FII and Ion Trapping Experiments
at Tristan AR

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KEK

Sept. 17, 1997
FII and Ion Trapping Experiments at Tristan AR

1. Fast Ion Instability
2. Ion Trapping Effect
3. Dust Trapping
High Beam Current Experiments for the KEKB Conducted at the TRISTAN Accumulation Ring

Y. Funakoshi

for the AR high beam current study group

High Energy Accelerator Research Organization (KEK)
1994 Dec. Preliminary study
1995 Mar. preliminary study
1996 Mar. 1st experiment

Jul. 1-22 2nd experiment
Oct. 17- Dec. 2 3rd experiment

Dedicated machine time of about 10 weeks was devoted to the experiment.

3rd experiment

ARES: operated for 4 weeks
store 500 mA
various tests done

SCC: operated for 2 weeks
stored 500 mA
various tests done

Feedback: performance was tested with multibunch mode
<table>
<thead>
<tr>
<th>Study or operation item</th>
<th># of shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARES96</td>
<td>16.5</td>
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<tr>
<td>ARES95</td>
<td>4</td>
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<tr>
<td>SCC</td>
<td>20</td>
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<tr>
<td>Feedback</td>
<td>9.5</td>
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<tr>
<td>Fast ion instability</td>
<td>7.5</td>
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<tr>
<td>Multibunch instability</td>
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<td>SCC warmup</td>
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<td>ARES95 aging</td>
<td>16.5</td>
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<tr>
<td>Machine tuning</td>
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<tr>
<td>Trouble</td>
<td>13.5</td>
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<td>Gas desorption from vacuum chamber</td>
<td>19.5</td>
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<tr>
<td>Linac study and maintenance</td>
<td>26</td>
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</table>

Table 3: The operation statistics in the third experiment
What is the AR?

- The TRISTAN Accumulation Ring (AR) was designed and operated as the injector of the TRISTAN Main Ring.
- When the TRISTAN project was terminated in 1995, the main role of the AR was switched to a SOR machine.

- **Operation energy**
  - Injector of the TRISTAN: 8 GeV
  - SOR: 6.5 GeV
  - This experiment: 2.5 GeV

- Circumference: 377 m

- Number of Klystrons: 2 (East and west sections)
Site Layout of Accelerators

AR (Accumulation Ring) has been used as
(1) an injector of the TRISTAN Main Ring,
and also used as
(2) the SOR (Sodium-Orbit Radiation) facility.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>Particles</td>
<td>electrons</td>
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<tr>
<td>Circumference $C$</td>
<td>377 m</td>
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<td>RF frequency $f_{RF}$</td>
<td>508.58 MHz</td>
</tr>
<tr>
<td>Harmonic number $h$</td>
<td>640</td>
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<tr>
<td>Beam energy $E_b$</td>
<td>2.5 GeV</td>
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<td>Beam current $I_b$</td>
<td>573 mA (max)</td>
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<td>Tune $\nu_x/\nu_y$</td>
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<td>Momentum compaction $\alpha$</td>
<td>0.0129</td>
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<td>Natural chromaticity $\xi_{x0}/\xi_{y0}$</td>
<td>-14.5/-13.7</td>
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<tr>
<td>Chromaticity corrected $\xi_x/\xi_y$</td>
<td>$\sim$7/7</td>
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<td>Radiation loss/turn $U_0$</td>
<td>0.1458 MeV</td>
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<td>RF voltage $V_e$</td>
<td>0.6–2.5 MV</td>
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<tr>
<td>Synchrotron tune $\nu_s$</td>
<td>0.018–0.036</td>
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<td>Natural bunch length $\sigma_l$</td>
<td>2.0–0.94 cm</td>
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<td>Energy spread $\Delta E/E$</td>
<td>$4.40 \times 10^{-4}$</td>
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<tr>
<td>Damping time $\tau_e/\tau_\beta$</td>
<td>21.6/43.1 msec</td>
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<tr>
<td>Natural emittance $\varepsilon_{x0}$</td>
<td>43.6 nm</td>
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Table 2: Main machine parameters of the AR
Experiments on the fast beam-ion instabilities at the TRISTAN AR

Experiment group:

Presented by Y. Funakoshi

1. Introduction
2. Theory
3. Experimental setup
4. Experimental Procedure and results
5. Summary
1. Introduction

In high current and low emittance rings, new type of beam-ion instability named "fast beam-ion instability (FBII)" is proposed (T.O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5487(1995) and G.V. Stupakov, T.O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5499(1995)).

