November 2, 2007

Beam-Ion Instability in PEP-II

S. Heifets, A. Kulikov, Min-Huey Wang, U. Wienands

full text SLAC-PUB-12959

1 Abstract

Study the ion effects in the PEP-II electron ring

2 Basics

Ion production rate

$$S_0 = \frac{d^2 N_i}{dsdt} = \sigma_i^+ n_g N_B \frac{c}{s_b}. \tag{1}$$

Typical $\sigma^+ \simeq 2$ Mbarn. At normal temperature

$$n_g = 3.2\,10^7 \frac{P}{nTorr} \quad \mathrm{cm}^{-3}. \tag{2}$$

Ions are trapped and oscillate with the frequency $\Omega^i_{x,y}$,

$$(\frac{\Omega^{(i)}_{x,y}}{c})^2 = \frac{2N_b r_p}{A\sigma_{x,y}(\sigma_x + \sigma_y)s_b}. \tag{3}$$

Criterion of stability:

$$\frac{\Omega^{(i)}_{x,y} s_b}{2c} < 1, \qquad \text{(uniform train)}$$
$$|\cos(\psi_{x,y} + \alpha_{x,y})| < \cos(\alpha), \quad \text{(with a gap)}$$
$$\psi_{x,y} = \Omega^{(i)}_{x,y} T_0 (1 - \frac{T_g}{T_0}),$$
$$\sin(\alpha_{x,y}) = \frac{\Omega^{(i)}_{x,y} T_g/2}{\sqrt{1 + (\Omega^{(i)}_{x,y} T_0/2)^2}}.$$

The tune shift for last bunch

$$\Delta Q_y = \frac{\pi r_e}{\gamma} (\frac{c}{\omega_y})^2 n_i Q_y. \tag{4}$$

Quasi-static distribution (continuity equation + Poisson equations + energy conservation)

