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# BEAM-BEAM DAMPING OF THE ION INSTABILITY*

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*Abstract*

The electron storage ring of the proposed Electron Ion Collider at BNL (BNL EIC) has bunch charges as large as 50 nC and bunch spacings as small as 10 ns. For molecules like carbon monoxide (CO) a dangerous buildup of positive ions is possible and a significant fraction can survive allowable clearing gaps. This beam ion instability (BII) is thus multi-turn and the weak damping required to stop the ion instability with an ideal clearing gap is ineffective here. The beam-beam force is highly nonlinear and a potent source of tune spread. Simulations employing several macro-particles per electron bunch and several ion macro-particles are used to estimate maximum gas densities for CO and H2. A simplified model is introduced and compared with simulations.

## INTRODUCTION

Ions have always been a source of difficulty in electron rings [1–15]. As an electron bunch passes through the vacuum, positive ions are generated which act upon subsequently passing electron bunches. During gaps in the electron bunch train ions are partially cleared. In the approximation that ions are cleared to the point of irrelevance the instability is referred to as the fast beam ion instability (FBII). In this approximation the first electron bunch in the train undergoes a free betatron oscillation. It creates ions that act upon following bunches. The second bunch is driven by the first and acts upon subsequent bunches, and so on. Real bunches always undergo a noiselike betatron oscilation of rms amplitude $A_{rms} = \sqrt{\beta(s)\epsilon/N}$ where $\beta(s)$ is the beta function, $\epsilon$ is the rms unnormalized emittance, and $N$ is the number of electrons in the bunch. The inverse correlation time of this random process is the betatron frequency spread. This random noise will lead to residual oscillations that are similar to oscillations created by noise in a feedback system and a similar formalism can be applied [4]. In electron storage rings nonlinearities in the restoring force cause the instability to saturate and the FBII usually manifests as an increased vertical beam size. Such a situation could be devastating in an electron ion collider (EIC).

In an EIC any oscillations of the electron bunches will influence the ion bunches via the beam-beam force [16]. Since ions have no radiation damping this can result in continuous emittance growth. For a simple model consider a proton at the interaction point with vertical offset $y_p(n)$ and angle $y'_p(n)$ on turn $n$. Let the vertical beta function at the interaction point be $\beta^*$ and let the electron bunch offset be $y_e(n)$. With a small amplitude beam-beam tune shift of $\Delta Q_{bb}$ the one turn map for the proton is

$$z_p(n) = z_p(n-1)e^{-i\psi_p} + 4\pi i\Delta Q_{bb} y_e(n), \qquad (1)$$

where $z_p(n) = y_p(n) + i\beta^* y'_p(n)$ and $\psi_p = 2\pi Q_p$, where $Q_p$ is the vertical proton tune. Assume $y_e(n)$ is a stationary random process with rms amplitude $\sigma_y$ and correlation function $\rho_e(m)$. This yields a growth rate

$$\frac{d\langle|z_p|^2\rangle}{dn} = (4\pi\Delta Q_{bb}\sigma_y)^2 \sum_{m=-\infty}^{\infty} \rho_e(m)\cos(m\psi_p), \qquad (2)$$

where angular brackets denote expectation value. For white noise the sum in Equation (2) is 1 while for slow closed orbit motion it is very small.

If a feedback system is operating, $\sigma_y$ will be strongly influenced by the noise level in the feedback system [4] and the correlation time of $\rho_e(m)$ will include the feedback damping time. While it might be possible to build a damping system with adequately low noise we have found that one needs $\sigma_y \lesssim \sqrt{\epsilon\beta^*} \times 10^{-4}$ for the equivalent white noise oscillation, which is extremely challenging.

Therefore, the BNL EIC baseline design is such that BII will be collisionlessly damped by tune spread in the electron beam. The largest source of tune spread is the beam-beam force, which is always present during luminosity production.

