SIMULATIONS OF RHIC COHERENT STABILITIES DUE TO WAKEFIELD AND ELECTRON COOLING*

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Abstract

The Electron cooling beam has both coherent and incoherent effects to the circulating ion beam. The incoherent longitudinal cooling could reduce the ion beam energy spread and hence cause 'over-cooling' of the ion beam. Depending on the beam densities and cooling length, the coherent interaction between the ion and electron beam could either damp or anti-damp the ion coherent motions. Using the tracking codes, TRANFT, the threshold for 'over-cooling' has been found and compared with theoretical estimation. The transverse coherent effect of electron cooling has been implemented into the codes and its effect for the bunched ion beam is shown.

INTRODUCTION

Although the major task of RHIC-II electron cooling is to compensate the transverse emittance growth due to IBS, the longitudinal cooling could also happen for certain cooling schemes [1]. As a result, the energy spread of the ion beam decreases with the cooling process and may eventually destroy the Landau damping. Depending on the specific impedances of the machine, either longitudinal or transverse coherent instabilities will take place and thus cause emittance deterioration or beam loss. On the other hand, the electron beam itself can also coherently interact with the ion beam and thus affect the instability threshold and growth rate. A tracking code, TRANFT, is used to study the coherent instability of the RHIC ion beam with the coherent effects of the electron cooling being taken into account. In section 2, we describe the simulation algorithm and the impedances used for the RHIC simulation. In section 3, the simulation results are shown and the energy spread threshold for the instability is compared with analytic formula derived from the coasting beam dispersion relation. For the current ions per bunch, when the chromaticity is set to a slightly positive value at the top energy, the longitudinal instability happens before the transverse instability as the energy spread decreasing. However this is not true for a longer bunch with the same longitudinal phase space density. For fixed bunch length and increasing particle numbers, the transverse head-tail instability happens before the longitudinal instability but its growth can be suppressed by the coherent damping effect of the electron beam, which is shown in section 4. We make conclusion in section 5.

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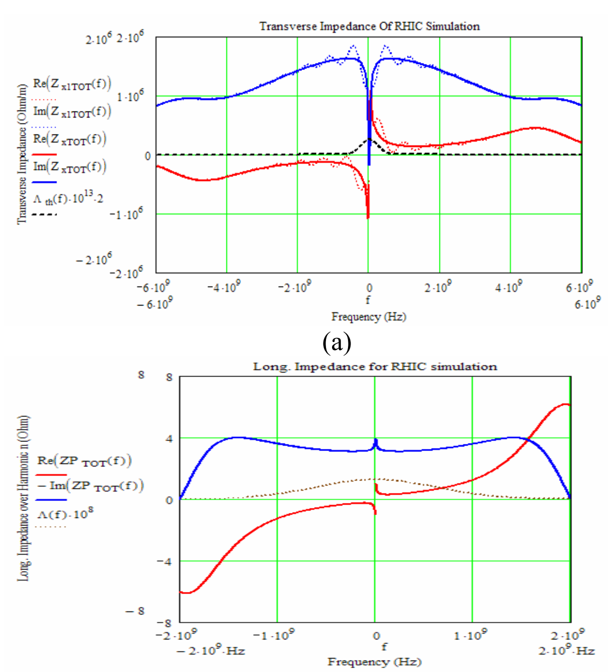
TRACKING CODES DESCRIPTION

The FORTRAN program TRANFT simulates coherent instability in circular machine by using FFT algorithms. Each ion bunch is represented by $10^4 \sim 10^5$ macro particles, which are updated every turn according to the coherent kicks due to the wake field and the electron beam [2]. The kicks due to Wakefield are calculated in frequency domain by multiplying the Fourier component of the current with the impedances. The transverse impedances include the resistive wall, space charge, abort kicker, bellows and bpms [3]. The longitudinal impedances include the resistive wall, space charge and resonant impedance which give the measured $Z_{//}/n = 3j\Omega$ over the beam spectrum [4]. The longitudinal and transverse impedance are plotted in Figure 1. For non-magnetized electron cooling, the transverse kick due to the electron cooling beam is given in [5].



(a)

(b)

Figure1: (a) RHIC Transverse Impedance. The dot curves are for step form bpm impedances. (b) RHIC Longitudinal Impedance over harmonic $Z_{//}/n$. The Gaussian curves in both graphs roughly show the range of beam spectrum.

