Afternoon Discussions

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Experimental Observations of the Fast Beam-Ion Instability at the Advanced Light Source

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Abstract

We present results of experimental observation of the fast beam-ion instability (FII). Results suggest that we observe the instability with ~80 ntorr of HE added to the vacuum.
**Advanced Light Source (ALS)**

"3rd Generation Light Source"

A 1.5 GeV electron storage ring optimized for producing high brightness synchrotron radiation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Energy</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>Frf</td>
<td>500 MHz</td>
</tr>
<tr>
<td>l_{bunch}</td>
<td>1-2 mA</td>
</tr>
<tr>
<td>h</td>
<td>328</td>
</tr>
<tr>
<td>$\varepsilon_{x,y}$</td>
<td>4.1,0.12 nm-rad</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.5e-3</td>
</tr>
<tr>
<td>Circumference</td>
<td>196.8 m</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>7e-4</td>
</tr>
<tr>
<td>$\sigma_l$</td>
<td>5 mm</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>0.0075</td>
</tr>
<tr>
<td>$&lt;\sigma_{x,y}&gt;$</td>
<td>160,30 $\mu$m</td>
</tr>
</tbody>
</table>

ALS is currently operating for users at design current. 5 ID's installed and 12 operational beamlines.

Under normal multibunch conditions, FB systems are used to control longitudinal and transverse coupled bunch instabilities driven by cavity HOMs and resistive wall impedance.

**Experimental Procedure**

- Setup conditions where the FBII is expected with growth rates at least an order of magnitude above growth rates from cavity HOMs and resistive wall impedance and ion trapping of helium not expected. Add helium gas to vacuum to get large growth rates but minimize effects of Coulomb scattering. Helium also poorly pumped by passive titanium sublimation pumps.
- Turn off all active pumping except for pumps on either side of RF cavities; add helium to storage ring on either side of RF cavities and let it equilibrate in ring. Raise pressure to ~80 nTorr He.
- Record transverse beam profile and beam spectrum for a variety of fill patterns at nominal and elevated storage ring vacuum pressure.
- Longitudinal, horizontal, and vertical coupled bunch FB systems are on for all measurements. Vertical damping rate ~$(400 \, \mu\text{sec})^{-1}/\text{mA}$.

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ALS TRANSVERSE FEEDBACK SYSTEM

System Features:
• 100 kHz->250 (220) MHz BW
• high gain/low noise receivers (3 GHz heterodyne detection), current dependent gain
• 2 PUs w/quadrature processing, $\beta_{x1,2,k}=12$ m, $\beta_{y1,2,k}=6$ m, $\Delta \theta_{x1,2}/2\pi=0.18$, $\Delta \theta_{y1,2}/2\pi=0.68$, $\Delta \theta_{x2,k}/2\pi=0.95$, $\Delta \theta_{x2,k}/2\pi=0.92$, +/- variable attenuators (mixers in PIN diode mode)
• 150 W amplifiers driving stripline kickers (single plate only), maximum kick of $-1$ kV
• 2 tap analog notch filter for removing DC orbit offsets

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Introduction to the "Fast beam-ion instability"

"classic" ion trapping occurs when the motion of ions is stable in the beam's potential well over many beam passages. The ion motion becomes unstable for large enough gap in the filling pattern (i.e. clearing gap). This is the typical "passive" solution for curing ion problems.

For high currents and low emittances, transient interactions between the beam and ions can cause significant beam oscillations. Predicted to be important for flavor factories (PEP-II, KEKB, DAFNE), NLC linac and damping rings, 3rd generation light sources. Similar effect predicted for positively charged bunch and atomic electrons.
Experimental Results

Nominal Pressure

- longitudinal, horizontal, and vertical CB FB systems operational
- nominal vacuum pressure ~0.25 ntorr.
- 320/328 bunches filled (normal filling pattern for users)
- sideband signals disappear for 240/328 and 164/328 fill patterns.
- ~2-3% vertical beam size increase. Probably due to ion trapping of CO/N2.

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Initial Measurements (cont.)

- near the betatron coupling resonance \((\sigma_{y}=2\sigma_{y0})\), the frequency reduces as expected.

