ACCELERATOR PHYSICS DESIGN REQUIREMENTS AND CHALLENGES OF RF BASED ELECTRON COOLER LEReC

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Abstract

The Low Energy RHIC electron Cooler (LEReC) is presently under construction at BNL to improve the luminosity of the Relativistic Heavy Ion Collider (RHIC). Required electron beam and its acceleration will be provided by the photoemission electron gun and the RF linear accelerator. As a result, LEReC will be the first bunched beam electron cooler. In addition, this will be the first electron cooler to cool beams under collisions. In this paper, we describe accelerator physics requirements, design considerations and parameters, as well as associated challenges of such electron cooling approach.

INTRODUCTION

Mapping the Quantum-Chromo-Dynamics (QCD) phase diagram is one of the fundamental goals in the heavy-ion collision experiments. The QCD critical point is a distinct feature of the phase diagram, the existence of which is predicted by various QCD models. The beam energy scan phase-I (BES-I) runs for physics, motivated by the search of the QCD critical point, were successfully conducted at RHIC in 2010-11. Driven by physics and the BES-I results, the future physics program called BES-II is proposed. However, required event statistics is much higher than previously achieved and relies on significant luminosity improvement in RHIC with the help of electron cooling [1].

Although maximum required electron energy is not very high, and typical electrostatic DC acceleration is an option (which was considered in the past [2]), an approach based on the RF acceleration was chosen. Such a scheme of cooling with bunched electron beam is also a natural approach for high-energy electron cooling which requires RF acceleration. As such, LEReC is also a prototype for future high-energy electron coolers, both in physics and technology.

COOLER REQUIREMENTS

The LEReC design is based on the non-magnetized cooling approach with zero magnetic field on the cathode and no magnetic field in the cooling region. For non-magnetized cooling to be effective one needs to have strict control not only of the longitudinal velocity spread of electrons as in typical low-energy magnetized coolers but also of the transverse electron velocities (both the velocity spread and the average beam velocity), similar to the FNAL cooler [3].

The friction force acting on the ion with charge number Z inside a non-magnetized electron beam with velocity distribution function $f(v_e)$ is

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e, \quad (1)$$

where e and m are the electron charge and mass, V and v_e are the ion and electron velocities respectively, and n_e is electron density in the particle rest frame (PRF). The Coulomb logarithm $\ln(\rho_{\max}/\rho_{\min})$ is kept under the integral because the minimal impact $\rho_{\min}$ parameter depends on electron velocity.

Table 1: Electron Beam Parameters for Cooling

Electron beam energy, MeV	1.6-2.6
Charge per single bunch, pC	130-200
Number of bunches in macrobunch	30-24
Total charge in macrobunch, nC	3-5
Average current, mA	30-55
RMS normalized emittance, μm	< 2.5
Angular spread, mrad	< 0.15
RMS energy spread	$<5 \times 10^{-4}$
RMS bunch length, cm	2-3
Length of cooling sections, m	20

To maximize cooling power and not to overcool a core of ion distribution, which is important for colliding beams, electron beam rms velocity spreads are chosen close to those of the ion beam. The ion beam has rms momentum spread in the range of σ_p=4-5×10^{-4}. This sets the requirement for the rms momentum spread of electron beam to < 5×10^{-4}.

For the rms normalized emittance of the ion beam, 2.5 μm at γ=4.1, and 30 m beta function in the cooling section, the ion beam rms angular spread in the lab frame is 0.14 mrad. This gives the requirement for the electrons angular spread θ in the cooling section < 0.15 mrad.

For electron beam parameters in Table 1 the temperature of the longitudinal degree of freedom is

$$T_{\parallel} = mc^2 \beta^2 \left(\frac{\Delta p}{p}\right)^2 \approx 0.12\ eV$$

