SIMULATION OF MAGNETIZED BEAMS

Dong Wang*, Ilan Ben-Zvi, Xiangyun Chang, Jorg Kewisch, Christoph Montag, Brookhaven National Laboratory, Upton, NY 11973, Feng Zhou, UCLA, Los Angels, CA 90095

Abstract

The angular momentums of particles in a bunch of beam are of importance in many applications. Usually the angular momentums are related to the end field of solenoids. In electron cooling facilities the solenoid fields are widely used as they are found very helpful not only in focusing and guiding the charge paticle beams but also in enhancing the cooling rates. The RHIC electron cooler is a chanllenging project because it requires a high performance facility including a solenoid with high quality strong field (1 Tesla). Issues cause by the end fields of the solenoid have been studied to minimize the extra temperature and coherent motions. In this paper we report recent results in simulating the angular momentums of the electron beam and its application on the RHIC electron cooler.

INTRODUCTIONS

The Relativistic Heavy Ion Collider (RHIC) [1] is an accelerator complex consisting The main goal of the RHIC is to provide head-on collisions at energies up to 100 GeV/u per beam for very haevy ions, which are defined to be gold $^{197}Au^{79+}$, but the program also calls for lighter ions all the way down to protons and polarized protons. Luminosity requirements for the heaviest ions are specified to be in the 10^{26}~$10^{27}cm^{-2}s^{-1}$ range. A first upgrade of the luminosity by about a factor four consists of increasing the number of bunches from about 60 to about 120 and decreasing beta* from 2m to 1m. Luminosity can be further enhanced by decreasing the beam emittance by the electron cooling the gold beams at storage energy. With electron cooling [2] [3] the beam emittance can reduced and maintained throughout the store and the luminosity increased until non-linear effects of the two colliding beams on each other limit any further increase (beam-beam limit).

An electron beam is considered magnetized when its radius of transverse Larmor oscillations is much smaller than beam radius. If the solenoid field lines are perfectly parallel, these oscillations can increase the duration of an electron-ion interaction thus increasing the friction force (assuming that there are several Larmor oscillations in the cooler). In this case the cooling rate is mainly determined by the electron longitudinal energy spread, which can be made much smaller than the transverse one.

The calculations of electron cooling for RHIC show that a strong longitudinal field, among other requirements, is needed to achieve required cooling rate. Figure 1 shows the layout of this energy recovery linac (ERL) machine. Table 1 gives major parameters of the RHIC electron cooler.

* Email: dongwang@rocko.mit.edu

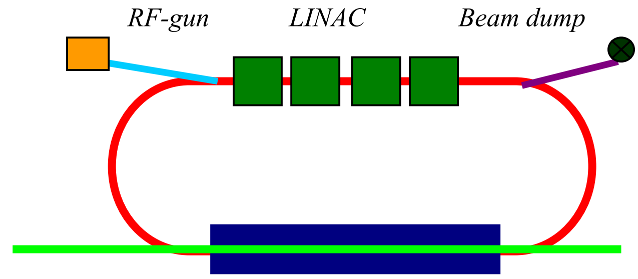

Figure 1: is the sketch of the RHIC e-cooling facility

Table 1: Parameters of electron beam for RHIC cooler

Final Beam energy	55MeV
Solenoid field	1 Tesla
Length of solenoid	~ 30 m
Charge per bunch	10 nc
Repetition rate	9.4MHz
Average current	94 mA
Bunch length at Linac	~5~10 mms
Injection energy	2.5 MeV

However, the end fields of a solenoid have radial components and can give beam extra angular momentum.

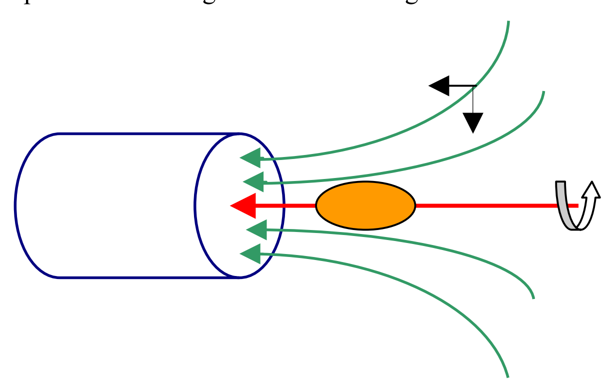

Figure 2: Beam acquires angular momentum from end field of solenoid

There are two main effects in cooler solenoid due to the angular momentum,

1) angular momentum itself means certain transverse temperature .

2) it will cause coherent radial motion in longitudinal magnetic field in the cooler.

Particle tracking show clearly above two major effects. In this simulation the modified PARMELA [4] is used to include major fields and forces, i.e., cavities(gun, lianc, buncher, rotation), magnets (dipole, quads, sextupole, solenoid), space charge, etc.

