Tune/Orbit Measurements

T. Ieiri

Thankful contributions by:
H. Fukuma, Y. Funakoshi, M. Masuzawa, Y. Ohmi, Y. Ohnishi and M. Tobiyama

Topics I : Measurement of Beam-Beam Kick

What to be done:

• The effective horizontal beam size at IP was measured using a linear part of a beam-beam kick under various conditions.

Outline:

• Beam-beam kick detection
• Measurements with calculation
  - Crab ON/OFF
  - Emittance change
  - Intensity change
• Summary

Beam-Beam Kick Detection 1

- Beam-Position Shift at Detector

$$\Delta X_{det.} = \frac{\sqrt{\beta_{det.}\beta_x^*}}{2sin(\pi\nu)}\theta_{b-b}\cos(\pi\nu - |\Delta\varphi_d|)$$

$$\Rightarrow \quad \Delta X_{det.} \propto \theta_{b-b}$$

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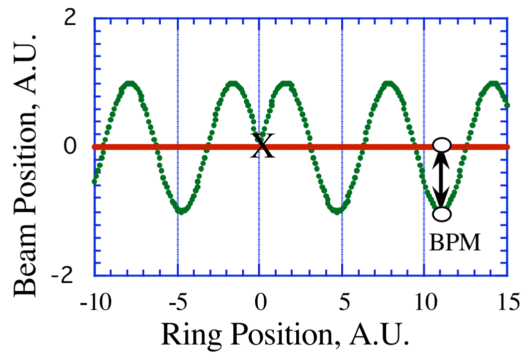


- Beam-beam Kick (Rigid Gaussian)

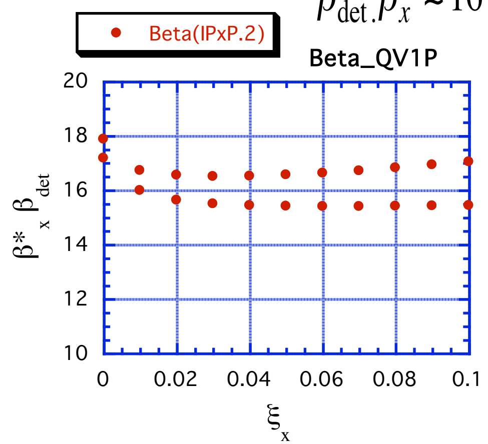
Δ_x: Horizontal Offset

$$\theta_{b-b} = \frac{-2r_e N_b}{\gamma}\Delta_x \int_0^{\infty} \frac{\exp(-\frac{\Delta_x^2}{(t+2\Sigma_x^2)})}{(t+2\Sigma_x^2)^{3/2}(t+2\Sigma_y^2)^{1/2}}dt \qquad \Delta_y = 0$$

$$\theta_{bb}^+ \approx \frac{-1.94\cdot r_e N^-}{\gamma^+}\frac{\Delta_x}{\Sigma_x^2} \quad \Rightarrow \quad \frac{\theta_{bb}^+}{\Delta_x} \propto \frac{N^-}{\Sigma_x^2} \qquad |\Delta_x| < \Sigma_x$$

<Dynamic Beta>

$\beta_{det.}\beta_x^* \approx 16$



- Effective Horizontal Size at IP

$$\Sigma_x = \sqrt{(\sigma_x^+)^2 + (\sigma_x^-)^2}$$

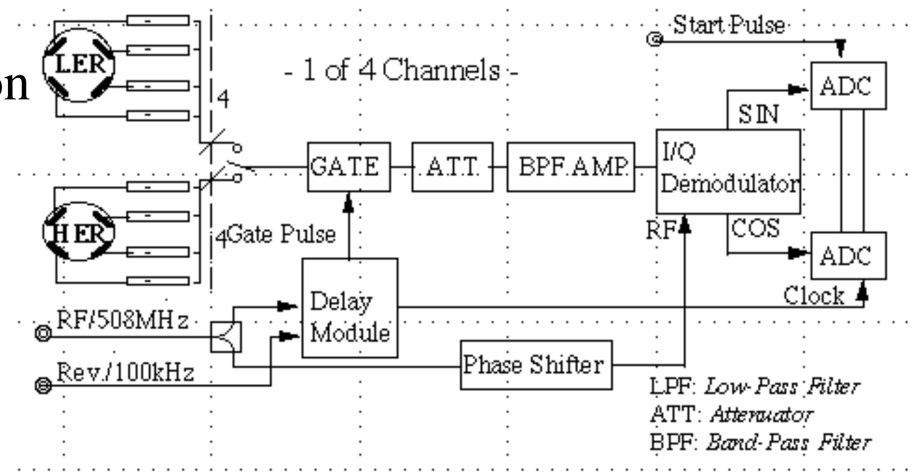
By Fukuma & Funakoshi

Beam-Beam Kick Detection 2

<How to detect beam-beam kick>

- Gated BPM can detect the beam position of a specific bunch.
- Compare the position of between a colliding and non-colliding bunches during the orbit scanning at IP.

<Gated Beam-Position Monitor at FB4>



<Performance of G-BPM>

Pick-up	Button
Detector Bandwidth	508 +/- 30 MHz
Resolution of Position and Phase	20 μm @turn-by-turn 3 ~ 5 μm @average 0.3 deg. @turn-by-turn
Isolation of Gate	40 dB @ 3-bucket spacing

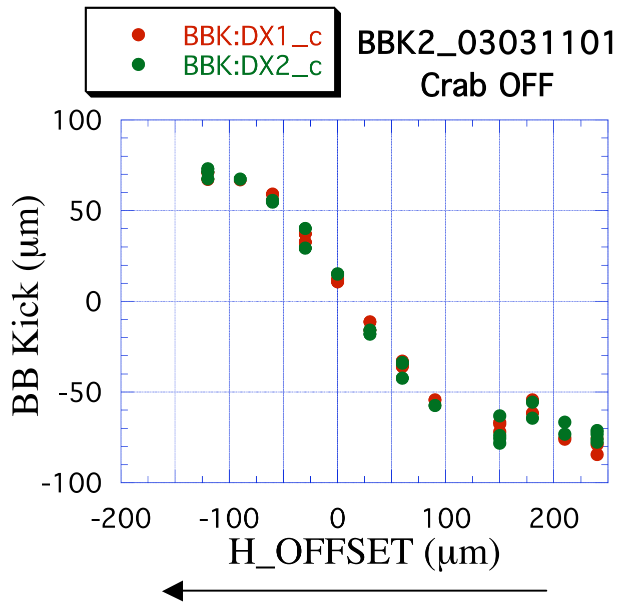
<Optics Parameter at Pickup>

	LER QV1P.2	HER QX6E.2
β_x (m)	22.38	43.05
β_y (m)	22.50	4.34
φ_x from IP	22.68	23.33
φ_y from IP	21.67	21.51
η_x (m)	<0.001	<0.001

Measurement with Crab Cavity ON/OFF

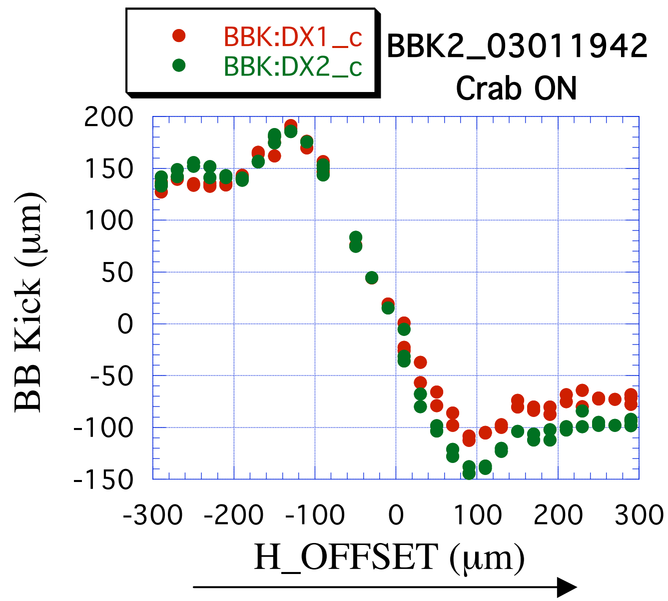
ε_x L/H=18/24 nm

OFF



Bunch Current: 0.73/0.42 mA

ON(1.31/0.92 MV)



Bunch Current: 0.64/0.47 mA

$\Sigma_{x\_x'=11}$=230 +/- 3 μm (OFF) ⇨ $\Sigma_{x\_x'=00}$=167 +/- 3 μm (ON)

- Horizontal effective size at IP reduces to 72% by the crab.