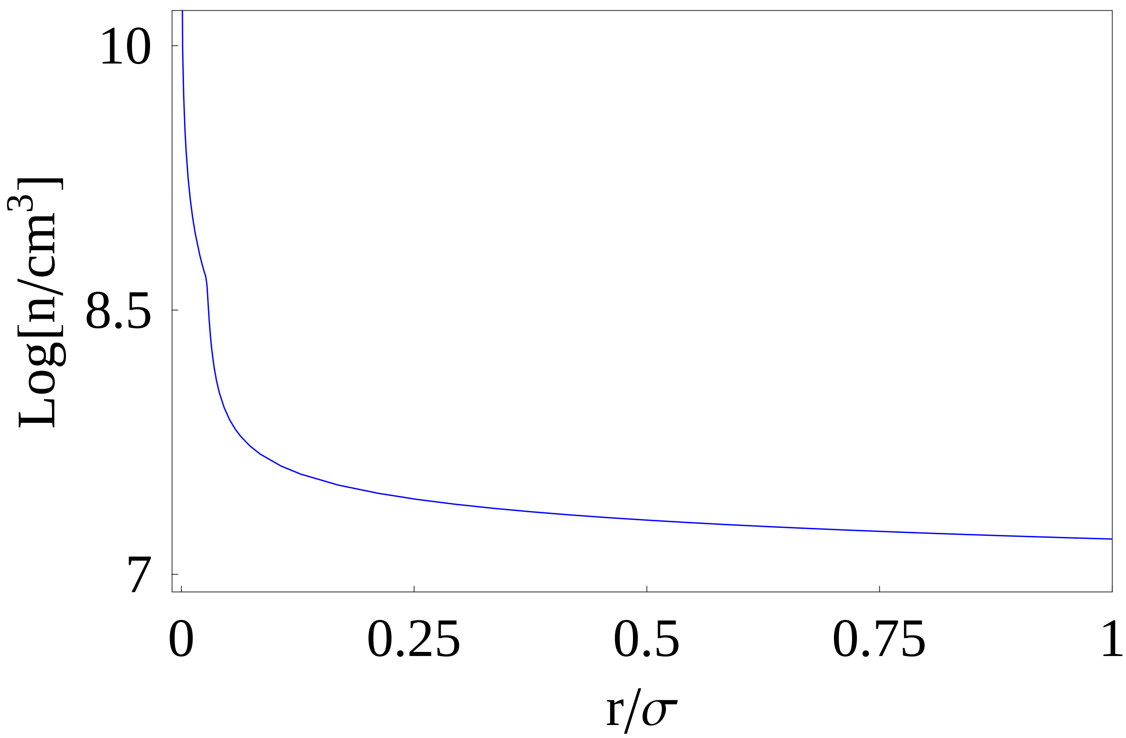

Figure 1: Density profile for round geometry. The density rolls off from $n(0) = 1.3\,10^{10}\ cm^{-3}$ on the beam line given by the condition of neutrality to the average density across the beam pipe $n \simeq 10^7\ cm^-3$

3 Linear theory

The phase modulation $y(s,z) \propto \cos[\omega_\beta s/c - \Omega_i z/c]$, gives the force for ions located at $s = ct - z$

$$F(s,t) \;\propto\; y(s,z)_{z->ct-s} = \;\cos[\Omega_i t - (\Omega + \omega_\beta)s/c],$$

in resonance with ion oscillations.

In turns, for the beam

$$F(s,z) \;\propto\; Y(s,t)_{t->(s+z)/c} \;=\; \cos(\omega_\beta s/c - \Omega_i z/c),$$

in resonance with β-oscillations.

Use:

$$\tau = \frac{\omega_y s}{c}, \quad \zeta = \frac{\Omega_y^{(i)} z}{c},$$

Beam-Ion Instability:

Zenkevich-Koshkarev: uniform fill, no gap: $a \propto e^{\Gamma_n t}$,

$$\Gamma_n = \frac{2\pi^2 r_e c^2}{\gamma} n_i \frac{n\omega_0 - \omega_y}{\omega_y} \rho(|n\omega_0 - \omega_y|)$$
$$\omega_\beta < n\omega_0 < \Omega_i + \omega_\beta, \quad \mathrm{max\,growth}\, n\omega_0 \simeq \Omega_i.$$

Raubenheimer-Zimmermann: large clearing gap, non-resonance growth

$$a \propto e^{\sqrt{\tau/\tau_0}}, \quad \frac{1}{\tau_0} = \Lambda_0 \zeta^2,$$
$$\Lambda_0 = \frac{2r_e}{\gamma\,\Omega_{i,y}} \langle \frac{S_0}{\sigma_y(\sigma_x + \sigma_y)} \rangle \left(\frac{c}{\omega_y}\right)^2.$$

Stupakov: (R-Z) + Ω-variation along the ring

$$a \propto e^{\tau/\tau_S}, \quad \frac{1}{\tau_S} = \frac{\Lambda_0 \zeta^2}{\epsilon\zeta}, \quad \epsilon = \frac{\Delta\Omega}{\Omega}, \qquad (5)$$

the same as Z-K, if $\frac{S_0 z}{2\pi\sigma_x\sigma_y} \to n_i$.

Pestrikov: (R-Z) + ω_β-variation along the train

The growth is limited by $\frac{\Lambda_0 \tau}{8} < 1$.

4 PEP-II parameters

Typical parameters HER:

$E = 9.1$ GeV, $N_b = 4.5\,10^{10}$, $I_b = 1.75$ A,

$T_0 = 7.3\mu s$, $h/2 = 1746$, $s_b = 4.2$ ns,

$\sigma_{x,y} = 800/150\,\mu m$,

$P = 2$ nTorr.

Then,

$S_0 = 1.4\,10^9\ 1/(cm\,s)$, $\Omega_{i,y} = 50$ MHz for $A = 28$,

$\Omega_{i,x} s_b/2c = 0.04$, $\Omega_{i,y} s_b/2c = 0.10$ (one-turn stable).

One turn ions: $n_i^{turn} = 1.3\,10^6\ cm^{-3}$ gives

tune shift $\Delta Q_y = 0.0030$.