The FBII occurs in the single passage of the bunch train. The ions created by the head of the bunch train affect to the tail.

In KEKB the e-folding time of the amplitude growth is about 70 turns for the number of bunches of 500 and a pressure of 10^-9 Torr.

On experiments, John Byrd et al. reported the experiments at the ALS where the results suggest that they observe the FBII with 10nTorr of He added to the vacuum (J. Byrd et al., SLAC-PUB-7389(1996)).
2. Linear theory

In the linear theory by K. Yokoya, the unstable mode of the oscillation is given by

\[ y_n = a_n e^{i(\Theta_n - k s)}, \quad \Theta = \sqrt{\frac{2 \frac{z N m r_e L}{A M_N \Sigma_y (\Sigma_x + \Sigma_y)}}{A M_N \Sigma_y (\Sigma_x + \Sigma_y)}} \]

\( n \) : bunch id

Amplitude growth factor \( G \) is given by

\[ G = \left| \frac{a_n}{a_0} \right| = 1 + \frac{1}{\Gamma} e^{\sqrt{\Gamma}}, \quad \Gamma = \sqrt{\frac{2 m \beta y \sqrt{L}}{M_N \gamma \sqrt{A}} \frac{n_g \sigma_i}{\Sigma_x \Sigma_y}} \left[ \frac{r_e z N}{\Sigma_x \Sigma_y} \right]^{\frac{2}{3}} \frac{s n}{2} \]

Tune shift along the bunch train is

\[ \Delta \nu_y = R Kn, \quad K = \frac{z n_i r_e \beta y}{\gamma \Sigma_y (\Sigma_x + \Sigma_y)} \]

L : distance between bunches, \( N \) : number of electrons / bunch, \( m, M_N \) : electron and nucleon mass, \( \Sigma_x, y \) : convolution of beam size of electrons and ions, \( k \) : betatron wave number; \( \sigma_i \) : ionization cross section, \( n_g \) : number density of the residual gas.
Characteristics of the FBII are

0) the instability being I on- related,

1) Short growth time of the instability,

2) The oscillation amplitude increasing along the bunch train,

3) The oscillation phase

\[ y_n = a_n \, e^{i(\Theta n - ks)}, \quad \Theta = \sqrt{\frac{2zNmr_eL}{AM_N\sum_y(\Sigma_x + \Sigma_y)}}, \]

4) Tune-increase along the bunch train.
3) Instrumentation

A) Transient (or single-pass) beam position monitor (BPM) system
Observation of the oscillation of every bunch up to 1600 turns

B) Nitrogen gas injection system
To increase the growth rate of the FBII

C) Bunch feedback system
Suppression of instabilities to store several hundred mA
Study of growth rate

D) Spectrum analyzer
Observation of beam spectrum

E) Synchrotron light monitor
Observation of beam oscillation
(Observation of beam size (Photo diode array))

F) Beam and bunch current monitor
The BPM system which we used is a part of the transverse feedback system.

The system has a 1Mb memory which is capable of storing the transverse position of every bunch up to 1600 turns after digitizing the signal by 8 bit ADC.

The ADC count \( U \) is expressed as \( U = k_m y l_b \).
(y : the vertical beam position, \( l_b \) : the bunch current)
The constant \( k_m \) was determined to be 46 count/mm/mA by making orbit bumps at the pick up.

Data taking by the BPM system was triggered freely without synchronization with any signal.
C) Bunch feedback system

Throughout the experiment the transverse feedback system was employed to store the beam current of several hundred mA. The damping time of the vertical feedback system was estimated to be 800 μs at the bunch current of 4mA.

