HIGH-ENERGY ELECTRON COOLING BASED ON REALISTIC SIX DIMENSIONAL DISTRIBUTION OF ELECTRONS*

A.V. Fedotov#, I. Ben-Zvi, D. Kayran, E. Pozdeyev BNL, Upton, NY 11973
A. Sidorin, A. Smirnov, JINR, Dubna, Russia

Abstract

The high-energy electron cooling system for RHIC-II is unique compared to standard coolers. It requires bunched electron beam. Electron bunches are produced by an Energy Recovery Linac (ERL), and cooling is planned without longitudinal magnetic field [1]. To address unique features of the RHIC cooler, a generalized treatment of cooling force was introduced in BETACOOL code [2] which allows us to calculate friction force for an arbitrary distribution of electrons. Simulations for RHIC cooler based on electron distribution from ERL are presented.

FRICTION FORCE MODELS

The traditional electron cooling system employed at low-energy coolers is based on an electron beam immersed in a longitudinal magnetic field of a solenoid. Although extensive studies of the magnetized cooling approach for RHIC showed that such approach is feasible [1, 3-4] and would provide required luminosities for the RHIC-II, the baseline was recently changed to the non-magnetized one.

Electron cooling for RHIC using the non-magnetized electron beam significantly simplifies the cooler design. Generation and acceleration of the electron bunch without longitudinal magnetic field allows us to reach a low value of the emittance for the electron beam in the cooling section. For cooling of Au ions in RHIC at the beam energy of 100 GeV/nucleon, the kinetic energy of the electron beam has to be 54.3 MeV. Such a high-energy electron cooling system for RHIC is based on the ERL.

In the particle rest frame (PRF) the friction force acting on the ion with a charge number Z passing through an electron beam of density n_e can be evaluated in the absence of magnetic field by numerical integration of the following formula [5]:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m}\int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right)\frac{\vec{V}-\vec{v}_e}{\left|\vec{V}-\vec{v}_e\right|^3} f(v_e)d^3v_e, \quad (1)$$

where e and m are the electron charge and mass, V and v_e are the ion and electron velocities, respectively. The Coulomb logarithm is kept under the integral because the minimal impact parameter depends on electron velocity:

$$\rho_{\min} = \frac{Ze^2}{m}\frac{1}{\left|\vec{V}-\vec{v}_e\right|^2}. \quad (2)$$

At a given value of the ion velocity the maximum impact parameter is constant and determined by either the dynamic shielding radius or by the time of flight of an ion through the cooling section.

In the absence of longitudinal magnetic field in the cooling section the electron motion in transverse planes is uncoupled. Correspondingly, the electron bunch can have different thermal velocity in the horizontal and vertical planes. In this case the friction force can not be presented as a sum of radial and longitudinal components, but it is a vector with all three different components. The components of 3D friction force can be calculated as an integral over electron velocity for a given distribution function. A standard assumption is that thermal velocity distribution is Gaussian.

Note that one typically uses Eq. (1) assuming uniform electron density and global rms parameters of the whole beam. In reality, rms velocity spread at large amplitudes may be much larger than at small amplitudes due to various effects, as well as for bunched electron beam the local velocity spread in various longitudinal slices along the electron bunch maybe significantly different from global projected values of the whole distribution. Knowledge of how such local rms velocity spread and local density distribution affects cooling is important.

To address these goals, new algorithms were implemented in BETACOOL code [2] which calculate electron cooling based on the local properties of electron distribution. These algorithms are referred to as "local" models of the friction force calculation. The distribution of electrons can be generated with external code, for example, in the case of RHIC-II simulations such electron distribution is an output of PARMELA code [6], which is used to simulate electron beam transport to the cooling section. The distribution of electrons is then read into BETACOOL and is referred to as "electron array".

For the friction force calculation the local model uses local parameters within electron array calculated as a function of the ion coordinates. The program first finds local number of electrons N_{loc} which have minimum distance to the ion position (the value of N_{loc} is an input parameter). For N_{loc} found, the program calculates mean and root mean square parameters for all the coordinates and velocity components, which are used to calculate the local density of the electrons.

The local density and rms parameters found can be used in calculation of the friction force with analytic formulas and assumption of Gaussian velocity distribution. Such a model is called here "local-Gaussian". In most cases, this approach is sufficient. It allows to compare cooling process based on local characteristics of electron

*Work supported by the U.S. Department of Energy
#fedotov@bnl.gov

distribution with the one expected based on the friction force calculation using projected global rms parameters of the whole distribution.