Ratio of Slope:

$$\frac{\left.\frac{\Delta k}{\Delta x}\right|_{x'=0}}{\left.\frac{\Delta k}{\Delta x}\right|_{x'=11}} = 2.14$$

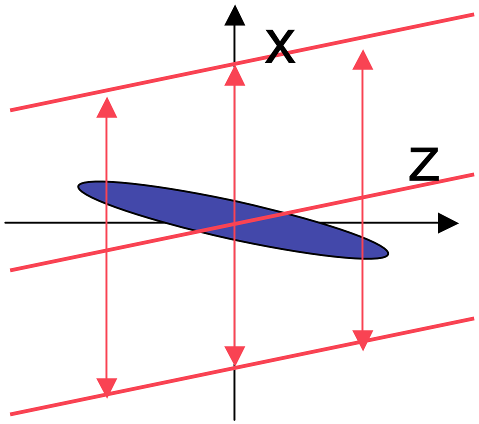
- HER current was lost from 15 to 13.5 mA during scan.
- Horizontal offset agrees with the orbit displacement at IP within 10%. (by Masuzawa)

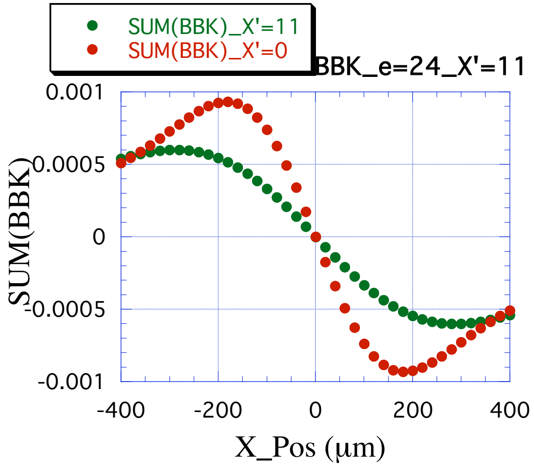
Calculation of Beam-Beam Kick with and without Crossing Angle

Use code “BBWS” by Ohmi

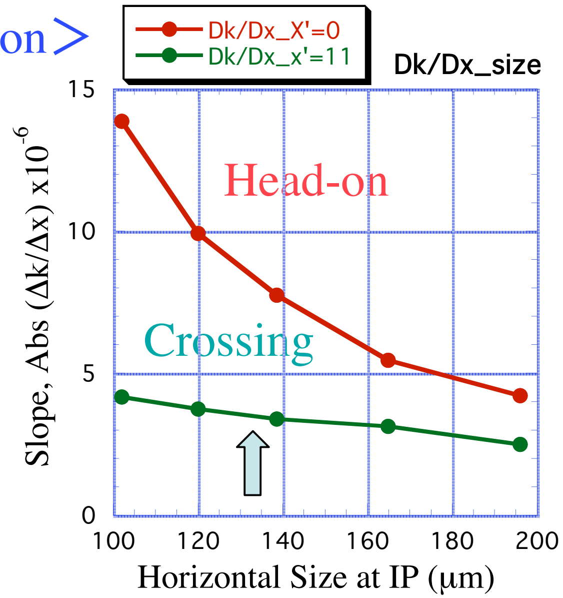
How to calculate the kick with an angle of 22 mrad

ε_x=24 nm





<Slope in Linear Region>



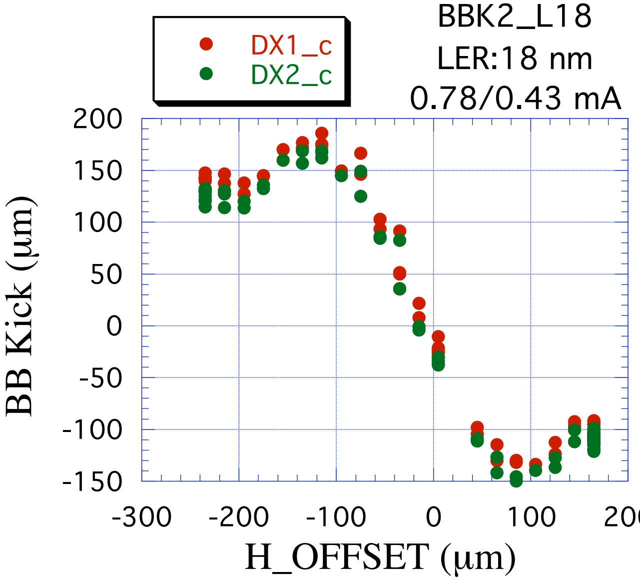
- A particle is horizontally moved and the kick data are summed up, including the longitudinal profile.

Result:

- The horizontal size reduces due to the crabbing.
- Smaller the size, more effective the crabbing.
- The measurement is consistent with the calculation.

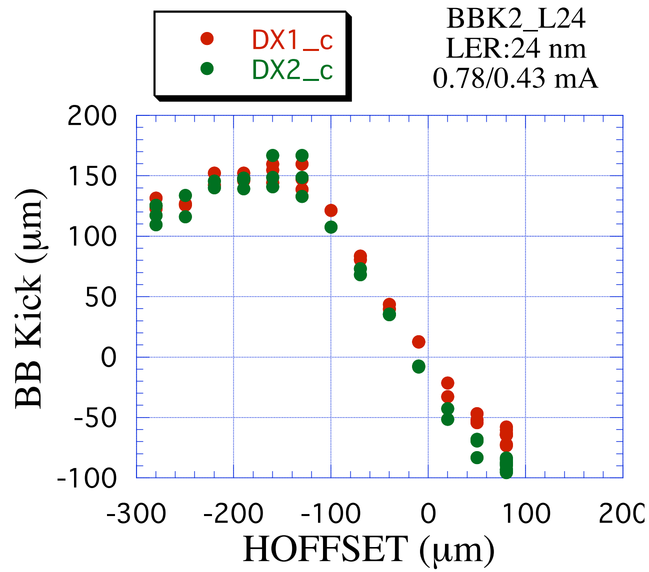
Emittance Change under Crab ON

ε_x L/H=18/24 nm
V_{crab}: 1.48/1.00 MV



$\Sigma_{e=18/24}$=144 +/- 3 μm

ε_x L/H=24/24 nm
V_{crab}: 1.28/1.00 MV



$\Sigma_{e=24/24}$=188 +/- 8 μm

Result:

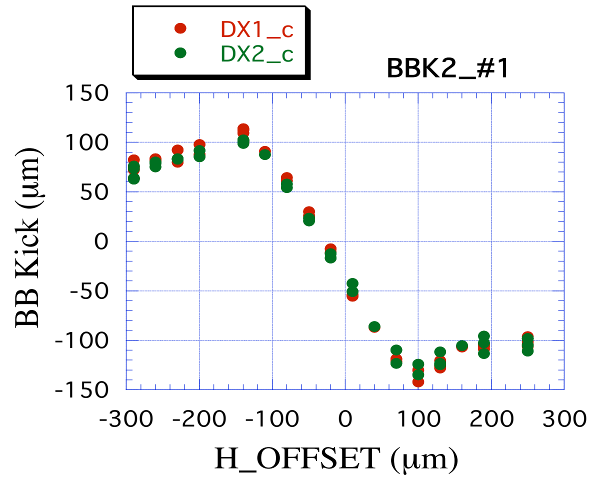
- Effective horizontal size at IP reduced to 77%.
- An expected reduction value is 93%. (No beam-beam effect)

Intensity Change under Crab ON

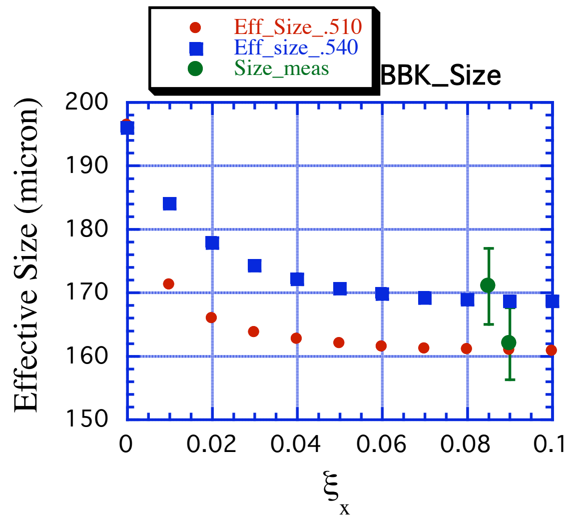
ε_x L/H=24/24 nm V_{crab}: 1.45/0.85 MV

Ie+ / Ie-
0.90/0.40 mA

$\Sigma_{I=90/40}$=171 +/- 7 μm

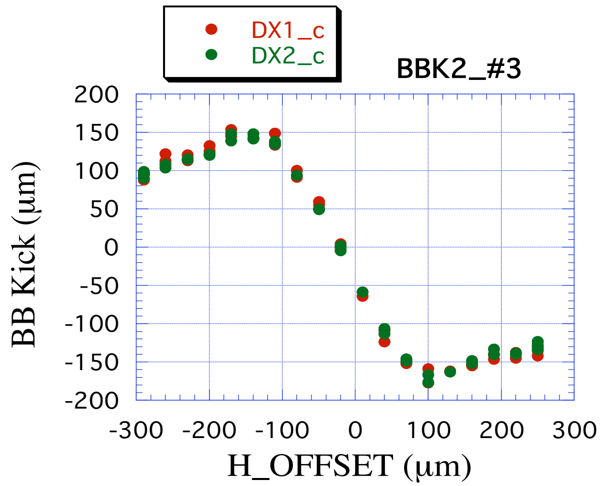


<Calculated Effective Size>



Ie+ / Ie-
0.80/0.50 mA

$\Sigma_{I=80/50}$=162 +/- 6 μm



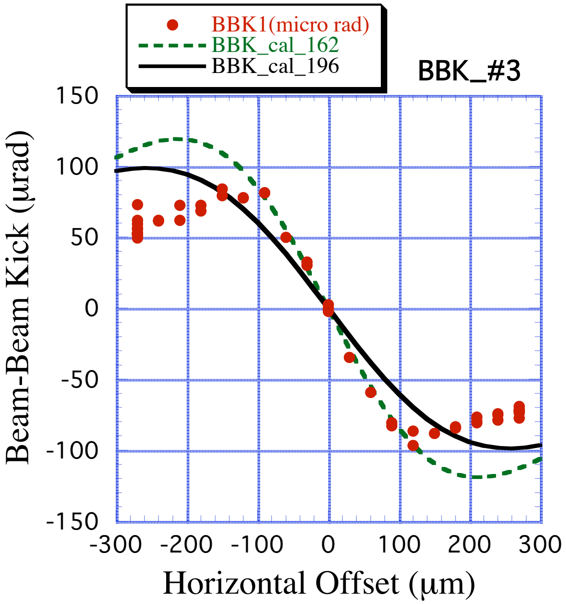
Result:

