COOLING DYNAMICS STUDIES AND SCENARIOS FOR THE RHIC COOLER*

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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 β^* (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 β^* 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 β^* [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.

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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=5e9 ions per bunch, initial normalized 95% emittance ε_i=12 π um), for example.

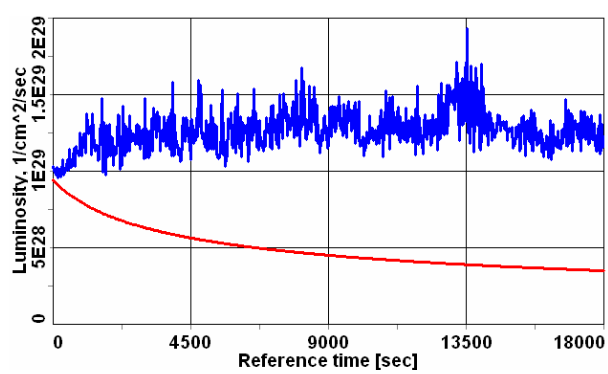

Figure 1: RHIC-II luminosity for Cu-Cu collisions at 100 GeV/u with (blue top curve) and without (red) cooling.

In Fig. 1, β^*=1m was assumed for both scenarios with and without cooling. An extra luminosity increase may be obtained if one starts with the smaller β^* (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.

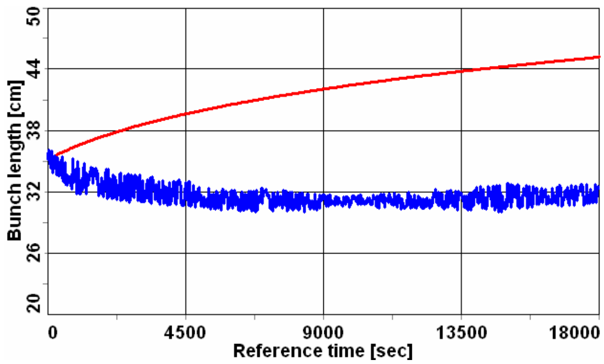

Figure 2: Bunch length with (blue) and without (red top curve) cooling for Cu-Cu collisions of Fig.1.

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:

$$\frac{1}{\tau_{cool}} = \frac{2}{\pi\gamma^5} \frac{N_e r_i r_e c \eta}{\beta^3 \varepsilon^{5/2}} \frac{\Lambda_c \sqrt{\beta_i}}{\sigma_s \sqrt{2\pi}}, \qquad (1)$$

where ε is an unnormalized rms emittance, β_i is ion beta function, σ_s is an rms length of electron bunch, and η is the fractional length of the cooler. Using an approximate formula for the IBS (its accuracy is discussed in [8]):

$$\frac{1}{\tau_{ibs}} = \frac{N_i r_i^2 c}{\gamma^3 \beta^3 \varepsilon^{3/2} \sqrt{\beta_i}} \frac{\Lambda_{ibs}}{\sigma_p^2 \sigma_s \sqrt{2\pi}}, \qquad (2)$$

the equality of heating and cooling rates gives

$$N_{ec} \approx \frac{r_i}{r_e} \frac{N_i}{\eta} \frac{\Lambda_{ibs}}{\Lambda_c} \frac{1}{g_f}, \qquad (3)$$

where g_f is the flatness parameter of ion distribution defined as

$$g_f = \left(\frac{v_{longitud.}}{v_{tranverse}} \right)^2 = \frac{\sigma_p^2}{\gamma^2 (\varepsilon / \beta_a)}. \qquad (4)$$

where σ_p is rms momentum spread, ε is rms emittance and β_a is the beta-function averaged over the ring. Note that expression for N_{ec} in Eq. (3) is just an order of magnitude estimate. Numerical factor in Eq. (3) depends on which expression is used for the friction force or the IBS. In the case of equilibrium between the amplitude-dependent ("detailed") IBS and cooling [9] one gets numerical factor of about 2 in Eq. (3), for example. Taking the following parameters of RHIC: N_i=1*10^9, η=0.0078, Λ_{ibs}=20, g_f=0.2, and assuming that the cooler will have magnetized cooling logarithm Λ_c=2 one gets critical number of electrons about N_{ec}=1-3*10^{11} (depending on which expression is used for the IBS and cooling rate). Although this is just an order of magnitude estimate, computer simulations with accurate model for the IBS showed that this number is very close to the one found in simulation (N_{ec}=3*10^{11} for the friction force in Eq. (1) and the IBS calculated for the RHIC lattice [3]). For operation with the number of electrons per bunch with N_e which is significantly smaller than the critical number only the core of beam distribution is being effectively cooled. Such distribution with a pronounced core requires very accurate treatment of the IBS, the beam-beam diffusion and collective instabilities. Figure 3 shows beam profiles resulting from the magnetized cooling based on the N_e=1.2*10^{11} per bunch which provides average luminosity for Au-Au collisions L=7*10^{27} [$cm^{-2}s^{-1}$] during a 4-hour time store. Figure 4 shows resulting beam profiles for N_e=3*10^{11}.

