Measurement and simulation of synchro-beta sideband due to electron cloud induced head-tail instability

J.Flanagan, K.Ohmi, E. Benedetto, H. Fukuma, S. Hiramatsu, M. Tobiyama, H. Ikeda, T. Ieiri, K. Oide, Y. Funakoshi, E. Perevedentsev, S. Uehara, S. Uno

ILC DR workshop at Cornell

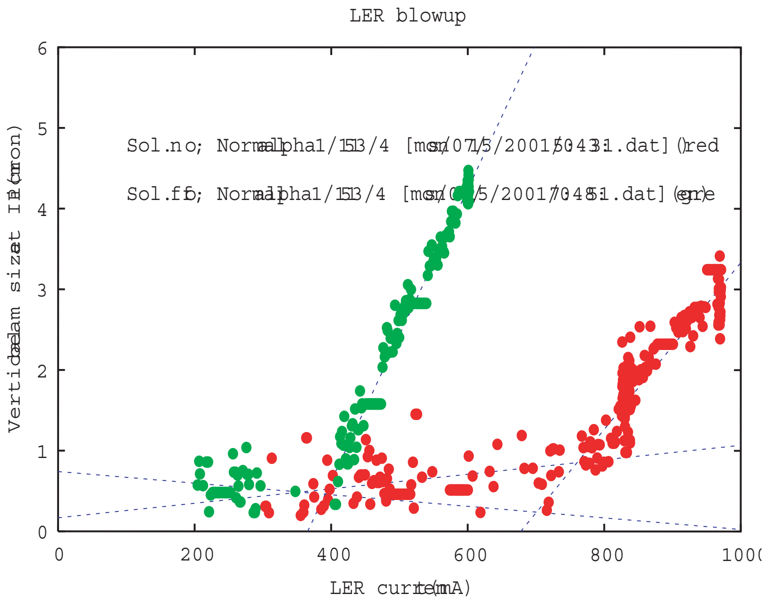
26-28 Sep., 2006

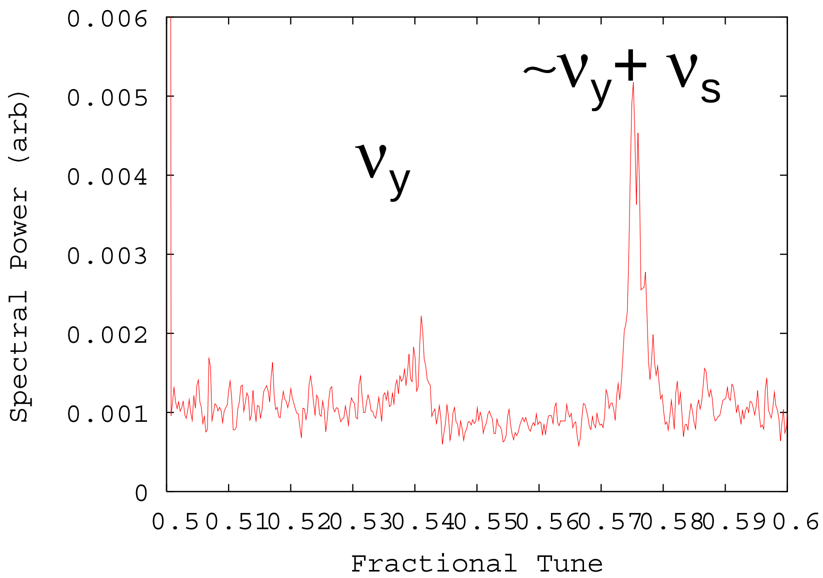
Single bunch instability due to electron cloud

- Beam size blowup has been observed above a threshold current (~400 mA).
- Synchro-betatron sideband, $\sim\nu_y+\nu_s$, has been observed above the threshold.
- The threshold of emittance growth and sideband appearance synchronize on/off of the solenoid magnets.
- Luminosity degradation occur simulteneously.

Measurements of the single bunch instability

- Beam size blow-up
- Synchro-beta sideband





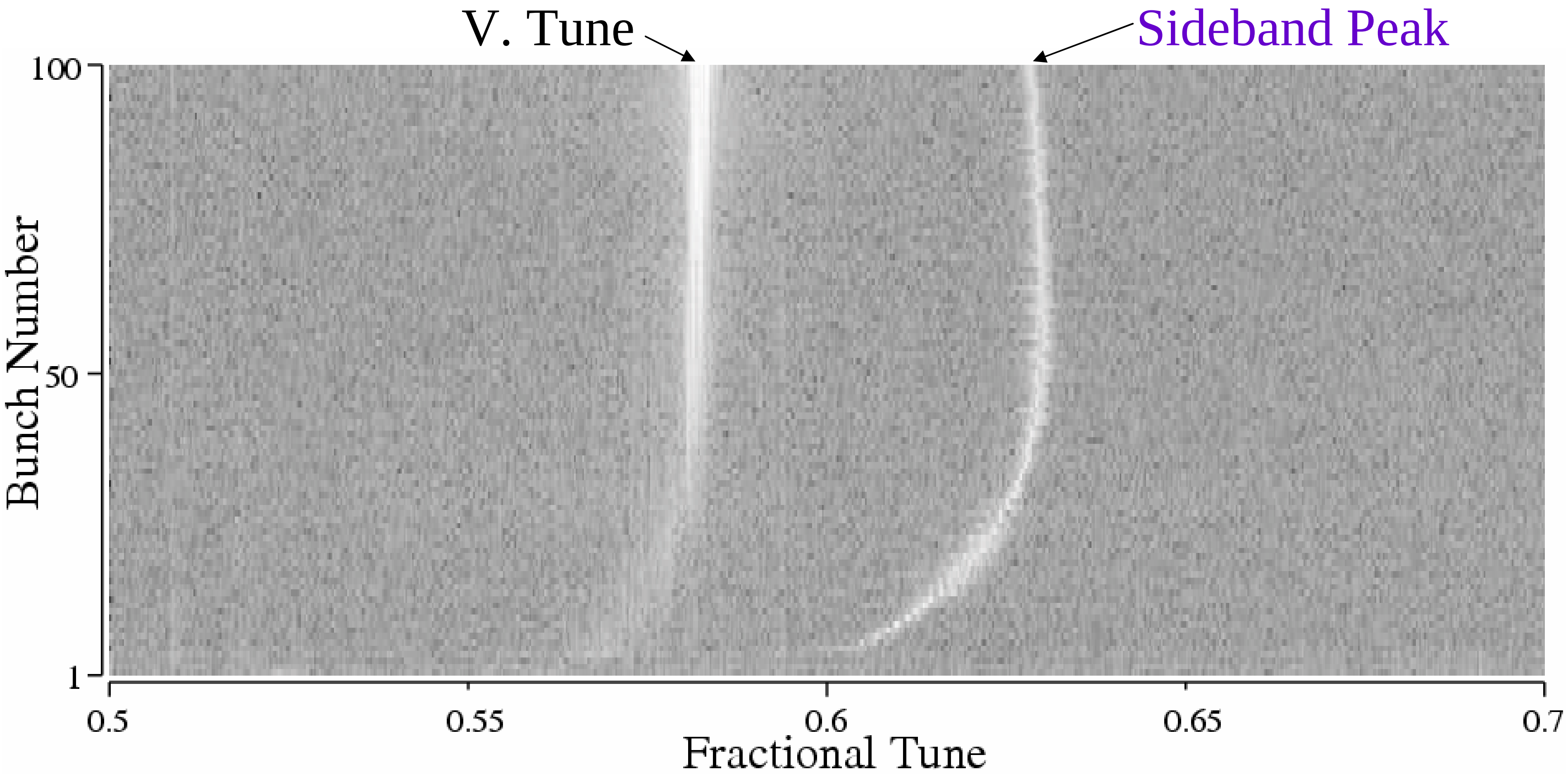
Observation of synchro-beta sideband

- Vertical betatron sidebands found at KEKB which appear to be signatures of fast head-tail instability due to electron clouds.
  - J.W. Flanagan, K. Ohmi, H. Fukuma, S. Hiramatsu, M. Tobiyama and E. Perevedentsev, PRL 94, 054801 (2005)
- Presence of sidebands also associated with loss of luminosity during collision.
  - J.W. Flanagan, K. Ohmi, H. Fukuma, S. Hiramatsu, H. Ikeda, M. Tobiyama, S. Uehara, S. Uno, and E. Perevedentsev, Proc. PAC05, p. 680 (2005)
- Further studies have been performed:
  - Single beam studies:
    - Varying RF voltage
    - Varying chromaticity
    - Varying initial beam size below blow-up threshold (emittance)
  - In-collision studies:
    - Looking at specific luminosity below sideband appearance threshold
    - Looking at specific luminosity closer to head and tail of LER bunch

Beam spectrum measurements

- Bunch Oscillation Recorder
  - Digitizer synched to RF clock, plus 20-MByte memory.
  - Can record 4096 turns x 5120 buckets worth of data.
  - Calculate Fourier power spectrum of each bunch separately.
- Inputs:
  - Feedback BPMs
    - 6 mm diameter button electrodes
    - 2 GHz ($4xf_{rf}$) detection frequency, 750 MHz bandpass
  - Fast PMT
    - Used in initial studies, agreed with BPM data

Fourier power spectrum of BPM data



- LER single beam, 4 trains, 100 bunches per train, 4 rf bucket spacing
- Solenoids off: beam size increased from 60 μm ->283 μm at 400 mA
- Vertical feedback gain lowered
  - This brings out the vertical tune without external excitation

Strong Head-tail instability and synchro-beta sideband

- Mode coupling theory
- Eigenvalue problem for synchro-beta modes

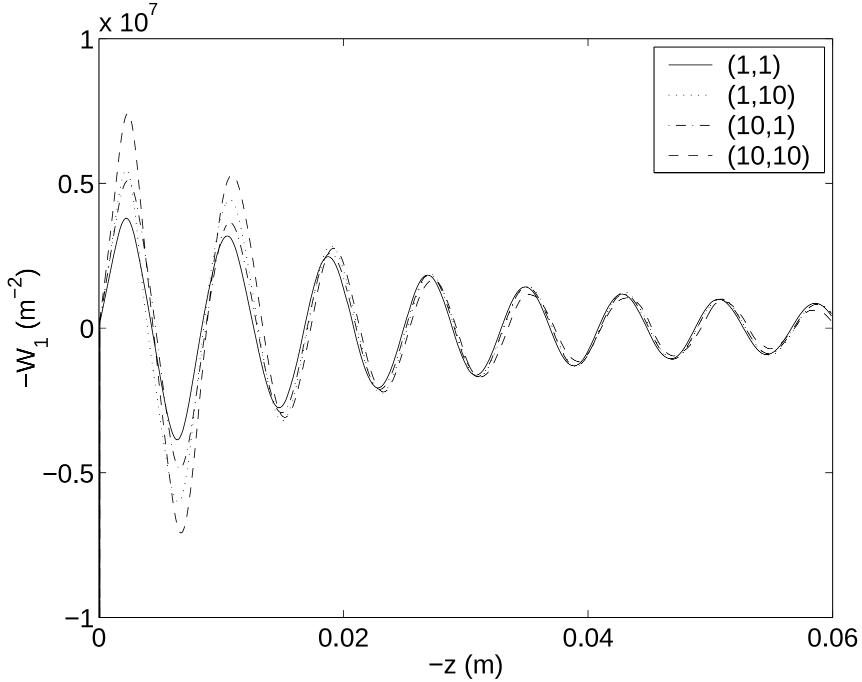
$$M\mathbf{v}_\ell = \lambda_\ell \mathbf{v}_\ell$$

$$\lambda_\ell \approx \omega_\beta + \ell\,\omega_s$$

- Merging ℓ and ℓ +1 mode, system becomes unstable.

