Variations of Betatron Tune Spectrum due to Electron Cloud Observed in KEKB

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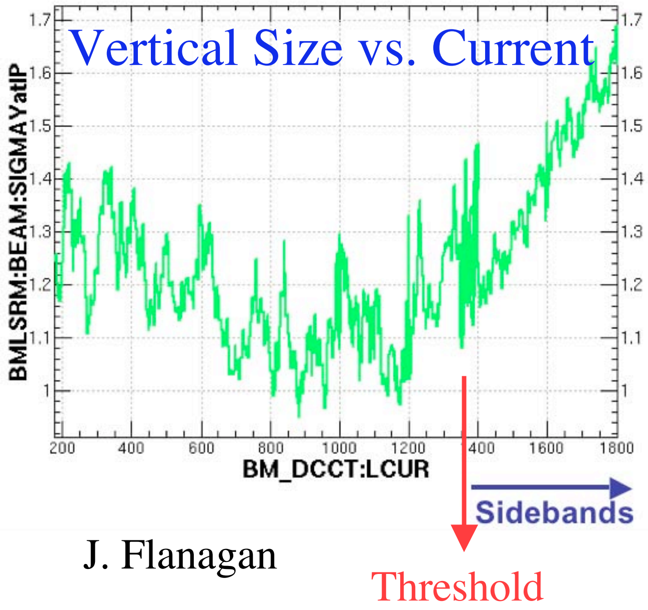
Thanks to H. Fukuma, Y. Ohnishi and M. Tobiyama

Outline

- Introduction: Motivation, KEKB
- Tune Spectrum: Tune Shift, Tune Slope, Width
- Experiment: Method, Tune Monitor, Conditions
- Results: Measurement without Solenoid
- Summary

Motivation

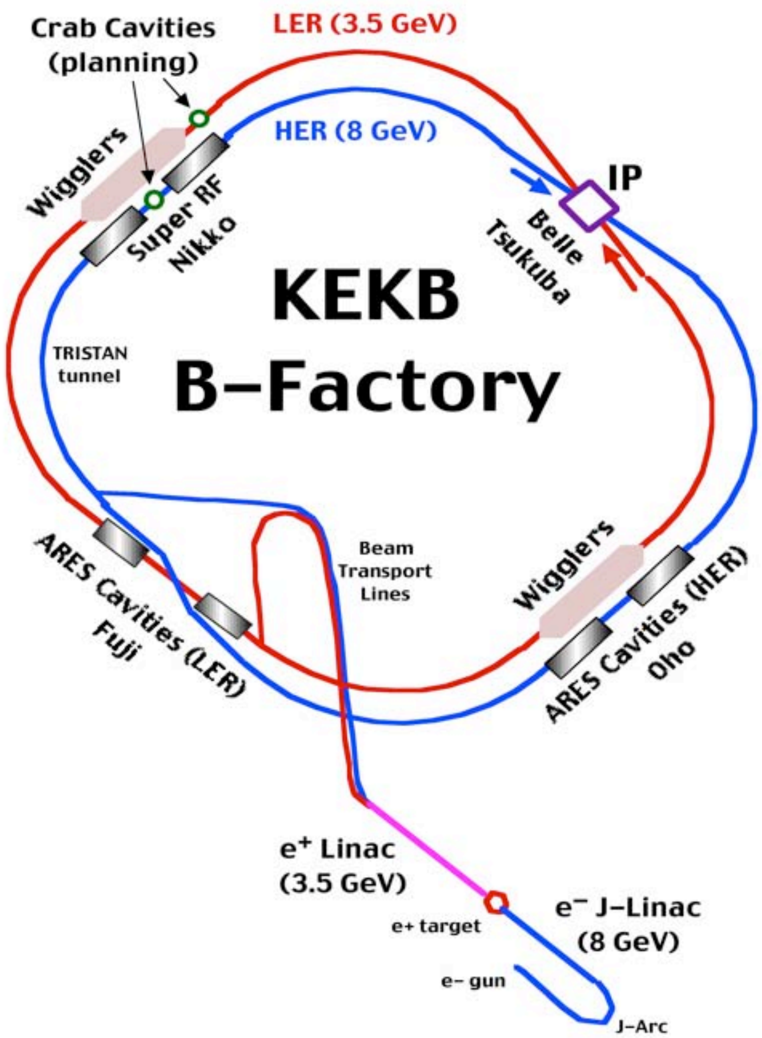
- The LER suffers from an increase of the vertical beam size.
- Caused by a strong head-tail instability due to electron clouds.
- A resonator-like wake is proposed to explain the instability.
- The mechanism is not fully understood.
- Can the tune spectrum catch the wake?
- The detection is an integrated value over a whole bunch.



J. Flanagan

KEKB

- Low Energy Ring
  - 3.5GeV (positron)
- Circumference
  - 3018m
- Harmonic Number
  - 5120
- Bunch Spacing
  - 6 or 8 ns
- Bunch Intensity
  - 1.2 to 7.2x10^{10} /bunch



Tune Slope and Tune Shift

- Electro-magnetic forces acting on a bunch change the tune.

$$\boxed{\Delta\nu_y = \frac{1}{4\pi E}\oint \beta \frac{dF_y}{dy} ds}$$

F_y: Forces acting a bunch
$\Delta\nu>0$: Focusing, $\Delta\nu<0$: Defocusing

- Short-range wake due to impedance and electron cloud.

$$\Delta\nu = -\frac{T_0 I_b}{4\pi E/e}\left(\sum_i \beta_i k_{i\_imp} + \sum_j \beta_j k_{j\_ec}\right)$$

k_{i_imp} : kick factor by impedance V/(Qm) Defocusing wake

k_{j_ec} : **kick factor by electron cloud** V/(Qm) ??

$$\Delta\nu/\Delta I_b \propto \left(\sum_i \beta_i k_{i\_imp} + \sum_j \beta_j k_{j\_ec}\right)$$: **Tune slope**

