Observations of Beam-Beam Tune Spectrum and Measurement of Coherent Tune Shift at KEKB

T. Ieiri, Y. Ohnishi, M. Tobiyama and S. Uehara
KEK, Japan

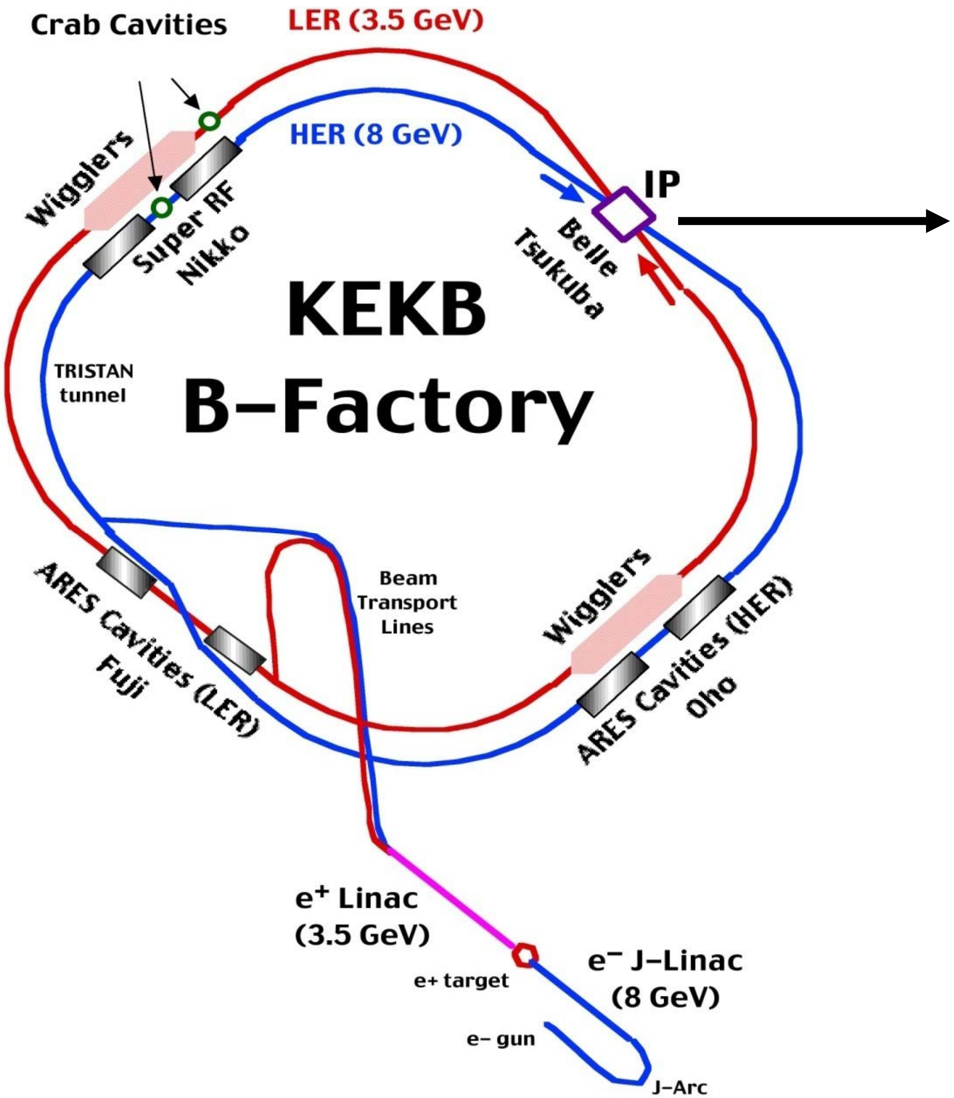
Outline

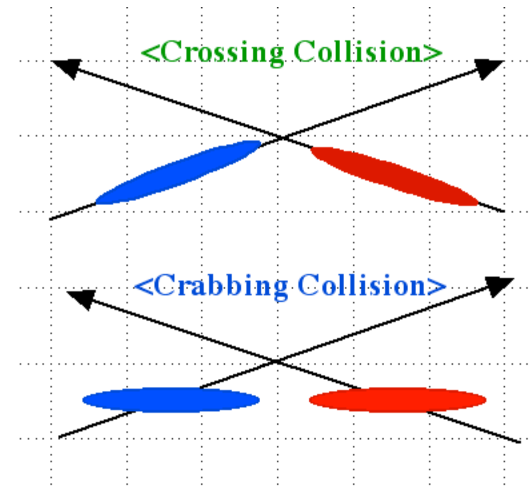
- Motivation, KEKB and Crabbing Collision
- Coherent Beam-Beam Tune Shift
- Gated Tune Monitor
- Nonlinear Resonance in the Tune Spectrum
- Measurement of Coherent Beam-Beam Tune Shift
- Summary

Motivation

- Coherent beam-beam tune shift is useful parameter in colliders.
- The measurement is not easy in double-ring colliders, because of different beam parameters.
- KEKB has realized effective head-on collision by crab cavities through crossing collision.
- Dynamic effects are important issues.
  - Specific luminosity decreases with increase in bunch current.
  - Bunch current is limited by lifetime.