Ordinary type of wake field

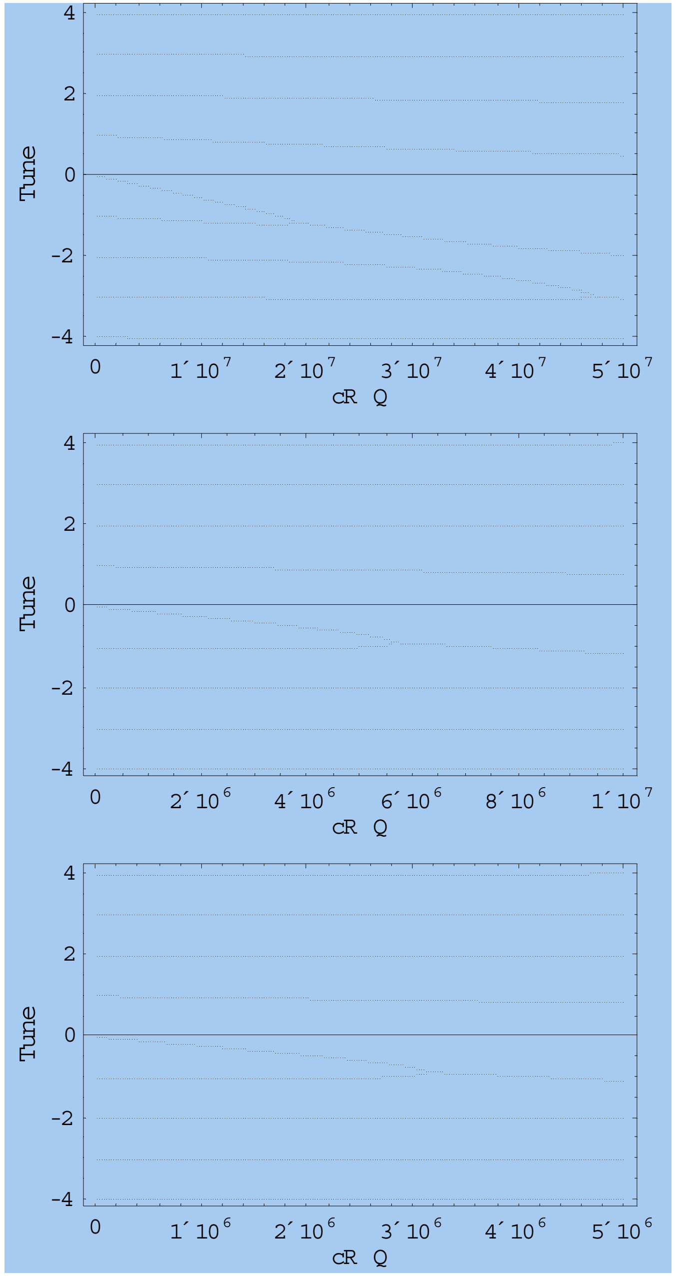
(Vertical wake field given by the numerical method)



Q~3-10

- The wake field is calculated by perturbation of head-pert of a bunch.
- Electrons, which are pinched and concentrated due to the bunch, are not considered. Limit of wake field approximation.

K. Ohmi, F. Zimmermann, E. Perevedentsev, PRE65,016502 (2001)



Threshold of strong head-tail instability

- Modes with ℓ=0 and -1 merge.
- Current dependent tune shift is "negative".
- Incoherent tune shift is not included.

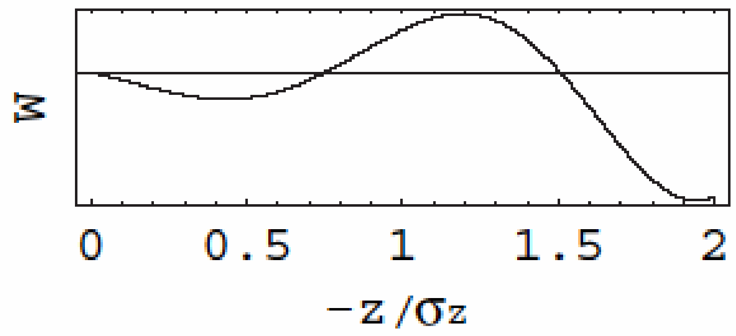


FIG. 5: Model focusing wake. The horizontal axis is longitudinal position normalized to the bunch length.

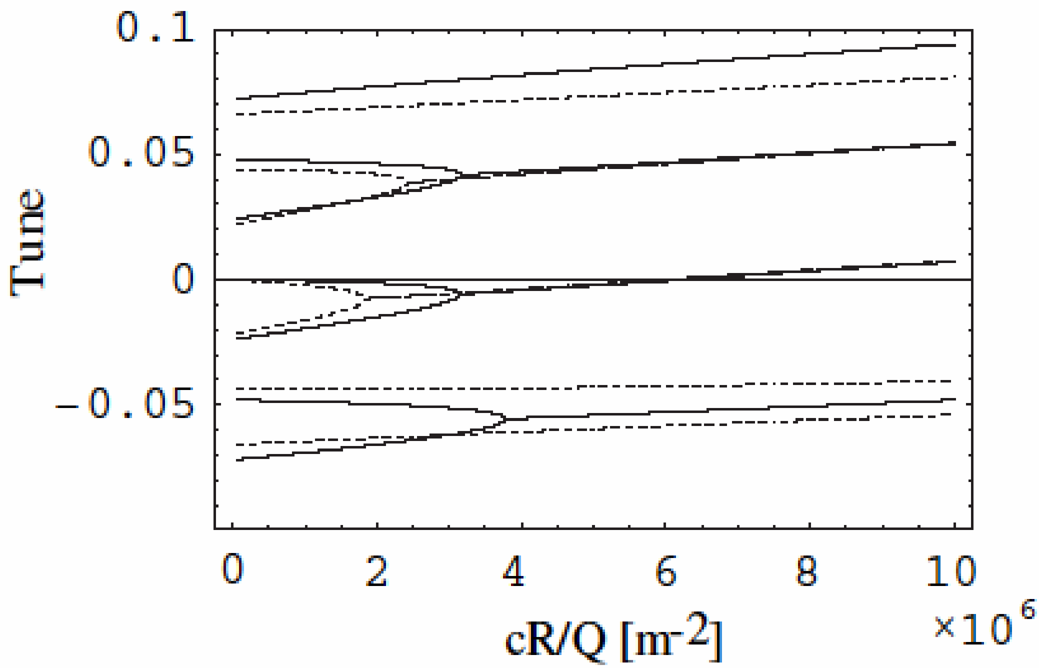


FIG. 6: Example mode spectrum for model focusing wake at $\nu_s = 0.022$ (dashed lines) and $\nu_s = 0.024$ (solid lines).

←Model focusing wake

- Wake field may be enhanced at the tail part of the bunch because of increase of the cloud density.
- Mode coupling pattern is changed. Merging between ℓ=1 and 2 modes is possible.

←Mode spectrum using model wake and airbag charge distribution. Incoherent tune shift is considered.

Value of Q chosen to give small ν_s dependence on mode separation, but other solutions possible (in fact more common).

Effect of varying synchrotron tune (RF voltage)

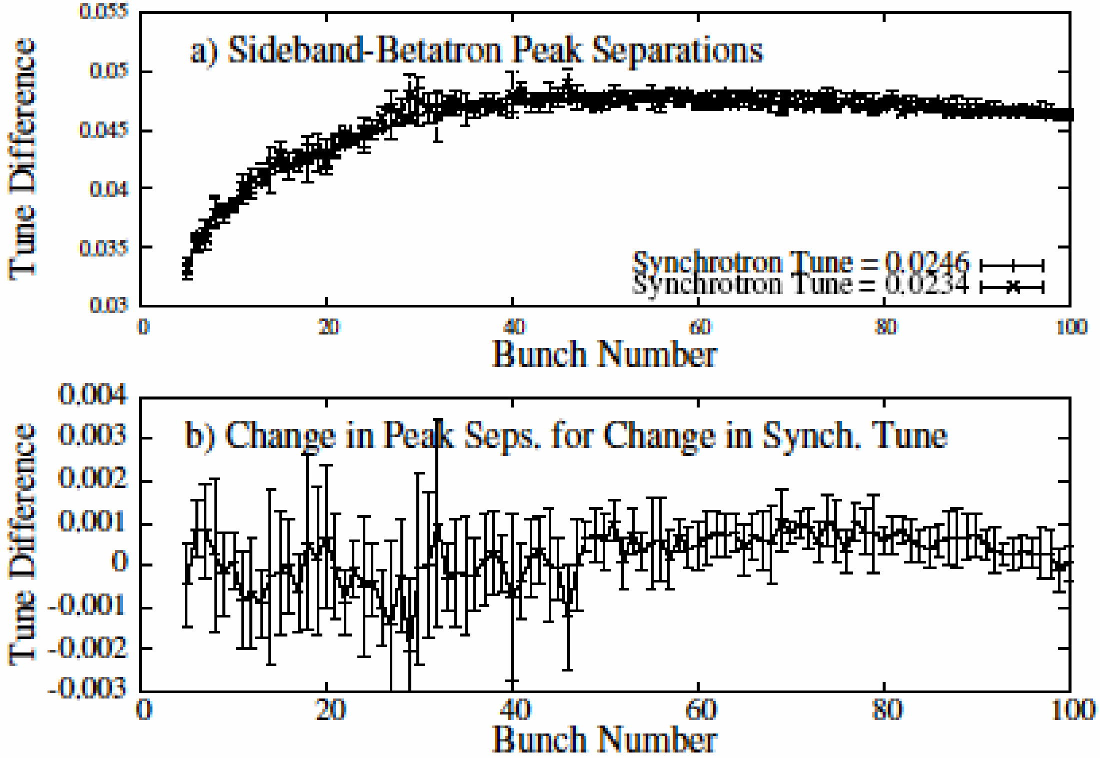
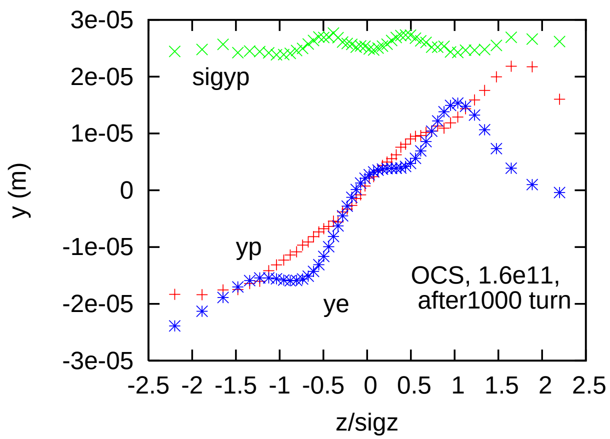


FIG. 3: Effect of changing synchrotron tune on the separation between sideband peak and betatron peak. In a), the sideband-betatron peak separation is plotted along the bunch train for $\nu_s = 0.0246$ (solid lines) and $\nu_s = 0.0234$ (dashed lines). In b), the difference between the two curves is plotted. Statistical 1-sigma error bars are shown.

Simulation for the sideband

- “Particle In Cell” based strong-strong simulation.
- FFT of beam dipole moment or <yz>.
- At first, relative small cloud (several σ_{xy}) did not give sideband.
- Increasing cloud size (>10 σ_{xy}), a clear upper sideband signal is seen (E. Benedetto).



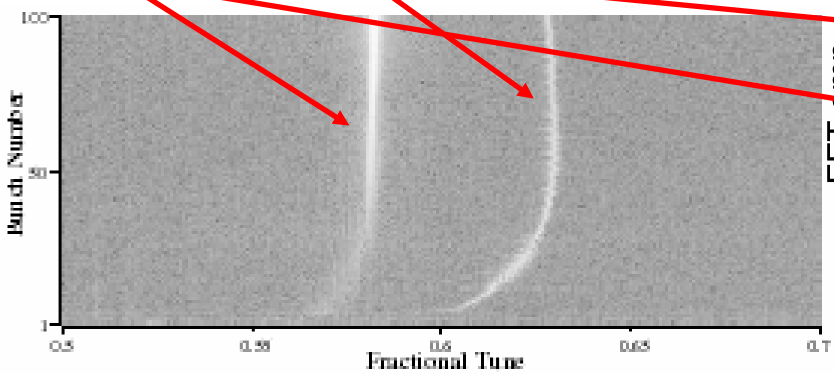
Electron cloud induced head-tail instability

- E. Benedetto, K. Ohmi, J. Flanagan
- Measurement at KEKB

Simulation (PEHTS)
HEADTAIL gives
similar results

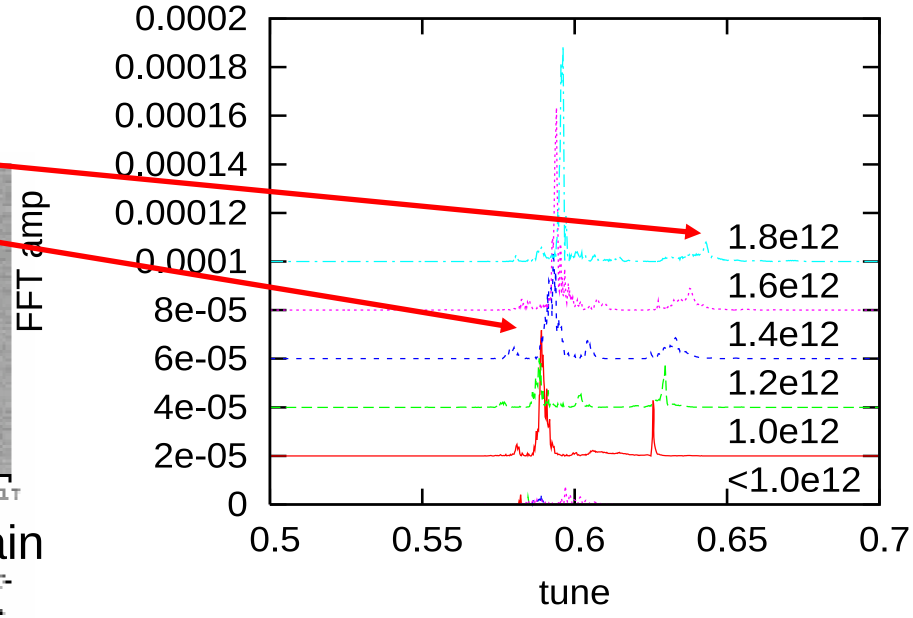
Betatron sideband

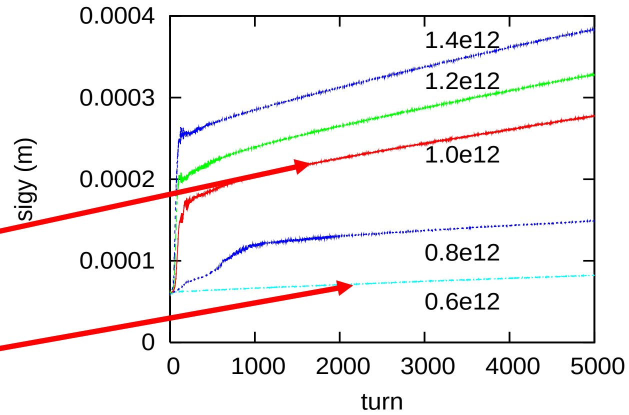
Tail of train



Head of train

FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are spaced 4-rf buckets (about 8 ns) apart. The bright, curved line on the left is the vertical betatron tune, made visible by reducing the bunch-by-bunch feedback gain by 6 dB from the level usually used for stable operation. The line on the right is the sideband.