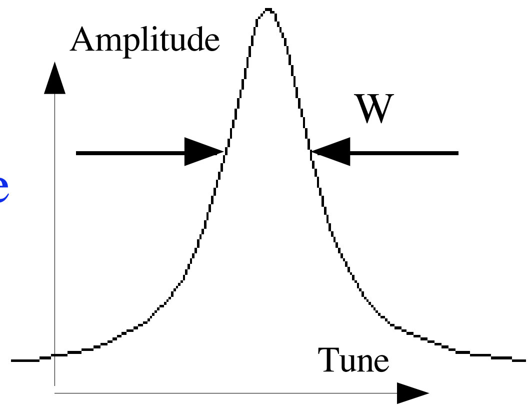
- Space charge due to electron cloud causes a positive **tune shift**.

$$\Delta\nu_y = \frac{r_e}{2\gamma}\int \rho\beta_y ds$$

ρ: cloud density /m^3

Spectrum Width (Tune Spread)

A Resonant Curve
in Tune Spectrum



- Width depends on various effects.

$$W_m = \sqrt{W_b^2 + W_c^2 + W_0^2}$$

W_b: Head-tail damping, Beam-beam tune spread, Cloud effect?
W_c: Feedback damping, Nonlinear magnetic field, Fluctuation of magnetic field, ---
W_0: Resolution bandwidth of an analyzer

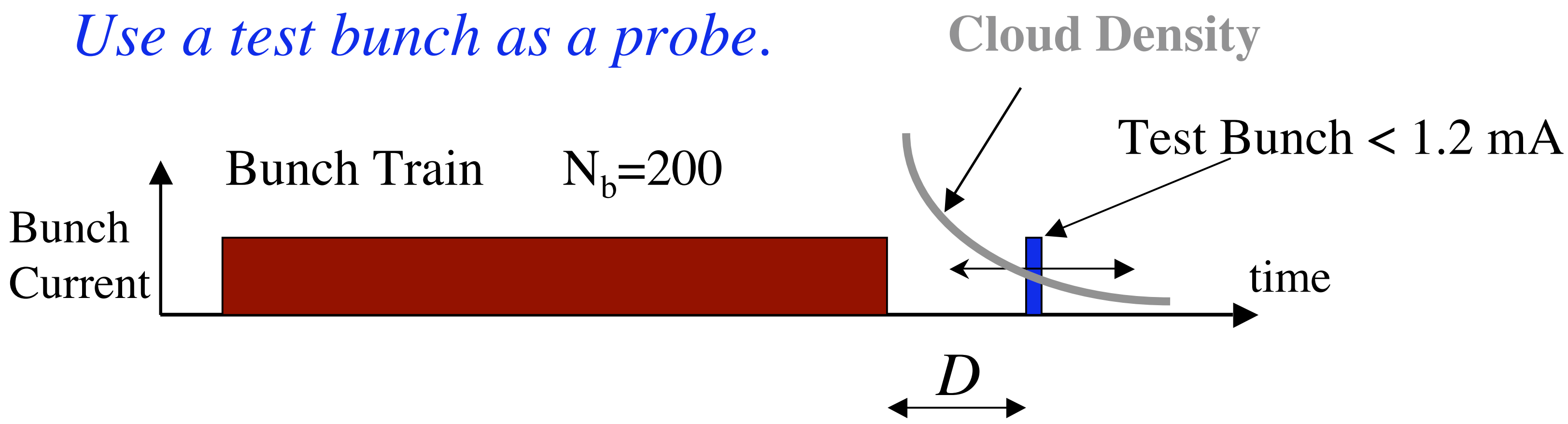
- We want to measure Width due to Electron Cloud.
- it can be measured, by comparing bunch-by-bunch tune spectra.

$$\boxed{\Delta W_{ec} = \pm\sqrt{\left|W_m^2 - W_{m0}^2\right|}}$$

W_{m0} : Width w/o cloud effect
ΔW_{ec}>0: damping
ΔW_{ec}<0: anti-damping

How to measure cloud effect

Use a test bunch as a probe.



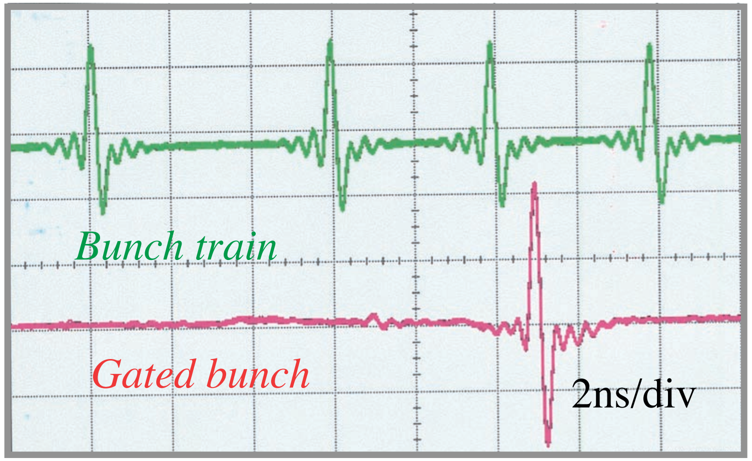
1. A bunch train was stored on ahead.
   Cloud remains and rapidly decays after passing through a train.
2. A test bunch was injected one by one from behind.
3. The tune spectrum was measure during each injection
   under constant train-current.

Gated Tune Monitor

Specifications:

- Resolution 1~2 x10^{-4}
- Sweep Time 1.9 sec
- Gate Isolation >40 dB
- Dynamic Range > 60 dB
- Noise Level ~0.3μm

<Bunch Signal from Button>



Note:

- Excite only a bunch to be measured with a constant level.
- Detect the lowest betatron frequency of a specific bunch.
- Transverse feedback is off for a measured bunch; no feedback damping effect.
- Other bunches are damped by feedback; no coupled-bunch instability.
- Measure a non-collision bunch; no beam-beam effect.
- Used a 2nd tune monitor to watch tune variations due to other reasons.

