High-Current ERL-Based Electron Cooling System for RHIC

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Abstract. The design of an electron cooler must take into account both electron beam dynamics issues as well as the electron cooling physics. Research towards high-energy electron cooling of RHIC is in its 3rd year at Brookhaven National Laboratory. The luminosity upgrade of RHIC calls for electron cooling of various stored ion beams, such as 100 GeV/A gold ions at collision energies. 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.

Keywords: Electron cooling. High energy. Energy Recovery Linac Magnetized beam. Non-magnetized beam. Superconducting RF gun.
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INTRODUCTION

The main goal of cooling in a collider is to increase the luminosity, which depends on the details of ion beam's energy and distribution, the properties of the cooler's electron beam and the design of the cooling section. For electron cooling of gold ions in RHIC, the electron energy has to be about 55 MeV and electrostatic acceleration of the electron beam is impossible. RF acceleration of a high-charge bunched electron beam results in an electron transverse velocity spread which is orders of magnitude larger than in conventional coolers. This large temperature of the electron beam has to be carefully minimized by a careful design of the accelerator, and possibly compensated by a strong magnetic field in the cooling solenoid, leading to strong magnetized cooling[1].

The cooling at electron energy of 55 MeV is obviously quite challenging considering that the cooling time is proportional to the energy to the power of 7/2, and that our energies are at $\gamma\sim100$, an order of magnitude higher than even the FNAL Recycler electron cooler, which is at $\gamma\leq10$. Getting the necessary integrated luminosity

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also brings in various other complications, such as recombination and beam disintegration loss mechanisms.

The R&D towards electron cooling of RHIC[2] proceeds along two directions. The first direction is cooling theory, comprising simulation and experiments in IBS and beam cooling. The other is electron accelerator design and experiments. The cooling theory proceeds to obtain an accurate, benchmarked estimate of the luminosity increase, accounting for the electron beam properties, IBS, cooling friction force, recombination, beam disintegration, instabilities, magnetic field errors, and the properties of the RHIC collider. The electron accelerator design proceeds to develop accelerator components and systems that deliver the best performance for cooling RHIC, carry out the beam dynamics calculations and build components and accelerator systems to benchmark the performance of the challenging accelerator elements.

The performance of the electron beam is fed into the cooling calculations and vice versa. Thus the two research directions have been evolving for a while, getting more consistent and realistic. One of the items under investigation is the comparison of magnetized and non-magnetized electron cooling. Some of the results of such a comparison are discussed below. It should be noted that progress in the generation of high brightness electron beam makes non-magnetized electron beam cooling feasible for RHIC. The issue of recombination in cooling highly charged gold ions seems to be problematic at first glance. Upon careful examination, it is observed that the required luminosity increase can be obtained with a low charge (as low as 2.5 nC) bunches and large beam in the cooling section, thus reducing the recombination rate to well below the beam disintegration rate with no magnetic fields at all in the cooling section. In addition, the use of a low field helical undulator further suppresses recombination[3] to the extent that it is negligible compared to beam disintegration even with a higher electron beam charge.

In this paper, we review the electron cooling of RHIC using magnetized and non-magnetized electrons. We discuss some of the accelerator issues and observe that with the current performance estimated for the cooler's electron beam, non-magnetized cooling is feasible and advantageous for RHIC.

MAGNETIZED ELECTRON COOLING

Luminosity of RHIC with Magnetized Electron Cooling

Using results from the electron beam dynamics calculations on the electron beam parameters and the cooling solenoid, we use the code BetaCool[4] to carry out cooling dynamics simulations.

The simulations show that the design goal for the electron cooler of RHIC, an order of magnitude increase in the integrated luminosity over about a 4 hour (at least) run, can be achieved[5,6], provided that the electron beam can be stretched sufficiently without spoiling its emittance too much.