Head-tail regime

Incoherent regime

Feedback does not suppress the sideband

- Bunch by bunch feedback suppress only betatron amplitude.

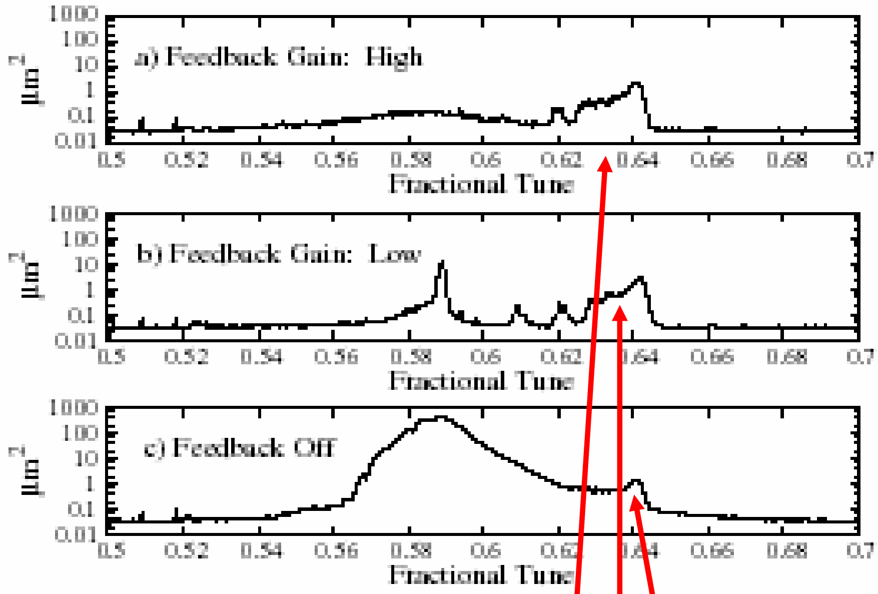
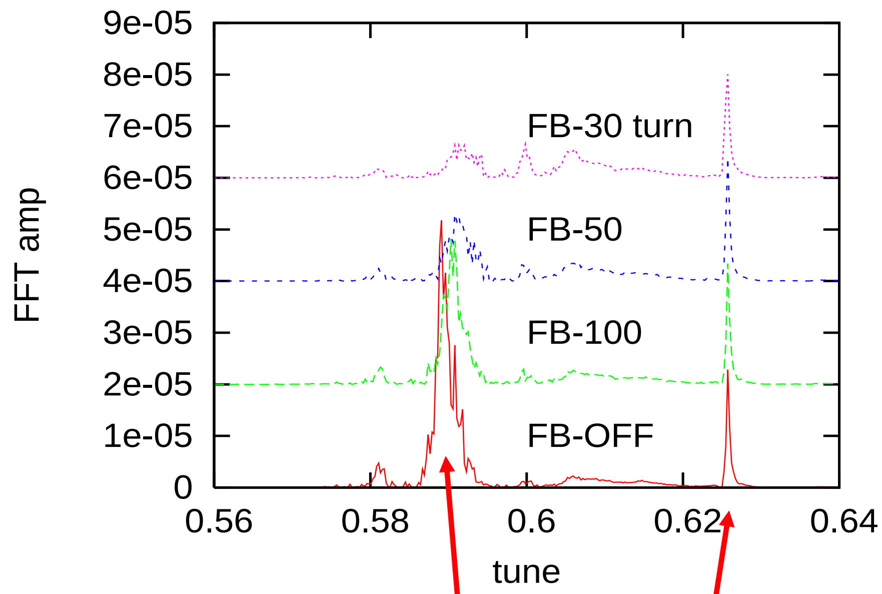


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

Sideband signal is Integrated over the train



Betatron sideband

Simulation (PEHTS)

Effect of Changing Emittance

- Experiment was done to see if the beam blow-up and sideband-appearance thresholds change when the initial vertical beam size is changed.
- Vertical beam size at low current was changed by using a dispersion bump (iSize) to change the emittance, then beam current ramped up.
  - Beam size data taken continuously, beam spectrum data taken at 50 mA steps.

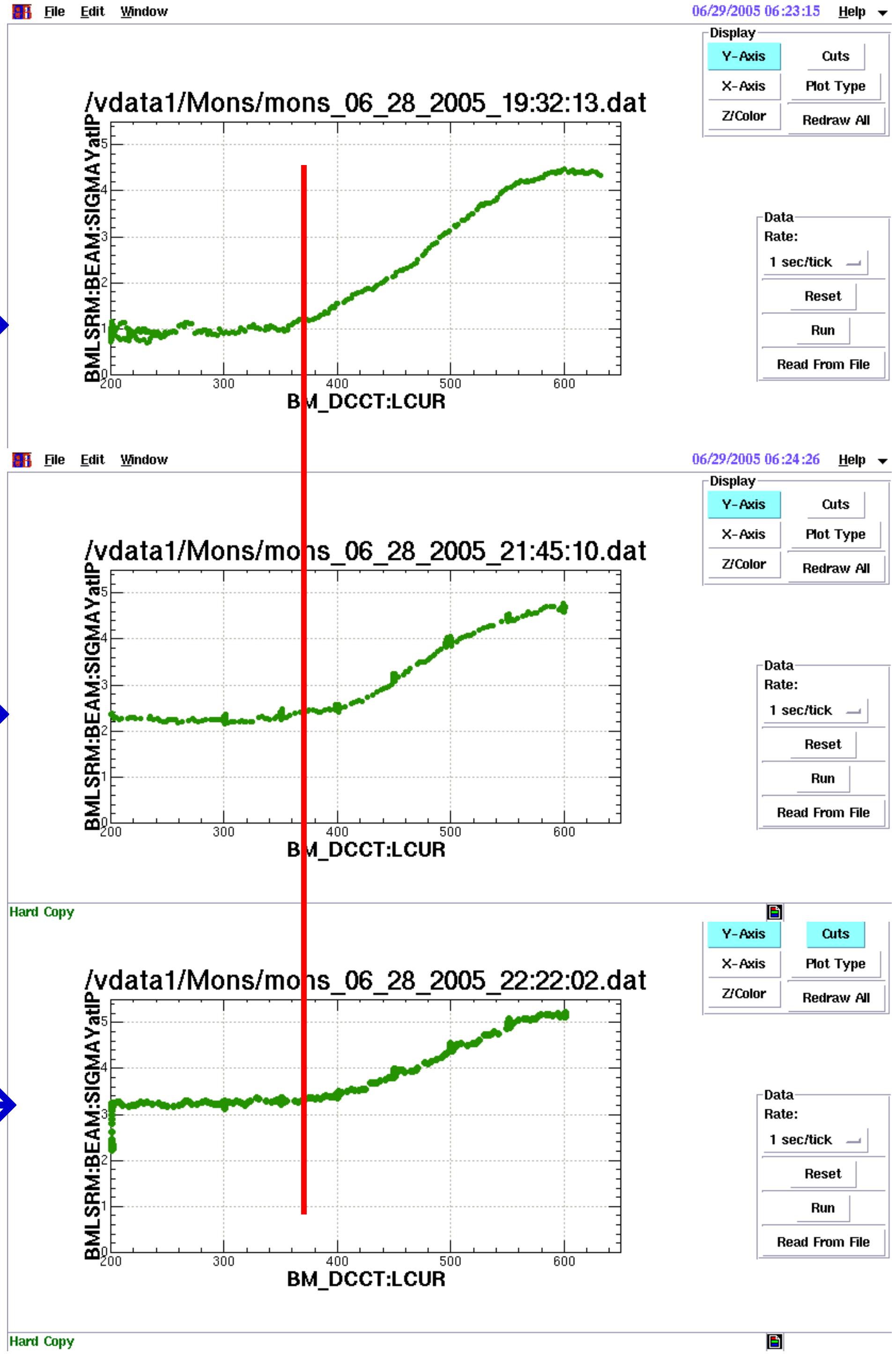
Blowup Threshold dependence on ε_y (iSize Bump)

Pattern: 4/200/4

σ_{y0} = 1 μm→

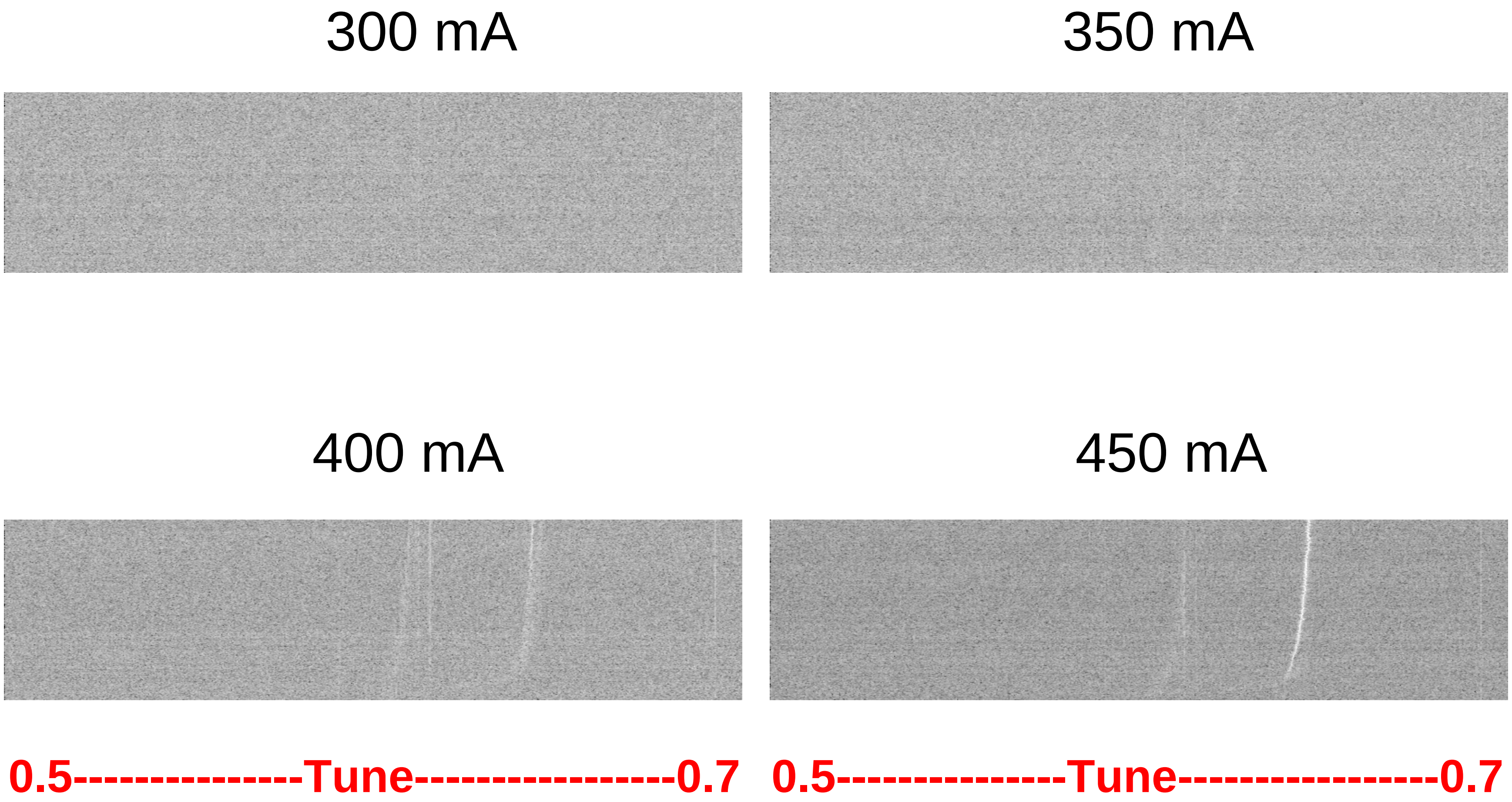
σ_{y0} = 2.2 μm→

σ_{y0} = 3.2 μm→



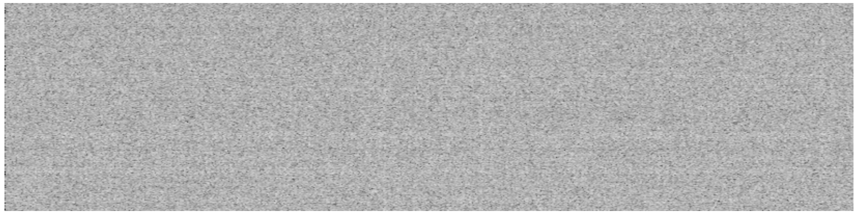
Beam-size blowup threshold does not change much, if at all.

