STUDIES OF ION BEAM INSTABILITIES FOR LOW ENERGY RHIC OPERATIONS WITH ELECTRON COOLING*

G. Wang#, M. Blaskiewicz and V. N. Litvinenko, BNL, Upton, NY 11973, U.S.A.

Abstract

Electron cooling has the potential to compensate the emittance growth of the circulating ion beam due to intra-beam scattering at low energy. A test of electron cooling for RHIC low energy operations has been planned at IP2. It is useful to investigate beam stability at the design stage to set limits on various beam parameters and avoid 'overcooling' of the ion beam. Furthermore, in the presence of electron cooling, the coherent interaction between the electron beam and ion beam could also play a role in the beam stability.

In this work, we first present simulation results of ion beam instability in the absence of coherent electron-ion interactions. Then, we apply the hydrodynamics model to obtain the one pass change of ions' location and momentum due to the dipole mode coherent electron-ion interaction. Finally, we include this one pass map into the simulation code, TRANFT, to study the effects of this coherent electron-ion interaction for RHIC Low Energy electron Cooling (LEeC).

INTRODUCTION

Colliding Au ion at $\sqrt{s} = 7.7GeV \sim 20GeV$ helps high-energy physicists searching for the QCD phase transition critical point. In 2010, RHIC had a test run at this energy range and some limitations in beam lifetime were observed [1]. To counteract one of the major limitations, intra-beam scattering (IBS), an electron cooling system is currently under design. Although the cooling system is not designed to reduce the initial ion bunch length or emittances substantially, it is important to know the instability thresholds in the low energy operation to prevent ion beam from being inadvertently 'overcooled'. In addition, apart from the desirable cooling force originated from electron-ion scattering, circulating ions also interact with the electrons coherently. As electron beam is refreshed after each revolution, the system is not closed and free energy can be brought into the ion beam, which in principal could make the ion beam motion unstable under unfavourable circumstances.

In this work, we focus on the beam energy of 3.8 GeV/n, i.e. $\sqrt{s} = 7.7GeV$. We start with finding instability thresholds for bunch length in the absence of the coherent electron ion interaction, using a simulation code TRANFT. To study the effects of electron-ion transverse coherent interaction, we implemented a hydrodynamic model developed by V. Parkhomchuk et.al into the simulation[2]. For the currently designed parameter, the effects of the transverse coherent dipole mode interaction have been found small.

INSTABILITY THRESHOLDS DUE TO MACHINE IMPEDANCES

At $\gamma = 4.1$, space charge has the dominant contributions to both longitudinal and transverse impedance as shown in fig. 1. Other longitudinal RHIC impedances included in the simulations are previously measured 3 ohm inductive broad band impedance and the resistive wall impedance[3]. The broadband impedance is modelled as a resonator with $Q = 2$ and $f_r = 2GHz$, and low frequency formula is applied for resistive wall impedance.