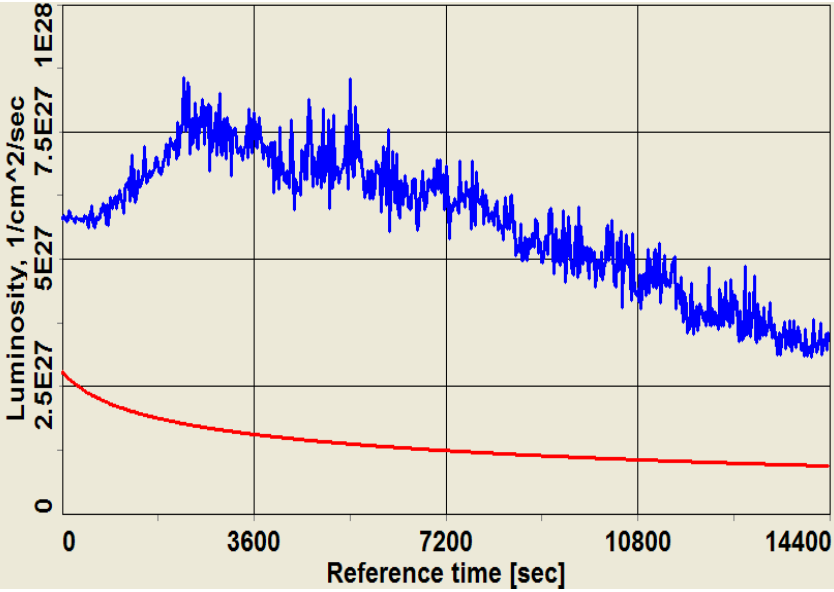

FIGURE 1. Luminosity of RHIC for gold-gold collisions at 100 GeV/A per beam as a function of time in collision with magnetized cooling. The red line represents the luminosity without electron cooling, which decays due to IBS. The blue curve represents the luminosity of the cooled collider. The decline in luminosity here is due to ion beam loss by disintegration in the interaction points.

The order of magnitude luminosity increase (from $7\text{x}10^{26}$ to about $7\text{x}10^{27}$ for gold at 100 GeV/A) can be also achieved for some other ion species and at various energies.

The integrated luminosity under cooling in Figure 1 is calculated from the percentage of the beam burned during 4 hours, for 3 IPs, 112 bunches of 10^9 gold ions, with interaction point beta*=0.5 meters.

The decay in the luminosity curves is either from IBS (for no cooling) or beam disintegration due to the high luminosity (under cooling).

The challenge for the electron beam comes mainly from the requirement for a large charge at a low emittance. The required charge can be estimated from the critical number of electrons, defined as the number of electrons required to achieve equilibrium between electron cooling and IBS heating. The critical number can be written as:

$$N_{ec} \approx \frac{r_i}{r_e}\frac{N_i}{\eta}\frac{\Lambda_{ibs}}{\Lambda_c}\frac{1}{g_f}, \qquad \text{where} \quad g_f = \left(\frac{v_{longitud.}}{v_{tranverse}}\right)^2 = \frac{\sigma_p^{\ 2}}{\gamma^2(\varepsilon/\beta_a)} \tag{1}$$

For cooling of the whole beam to take place at all, the number of electrons has to be higher than the critical number. Below the critical number, one may observe cooling of the core of the ion beam.

Taking the following parameters of RHIC: Number of ions per bunch $N_i=10^9$, fraction of cooling solenoid filling the RHIC circumference η=0.0078, IBS Coulomb log Λ_{ibs}=20, ion velocity form factor g_f=0.2, and assuming that the cooler will have magnetized cooling logarithm Λ_c=2 one gets critical number of electrons about N_{ec}=1-3 10^{11}, depending on the IBS model.

In simulations we see clearly the effect of cooling below and above the critical number. First, a gold bunch is cooled in a BetaCool simulation by 1.2x10^{11} electrons, which is estimated to be below the critical number. We observe cooling of the core of the ions, forming a bi-Gaussian distribution. While cooling with 3x10^{11} electrons, estimated to be above the critical number, we observe that good cooling is provided for the complete beam. The RMS emittance of the beam does not decrease as a function of time under cooling (or may even grow) below the critical number. Thus the simple approximate formula works reasonably well. Below the critical number the luminosity still increases, but the luminosity gain is smaller and the beam-beam parameter is larger. In addition, the centrally peaked "double Gaussian" distribution may lead to beam-beam instabilities for a much smaller value of the beam-beam parameter[7].