$\sigma^*_{y0} = 1\ \mu m$

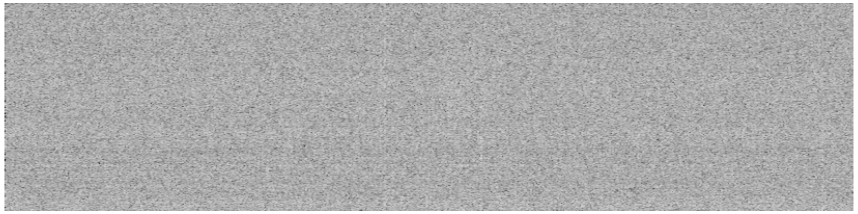


$\sigma^*_{y0} = 2.2\ \mu m$

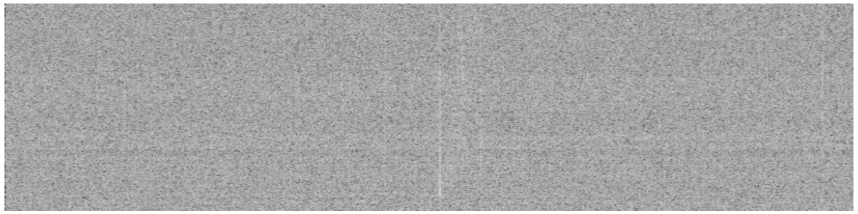
300 mA



350 mA

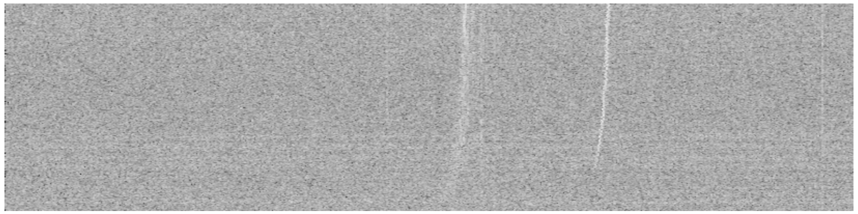


400 mA



0.5---------------Tune-----------------0.7

450 mA

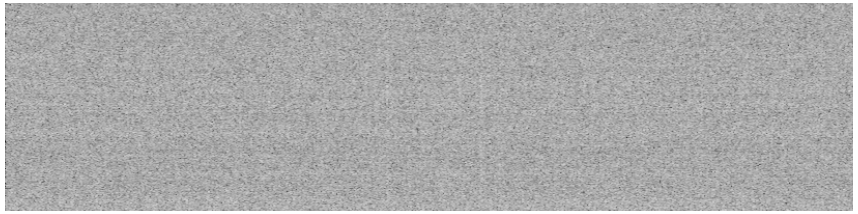


0.5---------------Tune-----------------0.7

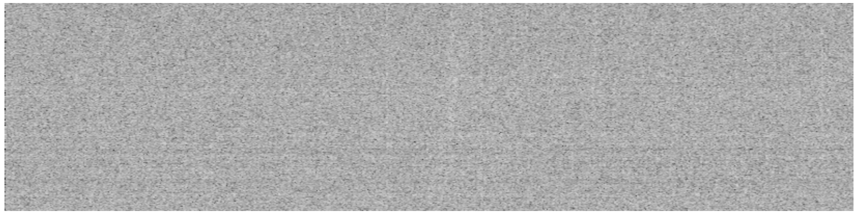
$\sigma^*_{y0} = 3.2\ \mu m$

300 mA

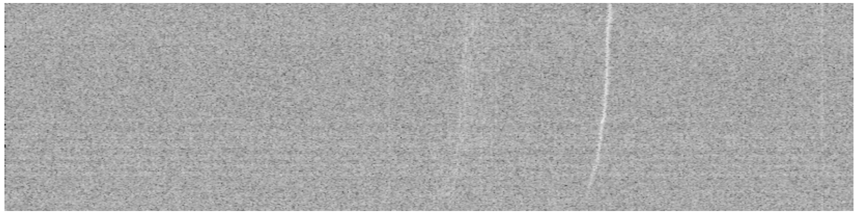
350 mA



400 mA

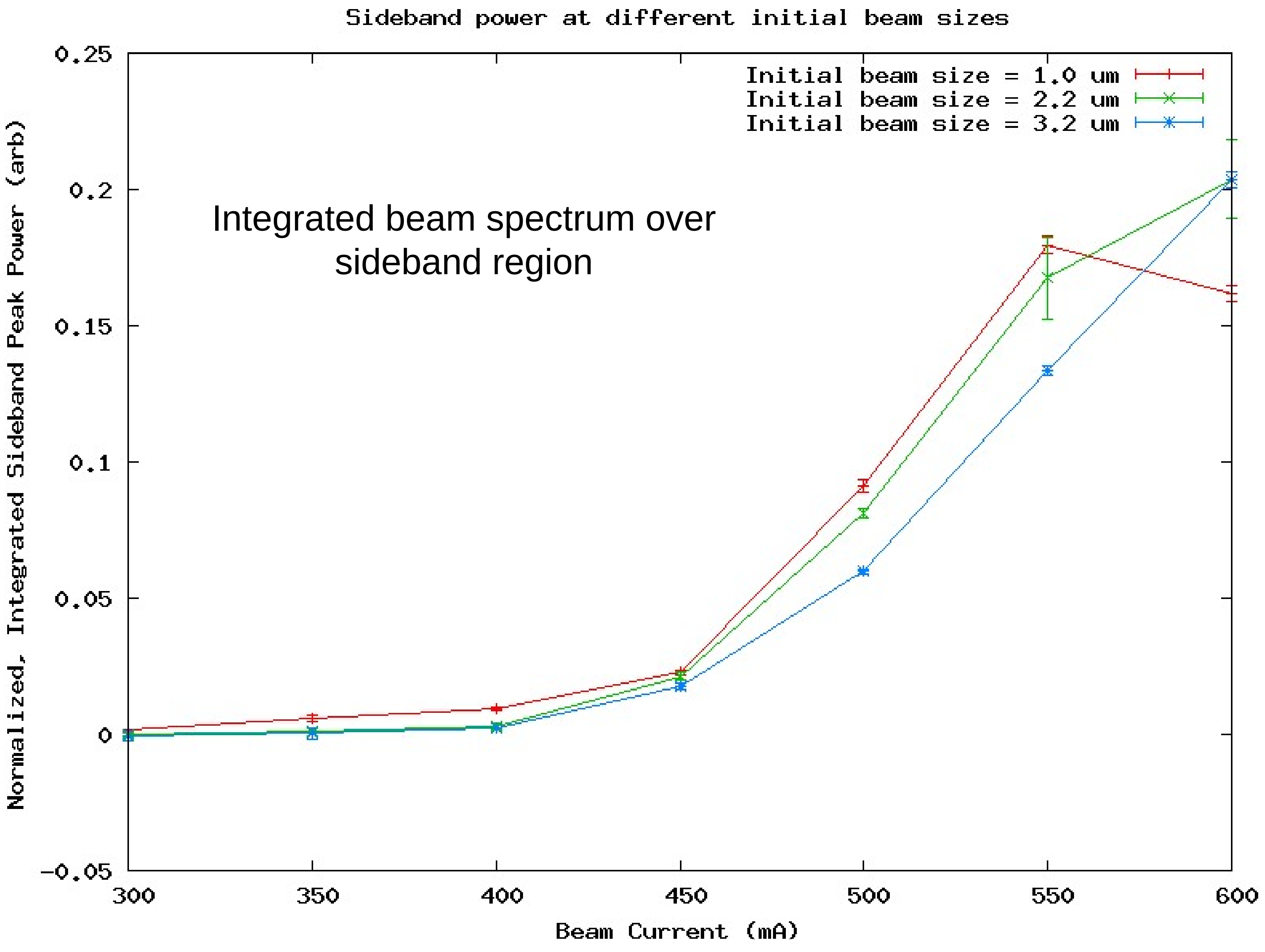


450 mA



0.5---------------Tune-----------------0.7 **0.5---------------Tune-----------------0.7**

Sideband growth at different σ^*_{y0}



Effect of Changing Emittance

- Conclusion: Threshold is found not to depend on initial vertical beam size.
- Can we understood this behavior?
- Threshold

$$\rho_{e,th} = \frac{2\gamma\nu_s \, \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L}$$

$Q=\min(Q_{nl}, \omega_e\sigma_z/c)$

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$$

- ω_e of numerator is cancelled by ω_e in Q. $\omega_e\sigma_z/c=2.5$ for KEKB.
- K is an enhancement factor for cloud size.

K. Ohmi, Snowmass 2005

$Q_{nl}<\omega_e\sigma_z/c$ in the Damping ring

- $Q=Q_{nl}=3\text{-}10$,

$$\rho_{e,th} = \frac{2\gamma\nu_s\,\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

- $\omega_e\sigma_z/c$ contributes to Landau damping, while contributes to electron pinching and accumulation.
- Threshold given by the simulation shows KQ~15 for KEKB, while 60 for ILC damping ring. The enhancement is due to electron pinching and accumulation.

Threshold by analytic theory and simulation

- Threshold given by simulation is compared by the analytical estimates for KQ=15.

	TDR (b=30)	TDR(b=15)	OTW	OCS	PPA	BRU	MCH	DAS	KEKB
ρe,th (m-3)	5.38E+11	1.29E+12	1.70E+12	6.19E+11	1.31E+12	2.28E+12	1.34E+12	4.66E+11	5.30E+11
ρe,th(sim)	1.20E+11	2.40E+11	4.00E+11	1.40E+11		2.00E+11	3.00E+11	1.20E+11	4.00E+11
ρana/ρsim	4.49	5.37	4.24	4.42		11.0	4.46	3.89	1.33

- The systematic difference (4x) between simulation and linear theory may be due to the cloud pinching.
- Incoherent effect is strong in BRU. Coherent threshold has not obtained yet.
- Simulations are accurate because the pinching is taken into account.
- Note that ρ_{th}(ana.) has dependence on $1/\beta_y$ but ω_e has $1/\mathrm{sqrt}(\beta_y)$.

K. Ohmi, CERN-ILCDR05

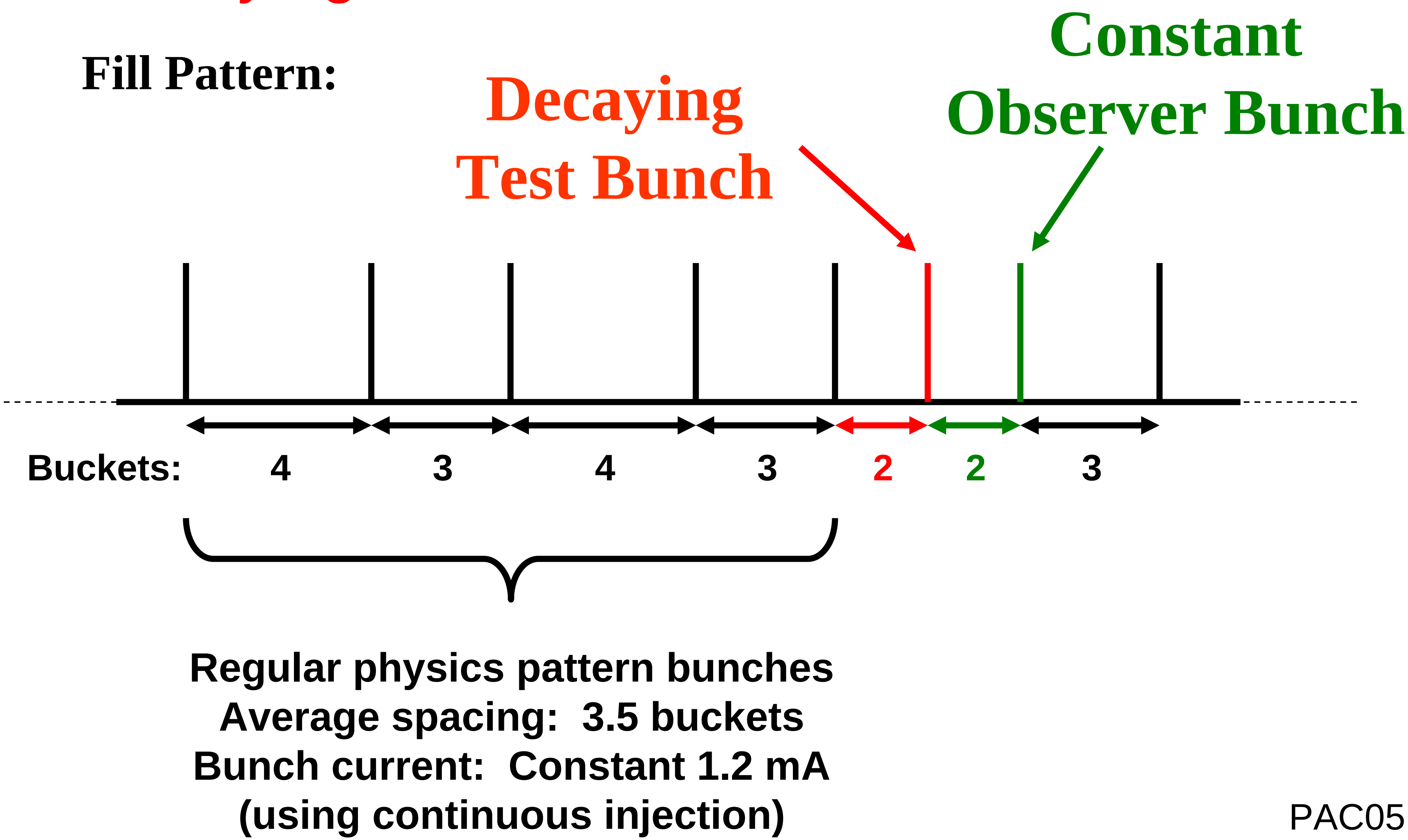
Variety of measurements

- Cloud density is controlled by changing spacing or bunch current of preceding bunch.
- Variables depending on bunch current is measured for various cloud densities.