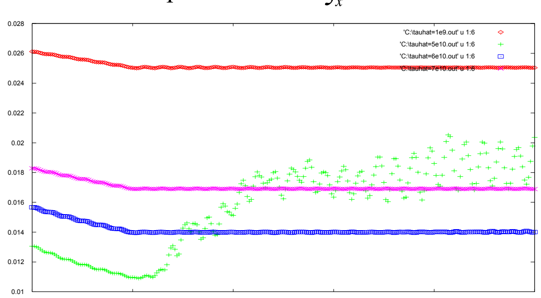
SIMULATION RESULTS

Since the rf voltage and harmonic number were kept the same for all simulations, the momentum spread was always proportional to the bunch length. In order to investigate the momentum spread threshold of overcooling, the initial bunch length was gradually reduced from its current operational value to the point where either longitudinal or transverse instability was observed. Table 1 shows the beam parameters we used for the simulation. About 10^5 macro-particles were tracked in

Table 1: Parameters for RHIC Instability Simulation

Beam Energy	100
Beam Particle	Au^{79+}
RMS Emittance $\varepsilon_x(\pi \cdot mm \cdot mrad)$	4.2
Bunch Population	10^9
RF Voltage (MV)	3
RF Harmonic number	2520
Chromaticity ξ_x	2

the simulation. The initial longitudinal distribution was parabolic and the initial rf voltage was linear. The beam was adiabatically matched to a sinusoidal rf voltage within 1000 turns. As shown in Figure 2a, for initial $\delta p/p \le 1.4\times10^{-4}$ the longitudinal emittance started to grow rapidly. After a few hundreds turns, the momentum spread increased well above the stability threshold and the growth was suppressed as the beam reached to its new equilibrium. Figure 2b shows the longitudinal beam profile after 5000 turns. No transverse instabilities were observed for 10^9 ions per bunch and $\xi_x = 2$. Since the



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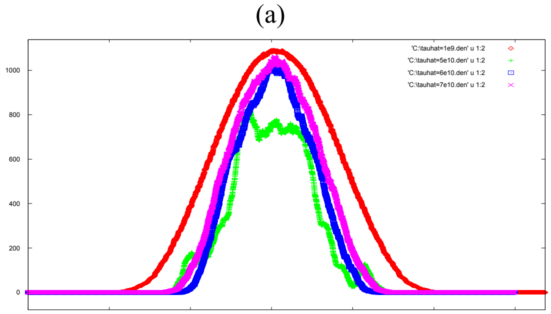


Figure 2: (a) Momentum spread evolution. The decreasing before 1000 turn is due to the mismatch of the longitudinal phase space; (b) Longitudinal beam profiles after 5000 turns.

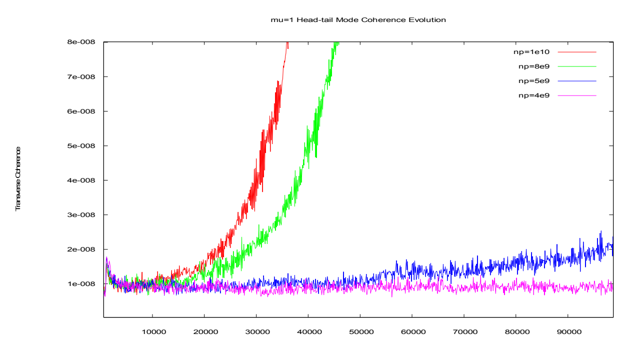
synchrotron oscillation was slower than the longitudinal instability growth rate, the dispersion relation for a coasting beam should be able to estimate the instability threshold. The theoretical prediction is given by the Keil-Schnell criteria.

$$\sigma_{p,th} = \sqrt{\frac{(Z_{//}/n) I_{peak} Z_i e}{(2\ln 2) m_i c^2 \gamma_0 \beta_0^2 |\eta|}} = 1.5\times10^{-4} \qquad (1)$$

Comparing Equation 1 with the simulation results, we see that the agreement is within 10%. Because of the non-linear component of the rf voltage and the wake field, the transverse higher order head-tail modes were actually landau damped by the synchrotron tune spread. As the number of particle inside the bunch increasing, the landau damping would eventually cease and for weak coupling and short bunch, the threshold can be estimated by the following dispersion relation [7].

$$Z_{eff} = \left[i\Lambda_\mu \int_0^\infty dH_s \left(\frac{H_s}{\nu_s(H_s)^2} \right)^{|\mu|} \frac{\psi_0(H_s)}{(Q_R - \mu\nu_s(H_s) + iQ_I)} \right]^{-1} \qquad (2)$$

, where $Q \equiv Q_R + iQ_I = (\Omega + \omega_y)/\omega_0$ is the coherent tune shift and $\Lambda_\mu = ecI_{av}\left(2^{|\mu|}|\mu|!\right)^{-2}\left(2\eta/\beta_0^2 E_0\right)^{|\mu|}/2E\omega_y$. The effective impedance Z_{eff} is defined as