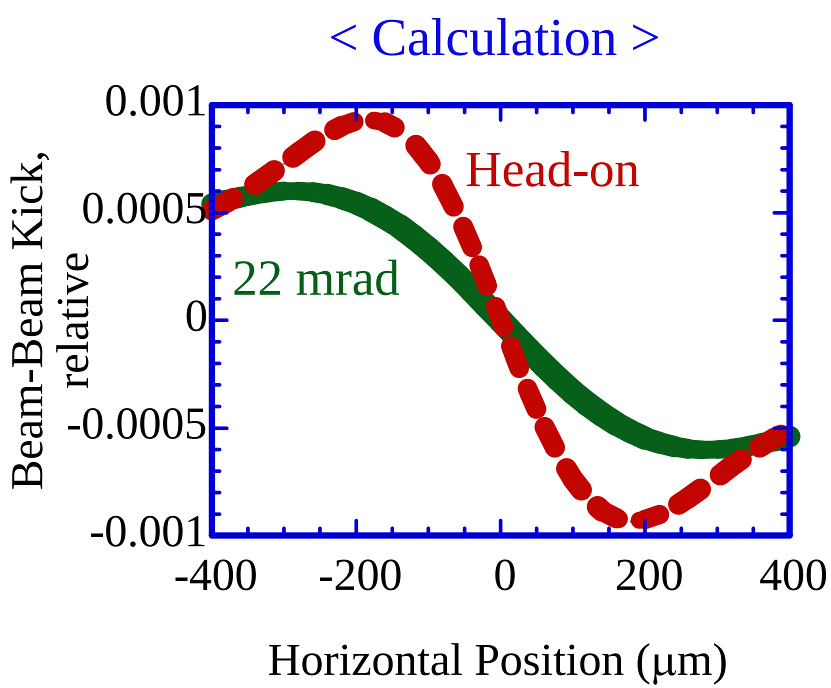
KEKB with Crab Cavity

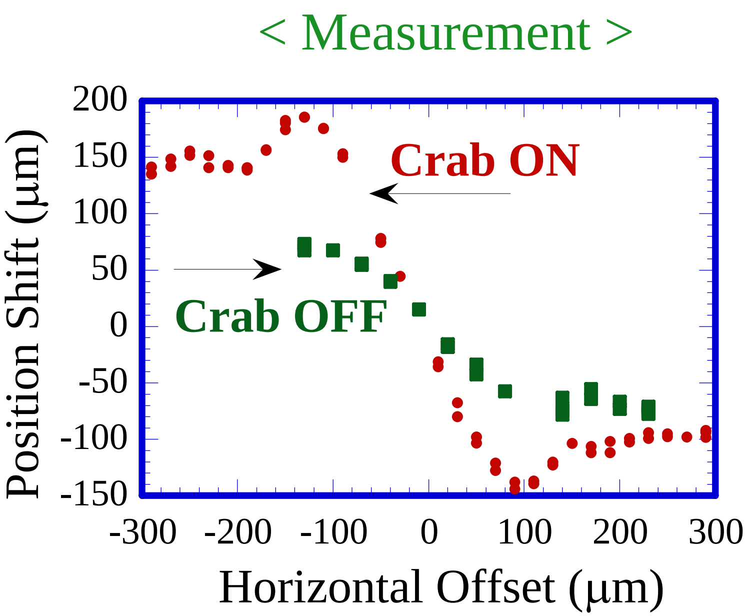




- Asymmetric Beam Energy
  - 8GeV (electron)
  - 3.5GeV (positron)
- Circumference, Harmonic Number
  - 3018 m   h=5120
- The Maximum Luminosity
  - 1.7 x 10^{34} cm^{-2} s^{-1}

Beam-Beam Kick

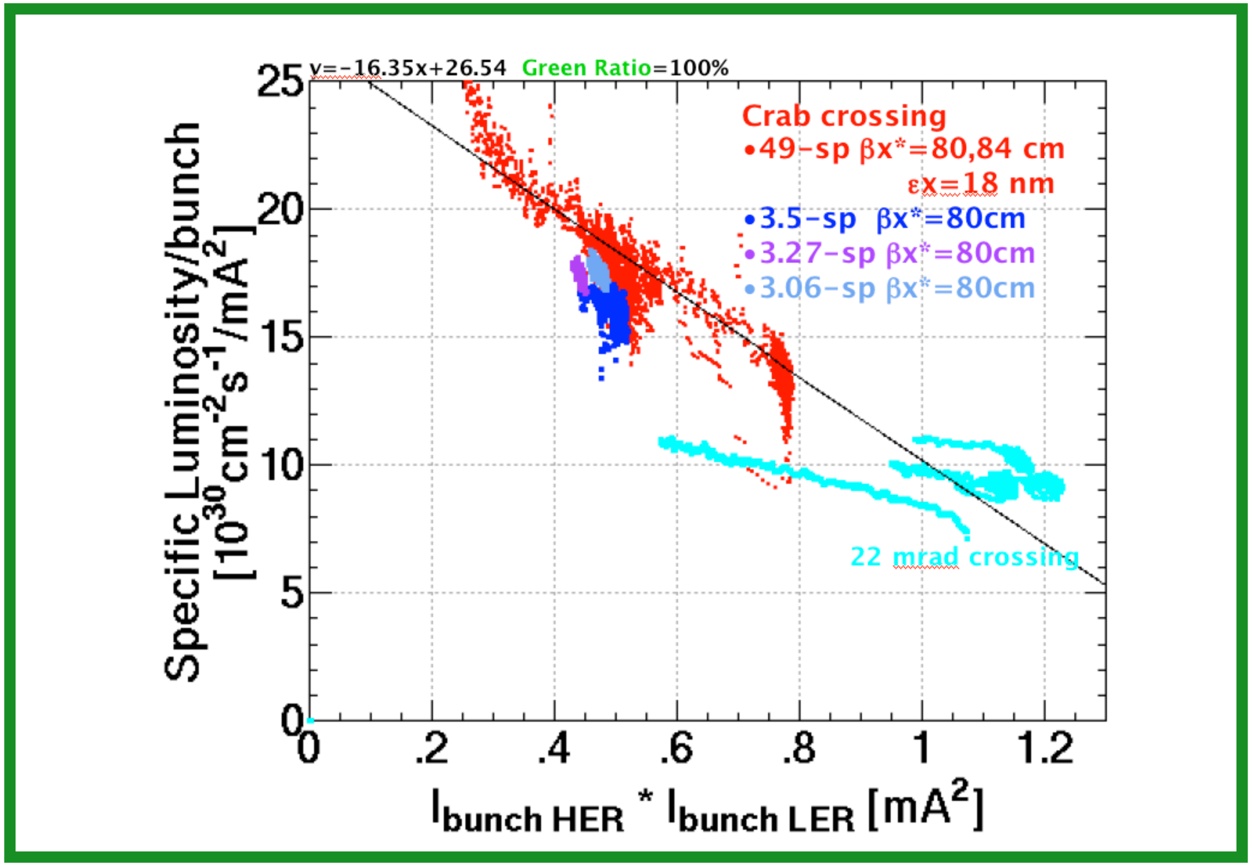




- Crabbing collision increased beam-beam kick
- Decreased effective horizontal beam size
- Improved specific luminosity

Specific Luminosity

By H. Koiso



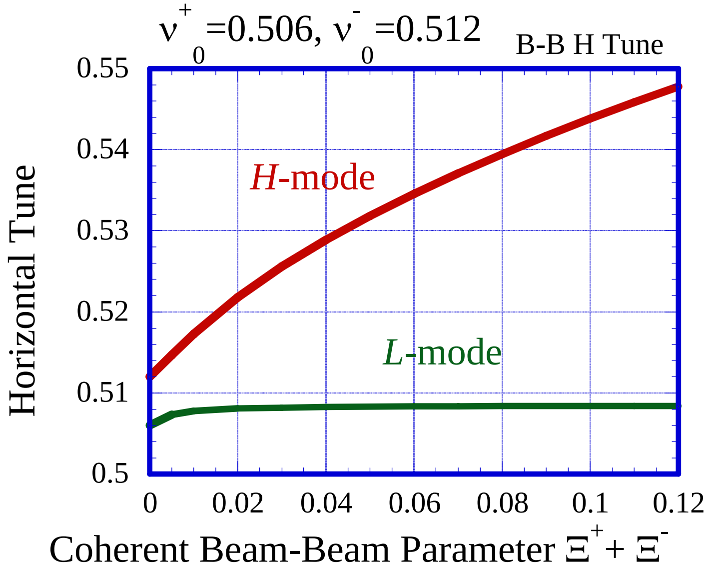
- Specific luminosity decreases with bunch current.
- The bunch current is limited by lifetime.