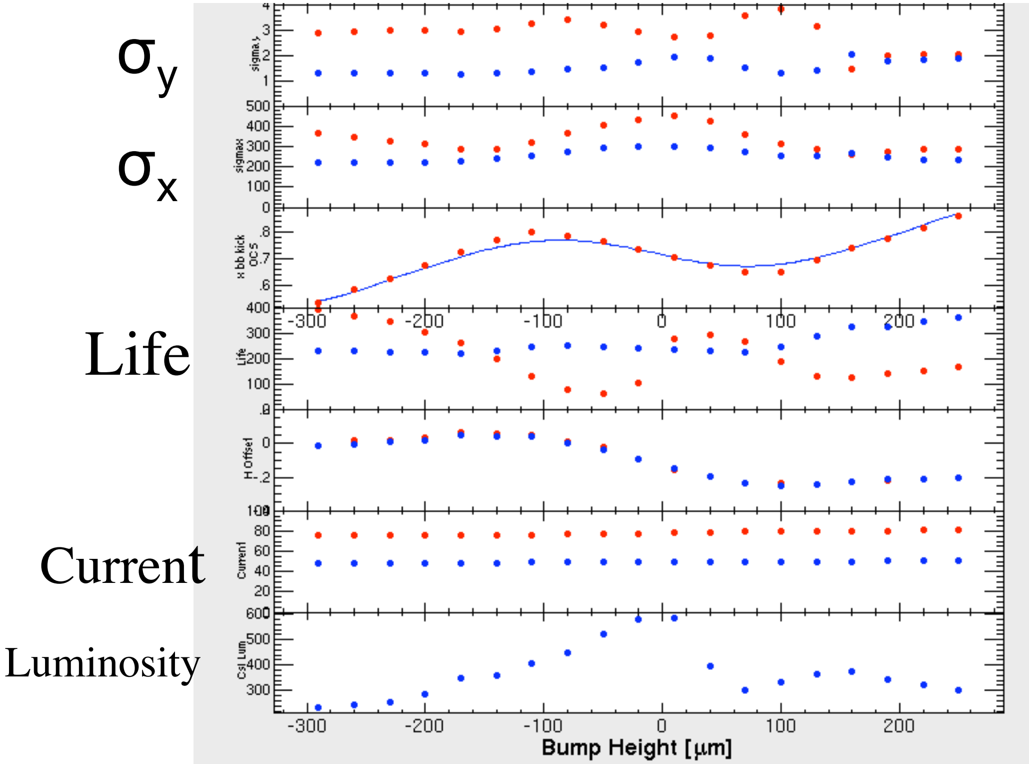
- The measured size agrees with the calculation.
- However, the local peaks of the beam-beam kick curve indicate a very small size of Σ_x=95 μm. ?

Note a local peak takes place at a size of $1.32\Sigma_x$.

Beam Size during Scanning

By Funakoshi





Result:

- In the large offset region, the kick data deviates from a Gaussian.
- Does a beam profile change?

Summary 1

- The horizontal effective beam size at IP was estimated from a linear part of beam-beam kick around the center.
  Results are:
  - Effect of Crab Cavity: Σx=230 mm(OFF)、Σx=167 mm(ON)
  - Effect of Emittance: Σx=188 mm (24 nm) -> 144 mm(18 nm)
- These estimated sizes are consistent with the expectation.
- However, the estimated size from the local peaks indicates a very small size.
  The beam-beam kick curve deviates from a Gaussian in a large offset region.
  - One speculation is a change of a beam shape or the size during the scanning.
  - The reason is unclear.
- The calculation shows that the crab cavity switching from crossing collision to head-on collision reduces the effective horizontal size to 56 to 77 %.
- The crabbing effect depends on an original beam size.

Topics II : Study on Beam-Beam Tune Shift

Motivation:

- Coherent Tune Shift in a Two-Ring Collider
  - Energy asymmetry and Different tune
- Dynamic Effects
  - Decreasing the specific luminosity, Beam-beam limit?
  - Short lifetime at high current, What happens in collision?

Outline:

- Beam-beam parameters
- Nonlinear resonance in the tune spectrum
- Measurement of coherent beam-beam tune shift
- More observation of the spectrum
- Summary

Luminosity and Vertical Beam-Beam Parameter

$$L \equiv \frac{N^+ N^- f_0}{2\pi \Sigma_x \Sigma_y} R$$

R: Reduction factor

$$= \frac{f_0}{r_e} \left(\frac{N^+\gamma^+ N^-\gamma^-}{N^+\gamma^+ + N^-\gamma^-} \right) \left(\frac{\Xi_x^+}{\beta_x^+} + \frac{\Xi_x^-}{\beta_x^-} + \frac{\Xi_y^+}{\beta_y^+} + \frac{\Xi_y^-}{\beta_y^-} \right) R$$

$$L \approx \frac{f_0}{r_e} \left(\frac{N^+\gamma^+ N^-\gamma^-}{N^+\gamma^+ + N^-\gamma^-} \right) \left(\frac{\Xi_y^+ + \Xi_y^-}{\beta_y^*} \right) R \qquad \beta_x >> \beta_y$$

$$= \frac{f_0}{r_e} \left(\frac{N^+\gamma^+ N^-\gamma^-}{N^+\gamma^+ + N^-\gamma^-} \right) \left(\frac{\overline{\xi}_y}{\beta_y^*} \right) R$$

Luminosity ⇨	$\overline{\xi}_y$
$\Delta\nu_{bb}$ ⇨	$\Xi_q^+ + \Xi_q^-$

Coherent Beam-Beam Parameter:

$$\Xi_q^\pm = R_q^\pm \frac{r_e}{\gamma_\pm} \frac{\beta_q^\pm}{2\pi \Sigma_q (\Sigma_x + \Sigma_y)} N_\mp$$

Beam-Beam Tune Shift:

$$\Delta\nu_{bb} = \nu_H + \nu_L - \nu_0^+ - \nu_0^-$$

Intensity Parameter, Nγ:

$$F(N\gamma) = \frac{N^+\gamma^+ N^-\gamma^-}{N^+\gamma^+ + N^-\gamma^-}$$

Beam-Beam Parameter and Tune Shift:

$$\overline{\xi}_q = \Xi_q^+ + \Xi_q^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y} \Delta\nu_{bb}$$

Y: Yokoya Factor

Horizontal Beam-Beam Parameter and Emittance

$$\Xi_x^+ + \Xi_x^- = R_x^+ \frac{r_e}{\gamma_+} \frac{\beta_x^+}{2\pi\Sigma_x(\Sigma_x + \Sigma_y)} N_- + R_x^- \frac{r_e}{\gamma_-} \frac{\beta_x^-}{2\pi\Sigma_x(\Sigma_x + \Sigma_y)} N_+$$

$$\xi_x \approx R_x^* \frac{r_e \beta_x^*}{2\pi\Sigma_x^2} \left(\frac{N_-}{\gamma^+} + \frac{N_+}{\gamma^-}\right)$$

$$= R_x^* \frac{r_e}{4\pi\varepsilon_x} \left(\frac{N_-}{\gamma^+} + \frac{N_+}{\gamma^-}\right)$$

$$\Sigma_x^2 = (\sigma_x^+)^2 + (\sigma_x^-)^2$$

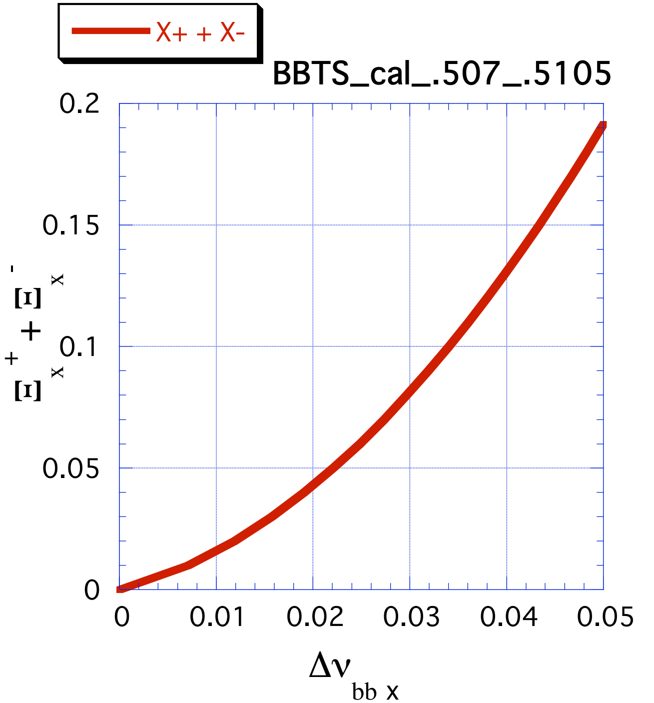
$$\approx 2(\sigma_x^*)^2$$

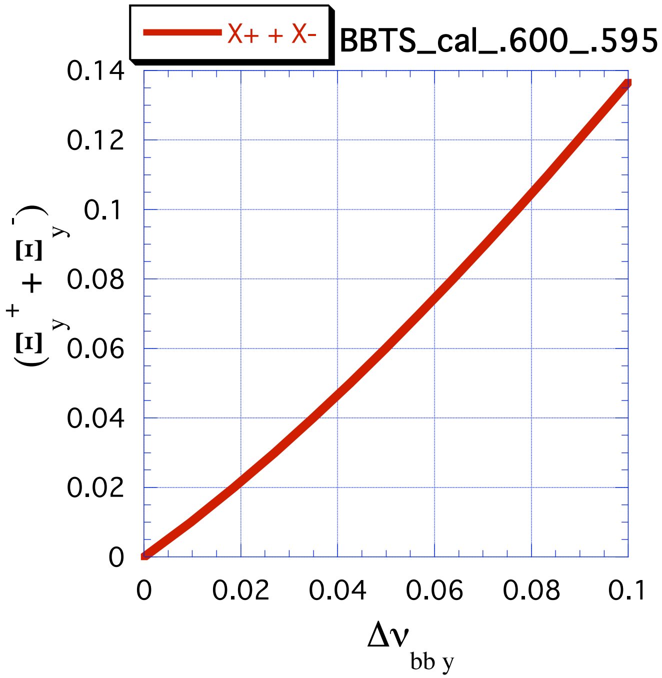
$$= 2\varepsilon_x \beta_x^*$$

Intensity Parameter, N/γ: $G(N/\gamma) = \frac{N_-}{\gamma^+} + \frac{N_+}{\gamma^-}$

$$\Delta\nu_{bb\_x} \Rightarrow \Xi_x^+ + \Xi_x^- \Rightarrow \varepsilon_x$$

Coherent Tune Shift and Beam-Beam Parameter





$$\bar{\xi}_x = \Xi_x^+ + \Xi_x^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y_x} \Delta\nu_{bb\_x}$$

$$\bar{\xi}_y = \Xi_y^+ + \Xi_y^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y_y} \Delta\nu_{bb\_y}$$