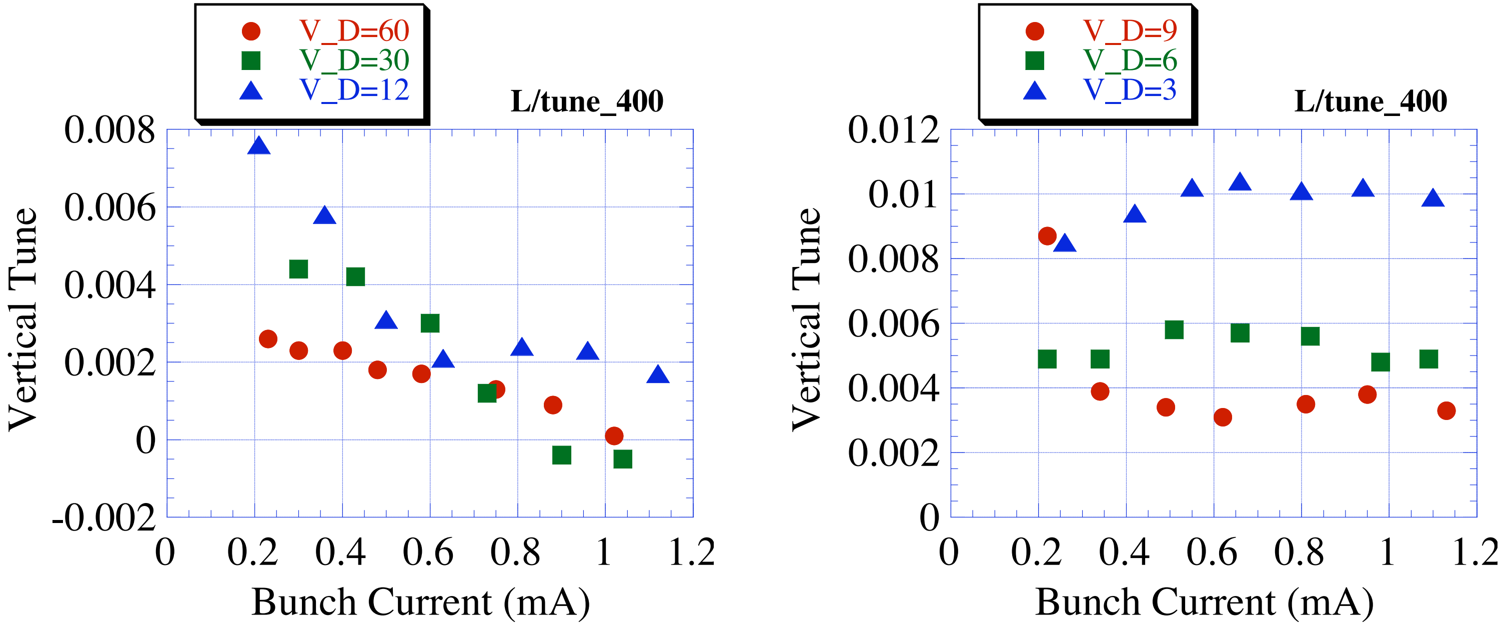
Machine Conditions

Beam, Energy	Positron, 3.5 GeV	
Bunch Structure of Train	4/200/4*	
Solenoid Field	OFF	
Bunch Current in Train	0.5 mA	0.7mA
Instability Threshold Condition	just below	above
Synchrotron Tune ν_s	0.025	
Chromaticity ξ_x, ξ_y	1.6, 4.6	

*: n/m/l : number of train/ number of bunches in train/ bunch spacing in RF unit

Current-Dependent Vertical Tune

After a train



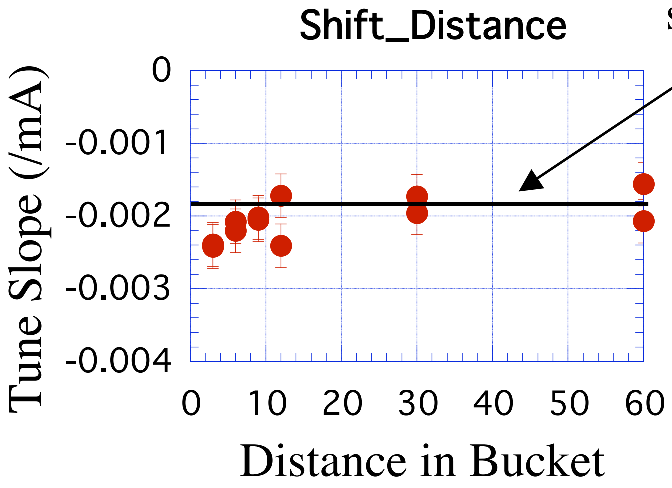
- Tune of the head bunch in train is used as the reference.

- The tune does not change linearly.
- Approximated by two slopes, around 0.4mA and 0.8mA.

Tune Slope

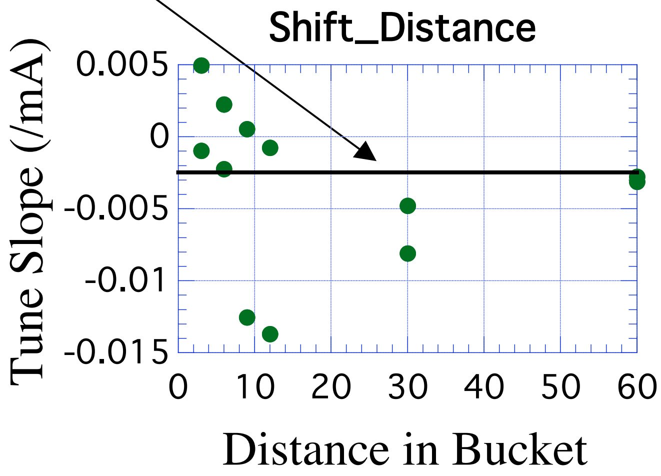
- Two values correspond to the slope around 0.4 mA and 0.8 mA.

Horizontal



Tune slope in single bunch

Vertical



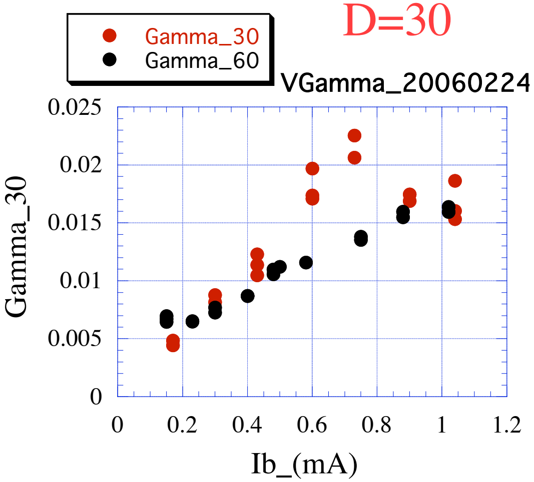
- Horizontal tune slope shows no significant change.
- Vertical tune slope largely changes around D=10, depending on bunch current.
- Positive tune slope (focusing wake) at D<10.