Coherent Beam-Beam Tune Shift

- Beam-beam interaction produces a new set of two tunes.
- We call two modes the *H-mode* and the *L-mode*.

$$\cos\mu_{qH} + \cos\mu_{qL} - (\cos\mu_{q0}^{+} + \cos\mu_{q0}^{-}) \qquad \mu_q^{\pm} = 2\pi\nu_q^{\pm}$$

$$= -2\pi(\Xi_q^{+}\sin\mu_{q0}^{+} + \Xi_q^{-}\sin\mu_{q0}^{-})$$



- Coherent beam-beam parameter

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

- Coherent beam-beam tune-shift

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

Y: Yokoya Factor

$$\Delta\nu_{bb} = \nu_H + \nu_L - \nu_0^{+} - \nu_0^{-} \qquad \Delta\nu_{bb} = \nu_\pi - \nu_0\text{, in case of } \nu_0^{+} = \nu_0^{-}$$

Luminosity and Emittance

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

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

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

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

$$\beta_x >> \beta_y \qquad \approx R_x^* \frac{r_e}{2\pi(\varepsilon_x^+ + \varepsilon_x^-)} \left(\frac{N_-}{\gamma^+} + \frac{N_+}{\gamma^-}\right)$$

$\Xi_y^+ + \Xi_y^-$

R_L, R^*_x: Factors
due to hourglass effect

$$N^+ \gamma^+ \neq N^- \gamma^-$$

$$\beta_x^+ = \beta_x^- = \beta_x^*$$

Luminosity → $\bar{\xi}_y$

$\Delta \nu_{bb\_y}$ → $\Xi_y^+ + \Xi_y^-$

$\Delta \nu_{bb\_x}$ → $\Xi_x^+ + \Xi_x^-$ → ε_x

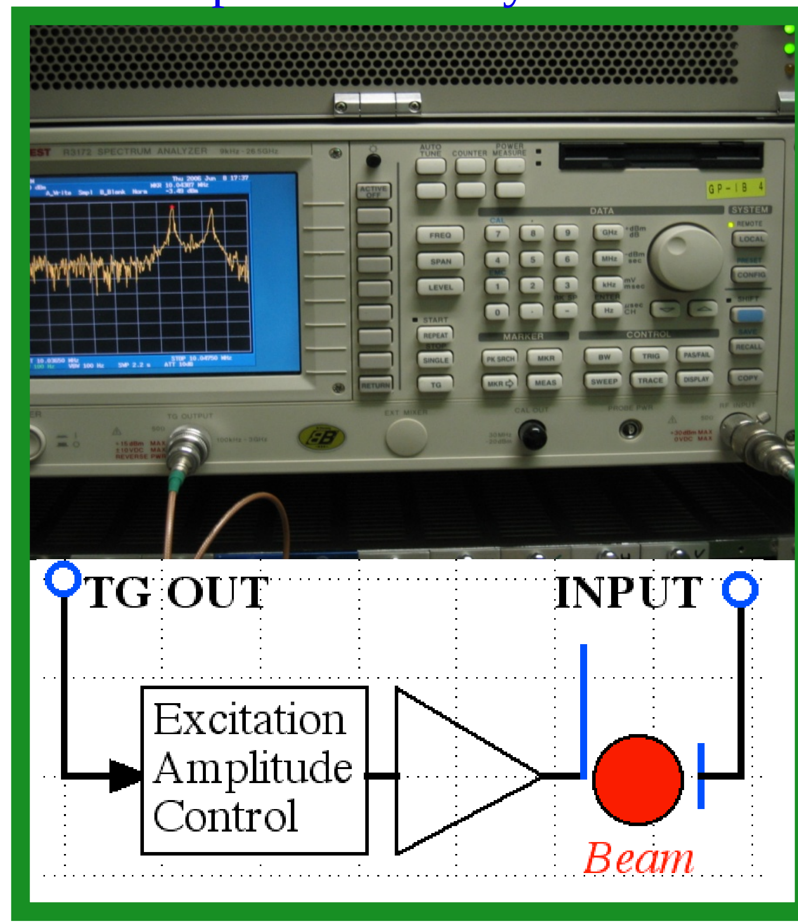
Gated Tune Monitor

Bunch-by-Bunch Tune Measurement

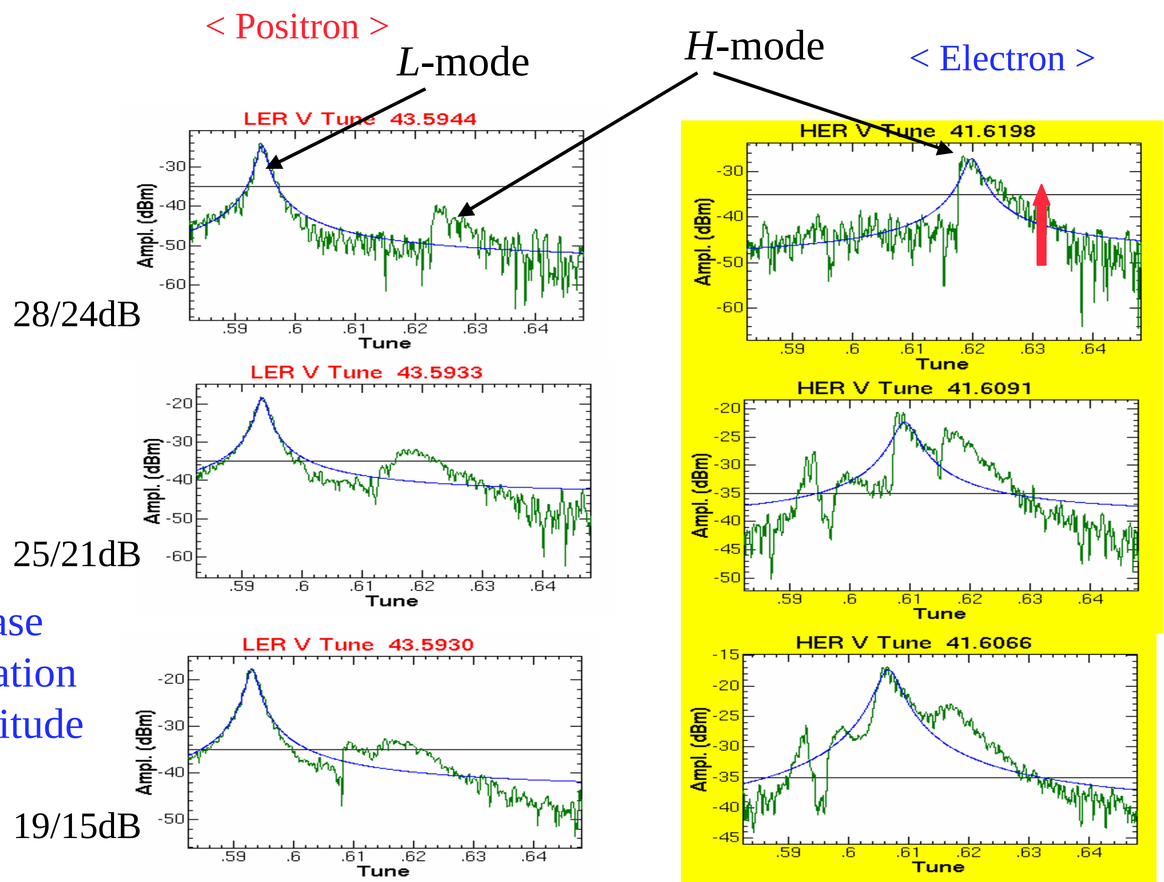
The specifications are:

- Be available with minimum bunch spacing of 4 ns.
- Bunch charge is larger than 3 nC.
- The measurement (sweep) time is 2.0 s.
- The resolution of the tune is $\delta\nu$=0.0001.
- Noise level corresponds to an oscillation amplitude of 0.3 μm.