Example: $\Delta\nu_{bb\ x}$=0.04 Y_x=1.31 -> ξ_x=0.08 $\Delta\nu_{bb\ y}$=0.06 Y_y=1.23 -> ξ_y=0.058

Nonlinear Effect in Vertical Spectrum

BR~74%
1.5/0.3mA

• Changing excitation amplitude:

0-mode *like*

π-mode *like*

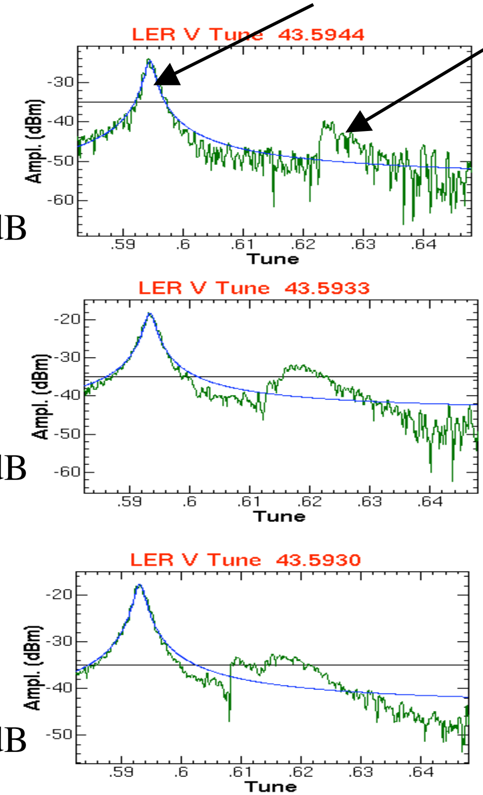
Tune H / V
LER: .5055/.5919
HER: .5111/.5930

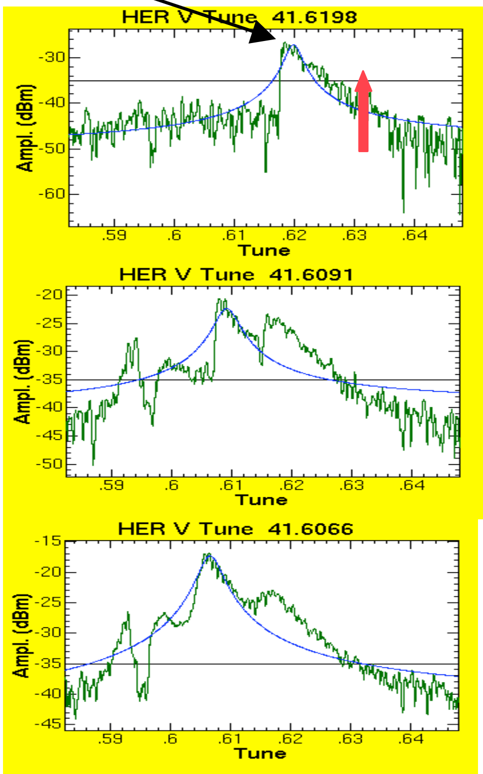
28/24dB

25/21dB

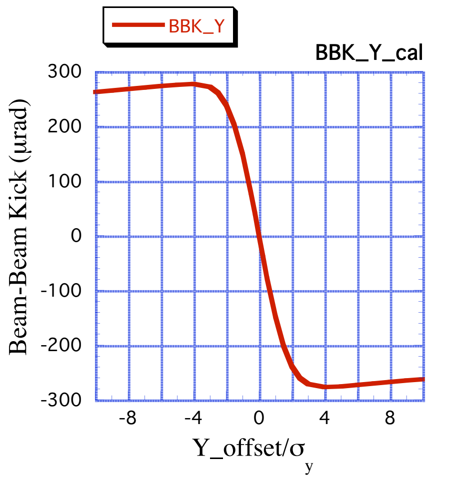
19/15dB

Increasing Amplitude





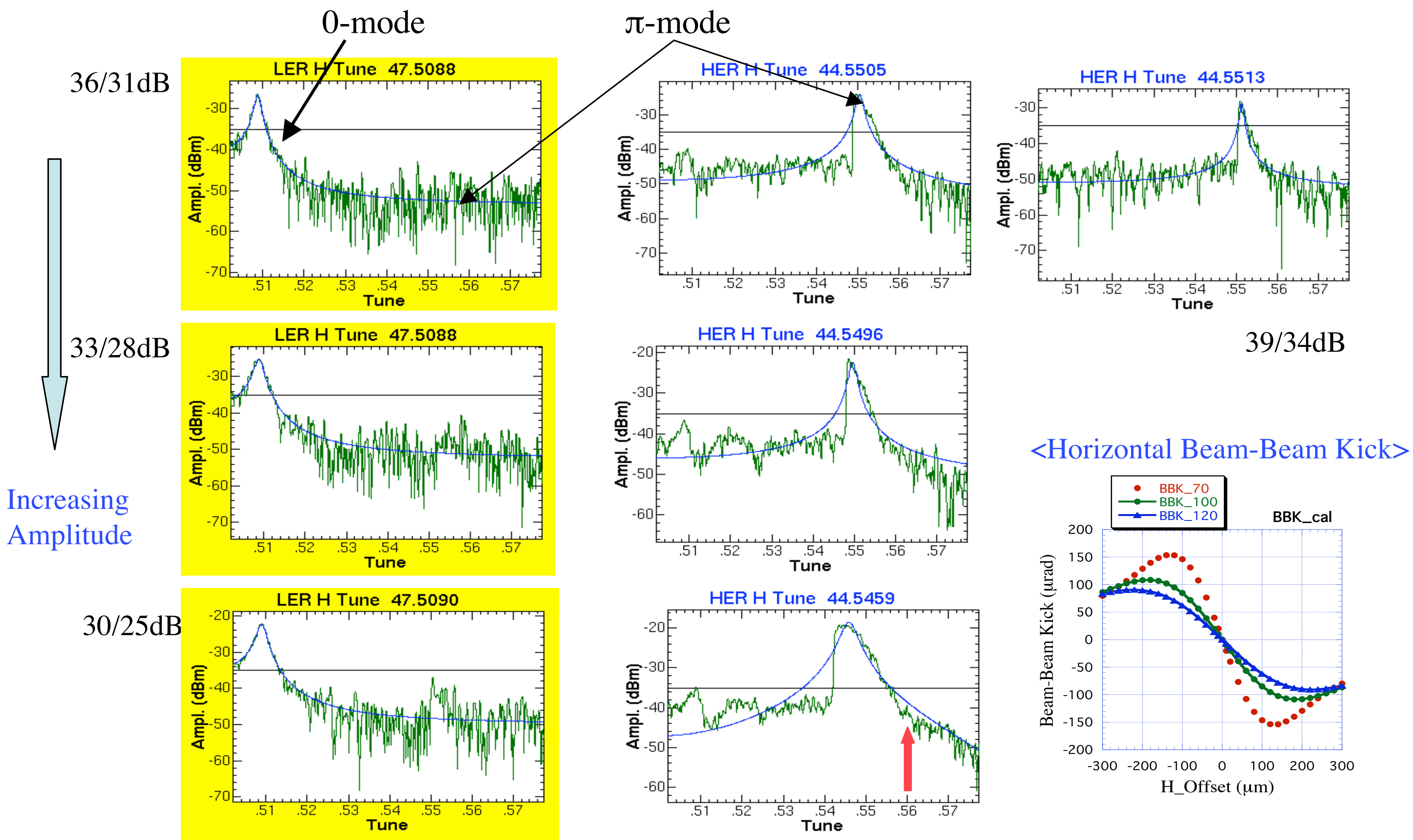
<Vertical Beam-Beam Kick>



Result:

- The 0-mode appears clearly in the positron bunch and the π-mode is clear in the electron bunch.
- The peak of the π-mode spectrum shifts to a lower tune due to the nonlinear beam-beam force.

Nonlinear Effect in Horizontal Spectrum



• Coherent beam-beam tune shift should be determined by an edge, not a peak in the spectrum.

