Electron Cooling for RHIC*

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Introduction

The Accelerator Collider Department (CAD) at Brookhaven National Laboratory is operating the Relativistic Heavy Ion Collider (RHIC), which includes the dual-ring, 3.834 km circumference superconducting collider and the venerable AGS as the last part of the RHIC injection chain.

CAD is planning on a luminosity upgrade of the machine under the designation RHIC II. One important component of the RHIC II upgrade is electron cooling of RHIC gold ion beams. For this purpose, BNL and the Budker Institute of Nuclear Physics in Novosibirsk entered into a collaboration aimed initially at the development of the electron cooling conceptual design, resolution of technical issues, and finally extend the collaboration towards the construction and commissioning of the cooler. Many of the results presented in this paper are derived from the Electron Cooling for RHIC Design Report [1], produced by the BINP team within the framework of this collaboration. BNL is also collaborating with Fermi National Laboratory, Thomas Jefferson National Accelerator Facility and the University of Indiana on various aspects of electron cooling.

Electron cooling of RHIC gold ions is a challenging and interesting project, for the following reasons:

1. The RHIC gold beam evolution is dominated by Intra-Beam Scattering (IBS), which leads to emittance growth and beam loss. Cooling has to be done during the storage phase of the machine to keep IBS in check. That means the following unique consequences:
    a. Cooling of a bunched beam.
    b. Cooling of a 100 GeV/A ions, requiring over 50 MeV cooling electron beam.
    c. The electron accelerator cannot be an electrostatic machine.
2. The RHIC cooler will be the first instance of direct cooling of a collider.
3. The two rings would require two coolers operating simultaneously.
4. Electron capture by the fully stripped gold ions is an important factor to consider.
5. Beam disintegration due to the collision process is a significant lifetime limiting effect under cooling.
6. The solenoid of the cooler is a particularly challenging device, a 30 m superconducting solenoid at a field of 1 Tesla, with a required field precision of 10^{-5}.

The technical development of the electron accelerator is a challenge for a number of reasons:

1. The accelerator has to transport a magnetized electron beam without the benefit of a continuous solenoidal field.

2. The average current of the accelerator has to be of the order of 100 mA (at an energy of 50 MeV this corresponds to a power of 5 MW, and if dumped at this energy it would lead to complications of the beam dump due to induced radioactivity)
3. The single bunch charge has to be of the order of 10 nC. Yet, this charge has to be compressed to a bunch length of approximately 30 ps to be accelerated by a linear accelerator. This corresponds to a peak current of about 330 amperes.
4. The electrons have to be debunched before entering the cooling region, to reduce the electrostatic interaction with the ion beam and reduce its energy spread to the required level. Then, following the cooling, the electrons have to be rebunched in order to decelerate them successfully for energy recovery.
5. The electron source is particularly challenging. Two approached are being considered, a DC gun and a photoinjector.

The unique features of the RHIC cooler mentioned above offer some interesting opportunities in electron cooling R&D:

1. Control of the complete phase space of the ion beams by special modulation of the electron beam parameters.
2. Cooling of a collider may have interesting implications concerning the beam-beam parameter and collision generated noise.

The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory consists of two rings in which counter-rotating beams of particles collide head-on at up to six interaction points.

Some of the relevant parameters of RHIC are given in Table 1.

Circumference (m)	3834	Momentum spread $\Delta p/p$	$1.0*10^{-3}$
Revolution frequency (kHz)	78	Bunch Length r.m.s. [m]	0.22
Horizontal tune	28.19	Vertical tune	29.18
Transition energy γ_t	22.8	Top energy, gold ions [γ]	106.6

Table 1. A few parameters of the RHIC machine.

The injection complex of RHIC starts with a linear accelerator (for protons) or a tandem Van de Graff accelerator (for heavier ions), followed by a booster ring, and culminating at the Alternating Gradient Synchrotron (AGS) which then inject into RHIC. The complex is shown in the aerial photograph with graphic overlays (Figure 1).

