R&D TOWARDS COOLING OF THE RHIC COLLIDER*

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Abstract

We introduce the R&D program for electron-cooling of the Relativistic Heavy Ion Collider (RHIC). This electron cooler is designed to cool 100 GeV/nucleon bunched-beam ion collider at storage energy using 54 MeV electrons. The electron source will be an 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 bunch frequency is 28.15 MHz, with bunch charge of 10 nC. The R&D program has the following components: The photoinjector, the superconducting linac, start-to-end beam dynamics with magnetized electrons, electron cooling calculations and development of a large superconducting solenoid.

INTRODUCTION

The Collider-Accelerator Department (C-AD) 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. One important component of the luminosity upgrade is electron cooling of RHIC. In addition, electron cooling is essential for eRHIC, a future electron-ion collider. This project has a number of new features as electron coolers go: It will cool use 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 beam and a linear RF accelerator as the electron source.

The linac will be superconducting with energy recovery. The electron source will be a photocathode gun. The project is carried out by the Collider-Accelerator Department at BNL in collaboration with the Budker Institute of Nuclear Physics [1] and Jefferson National Accelerator Facility.

The parameters of the electron beam for the RHIC electron cooler are: Bunch charge 10 nC, average current 94mA (RHIC) or 280mA (eRHIC), energy up to 54 MeV, rms normalized emittance 50 µm, energy spread 0.02%.

We simulated the performance of the cooler with the computer code Simcool [2]. Figure 1 shows the performance of the cooler for a proton beam at a few energies.

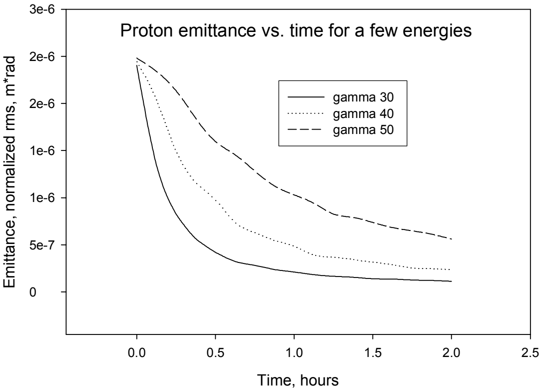

Figure 1. Cooling proton beams at RHIC.

The two RHIC rings would require two coolers operating simultaneously. In the following, we will describe the ongoing R&D program aimed at reducing the risks associated with a construction of this novel device.

ELECTRON GUN

We will produce the electron beam with a CW photoinjector (laser photocathode RF gun). The cathode of the gun will be immersed in a magnetic field to produce a 'magnetized' electron beam.

Photocathode development

We plan on using CsK_2Sb (cesium potassium antimonite) cathodes. These cathodes exhibit a very high quantum efficiency of over 5% for green light [3]. This material is sensitive to contaminants and we have initiated a research program to study the deposition and lifetime issues for various vacuum qualities. The UHV deposition system is shown in Figure 2. The rightmost chamber is the deposition chamber, the middle one is a storage chamber and the one on the left is a test chamber. A manipulator arm allows the transfer of targets between chambers.

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Laser development

We will use a highly efficient, diode-pumped, solid-state laser at a wavelength of 1064nm, where commercially available oscillators can provide continuous mode-locked operation with 10’s of watts. we need an efficient method to convert the light to 532nm as well as reduce the pulse repetition frequency from about 80 to 100 MHz to 9.4 or 28 MHz. We are investigating a resonant multi-pass cavity. The IR pulse stream passes once through the bowtie cavity, the 2nd harmonic at 532nm is trapped for a number of turns in the cavity and is coherently converted with high efficiency.

CW photoinjector development

We adopt the design of the Los-Alamos / Advanced Energy Systems of a 2.5 cell, 700 MHz normal-conducting photoinjector. The device will be powered by a 1 MW CW klystron and produce about 2.5 MeV beam at over 100 mA. Figure 4 shows an outline of the photoinjector with the calculated electric field distribution.