Longitudinal feedback system was not used in the experiment.

D) Spectrum analyzer

As an axially instrument a spectrum analyzer HP8562E connected with a vertical button pick up was used for taking the beam spectrum. The observed frequency range was 3f_{BE} to 4f_{BE}.

From the noise level of the beam spectrum, detectable oscillation amplitude was estimated to be larger than 30μm at the beam current of 100mA.
The nitrogen gas was intentionally leaked into the vacuum duct to increase the growth rate of the FBII.

The pressure near the injection point of the gas was measured by a residual gas analyzer (RGA).

After the leak of the gas, the partial pressure of the gas component whose atomic number is 28, $P_{28}$, was increased to $6.0 \times 10^{-6}$ Torr at the RGA.

The pressure distribution around the injection point of the gas was calculated from the reading of the RGA and the pumping speed of the vacuum pumps.

The average value of $P_{28}$ in the ring was obtained to be $8.4 \times 10^{-8}$ Torr from the RGA and CCGs.

The vertical emittance growth by Coulomb scattering is estimated to be $3.8 \times 10^{-10}$ m.
Fig. 3.18 Pressure bump of the nitrogen gas injection area
2) Analysis of BPM data (X. Zhang)

A) FFT

As the oscillation includes a large component of synchrotron oscillation we employed Fourier analysis for the data of 1600 turns to extract betatron oscillation.

The amplitude were normalized by the bunch current because the distribution of the bunch current was not uniform due to the short beam life of about 10-14 min.

B) Complex demodulation

Amplitude and phase of betatron oscillation was obtained for every bunch and every turn by complex demodulation method.

C) Fourier transform

To determine the tune precisely the Fourier transform was adopted.

\[ \phi(v_y) = \frac{1}{N} \sum_{n=1}^{N} y(n) w(n) \exp(-2\pi i n v_y) , \quad w(n) = 2\sin^2\left(\frac{n \pi}{N}\right) \]

Tune was determined such that \( \phi(v_y) \) was maximized.
3) Results

A) Amplitude and phase after adding the gas

Analyzed data clearly shows the amplitude growth along the bunch train. The maximum amplitude is about 200µm or larger.

As the amplitude of 200µm is well above the sensitivity of the spectrum analyzer and the sidebands were not observed at almost same current before adding the gas, we conclude that the observed oscillation is caused by the addition of the gas.

The oscillation phase decreases along the bunch train, which exhibits the oscillation mode is unstable as expected by the theory.

The total phase shift from head to tail of the bunch train is about 3 radians. Assuming the 2% coupling the linear theory gives three times larger phase shift than the observation.
100 bunches, 2ns spacing, 170mA, feedback damping time 1.9ms

Zoomed spectrum

100 bunches, 2ns spacing, 178mA, feedback damping time 1.9ms

Zoomed spectrum

Fig. 4.9 Vertical betatron sidebands spectrum
Oscillation amplitude along the bunch train

Oscillation phase along the bunch train
200 bunches, 2 ns bunch spacing, 155 mA, feedback damping time 7.2 ms, vacuum pressure 0.38 mPa

![Graph showing phase of each bunch observed at fixed position for 200 bunches.]

168 bunches, 2 ns bunch spacing, 140 mA, feedback off, vacuum pressure 2.8 μPa

![Graph showing phase of each bunch observed at fixed position for 168 bunches.]

Fig. 4.12 Phase of each bunch observed at fixed position
Fig. 4.12 Phase of each bunch observed at fixed position

168 bunches, 2 ns bunch spacing, 205 mA,
feedback damping time 0.8 ms, vacuum pressure 2.63 μPa

100 bunches, 2 ns bunch spacing, 115 mA,
feedback damping time 0.8 ms, vacuum pressure 16.1 μPa
B) Normalized phase advance per bunch

\[ \Theta_{\text{nor.}} = \frac{\Theta}{\sqrt{N L}} = \frac{2 z m r_e}{A M_N \Sigma y (\Sigma x + \Sigma y)} \]

\( \Theta_{\text{nor.}} \) was plotted for almost all data taken by BPM.