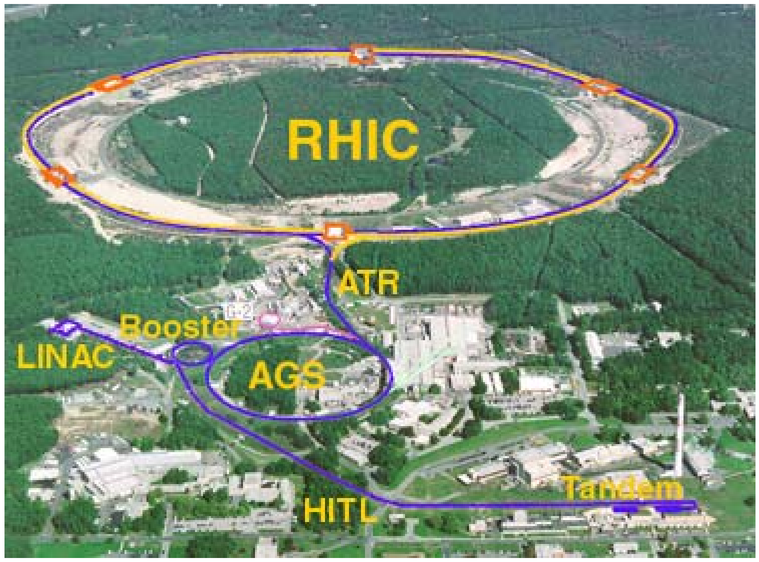

Figure 1. The RHIC accelerator complex. HITL stands for Heavy Ion Transfer Line and ATR for AGS to RHIC transport line. The six interaction points are labeled by the clock face, with the north-most (top of the figure) designated as the 12 O'clock IP. The cooler will be located above the 4 O'clock IP, close to 3 O'clock.

RHIC began operations in the summer of 2000 and has already generated a large body of results and a number of scientific publications.

RHIC Luminosity Upgrade and Electron Cooling

The RHIC lattice allows for simultaneous operation at six different interaction regions, each with a design luminosity of 2×10^{26} cm^{-2} s^{-1} for gold beams. Beam store times are typically 10 hours. It is expected that this design luminosity will be reached during the FY2001 heavy ion run. Due to the long time-scale of any significant upgrade of a machine such as RHIC, we have already started planning various RHIC luminosity-upgrades. The machine parameters are shown in Table 2 in column "RDM" (RHIC Design Manual).

Scheme	Units	RDM	RDM+	RHIC II
Initial Emittance	(95%), [μm]	15	15	15
Final Emittance	(95%), [μm]	40	40	< 6
IP beta function,	β* [m]	2.0	1.0	1.0
Number of bunches, M		60	120	120
Bunch population, N	$[10^{9}]$	1.0	1.0	1.0
Beam-beam parameter per IR, ξ		.0016	.0016	.004
Angular beam size,	[μrad]	108	153	95
RMS beam size,	[μm]	216	150	95
Peak Luminosity, L0	$[10^{27}\ cm^{-2}\ s^{-1}]$	0.8	3.2	8.3
Average Luminosity, <L>	$[10^{27}\ cm^{-2}\ s^{-1}]$	0.2	0.8	7

Table 2: The luminosity performance of RHIC in scenarios of Au+Au collisions at 100 GeV/nucleon. The luminosity averages given for "RDM" and "RDM+" are averaged over a 10 hour store. For the "RHIC II" scenario luminosity is averaged over 5 hours due to the beam-beam burn-off from actual collisions.

A first upgrade of the luminosity by about a factor of four consists of increasing the number of bunches from about 60 to about 120 and decreasing β* from 2 m to 1 m. This will not require any substantial new hardware. However, due to the larger beam size in the interaction triplets the non-linear local correction elements will have to be carefully optimized. It is expected that this level of performance can be reached during the FY2003 running period. The machine parameters for this enhanced luminosity are shown in column "RDM+".

Alternatively the luminosity can be enhanced by increasing the number of ions per bunch or by de-creasing the transverse emittance of the beam. However, already at the present bunch intensity and beam emittance the luminosity is expected to decrease very rapidly during a store due to intrabeam scattering (IBS). This is the reason for the large difference between peak and average luminosity in Table 1. To overcome this limitation we are proposing to counteract intrabeam scattering by electron cooling the gold beams at storage energy.

Cooling the gold beams at 100 GeV/nucleon requires electron beam energy of about 52 MeV and an average beam current of about 100 mA. The electron accelerator would be a superconducting, energy-recuperating linac very similar to an existing linac operating for a free electron laser at TJNAF, which operates at about 50 MeV and CW, 5 mA average current. With electron cooling the beam emittance can be reduced and maintained throughout the store and the luminosity increased until non-linear effects of the two colliding beams on each other limit any further increase (beam-beam limit). With the parameters shown in Table 1 in column "RHIC II" a 35-fold luminosity increase over RHIC design luminosity could eventually be achieved.