SUPERCONDUCTING LINAC

Following some initial acceleration to about 2.5 MeV the beam will be injected into a 703.75 MHz superconducting Energy Recovery Linac (ERL). Each linac cavity has 5 cells with aperture of 19 cm diameter. We plan to intercept the Higher-Order Mode (HOM) power by ferrite absorbers located in the beam pipe at room temperature [4]. Following the initial 20 cm beam-pipe at 19 cm diameter (serving to block the fundamental mode), the beam pipe is enlarged to 24 cm diameter in order to conduct the HOMs. For the TE11 mode, the enlarged pipe (24cm) has a cutoff frequency of 732 MHz, which is below all HOMs.

This structure has been simulated by MAFIA. Figure 5 shows some electric field patterns of HOMs with the lowest frequencies. HOM with higher frequencies will be less important. Table 1 shows the external Q, which measures how much power drains to the beam pipe and will be absorbed by the ferrite. Most modes couple extremely well to the ferrite with the exception of three TM modes clustered between 952 to 964 MHz. A separate coupler will drain these modes.

We investigated the Beam Break-Up (BBU) of the new cavity [4] using the computer simulation code TDBBU developed in Jefferson Lab. We simulated an ERL with a circumference of 251 RF wavelengths, about 108 meters. The bunch repetition rate was fixed at 9.4 MHz. Simple transverse optics was assumed as the design of the cavity and transport is still underway. R/Q and Q values of major HOMs with ferrite HOM absorbers were calculated by MAFIA. The preliminary results are shown in Figure 5. The threshold current can exceed 1000 mA for a reasonable distribution of frequencies of the HOMs of 0.001 rms.

MAGNETIZED BEAM TRANSPORT

Figure 6 is a schematic layout of the RHIC high-energy cooler [5]. There are a few straight sections in RHIC where the electron cooler may be introduced. We are considering a placement next to IP4 of RHIC, in the straight section between Q3 and Q4, which can accept about 30 m long solenoids. The electron accelerators will reside outside the RHIC tunnel.

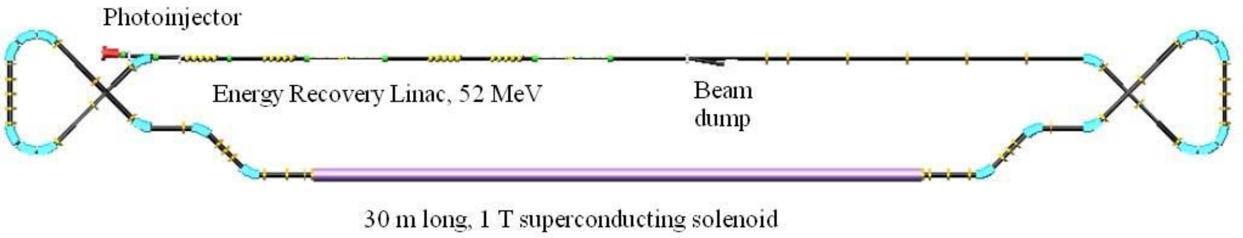

Figure 6. Schematic layout of the high-energy cooler.

The lattice can debunch the beam in order to reduce the space-charge interaction of the electron and ion beams or to reduce the energy spread of the electron beam. The beam transport has to obey certain rules in order to preserve the magnetization of the beam in the transport with discontinuous magnetic field. Emerging from the long cooling solenoid, the electron beam will be separated from the ion beam, rebunched (to match the linac acceptance) and decelerated to recover its energy. We dump the beam at about 2.5 MeV.

Merging the low energy and high-energy beams at the entrance of the linac uses two weak dipoles with a Stabenov Solenoid. The linac design assumes the use of 3rd harmonic cavities for additional control of the longitudinal phase space.

We propose to use two solenoids with opposing fields in the cooling section to eliminate coupling in the ion beam. A quadrupole matching section between the solenoids maintains magnetization.

A start to end simulation with PARMELA for non-magnetized beam shows energy spread of 8×10^{-5} in the cooling solenoid and a normalized emittance of 24 microns rms to 10 nC bunches. For a magnetized beam the simulation, a transverse temperature of 100 eV is seen past the linac and 1500 eV inside the cooling solenoid. Part of the temperature growth in the linac is due to a conflict between emittance correction and magnetized beam transport. We have ideas on how to resolve that. A simplification of the debunching section can lead to additional reduction of temperature.