and the transverse degree of freedom

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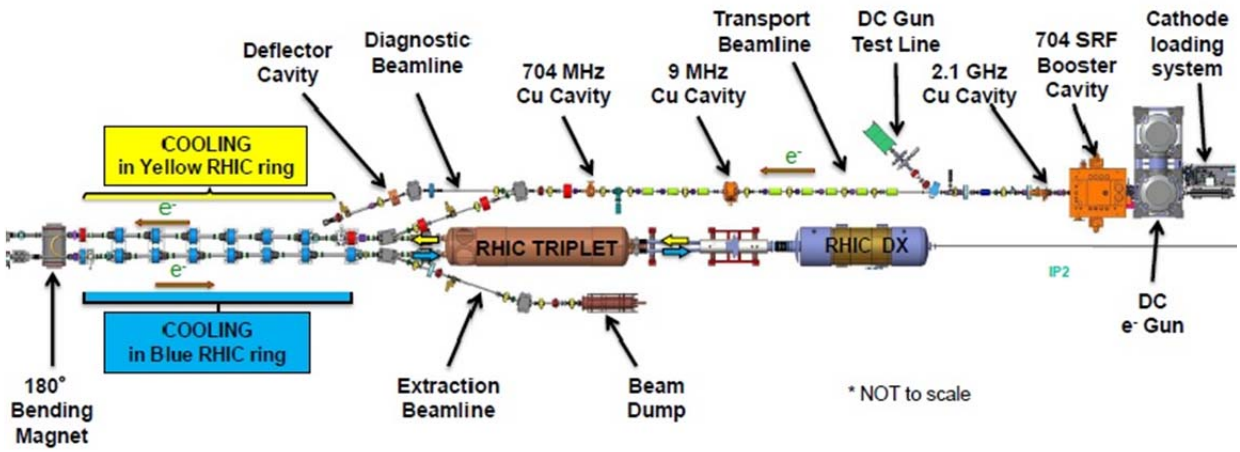

Figure 1: Layout of LEReC accelerator.

$$T_{\perp} = mc^2\beta^2\gamma^2\vartheta^2 \approx 0.17\ eV$$

where θ is rms angular spread and $\Delta p/p$ – rms momentum spread of electrons in the cooling section. As a result, the velocity distribution is slightly anisotropic with the transverse rms velocity spread of $1.7\cdot10^5\ m/\sec$ and the longitudinal velocity spread $1.5\cdot10^5\ m/\sec$ in the PRF.

With the friction force maximum being located close to the longitudinal rms velocity spread of the electrons, one gets a requirement for matching electron and beam energies to better than the rms velocity spread, which for our parameters is < 5×10^{-4}. Energy stability of the electron beam should be better than this, at about 2×10^{-4} rms.

To keep the transverse angle of the electron beam trajectory < 0.15 mrad an integral of residual transverse magnetic field in cooling region should be kept below 1 Gauss·cm. A shielding of residual magnetic field to such level will be provided by several concentric cylindrical layers of high permeability alloy [4].

Some cooling section space is taken up by short (10 cm) weak solenoids (to control angular spread due to the transverse space charge), steering dipoles and beam position monitors to keep the electron and ion beam in close relative alignment. A description of beam instrumentation for the LEReC project can be found in Ref. [5].

Since the electron beam does not have any magnetization, the space used by the solenoids will be lost from the cooling process. Longitudinal field of 1 G produces rotational angles of 75 μrad at γ=4. Design of these solenoids, placed every 3 m, was optimized to maximize the space between them which satisfies requirement on longitudinal magnetic fields in the cooling region to be $B_z < 1$ G.

The charge per bunch needed for cooling depends on the energy at which cooling is applied. For the 9 MHz RF system in RHIC at γ=4 ion bunches are long (3 m rms length). As a result, we can place a macro-bunch of electrons consisting of 30 individual electron bunches on a single ion bunch. The use of such macro-bunches allows us to split the total charge of 3 nC required for cooling, into 30 bunches with 0.1 nC per bunch, for example. Although an individual electron bunch occupies a small portion of the ion bunch, all ions could be cooled as a result of the synchrotron oscillations.

ELECTRON ACCELERATOR

One of the first challenges for such an approach is providing transport of electron bunches to the cooling sections while preserving beam emittance and energy spread at the level required for cooling ("cold" beam) [6].

Layout of the LEReC accelerator is shown in Fig. 1. Electron beam will be generated by illuminating a multi-alkali (CsK_2Sb or NaK_2Sb) photocathode with green light (532 nm) from a laser. The photocathode is inserted into a DC gun with design operational voltage of 400-500 kV. The 704 MHz fiber laser will produce bunch trains with individual electron bunches of about 80 ps full length at ~9 MHz bunch train repetition frequency. The bunch train repetition rate will be the same as the repetition rate of ion bunches in RHIC. An optical system will allow creating dedicated bunch patterns for different RHIC energies and ion bunch lengths. Each bunch train will be followed by a long gap (about 100 ns) corresponding to the gap between ion bunches, as illustrated in Fig. 2. A mode of operation with full continuous wave (CW) at the 704 MHz frequency (no macro-bunches) is also being considered. Such mode simplifies RF commissioning due absence of transient beam loading however it puts more demand on the photocathode due to a requirement of higher average current of up to 85 mA.