\( \Theta_{\text{nor.}} \) scatters between 0.03 and 0.13 \( \text{rad/(mA\cdot m)^1/2} \), while the linear theory predicts 0.07 to 0.14 assuming the coupling of 10 to 1\% respectively.

C) Oscillation pattern along the bunch train

Oscillation pattern was plotted for consecutive 6 turns along the train.

The pattern after adding the gas clearly shows snake-like shape.

This pattern is observed even before adding the gas.
Normalized phase advance per bunch

- Strong Feedback
- Weak Feedback
- Feedback off
- 4ns spacing, strong feedback

Theta (radian/mA$^{1/2}$/m$^{1/2}$)

Bunch train > 100
Theoretical value

Inj. $N_2$
Stop $N_2$
Inj. $N_2$

File No.
Oscillation pattern of the bunch train observed at the fixed position in the ring

200 bunches, 2 ns bunch spacing, 155 mA, feedback damping time 7.2 ms, vacuum pressure 0.38 μPa

Fig. 4.10(a) Oscillation pattern of the bunch train for consecutive 6 turns
Oscillation pattern of the bunch train observed at fixed position in the ring
100 bunches, 2 ns bunch spacing, 170 mA,
feedback damping time 1.9 ms, vacuum pressure 16.1 μPa

Fig. 4.10(b) Oscillation pattern of the bunch train for consecutive 6 turns
Oscillation pattern of the bunch train observed at fixed position in the ring
100 bunches, 2 ns bunch spacing, 170 mA, feedback damping time 1.9 ms, vacuum pressure 16.1 μPa

Fig. 4.10(b) Oscillation pattern of the bunch train for consecutive 6 turns
Oscillation pattern of the bunch train observed at fixed position in the ring
168 bunches, 2 ns bunch spacing, 140 mA, feedback off, vacuum pressure 2.8 μPa

Fig. 4.10(c) Oscillation pattern of the bunch train for consecutive 6 turns
D) Amplitude growth after bunch feed back was turned off

Saturation of the amplitude was observed, though the data of more turns than 1600 seems necessary to conclude it.

Growth time which includes the contribution from all instabilities is about 360 µsec.

E) Tune shift along the bunch train

The linear theory predicts tune shift of $2 \times 10^{-5}$/ bunch.

The data shows that the tune is almost constant or decreases along the train, which can not be explained by the theory.

Amplitude dependent tune shift, current dependent tune shift etc. ?????
Fig. 4.11 Amplitude growth rate estimation

100 bunches, 2ns, 107mA, feedback off, bucket b122, Bunchid 100
100 bunches, 2 ns bunch spacing, 107 mA, feedback turned off at beginning, vacuum pressure 15.7 \mu Pa

50 bunches, 53.5 mA, 4 ns bunch spacing, feedback damping time 3.0 ms, vacuum pressure 15.6 \mu Pa

Fig. 4.15 Oscillation amplitude as a function of bunch id and time
100 bunches, 2 ns spacing, feedback damping time 3.2 ms, 107 mA, vacuum 16.1 μPa

125 bunches, 2 ns bunch spacing, 110 mA, Vacuum 2.24 μPa, feedback turned on at the beginning (3.6 ms)

Fig. 4.15 Oscillation amplitude as a function of bunch id and time
168 bunches, 2 ns bunch spacing, 140 mA, feedback off, vacuum pressure 2.8 \mu Pa

200 bunches, 2 ns bunch spacing, 155 mA, feedback damping time 7.2 ms, vacuum pressure 0.38 \mu Pa

Fig. 4.15 Oscillation amplitude as a function of bunch id and time
100 bunches, 2 ns bunch spacing, 139 mA, feedback damping time 2.3 ms, vacuum pressure 16.1 μPa

100 bunches, 2 ns bunch spacing, 170 mA, feedback damping time 1.9 ms, vacuum pressure 16.1 μPa

Fig. 4.15(a) Oscillation amplitude as a function of bunch id and time
4. Experimental procedure and results

1) Experimental procedure and observations

A train of 100 bunches was stored with 2ns spacing.