Therefore one can see that for RHIC, the charge of the electron beam must be at least 20 nC in order to provide magnetized cooling. In addition, we have requirements for the beam emittance and magnetization and the solenoid length, to achieve the values of the cooling logarithm and fill factor that enter the critical number and affect the cooling speed. The numbers used to achieve the target luminosity growth of Figure 1 are two solenoids at 40m long each, solenoid field of B=5T, electron, emittance 50μm, energy spread 3x10^{-4}.

In the following section we will see what it takes to generate this electron beam.

Generating the Magnetized Electrons

The 20 nC, 54 MeV, 9.4 MHz beam has a beam power of about 10 MW, This is a high enough beam power that calls for Energy Recovery Linac (ERL) for electrical power savings and beam-dump radiation mitigation. The ERL configuration is shown in Figure 2. The critical items in the system are the RF gun, which has to produce a CW high-charge, low emittance beam, the ERL which must be capable of about 200 mA current with no beam breakup, the debuncher which has to stretch the beam and reduce its energy spread without emittance degradation and the solenoids, which are long, high-field and very precise.

In order to produce the high-charge, low emittance beam, we are developing a superconducting laser-photocathode RF gun[8]. A 3-D graphic of the gun's prototype is shown in Figure 3. The advantage of using an RF gun is the ability to provide a high electric field gradient and large energy gain as close to the cathode as possible. This is essential in order to avoid a large emittance growth due to linear and non-linear space-charge forces due to the large charge. The RF superconductivity's small surface resistance allows us to operate the gun in a continuous (CW) mode with affordable electric power. This prototype gun has a single cavity accelerating section, so it will be capable only of 2 to 3 MeV energy. The RHIC electron cooler will use a twin-cavity, or as is better known as a "1 ½ cell" gun[9], since the cavity containing the cathode is shorter due to the lower average speed of the electrons at that point. The 1 ½ cell gun will provide a 4 to5 MeV beam with improved emittance. At the beam current of 200 mA, the input RF power of the gun will be close to 1 MW, all of which going into beam power.

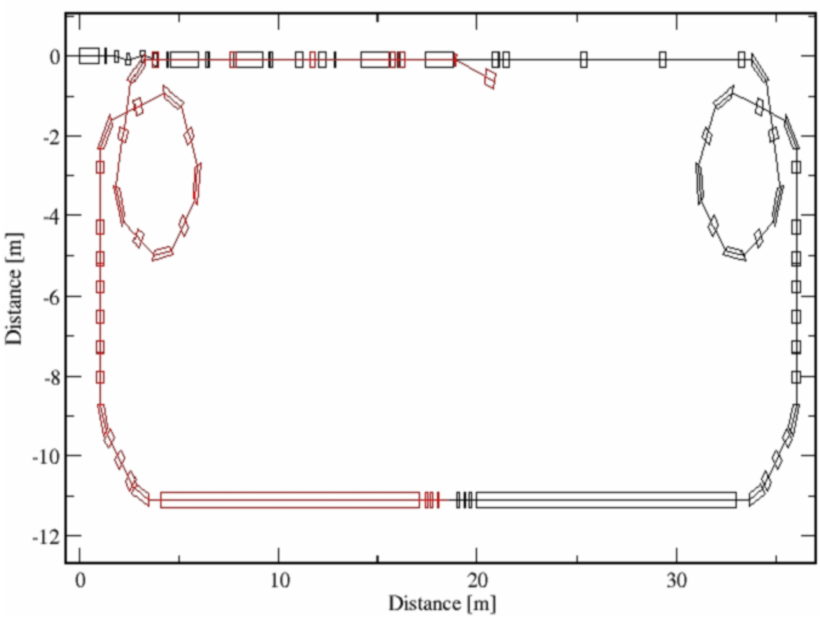

FIGURE 2. Layout of the ERL and cooling section for the RHIC magnetized beam electron cooler. The beam starts at the top left corner, which is the location of the electron gun. The beam is next merged with the returning high-energy beam. Both beams enter the linac, comprising most of the top horizontal line. The bottom contains the long solenoids, in which the electrons move together with the RHIC ion beam. The transport system between the linac and the solenoid contains a beam debunching optics and RF cavity, and the inverse operation is done on the return leg.