In another local model, an assumption that local velocity distribution is Gaussian is not used. The velocity components are calculated directly which allows us to study friction force for an arbitrary velocity distribution. Here, we refer to this model as "local-arbitrary". The distribution function of the local electrons in the velocity space is given as a series of δ- functions:

$$f(v) = \frac{1}{N_{loc}} \sum_{j=1}^{N_{loc}} \delta\left(\vec{v} - \vec{v}_j\right). \quad (3)$$

In this case, the friction force components are calculated as follows:

$$F_\alpha = \frac{4\pi n_e Z^2 e^4}{m} \frac{1}{N_{loc}} x \sum_{j=1}^{N_{loc}} \frac{\left(V_\alpha - v_{j,\alpha}\right) L_{C,j}}{\left(\sqrt{\left(V_x - v_{j,x}\right)^2 + \left(V_y - v_{j,y}\right)^2 + \left(V_z - v_{j,z}\right)^2}\right)^3} \quad (4)$$

where V_α are the components of ion velocity in the particle rest frame, $v_{j,\alpha}$ – the velocity components of j-th electron (α = x, y, z). The minimum impact parameter in the Coulomb logarithm $L_{C,j}$ is calculated via velocity of jth electron.

ELECTRON DISTRIBUTION AND COOLING PERFORMANCE

To ensure good cooling performance, a quality of the electron beam should not suffer significantly as a result of electron beam transport in ERL, merging of the electron and ion beam, transport through the cooling section and interactions with the ion beam.

With the non-magnetized cooling approach, electron angles in the cooling section should be comparable to the angular spread of the ion beam being cooled. With 95% normalized emittance of ions 15 [mm mrad] and ion beta-function in the cooling section of 400 [meters], the rms angular spread of ions is 7.6 [μrad]. The goal is presently set to minimize total rms angular spread of electrons in the cooling sections to about 10 [μrad]. Several contributions to the angular spread were identified (see "RHIC-II Feasibility Study" document in Ref. [1]). They will be minimized by a proper design of the cooling section. Taking into account residual contributions to the angular spread, in order to have total rms spread around 10 [μrad], contribution from electron beam emittance should not be significantly larger than 7.5 [μrad]. Such an rms angular spread corresponds to rms normalized emittance of 3 [μm]. The cooling power needed requires electron bunch charge around 5nC.

The rms momentum spread of the ion beam is about $5 \cdot 10^{-4}$. An effective longitudinal cooling is obtained with the rms momentum spread of the electron beam around $3 \cdot 10^{-4}$. The cooling efficiency is significantly affected when the average energy of the electron beam is comparable or bigger than the rms energy spread of the ion beam. This sets a requirement on average energy deviation of the electron beam to be around $3\text{-}5 \cdot 10^{-4}$.

Simulations of electron beam dynamics, including compensation of space-charge defocusing in the cooling section, were performed using PARMELA code [6]. Electron distributions used in these studies were obtained by starting with the uniform cylinder (beer-can) at the cathode and tracking it through the ERL. Additional simulations showed that optimization of the shape of electron distribution at the cathode may further decrease beam emittance per given charge [7].

In general, electron beam dynamics simulations are aimed at minimization of global projected rms emittance and momentum spread while local rms velocity spread could have smaller values which would enhance cooling.

Another feature of electron distribution resulting from RF acceleration is that longitudinal rms velocity spread of electrons is not Gaussian, as shown in Fig. 1. As a result, different cooling dynamics can be observed in simulations when assumption of Gaussian velocity distribution is used instead of calculation using Eq. (4). This is shown in Figs. 2 and 3, where only electron cooling was included in simulations, with all other effects turned off. During simulations electron beam was kept in a fixed position with respect to the center of the ion bunch. In Fig. 2, one can see that the hollow longitudinal velocity distribution (Fig. 1) prevents collapse of the distribution core which happens for Gaussian velocity distribution in Fig. 3, otherwise.

The effect of hollow velocity distribution is less pronounced when intrabeam scattering is included in simulations, which prevents core collapse as well. Also, an electron bunch with the rms length of about 1 cm is being constantly swept back and forth through the ion bunch. As a result, with all effects being included in simulation, cooling dynamics becomes practically the same whether one uses non-Gaussian (Fig. 1) or Gaussian velocity distribution of the electrons.

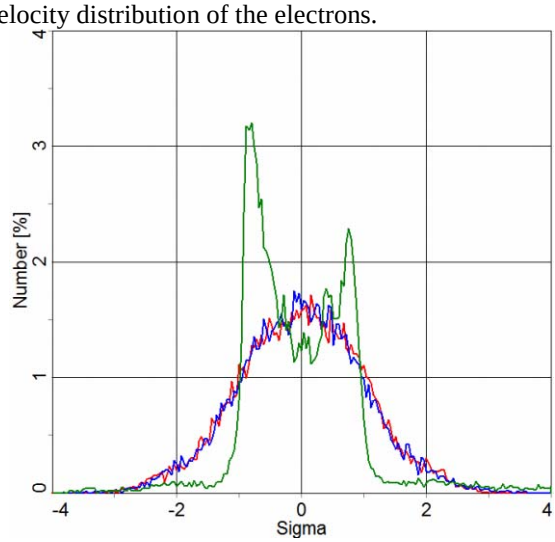

Figure 1: Histogram of velocity distribution of electrons at the start of the cooling section. Red and blue – horizontal and vertical; green – longitudinal.