All electron-cooling systems in operation to date can be classified as *low energy* systems. These systems are characterized by the use of a conventional Cockcroft-Walton (C-W) high-voltage supply to bias the electron source with respect to the cooling region, and by a continuous longitudinal (solenoidal) magnetic field to confine (focus) the electron beam. Modern commercial C-W voltage generators are limited to about 0.6 – 1 MV, about a factor of 2 – 3 times higher than the electron systems in operation today; this is the principal technical limitation in the low energy regime.

Fermilab is currently developing a 5 MeV dc electron cooling system to cool 8.9 GeV/c antiprotons. To date, this is the only funded R&D project that would qualify (if successful) as a high-energy system.

For higher electron energies the most promising approach would appear to be the rf acceleration of bunched electron beams in an energy-recovering linac system.

THE RHIC ELECTRON COOLING SYSTEM

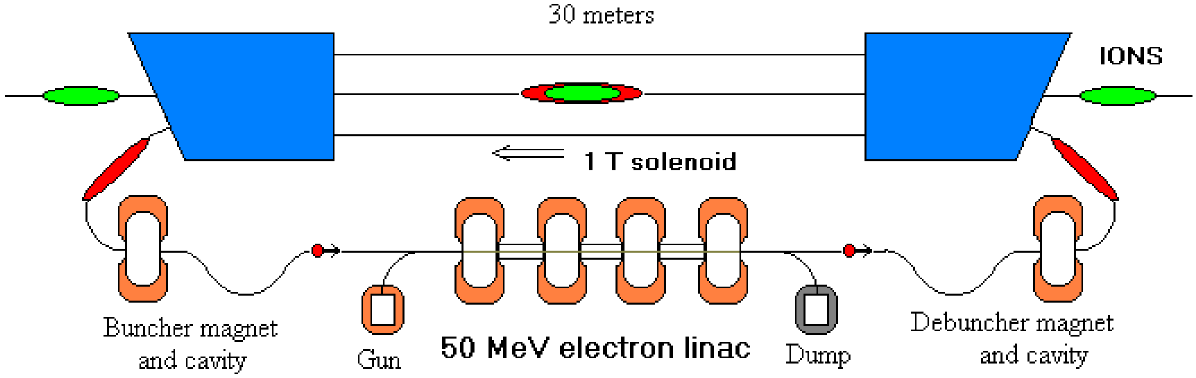

Figure 2: A schematic diagram of the proposed EIC electron cooling system.

Figure 2 shows schematically the proposed RHIC electron cooling system; consisting of a cooling section solenoid, bunching and debunching optical inserts and cavities, an electron linac structure, an electron gun and a beam dump. Solenoidal transport of the electron beam through an extended cooling section is needed to suppress space-charge divergence of the electron bunch and prevent electron-ion transverse instabilities. The electron gun has to be properly immersed in a solenoidal magnetic field in order to match the beam size and divergence to the magnetic field strength in the cooling section. The debunching optical insert has to match the electron bunch length to the ion bunch length and the rf cavity has to reduce the electron relative momentum spread to a value of about 10^{-4} required for effective cooling. After deceleration and beam energy recovery the electron beam of about 1 MeV is dumped. The cooling section length of 30 m is the longest possible available straight section in RHIC.

The RHIC electron cooler performance is being studied by the BINP team, headed by V.V. Parkhomchuk. The parameters selected for the cooler are given in Table 3 [1].

Number of electron in a single cooling bunch		N_e= 0---10^{11}
Electron bunch length r.m.s.	[cm]	σ_s =20
Frequency of repetition ion bunches	[MHz]	f_b=4.6
Average electron current	[mA]	Iav=0---74
Peak electron current	[A]	I_{peak}= 0--- 9.6
Magnet field at cooling section	[kG]	B=10
Transverse electron temperature in beam's reference system	[eV]	$T_\perp$=1000
Electron beam diameter	[mm]	a=2

Table 3. Parameters for the RHIC electron cooler

The ranges shown in Table 3 for the electron number and derived quantities refer to the range under study. The luminosity which is calculated for RHIC with various cooling currents is shown in Figure 4 [1].

