STATUS OF THE R&D TOWARDS ELECTRON COOLING OF RHIC*

I. Ben-Zvi**, J. Alduino, D. Barton, D. Beavis, M. Blaskiewicz, J. Brennan, A. Burrill, R. Calaga, P. Cameron, X. Chang, A. Drees, A. V. Fedotov, W. Fischer, G. Ganetis, D. Gassner, J. Grimes, H. Hahn, L. Hammons, A. Hershcovitch, H-C Hseuh, D. Kayran, J. Kewisch, R. Lambiase, D. Lederle, V. Litvinenko, C. Longo, W. MacKay, G. Mahler, G. McIntyre, W. Meng, B. Oerter, C. Pai, G. Parzen, D. Pate, D. Phillips, S. Plate, E. Pozdeyev, T. Rao, J. Reich, T. Roser, A. Ruggiero, T. Russo, C. Schultheiss, Z. Segalov, J. Smedley, K. Smith, T. Tallerico, S. Tepikian, R. Than, R. Todd, D. Trbojevic, J. Tuozzolo, P. Wanderer, G. Wang, D. Weiss, Q. Wu, K. Yip, A. Zaltsman, BNL
A. Favale, D. Holmes, J. Sredniawski, H. Bluem, M. Cole, J. Rathke, T. Schultheiss, A. Todd, AES
V. Parkhomchuk, V. Reva, BINP
A. Burov, S. Nagaitsev, L. Prost (Fermilab), A. Sidorin, A. Smirnov, JINR
Y. Derbenev, P. Kneisel, J. Mammosser, L. Phillips, J. Preble, C. Reece, R. Rimmer, J. Saunders, M. Stirbet, H. Wang (Jefferson Lab), A. Aleksandrov, D. Douglas, Y. Kang, ORNL
D. Abell, G. Bell, D. Bruhwiler, R. Busby, J. Cary, D. Dimitrov, P. Messmer, V. Ranjbar, D. Smithe, A. Sobol, P. Stoltz, Tech-X

Abstract

The physics interest in a luminosity upgrade of RHIC requires the development of a cooling-frontier facility. Detailed calculations were made of electron cooling of the stored RHIC beams. This has been followed by beam dynamics simulations to establish the feasibility of creating the necessary electron beam. The electron beam accelerator will be a superconducting Energy Recovery Linac (ERL). An intensive experimental R&D program engages the various elements of the accelerator, as described by 24 contributions to the 2007 PAC.

INTRODUCTION

Planned major upgrades of RHIC include the RHIC-II electron cooling upgrade, and construction of an electron-ion collider (eRHIC). Electron cooling will impact the luminosity at various collision energies both for heavy ions and protons [1]. Electron cooling of RHIC at top energy of 100 GeV/A requires electron beam energy up to about 54 MeV at an average current of between 50 to 100 mA and a particularly bright electron beam, with a bunch charge of 5 nC and normalized RMS emittance of about 3 mm mrad. The accelerator comprises a superconducting 1 ½ cell RF gun with a laser-photocathode and SRF ERL at 703.75 MHz. Research towards high-energy electron cooling of RHIC, now in its 6th year, include simulations and benchmarking experiment to establish with some precision the performance of the cooler (this objective practically completed) and development of hardware for cost and risk reduction. This paper follows a report on R&D towards electron cooling of RHIC presented at EPAC06 [2], thus the objective of this paper is to point to most recent progress and the status of this work, as reported in multiple papers presented in this conference.

*Work done under the auspices of the US Department of Energy.
** ilan@bnl.gov

PROGRESS IN SIMULATIONS

Electron Cooling Simulations

The Tech-X VORPAL code has been used extensively to simulate the friction force from first principles. VORPAL simulations of Coulomb collisions in external fields have resolved large uncertainties in the predicted friction force on ions. A molecular dynamics approach has been used to study small periodic domains. Operator splitting works well, using a semi-analytic model for electron-ion collisions, and electrostatic PIC to incorporate e-/e- interactions and arbitrary external fields. This approach scales well up to >100 processors. A generalized algorithm was developed for scaling such simulations up to the full transverse extent of the electron and ion beams. This is necessary to determine whether friction forces will be reduce by effects such as radial space charge fields, the crossing of nearby ion trajectories, and field errors, fringe fields, etc. for ions far from the beam axis. These algorithmic developments address various issues, including more effective suppression of the diffusive ion dynamics and much faster treatment of distant electron-ion collisions [3].

The design of the cooler has non-magnetized electrons but in the presence of weak solenoids and possibly a helical undulator magnet. To understand the effect of these magnets on the cooling rate, numerical models of cooling in the presence of external fields from first principles in VORPAL were made. The n-body problem is solved by exact calculation of pair-wise collisions. Friction force simulations of the proposed RHIC cooler were made, including fringe field and finite interaction time effects [4]. Further work includes the study of the friction force reduction due to various types of error fields, as a function of integrated amplitude and wavelength spectrum. Different error field models were considered, from a sum of coherent sinusoidal terms to a Markov process [5].

The JINR BETACOOL code simulated cooling dynamics in the presence of IBS and many other processes in the storage ring. It is a critical design tool for the RHIC cooler. A generalized 3-D treatment of the cooling force was introduced in the BETACOOL code which allows to calculate the friction force from an arbitrary six-dimensional distribution of the electrons. Simulations for the RHIC cooler based on a realistic electron distribution from the ERL were calculated with BETACOOL [6]. In addition, BETACOOL has been benchmarked against VORPAL for calculations with a helical undulator and the effect on recombination was studied [7].

The stability of the circulating ion beam in the presence of electron due to two stream instabilities of varies modes or due to the reduction of the Landau damping due to longitudinal cooling of the momentum spread was studied. Simulation and theoretical results calculated the thresholds of the instabilities caused by these effects [8].

