Electron Cooling in the Presence of Undulator Fields

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Presented at the 22nd Particle Accelerator Conference
Albuquerque, NM
June 25-29, 2007

June 2007

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Abstract

The design of the higher-energy cooler for Relativistic Heavy Ion Collider (RHIC) recently adopted a non-magnetized approach which requires a low temperature electron beam [1]. However, to avoid significant loss of heavy ions due to recombination with electrons in the cooling section, the temperature of the electron beam should be high. These two contradictory requirements are satisfied in the design of the RHIC cooler with the help of the undulator fields. The model of the friction force in the presence of an undulator field was benchmarked vs direct numerical simulations with an excellent agreement. Here, we discuss cooling dynamics simulations with a helical undulator, including recombination suppression and resulting luminosities.

ELECTRON COOLING FOR RHIC-II

The present performance of the RHIC collider with heavy ions is limited by the process of Intra-Beam Scattering (IBS) [2]. To achieve required luminosities for the future upgrade [3] of the RHIC complex (known as RHIC-II) an electron cooling system was proposed [4].

The baseline of the heavy-ion program for RHIC-II is operation with Au ions at total energy per beam of 100 GeV/nucleon. For such an operation, the electron cooling should compensate IBS and provide an increase by about factor of 10 in an average luminosity per store.

For RHIC-II operation with the polarized protons, the electron cooling should assist in obtaining required initial transverse and longitudinal emittances or prevent their significant increase due to IBS. Although IBS is not as severe for protons as for heavy ions, a proposed increase in proton intensity for RHIC-II upgrade makes IBS an important effect as well.

In a traditional low-energy electron cooler, where the magnetic field is used for the transport of an electron beam through the cooling section from the gun to the collector, the longitudinal magnetic field changes the collision kinetics significantly. The magnetic field limits transverse motion of the electrons. As a result, the efficiency of electron cooling is determined mainly by the longitudinal velocity spread of the electrons. Such cooling is typically referred to as "magnetized cooling" [5, 6].

However, if an rms velocity spread within electron beam is comparable to the one of the ion beam, the cooling can be done without the help of the strong external magnetic field.

Such type of cooling is referred to as the "non-magnetized cooling"; although a weak external field can be still employed, for example, to ensure focusing and alignment of electron and ion beams. The first cooling system which is based on the non-magnetized approach was constructed at the FNAL Recycler ring [7].

Although extensive studies of the magnetized cooling approach for RHIC showed that such approach is feasible [1] and would provide required luminosities for the RHIC-II, the baseline was recently changed to the non-magnetized one. Electron cooling at RHIC using the non-magnetized electron beam significantly simplifies the cooler design. The 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. The cooling rate required for suppression of the Intra-Beam Scattering (IBS) can be achieved with a relatively small charge of the electron bunch ~ 5 nC.

Since non-magnetized cooling requires low temperature of the electrons, a possible problem which one can encounter in cooling of heavy ions is a high recombination rate of ions with the electrons. In the present design, suppression of the ion recombination is based on employing fields of a helical undulator in the cooling section [8]. In the presence of undulator field, electron trajectories have coherent azimuthal angle which helps to suppress recombination. The critical point is to understand how electron cooling force is affected as a result of such recombination suppression, which is explained in this article.

FRICTION FORCE IN THE PRESENCE OF UNDULATOR FIELDS

In the presence of an undulator field, the trajectories of all the electrons have the same coherent azimuthal angle $\theta$, determined by the undulator period $\lambda$ and magnetic field value $B$ at the axis:

$$\theta = \frac{eBA}{2\pi p}$$

where $p$ is the electron momentum. Since the recombination cross section is approximately inversely proportional to the electron energy in the ion rest frame, the ion beam life time can be sufficiently improved. One can expect that at impact parameters significantly larger than the electron rotation radius

$$r_0 = \frac{\theta\lambda}{2\pi} = \frac{eBA^2}{2\pi \cdot 4\pi^2 pc}$$

*Work supported by the U.S. DOE Office of Science, Office of Nuclear Physics, including grant #DE-FG02-04ER84094.

