Cooling Dynamics Studies and Scenarios for the RHIC Cooler

A.V. Fedotov, I. Ben-Zvi, V.N. Litvinenko, et. al.

To be presented at Particle Accelerator Conference
Knoxville, Tennessee
May 16-20, 2005
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
COOLING DYNAMICS STUDIES AND SCENARIOS FOR THE RHIC COOLER*

A.V. Fedotov, I. Ben-Zvi, V. N. Litvinenko, BNL, Upton, NY 11973
A. Sidorin, A. Smirnov, G. Trubnikov, JINR, Dubna, Russia

Abstract

In this paper, we discuss various electron cooling dynamics studies for RHIC. We also present simulations [1] 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. Electron cooling at various collision energies both for heavy ions and protons is also discussed.

ELECTRON COOLING FOR RHIC

There are various possibilities of using electron cooling at RHIC [2,3]. Direct cooling at the top energy can be considered as a base line approach for RHIC-II. However, for eRHIC [4] project, it is important that cooling is fast enough to allow reduction of the rms beam parameters, especially the rms bunch length. In this case, pre-cooling at low energy becomes very attractive due to a very strong dependence of the cooling time on energy. For the same reason, cooling is very effective for scenarios with collisions at low energy.

Cooling at Full Energy

Electron cooling of Au ions at storage energy of 100 GeV/u allows to reach desired increase in the integrated average luminosity for the RHIC upgrade, which is a factor of 40 increase compared to designed RHIC values. For present RHIC operation without electron cooling, the $\beta^*$ (the beta function at the IP) is limited to about 1 meter (or slightly less) due to the fact that emittance is increased by a factor of 2 because of the IBS. Further reduction of the $\beta^*$ with such an increase of emittance would lead to a significant angular spread and beam loss. On the other hand, keeping rms emittance constant (by cooling), allows us to start a store cycle with smaller values of the $\beta^*$ [5,6].

Pre-cooling at Low Energy

Pre-cooling at low energy may be very attractive. This is due to the fact that cooling is much faster at lower energy as well as that needed charge of the electron beam is smaller [3]. Also, such a pre-cooling at low energy allows cooling of protons for which a direct cooling at similar high energy is ineffective [4]. In Ref. [3], a pre-cooling was explored above the transition energy to avoid the instabilities of cooled ion beam near transition.

Cooling at Various Collision Energies

Fast cooling at low energies also makes such energies attractive for collisions, which is under consideration for RHIC-II and eRHIC. Rapid cooling of beam core immediately leads to problems with a large beam-beam parameter. To keep the beam-beam parameter at an appropriate level, one can vary dynamically parameters of the electron beam (see, for example, [5,6]).

Cooling of various ion species

For Au-Au collisions at 100 GeV/u with electron cooling, the store time is limited to about 4 hours due to a rapid ion "burn-off" in the IP (large cross section from dissociation and bound electron-positron pair production). However, for other ion species, for which the cross section of such a "burn-off" process is small, longer stores can be tolerated with essentially constant luminosity. This is shown in Fig. 1 for Cu-Cu collisions at 100 GeV/u (for parameters: 112 bunches, $N_i=5\times10^9$ ions per bunch, initial normalized 95% emittance $\varepsilon_i=12 \pi \mu m$), for example.

In Fig. 1, $\beta^*=1m$ was assumed for both scenarios with and without cooling. An extra luminosity increase may be obtained if one starts with the smaller $\beta^*$ (which is possible with cooling), as for the case of Au-Au ion collisions [5].

Additional benefit comes from the longitudinal cooling which prevents bunch length from growing and beam loss from the bucket (as shown in Fig. 2). Also, it maximizes the useful interaction region which increases an effective luminosity in the detector.

*Work supported by the U.S. Department of Energy

fedotov@bnl.gov
EQUILIBRIUM BETWEEN COOLING AND IBS

One can roughly estimate number of electrons required to reach equilibrium between cooling and IBS. The cooling rate using empiric friction force formula [7] is:

$$\frac{1}{\tau_{cool}} = \frac{2}{\pi \gamma^5 \beta \sigma}\sqrt{\frac{\beta}{s}}$$

where $\eta$ is an unnormalized rms emittance, $\beta_i$ is ion beta function, $\sigma_i$ is an rms length of electron bunch, and $\gamma$ is the fractional length of the cooler. Using an approximate formula for the IBS (its accuracy is discussed in [8]):