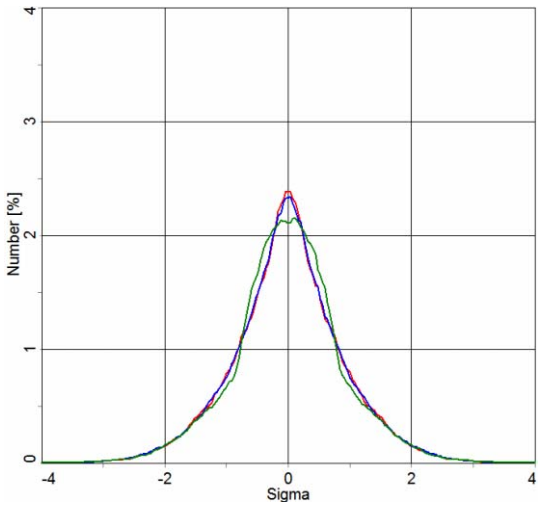

Figure 2: Horizontal (red), vertical (blue) and longitudinal (green) ion beam profiles after 5 minutes of cooling based on velocity distribution shown in Fig. 1.

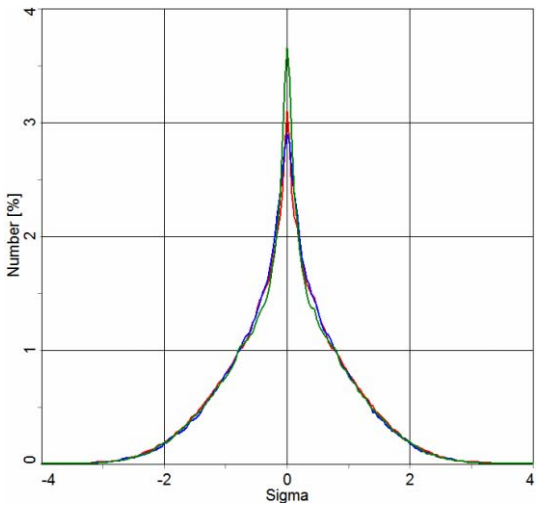

Figure 3: Horizontal (red), vertical (blue) and longitudinal (green) ion beam profiles based on assumption of Gaussian velocity distribution in all three planes.

A practical application in which the use of the local friction force model was found useful is compensation of the space-charge defocusing in the cooling section. Control of the angular spread in the cooling section requires weak solenoids (with the field of about 200 G placed every 10 meters) [1].

After cooling of an ion bunch in one ring of RHIC the same electron bunch is turned around and passes the cooling section in the opposite direction to cool an ion bunch in the second ring. Thus, it is important that a quality of an electron beam is not affected significantly after a first pass through the cooling section.

First, compensation of the space charge was done by controlling the rms angular spread of the whole distribution. Resulting distribution was used in simulations with the local model of the friction force. The cooling performance observed was not as good as expected. Subsequently, another approach was taken by controlling only the rms spread in the core of the distribution, which resulted in the distribution with very small angular spread in the core and large spread in the tails. But the cooling performance was improved.

Simulation of the luminosity based on electron distribution after the first pass through the cooling section is shown in Fig. 4, using local model (red middle curve) and global rms parameters (blue lower curve). The local model shows more effective cooling since most of the particles in the core of the distribution have small angular spread. However, one can also see that cooling performance is not as good as based on the distribution at the start of the cooling section (black upper curve) since large amplitude particles experience non-linear space charge force which is not compensated. As a result, after passing through the cooling section, the portion of the beam which has small rms angular spread, corresponds to smaller effective charge than the one of an initial bunch. An optimum design for the cooling section is being investigated.

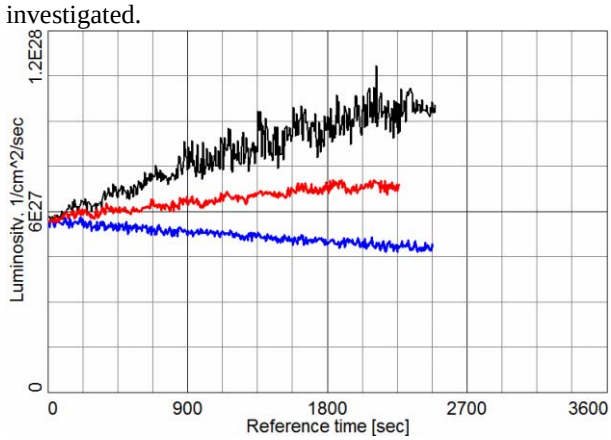

Figure 4: Initial luminosities. Black – using electron distribution at the start of the cooling section. Red (based on the local model) and blue (based on global parameters) using distribution at the end of the cooling section.

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