ERL FOR LOW ENERGY ELECTRON COOLING AT RHIC (LEReC)*

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Abstract

Low-energy RHIC Electron Cooler (LEReC) system is presently under design at Brookhaven National Laboratory. The electron cooling system needed should be able to deliver an electron beam of adequate quality in a wide range of electron beam energies (1.6-5 MeV). Since acceleration of electron beam is provided by the 704 MHz RF system the electron beam must be bunched and space-charge effects must be considered. An increase of electron beam temperatures by space-charge forces should be carefully avoided. We discuss the layout of the cooler and present the results of optics calculations using the computer code PARMELA.

INTRODUCTION

The nuclear physics program for the Relativistic Heavy Ion Collider (RHIC) for the 2019 and 2020 run periods concentrates on the search for the QCD phase transition critical point. While measurements at the energies of $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.6, 19.6, 27 GeV have been performed in the 2010, 2011 and 2014 runs, a significant luminosity improvement at energies below $\gamma = 10.5$ is required, which can be achieved with the help of an electron cooling upgrade called Low Energy RHIC electron Cooler (LEReC) [1].

Table 1: Electron Beam Kinetic Energies and Bunch Charges

Energy [MeV]	Gamma	Charge per bunch [pC]	Bunches per train	Beam Current [mA]
1.58	4.10	100	30	30
2.04	5.10	100	30	30
2.65	6.18	150	24	33
3.48	7.80	200	21	40
4.85	10.50	300	18	50

In order to cover the range of ion beam energies electron bunches must be produced with an energy range between 1.6 and 5 MeV. Table 1 lists the beam energies and beam currents required for electron cooling. Table 2 lists the ion parameters for the highest and lowest energy.

Table 2: Ion Parameters at the Highest and Lowest Energy

Gamma	4.1	10.7
RMS bunch length	3.2 m	2 m
Number of ions	$0.5\cdot10^9$	$2\cdot10^9$
Peak Current	0.24 A	1.6 A
Frequency	9.1 MHz	9.34 MHz
Cooling section beta function	30 m	30 m
RMS bunch size	4.3 mm	2.7 mm
RMS angular spread	140 μrad	90 μrad
Cooling sections	2x20 m	2x20 m

The LEReC will be the first electron cooler using a bunched electron beam. This allows the use of RF cavities to accelerate the electron beam and removes the limitation of the beam energy of the cooled ions caused by the availably of DC voltage sources. The ERL concept allows accelerating a sufficiently large electron current to fulfil the cooling requirements.

The LEReC will be built reusing the SRF gun and five-cell cavity of Brookhaven's Energy Recovery Linac. Both devices are designed for the frequency of 704.75 MHz with a wave length of 42.6 cm. The electron bunches have a RMS length up to 3.5 cm, much less then the ion bunches which will use a 9 MHz RF system. Sufficient cooling will be obtained by merging electron bunch trains with up to 30 electron bunches with each ion bunch. The friction force acting on the ions scales near the force maximum as

$$\vec{F} = -\frac{4\pi\, Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 \left((\gamma\sigma_{r'e})^2 + \sigma_{pe}^2 + (\gamma\sigma_{r'i})^2 + \sigma_{pi}^2\right)^{3/2}}$$

where $\sigma_{r'e}$ and σ_{pe} are the angular and momentum spread of the electron beam in the laboratory system. In a bunched system both of these parameters are degraded by the space charge forces. Table 3 lists the electron beam requirements.

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Table 3: Electron Parameters at the Highest and Lowest Energy

Gamma	4.1	10.7
Charge per ion bunch	3 nC (30x100pC)	5.4 nC (18x300pC)
RMS norm. emittance	< 2.5 µm	<2 µm
RMS energy spread	$<5\cdot10^{-4}$	$< 5\cdot10^{-4}$
RMS angular spread	<150 µrad	<100 µrad

DESIGN OF THE LEReC

The electron bunches will be created using a DC photo-cathode electron gun to be built for LEReC by Cornell University which will operate at 400 kV. A similar gun at Cornell University has already delivered beams of the required quality (300 pC, 50 mA, ε_n=1µ). The SRF gun used in the Brookhaven ERL will be transformed into a cavity (then called "SRF booster") and will provide an energy boost between 1.2 and 1.6 MeV. The power couplers of the SRF booster can provide enough power for the two lowest electron energies to operate without energy recovery. This mode of operation will be used in Phase I of the project. Figure 1 shows the layout for the Phase I of the LEReC project.