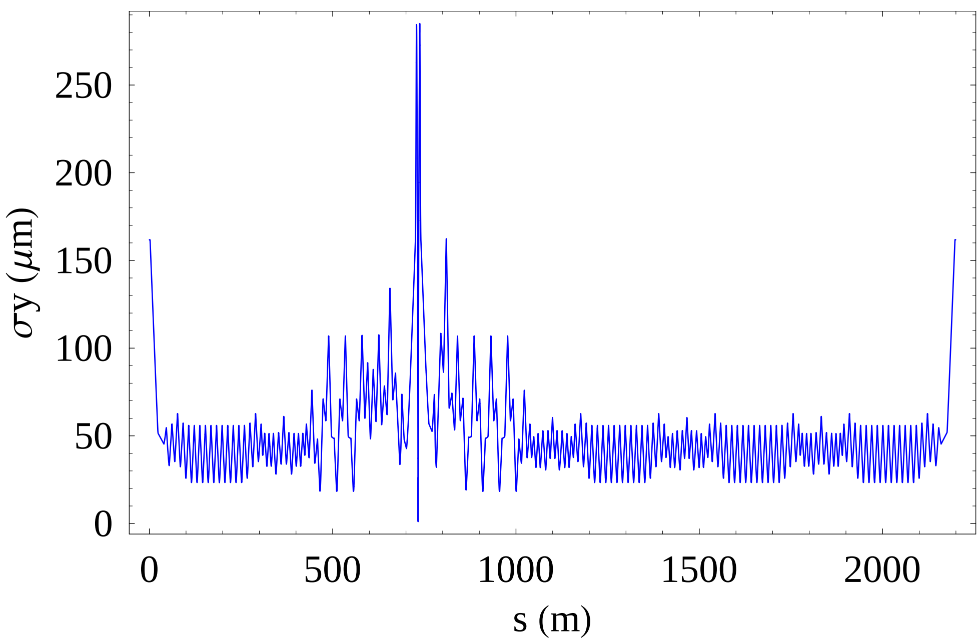

Figure 2: Variation of the rms σ_y in HER PEP-II (90^o phase advance optics).

$$\Delta\Omega/\Omega = 0.141, (90^{\circ}\,\mathrm{lattice}),$$
$$\Delta\Omega/\Omega = 0.109, (60^{\circ}\,\mathrm{lattice}).$$

Stupakov's theory gives $\tau_S = 192\,\mu s$, or less than 20 turns.

Pestrikov's theory can be ignored for first 350 ms.

Much earlier the linear theory is not applicable.

Nonlinear theory:

$a \propto (\tau - \tau_0)^{1/3}$ when the beam amplitude a reaches few rms σ_y.

Example of such behavior is shown in Fig. (3).