Beam Dynamics Theory and Simulations

Non-magnetized electron cooling of RHIC requires an electron beam energy of 54.3 MeV, electron charge per bunch of 5 nC, normalized rms beam emittance of 3 mm-mrad, and rms energy spread of $3*10^{-4}$. A lattice of a two-pass SRF ERL was designed, and simulated with PARMELA to provide electron beam parameters satisfying the RHIC electron cooling requirements [9]. In addition, a multi-parameter program was used for optimizing the injector and the emittance by shaping the charge distribution in the bunch [10]. The substantial demands on the beam quality of the electron beam demand a new level of fidelity in beam dynamics simulations. New developments in the code MaryLie/IMPACT have improved the space-charge computations for beams with large aspect ratios and the beam dynamic computations for rf cavities. Recent work with this code includes the effects of space charge and nonlinearities, and aims to assess the tolerance for errors and nonlinearities in the design of the ERL [11]. Beam current dependent effects such as space charge, wake fields, CSR and trapped ions may reduce the beam quality. Recent studies include the defocusing effect of the space charge at the cooling section and its compensation by weak focusing solenoids, estimation of the energy spread and emittance growth cased by wake fields and ion trapping and its mitigation [12]. The electron beam must be aligned to better than 5 microradians relative to the ion beam over the 100m-long cooling section, presenting a formidable task. The beam alignment requirements and the techniques proposed to meet those requirements were considered [13]. Beam diagnostics for accurate characterization of the three dimensional beam phase space at the injection and recirculation energies, transverse and longitudinal beam matching, orbit alignment, beam current measurement, and machine protection have been designed [14]. Finally, a study of an optional approach for the generation of the electron beam, using a normal-conducting low-frequency RF gun has been carried out [15].

ERL AND ITS COMPONENTS

The ERL of the RHIC II electron cooler must produce a high repetition rate of large bunch charges at a low emittance. This is an unprecedented performance which necessitated the development of a few new accelerator components that will be briefly described in this section.

An R&D ERL [16] is under construction, with commissioning to start in February 2009. This ERL will use a ½ cell gun and a single 5-cell cavity for validating the components and to address many outstanding questions relevant for high current, high brightness energy-recovery linacs. The 1 MW CW klystron and its power supply, shown in Fig. 1 a and b are in place and tested.

Figure 1: a. (left) the CPI klystron. b. (right) the 95kV 20A DRC power supply.

Magnet System

A unique problem of ERLs is emittance growth due to the merger system, which mixes transverse and longitudinal degrees of freedom, and consequently violates emittance compensation conditions. A merger system based on zigzag scheme resolves this problem and has been developed for the BNL ERL [17]. Unique features were designed into the magnets for the R&D ERL. 3-D simulations of the fields in these magnets, particle tracking and analysis of the effects of various dipole and quadrupole magnet's on the beam parameters, both in the in zigzag merging systems and the return loop were made. A uncommon method of setting requirements on the quality of magnetic field and transferring them into measurable parameters as well as into manufacturing tolerances has been employed, and simulation were compared with results of magnetic measurements[18].

SRF ERL Cavity

We developed a 5-cell ERL cavity at 703.75 MHz for the ERL. The cavity and cryostat were fabricated by Advanced Energy Systems (AES) [19], and processed and tested at Jefferson Laboratory. The process yielded a good performance with the cavity reaching 20 MV/m acceleration, with a Q of 1e10 at a field of 19 MV/m (starting from a low field Q of 4e10) [20]. This "single mode" cavity has strong damping of all HOM through the 24 cm diameter beam pipe and 1 V/pC loss factor, thus it is ideal for multi-ampere current ERLs.

Superconducting RF Gun

The production of a high bunch charge at low emittance requires a high RF electric field at the cathode. For CW operation, a SRF gun is most advantageous. A SRF gun is under construction for the ERL by BNL and AES [19]. The cathode insertion for the gun is made through a demountable quarter-wave choke-joint, and care must be taken with multipacting over the length of the joint. The multipacting has been analyzed via calculations and experimental measurements and the effect of introducing multipacting suppression grooves into the structure was analyzed for several alternative designs. Furthermore, the problems encountered in cleaning the choke joint surfaces, factors important to the secondary electron yield, were evaluated. This design is being implemented on the BNL 1.3 GHz photoinjector [21].

Diamond Amplified Photocathode

We combine a high Quantum Efficiency (QE) photocathode with a diamond window, which offers protection of the gun and cathode from each other. The amplification gain in the diamond results from the generation of a large number of electron-hole pairs. In measurements we have achieved reproducibly gains of two orders of magnitude, and good theoretical understanding of the gain dependence on the field using a plasma separation model [22]. In addition, we started to implement algorithms, within the VORPAL particle-in-cell framework, for modeling of secondary electron and hole generation, and for charge transport in diamond. The algorithms include elastic and various inelastic scattering processes over a wide range of charge carrier energies [23]. The thermal emittance is a very important characteristic of cathodes. A lower thermal emittance cathode can lead to a lower beam emittance. A diamond amplified photocathode, being a negative electron affinity (NEA) cathode, promises to deliver a very small thermal emittance. A carefully designed experiment aimed at measuring the emittance of secondary emission from diamond is in progress. Various schemes were simulated. Systematic errors, including aberrations, were evaluated and shown to be well controlled and evaluated [24].

SUMMARY

A significant progress has been made in the R&D towards high energy electron cooling of RHIC, much of it reported in the proceedings of this conference, PAC 2007. The feasibility of electron cooling of RHIC for a significant luminosity increase has been established and extensive R&D is being carried out on accelerator components and techniques, to culminate in the commissioning of a 0.5 ampere average current ERL starting in February 2009.

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