Beam Conditions for Coherent Tune-Shift Measurement

Ring	LER	HER	LER	HER	
Crab	0.94MV	1.43MV	OFF		
Emittance: ε_x	24	24	18	24	nm
Beta*: $\beta x/\beta y$	80/0.59	80/0.59	59/0.65	56/0.59	cm
Tune: νx	45.507	44.510	45.527	44.512	
Tune: νy	43.595	41.595	43.567	41.584	
νs	-0.0249	-0.0216	-0.0249	-0.0216	
Bunch spacing	192		320		ns

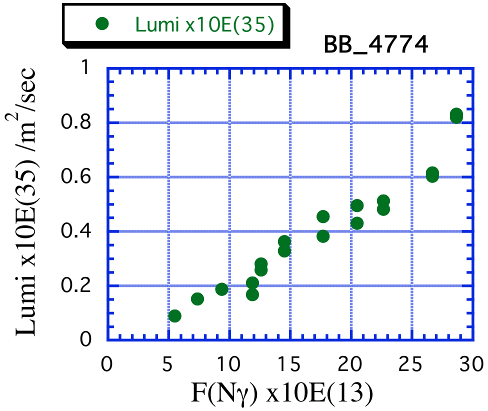
- Crab ON: Collision with zero-offset and almost the same tune, 20070401
- Crab OFF: 20061212

Vertical tune Shift and Beam-Beam Parameter

Luminosity

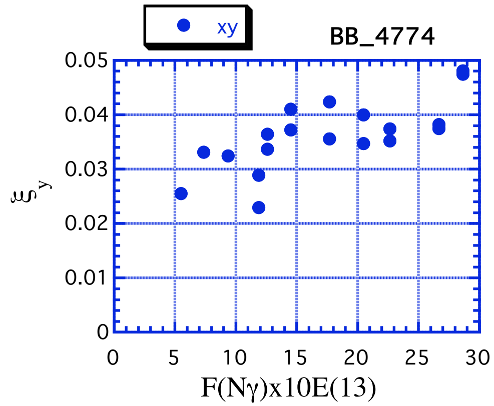
⇩

Incoherent
Beam-beam parameter



BR=130 - 150%

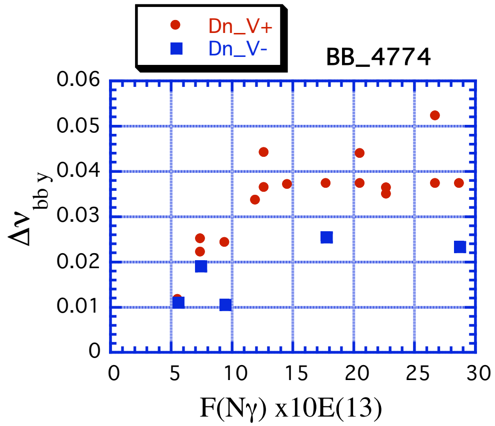
By Uehara

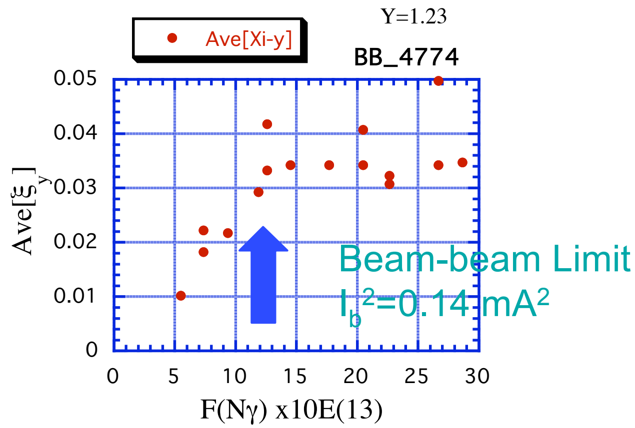


Tune Shift

⇩

Coherent
Beam-beam parameter



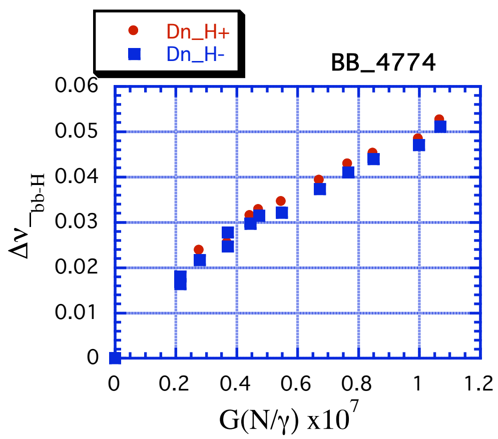


Result:

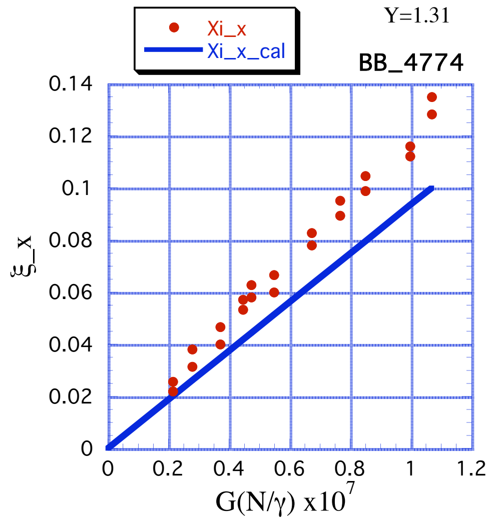
- The ξ_y obtained from the luminosity agrees with the Ave[ξ_y] obtained from the coherent tune shift.
- Both parameters saturate around 0.04.
- We can estimate the beam-beam limit at a current product of about 0.14 mA^2.

Horizontal Tune Shift and Emittance

<Beam-Beam Tune Shift>



<Beam-Beam Parameter>

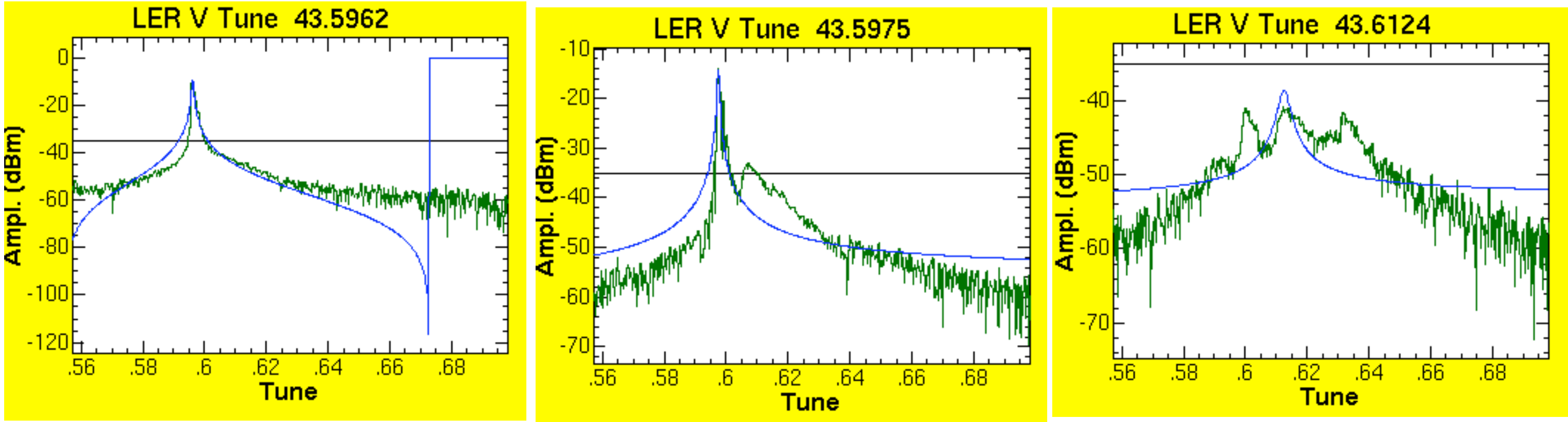


Result:

- The estimated ξ_x does not saturate over 0.1.
- It is higher than calculated values using a constant emittance.
  - Need more consideration.

Intensity Dependent Spectrum

0.91/0.12mA　　0.84/0.38mA　　Ie^{+} / ie^{-}　　0.81/0.58mA



While increasing electron bunch (opposite beam) intensity,
we observed a change of the spectrum of a positron bunch (own beam) with a constant excitation level:

Result:

- Spectrum is getting broader as increasing intensity of opposite beam.
- The beam-beam mode splits into two peaks.
- The 0-mode spectrum damps and the π-mode slightly grows.
- After that, we observed a short lifetime of the own beam.