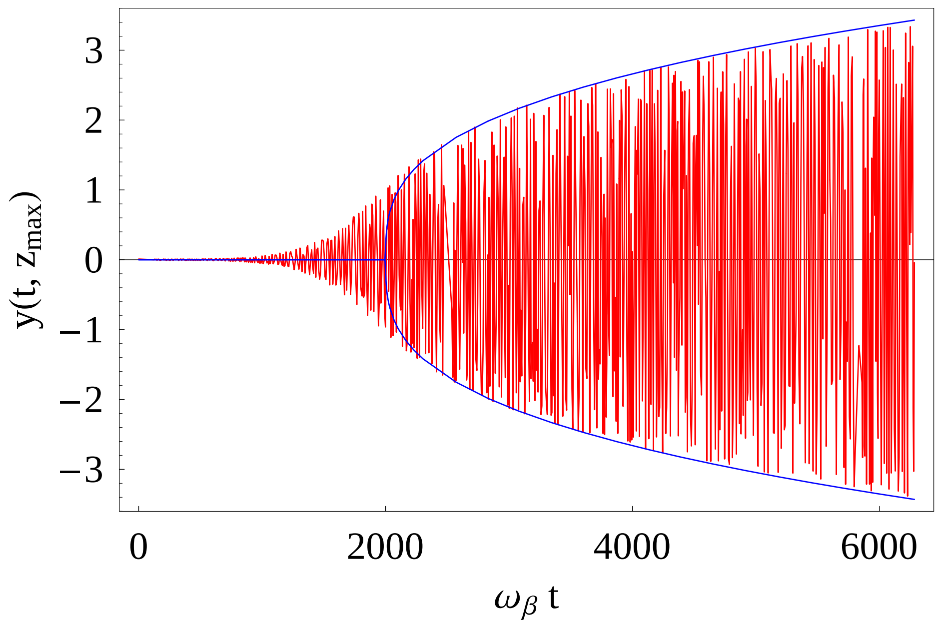

Figure 3: Nonlinear growth of instability. The power law $a \propto (\tau - \tau_0)^{1/3}$ at large $\tau > \tau_0$ replaces the initial exponential growth of the amplitude for a bunch at the tail of the train. Numerical results (red line) agrees with analytic estimate for the envelope of oscillations (blue line).

5 Effect on rms:

The optical model predicts transverse rms factor 2-3 smaller than measured $4 - 5\,\mu m$.

$s(m)$	σ_x (μ m, MAD)	σ_y (μ m, MAD)
733.10	128.93	1.103

Can it be result of ions?

The TFB has limit $\tau_{FB} \simeq 0.1$ ms.

Model:

$$\frac{da(\tau)}{d\tau} = \frac{\Gamma\, a(\tau)}{1 + \alpha\, (a(\tau)/\sigma_y)^3} - \Gamma_{FB}\, a(\tau), \tag{6}$$

Linear growth $a(\tau) = a(0)e^{\Gamma\tau}$. With TFB off, $a(\tau) \simeq \tau^{1/3}$ for $\alpha \simeq 0.1$.

For large $\Gamma_{FB} > \Gamma$, the asymptotic $a_\infty = 0$.

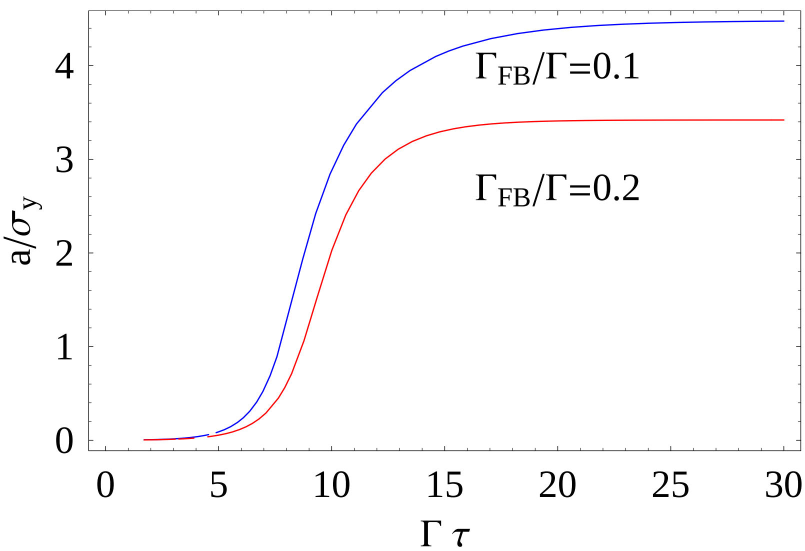

Figure 4: Saturation of the instability with the TFB turned on. $a(0) = 10^{-3}$, $\Gamma_{FB}/\Gamma = 0.1$ and 0.2.

Another model: $a_\infty - > const$,
$a(t) = a_0 + (a_\infty - a_0)\ \tanh(\frac{t}{\tau_0})$ provided $g = 0$:

$$\frac{da(t)}{dt} = \frac{a_\infty - a_0}{\tau_0}\,[1 - (\frac{a(t) - a_0}{a_\infty - a_0})^2] - g_{FB}\,a(t). \tag{7}$$

