ELECTRON COOLING OF RHIC*

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Abstract

We report progress on the R&D program for electron-cooling of the Relativistic Heavy Ion Collider (RHIC). This electron cooler is designed to cool 100 GeV/nucleon at storage energy using 54 MeV electrons. The electron source will be a superconducting RF photocathode gun. The accelerator will be a superconducting energy recovery linac. The frequency of the accelerator is set at 703.75 MHz. The maximum electron bunch frequency is 9.38 MHz, with bunch charge of 20 nC. The R&D program has the following components: The photoinjector and its photocathode, the superconducting linac cavity, start-to-end beam dynamics with magnetized electrons, electron cooling calculations including benchmarking experiments and development of a large superconducting solenoid. The photoinjector and linac cavity are being incorporated into an energy recovery linac aimed at demonstrating ampere class current at about 20 MeV.

INTRODUCTION

We provide an update on the status of the electron cooling project of RHIC. Various advances were made in the component design and the theory and simulations of the electron cooler since last report [1].

The electron cooling of RHIC is the main element of the luminosity upgrade which has been called RHIC II. In addition, electron cooling is essential for eRHIC, a future electron-ion collider. Both RHIC II and eRHIC are in the DOE 20 years facility roadmap. This project has a number of new features as electron coolers go: Using 54 MeV electrons, it will be the first attempt to cool a collider at storage-energy; and it will be the first cooler to use a bunched electron beam and a linear RF accelerator as the electron source. The cooling of ions at γ~100 is significantly more difficult than traditional coolers which operate at about $\gamma<2$, since the laboratory frame cooling time τ scales with $\gamma^{5/2}$. We use the empirical formula for magnetized cooling due to V. Parkhomchuk:

$$\tau = \frac{A}{Z^2}\frac{\gamma^2}{4\pi r_p r_e n_e c\eta\Lambda_c}\left(\frac{\gamma\varepsilon_{in}}{\beta_{ic}}\right)^{3/2}$$

Here r_p, r_e, c are fundamental constants (classical radius of the proton and electron and velocity of light). Fortunately, for cooling fully stripped gold ions, the factor of ion mass to its charge squared, A/Z^2, helps. Another helpful item is that the normalized ion beam emittance at RHIC, ε_{in}, starts out small. The only parameters under control of the designer are η (the fraction of the ring occupied by the cooling solenoid), n_e, the density of the cooling electron beam and β_{ic}, the beta function of the ion beam at the cooler.. This forces us to use a very long solenoid and a very high electron beam current. It is also a basic fact of electron beam sources, that a high bunch charge incrreases the beam emittance. Thus the Coulomb logarythm Λ_c becomes small. This forces us to design an electron source with a very small emittance for the given (large) charge and to increase the solenoid magnetic field.

Clearly the subject of electron cooling at this high energy is complex and involves significant R&D on a variety of subjects. This work is carried out by a number of collaborations with various institutes. It is impossible to cover this subject in one paper, however these proceedings include many other papers concerned with the various aspects of the science and technology of cooling RHIC. We will refer the reader to details in these other papers. Additional detail can be found in the ZDR on electron cooling of RHIC at our web site [2]. The main parameters of electron cooled RHIC are given in Table 1.

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Table 1: RHIC with and without electron cooling.

Gold 100 GeV/n	**Units**	**no cooling**	**cooling**
Emittance (95%)	$\pi\,\mu$m	$15 \rightarrow 40$	$15 \rightarrow 10$
β-function in IR	m	1.0	0.5
Number of bunches		112	112
Bunch population	10^9	1	$1 \rightarrow 0.3$
Beam-beam / IR		0.0016	0.004
Peak luminosity	**10^{26} cm^2 s^{-1}**	**32**	**90**
Ave. store lumen.	**10^{26} cm^2 s^{-1}**	**8**	**70**
Polarized Protons	**250 GeV**		
Emittance (95%)	$\pi\,\mu$m	20	12
β-function in IR	m	1.0	0.5
Number of bunches		112	112
Bunch population	10^{11}	2	2
Beam-beam per IR		0.007	0.012
Ave. store lumen.	**10^{30} cm^2 s^{-1}**	**150**	**500**

CALCULATING THE COOLING RATE

High-energy electron cooling of RHIC presents many unique features and challenges. An accurate estimate of the cooling times requires a detailed calculation of the cooling process, which takes place simultaneously with various diffusive mechanisms in RHIC. In addition, many unexplored effects of high-energy cooling in a collider complicate the task of getting very accurate estimates of cooling times. To address these high-energy cooling issues, Fedotov et. al. [3] present a detailed study of cooling dynamics based on computer codes, including an update on code development and its application to the high-energy cooling dynamics studies for RHIC. This work involves collaborations with JINR, Dubna, Moscow Region, and Tech-X, Boulder, Colorado. Also, a collaboration was established with an INTAS project [4], aimed at similar topics of high-energy cooling for the HESR ring of the FAIR project at GSI [5].

The collaboration with JINR revolves around the development of the dynamic electron beam cooling code BETACOOL [6], which has been enhanced with various features essential to the particular conditions of electron cooling of RHIC (e.g. arbitrary ion distribution, bunched beams and much more), as well as a capability to accept parameterized friction force calculated by models or other programs (see below).