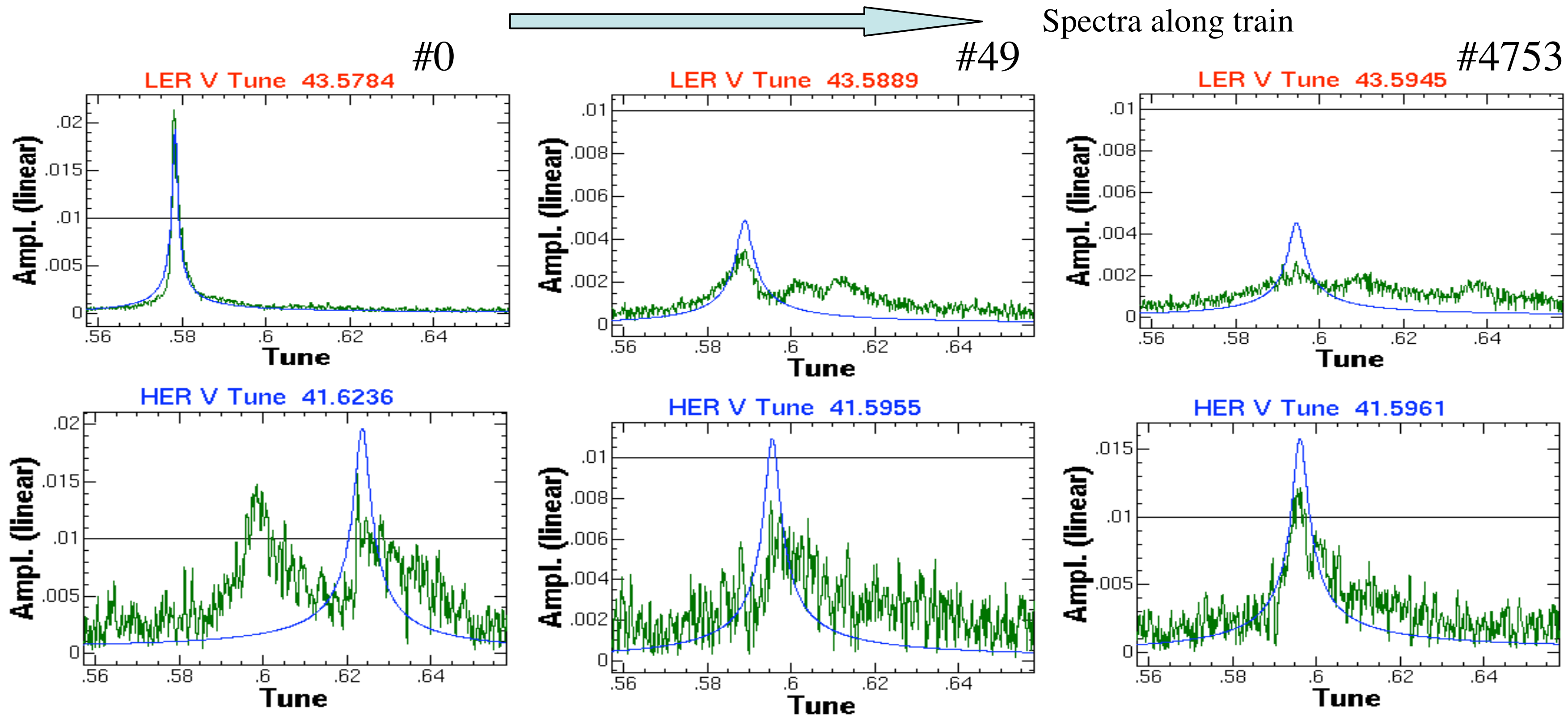
Summary 2

- Because of the nonlinear beam-beam force, the coherent tune shift is obtained from the maximum tune shift (edge) not from a peak in the spectrum.
  - Much difference between the peak and the edge.
  - Not easy to measure the edge automatically.
- The estimated parameter, $\Xi_y^+ + \Xi_y^-$, from the coherent tune shift is consistent with the parameter, ξ_y, from the luminosity monitor.
- The ξ_y is saturated with about ~0.04, at a low bunch current of 0.14 mA^2, the beam-beam limit. The current is about 0.5 mA^2 in usual operations.
- The ξ_x is not saturated over 0.1.
- The ξ_x is higher than an expectation, the reason is not understood.
- When an *opposite* bunch had a higher intensity than an optimum value, the tune spectrum of an *own* bunch was widened and the 0-mode damped and the beam-beam mode split with distortion. The phenomena resemble those at high level excitation.

Tune Spectra in Usual Operations

Pilot LER; .5058/.5816 HER; 0.5109/.5896 LER V#0; 0.5715: single beam

3.06 spacing
0.9/0.43mA



Result:

- The sideband appears in the LER Vertical spectrum, except that of a leading bunch.
- The spectra are related to the electron cloud and the beam-beam.
- A tune shift is larger than that in a single beam.

Excitation Amplitude Dependence _20071126

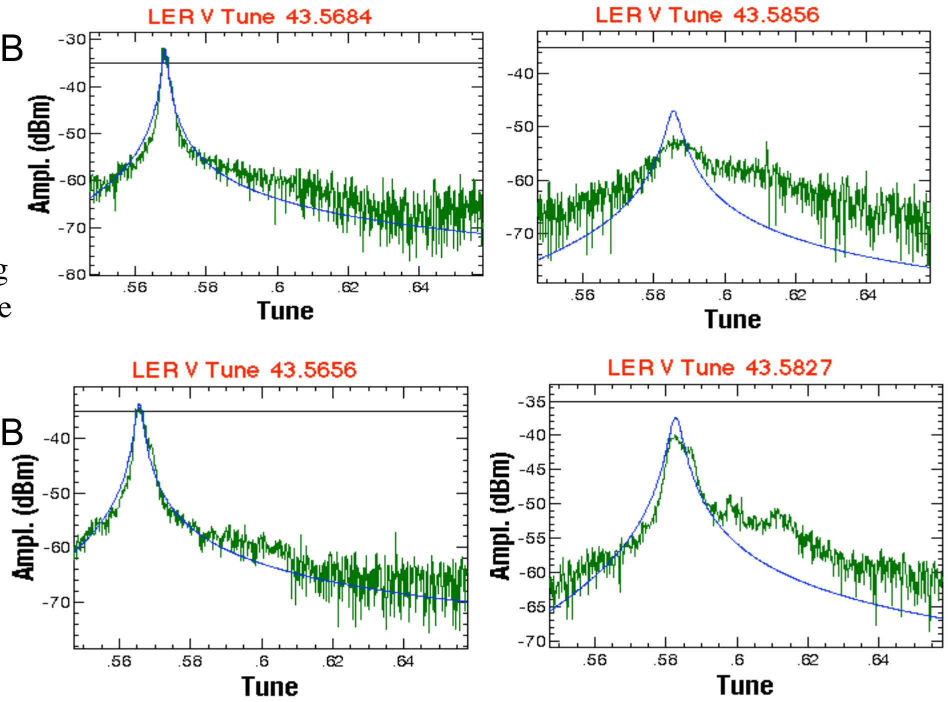
0.95/0.43 mA
0.91/0.36 mA

#0 #4753

26/27 dB

Increasing Amplitude

19/20 dB



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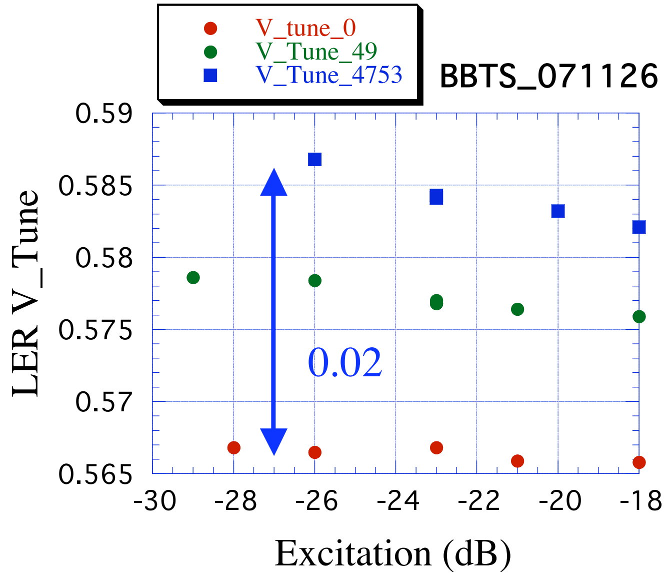
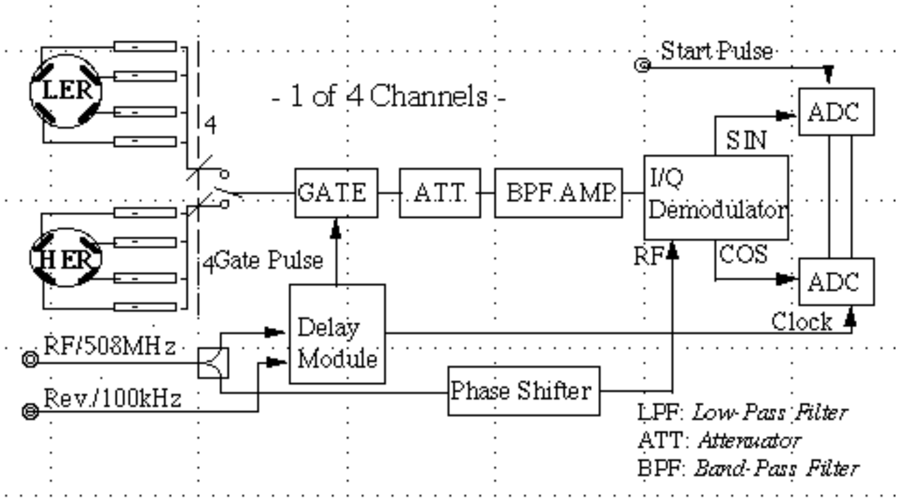


Slope:
-1.0 x10e(-4) @# 0
-2.7 x10e(-4) @# 49
-5.4 x10e(-4) @#4753

Complex Phenomena due to Electron Cloud and Beam-Beam:

- Vertical tune decreases with increasing excitation level.
- The nonlinearity was not observed under a single beam, even in a cloud.
- The nonlinear effect is strong in the backward bunch in a train.
- Tune shift along a train is larger that that in a single beam.

Topics III: Bunch-By-Bunch Orbit Measurement



<Performance>

Pick-up	Button
Detector Bandwidth	508 +/- 30 MHz
Resolution of Position and Phase	20 μm @turn-by-turn 3 ~ 5 μm @average 0.3 deg. @turn-by-turn
Isolation of Gate	40 dB @ 3-bucket spacing

- Also use Gated Beam-Position Monitor.