Width vs Bunch Current

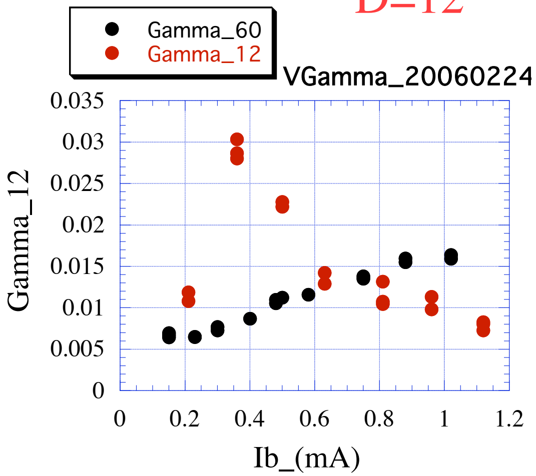
- Width has a peak at large D.
- Width decreases at small D and in high bunch current.

- Black dots are reference widths measured at D=60.

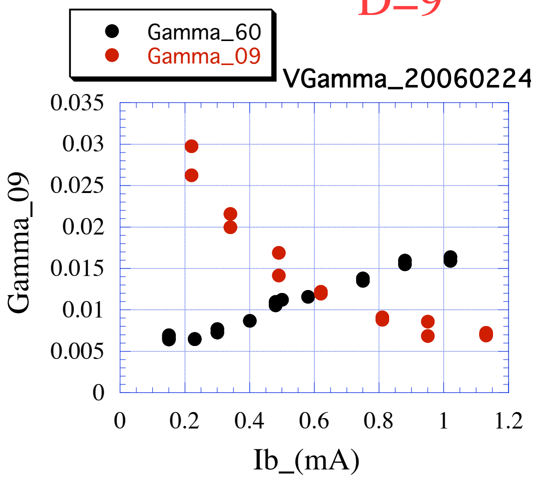
D=30



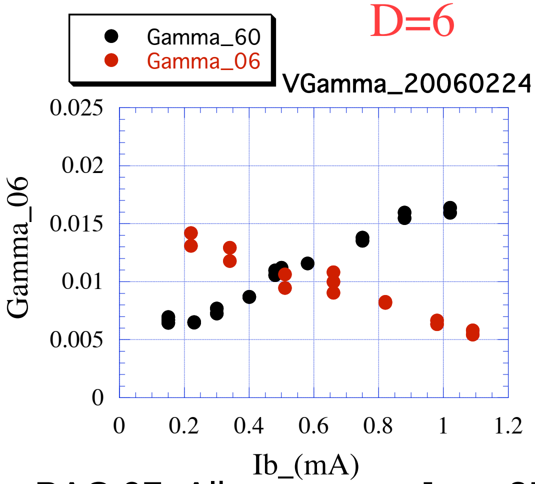
D=12



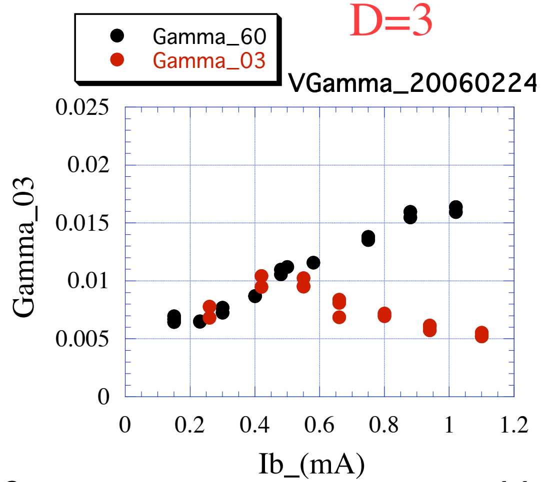
D=9



D=6

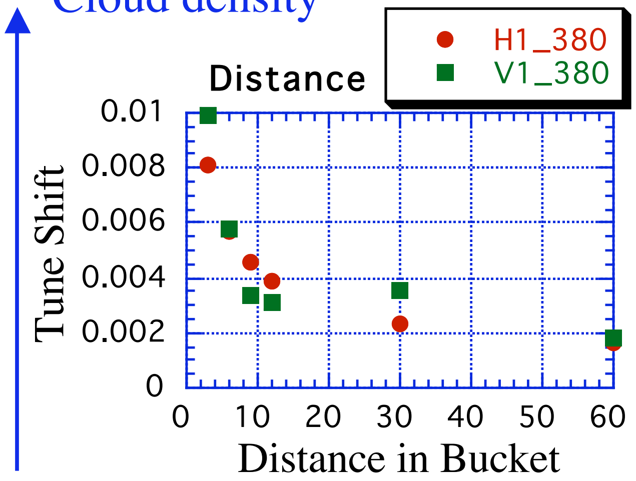


D=3



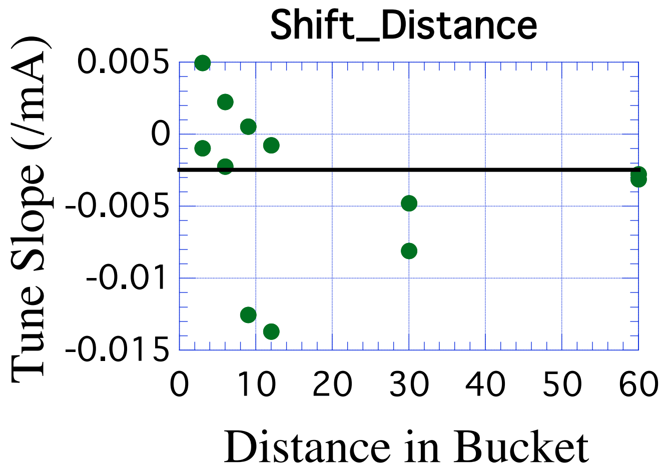
Tune Shift, Tune Slope and Width vs Distance