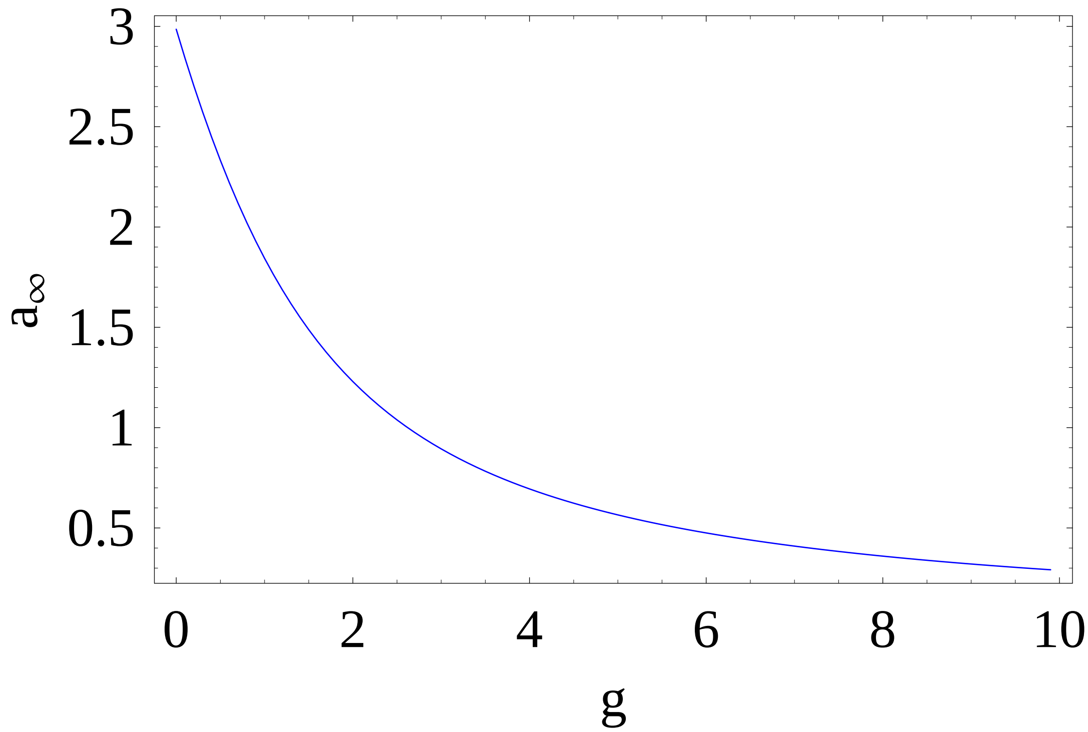

Figure 5: Asymptotic value of $a(t)$ for the second model vs. the TFB damping parameter g_{FB}. Parameters: $a_0 = 0.1$, $\tau_0 = 1.0$.

Cross-talk beam-ion/beam-beam

The beam-beam tune spread $\Delta\omega_\beta$ is equivalent to increasing TFB damping effectively replacing Γ_{FB} by $\Gamma_{FB} + \Delta\omega_\beta$.

For reasonable $1/\Gamma \simeq 200\,\mu s$, $1/\Gamma_{FB} = 500\,\mu s$, the beam can be stabilized by quite low beam-beam tune spread $\xi_{BB} = 0.005$.

6 Gap instability

Motivation: reduce rf transients reducing the ion gap. The transients were, indeed, reduced.

However (U. Wienand), the beam became unstable when the gap was less than 15 bunches.

The gap instability had character of the transient phenomena starting from the head of the train and spreading toward the tail.

The beam oscillates with large amplitude but the beam is not lost for hours.

The coherent oscillations have frequency consistent with the ion Ω_i.

The oscillations affect the luminosity. Some of the experimental results are shown in Figure