0-7803-7739-9 ©2003 IEEE

MUTLI-PARTICLE TRACKING

The canonical angular momentum can be expressed in following ways,

$$M = pr^2\theta' - e\Phi(r,z)/2\pi c \quad \text{or,}$$
$$M = xp_y - yp_x$$

Here, x,y,p_x,p_y, are the transverse Cartisian coordinates and their conanically conjugated momenta, r,θ,z are the cylindrical coordinates, the prime denotes a derivative along the axis z, p=γβmc is the total momentum, Φ is the magnetic flux inside a circle enclosed by the electron offset r, e is the charge of electrons. Different phase spaces of magnetized beam are exploited to find best way to reveal the behavior of this kind of beam. See Figure 3.

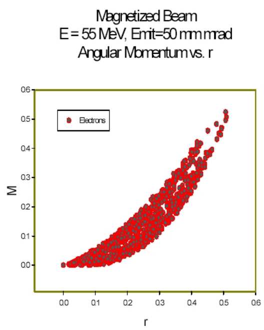

Figure 3: Angular Momentum

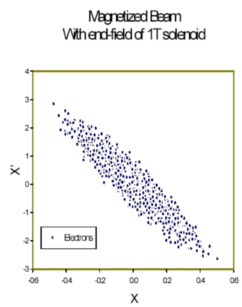

Figure 4: (x, x')

The horizontal axis is r and the vertical axis is M. Figure 4 is normal (x, x') phase space. To better observe the evolution of the angular momentum several other methods are explored, say, rθ' vs. r, x' vs. y or y' vs. x, xy' vs. r, or yx' vs. r, xy' vs. x(or y)., see Figures 5 to 10.

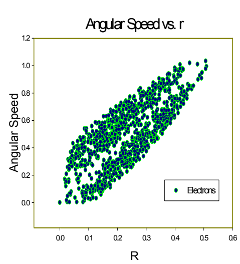

Figure 5: rθ' at start

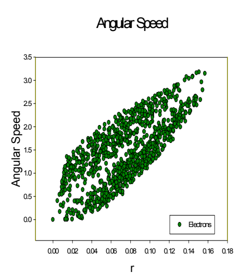

Figure 6: rθ' after a drift

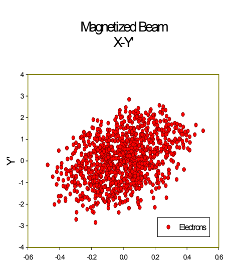

Figure 7: (x, y') at start

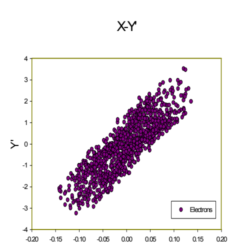

Figure 8: (x, y') after a drift

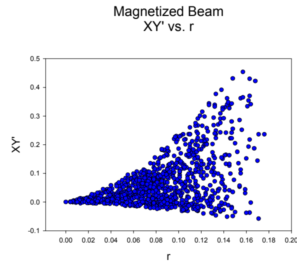

Figure 9: xy' vs. r

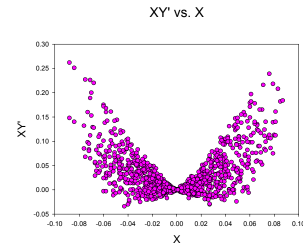

Figure 10: xy' vs.x

Besides the M itself (Figure 3), the rθ' is found very useful since it has pretty concise and certain shape (linear correlation, thermal AM is flat in this phase space) in phase space therefore easy for comparing the its amount and distribution of a bunch at different locations. The (x, y') or (y, x') also has some patterns for magnetized beam. They might be useful in measuring the magnetized beam with (x, y) tomography technique. What is different from the (rθ', r) phase space is that their shape vary along the beam line as shown in Figure 7 and 8. Other phase spaces have rather complicated patterns and are not invariants.

MATCHING AND START-TO-END SIMULATION

The basic principle of matching or eliminating the angular momentum in a solenoid can be illustrated by the Busch's theorem.

$$\dot{\phi} = -\frac{e}{2\pi\gamma m_e r^2(s)}[\Phi(s) - \Phi_{cathode}]$$

It shows that one needs to give electrons certain amount of angular momentums which may exactly cancel the effects of the end field of cooler solenoid. The traditional electron coolers don't have this issue since the continuous solenoids are adopted from the start to the end. For high energy cooler like one for the RHIC one has to use discrete elements (sc linac etc.) to accelerator intense beam(10 nc) to 55 MeV. For this purpose some detailed analytical approaches have been performed under some assumptions (linear optics, zero energy spread, etc.) [5] [6]. The point is that the beam must be magnetized when it was born on the cathode and the angular momentum must be preserved through the whole beam line, gun, linac, transport, then canceled by the end field of cooler solenoid. In reality the situation are more complicated than linear single particle dynamics. The questions then become what kind angular momentum distributions are needed for a bunch of electrons and how significant the distortions due to various reasons could be.

The simplest case of matching is the cancellation of the angular momentums caused the same end field but with opposite field directions. Electrons acquire the angular momentum from a solenoid with opposite field then enter the cooler solenoid. The angular momentums would be canceled if the beam is focused properly at the entrance of solenoid. For a global matching one needs to make the transform as a rotationally invariant mapping.