Cloud density



Focusing

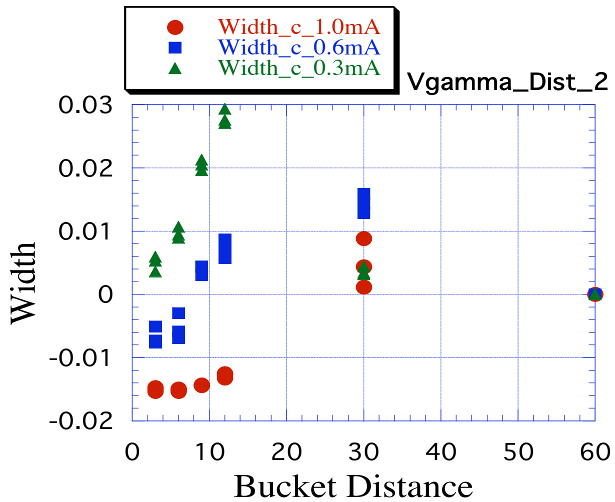
Defocusing



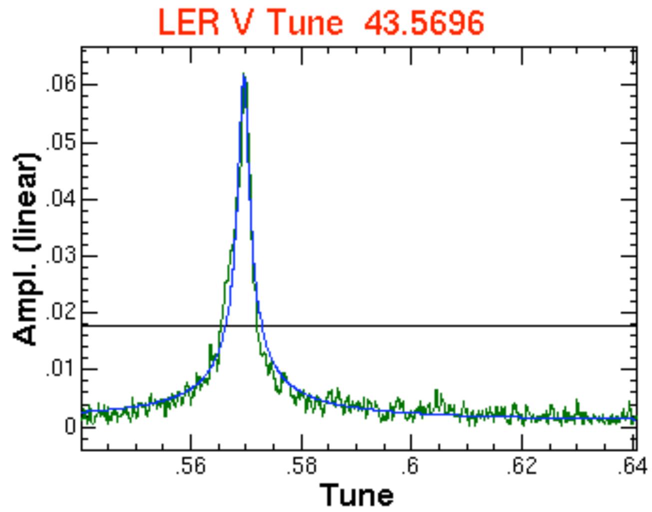
$$\Delta W_{ec} = \pm\sqrt{\left|W_{D<60}^{2} - W_{D=60}^{2}\right|}$$

Damping

Anti-damping



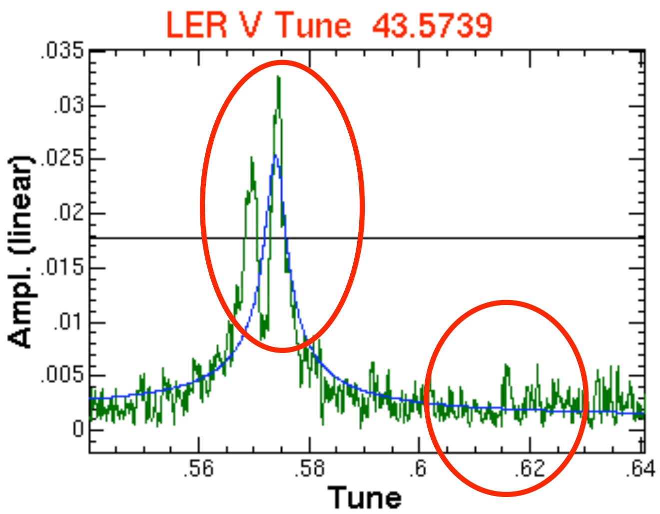
Tune Spectrum above threshold



Train:380 mA
just below threshold
D=3

$$\Delta\nu = 0.010$$

$$\rho_e = 1.4\times10^{12}\ \mathrm{m}^{-3}$$



- Observed two-peak spectrum and *sideband* (?)

Train:580 mA
above threshold
D=3

$$\Delta\nu = 0.020$$

$$\rho_e = 2.8\times10^{12}\ \mathrm{m}^{-3}$$

Why does the spectrum change ?

- Oscillatory wake force is proposed.
  - Defocusing and focusing forces alternatively change.
- The wavelength is comparable to the bunch length.
- It depends on bunch density.
- So, wake properties may change, depending on bunch intensity.

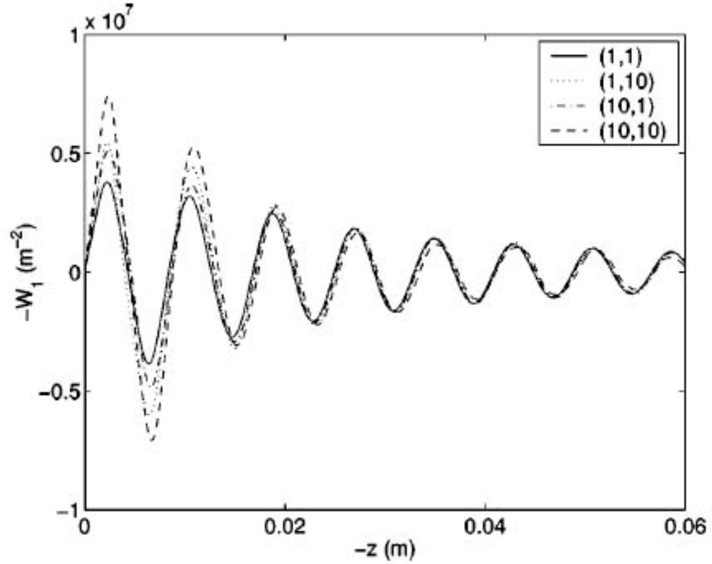


FIG. 1. Vertical wake force (W_1) induced by an electron cloud. Each line corresponds to a different size of the electron cloud: (1,1), (1,10), (10,1), and (10,10), in units of (σ_x, σ_y).