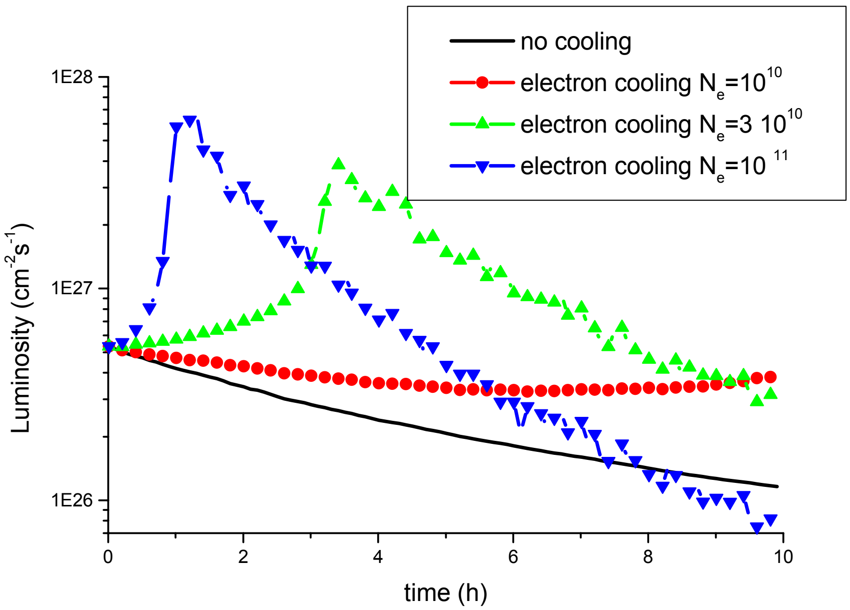

Figure 4. The luminosity of RHIC for no cooling and 3 values of cooling electron bunch size: 10^{10}, $3\text{x}10^{10}$ and 10^{11} electrons, taken from [1].

Figure 4 shows clearly that beam loss rate is dominating the cooling performance and the cooling strategy. In the next section we will take a look at the beam loss issues.

BEAM LOSS ISSUES

The design of an electron cooling system for gold ions at RHIC is greatly affected by two beam lifetime issues: One is the rather well recognized beam recombination, in which ions capture an electron in the cooler section and thus are lost rapidly from the storage ring. The other one is unique to a heavy ion collider: Beam loss due to the collision process.

Electron capture in the cooling section

Ion charge exchange by the electron beam recombination is an additional source of losses. The value of radiative recombination coefficient α is given by the equation [2]:

$$\alpha_{rec} = 3.02 \times 10^{-13} \frac{Z_i^2}{\sqrt{T_e}} \left[\ln\left(\frac{11.32 Z_i}{\sqrt{T_e}} \right) + 0.14 \left(\frac{T_e}{Z_i^2} \right)^{1/3} \right] (\text{cm}^3\text{s}^{-1}),$$

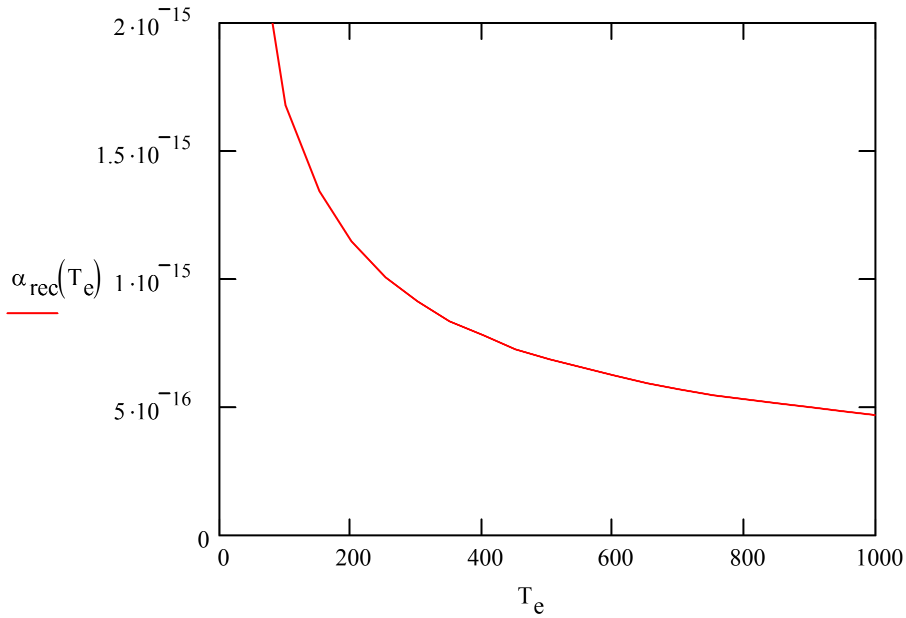

Figure 5. The recombination coefficient for fully stripped gold ions as a function of electron temperature in eV.