<Optics Parameter at Pickup>

	LER QV1P.2	HER QX6E.2
β_x (m)	22.38	43.05
β_y (m)	22.50	4.34
φ_x from IP	22.68	23.33
φ_y from IP	21.67	21.51
η_x (m)	<0.001	<0.001

Position along Train

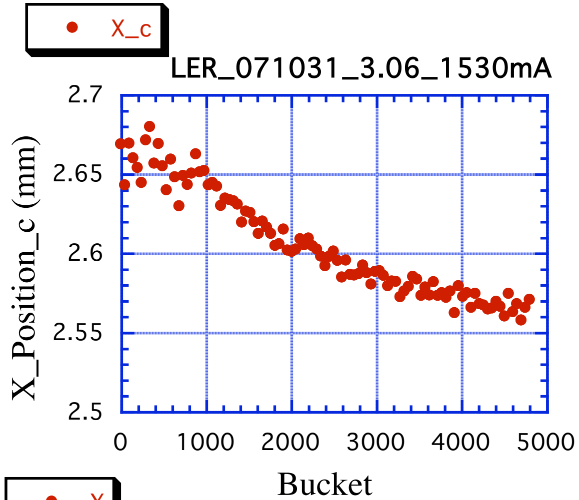
- measured every 49-bucket -

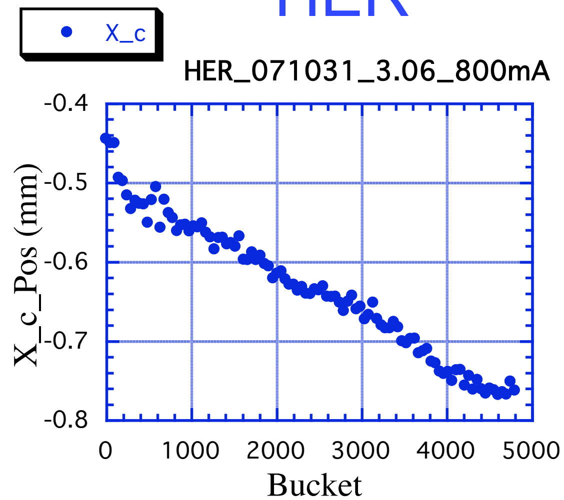
Crabbing Collision, 3.06 spacing,
N=1585, LER: 1530 mA, HER: 800 mA

LER

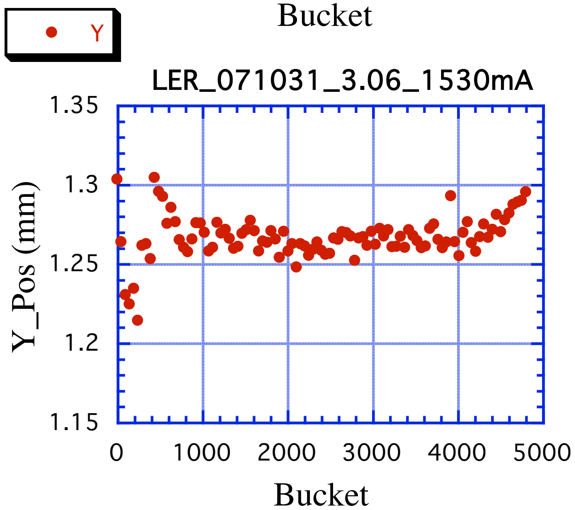
HER

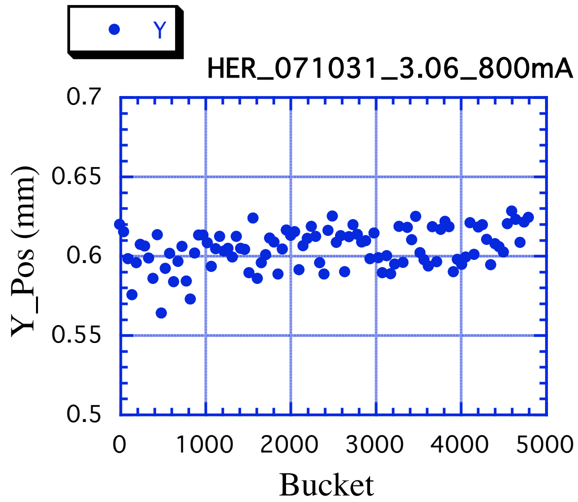
X





Y

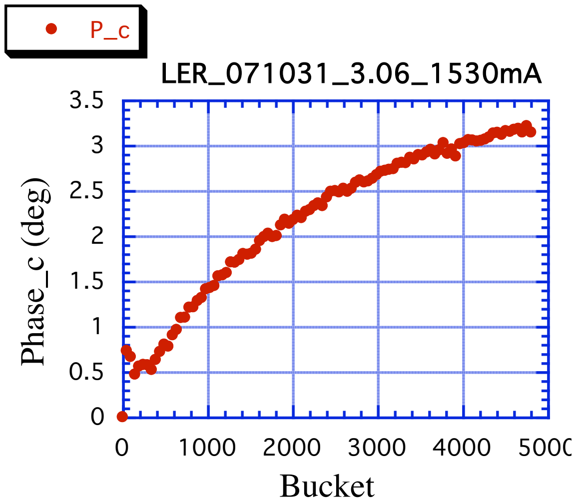




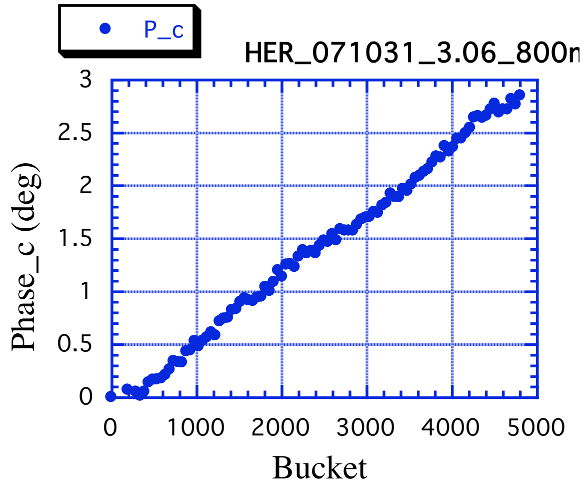
Phase along Train with 3.06 & 3.27 spacing

Z

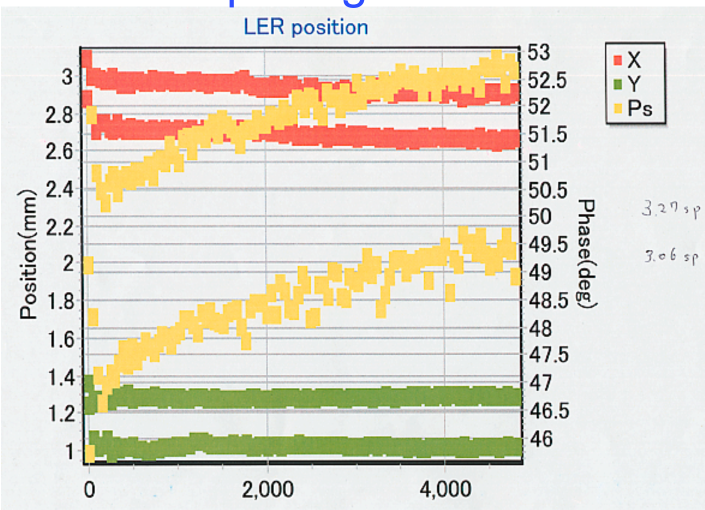
LER

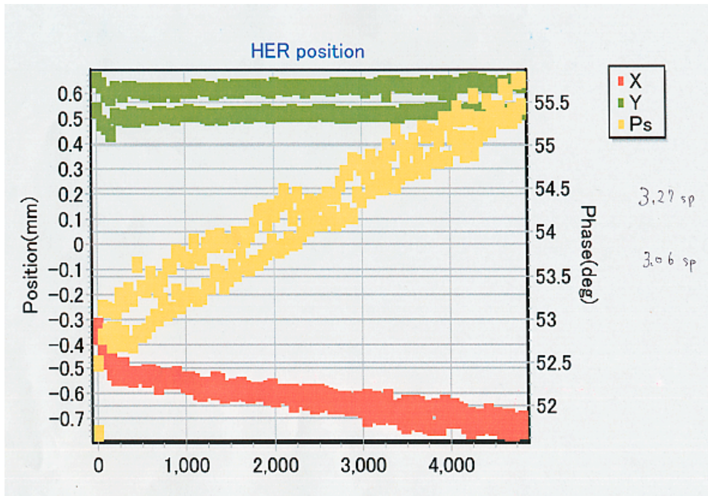


HER



- 3.06 and 3.27 spacing



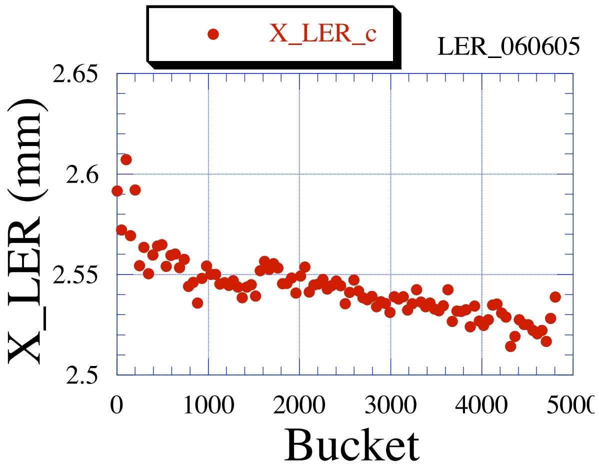


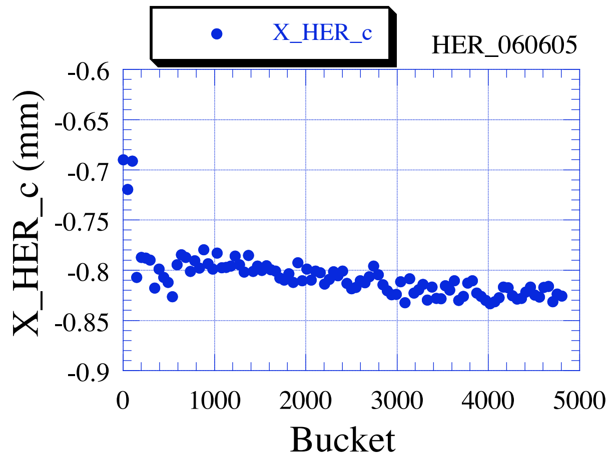
Position along Train with 3.5 spacing, w/o crab