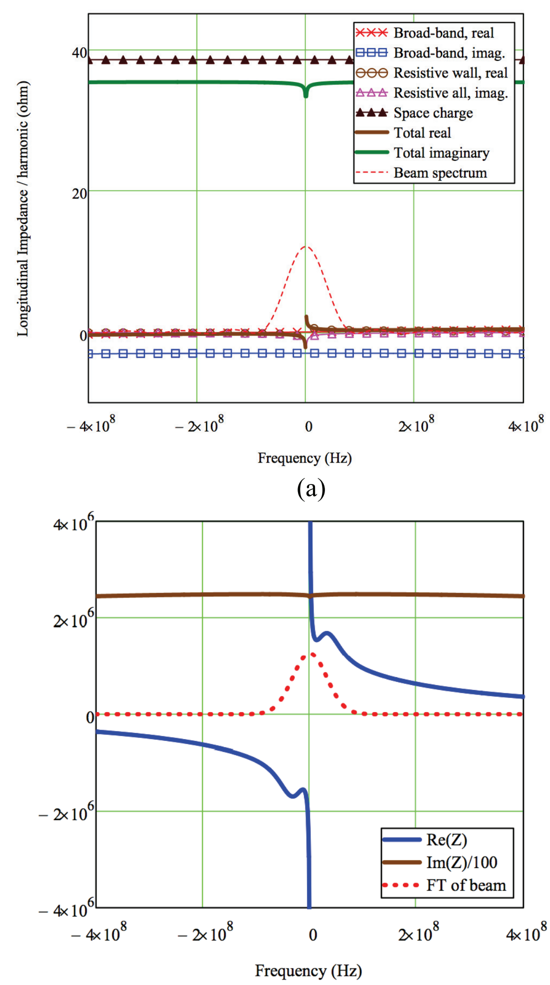

Figure 1: RHIC impedances used in the simulation. (a) the ordinate is $Z_{\parallel}/p$ and the red dot curve is the beam line charge density spectrum in arbitrary units. (b) transverse impedance.

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#gawang@bnl.gov

Table 1: RHIC Au^{+79} Beam Parameters at 3.8 GeV/n

Beam energy, γ	4.1
Bunch intensity	10^9
Emittances, rms, ε_n	$2.5\,\pi\cdot mm\cdot mrad$
Bunch length, rms	1.5 m
Peak current, I_{peak}	1 A
Energy spread, rms, $\delta\gamma/\gamma$	$4\cdot 10^{-4}$
Beta function at e-cooler	30 m
Beam size at e-cooler, rms	4.3 mm
Betatron tune, $Q_{x,y}$	28.15
Synchrotron frequency	973 Hz

The longitudinal impedance $Z_{\parallel}/p$ and initial proton bunch spectrum are plotted in fig.1a. The transverse impedance used in the simulation includes the contribution from space charge, bellows, resistive wall, bpms and abort kicker[4, 5]. In the simulation, we assume 28 MHz rf cavities with 450 KV voltage, -2 units of linear chromaticity and parameters listed in Table 1 for the nominal RHIC Au^{+79} beam. For the nominal beam parameters, no instabilities were observed from the simulation. The bunch length is then reduced until either the coherent transverse or longitudinal motion become unstable. The transverse coherence is monitored by the quantity,

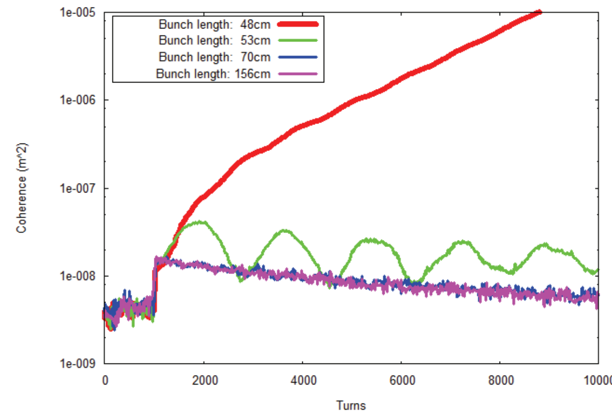
$$Coherence = \frac{\int_{bunch} I(t)\left[\langle x(t)\rangle^2 + \langle p(t)\rangle^2\right]dt}{\int_{bunch} I(t)dt},$$

where $I(t)$ is the instantaneous current, $\langle x(t)\rangle$ is the average displacement at longitudinal location t and $\langle p(t)\rangle$ is the average transverse angle multiplied the average beta function. As shown in fig. 2(a), transverse head-tail instability took places with a rise time of 1500 turns when the rms bunch length was reduced to 48 cm. After 10000 revolutions, the head-tail instability drives the tail of a 48 cm long bunch deviating from the centre of the vacuum chamber by 6 mm. Although for a 48cm long bunch, the rms energy spread was reduced by a factor of 4 from its nominal value, no longitudinal instabilities were observed from the simulation.