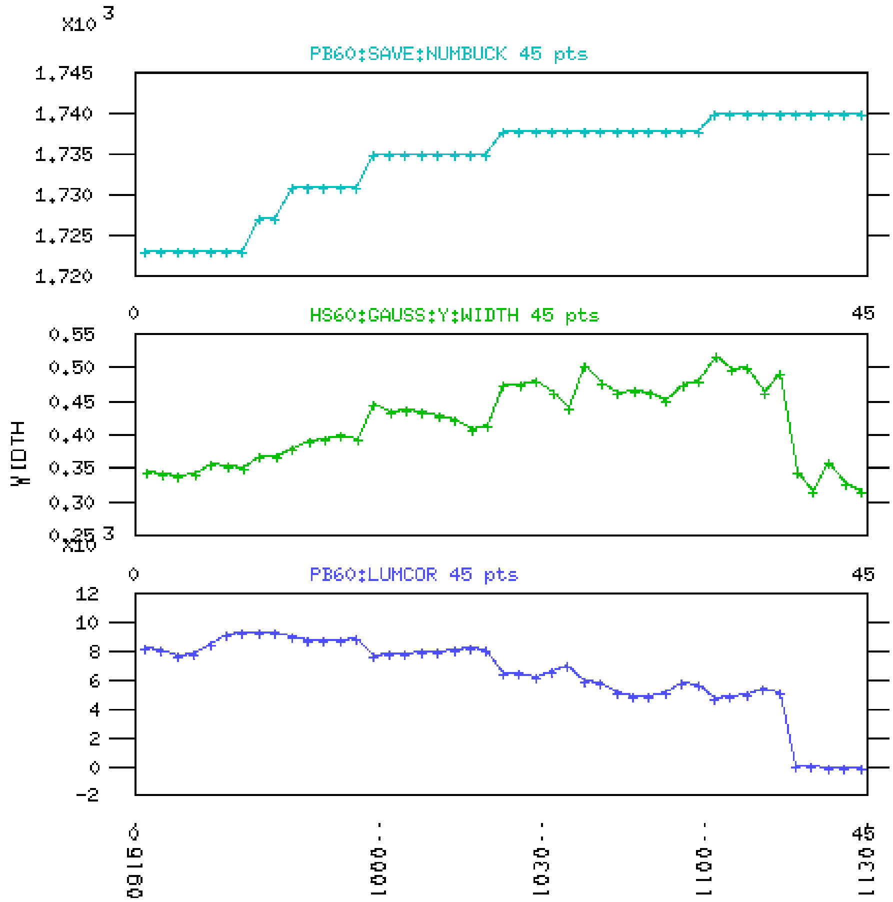

Figure 6: Gap instability. Variation of the number of bunches (top pane), the vertical rms σ_y of the electron beam, and the luminosity (bottom pane) with time. The total time span about 3 hours.

Possible explanation: ions trigger the instability. Ions are stable if $T_g/T_0 < 0.002$ and $0.012 < T_g/T_0 < 0.014$, which is in a reasonable agreement with experiment.

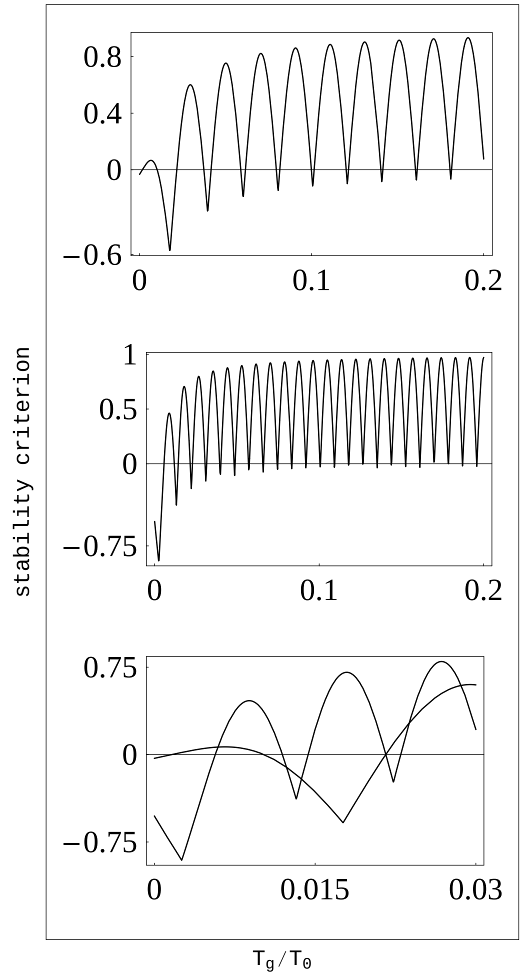

Figure 7: Multi-turn criterion of stability in x-plane (top) and y-plane (middle). The bottom pane shows zooming for both planes. Positive values correspond to unstable ions. For large gaps, almost all ions are unstable. For the gaps $T_g/T_0 < 0.002$ and $0.012 < T_g/T_0 < 0.0143$, ions are stable in both planes. Note that stability first starts in x-plane.