In an ERL the emittance of the gun by itself is something that is difficult to measure and not very relevant. One has to consider the properties of the electron bunch following the beam merging system (which may introduce huge emittance growth unless properly designed) and the linac. All of these elements must perform together to recover part of the linear emittance growth, in what is known as emittance compensation[10].

The beam merger which we will use has been developed by our group[11]. It is called the "Z-bend" merging system, and it is capable of reducing the emittance growth in the bending plane to a negligible level. The linac, like the gun, is superconducting at 703.75 MHz (a harmonic of the RHIC revolution frequency) and has been designed[12] to accelerate a high-current electron beam with negligible emittance growth and high-stability.

The performance of the system from the gun to the end of the linac (including the Z-bend merging system) is given in Table 1.

The notable feature of the system is that the low emittance, at about 30 microns for a high bunch charge of 20 nC and a very high magnetization emittance of 380 microns. This is not necessarily the best possible result, since a different bunch shape (elliptical bunch instead of the uniform-Gaussian distribution used for the computation in Table 1) can improve the results even further. However, the main issue in getting this beam to the cooling solenoid is the debunching operation. It is necessary to debunch the beam for two reasons: First, to reduce the longitudinal energy spread, second, to reduce the electron charge density in the cooler and thus avoid a short Debye length which would otherwise result is a lower Coulomb logarithm.

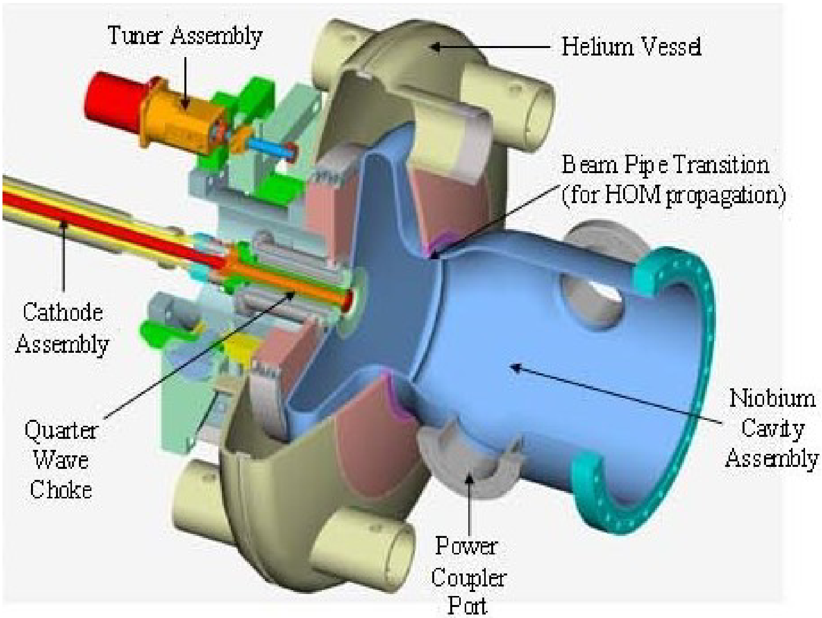

FIGURE 3. Layout of the superconducting laser photocathode RF gun. Details that are not shown to avoid complicating the figure are the cryostat, fundamental power coupler and details of the photocathode insertion mechanism (load-lock). The solid niobium cavity is shown in blue. The photocathode assembly is retractable into the load-lock chamber for cathode replacement under ultra-high vacuum conditions. The large beam pipe is designed to allow High-Order Mode (HOM) power to escape the cavity towards a ferrite microwave damping section located in the beam pipe outside the cryostat (not shown).