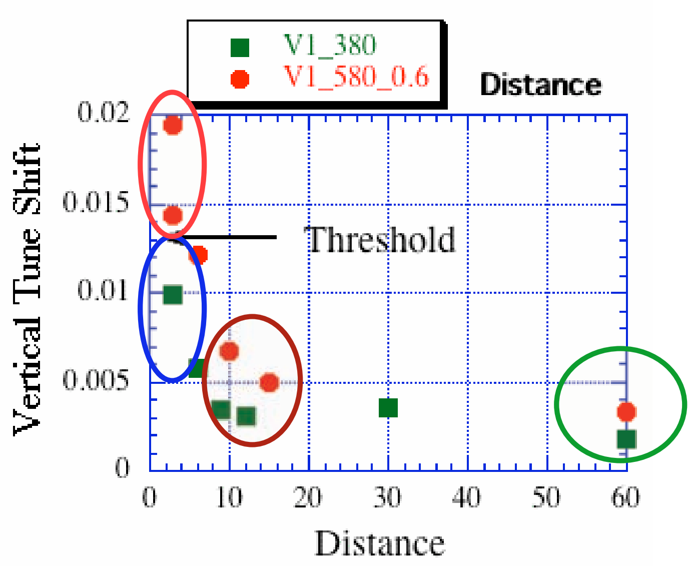
- Wake function : $$W_1(z) \propto \sin(\frac{\omega_R}{c} z)$$

From K. Ohmi et al.,
Physical Review E 65, 016502 (2002)

- Electron frequency:

$$\omega_R \approx \omega_e \qquad \omega_e = c\left(\frac{2 r_e N_b}{\sigma_y(\sigma_x + \sigma_y)\sqrt{2\pi}\sigma_z}\right)^{1/2} \qquad \begin{array}{l} \omega_e \approx 2\pi \cdot 30 \sim 40\,\mathrm{GHz} \\ \lambda_e \approx 7.5 \sim 10\,\mathrm{mm} \end{array}$$

Summary



- Tune shift and width (spread) were measured behind a bunch-train using a test bunch.

1. Spectrum dynamically varied, dividing into 4 regions.

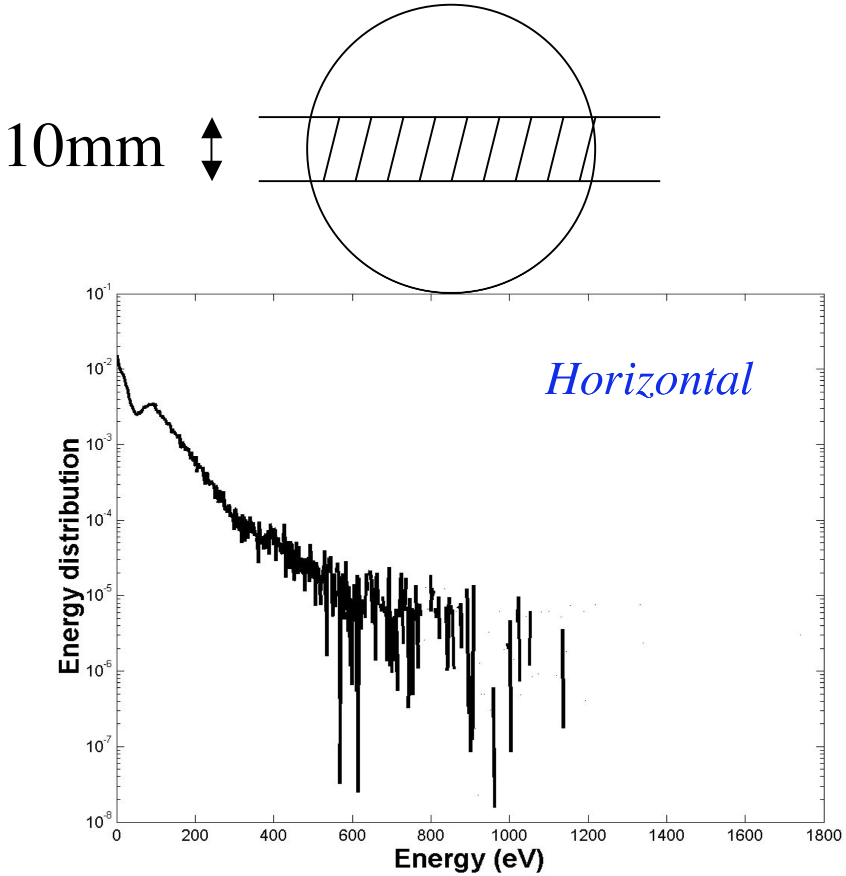
- **Region 0:** E-cloud effect is small.
  Head-tail damping and negative tune slope due to impedance.
- **Region I:** The cloud density just grows.
  Large negative tune shift slope (defocusing wake) and wide tune spread.
  Suggest nonlinear fields and/or a change in the cloud distribution.
- **Region II:** High cloud density just below threshold
  Tune slope changed from negative to positive (focusing wake).
  Narrow tune spread or Anti-damping effect
- **Region III: Higher cloud density above threshold**
  Positive tune slope with narrower tune spread
  Splitting tune spectrum and go to instability

Summary (cont'd)

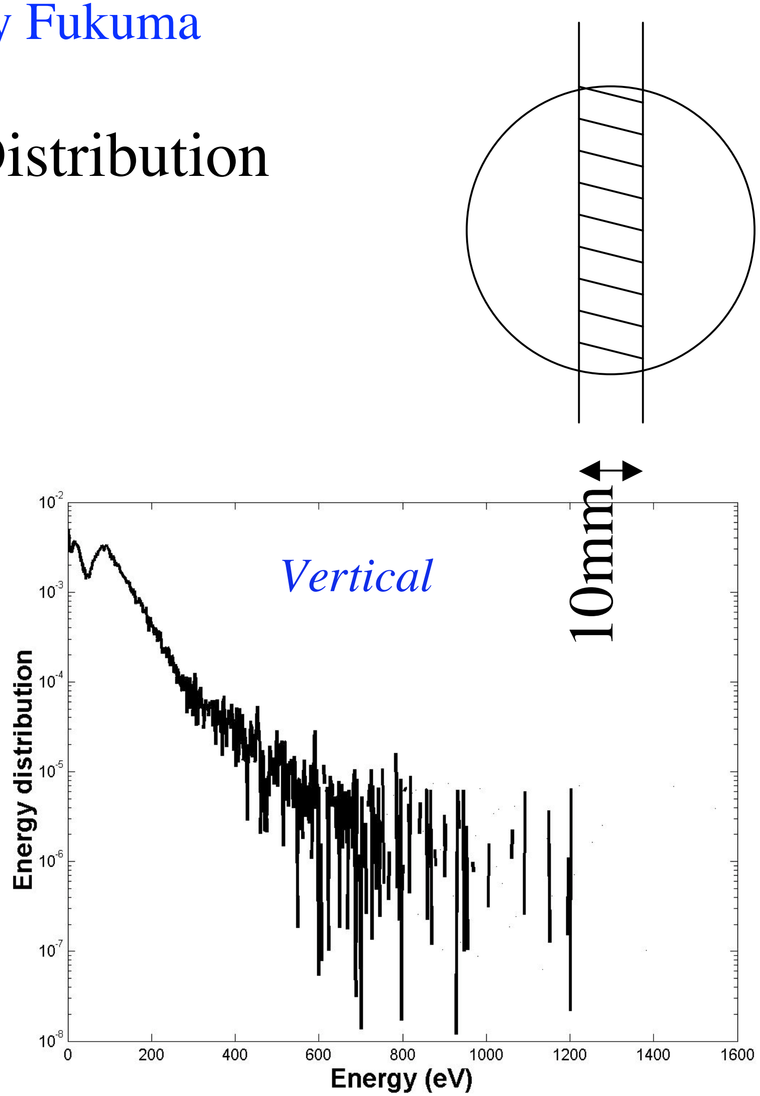
2. **We believe the variations in the tune slope and in the width are related to alternating wake field.**
3. **Width is a good parameter for evaluating nonlinear tune-shift.**
4. **Horizontal width was small and almost constant.**
   - **Tune slope was negative and linear.**
   - **No Wake effect, although tune-shifts were comparable.**
5. **Need to confirm these results including simulation.**

