Beam Dynamics Measurements in the Vicinity of a Half-integer Resonance

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  - Dynamic Beam-Beam Effects
  - Beam-Beam Tune Shift
  - Half-integer Stopband
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  - Tune Spectrum
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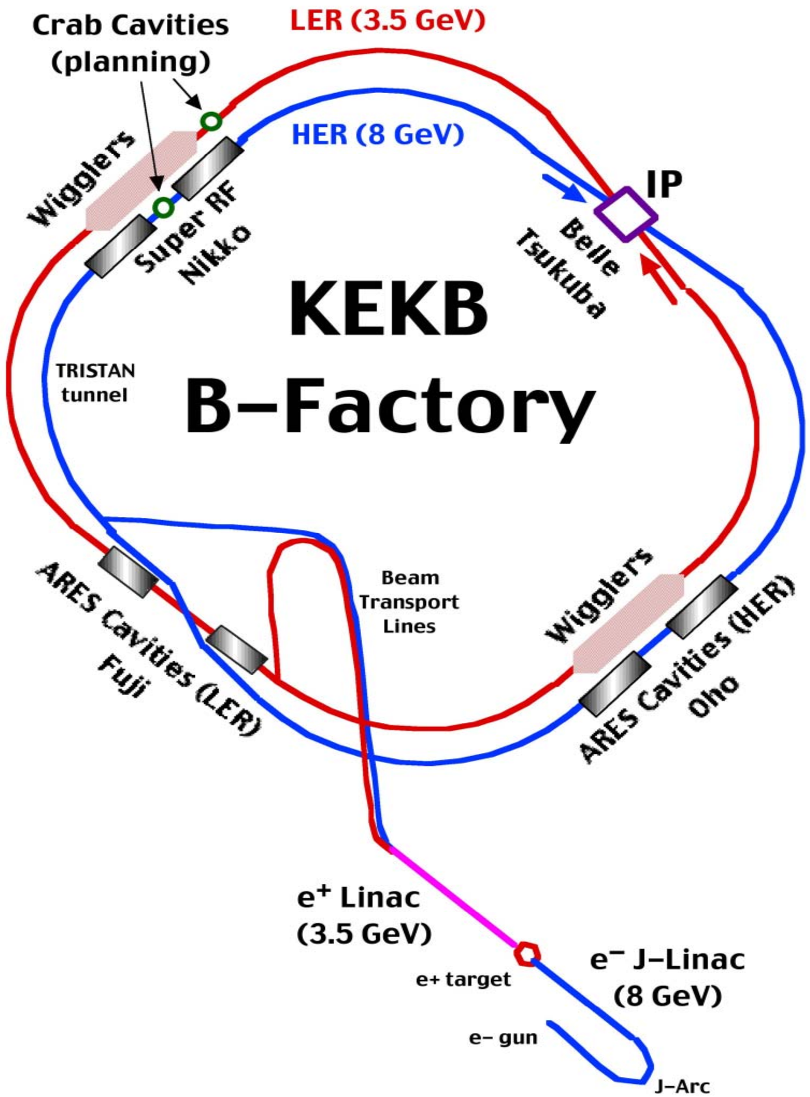
Motivation

- Setting the betatron tune near to a half-integer is crucial to produce high luminosity in circular colliders.
- Dynamic beam-beam effects result in optics distortion: emittance growth and beta beat.
- On the other hand, approaching a half-integer, we would encounter stopband, beta beat.
- KEKB reaches a high beam-beam parameter of ξ_x=0.1.
- Fractional tune is set around 0.506 in horizontal plane.
- Dynamic beam-beam effects and half-integer stopband are important issues for KEKB.