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

$$
\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m_e} \int \frac{\vec{V}_i - \vec{V}_e}{|\vec{V}_i - \vec{V}_e|^3} f(v_e) d^3v_e,
$$

where $n_e$ is electron density in the Particle Rest Frame
(PR), $v_e, V_i$ are the electron and ion velocity, $L_c$=
Coulomb logarithm:

$$
L_c = \ln \frac{\rho_{\text{max}}}{\rho_{\text{min}}}.
$$

For the RHIC parameters, the maximum impact parameter is determined by the time of flight of the ion
through the cooling section and it is not affected by the
undulator field. However, the minimum impact parameter
$\rho_{\text{min}}$ which is determined by a relative velocity between an
ion and electron as

$$
\rho_{\text{min}} = \frac{Ze^2}{m_e} \left| \frac{V_i - V_e}{V_i - V_e} \right|^2,
$$

has to be replaced by $r_0$ value, in the presence of the
undulator field. Therefore, the friction force is expected to
be reduced by a factor of the order of

$$
\ln \frac{\rho_{\text{max}}}{\rho_{\text{min}}} = \ln \frac{\rho_{\text{max}}}{r_0}.
$$

To make sure that such a representation of the friction
force is accurate, an undulator field was implemented in
the VORF'AL code [9], and numerical simulations were
performed for different strength of the magnetic field $B$
and pitch period $\lambda$ [lo].

An example of such a comparison between VORF'AL
simulation (dots with error bars) of the friction force
experienced by Au ion with $Z=79$ during a single
interaction with the electron beam and numerical
integration of the force expression in Eq. (3) with the
minimum impact parameter calculated according to Eq.
(2) is shown in Fig. 1. Simulation parameters were (in the
PRF): interaction time $t=0.9$ nsec, for ion velocity of
$3.0 \times 10^5$ [m/s], electrons parameters: rms velocity spread
$\Delta_v = 3.0 \times 10^5$ [m/s] and $\Delta_{\text{long}} = 3.0 \times 10^5$ [m/s] transverse and
longitudinal, respectively, density $n_e = 7.32 \times 10^{13}$ m$^{-3}$. The
force [eV/m] is plotted vs angle [rad] of an ion velocity
vector with respect to the longitudinal direction.

In all simulated cases, it was found that the friction
force scales as predicted by a modified logarithm in Eq.
(6). This confirmed our expectations that with a modest
reduction of the friction force values one can introduce
relatively large azimuthal coherent velocity of electrons to
suppress recombination.

![Figure 1: Longitudinal component of the friction force (eV/m) vs angle (rad) for the ion with velocity of $3 \times 10^5$
m/s in PRF. Comparison is shown for zero magnetic field $B=0$ (upper curve) and for an undulator with $B=10$ G
and different periods $\lambda=8, 16$ and 24 cm (lower curve). VORF'AL results - dots with error bars; numerical
integration - solid lines.](image)

Impact of undulator fields was further investigated by
including errors in the alignment of individual sections of
the undulator. Even with relatively high offsets of 3 mm
no significant effect on the friction was observed [10]. A
detailed study of the effects of magnetic field errors on
the friction force was also performed [11].

**RECOMBINATION CALCULATION**

The ion beam life time due to recombination in the
cooling section is calculated via recombination coefficient
$\alpha_i$ by the following formula:

$$
\frac{1}{N} \frac{dN}{dt} = -\frac{\alpha_i n_e l_{\text{cool}}}{\gamma^2 C},
$$

where $C$ is the ring circumference and $l_{\text{cool}}$ is the length of
the cooler. The recombination coefficient $\alpha_i$ is calculated
in PRF by averaging of the classical cross section of
radiative recombination (cooling is applied to fully
stripped ions) over the distribution function, taking into
account coherent velocity of electrons in the undulator.