Extra: Simulation (1) by Fukuma

Electron Energy Distribution



abs(y)<5mm

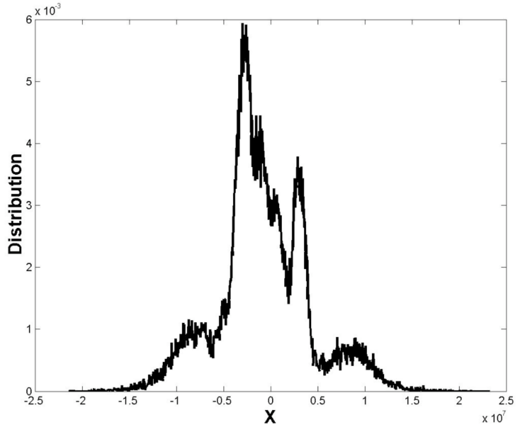


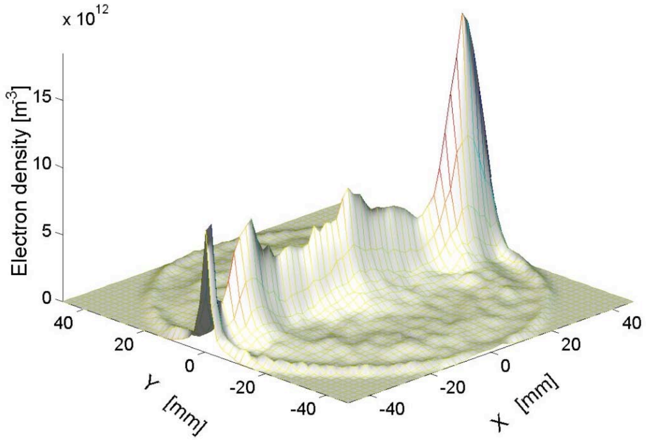
abs(x)<5mm

Extra: Simulation (2) by Fukuma

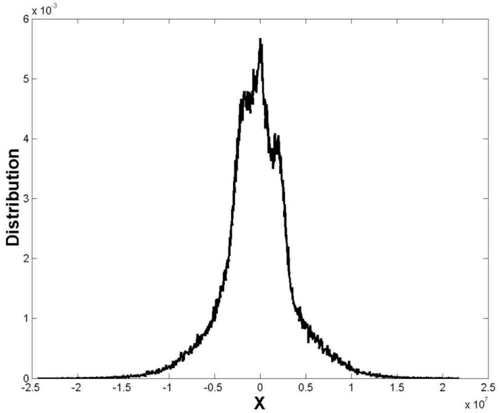
- Velocity (Vx) & Cloud distributions

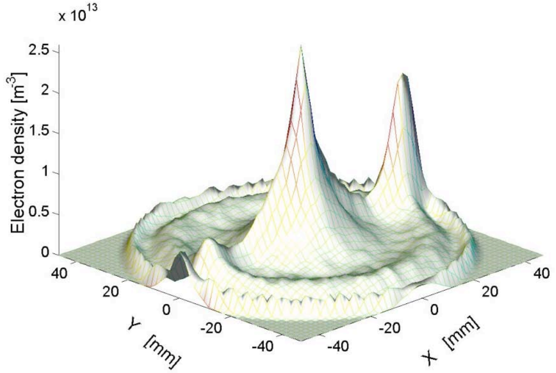
#6th bunch





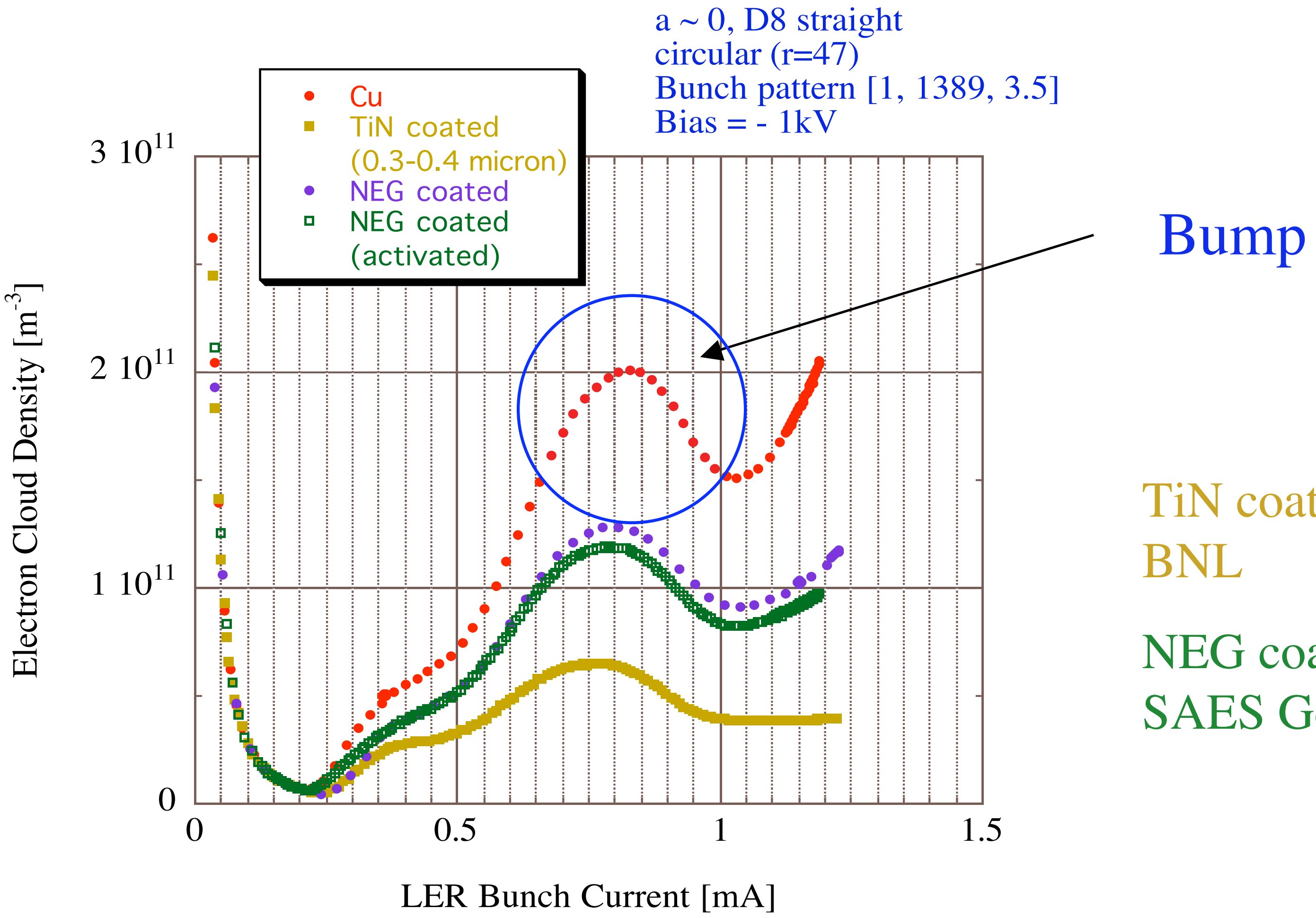