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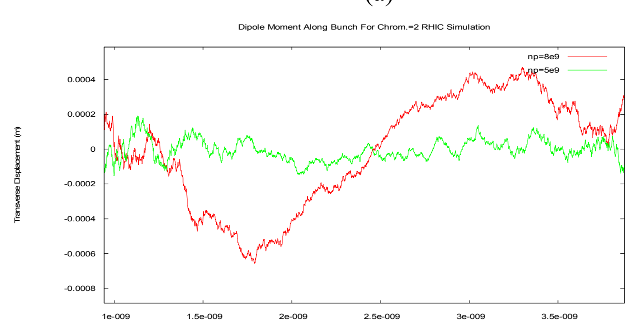

(b)

Figure 3: (a) The transverse coherence evolution for head-tail mode. The vertical axis is the coherence as defined in [2]. The red green blue and purple curve are for bunch population of 10^{10}, 8×10^9, 5×10^9 and 4×10^9 respectively. (b) A snapshot of the transverse displacement along the bunch. The red and green curves are for 8×10^9 and 5×10^9 ions per bunch.

$$Z_{eff} \equiv \sum_{n=-\infty}^{\infty} \left(n - Q_y + \frac{\xi_x}{\eta} Q_y \right)^{2|\mu|} Z\left(n\omega_0 - \omega_y + \mu\omega_{s0}\right) \quad (3)$$

The simulation result for $\xi_x = 2$ is shown in Figure 3. As the bunch population going beyond 4×10^9, the transverse motion became unstable and the growth rates were in order of 10^{-5} per turn, which agree with the prediction of Equation 2, $n_p \approx 3.5\times10^9$ as shown in Figure 4. In the

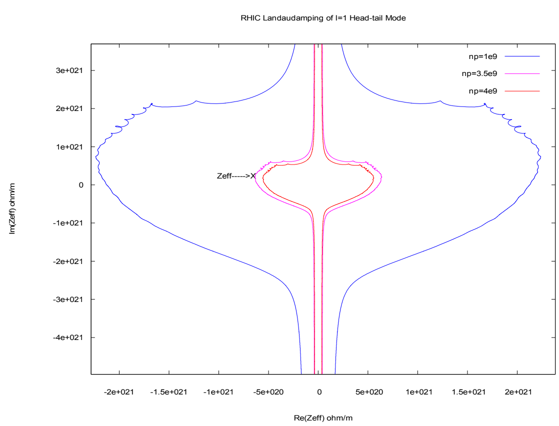

Figure 4: Stability threshold contours for $\mu = 1$ head-tail mode. The blue, purple and red curve are the stability threshold contours for bunch population of 10^9, 3.5×10^9 and 4×10^9 respectively. The 'X' marks the effective impedance calculated directly from the definition, Equation (3), using the impedance shown in Figure 1.

presence of the cooling electron beam, the slow higher order head-tail instability could be suppressed by the coherent two stream interaction. As shown in Figure 5, the coherent damping effect of the electron beam is small for the current electron cooler design but can be increased dramatically by increase the cooling section length since the damping rate is proportional to l_{ec}^4.

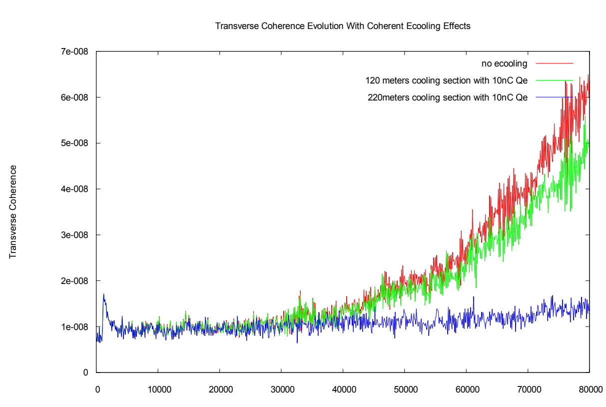

Figure 5: The Transverse Coherence Evolution With varies E-cooling Parameters. The bunch population is 6×10^9 and the chromaticity is 2.

CONCLUSION

The single bunch simulation shows that the longitudinal microwave instability threshold can be accurately estimated by the coasting beam formula and for the current operational beam parameters, the threshold was found to be $\delta p/p \approx 1.5\times10^{-4}$. The transverse motion is stable for $\xi_x = 2$ and $n_p \leq 4\times10^9$. High order head tail instability will occur if the bunch population is beyond the Landau damping threshold determined by the synchrotron frequency spread. The growth rate of $\mu = 1$ head-tail mode is in the order of $10^{-5} \sim 10^{-4}$. This slow growth can be suppressed by the coherent force exerted by the cooling electron beam and in order to increase the high order head-tail instability threshold substantially, the length of the cooling section has to be at least 200 meters.

ACKNOWLEDGEMENT

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