## MODEL AND SIMULATIONS

The BII simulations use macro-particles for both the electrons and the ions. The ionization happens continuously around the ring but for the purposes of simulation the ions are confined to $N_{slice}$ thin lenses spaced evenly around the ring. Each ion slice corresponds to particular values of $\beta_x$ and $\beta_y$. Ion macro-particles are generated in balanced pairs according to the appropriate two dimensional Gaussian distribution. By using pairs no additional noise is added. These ions are added to the ones already present in the slice. The ions barely move during the passage of a single electron bunch so the momentum kick to the ions is calculated assuming the ions are stationary. To calculate the kick the centroid and rms values for the electron bunch are calculated. The Basetti-Erskine formula is used to calculate the ion kicks. The ion kicks are summed and conservation of momentum is used to get the net kick to the electron bunch. The same kick is given to each electron macro-particle in the bunch. This approximation correctly includes the coherent tune shift due to the ions but neglects the incoherent tune shift due to the ions. In the future we will include the incoherent force from the ions. Next, the ions are time drifted until the next electron bunch arrives, removing any that get outside the aperture. The process repeats over the rest of the bunch train. The electrons are transported, including RF and chromatic effects, to the next ion slice and the process repeats. At the end of the turn a single weak-strong beam-beam kick is applied and the process repeats.

Ion-ion forces are neglected since the electric fields from the electrons are much larger than the electric fields of the

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ions. Electron-electron forces are neglected because of relativistic cancellation.

To reduce transients we turn on the beam-beam force using a linear ramp over the first 100 turns and after that we ramp up the gas density over the next 100 turns.

We have done simulations for parameters relevant to the BNL EIC.The small amplitude oscillations of $H2^+$ are unstable and simulations bear out that partial pressures as high as $10^{-6}$ Pa do not lead to instability. That leaves $CO^+$ as the likely dominant ion. Figure 1 shows simulation results at 10 GeV for 1160, 27.5 nC bunches with a 100 bunch gap. Figure 2 shows simulation results at 10 GeV for 599, 54.9 nC bunches with a 31 bunch gap. The beam-beam tune shift was 0.05 for both planes. The curves are labeled with the density of CO in units of $10^{12}\mathrm{m}^{-3}$. At 300 K a density of $24.2\times10^{12}\mathrm{m}^{-3}$ corresponds to a partial pressure of $1.00\times10^{-7}$Pa. The ionization cross section was $2\times10^{-22}\mathrm{m}^2$.

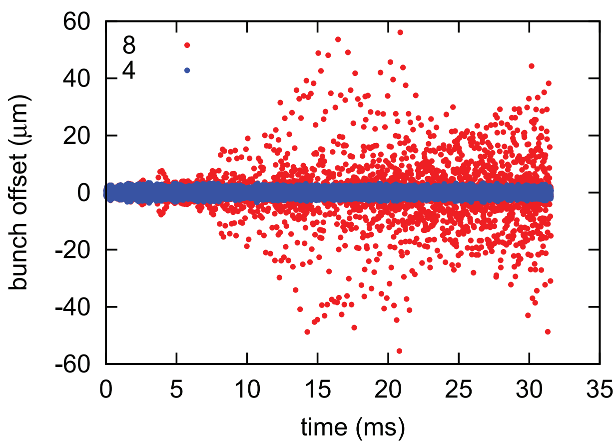


Figure 1: Simulations for 1160 electron bunches using $10^4$ macro-particles per bunch. About 0.5% of the bunches are plotted but the envelope is unaffected. A density of $4\times10^{12}\mathrm{CO/m}^3$ is stable.