<Spectrum Analyzer>



Nonlinear Resonance in Tune Spectrum, Vertical



Increase Excitation Amplitude

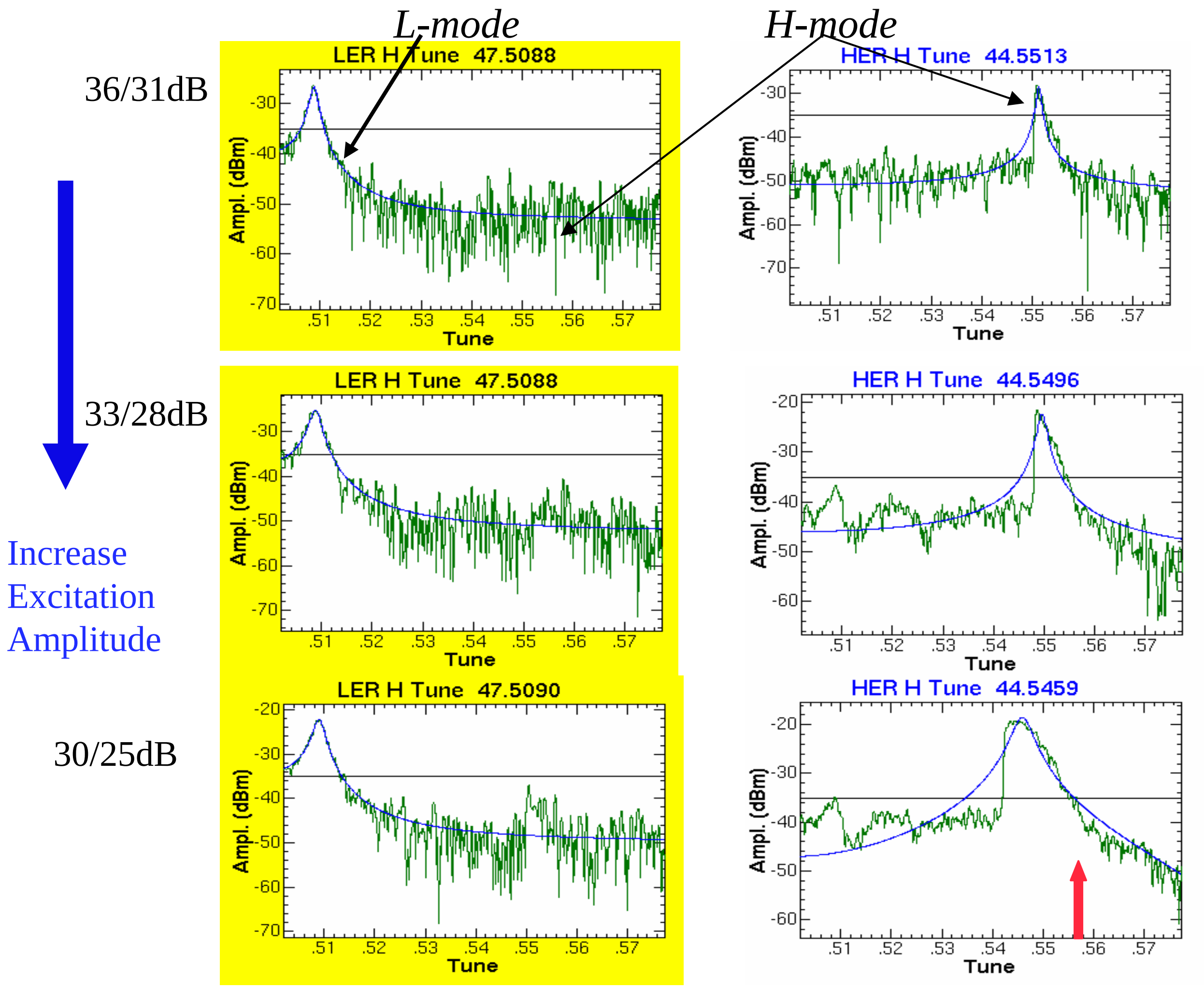
Bunch Current 1.5/0.3mA

Tune H / V
e+: .5055/.5919
e-: .5111/.5930

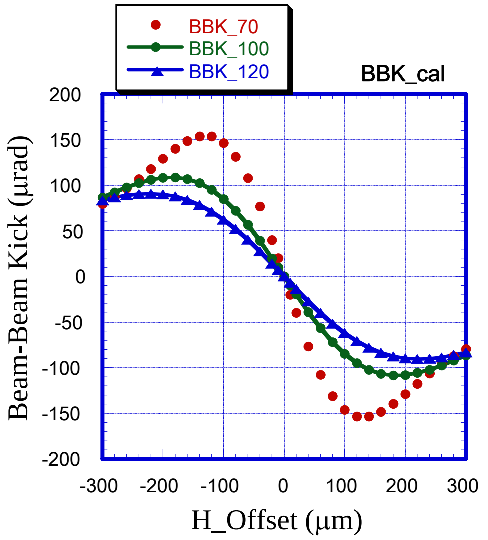
Result:

- The *L*-mode appears clearly in e+ bunch and the *H*-mode is seen in e- bunch.
- The peak of the *H*-mode spectrum shifts to a lower tune.

Nonlinear Resonance in Tune Spectrum, Horizontal



<Horizontal Beam-Beam Kick>



- The amplitude-dependent tune is caused by nonliner beam-beam kick.
- Coherent beam-beam tune shift is determined by an edge, not a peak in the spectrum.

Nonlinear Resonance causes Hysteresis

π-mode or *H*-mode spectrum

< Resonant Curve >

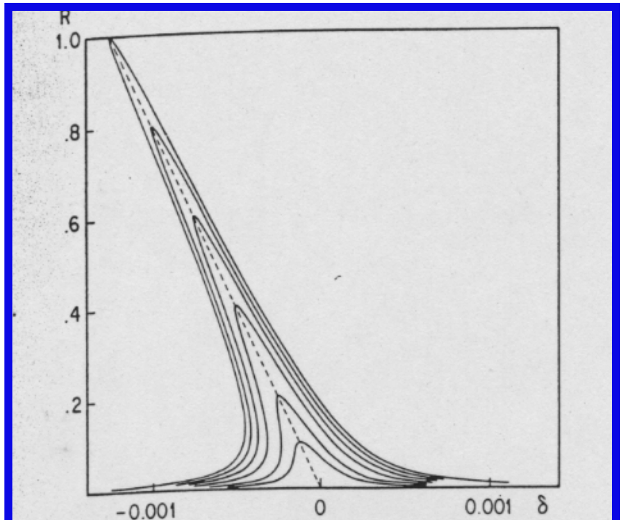


Fig. 3. Power response of the π mode against the sinusoidal rf kick of the deflector: $Q = 0.1, 0.2, 0.4, 0.6, 0.8$ and 1.