Experiment-steps are,

(1) No leakage of the nitrogen gas

We confirmed that the vertical betatron sidebands observed by the spectrum analyzer were disappeared at the beam current of 260 mA.

(2) Leakage of the gas in the ring

The vertical betatron sidebands remained down to the beam current of 173 mA.

(3) Addition of more gas

The beam was injected up to 190 mA. Vacuum pressure was 8.4 x 10^{-8} Torr.

The intermittent vertical oscillation, which was not observed before and in the first leak of the gas, appeared in the synchrotron light monitor.

Strong vertical betatron sidebands were observed in the spectrum taken by the spectrum analyzer.
5. Summary

An experiment for the search of the FBII was carried out at the TRISTAN AR.

- Observed characteristics of the instability such as

  1) Ion-related phenomena,
  2) Growth of the oscillation amplitude along the bunch train,
  3) Short growth time of the instability less than several ms,
  4) Change of oscillation phase from the head to tail of the bunch train which agrees with the theory within a factor of the magnitude,

shows that the observed instability can be interpreted as the FBII.

- Remaining questions are

  why is the tune shift along the train not observed?,
  why does very similar oscillation pattern to that observed after adding the gas appear in better vacuum condition?

- It was demonstrated that the transient observation of the bunch oscillation by the BPM is the useful tool for the study of instabilities.
My personal impression

1. FII does exist.

2. Bunch oscillations saturate but they remain finite even with a strong feedback.

3. The saturated amplitude depends on the strength of the feedback.

4. Then, the feedback is still very important.

5. Another way to mitigate the instability such as an introduction of some additional bunch gaps could be needed.

6. Unfortunately (for us) and fortunately (for us), PEP II HER was commissioned earlier than ours.

Maybe, we can learn many from PEP II results.
Experimental Study of the ion trapping phenomenon in TRISTAN-AR

S. MATSUMOTO, H. Fukuma, K. Ohmi,
M. Tobiyama, E. Kikutani, M. Suerake,
K. Satoh Y. Funakoshi

• motivation

• experiments and results

• conclusion
0 Motivation

We operated the machine with 640 bunches.

( full rf buckets )

⇒ We found

- $I_{\text{beam}} \leq 20 \text{mA}$. 
- Oscillation at the 1st lower sideband 
  $(1-8\nu_y)$ was observed. 

↑ fractional part of v. tune

⇒ We suspected that the 2-beam instability 
  due to the trapped ions took place.

Questions may arise...

- Are there trapped ions in multi-bunch operation?
- If we have trapped ions, do they induce the
  instability that we observed?
<table>
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<th>Parameters</th>
<th>Value</th>
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<td>Revolution freq.</td>
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<td>$\epsilon_x$</td>
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<td>$\nu_x$</td>
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<td>Vertical tune</td>
<td>$\nu_y$</td>
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<td>Average vacuum</td>
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<tr>
<td>$508.58$ MHz</td>
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<td>$640$</td>
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<tr>
<td>$794.66$ KHz</td>
<td></td>
</tr>
<tr>
<td>$377.26$ m</td>
<td></td>
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<tr>
<td>$43.6$ nm</td>
<td></td>
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<tr>
<td>$10.16$</td>
<td></td>
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<tr>
<td>$10.23$ ($\delta \nu_y = 0.23$)</td>
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</tr>
<tr>
<td>$23 \times 10^{-7}$ Pa</td>
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</table>

- We operated the machine with 64 bunches (instead of 640), to save time (for injection).

10RF buckets

- 64 bunches are enough to trap ions ($^{16}$O$^+$).
2 Experiments and Results

Experiment 1

identify the unstable mode
and measure the growth rate.

- By utilizing the transverse feedback system, first we store the beam and then switch the feedback off.

- We take the position data of every bunch for 1600 turns.

- FFT

Experiment 2

measure tune shift (due to the trapped ions)

- Shaking the beam by an rf kicker and observe the amplitude of the beam oscillation, the rf kicker frequency is scanned.
Oscillation at

\[ I = 113 \text{ mA} : \ 3^{\text{rd}} \]
\[ I = 80 \text{ mA} : \ 2^{\text{nd}} \]

Lower sidebands grows LINEARLY.