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Elevated Pressure Results

Vertical beam blowup
- dedicated diagnostic photon beam line measures average transverse beam cross section.
- $\beta_x=0.35$ m, $\beta_y=22$ m, $\eta_x=0.01$ m

Each image is ~80 mA total beam current in 160 consecutive bunches (out of 328 possible). The left is at nominal pressure and the right is with 80 ntorr He.

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Synchrotron Light Images (cont.)

- We see between a factor 2-3 increase in average vertical beam size. Horizontal size is unaffected. Single bunch images show no increase with higher gas pressure.
- Simulations show a similar saturation effect.
- Variation of vertical FB gain has no effect on beam size or sidebands.

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Observation of Instability Threshold

- at a given pressure, we can vary the instability growth rate by varying the length of the bunch train (using a fixed current/bunch)
- for the experimental conditions, the theory predicts a growth rate of ~1/msec at about 8 bunches. Our FB damping rate for 0.5 mA/bunch is ~1.2 msec.

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Sideband Frequency versus Current per Bunch
July ALS Data

Peak Sideband Revolution Harmonic

- 240 Bunches - nominal tunes
- 240 Bunches - coupled
- 160 Bunches - coupled?
- Theory
Vertical beam spectrum

- record the amplitudes of all vert betatron sidebands over 250 MHz range
- plot the linear difference of lower-upper sideband amplitude
- peak frequency of sideband pattern agrees with calculated coherent ion frequency
- coherent oscillations not always observed (decoherence?)

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Variation along bunch train

To measure the variation in vertical oscillation amplitude and/or vertical beam size along the bunch train, we measured the bunch intensity as the vertical aperture was reduced using a beam scraper.

The tail of the train is scraped more than the head, indicating that the tail is oscillating at larger amplitudes, as predicted by the theory. When the expt. is repeated at nominal pressure, the beam is scraped uniformly.

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Summary and Conclusions

• FBII probably not observed at nominal pressure.
• Vertical blowup observed when 80 ntorr helium is added in a regime where trapping not expected. Growth from gas scattering does not explain effect.
• Instability threshold at fixed pressure close to expected value.
• Frequency of coherent oscillations agrees with ion frequencies.
• Coherent oscillations increase along bunch train, demonstrating the transient nature of the effect.
• Growth saturates at 2-3*σv.
• Probably FBI but more studies necessary to extrapolate results to different regimes.

Future Plans

• next run planned for June 1997.
• vary gas pressure measure instability threshold.
• study effect of noise in TFB system
• measure tune and amplitude along bunch train.
• test potential damping mechanisms (i.e. fill with series of short trains)

Thanks to Alan Jackson and the ALS operations group

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References


240 Bunch Simulation in ALS

Revolution Harmonic
Initial Measurements

Beam conditions:
- longitudinal, horizontal, and vertical CB FB systems operational
- nominal vacuum pressure ~1 ntorr.
- 320/328 bunches filled (normal filling pattern for users)
- sideband signals disappear for 240/328 and 164/328 fill patterns.
Bunch Centroid vs. Gap Size in NLC DR

- No Gap
- 2 Bucket Gap
- 4 Bucket Gap
- 6 Bucket Gap

Ion Wavelength = 6 Buckets
Ion Density versus Time

(ALS) 240 bunches full

10 turns

84 empty
Single Pass Beam-Ion Inst.

Normally ion trapping prevented using a gap $L > \omega_i^{-1}$

Modern rings have very small $\omega_i$'s, high currents and long trains
$\Rightarrow$ single pass effect in rings and in linacs/transport lines

Electron train

Positron beam
Incoherent Ion Frequency in ALS Cell

![Graph showing incoherent ion frequency in ALS Cell with frequency on the y-axis and distance (S) on the x-axis. The graph includes peaks labeled 'Vertical' and 'Horizontal'.]
240 Bunch Simulation in ALS