KEKB

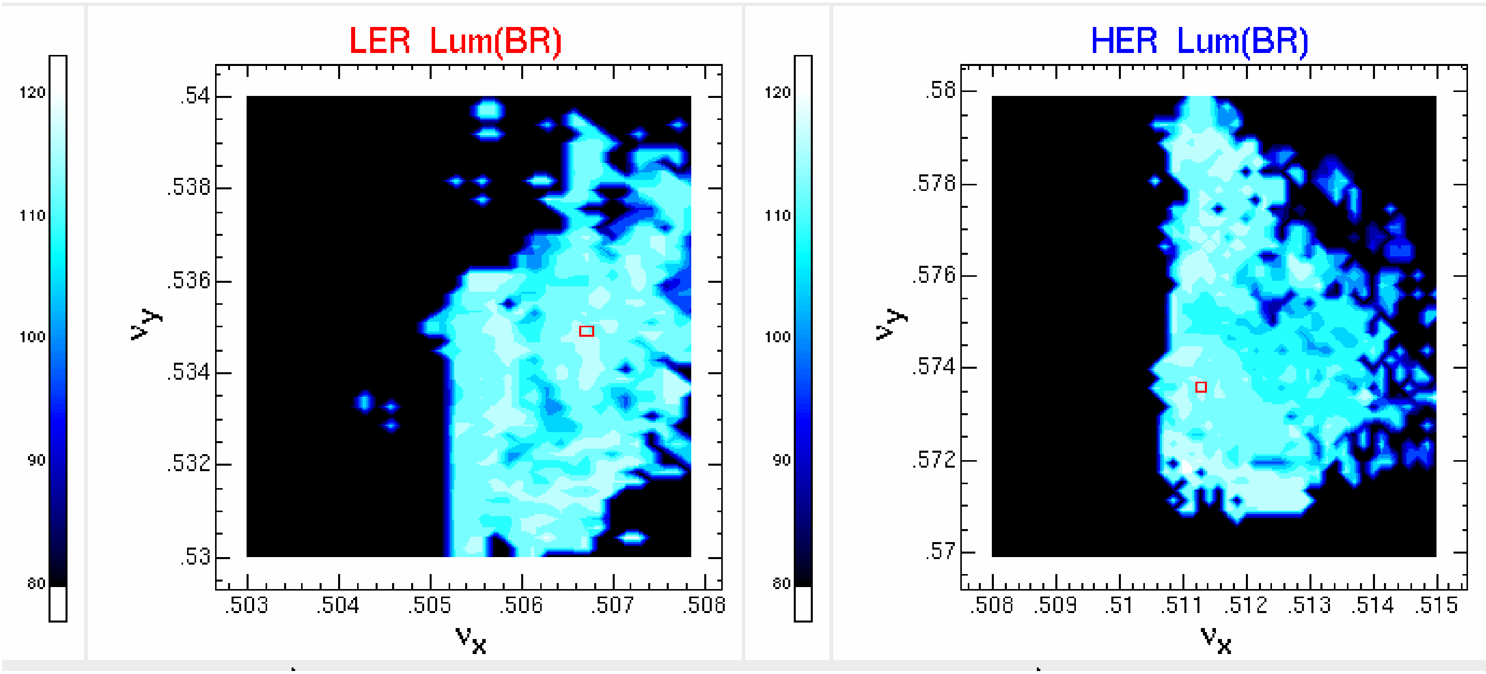
- Asymmetric Beam Energy
  - 8GeV (electron)
  - 3.5GeV (positron)
- Circumference
  - 3018m
- IP with Crossing Angle
  - 22 mrad horizontally
- The Maximum Luminosity
  - 1.6 x 10^{34} cm^{-2} s^{-1}



Machine Parameters

Ring	LER	HER	
Horizontal Emittance	18	24	nm
Beam Current	1719	1347	mA
Number of bunches	1389		
Bunch spacing	6 or 8		ns
Betatron tune ν_x/ν_y	**45.506**/43.531	44.512/41.578	
Beta at IP β_x^*/β_y^*	59/0.65	56/0.62	cm
Beam-beam parameter ξ_x/ξ_y	**0.117/0.096**	**0.073/0.055**	

Tune Diagram in Operations



- The operating points are crucial for raising luminosity and beam lifetime.
- Severe wall exists in the horizontal tune.