Tune →

K. Hirata, NIM A269, 7 (1988)

< Measurement >

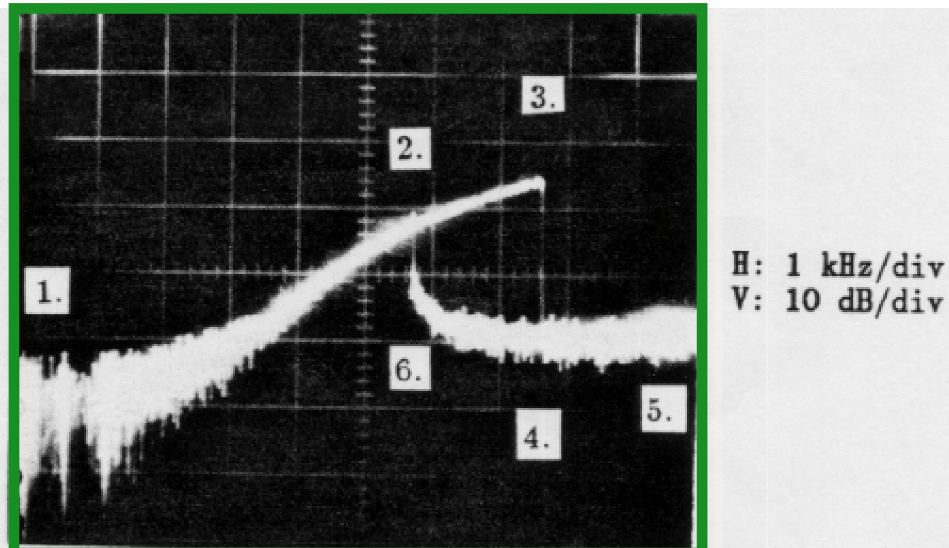


Figure 1. Hysteresis phenomena of the π-mode.

← Tune

Sweep direction

PAC’89 p.709

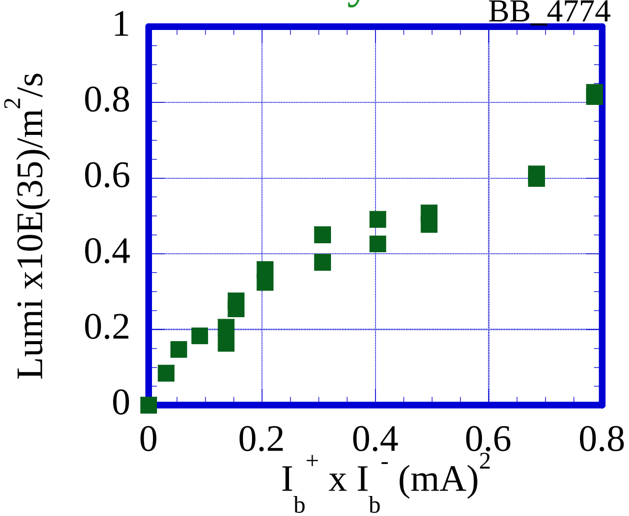
Measurement of Coherent Beam-Beam Tune Shift

< Beam Conditions under Crabbing Collision >

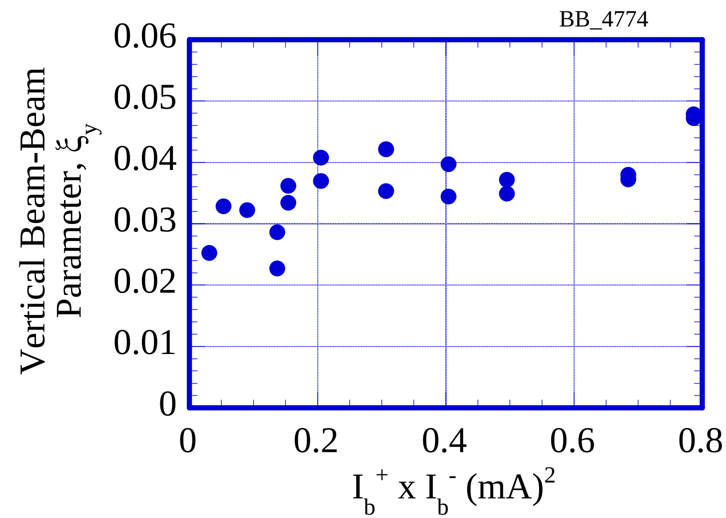
Ring	LER	HER	
Crab	0.94MV	1.43MV	
Emittance: ε_x	24	24	nm
Beta*: $\beta x/\beta y$	80/0.59	80/0.59	cm
Tune: νx	45.507	44.510	
Tune: νy	43.595	41.595	
νs	-0.0249	-0.0216	
Bunch spacing	192		ns