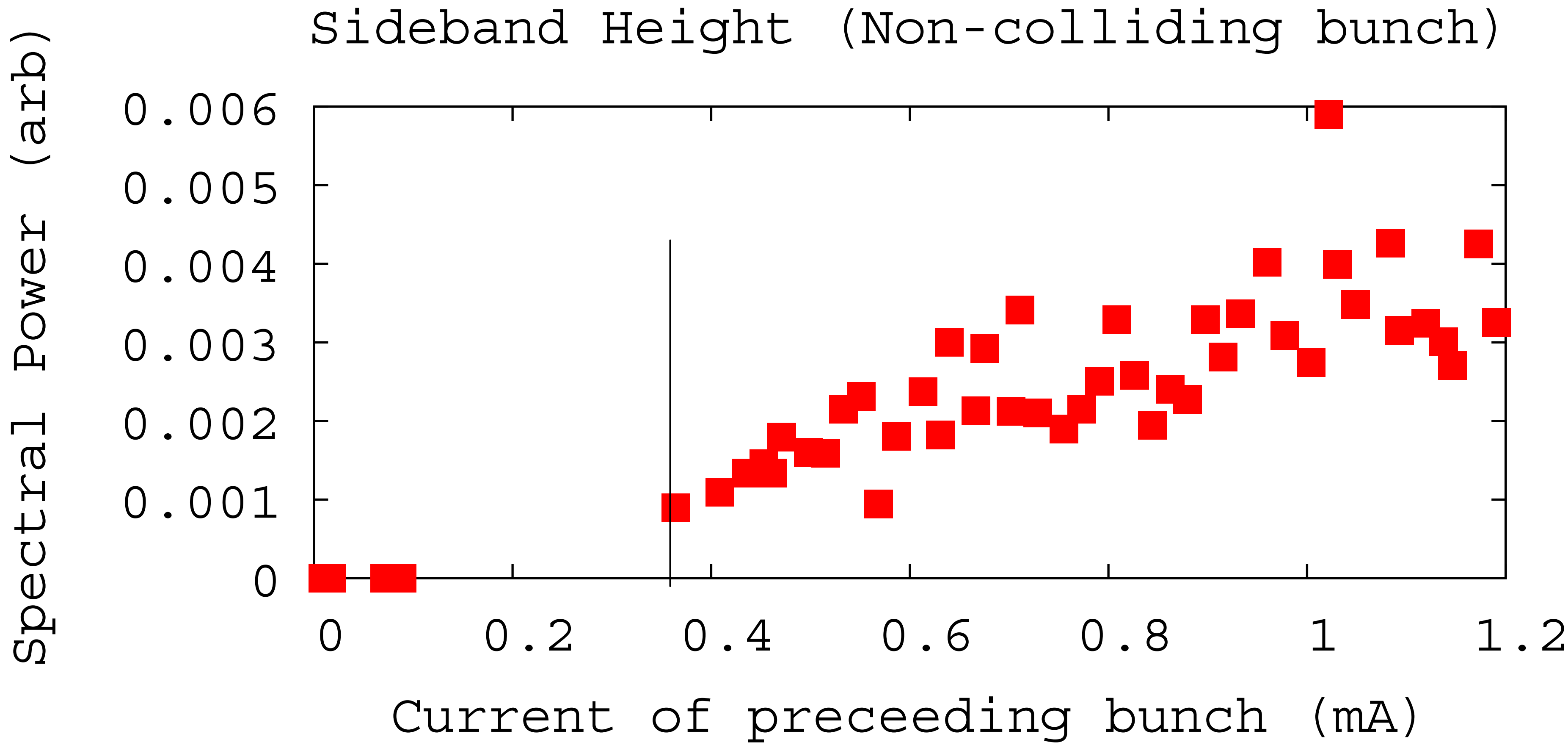
1. Luminosity and sideband measurement
2. Current dependent tune shift measurement.

Luminosity-sideband measurement

Decaying Cloud, Constant Bunch Current



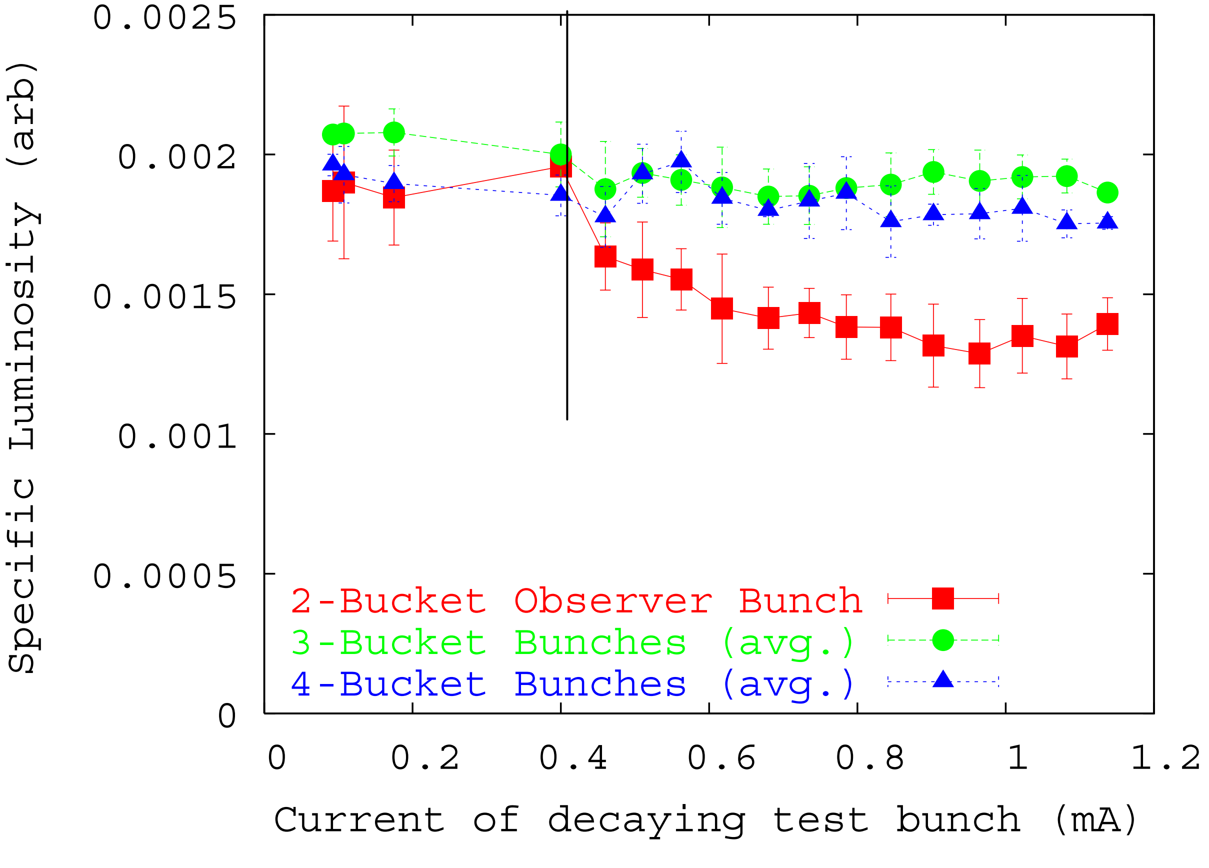
Decaying Cloud, Constant Bunch Current
Sideband Peak Heights



Sidebands disappear below test bunch current of ~0.4 mA

Decaying Cloud, Constant Bunch Current Specific Luminosity

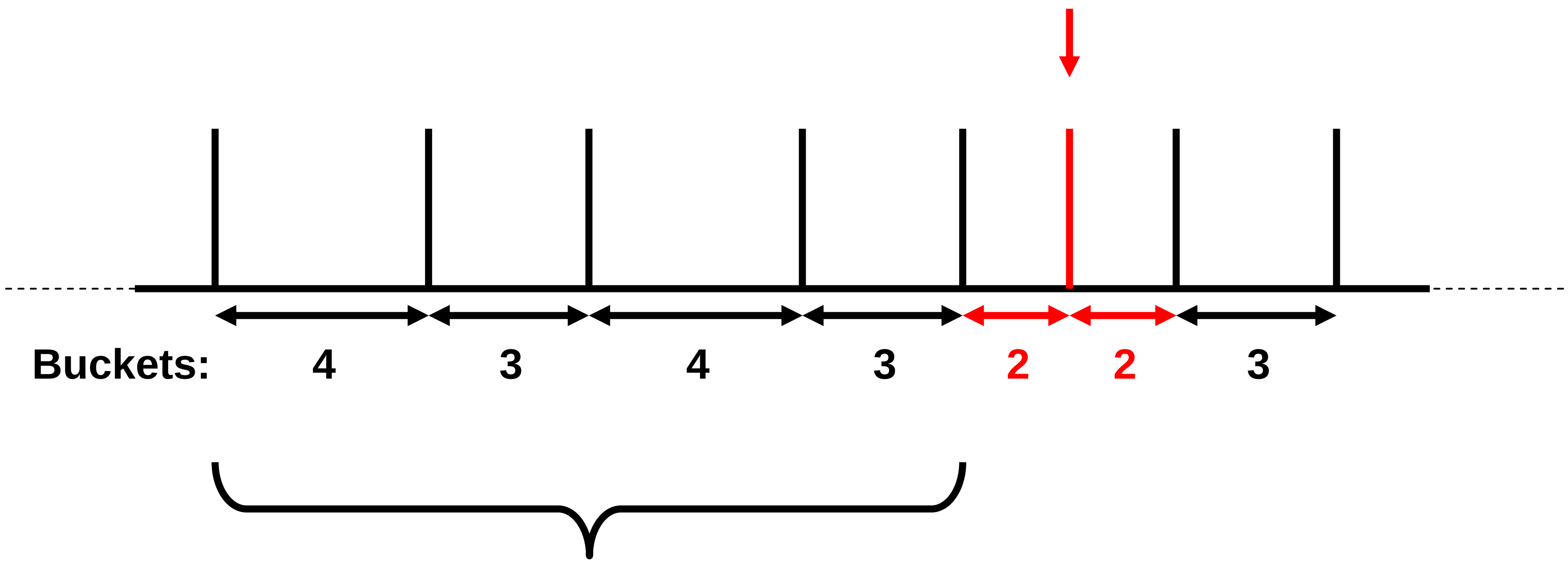
- Specific luminosity of observer bunch is lower than that of regular bunches above 0.4 mA, but is nearly the same below 0.4 mA.
  - Consistent with sideband behavior, and explanation that loss of specific luminosity is due to electron cloud instability.