Revolution Harmonic

0.00000000
0.00000001
0.00000002
0.00000030

200 mA
Theory

- conventional ion trapping - cleared by gap
- small emittances / many bunches → fast instability can build up along single train!
- ions are produced at typical rate

\[ 1.8 \times 10^9 \rho \text{[m}^{-1}] p_{\text{gas}} \text{[Torr]} \]

per meter and per second, where \( \rho \) is the longitudinal beam density
- they are trapped within the train if

\[ \pi f_{i,y} L_{\text{sep}} < c \]
- and then oscillate at a frequency

\[ f_{i,y} = \frac{c}{2\pi} \left( \frac{4N_br_p}{3L_{\text{sep}}\sigma_y(\sigma_x + \sigma_y)A} \right)^{\frac{1}{2}} \]
- linear treatment of beam-ion system predicts

\[ y_b(t) \approx \tilde{y} \frac{1}{\sqrt{8\pi t/\tau_c}} \exp \sqrt{t/\tau_c} \]

with characteristic time

\[ \tau_c^{-1}[s^{-1}] = \left[ \frac{0.6p[\text{Torr}] N_b^2 n_b^2 r_c r_p^2 L_{\text{sep}}^2}{\gamma \sigma_y^2 (\sigma_x + \sigma_y)^3 A^{\frac{1}{2}} \omega_b} \right] \]

- spread of ion frequency across bunch and variation along ring alleviate the effect somewhat, but give rise to exponential growth with e-folding time

\[ \tau_e \approx 2\tau_c \frac{aC^22\pi f_{i,y}}{c} \]

where \( a \approx 0.03-0.3 \) is the relative amplitude of a (harmonic) variation of the ion frequency along the ring
Simple linear theory:

\[ y_b(z) + \omega^2 y_b(z) = K_i \left[ y_i(z) - y_b(z) \right] \int_{-\infty}^{z} f(x) dx \]

\[ K_i = \frac{2 \sigma bion \rho_0}{\tau \Sigma x \Sigma y (\Sigma x + \Sigma y)} \]

\[ \Sigma^2 = \sigma^2_{bxy} + \sigma^2_{bxy} \]

\[ \Sigma^2 = \frac{3}{2} \sigma^2_{bxy} \]

\[ \omega_{inc} = \left[ \frac{2N \rho_0}{L_{sep} \sigma_y (\sigma_x + \sigma_y) A} \right]^{1/2} \]

\[ \omega_i \approx \sqrt{\frac{2}{3}} \omega_{inc} \]

\[ y_b(z) = \frac{\hat{y}}{2} \left[ J_0 (2\sqrt{\eta(z)}) \sin \left( \omega_i z + \omega_{ps} s + \phi \right) \right. \\
+ J_0 (2i\sqrt{\eta(z)}) \sin \left( \omega_i z - \omega_{ps} s - \phi \right) \] \]

\[ \eta(z) = \left[ \frac{K_{iw} \Sigma^2 s}{\omega_\beta 16 \Sigma^2} \right] \]

\[ \eta(z) = \text{trans length} \]

\[ \Rightarrow y_b(z) \sim \frac{\hat{y}}{M(z) \eta} e^{2\sqrt{\eta}} \sin \left( \omega_i z - \omega_{ps} s - \phi \right) \]

Large amplitude will define nonlinearity causes decoherence \( \Rightarrow \) slow growth

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Introduction

- classical beam-ion instability: ions are trapped over many turns; cured by clearing gap

- high current & small gradient stability within a very short of the last beam pipe inner radius

- for HER at 5 nTorr:
  ~ 400,000 ions / meter at end of train

- ion density ~ bunch number
ct = s + z  (time)

Electron Bunch train

Positron Bunch

Atomic Electrons
Theory

1. Linear treatment (Raubenheimer & Zimmermann)

Small centroid oscillations  
constant beam sizes $\xi_x, \xi_y$  
ions not overfocused  
uniform bunch population  

$$\gamma(t) = \gamma_0 \frac{1}{\sqrt{4\pi \tau_c}} e^{-\frac{t}{2\tau_c}} \quad (t \gg \tau_c)$$

where $\gamma_0$ is initial amplitude and

$$\frac{1}{\tau_c} = 5 \rho \text{[Torr]} N_b^{3/2} n_b^2 \tau_e \tau_p V_b \frac{L_{\text{sep}}}{c} \frac{\gamma^{1/2}}{\gamma - 3/2 (\xi_x + \xi_y)^{3/2} \omega_p} \frac{\sigma_{\text{ioniz}}}{2 \text{mbarn}}$$

with $N_b$ : number of particles / bunch  
$n_b$ : number of bunches  
$L_{\text{sep}}$ : bunch spacing  
$\sigma_{\text{ioniz}}$ : ionization cross section
2. include ion decoherence (Stupakov)

\[ \omega_i(x,s) \propto x \cdot s \cdot \text{dependence} \]
\[ s \cdot \text{dependent coupling} \quad \text{ions} \rightarrow \text{beam} \]
nonlinearity of force

\[ \gamma \sim \gamma_0 e^{t/\tau_e} \quad (y \lesssim \gamma_0) \]

purely exponential growth with
time constant \( \tau_e \)