#50th bunch





Direct measurement of Electron Cloud Density

From 2007 KEKB Review
By Kanazawa

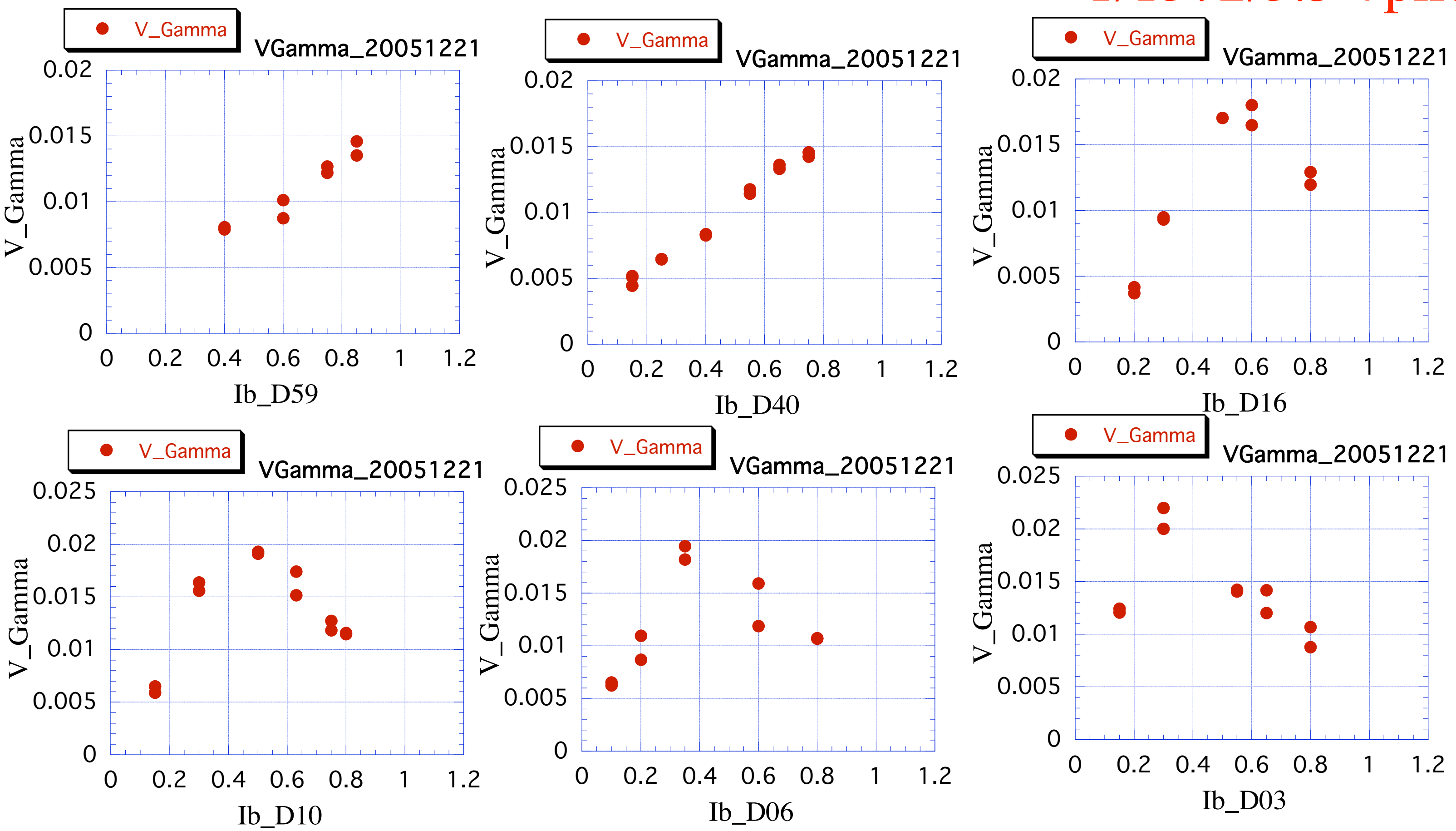


TiN coating: BNL

NEG coating: SAES Getters

Width vs Bunch Current with Solenoids

1/1372/3.5 +pilot



- Maximum width shifts to lower current as the cloud density increases.
- Width is larger than that in solenoids off.