Based on above studies on illustrating the angular momentums of a electron bunch, a start-to-end simulation is carried out for the RHIC electron cooling project. Beam is magnetized on the cathode (non-aero magnetic field at cathode) then accelerated through the RF gun and sc linac followed by a transport line to stretch the bunch before it is sent to the cooler solenoid. The Figure 11 is beam envelope along the beam line. Figure 12 and 13 show that the angular momentums of electrons in the bunch are mostly preserved (left bottom plot) but some distortions are observed, possibly due to the energy spread (the largest in RF gun where bean energy is the lowest).

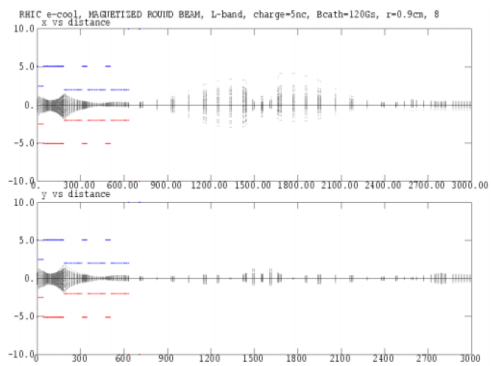

Figure 11: beam envelopes along the beam line

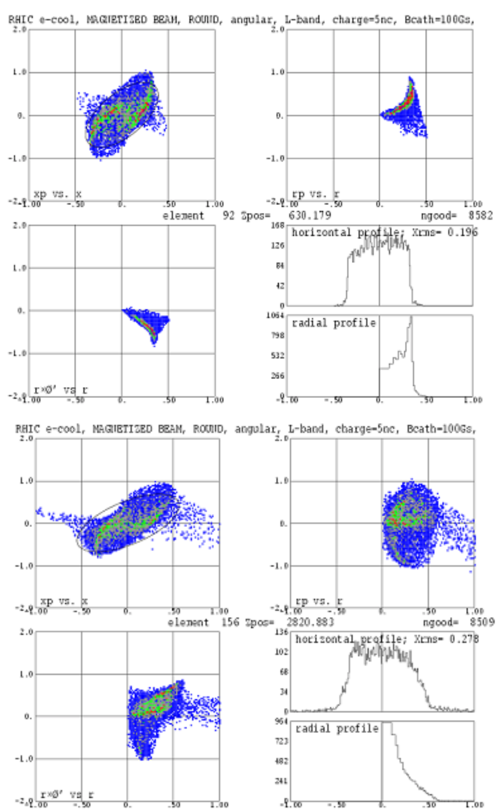

Figure 12 and 13: magnetization (left-bottom ones) at the exit of linac and entrance of the cooler solenoid

The magnetic field on the cathode is about 100 Gs while beam spot size is about 10 mm radius. In RF-gun the beam is accelerated to about 2.5 MeV then directed to the linac by a small angle bending magnet. Three sc cavities (L-band, now likely to use four or five 700MHz cavities) will further accelerate beam up to 55 MeV energy. A transport line is designed [7] to stretch the bunch to a few cm and energy spread is lowered by a rotation cavity.

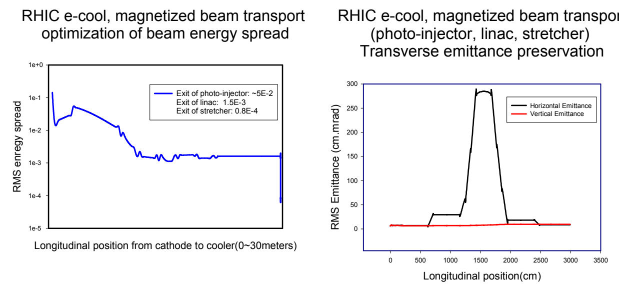

Figure 14 (left) and 15 (right): Evolutions of energy spread and beam emittances for the RHIC electron cooling beam

SUMMARY

The simulations of angular momentums have been studied. Different ways to describe the distributions of the angular momentums in a bunch beam are explored. It is found that some of them, M, transverse velocity and (x, y') or (y, x') are the best ways to understand the issue. The evolutions of angular momentums in solenoid, cathode, acceleration cavity and other beam line elements are simulated. The simulation has included more effects than the existing theory (space charge, energy spread, etc.) It proved that the magnetized beam in the RHIC cooler with strong solenoid magnetic field can be produced and transported to the cooler solenoid smoothly while keeping their angular momentums mostly preserved. The distortions observed need to be further minimized with fine compensations.

ACKNOWLEDGMENTS

We'd like to thank Lloyd Young and his coworkers in LANL for their discussions and helps in the PARMELA codes. We also thank the participants of RHIC e-cooling meetings for their discussions.

REFERENCES

[1] See, for example, T. Roser, these proceedings
[2] I. Ben-Zvi et al., these proceedings
[3] S. Nagaitsev (Fermilab). FERMILAB-CONF-01-171-E, PAC-2001-FOAC002, Jul 2001
[4] L. Young, et al., LANL, PARMELA
[5] Y. Derbenev, Nucl.Instrum.Meth.A441:223-233, 2000
[6] A. Burov, et al., Physical Review Special Topics on Accel. Beams 3:094002, 2000
[7] J. Kewisch, et al., these proceedings