Vertical Parameters

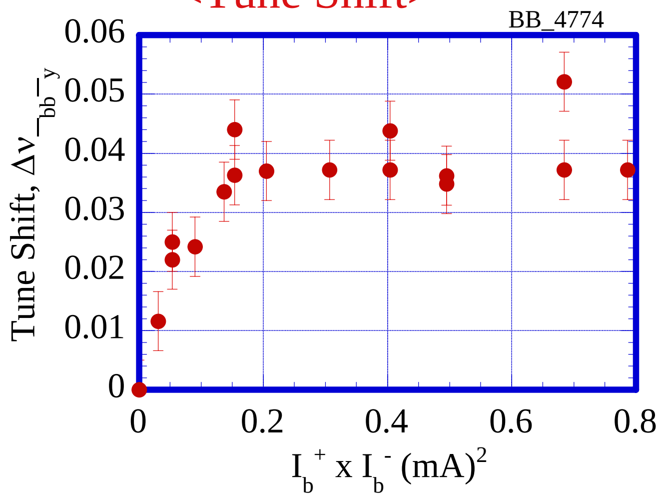
<Luminosity>



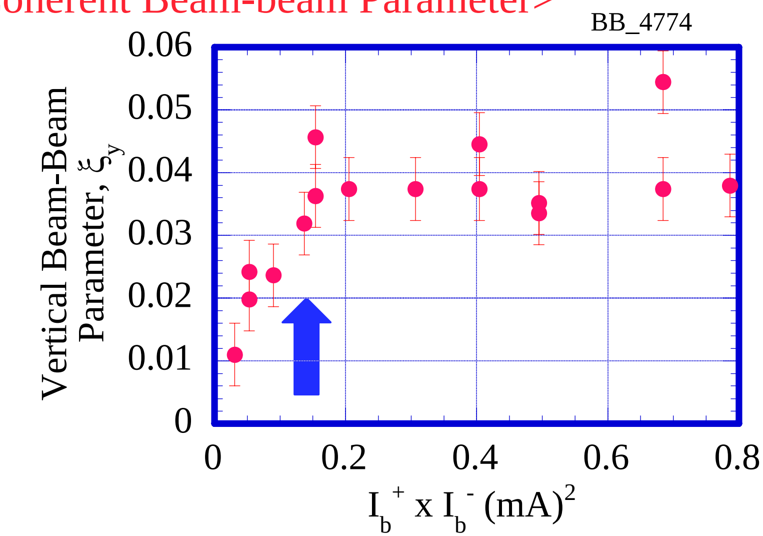
<Incoherent Beam-beam Parameter>



<Tune Shift>



<Coherent Beam-beam Parameter>



Beam-beam Limit @ I_b^2=0.14 mA^2

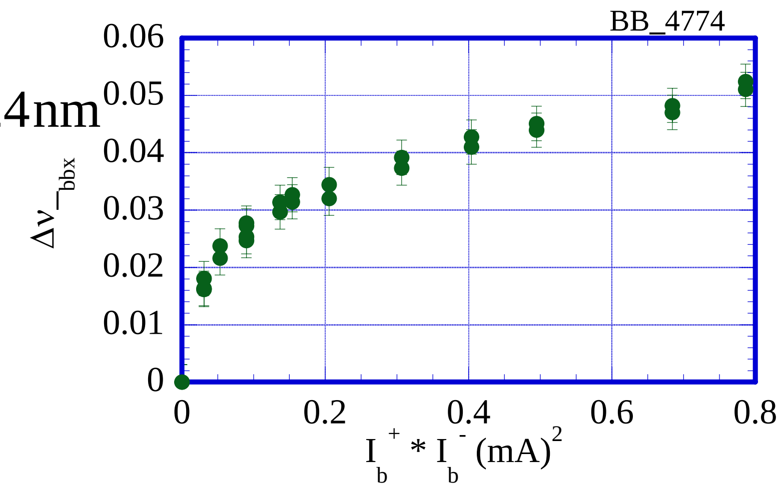
Horizontal Parameters

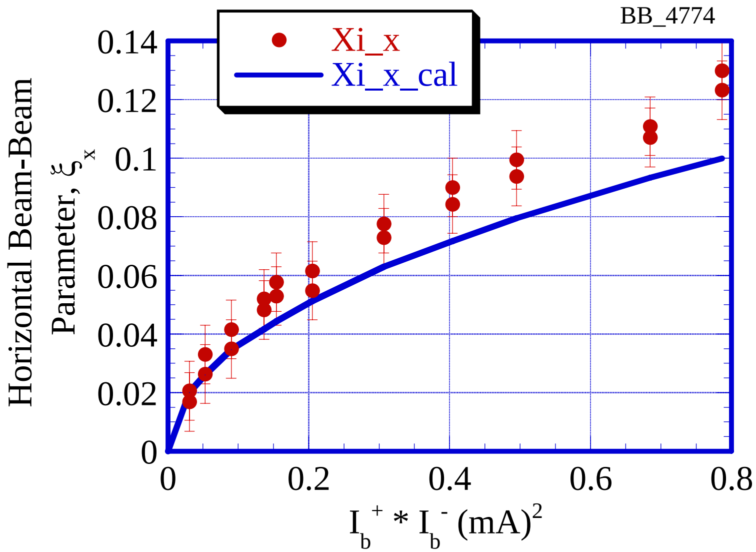
<Beam-Beam Parameter>

<Beam-Beam Tune Shift>

ε_x :

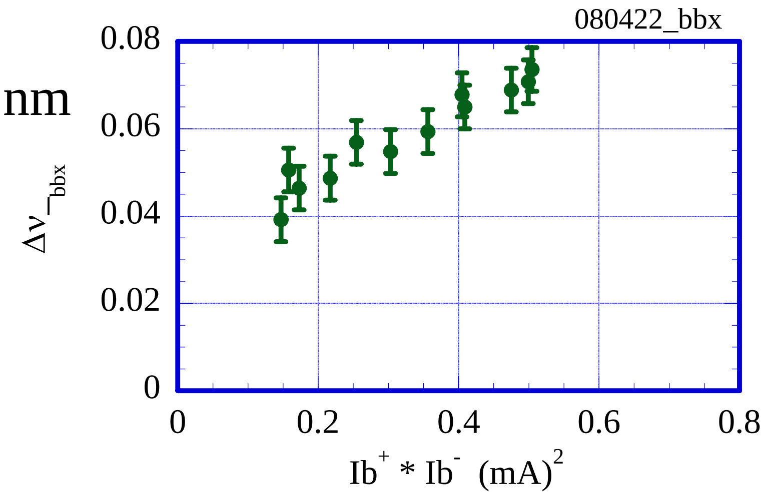
24/24nm

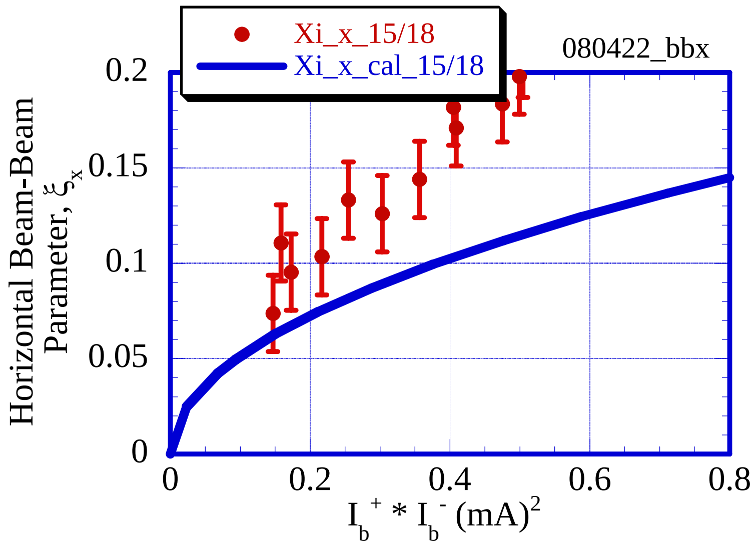




ε_x :

15/18nm





Intensity-Dependent Tune Spectra

While increasing electron bunch (opposite beam) intensity,
Spectrum of a positron bunch (own beam) with a constant excitation level:

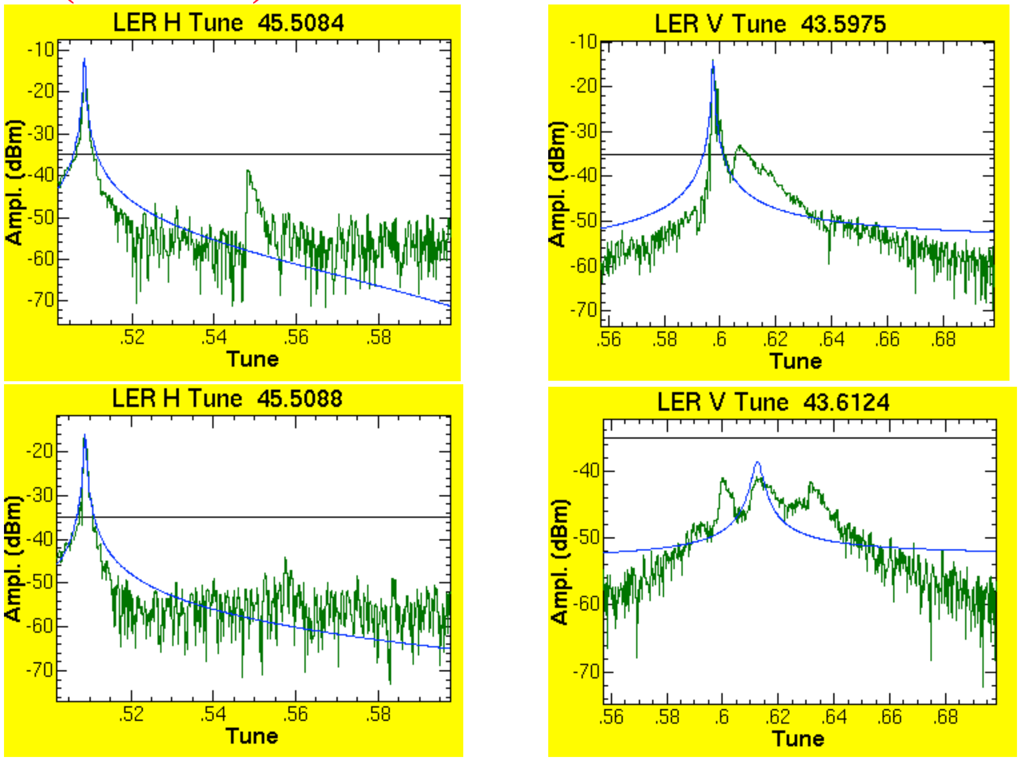
Ie^+ / ie^-

0.84/0.38mA

$\xi_q^+ \approx \xi_q^-$

0.81/0.58mA

$\xi_q^+ > \xi_q^-$



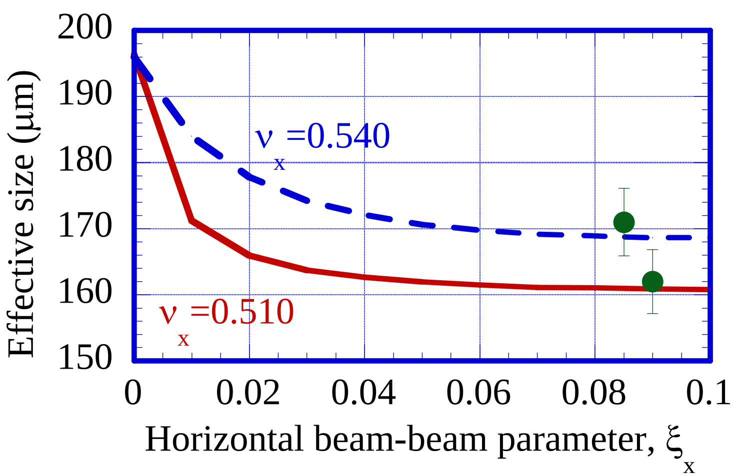
Results:

- Spectra are getting broader and have larger tune spread as increasing the beam-beam parameter.
- The vertical *H*-mode splits into two peaks.

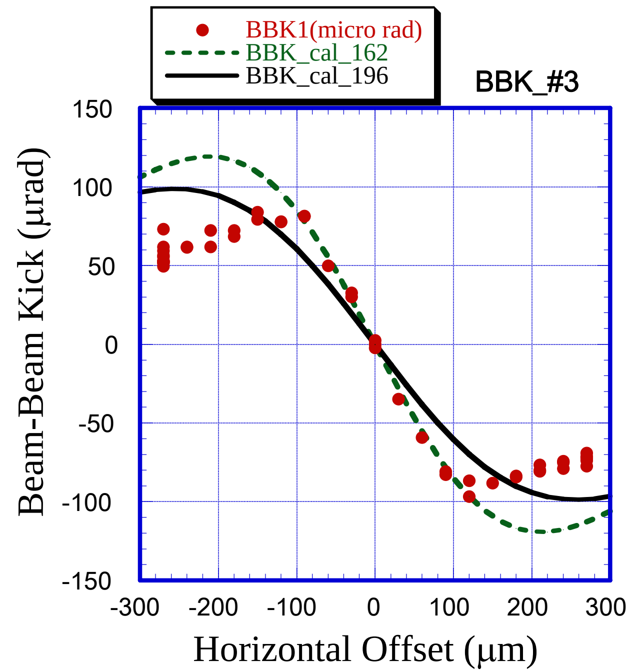
Horizontal Beam Size at IP

Estimated horizontal size from beam-beam kick measurement

<Beam Size>



<Beam-Beam Kick>



Result:

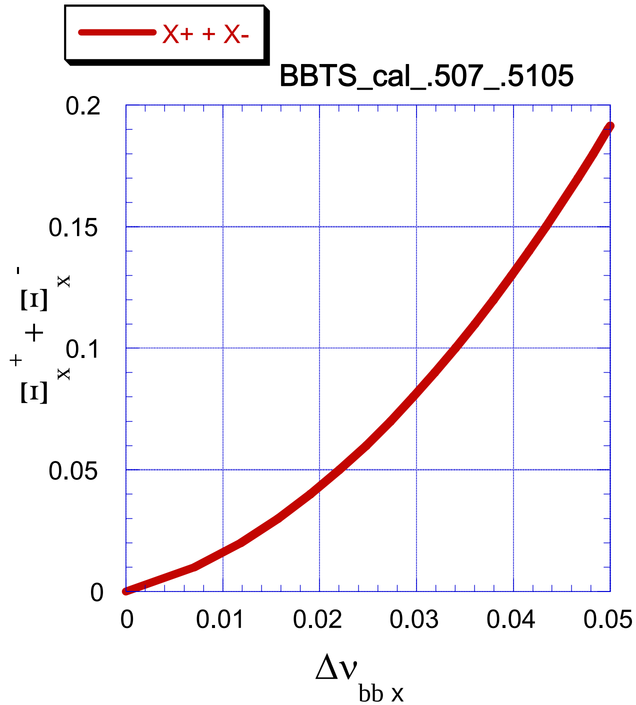
- Measured size around the center agrees with an expectation.
- However, the kick data deviates from a Gaussian in the peripheral region.

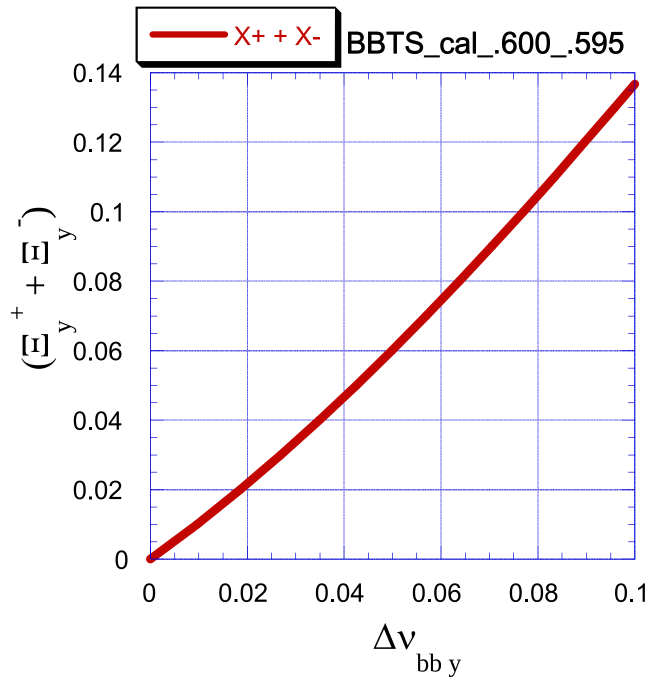
Summary

- 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.
- 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 around 0.05, at a low bunch current of 0.14 mA^2, the beam-beam limit. The current product is about 0.5 mA^2 in usual operations.
  - The results suggest decrease in specific luminosity with increase in bunch current.
- The ξ_x is not saturated above 0.1.
- The ξ_x is higher than expectation, predicts smaller emittance than natural.
  - Decrease in horizontal emittance would increase vertical emittance and reduce the luminosity.
  - The emittance reduction is inconsistent with the dynamic effect.
- Tune spectra widen as increasing the ξ_q.
- The horizontal profile deviates from a Gaussian in the peripheral region.
  - These results might be related to lifetime limitation.


Thank you for your attention!