Constant Cloud, Decaying Bunch Current Study

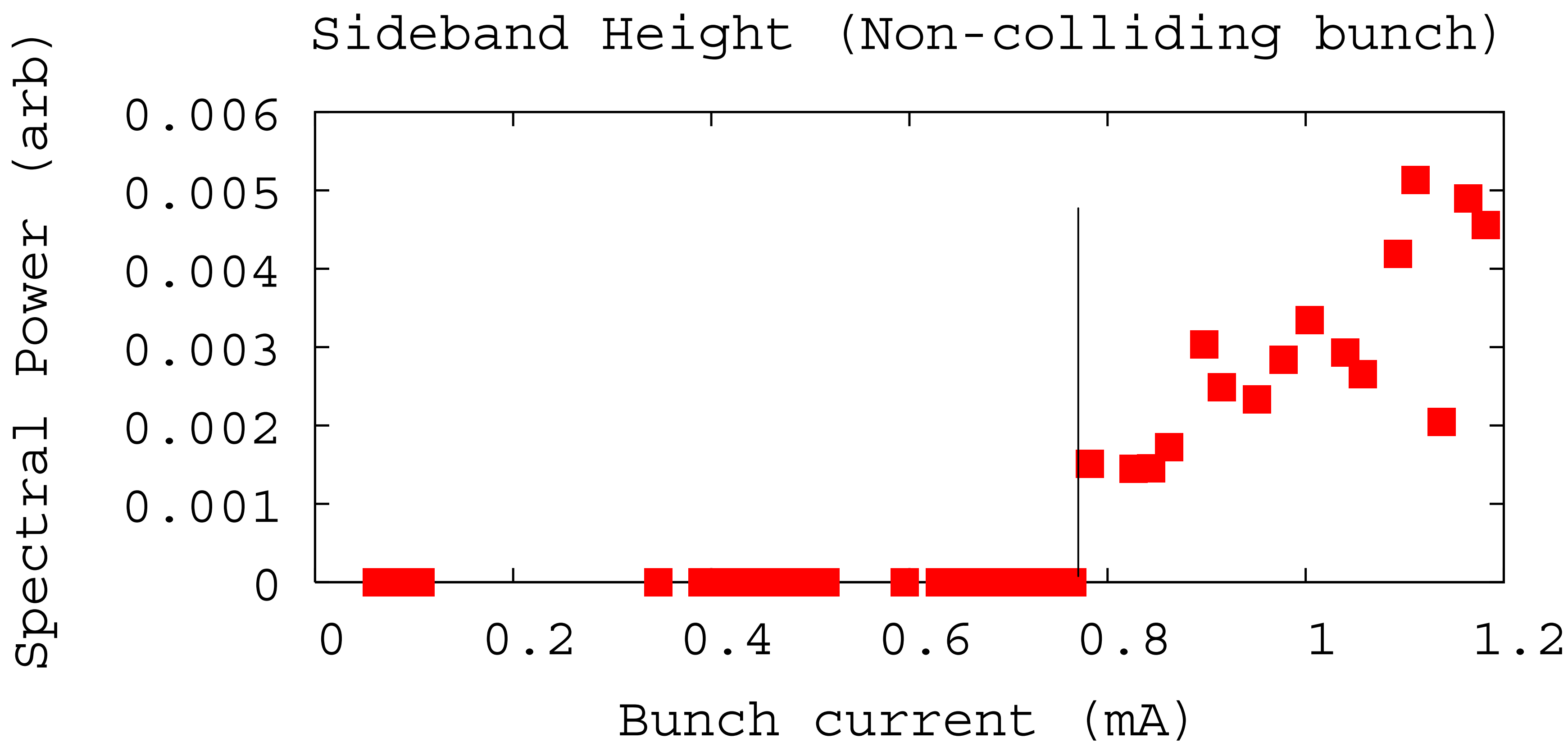
Fill Pattern:

Decaying Test Bunch



Regular physics pattern bunches
Average spacing: 3.5 buckets
Bunch current: 1.2 mA constant
(using continuous injection)

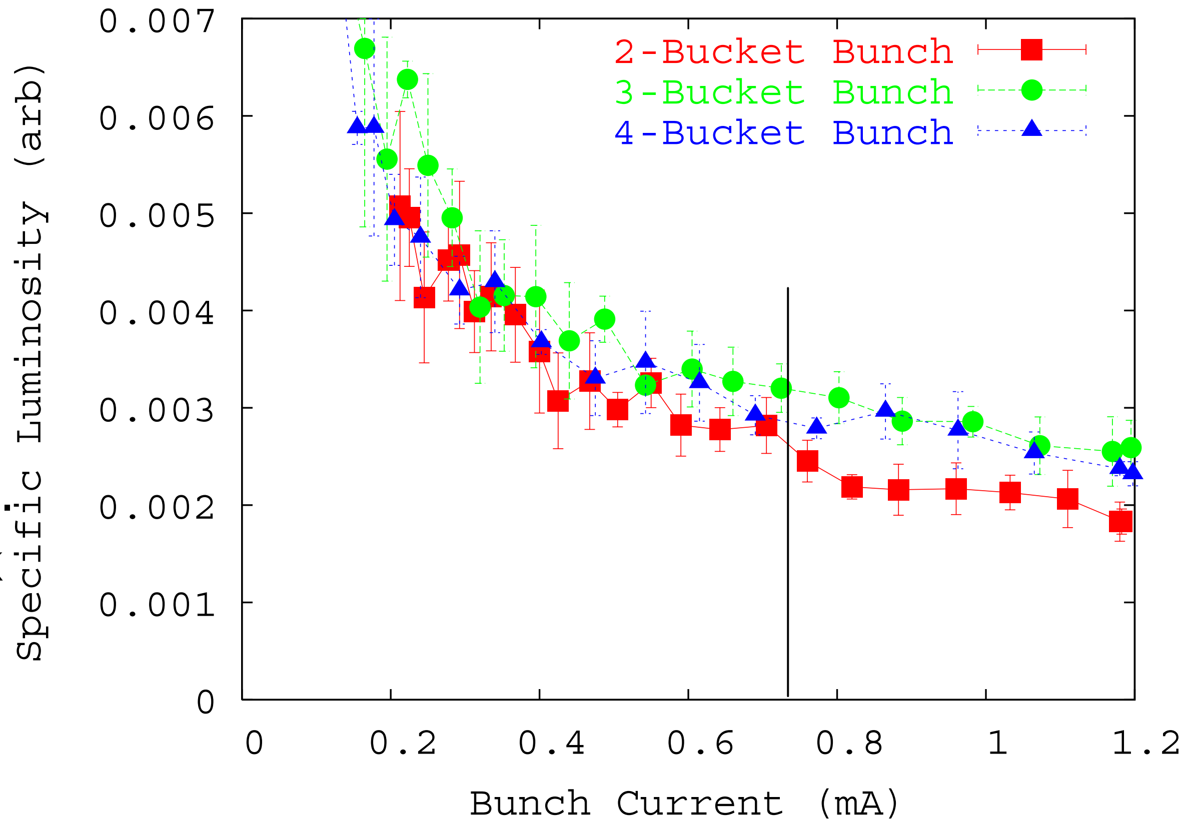
Constant Cloud, Decaying Bunch Current
Sideband Peak Heights



Sidebands disappear below test bunch current of ~0.75 mA

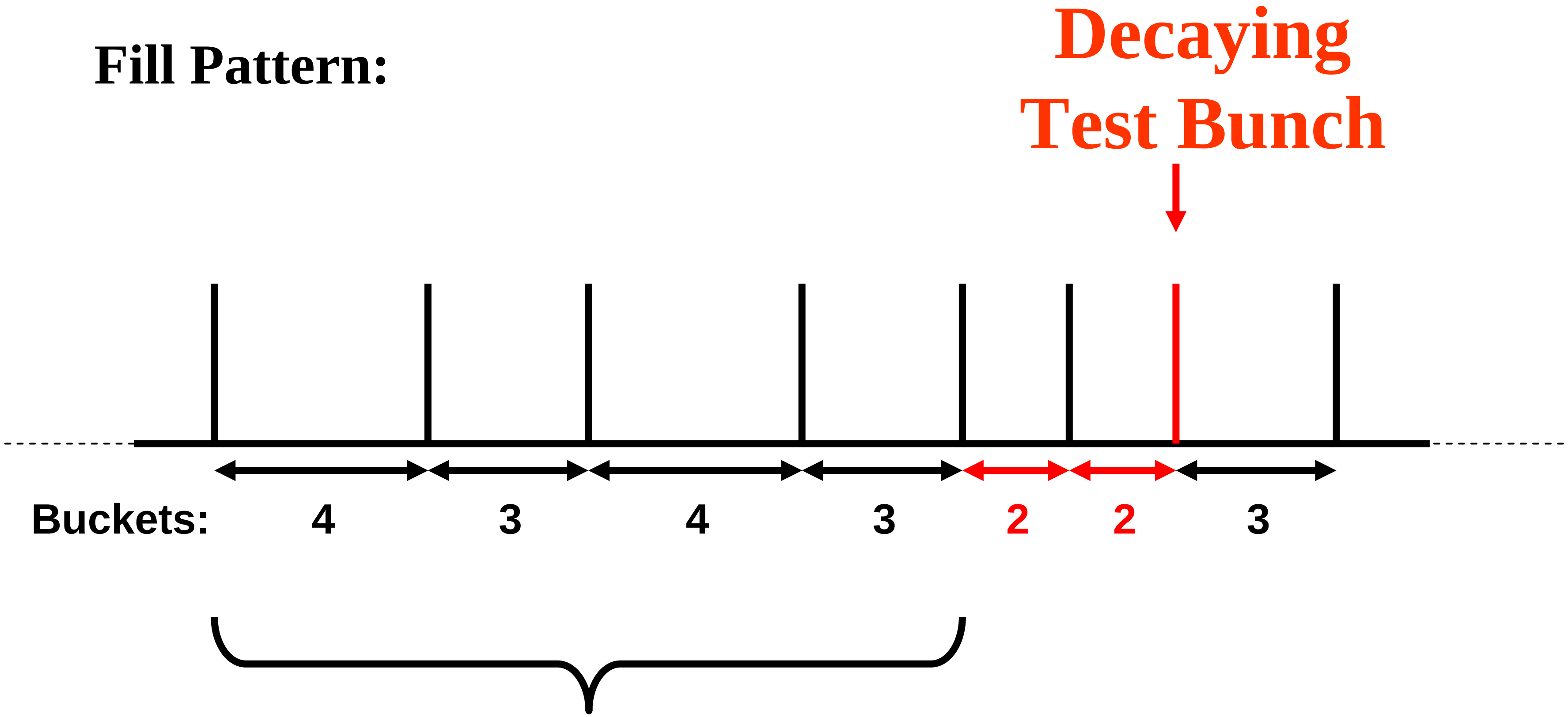
Constant Cloud, Decaying Bunch Current Specific Luminosity

- Specific luminosity of observer bunch is lower than that of regular bunches above 0.75 mA, but is nearly the same below 0.75 mA.
- Again, consistent with sideband behavior, and explanation that loss of specific luminosity is due to electron cloud instability.
- Also consistent with streak camera observations of vertical bunch size: bunch larger above ~0.8 mA.
  - H. Ikeda et al., PAC05 poster RPAT052.



Constant Cloud, Decaying Bunch Current
Study II

Fill Pattern:

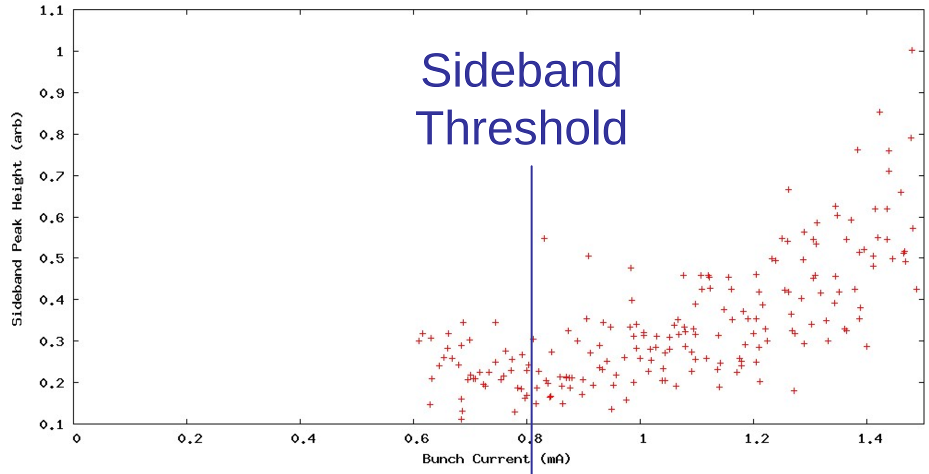


Regular physics pattern bunches
Average spacing: 3.5 buckets
Bunch current: 1.2 mA constant
(using continuous injection)

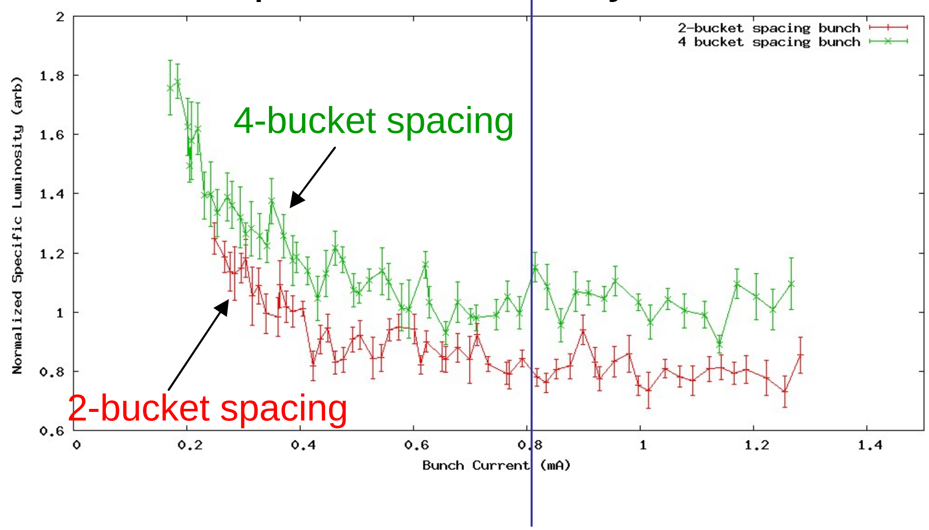
Sidebands and Spec. Lum.