However

- \( 2^{\text{nd}} \) Lower sideband is seen even we switch on the feedback.

- Other modes also grows.

To understand the mechanism, we consider 2-beam model and see the threshold and the growth time that the model predicts.
Measurement of Growth time of the sidebands, \( n = 5y \),
\( n = 1, 2, \ldots, 6 \) are plotted.

Feedback off

- 64-bunch mode, Initial current 80mA
Time evolution of lower sidebands

Feedback OFF / 113 mA

- 3 - Vy oscillation is growing.

feedback off here
Time evolution of lower side bands

\( (n - \nu_y; \; n = 1, 2, 3, \ldots, 6) \)

Feedback ON / 113.6mA / 64-bunch

Amplitude (ADC bits)

- 2 - \( \nu_y \) oscillation exists already.
2-beam model

(Keil, Zotter 1971; Koshkarev, Zenkevich 1972)

Equation of motion

\[
\begin{align*}
\dddot{y}_e + \nu_g^2 \omega_{rev}^2 y_e &= -\omega_e^2 (y_e - y_i) \\
\dddot{y}_i &= -\omega_i^2 (y_i - y_e)
\end{align*}
\]

where

\[
\begin{align*}
\omega_e^2 &= \frac{λ_i \, ec^2}{γ} \frac{1}{σ_y(σ_x + σ_y)} \\
\omega_i^2 &= \frac{λ_e \, e_p \, c^2}{A} \frac{1}{σ_y(σ_x + σ_y)}
\end{align*}
\]

and

\[
\begin{align*}
σ_x &= \sqrt{β_x \, ε_x} = 510 \text{ μm} \quad (β_x = \frac{c}{2π \nu_x}) \\
σ_y &= 120 \text{ μm} \quad (6\% \text{ coupling assumed})
\end{align*}
\]

\[
\begin{align*}
λ_i &= \text{line density of the ions} \\
λ_e &= \text{the electron} \\
\text{A mass of ion (CO}^+\text{ 28 assumed)}
\end{align*}
\]
\[
\begin{align*}
\begin{cases}
y_e & = e^{i(m\Theta - \omega t)} \\
y_i & = e^{i\Delta t} \\
\end{cases} \quad (n = \text{integer}, \; 0 < \Theta < 2\pi)
\end{align*}
\]

These solutions exist if the mode equation

\[
(\omega^2 - \omega_i^2)\left((\sigma - n\omega)\right)^2 - \omega_r^2 \nu_g^2 - \omega_e^2 = \omega_e^2 \omega_i^2
\]

is satisfied.

\(\sigma\) can be complex if \(m > \nu_g\). (2-beam instability)
2 - beam Instability (by CO\textsuperscript{ions})

\textit{ion frequency}

\textit{beam frequency}

\textit{Real and Imaginary}

\(m=13\)

\(m=12\)

\(m=11\)

\(3-\delta v_y\)

\(2-\delta v_y\)

\(1-\delta v_y\)

\(\Omega / \omega_{rev}\)

Beam Current (mA)

\textit{ion density/beam density} = 0.01 is assumed.
Observation of the beam response at 4th lower sideband.

Figure 3: The pictures of the display of network analyzer to observe the spectrum of the betatron sideband at $4 - \nu_y$. Each picture shows the spectrum observed when 20 buckets (Top), 50 buckets (middle), or 64 buckets (bottom) were filled. The span of each picture is 20 kHz. The bunch current was 0.65 mA (42 mA/64 bunches).
Weak-strong simulation result of the response (the amplitude of forced oscillation) of the beam.

- The beam is shaken at the frequency near 1-5V.
- The beam consists of 64 bunches (15mA).
③ Conclusion

- In the multi-bunch mode operation, ions (co) are trapped by the beam.

- 2-beam instability occurred at the current that the model predicts.

However,

What we observed here has nonlinear property, (e.g. growth rate) we need work on it.