Relation between Coherent Tune Shift and Beam-Beam Parameter



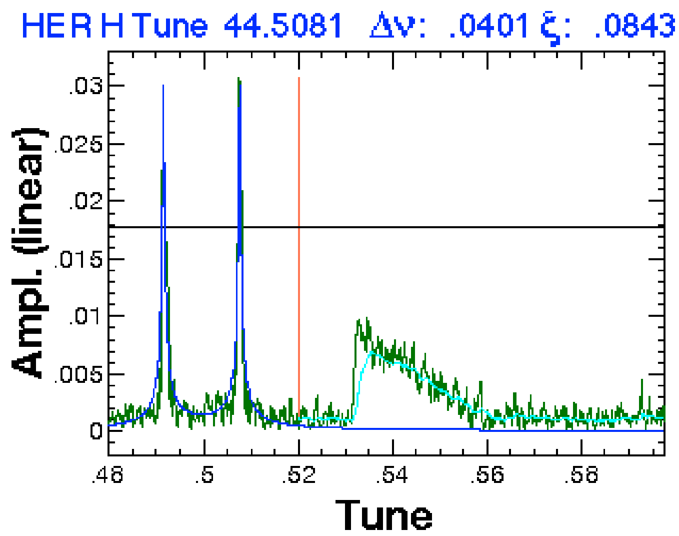


$$\bar{\xi}_x = \Xi_x^+ + \Xi_x^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y_x} \Delta\nu_{bb\_x}$$

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

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

How to determine Tune Shift and Beam-beam Parameter



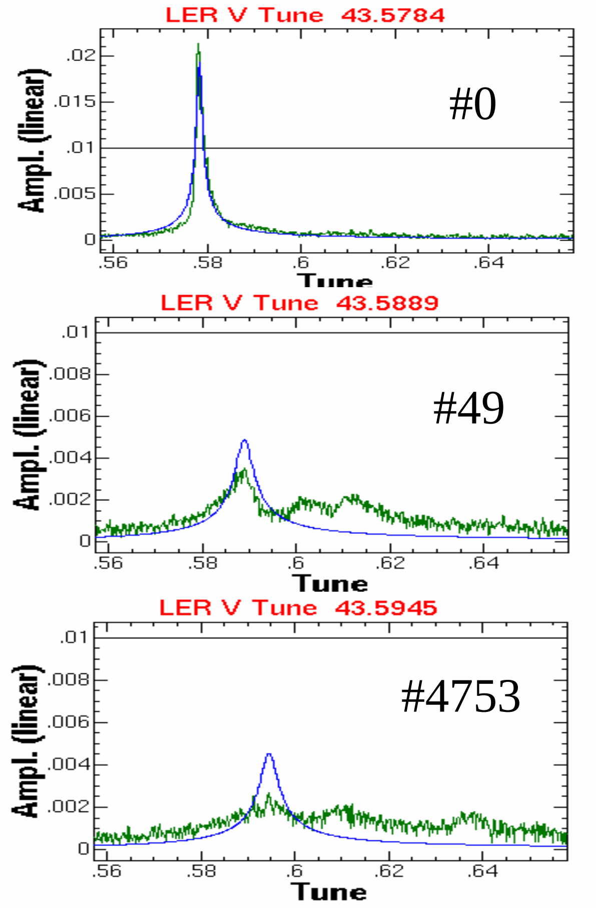
$$\bar{\xi}_x = \Xi_x^+ + \Xi_x^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y_x} \Delta\nu_{bb\_x} \qquad \bar{\xi}_y = \Xi_y^+ + \Xi_y^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y_y} \Delta\nu_{bb\_y}$$

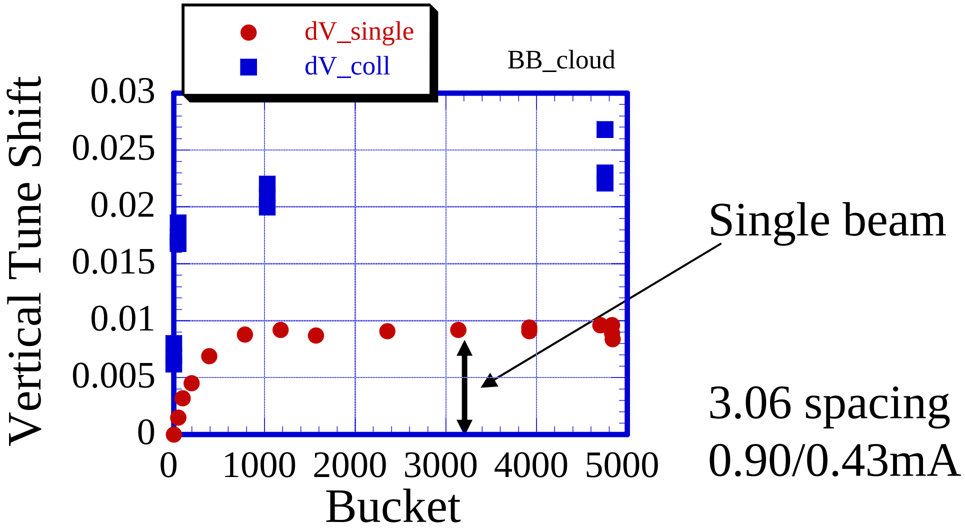
Example: $\Delta\nu_{bb\ x}$=0.04 Y_x=1.31 -> ξ_x=0.08 $\Delta\nu_{bb\ y}$=0.06 Y_y=1.23 -> ξ_y=0.058

Tune Spectra along Bunch Train

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

< Spectra along Train >





3.06 spacing
0.90/0.43mA

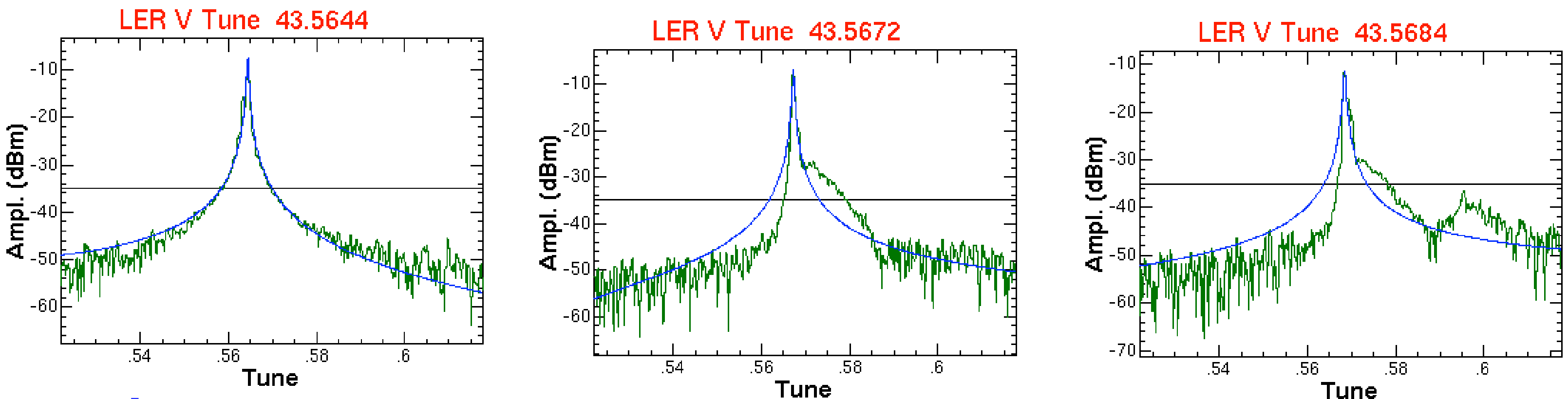
Result:

- Synergic effect of beam-beam and electron cloud!
- Spectrum changes, but, specific luminosity did not show a significant variation.

Intensity-Dependent Spectrum under Crossing Collision

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:

Ie^{+} / ie^{-} 0.45/0.00mA 0.45/0.36mA 0.45/0.58mA



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.