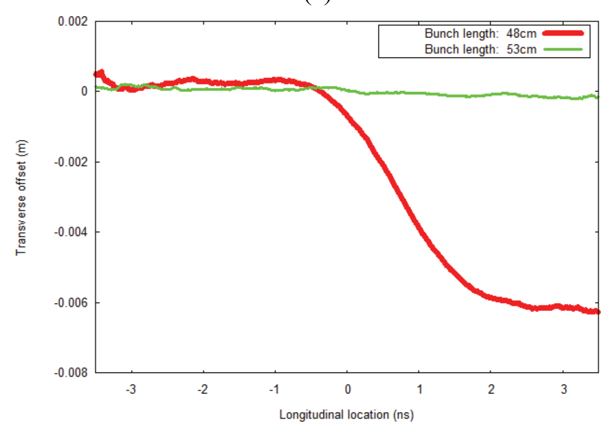
TRANSVERSE COHERENT ELECTRON-ION INTERACTION IN E-COOLER

As mentioned in the previous sections, the cooling electron beam could coherently interact with the circulating ion beam with the following mechanism:

- Transverse shot noise of ion beam introduces displacement of the instantaneous beam centroid;
- The displacements of ion beam centroids drive the electron beam centroid to oscillate;



(a)



(b)

Figure 2: simulation results of transverse head-tail instability. (a) Evolution of Au^{+79} beam transverse coherence for various rms bunch lengths; (b) Transverse offsets along the Au^{+79} bunch with rms bunch lengths of 48cm and 53 cm after 10000 turns.

- While oscillating, the electrons acts back to the ions and make their initial displacement either enhanced or reduced, depending on the specific parameters of the ion beam and the electron cooler.

Using a hydrodynamics model developed by V. Parkhomchuk et.al, in the co-moving frame, the coherent effect of the electron beam to the ion beam can be described by the following form [2]:

$$\begin{pmatrix} R_i \\ \dot{R}_i \end{pmatrix}_{out} = M_{ecool}\begin{pmatrix} R_i \\ \dot{R}_i \end{pmatrix}_{in}, \qquad (1)$$

where R_i is the displacement of the ion bunch centroid at a certain longitudinal location, $\dot{R}_i$ is the time derivative of R_i in co-moving frame, the subscript 'in' and 'out' describes the values are taken at the entrance and exit of the cooling section respectively. The one pass transfer matrix is given by

$$M_{ecool} = \begin{pmatrix} 1+\xi\left[\cos(\omega_0\tau)-1\right] & \frac{1}{\omega_0}\left[\xi\sin(\omega_0\tau)+(1-\xi\omega_0\tau)\right] \\ -\xi\omega_0\sin(\omega_0\tau) & 1+\xi\left[\cos(\omega_0\tau)-1\right] \end{pmatrix}, \qquad (2)$$

Table 2: RHIC e-cooler Parameters at 3.8 GeV/n

Bunch charge	2 nC
Emittances, rms, ε_n	$2.5\ \pi \cdot mm \cdot mrad$
Bunch length, full	24 cm
Peak current, I_{peak}	2.5 A
Energy spread, rms, $\delta\gamma/\gamma$	$5 \cdot 10^{-4}$
Beta function at e-cooler	30 m
Beam size, rms	4.3 mm
Cooler length	10 m
Electron density, co-moving frame	10^{14} m^{-3}

where $\omega_0 \equiv \sqrt{\omega_{ei}^2 + \omega_{ie}^2}$, $\omega_{ie} = \sqrt{Z_i n_e e^2 / (2\varepsilon_0 m_i)}$, $\xi \equiv \omega_{ie}^2 / \omega_0^2$, $\omega_{ei} = \sqrt{Z_i n_i e^2 / (2\varepsilon_0 m_e)}$, n_i and n_e are number density of ions and electrons respectively in the co-moving frame, and $\tau = L_{cool} / (\gamma\beta c)$ is the co-moving frame travel time inside the cooling section. As the coherent electron-ion interaction is an open system, the transfer matrix usually does not have unity determinant or amplitudes of its eigenvalues. Fig. 3 shows $\det(M_{ecool}) - 1$ and the eigenvalue amplitudes as a function of the co-moving frame electron density for parameters listed in Table 2, which suggest that coherent instability may happen at three orders of magnitude higher than the current designed value.