Radiative recombination of ions in rings with electron
coolers was extensively studied experimentally. Perfect
agreement between measurements and theoretical
prediction for the recombination coefficient was found in
a wide range of relative energies between the electrons
and ions ($>100$ MeV). However, in the region of extremely
small relative energies (which is the region typically used
for electron cooling), the measured recombination
coefficient for experiments with bare ions was found
significantly higher than predicted by standard theory of
radiative recombination. In the latest theoretical model
[12], which reproduces the measurements, the presence of
strong solenoidal magnetic field in the cooling section is
important for an additional recombination channel. This
mechanism is not expected to occur in the absence of the
solenoidal magnetic field as in the RHIC approach based
on the non-magnetized cooling. In addition, presence of
an undulator field introduces effective detuning towards relative energies where agreement between standard theory and measurements is good [13].

Since present design of the cooling section employs large beta-functions (400 meters for ions and 500 meters for electrons), the density of electron bunch was reduced compared to initial estimates, which in turn reduced the recombination rate. The parameters of undulator were originally set for magnetic field of 10 G and a period of 8 cm, corresponding to an effective temperature of 30 eV and recombination lifetime of 166 hours. However, recent studies of the optimum point between recombination loss and friction force reduction due to undulator fields suggest that strong suppression of recombination rate is perhaps unnecessary, and that parameters of the undulator may be relaxed to just 2 G with a period of 12 cm.

Table 1. Parameters of electron cooler for RHIC-II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>kinetic energy</td>
<td>MeV</td>
<td>54.3</td>
</tr>
<tr>
<td>rf frequency</td>
<td>MHz</td>
<td>703.75</td>
</tr>
<tr>
<td>bunch frequency</td>
<td>MHz</td>
<td>9.38</td>
</tr>
<tr>
<td>bunch charge</td>
<td>nC</td>
<td>5</td>
</tr>
<tr>
<td>rms emittance, normalized</td>
<td>µm</td>
<td>&lt;4</td>
</tr>
<tr>
<td>rms momentum spread</td>
<td></td>
<td>3×10⁻⁴</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>cm</td>
<td>0.8</td>
</tr>
<tr>
<td>rms beam length in cooling section</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>cooling section length</td>
<td>m</td>
<td>100</td>
</tr>
</tbody>
</table>

**COOLING PERFORMANCE**

To ensure good cooling performance a quality of the electron beam should not suffer significantly as a result of the electron beam transport in ERL, merging of the electron and ion beam, transport through the cooling section and interactions with the ion beam [1].

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 ion beam 95% normalized emittance of 15 [mm mrad] and beta-function in the cooling section of 400 [meters], the rms angular spread of ion beam is 7.6 [µrad].

In the baseline cooling simulations with 5nC electron beam we assumed “effective” rms angular spread of the electrons of 8.6 [µrad], which, for example, corresponds to the electron beam rms normalized emittance (thermal contribution) of 4 [µm], if no other contributions to electron angular spread are present. An emittance of 3 [µm] (demonstrated in simulations [1]) corresponds to rms angular spread of 7.5 [µrad] and allows to accommodate additional contributions from other sources. To have a minimum impact on cooling performance, the goal is to constrain total contribution to the rms angular spread of the electrons to about 10 [µrad].

Cooling dynamics studies for RHIC-II are being performed using the BETACOOOL code [14]. Typical simulation which include electron cooling, IBS, particle loss in collisions (burn-off), loss from the rf bucket and recombination is shown in Fig. 2. For details see “RHIC-II Feasibility Study” document in Ref. [1].

Figure 2  Electron cooling simulation of Au-Au luminosity: ion bunch intensity 1×10⁹, 111 bunches, β*=0.5m; using electron bunch parameters from Table 1. Average luminosity in 4 hour store is 7×10²⁷ cm⁻² s⁻¹.

**ACKNOWLEDGMENTS**

We would like to thank A. Burov, Ya. Derbenev, W. Fischer, A. Jain, J. Kewisch, T. Roser and the Accelerator Physics and Electron Cooling Groups of RHIC for useful discussions. We are grateful to the VORPAL team of Tech-X Corp. and BETACOOOL team of JINR, Russia.

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