$$\frac{1}{\tau_{ibs}} = \frac{N_i r_i^2 c \Lambda_{ibs}}{\gamma^3 \sqrt{\beta}}$$

the equality of heating and cooling rates gives

$$N_{ec} \approx \frac{r_i N_i \Lambda_{ibs}}{r_i \eta \Lambda_c g_f}$$

where $g_f$ is the flatness parameter of ion distribution defined as

$$g_f = \left(\frac{v_{longitudinal}}{v_{transverse}}\right)^2 = \frac{\sigma_p^2}{\gamma^2 (\varepsilon / \beta_a)}.$$
empiric magnetized friction force formula [7] and the IBS heating rate based on the Run-4 experiments [10] (both of which give a conservative estimate), a factor of 10 increase in RHIC-II luminosity over upgrade without cooling can be achieved with the following parameters of electron beam: $N_e=1.2\times 10^{11}$, $e_0=40$ um, $\sigma_p=3\times 10^{-4}$, and the cooler with the total length of solenoids per ring = 80 m, magnetic field of $B=2.5$ T, and an rms angle of magnetic field imperfections $\theta=8\times 10^{-6}$. Significant efforts are being made to study the friction force in detail both with direct numerical simulation and experiments (see [6] and references therein). Additional IBS studies were done during Run-5 to resolve some previous questions. These studies will show whether present parameters for the magnetized cooling may be relaxed and to what degree.

**NON-MAGNETIZED COOLING**

Generation of the electron bunch without longitudinal magnetic field allows us to achieve the transverse rms angular spread of electron beam smaller than the angular spread of ions, making the non-magnetized approach feasible. The problem of recombination can be overcome using the undulator field in the cooling section [11]. In the presence of the undulator field, trajectories of all electrons have the same coherent azimuthal angle $\theta$, determined by the undulator period $\lambda$ and the field value $B$ at the axis:

$$\theta = \frac{eB\lambda}{2\pi p c},$$

(5)

where $p$ is the electron momentum. With large $\theta$ the ion beam life time can be sufficiently improved. On the other hand, one can expect that for the impact parameters significantly larger than the electron rotation radius $r_0 = \frac{\theta \lambda}{2\pi}$, (6)

kinematics of binary collisions will be similar to the Rutherford scattering of free electron. In this case the friction force acting on the ion inside the electron beam with velocity distribution function $f(v_e)$ can be calculated with usual formula

$$F = -\frac{4n_e e^4 Z^2}{m} \int L \frac{\vec{v}_i - \vec{v}_e}{\sqrt{\vec{v}_i^2 - \vec{v}_e^2}} d^3 v_e,$$

(7)

where the logarithm of adiabatic collisions is given by

$$L = \ln \frac{P_{\text{max}}}{P_{0}}.$$

(8)

The friction force is then reduced only by a factor of the order of $\ln \frac{P_{\text{max}}}{P_{0}}$. As a result, one can expect sufficient suppression of the recombination without large loss in the friction force. To provide accurate calculation for the non-magnetized cooling and recombination in an undulator field, new algorithms were recently implemented in the BETACOOL [11].

The luminosity increase for RHIC-II based on preliminary simulations with the non-magnetized cooling approach is shown in Fig. 5. The following parameters of the cooler were used: total length of undulator sections per ring 100 m, normalized rms emittance of electron beam $\epsilon_0=2$ um, rms momentum spread $\sigma_p=10^{-4}$, number of electrons per bunch $N_e=3\times 10^{10}$ (5 nC) and $r_0=10$ um.

With both magnetized and non-magnetized cooling approach an average luminosity of $L=7\times 10^{27}$ [cm$^{-2}$s$^{-1}$] can be obtained during a 4-hour store for Au-Au ions collisions at 100 GeV/u. For details and recent updates we refer the reader to the E-cooler Design Report [3].

**ACKNOWLEDGMENTS**

We would like to thank A. Burov, Ya. Derbenev, W. Fischer, J. Kewisch, V. Parkhomchuk, T. Roser and the Accelerator Physics Group of Electron Cooling Project of RHIC for many useful discussions during these studies.

**REFERENCES**

[1] Simulations presented in this paper are done using BETACOOL program, http://tepta.jinr.ru
[6] A.V. Fedotov et al., TPAT090, these proceedings.
[10] J. Wei et al., TPAT081, these proceedings.