LER/1640mA

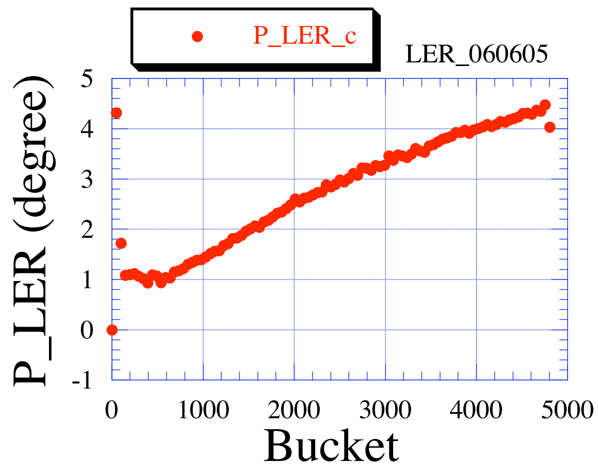
HER/1260mA

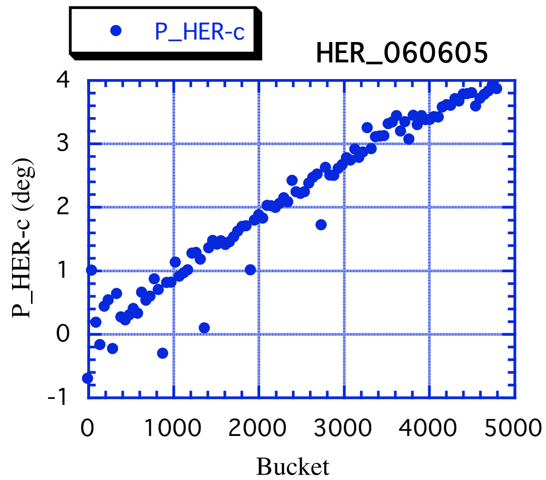
X





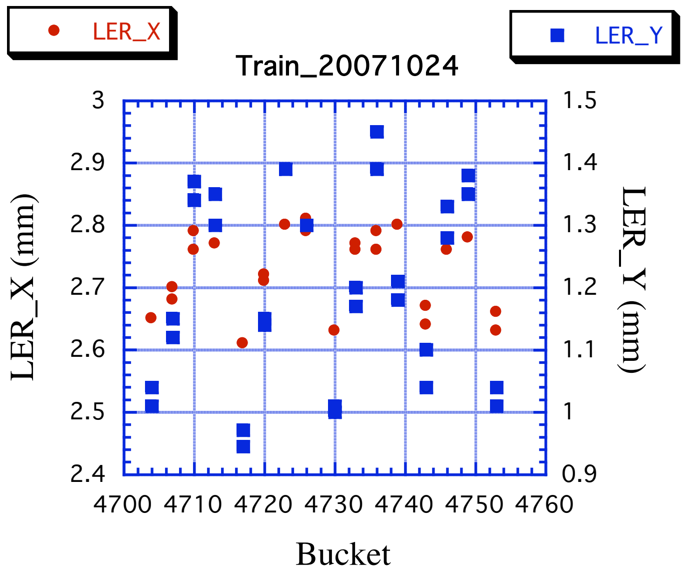
Z



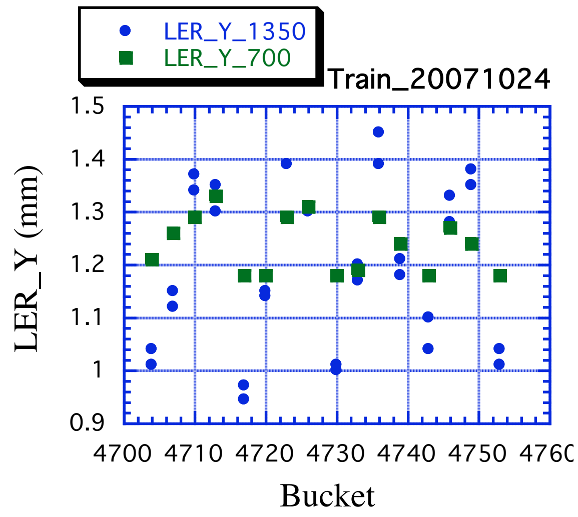


Details of Position along Train 1

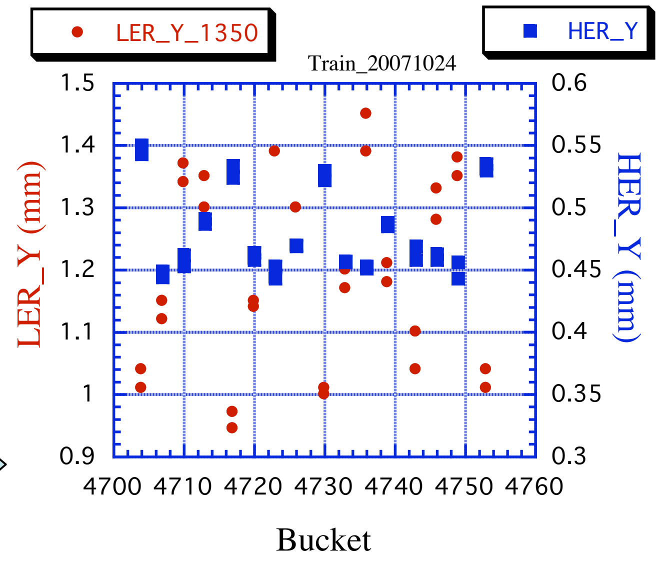
Collision, 1350 mA, N=1485
3.27 spacing: 3343333433334334



- Change beam current



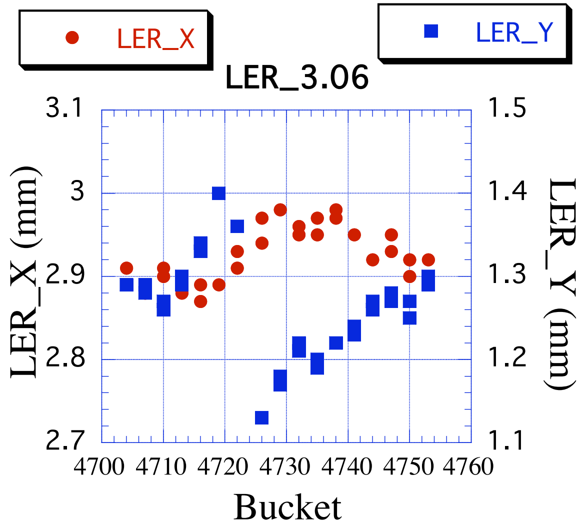
- A large displacement in vertical position around 4-bucket spacing
  - 300 ~ 400 μm@det
  4.8 ~ 6.5 μm@IP (unrealistic value!)
  - Depends on beam current
  - Opposite displacement between e+/e- bunches



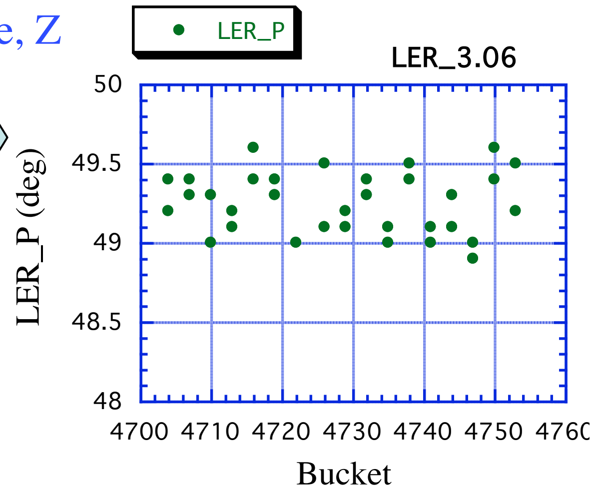
Details of Position along Train 2

Collision, 1500 mA, N=1585
3.06 spacing: 3333334333333333

X
&
Y



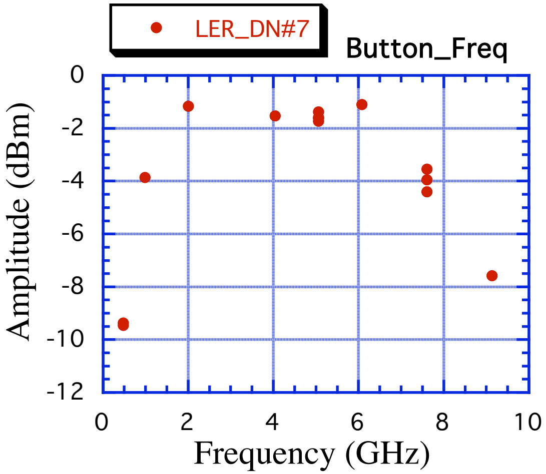
- Phase, Z



- Vertical position changes around 4-bucket spacing.
- Horizontal position and the beam phase does not change so much.

Summary 3

- Observed that horizontal position shifted inward along train.
  - Maximum shift in LER is 19 μm@IP, in HER 40 μm@IP
  - *Note the estimation does not consider the dynamic beta.*
- Vertical displacement is rather small, except the leading part of train.
- Phase shift is due to the transient beam loading.
  - Fortunately, the shifts of both beams are almost the same, 3 deg. @1500/800 mA.
- When the bunch spacing changed, we observed a large displacement of the vertical position.
  - 5 ~ 6 μm@IP, unrealistic value!
  - I suspect the button signal may be affected by wake fields.



<Button Signal>

<- Frequency Response

Time Response ->

N=1389, It=1680 mA