Condition of neutrality: $dN_i/ds = N_b/s_b$, $n_i = 4.7\,10^{10}$ cm^{-3} for PEP-II parameters.

Even if the actual density is only on the level of few percent of that, the tune shift is huge.

The growth rate $\propto n_i$, and beam-beam is insufficient to stabilize the beam with reduced gap.

The time it takes to build up such density, $t = (dN_i/ds)/S_0$. For PEP-II, $t = 0.26$ s, quite a macroscopic time for observations.

For large tune shifts, it is possible to hit a coupling resonance. Such a resonance does not kill the beam but can induce oscillations observed in experiment.

Ions change the beam optics, including D_x^* at IP and may lead to $s - \beta$ resonances and the flip-flop beam-beam behavior.

The beam spectrum also depends on the gap. In Z-K theory the strongest harmonics is $n\omega_0 = \mp\Omega_0 + \omega_y$. For uniformly distributed bunches harmonics separated by $\Delta\omega = 2\pi/\tau_b$, $\simeq 238$ MHz. For the train with a gap T_g, each of these harmonics is surrounded by the revolution harmonics with the number of modes $\delta n\omega_0 \simeq \pi/T_g$. One of the revolution harmonics can hit the resonance causing the beam instability.

However, in reality, some level of revolution harmonics is always present due to uneven fill of rf buckets or the residual coherent longitudinal motion of bunches, and such an explanation seems to be unlikely.

If the gap was reduced also in LER, the e-cloud instability was affected as well. This may explain the difference of stability of a single and colliding beams.

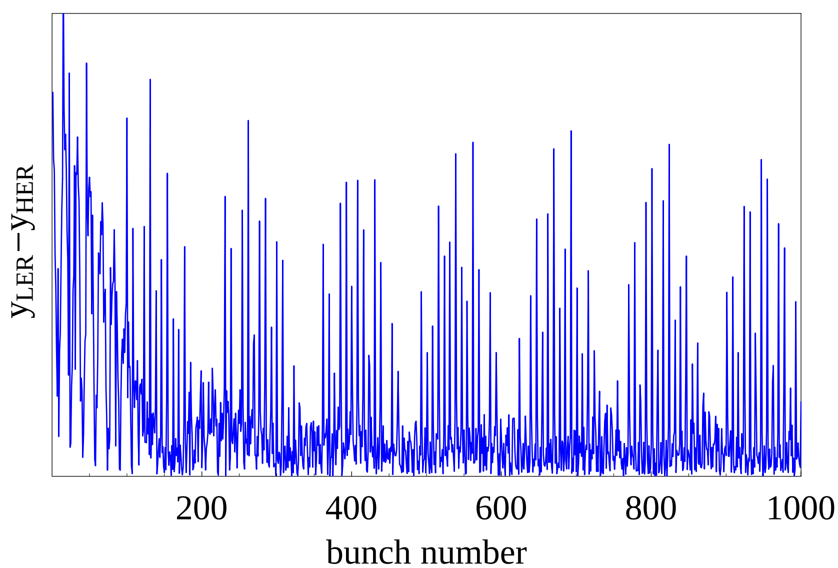

Figure 8: Relative offset of colliding beams modulated with the ion- and electron-frequencies. Result may be relevant for understanding the pattern of instability along the train.

Available results should be considered as preliminary and more studies are needed.

7 Summary

Existing linear theory of beam-ion interaction should be extended to nonlinear regime.

The saturation level may depends on the TFB and affect luminosity and rms beam size.

The gap instability is the result of transition from the regime of the FII to the resonance Koshkarev-Zenkevich regime.

Questions:

why a single beam is stable?

why the tune seems to be locked on 1/2?

what is the mechanism of the cross-talk between beam-beam and beam-ion instabilities?

is there cross-talk between e-cloud/ion-instabilities dependencies on gap length?