3. Large-amplitude regime (Heifets)

\[ \gamma \sim \frac{t}{\tau_H} \cdot \gamma_0 \]

linear growth

We have

\[ \tau_c \ll \tau_e \ll \tau_H \]
## Parameters and Growth Rates for HER & ALS

<table>
<thead>
<tr>
<th>Storage Ring</th>
<th>PEP-II HER</th>
<th>ALS nominal</th>
<th>ALS experiment</th>
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</thead>
<tbody>
<tr>
<td>Beam energy $E$ (GeV)</td>
<td>9</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Ring circumference $C$ (m)</td>
<td>2200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Beam current $I$ (A)</td>
<td>1</td>
<td>$\geq 0.3$</td>
<td>0.15–0.3</td>
</tr>
<tr>
<td>Number of bunches $n_b$</td>
<td>1658</td>
<td>320</td>
<td>160, 240, 320</td>
</tr>
<tr>
<td>Av. hor. beam size $&lt;\sigma_x&gt;$ (mm)</td>
<td>1.25</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Av. vert. beam size $&lt;\sigma_y&gt;$ (mm)</td>
<td>0.2</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>Residual gas</td>
<td>CO, N$_2$</td>
<td>CO, N$_2$</td>
<td>He</td>
</tr>
<tr>
<td>Av. pressure (nTorr)</td>
<td>5</td>
<td>0.3</td>
<td>50</td>
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<tr>
<td>Ion density (m$^{-1}$)</td>
<td>$1.5\times 10^6$</td>
<td>2400</td>
<td>$2–4\times 10^4$</td>
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<tr>
<td>Ion frequency $f_{ion}$ (MHz)</td>
<td>3.5</td>
<td>15</td>
<td>32–80</td>
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<tr>
<td>Minimum gap clearing (buckets)</td>
<td>19</td>
<td>9</td>
<td>3–4</td>
</tr>
<tr>
<td>Actual gap (no. of buckets)</td>
<td>88</td>
<td>8</td>
<td>168–88</td>
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<tr>
<td>Tune shift along train $\Delta Q$</td>
<td>$6\times 10^{-3}$</td>
<td>$7\times 10^{-5}$</td>
<td>$0.6–1.2\times 10^{-3}$</td>
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<tr>
<td>Characteristic time $\tau_c$ ($\mu s$)</td>
<td>2</td>
<td>40</td>
<td>1–4</td>
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<tr>
<td>e-folding time $\tau_e$ ($\mu s$)</td>
<td>60</td>
<td>150–1500</td>
<td>12–350</td>
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<tr>
<td>Linear growth time $\tau_H$ (ms)</td>
<td>12</td>
<td>42</td>
<td>1–4</td>
</tr>
</tbody>
</table>
- macroparticle simulation (Raubenheimer)
- 20,000 macroparticles / bunch in 5 slices
- grid between +/- 5 sigma (25x25)
- integration over 1/4 FODO cell
- field of beam: Bassetti-Erskine formula
- field of ions: 2-dim. Coulomb law
- self-consistent evolution: instability grows from noise
ALS, 150 bunches, $10^{-6}$ Torr

$\Rightarrow \tau_c \approx 20$ ns (10 ns predicted)

instability saturates at $y = \tau_y$

$J_y(\varepsilon_y)$

$S$ [meter] every 10th bunch shown
Normalized Actions vs. S in NLC DR

Pressure = $10^{-6}$ Torr
Atomic Number = 28
Bunch number 90

- No Gap
- 2 Bucket Gap
- 4 Bucket Gap
- 6 Bucket Gap

Gaps after the 30th and 60th bunches

Ion Wavelength = 6 Buckets

Effect of gaps in bunch train (NLC DR)