The SRF booster (as well as the five-cell cavity used in Phase II) is too tall to be installed in the RHIC tunnel. It has to be placed in the 2 o'clock experimental hall. A transport beam line will bring the electrons to the "warm section" of RHIC.

Because a low energy spread is an important requirement for the electron cooling a warm cavity operating at 2111 MHz (3rd harmonic, located next to the SRF booster) removes the curvature of the bunch shape in the longitudinal phase space.

The SRF booster will not only accelerate the electrons, but also introduce an energy chirp, which causes ballistic stretching of the bunch as it drifts through the transport beam line. A warm 700 MHz cavity removes the energy chirp before electron and ion beams are merged in the cooling section.

The electron bunches are used to cool both RHIC ion beams. After passing through the first cooling section the electron beam is turned around in a single 180 degree dipole and is dumped after traversing the second cooling section.

The merging dog leg is achromatic, using two solenoids to match the dispersion function. The solenoids have opposing polarity and introduce only local vertical dispersion.

At the end of the first cooling section the electron beam turns around in a single 180 degree magnet and is merged with the counter-rotating ion beam. This turn-around is not achromatic. It turns out that the degradation of the transverse emittance by the unmatched dispersion is smaller than the degradation through space charge forces when strong focusing is employed to match the dispersion function.

Both cooling sections include eight solenoids, spaced 3 meters apart. They are used to keep the beam size constant and minimize the angular spread.

In the final configuration (Phase II) the beam will be accelerated to the final energy by the 700 MHz five-cell cavity, which is operated in ERL mode. Figure 2 shows the Phase II layout.

In the transition from Phase I to Phase II the five-cell cavity and an additional 3rd harmonic cavity will be installed. A 9 MHz warm cavity is added, which corrects the beam energy variation caused by beam loading by the

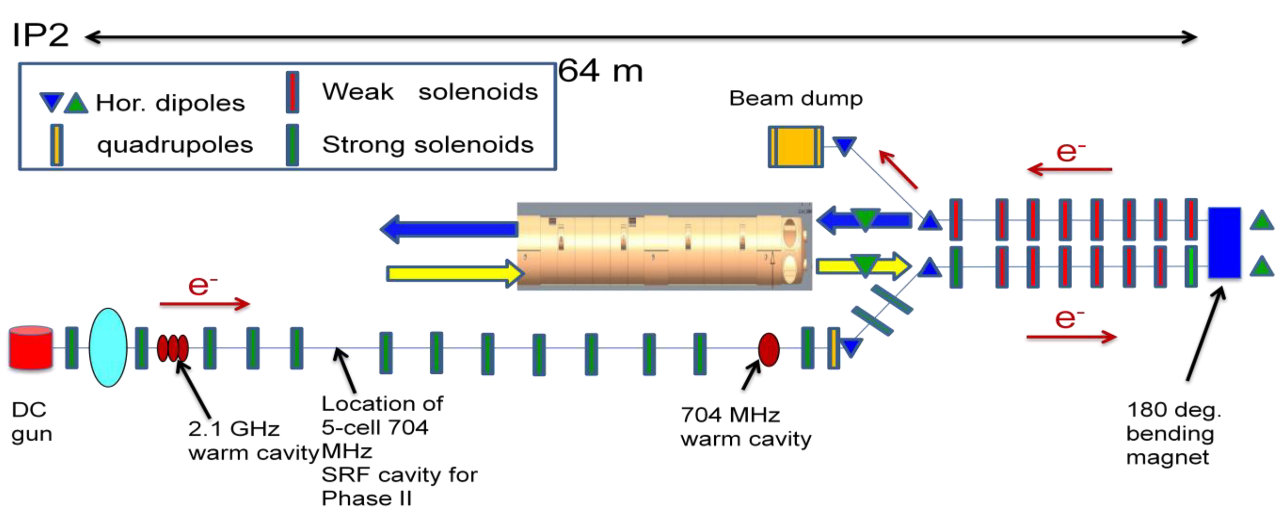

Figure 1: Layout for Phase I.