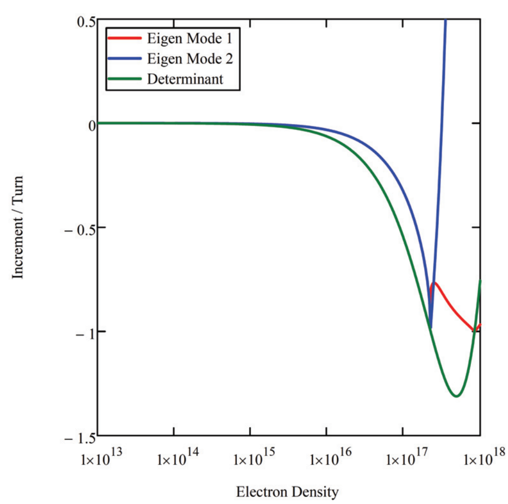


Figure 3: deviation of the determinant and eigenvalue amplitudes of M_{ecool} from unity. The abscissa is the electron density in co-moving frame in unit of m^{-3}.

Fig. 4 plots deviation of the determinant and the eigenvalues amplitudes as functions of the cooling section length, which suggests possible growth of transverse coherence when the cooling length is within certain ranges. For a bunched beam, the synchrotron motion mixes ions from different longitudinal slices and hence affects the building-up of the transverse coherence. To investigate the effects of the coherent electron-ion interaction to a bunched beam, we implemented the hydrodynamic model into TRANFT.

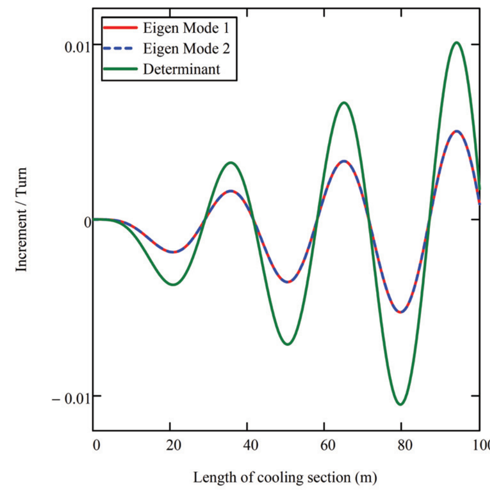


Figure 4: deviation of the determinant and eigenvalue amplitudes from unity as a function of cooler length.

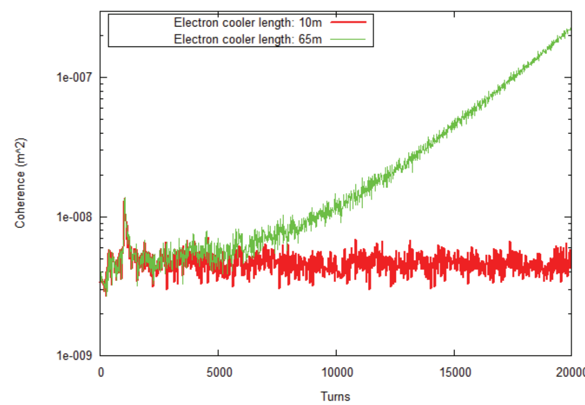


Figure 5: simulation results of the transverse coherence evolution in the presence of coherent electron-ion interaction.

As shown in fig. 5, the transverse motion was stable for the designed 10 meters long electron cooler (green curve). As the length of the cooler increased to 65 meters, slow coherence growth was observed from the simulation (red curve). The rise time is about 3300 turns, which is much slower than the expected rise time for an un-bunched beam.

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