The electron beam will be accelerated to the required energy by the 704 MHz SRF booster cavity and then transported to the first cooling section in the Blue RHIC ring, cool ions in the first cooling section, turned around between Blue and Yellow RHIC rings (using a 180 degree dipole magnet), cool ions in the Yellow ring and transported to the beam dump, as shown in Fig. 1.

To prevent degradation of energy spread due to the longitudinal space charge force, electron bunches require stretching. Such stretching is achieved by accelerating slightly off-crest in the 704 MHz SRF booster cavity to produce energy chirp (the correlation between particle position within the bunch and its energy). Since electrons are only slightly-relativistic a proper choice of the RF phase results in bunch stretching in a drift which follows (similar to ballistic compression with the opposite phase).

A series of warm RF cavities are used to obtain and control energy spread within electron bunches at the required level (Table 1). A warm 2.1 GHz cavity (3rd harmonic of the 704 MHz) is used to remove non-linear energy spread introduced by the RF curvature. After bunches are stretched another 704 MHz warm RF cavity is used to remove energy chirp. An additional 9 MHz warm RF cavity is being employed to remove bunch-by-bunch energy variation within the 30 bunch train (macro-bunch) caused by beam loading in the RF cavities. Design of these RF cavities is described in Refs. [7-9].

Based on tolerance studies, to keep rms energy spread of electron beam < 5×10^{-4} in the cooling sections, requires 2.5×10^{-4} voltage and 0.25 degrees rms stability for the 704 MHz SRF cavity (stability requirement for other cavities is less stringent). This in turn requires laser phase stability of 0.25 degrees or 1 ps rms.

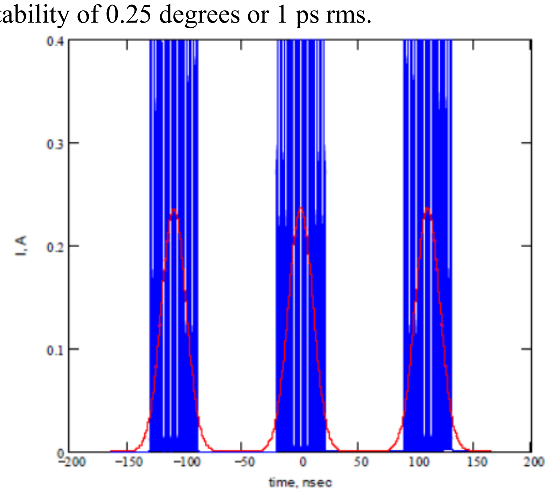

Figure 2: LEReC bunch structure. Thirty electron bunches (blue) spaced by 1.4 ns placed on a single ion bunch (red). For ion bunches with the 9 MHz RHIC RF system.

CHALLENGES

Successful operation of LEReC cooler requires stable CW operation of the gun with electron beam current up to 55 mA using trains of macrobunches and up to 85 mA for full CW mode with a long lifetime of a photocathode. To operate with such high current in photocathode DC gun electron beam needs to be generated off geometrical centre of the cathode which in turn may affect beam quality due to aberrations.

The achievement of very low transverse angular spread for the electron beam is being addressed by a proper beam transport and engineering design. The attainment of required low energy spread in the electron bunch relies on stretching of electron bunches, and RF gymnastics. A very tight requirement on impedance budget led to detailed wake fields simulations and special design of every vacuum element including instrumentation devices. The repeatability of low energy electron transport is challenging due to remnant fields in the optics and hardware. Electron beam with small emittance and energy spread should be provided for several energies of interest. Quality of the beam should be preserved through the entire beam transport since the same beam will be used for cooling in both RHIC rings.

Using bunched electron beam for cooling can also have some negative effects on ion beam lifetime. At such low energy it can lead to emittance growth of ions due to modulated focusing from the electrons. This effect led to a requirement to "lock" frequency of electron bunches to the revolution frequency of ion bunches to avoid emittance growth of ions due to the betatron resonances [10]. Also, for our regime of parameters, an additional effect of synchrotron motion of ions was found to be significant [11]. In addition, this will be the first electron cooler to cool beams under collisions. This puts special requirements on the control of the ion beam profile under cooling. Careful optimizations between electron cooling and ion beam lifetime due to various effects will determine how close one can actually get to the projected luminosity improvement.

SUMMARY

Electron cooler based on the RF acceleration is presently under construction at BNL. Many challenges associated with chosen approach and complications of low electron energies are being addressed by a proper physics and engineering design. Commissioning of full LEReC electron accelerator is scheduled to start in early 2018.

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