where T_e is the electron beam temperature in eV and Z_i is the ion's charge. This equation was found in good agreement with experimental results [3]. The dependence of the recombination coefficient on the electron temperature is shown in Figure 5, and we conclude that the electron temperature should be in the range of 400 to 1000 eV. The beam lifetime due to recombination is given by

$$\tau_{rec}=\gamma/(n_e\alpha_{rec}\eta)$$

where η is the fraction of the ring occupied by the cooler with an electron density n_e. Using an electron temperature of 1 KeV and fully stripped gold ions (Z_i=79) we get a recombination lifetime of $1.9\text{x}10^5$ seconds, or about 55 hours, well above the 10-hour typical storage time at RHIC.

Naturally, by increasing the electron transverse temperature to 1 KeV to reduce recombination, we pay the cost in cooling time. One way to reduce this penalty is to increase the solenoid magnetic field. This is shown [1] in Table 4, which provides the cooling time (in units of 1000 seconds) for two values of the solenoid magnetic field and five electron temperatures.

Te [eV]	0.1	1	10	100	1000
B=1kGs	1.4	2.0	3.3	6.5	16
B=10kGs	0.9	1.1	1.4	2.0	3.3

Table 4. Cooling rate (in 1000 seconds) as a function of electron temperature (in eV) and solenoid field (in kG), taken from [1]

Table 4 shows that for high electron temperature the influence of the magnet field is very significant, and for a temperature in the range of 100-1000 eV it is necessary to use high solenoid magnet field. This will require a 30 meters long superconducting solenoid, with a challenging requirement on precision.

The undulator scheme

An alternative to a large solenoid with a 10 kGauss field has been suggested by Derbenev [4]. In this scheme the cooling section comprises a low field solenoid and a helical undulator. The electrons move in a spiral trajectory under the undulator field. This motion provides the necessary effective electron temperature at a much smaller radius of the spiral. This increases the Coulomb integral and thus provides better cooling for the same level of recombination. In addition, the magnetized electron transport becomes simpler since this scheme requires a much smaller magnetization value.

Derbenev suggests a typical set of parameters for the scheme: A solenoid at about 0.6 kGauss, an undulator with a period of λ_u=12.6 cm and a peak field of 20 Gauss, to produce an effective electron temperature of 1 KeV. Both solenoid and undulator can be based on normal-conducting electromagnets. Here as in the superconducting solenoid, the main technical issue is the ability to do precise magnetic measurements on this system.

One may write a figure of merit f for the requirement to produce a particular electron temperature at a minimal radius for the electron circle of rotation. This would be $f=\beta_t/\rho$, where β_t is the transverse electron velocity (divided by c) and ρ is the Larmor radius for the solenoid, or the radius of the spiral in the undulator.

For the 1 Tesla solenoid and an electron beam of 50 MeV we have $f=eB/(\gamma mc)=5.9\ m^{-1}$, whereas for the undulator we have $f=2\pi/\lambda_u=50\ m^{-1}$. Thus the undulator can produce a given effective electron temperature for a much small radius.

Beam burn-off

At a high luminosity, gold collisions at 100 GeV/A exhibit beam losses that are dominated by bound electron-positron production and Coulomb dissociation. [5]. The cross section for both effects is 212±10 barns. To lose beam on this mechanism means that the collider reached an optimal luminosity, delivering the maximal rate of data to the experiment. Further increase in the luminosity can be made only by increasing the frequency of injections or number of bunches in the ring.

After reaching an electron bunch intensity $N_e=2x10^{10}$, an increase in the cooling current does not improve the integrated luminosity over a 10 hours run period. The disintegration cross section σ_{tot}=212 barns limits the integrated luminosity through:

$$\left(\int Ldt\right)_{\max} = \frac{N_i n_b}{n_{IP}\sigma_{tot}}$$

where n_b=60 is the number of bunches in the storage ring, and n_{IP}=6 is the number of interaction points delivering this luminosity. From the equation for the integrated luminosity we can see that the maximal integrated luminosity (over time $0-\infty$) equals 47 1/μbarn. An integrated luminosity of 38 1/μbarn is reached at a cooling bunch of $2x10^{10}$ electrons, showing that at this cooling rate 80% of the ions were lost due to IP collisions.