Table 1. Beam dynamics parameters from gun to end of linac.

Charge	20nC
Radius (Transverse uniform distribution)	12mm
Magnetization	380mm.mr
Longitudinal Gaussian distribution	4degrees, 16ps
Maximum field on axis of gun cavity	30MV/m
Initial phase	30deg.
Energy at gun exit	4.7MeV
Energy spread at gun exit	rms 1.87%
Bend angle	10degrees
Energy at linac exit	55MeV
Final emittance (normalized rms)	30mm.mr
Final longitudinal emittance	100deg.keV

The difficulty with the debunching transport system is the large magnetization and high space-charge. However, a careful design should keep the final emittance at about 50 microns (thermal in the solenoid), a value that has been used in the cooling simulations.

NON-MAGNETIZED ELECTRON COOLING

Due to the high energy of the RHIC ion beam, the effective longitudinal velocity introduced by the magnetic field error limits the cooling rate from magnetized cooling to a degree that non-magnetized cooling can successfully compete. Since the superconducting magnet experts feel reluctant to promise a field error much smaller than 10^{-5} for the long, multi-Tesla field superconducting solenoid, the benefit of fast magnetized cooling which peaks for ions moving at about the effective electron velocity, is greatly diminished. Using a non-magnetized beam with a lower charge (under 5 nC) enables us to reduce the transverse electron emittance to at or below the ions' normalized emittance. This provides for good cooling rates and has also the following other benefits: First, the elimination of the very long, high-field high-precision solenoids, which save a considerable amount of money and complication. Second, the reduction of the electron current by about a factor of 5 or more, simplifying the system and making it easier. Third, elimination of the bunch stretcher (debuncher), leading to simplification of the beam transport system and additional cost savings. Fourth, uniform cooling of the ions, avoiding fast cooling of the core and thus the generation of a peaked distribution which is problematic for reasons the beam-beam interaction. Fifth, since one does not have to deal with solenoid errors, it is possible to increase the ion beam size in the cooling section and thus lower the ion velocities and get better cooling speed. Sixth, the ability to use the analytic Budker formulae which provide a high level of confidence in the cooling rate. One may also add the recent demonstration of high-energy cooling with non-magnetized beam at Fermilab[13].

Luminosity Performance and Recombination Issues

For a non-magnetized beam, analytic and precise expressions were developed to calculate the friction force. From the friction force, one can arrive at the cooling rate, luminosity growth etc., taking into account the various relevant accelerator physics issues such as exact electron and ion velocity distributions, the competition between IBS and cooling, the effects of beam disintegration and recombination. Naturally, tracking a realistic ion distribution and allowing for the betatron and synchrotron motions is essential. At the RHIC cooling R&D project are using the BetaCool code, working in collaboration with the JINR Dubna group. In this particular case, the code integrates the friction force (2):

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e \qquad L = \ln\frac{\rho_{\max}}{r_0} \tag{2}$$

The result from BetaCool for the luminosity is given in Figure 4.

