^5 m/s and perpendicular velocity of $4.2\cdot10^5$ m/s. This cross-checking provides us with confidence in the simulation codes.

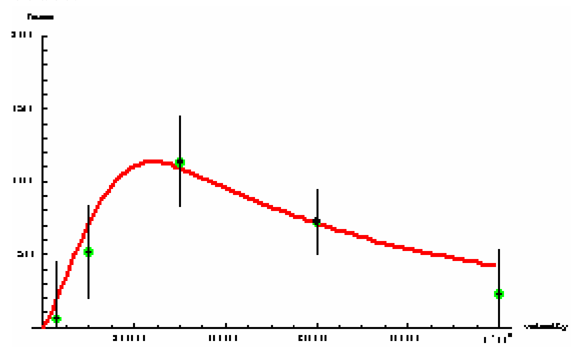

Figure 10. Force [eV/m] vs. ion velocity [m/s]: solid line (red) – numeric integration using BETACOOL; points with errors bar (3 rms deviation shown) – simulations using VORPAL.

As for experiments, we are fortunate that the FNAL high-energy electron cooler came into operations and its performance compares well with theory and simulations [2]. Comparison of the cooling rate and evolution of the antiproton beam distribution following a high voltage step done with BETACOOL compare well with the FNAL experiment, providing confidence in the code.

THE EXPECTED PERFORMANCE

The luminosity of RHIC II was calculated using BETACOOL for a variety of ions from protons to gold at 100 GeV/A. Using classical electron cooling, with electron beam parameters as given in Table 1, we use BETACOOL to calculate the cooling process. The parameters for gold are given in Table 2. The details of the cooling section are essentially the same for the other ions as well. The average luminosity achieved for gold ions over a 4 hour run period is $7\cdot10^{27}$ cm^{-2}sec^{-1}. Figure 11 shows the luminosity as a function of run time for gold with and without electron cooling. The noise seen in the luminosity is a numerical artifact. The drop in the luminosity towards the end of the store comes from particle loss due to beam disintegration in the interaction points due to the large luminosity.

Table 2: Main RHIC II gold beam parameters

Parameter	**Value**	**Units**
Normalized rms emittance	2.5	µm
Momentum spread, rms	$5\cdot10^{-4}$	
Ions per bunch	10^{9}	
Number of bunches	112	
Beta function in cooler section	400	m
Initial bunch length, rms	20	cm
Circumference of RHIC ring	3833	m
Cooling section length	80	m
Relativistic factor, γ	107.35	

The luminosity may be leveled off to be nearly constant by controlling the electron beam current or other parameters of the cooler (not shown).

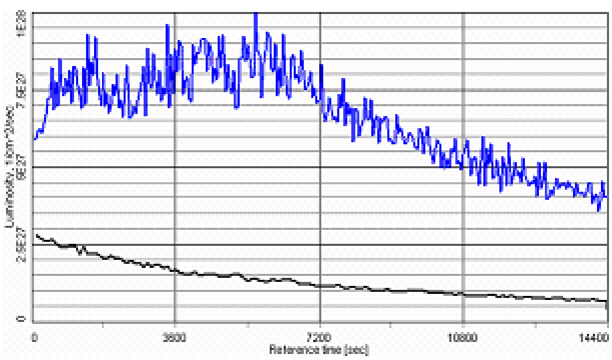

Figure 11. Instantaneous luminosity for 100 GeV/A gold on gold collisions as a function of time with – and without – electron cooling over a 4 hours run.

In addition, one may also maintain control of the gold bunch length by controlling the sweep amplitude of the short (under 1 cm) electrons over the ion bunch, which start at 20 cm rms.

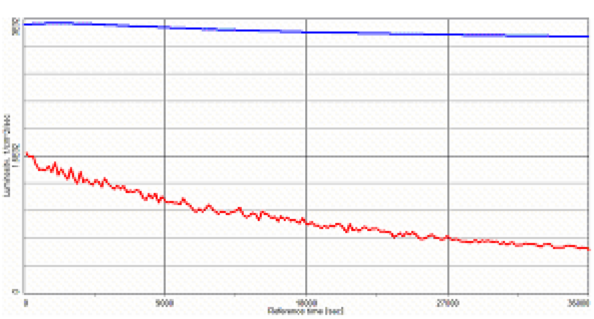

Figure 12. Instantaneous luminosity for 100 GeV/A p on p collisions as a function of time with – and without – electron cooling over a 10 hours run.

For copper ions with $8\cdot10^{9}$ ions per bunch we show an increase of the average luminosity by about a factor of 6 over a 6 hour run, and for silicon about a factor of 5 over a 10 hour run.

The luminosity for protons at 100 GeV (per beam) over a 10 hour store is about $3\cdot10^{32}$, about a factor of 3.5 larger than without cooling, for $2\cdot10^{11}$ protons per bunch. This assumes a proton rms normalized emittance of 2 µm. This is shown in Figure 12.

SUMMARY

A significant luminosity enhancement can be obtained for the full range of ions used at RHIC at an energy of up to 100 GeV/A. This requires a high-current, high-bunch-charge low emittance ERL for the electrons. Various advances in ERL science were made to achieve this goal.

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