Accurate calculation of electron cooling times requires an accurate description of the dynamical friction force. Therefore we explore [7] the magnetized friction force for parameters of the RHIC cooler, using the VORPAL code [8]. VORPAL can simulate dynamical friction and diffusion coefficients directly from first principles [9]. The physics of magnetized friction with magnetic field errors is being simulated for RHIC parameters using the VORPAL code [10]. Most theoretical treatments for magnetized dynamical friction do not consider the effect of magnetic field errors, except in a parametric fashion [11]. However, field errors can in some cases dramatically reduce the velocity drag and corresponding cooling rate. This work uses a simple analytical model for the magnetic field errors, which must be Lorentz transformed into the beam frame for use in the VORPAL simulations.

Other issues under investigation are the equilibrium process between intra-beam scattering within ion bunch and electron cooling, critical number of electrons needed, magnetized cooling logarithm and resulting requirements on parameters of electron beam, effects of solenoid errors, etc.[12]. This investigation includes simulations of various possibilities of using electron cooling at RHIC, which includes cooling at the top energy, pre-cooling at low energy, aspects of transverse and longitudinal cooling and their impact on the luminosity. Studies of electron cooling at various collision energies both for heavy ions and protons are also investigated.

This discussion underscores the significance of IBS for the cooling process. As a result of electron cooling, the core of beam distribution is cooled much faster than the tails, producing a denser core. A detailed treatment of IBS, which depends on individual particle amplitudes, was recently proposed by Burov [13], with an analytic formulation done for a Gaussian distribution. To understand the extent of the dense core formation in the ion distribution, the "core-tail" model for IBS, based on the diffusion coefficients for bi-Gaussian distributions, was employed in cooling studies for RHIC. In addition, the standard IBS theory was recently reformulated for rms parameters growth of a bi-Gaussian distribution by Parzen [14]. We compared various approaches to IBS treatment for such distribution, and show a significant effect on the luminosity of the collider [15].

The bi-Gaussians distribution has also an important implication for the beam-beam interaction [16]. Simulation studies are being performed to understand the beam-beam interaction of these double-Gaussian beams. The study looks at the effect of low-frequency random tune modulations on diffusion in double-Gaussian beams and compares the effects to those in beam-beam interactions with regular Gaussian beams and identical tune-shift parameters. It turns out that significant beam loss can take place unless extra care is taken in choosing the operating point.

BENCHMARKING EXPERIMENTS

We are carrying out two lines of benchmarking experiments. The first is to understand better the IBS and other diffusion mechanisms in RHIC, the other line is friction force measurements in low-energy electron coolers.

Dedicated IBS experiments are performed to benchmark the rms beam size growth, beam loss, and beam profile evolution both for a Gaussian-like beam and a longitudinal hallow beam. J. Wei et. al. [17] summarize the experimental bench-marking results. Good agreement was found between the models and the measurements, lending confidence to our understanding of IBS in RHIC.

Our objectives for friction force measurement include two major goals: 1) To make sure that we understand magnetized friction force formulas with a very good precision (not an order of magnitude estimate); 2) Try to perform experiments in present coolers which can help to explore various issues relevant to high-energy cooling.

Specifically, the following measurement were proposed and planned together with the ITAS project: (1) Accurate measurement of cooling force. (2) Benchmark new models of IBS. (3) Cooling with small cooling logarithm. (4) Effect of solenoid errors. Progress was made on all of these objectives with results presently being analyzed. The first set of experiments was carried out at the CELSIUS cooler ring [18].

Accurate alignment of the electron and ion beams in the RHIC electron cooling solenoids is crucial for well-optimized cooling. Shimming the solenoid field to an accuracy of a few parts-per-million is necessary at RHIC, and it might be accomplished by methods of beam-based alignment. Cameron et. al. are investigating [19] the details of a modulated quadrupole beam-based alignment, and this is also a subject of experiments with the ion beam at RHIC.

THE ELECTRON BEAM DYNAMICS

The linac will be superconducting with energy recovery. The beam dynamics development effort was described earlier by Kewisch et.al. [20]. An improved design of the injection side beam merging system [21] and stretcher [22] minimize emittance blow-up through coupling of longitudinal and transverse motions.

The theoretical work on cooling let to increased requirements on the electron accelerator: Besides a doubling of the bunch charge to 20 nC, the strength of the cooling solenoid was increased five-fold to 5 Tesla. Various measures were necessary, including the increase of the gradient in the RF gun (and thus transition to a superconducting RF gun), modified lattice and more. We are in the process of carrying out front-to-end simulation using different tracking codes.

Additional work is carried out on the beam dynamics with large angular momentum dominated beams, which require very large beam radii, yet small emittance. This situation places new demands on the modeling of particle motion in RF cavities using map-based techniques. A new method has been developed for computing nonlinear maps for arbitrary RF cavities [23]. High Current, High-Brightness Energy Recovery Linac

We pursue work on CW, high-current and high-brightness electron beams, in particular a superconducting, laser-photocathode RF gun capable of producing low emittance (about 2 micron rms normalized) 1.5 nano-Coulomb bunches at currents of the order of 0.5 ampere average and a 5-cell accelerator cavity capable of a few amperes of average current with sufficient damping of higher-order modes. In addition, we are constructing an energy recovery linac, operating at a frequency of 703.75 MHz, that will use these gun and cavity to demonstrate the feasibility and study the characteristics of thie ERL. This subject is covered in a few papers [24-31].

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