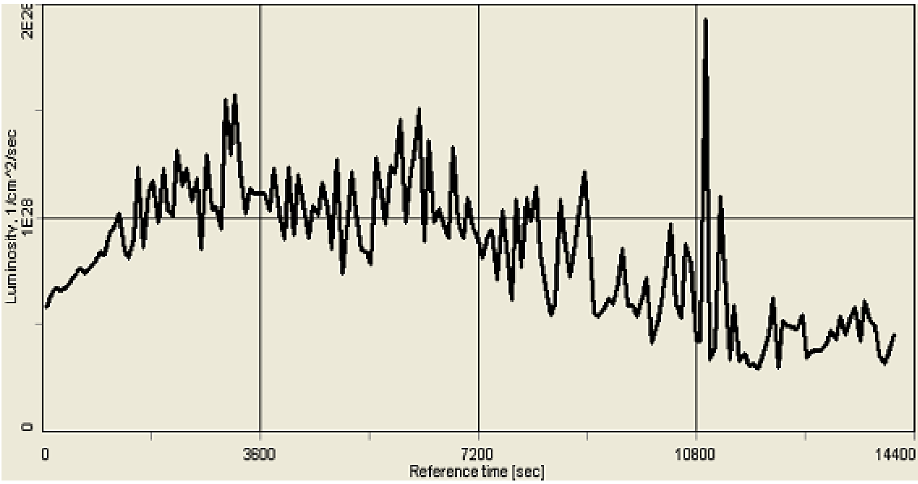

FIGURE 4. Luminosity of RHIC for gold-gold collisions at 100 GeV/A per beam as a function of time in collision with non-magnetized cooling. The decline in luminosity here is due to ion beam loss by disintegration in the interaction points in combination with recombination losses. The spikes are artifacts of the simulation.

The various cooler and beam parameters used in this simulation are given in Table 2. The discussion of the recombination (which is included in this simulation) and the electron beam parameters follow below.

Clearly, as one compares Figure 1 and Figure 4, the luminosity gain through electron cooling is just as good or better for the non-magnetized case. Also one observes a uniform cooling of the ion bunch, with no buildup of density spikes.

Table 2. Non-magnetized electron beam cooling parameters.

Rms momentum spread of electrons	0.1%
Rms normalized emittance	2.5 microns
Rms radius of electron beam in cooling section	0.3 mm
Rms bunch length	5 cm
Charge per bunch	5nC
Cooling sections	2x30 m
Ion beta-function in cooling section	200 m
IBS – Martini's model	exact RHIC lattice

The great surprise one may have from this result is the small role that recombination has to play here, since now we are dealing with highly charged gold ions and very cold electrons. It may help to remember that the decrease in electron bunch charge and the expansion of the beam size (from a beta function of about 60 meters to about 200 meters, possibly more) reduce considerably the electron charge density in the cooler and thus the recombination rate. Furthermore, the beam disintegration in the interaction points dominates the ion loss, and once enough ions are lost the recombination rate also declines. In addition, we can also use a helical undulator to rotate the electrons, producing a coherent velocity that reduces recombination with just a small sacrifice in cooling speed. Using an undulator with a period of λ_w=0.05 m, a field of B=0.002 T wound on a radius of R=0.05 m, we require a current of I=70 Amp to generate the field. Then we get (see eq. 3) the rotation radius as r_0=0.7μm, and the focusing results a beta function of β_w=180 m. The loss in Coulomb log due to the electrons helical motion with a radius of 0.7 microns is only 0.8, something that can be neglected. The coherent rotation is equivalent to better than an electron temperature of 22 eV, enough to make recombination negligible in the disintegration dominated system.

$$\theta = \frac{K}{\gamma} \approx \frac{93.4B\lambda}{\gamma} \qquad\qquad r_0 = \frac{\theta\lambda}{2\pi} \tag{3}$$

We carried out simulations[14] showing that the luminosity increase of an order of magnitude in RHIC can be achieved with no undulator and with an electron bunch charge of 2.5nC and with an emittance of 2 microns.

Generating the Non-Magnetized Electrons

Assuming the same gun as described above for the magnetized beam, and pretty much the same accelerator layout, we[9] use the parameters in Table 3.

Table 3. Beam parameters for gun for non-magnetized electrons.

Bunch length	16degrees (63ps) from head to tail.
Laser pulse shape	Ellipsoid
Lunch phase	about 35deg.
Maximum field on axis	30MV/m
Energy out of gun	4.7 MeV

The main difference is the use of an elliptical bunch shape[15] for the electron beam. This is significant, and leads to a large decrease in emittance, as can be seen in Table 4.

Table 4. RMS normalized emittance vs. bunch charge.

Charge/bunch (nC)	Emittance after linac (μm)
2.5	1.7
3.2	2.0
5	2.9

The longitudinal emittance is under 300 degree*keV, and following 3rd harmonic correction is reduced it to under 100 degree*keV, allowing electron energy spread of under 10^{-4}.

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