SUPERCONDUCTING SOLENOID

For high electron temperature, the influence of the magnet field is very significant, and for a temperature approaching 1000 eV, it is necessary to use a solenoid magnet field of about 1T. The required precision is of the order of the ions' angular spread, $\Delta\theta$. In our case $\Delta\theta$ is about 10^{-5}. Cooling simulations show that we require a solenoid error below $8\mathrm{x}10^{-6}$.

The superconducting solenoid for electron cooling in RHIC is designed for a 1 T field, with ample quench margin. The total available space for solenoids is approximately 26 meters. Naturally, we would like to use a very long solenoid to increase the cooling rate. In order to facilitate production, testing and installation, we plan to construct the solenoid in two sections of 13 meters each. We chose a rectangular conductor of 2.4 mm x 1.6 mm cross section to achieve good field quality, as well as a reasonable inductance. The desired field of 1 T is obtained at ~1kA with a two layer coil. The conductor has a rather large copper to superconductor ratio of 7:1 for simple quench protection, and still provides about 90% quench margin. Thus, the solenoid can be operated at significantly above 1 T, if needed. Figure 7 shows a transverse cross section of the solenoid.

The solenoid must meet very stringent field quality requirements. We anticipate that typical construction tolerances will not achieve the desired field quality. Consequently, the solenoid will also have concentric arrays of ~150mm long vertical and horizontal dipole correctors to compensate for any transverse components. These dipole correctors will be built using inexpensive printed circuit coils [6] and will provide corrections of up to 10^{-3} T with a maximum operating current of 2 A. We intend to develop a measurement system, using a mirror and magnetic needle, similar to that used at other laboratories [7].

COOLING RATE SOFTWARE

We simulated the performance of the cooler with the computer code Simcool [2] for the beam parameters provided in the introduction. Figure 8 shows the performance of eRHIC for a gold beam with and without cooling, for a constant beam-beam parameter of 0.005 in two IPs with β^*=1m. The disintegration cross section σ_{tot}=212 barns limits the integrated luminosity through rapid particle loss at the highest luminosity. After 5 hours of operation most of the beam has disintegrated, and the luminosity is maintained only through the cooling. The loss of particles and constant beam-beam parameter leads to a decline in the luminosity.

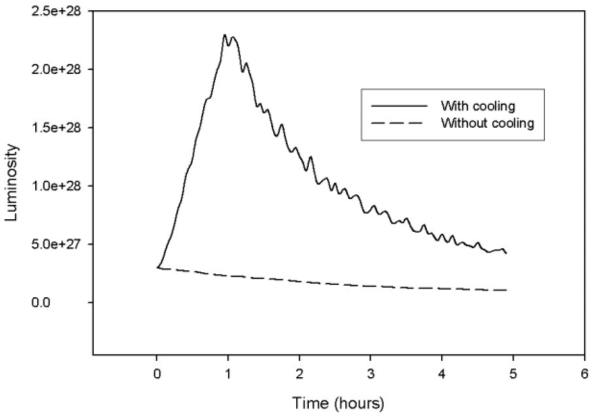

Figure 8. Luminosity of gold collisions in RHIC.

In order to complement Simcool and provide new capabilities in the code, BNL is collaborating with JINR Dubna on the code Betacool [8]. The new capabilities will include arbitrary distribution functions, improved IBS model bunched beams and more.

Analytical electron cooling calculations are not precise for this problem. BNL is collaborating with Tech-X [9] on a new code. Coulomb collisions between electrons and fully-ionized Au ions will be simulated from first principles. The charged particles are advanced using a fourth-order Hermite predictor-corrector algorithm, which has been shown in galactic dynamics simulations to tolerate the orders of magnitude variations in time step that are required to correctly resolve close binary collisions. The goal is to simulate the friction and diffusion coefficients for single ions passing once through the interaction region, as a function of the initial ion position and velocity.

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