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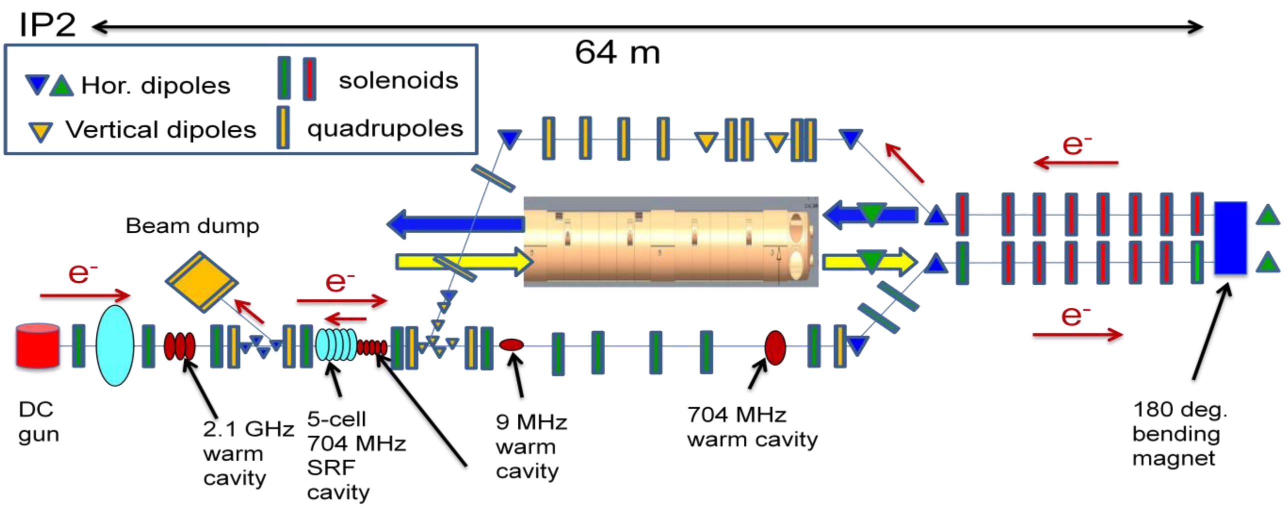

Figure 2: Layout for Phase II.

bunch trains. The beam transport for energy recovery including two zig-zag merging systems [2] for the energy recovery are installed and the beam dump is moved.

LEReC differs from most existing ERLs in that it operates in "push-pull" mode, i.e. the electrons move in the opposite direction through the cavity when the energy is recovered. This is possible since the gaps between the bunch trains are big enough to avoid collisions of the outgoing and incoming bunches.

The push-pull layout simplifies the merging systems on both sides of the 5 cell cavities, since it allows a fixed merger geometry while the ratio of the beam energies of the low and high energy electrons can be chosen independently for all ion energies.

SIMULATIONS

All simulations presented in this paper were made using the computer code PARMELA[3]. PARMELA is a 2-D program that assumes a round beam for the space charge calculations, which is the case for the LEReC.

A multi-threaded optimization program (written at BNL) was used which launches PARMELA for the function evaluation.

In the following results we take advantage of the fact that electrons that are too hot (i.e. have a too high velocity in the co-moving frame) do not contribute to the cooling but do not harm either. For the calculation at 1.6 MeV 130 pC bunches are tracked, and 100 pC (electrons with the lowest energy deviation) are used for the evaluation of the beam parameters expected in the cooling sections.

Since the set of electrons used for the calculation of the result is evaluated at each point of the curves the functions jumps when a cavity or space charge changes the energy distribution.