- Sidebands disappear at around a bunch current of 0.8 mA.
- Specific luminosity of 2-bucket and 4-bucket spacing bunches do not merge at that point, however.
  - Possible that sidebands continue, but below noise level.
  - OR, possible indication of the presence of an incoherent component below the sideband threshold.

Sideband Peak Height

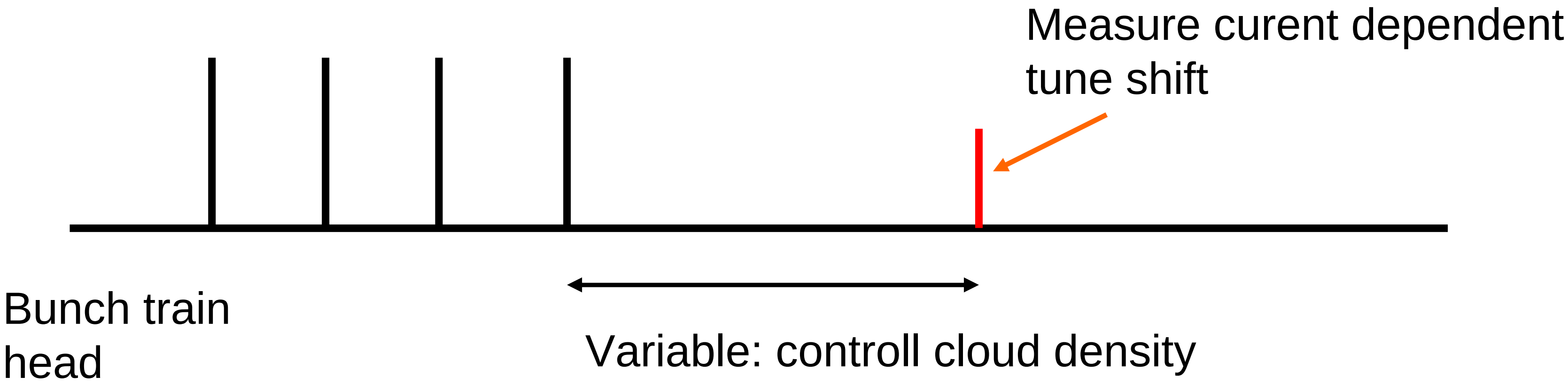


Specific Luminosity



Measurement of current dependent tune shift (Ieiri)

- The wake force is basically defocusing at $z<c/\omega_e$.
- Current dependent tune shift should be negative for low bunch current $\omega_e\sigma_z/c<1$ below the mode coupling threshold.



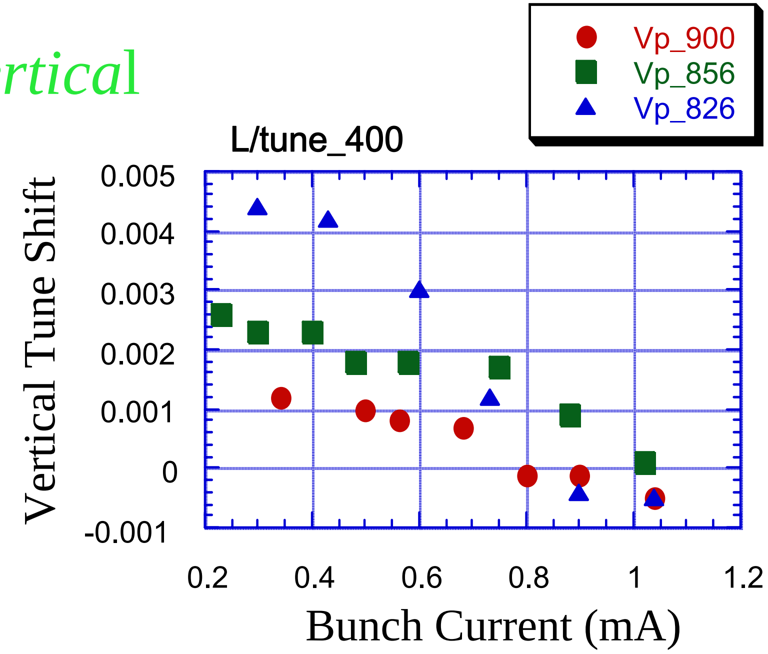
- Current dependent tune shift should have two component for $\omega_e\sigma_z/c<1$ and $\omega_e\sigma_z/c>1$ below the mode coupling threshold (low cloud density).

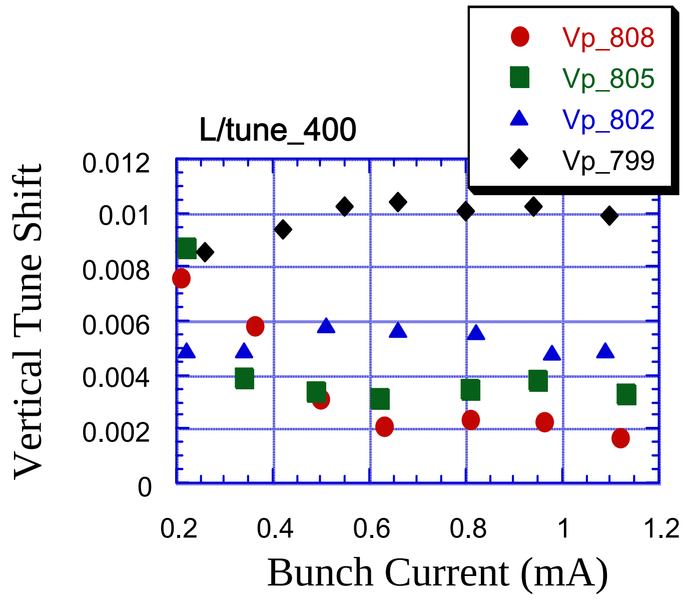
$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$$

- Near the threshold (high cloud density), tune shift behavior is disturbed by coupling with another mode.

Measurement 1 : Current-Dependent Tune-Shift (CDTS)

Vertical





Vp_799 & 802: high cloud density

Vp_805 & 808: low cloud density

Vp_856 & 900: No cloud

- The CDTS is not linear.
- Approximated by two lines.

$I>0.6$ mA, $\omega_e \sigma_z / c > 1$

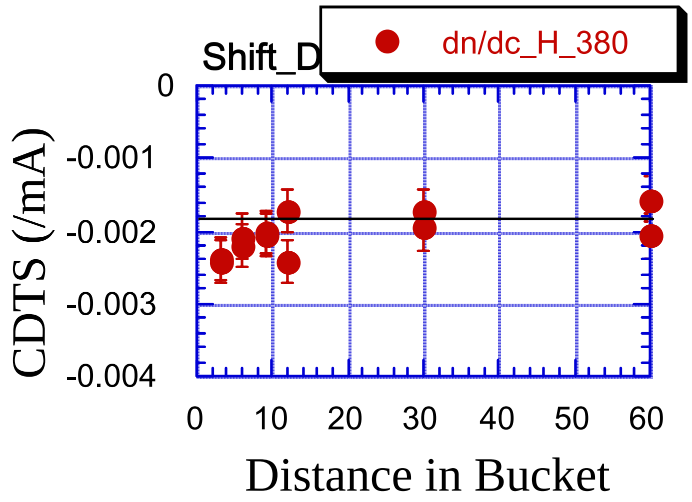
T. Ieiri KEKBreview 2006

Comment by KO

Measurement 1 : Current-Dependent Tune-Shift (CDTS)

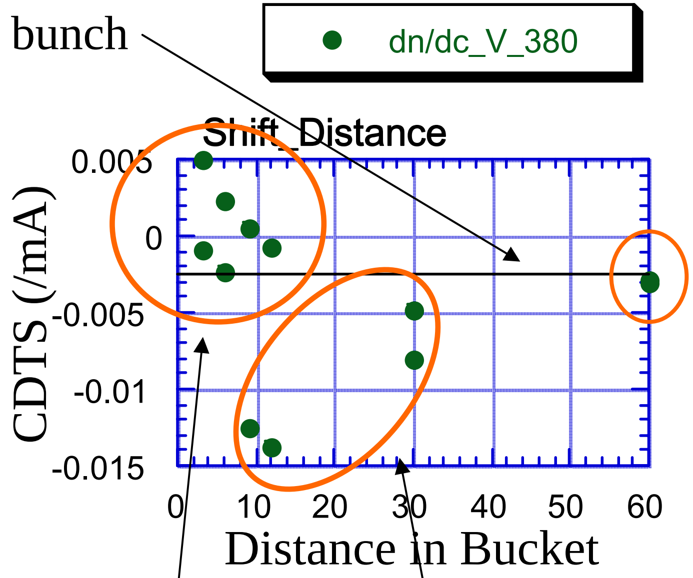
- Two values correspond to the CDTS around 0.4 mA and 0.8 mA.

Horizontal



Vertical

CDTS of single bunch



- The vertical CDTS abruptly changed around D=10.
- Positive CDTS at D<10.

Disturbed by another coupled mode, perhaps Comment by KO.

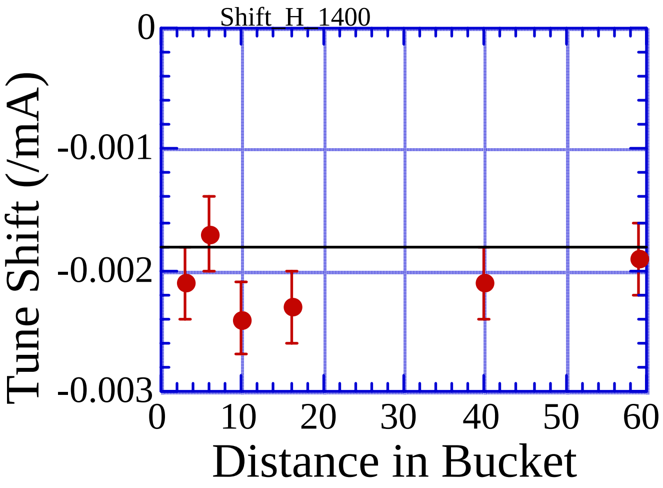
Defocusing nature of the wake at low cloud density

T. Ieiri KEKBreview 2006

Measurement 2 : Current-Dependent Tune-Shift (CDTS)

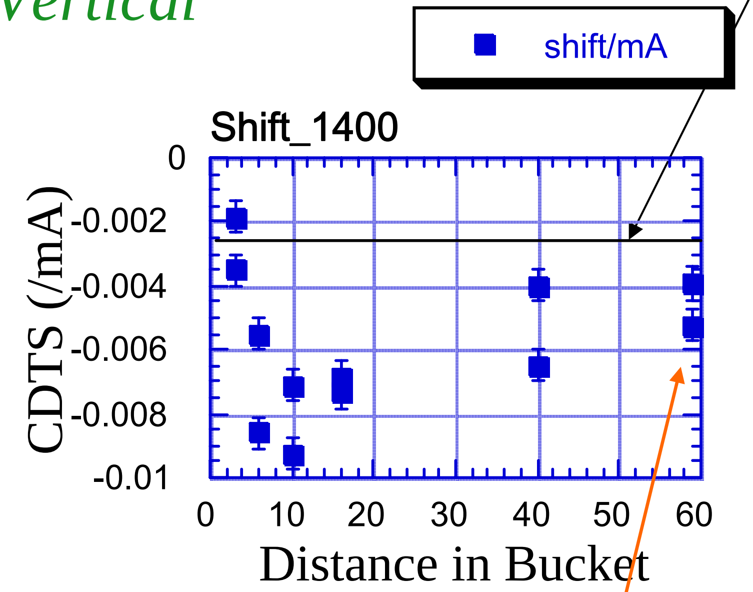
With solenoid

Horizontal



Vertical

CDTS of Single Bunch



- Horizontally, completely damped by solenoids.
- Vertically reduced, but the structure is preserved.