We analyzed our simulations by considering

$$\sigma(\bar{y}) \equiv \left(\frac{1}{N_T}\sum_{k=1}^{N_T}\bar{y}_k^2\right)^{1/2}, \tag{3}$$

where $\bar{y}_j$ is the bunch centroid and $N_T$ is the total number of bunch passages past a certain point. For no collective forces one should have $\langle\sigma(\bar{y})\rangle = \sigma_y/\sqrt{N_{sim}}$ where $\sigma_y$ is the rms bunch size, and $N_{sim}$ is the number of simulation macro-particles per bunch. For Figure 1 the fluctuation ratio is $\sigma(\bar{y})\sqrt{N_{sim}}/\sigma_y = 1.0073$. For Figure 2, $\sigma(\bar{y})\sqrt{N_{sim}}/\sigma_y = 1.016$. For both cases there is a slight amplification of the rms vertical fluctuation above what is expected for no coherent forces. This is expected, since collective forces are present and noiselike oscillations are enhanced. On the other hand, the average enhancement is less than 2% over the expected value. We plot the fluctuation ratio bunch by bunch in Figure 3. These averages use bunch data after the beam-beam and gas forces have been ramped

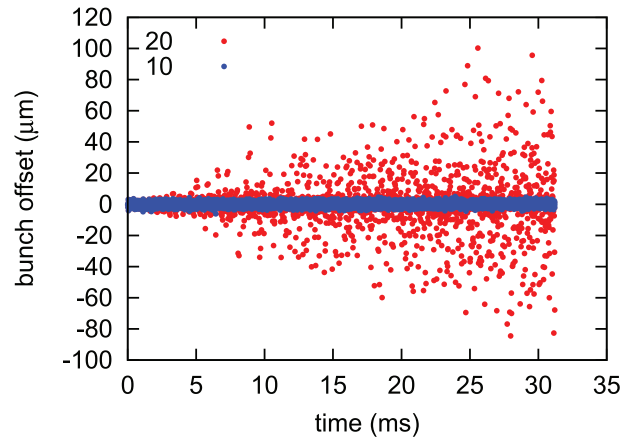


Figure 2: Simulations for 599 electron bunches using $2\times10^4$ macro-particles per bunch. About 0.5% of the bunches are plotted but the envelope is unaffected. A density of $10\times10^{12}\mathrm{CO/m}^3$ is stable.

up. While there is an increase in the value along the bunch train all values are below 1.3.

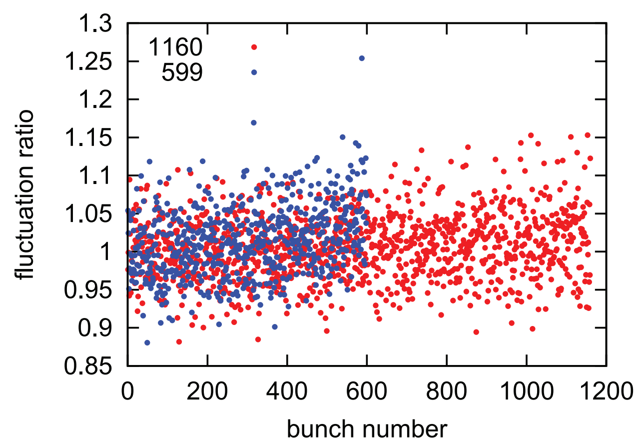


Figure 3: Bunch by bunch values of $\sigma(\bar{y})\sqrt{N_{sim}}/\sigma_y$ for the simulations in Figures 1 and 2.

## ANALYTIC ESTIMATES

Analytic estimates have been done before [1, 7, 14, 15] and this section borrows from that work. First consider ion generation. At a fixed location in the ring the number of ions per meter varies as

$$\frac{d\lambda_I}{dt} = \sigma_c n_I \lambda_e c, \tag{4}$$

where $\lambda_{e,I}$ is the line density of electrons or ions, $n_I$ is the number density of the molecule and $\sigma_c$ is the ionization cross section. We integrate this over the electon bunch train to estimate the ion line density. Assuming the small amplitude motion is stable during the bunch passage these ions will have rms dimensions comparable to the electron beam. After

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the bunch train passes a given point some fraction of the ions survive and they are generally driven to significantly larger amplitudes.