RESULTS FOR 1.6 MeV

Figure 3 shows the beam envelope for the Phase I accelerator and Figure 4 shows the projected emittance. The electron beam, generated in the DC gun, is focused with two solenoids to have a waist in the SRF booster so that the emittance is not degraded. Since the beam energy after the booster is still relatively low the projected emittance oscillates throughout the accelerator. The focusing in the transport section is chosen so that the average emittance in the cooling section is minimized.

The beam size in the cooling sections matches the size of the ion beams.

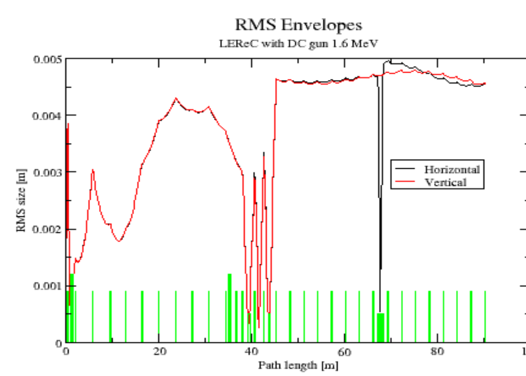

Figure 3: Beam envelope along entire electron beam transport through both cooling sections at 1.6 MeV.

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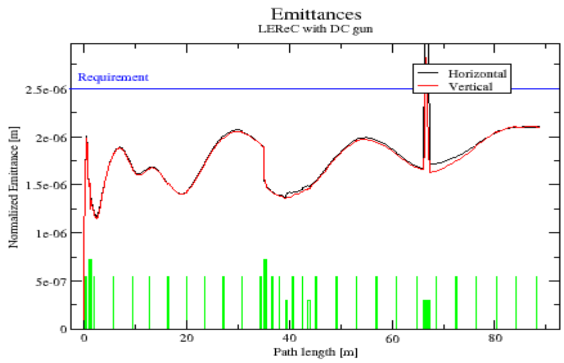

Figure 4: Projected beam emittance at 1.6 MeV. The wave in the emittance is caused by the differences of focusing of the longitudinal slices of the bunch.

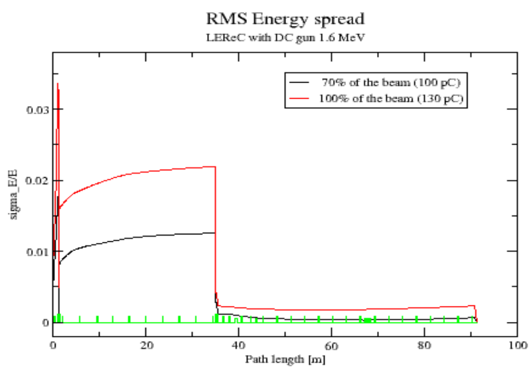

Figure 5: The red curve shows the energy spread of the whole beam (130 pC), the black curve shows the energy spread when only 70% (100 pC) are evaluated.

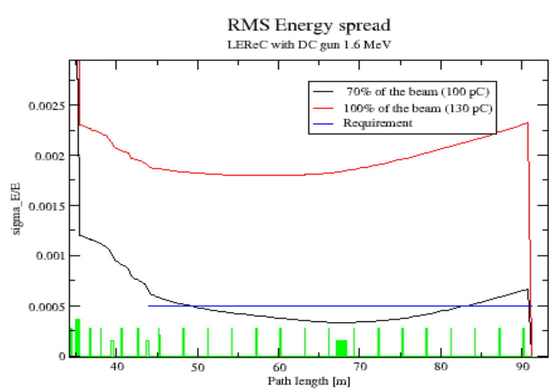

Figure 6: Energy spread in the cooling sections. The requirement is fulfilled.

Figures 5 and 6 show the energy spread of the beam and illustrate how the RMS values are dominated by the tails of the bunch. The intentional energy chirp in the transport section is removed by the warm 700 MHz cavity. Because space charge introduces an additional chirp as the electrons pass through the cooling section a small negative chirp is introduced by the cavity so that the energy spread is symmetric in both cooling sections. Figure 6 zooms into the cooling sections.