T. Ieiri KEKBreview 2006

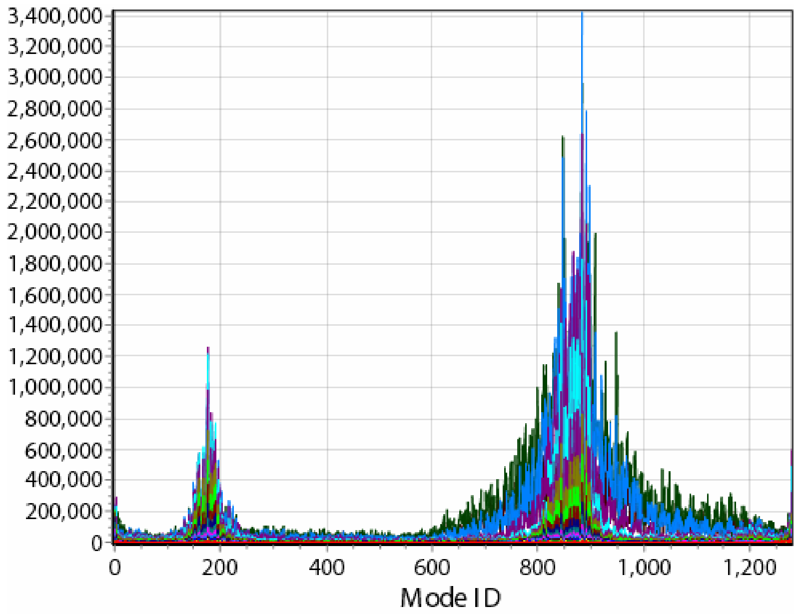
Electrons remain in solenoid,
if the accuracy is sufficient.

Comment by KO

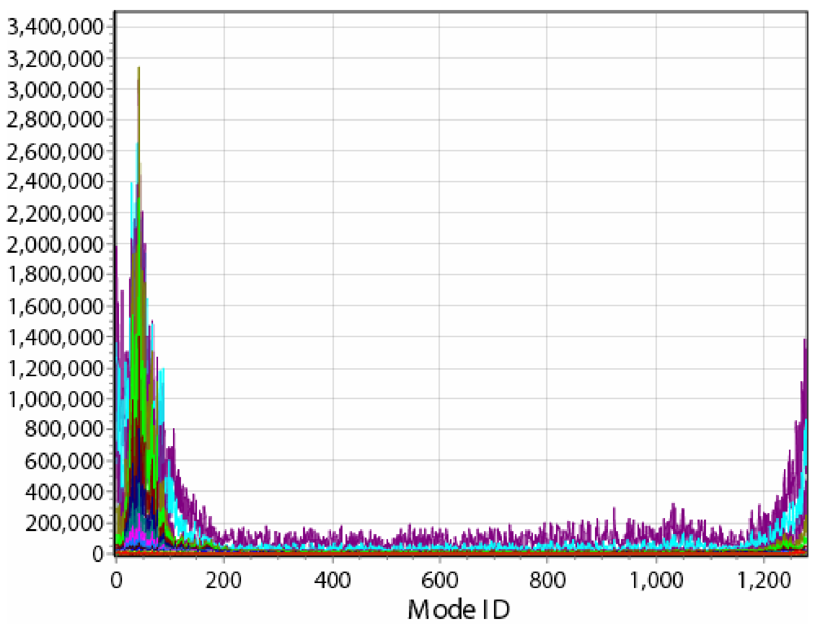
Coupled bunch instability

- Fast amplitude growth which causes beam loss has been observed.
- The mode spectrum of the instability depends on excitation of solenoid magnets.

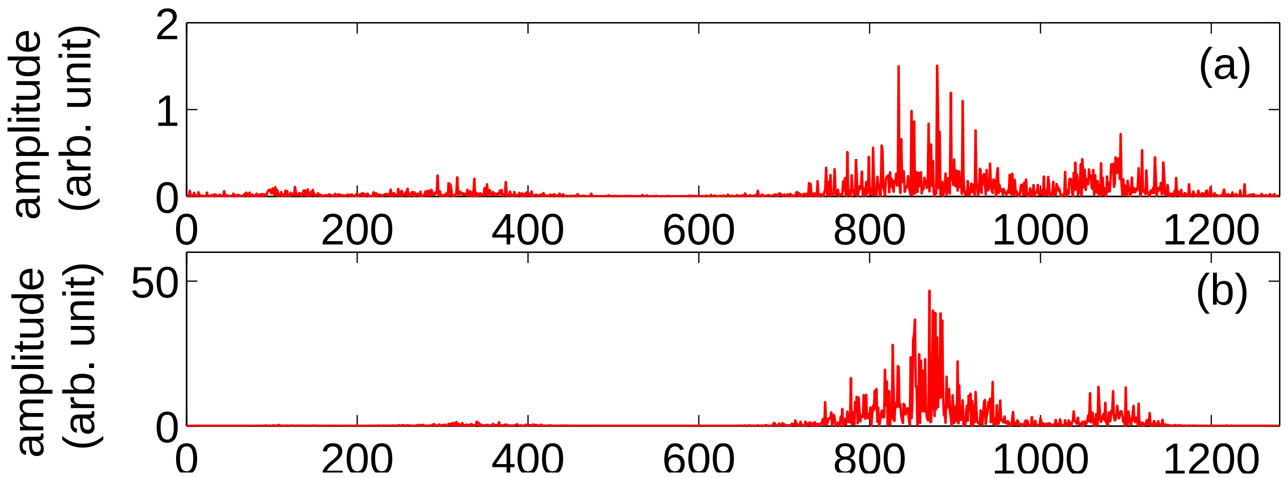
Solenoid off



on (measurement)

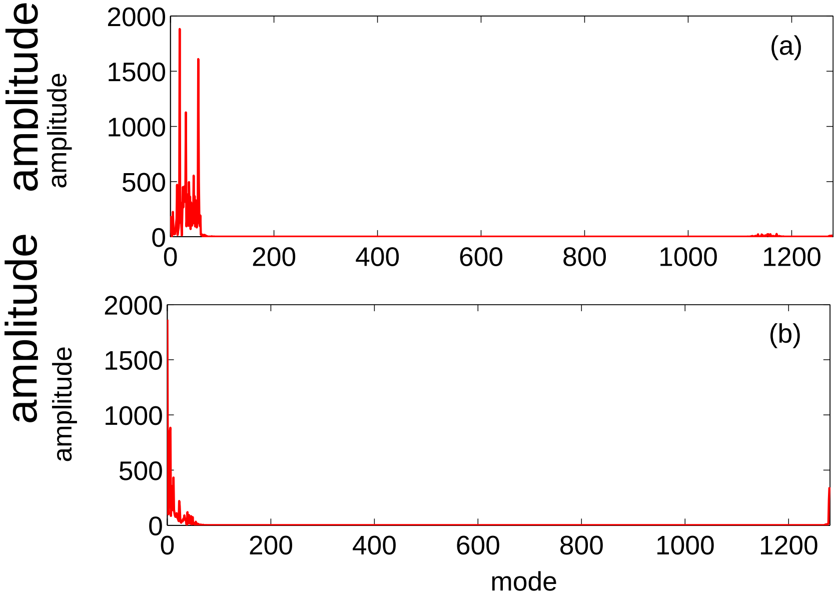


- Drift without solenoid, δ_{2max}=1.5



X, illum

Y, illum



Solenoid OFF

Solenoid ON

Summary

- Various beam measurements have been done for electron cloud instability in KEKB.
- Most of measurements can be explained by theory and simulation quantitatively. They are precision measurements.
- Measurements at lower emittance, high $\omega_e\sigma_z/c$, will be carried out.

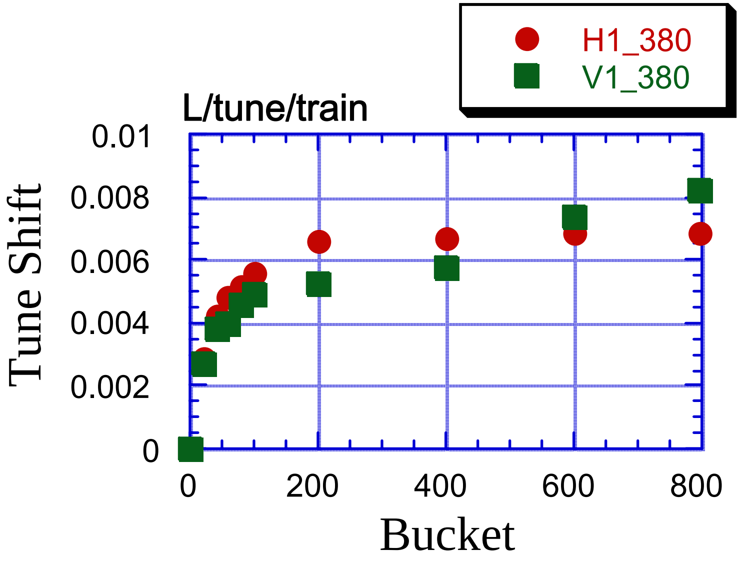
ECLOUD07

- Held in Daegu in Korea, April 9-12 or 13 2007.

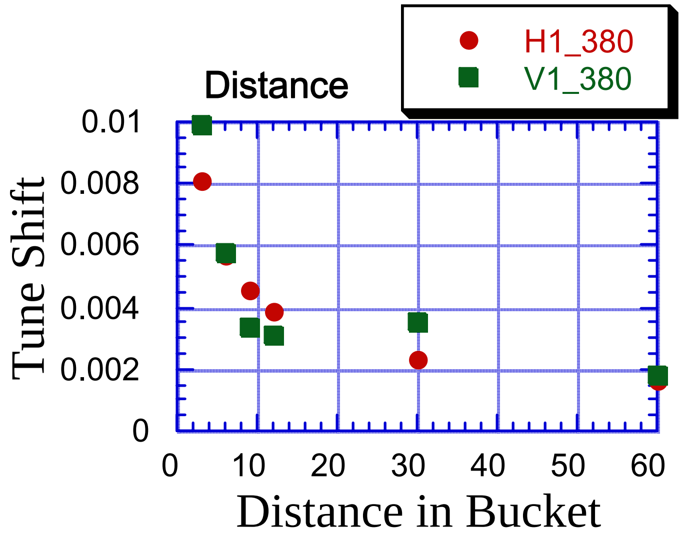
Measurement 1 : Bucket-Dependent Tune-Shift (BDTS)

Without Solenoids

Along Train



After Train

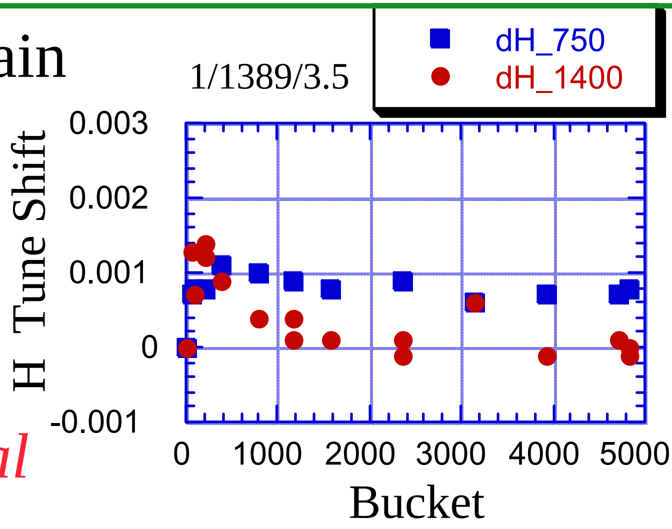


Note: The tune of the leading bunch of a train is used as a reference.

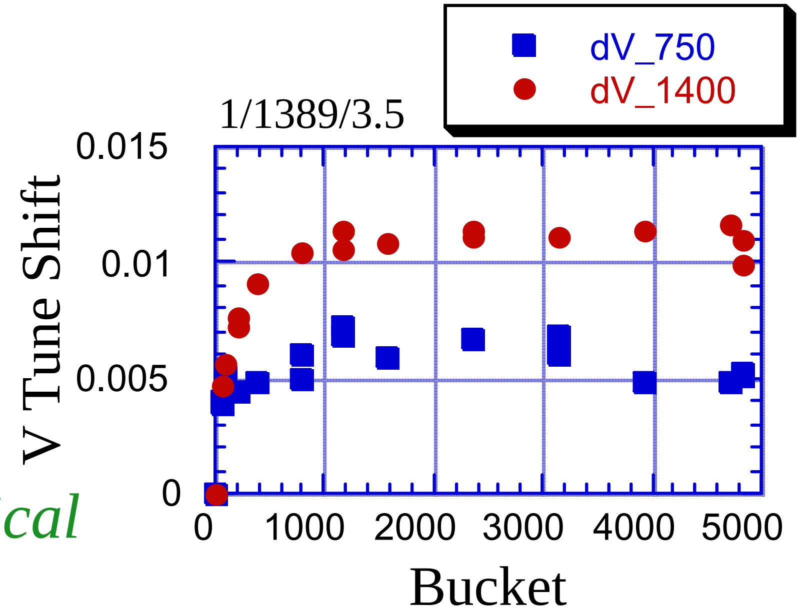
Measurement 2 : Bucket-Dependent Tune-Shift (BDTS)

With Solenoids

Along Train



Horizontal



Vertical

After Train