Therefore, as a first approximation, take $\lambda_I = \sigma_c n_I N_e$ where $N_e$ is the total number of electrons in the ring. These ions have rms sizes as the electron beam with $\sigma_x \gg \sigma_y$ (though [13] does not support this). The average electric field (in cgs) of the ions on the electrons is $E_I \approx e\lambda_I(y_e - y_I)/(\sigma_x\sigma_y)$ where the field is reduced by a factor of 2 from the small amplitude result owing to averaging over the two identical Gaussians. Consider the vertical electron offset $y_e(\theta, t)$ where $\theta$ is azimuth in the lab frame and $t$ is lab time. Taking a coasting beam approximation for the electrons and assuming a uniform distribution of ions yields the coupled equations

$$\left(\frac{\partial}{\partial t} + \omega_0 \frac{\partial}{\partial \theta}\right)^2 y_e + \omega_y^2 y_e = \omega_e^2 y_I, \tag{5}$$

$$\left(\frac{\partial^2}{\partial t^2} + \frac{\omega_I}{Q_I}\frac{\partial}{\partial t} + \omega_I^2\right) y_I = \omega_I^2 y_e. \tag{6}$$

In Eq. (6) $\omega_0 = 2\pi/T_{rev}$ with $T_{rev}$ the revolution period, $\omega_y = \omega_0 Q_y$ with $Q_y$ the vertical tune, and $\omega_e^2 = r_e\lambda_I c^2/(\gamma\sigma_x\sigma_y)$ with $r_e$ the classical electron radius. In equation (6) $\omega_I^2 = r_p\lambda_e/(A\sigma_x\sigma_y)$ with $r_p$ the classical proton radius and $A$ the atomic mass of the ion. The quality factor of the ions is $Q_I \approx 3$ which is mainly due to the Gaussian cross section, though variations in $\beta_x$ and $\beta_y$ play a role. Suppose $y_{e,I} = \hat{y}_{e,I}\exp(in\theta - \Omega t)$ with $\Omega \approx \omega_I$. Then for the unstable mode

$$Im(Q_y) = \frac{r_e\lambda_I Q_I c^2}{2\omega_0\omega_y\gamma\sigma_x\sigma_y}. \tag{7}$$

For the blue curves in Figures 1 and 2, Eq. (7) predicts $Im(Q_y) = 0.0051$ and 0.013, respectively. The maximum beam-beam tune shift of the electrons was 0.05. Figure 4 shows the measured tune distribution for the electrons and a parabolic distribution of half width $q_{1/2} = 0.01$, which is 20% of the maximum beam-beam tune shift. For a parabolic distribution of half width $q_{1/2}$ the maximum imaginary tune shift that can be stabilized is $\max(Im(Q)) = 4q_{1/2}/(3\pi)$. This corresponds to $\max(Im(Q)) = 0.0042$. Both stable curves corresponded to imaginary tunes somewhat larger than this.

## CONCLUSIONS

Both simulations and order of magnitude estimates suggest that BII in the BNL EIC should be Landau damped for reasonable gas densities. For the Landau damped systems there is a negligible enhancement (roughly 30%) in average amplitudes over the values without collective forces.

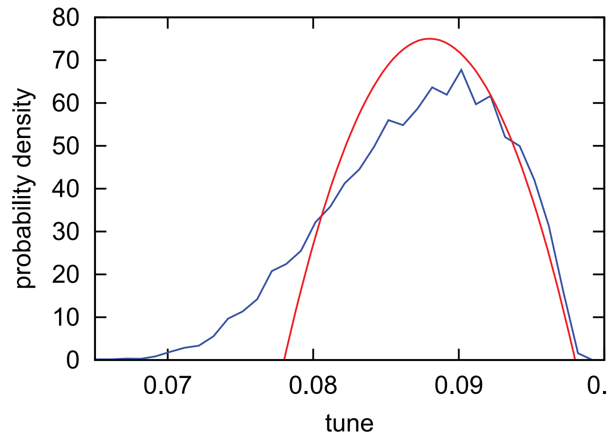


Figure 4: Vertical tune distribution for the particles in Figure 1. The half width of the parabola is $q_{1/2} = 0.01$, which is 20% of the maximum beam-beam tune shift.

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