RESULTS FOR 5 MEV

The Phase-II, the LEReC will operate in ERL mode for energies 2.6-5 MeV. This Phase of the project is presently under design with preliminary results for 5 MeV shown in Figures 7 to 9. After the booster and 3rd harmonic cavity the beam passes through a zig-zag merging section into the the 5-cell SRF cavity for additional acceleration.

We found it necessary to place a 3rd harmonic cavity after each accelerating cavity. Otherwise the quadratic shape of the bunch in longitudinal phase space will be distorted by the momentum compaction of the mergers and the energy spread cannot be removed later on.

A second zig-zag merger allows the beam to return through the 5 cell cavity for energy recovery.

The beam size in the cooling sections is adapted to the smaller ion beam size.

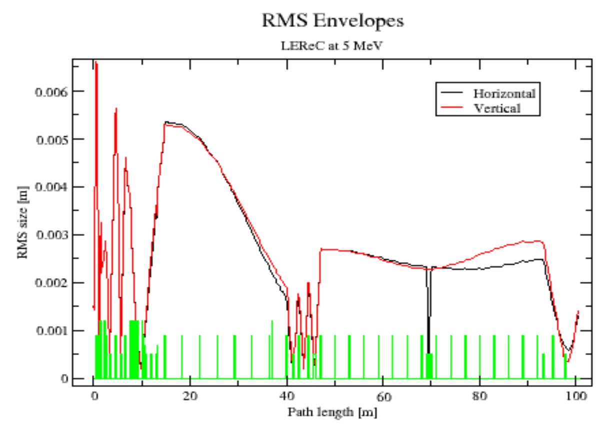

Figure 7: Beam envelope for 5 MeV operation.

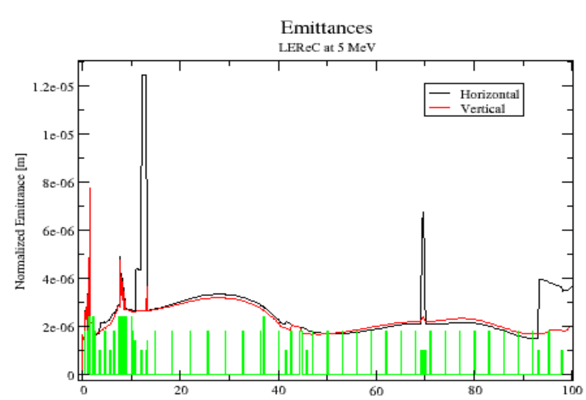

Figure 8: Normalized rms emittances. The spike in the horizontal emittance at the path length of 12 m is caused by the dispersion of the zig-zag merger.

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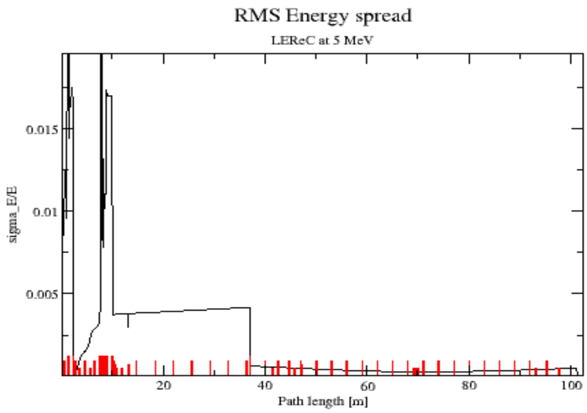

Figure 9: The energy spread calculated from tracking 330 pC charge and using 90% of the beam for the evaluation.

TIME LINE

Phase I of our project has been approved. The DC gun will be constructed by Cornell University in 2015 and commissioned at Cornell in 2016. Also in 2015 the cooling sections will be installed. The installation of the gun, SRF and RF components and beam dump in RHIc tunnel will be done in 2017. The system commissioning will start 2017 with electron beam commission to start in early 2018.

The RHIC Run-19 BES-II physics program (Phase I commissioning of cooling with Au ion beams) starts in October 2018, RHIC Run-20 BES-II (Phase II) at the end of 2019.

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