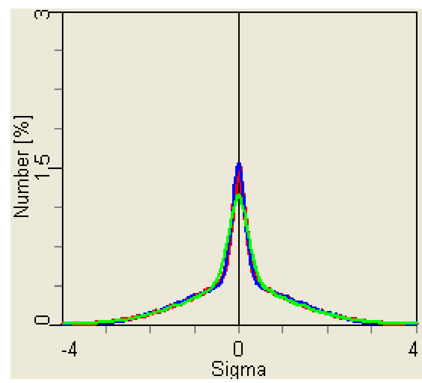

Figure 3: X, Y, and longitudinal beam profiles after 4 hours of magnetized cooling for Au-Au collisions at 100 GeV/u with number of electrons per bunch N_e=1.2*10^{11}.

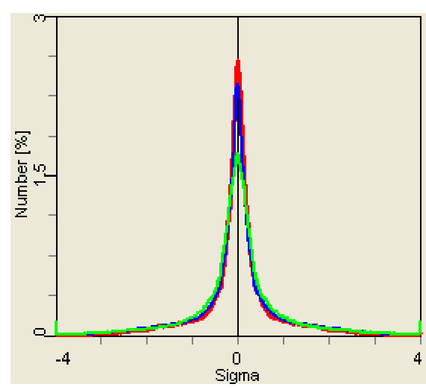

Figure 4: X, Y, and longitudinal profiles after 4 hours of magnetized cooling for Au-Au collisions at 100 GeV/u cooling with number of electrons per bunch N_e=3*10^{11}.

MAGNETIZED COOLING

Recently, a progress was made in defining required parameters for the magnetized cooling. Some modifications resulted from experimental studies of emittance growth in RHIC and its verification with computer models. Also, numerous improvements to computer codes were made [6]. Presently, using an

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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=1.2e11, ε_e=40 um, σ_p=3e-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 θ=8e-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 θ, determined by the undulator period λ and the field value B at the axis:

$$\theta = \frac{eB\lambda}{2\pi pc}, \qquad (5)$$

where p is the electron momentum. With large θ, 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

$$r_0 = \frac{\theta\lambda}{2\pi}, \qquad (6)$$

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

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m}\int L\frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e)d^3v_e, \qquad (7)$$

where the logarithm of adiabatic collisions is given by

$$L = \ln\frac{\rho_{max}}{r_0}. \qquad (8)$$

The friction force is then reduced only by a factor of the order of $\ln\frac{\rho_{max}}{\rho_{min}} / \ln\frac{\rho_{max}}{r_0}$. 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 ε=2 um, rms momentum spread σ_p=1e-4, number of electrons per bunch N_e=3e10 (5 nC) and r_0=10 um.

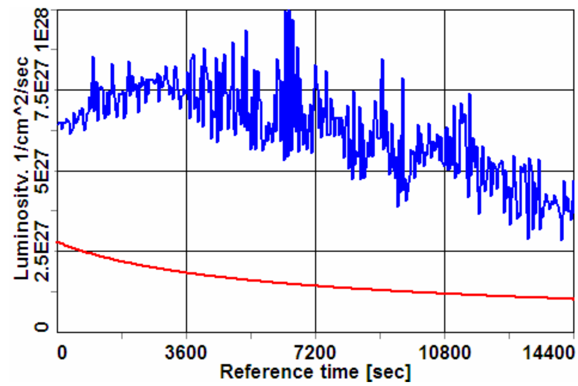

Figure 5: Luminosity with (blue) and without (red) non-magnetized cooling for Au at 100 GeV/u (112 bunches, 1e9 ions per bunch, normalized 95% emittance 15 π um).

With both magnetized and non-magnetized cooling approach an average luminosity of L=7*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].

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