BEAM-BEAM PARAMETER

The RHIC cooler, if constructed, may be the first electron cooled collider. This raises the interesting question: what will be the effect of electron cooling on the maximal beam-beam parameter? The main beam-beam parameter for the interaction is the linear tune shift at the IP:

$$\xi_{ii} = \frac{N_i r_i}{4\pi\varepsilon n_i}$$

The beam-beam parameter for RHIC storage at top energy is $\xi_{ii}=3.8\cdot10^{-3}$.
Experience with electron-positron colliders shows that, at any one collider, increased cooling helps to reach a higher tune shift and luminosity.
The maximal beam-beam tune-shift as a function of the number of turns in one cooling time may be estimated by a simple power fitting approximation due to A.N. Skrinsky:

$$\xi_{ii\max} = \frac{2}{N_{cooling}^{1/3}}.$$

The cooling rate of RHIC will not be fast enough to have a significant effect on the beam-beam parameter. Furthermore, there is a very large variability between in the scaling of this dependence among various electron-positron colliders. It is anybody's guess what the effect may be at RHIC, an ion-ion collider, however it would be interesting to see the result.

A pointed out by Parkhomchuk [1], what is more important is that the electron cooling system cools coherent fluctuations much faster, in fact faster by many orders of magnitude than that for the single-particle motion. As a result, the fluctuation generated by the beam-beam interaction will be damped very fast. This consideration provides hope to reach a high beam-beam tune-shift, but this must be the subject of a separate investigation.

TECHNICAL ISSUES AND PROPOSED R&D

To achieve an operating 100mA, 50MeV electron cooling system a number of R&D topics need to be addressed. These range from theoretical exploration of some fundamental questions and improved definition of system parameters (e.g., through simulation studies) to practical demonstrations of technical requirements. They include:

- Production, acceleration and transport of high-quality rf-bunched electron beams in a non-continuous magnetic field:
  - What will be the highest average-current that can be stably accelerated and energy-recovered in a superconducting linac?
  - How will feedback systems improve the multi-bunch multi-pass instability threshold current?
  - How does one achieve the required electron beam parameters in the solenoid?
  - Demonstrate optimal transport of a magnetized electron beam.
- Magnetic field in the cooling section:
  - What is the required field quality?
  - Investigate other options for magnetic field configuration (solenoid + undulator).
  - In practical terms, how does one attain and measure the required field quality in a 30 m long solenoid?
  - What are the required electron and ion beam diagnostics in the cooling section, and how can they be made compatible with the solenoid design?
- Cooling times and evolution of the ion beam distribution function:
  - What are the cooling times as a function of ion beam emittance and machine functions?
  - What is the effect of ion-electron recombination and how to mitigate it?

- Can theory be extended to the hot electrons (1 KeV) required to reduce recombination?
- What are the optimal electron beam current, size, distribution and length?

The Collider Accelerator Department at BNL plans to develop the superconducting energy-recovery linac and carry out a number of proof-of-principle experiments aimed towards the generation of the electron beam necessary to cool RHIC. This program will include the following:

- Operation of a superconducting energy-recovery linac at an energy and current suitable for electron cooling of RHIC, as described above. This item will push the energy recovery current to value well beyond anything done to date.
- Investigate and develop multi-bunch, multi-pass beam feedback systems. This is a new development for energy recovery linacs and is of intrinsic scientific interest.
- Development of specialized electron beam diagnostics that will permit the non-intercepting beam position and profile measurement of a very high power, continuous duty electron beam. The electron beam in an energy recovery linac may not be interrupted since that will disrupt the recovery. We must obtain beam profile information at locations where synchrotron radiation is not observable.
- Development of a debunching – rebunching system to match the electron beam to the ion beam of RHIC and measurement of the beam characteristics. Bunched beam operations are a new direction in electron cooling and have not been done before in any cooler.
- Generation of a magnetized electron beam and its transport through the superconducting linac. This is also a new area in electron cooling with the exception of the Fermilab recycler electron cooler, which is still under development.

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