Dynamic Beam-Beam Effects

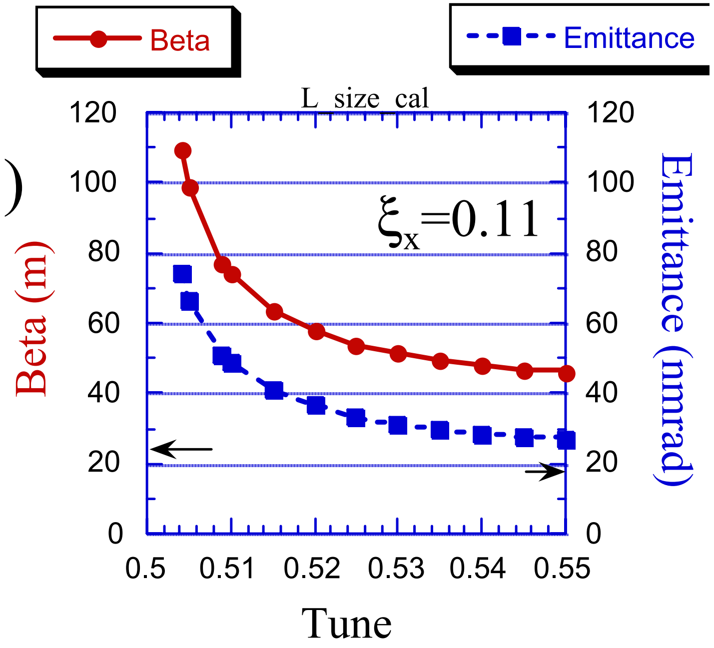
- Beta and Emittance change as a function of the tune.

- Dynamic Beta

$$\Delta\beta(s) = \frac{\beta_0(s)\ \beta^*}{2\sin(2\pi\nu)}\Delta k^* \cos(2\pi\nu - 2|\Delta\varphi_s|)$$

- Dynamic Emittance

$$\varepsilon_x \approx \frac{1+2\pi\xi_x \cot 2\pi\nu}{\sqrt{1+4\pi\xi_x \cot 2\pi\nu - 4\pi^2\xi_x^2}}\varepsilon_{x0}$$

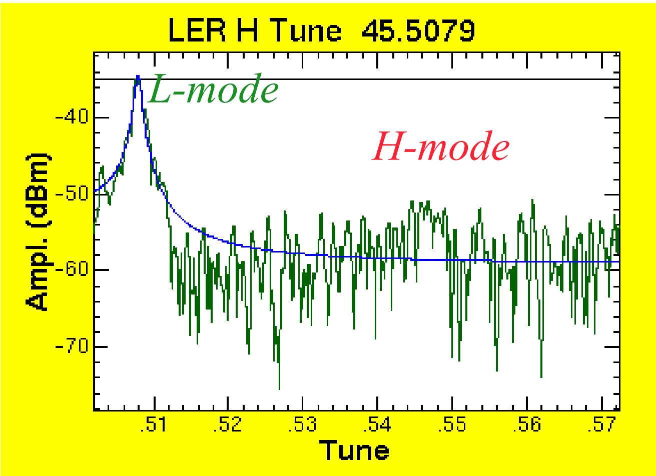


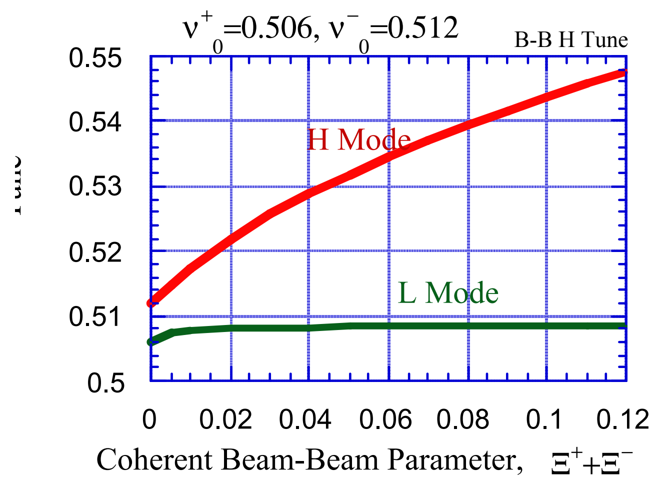
at LER SRM
β_{x0}=24.15 m
ε_{x0}=17.8 nmrad

Beam-Beam Tune Shift in double-ring colliders

- Beam-beam interaction produces a new set of two tunes.
- We call two modes the *H-mode* and the *L-mode*.
- Coherent beam-beam tune shift: $\Delta\nu_{bb} = \nu_H + \nu_L - \nu_0^+ - \nu_0^-$
- Coherent beam-beam parameter: $\Xi_q^+ + \Xi_q^- = \bar{\xi}_q = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y} \Delta\nu_{bb}$

An example





Half-Integer Stopband

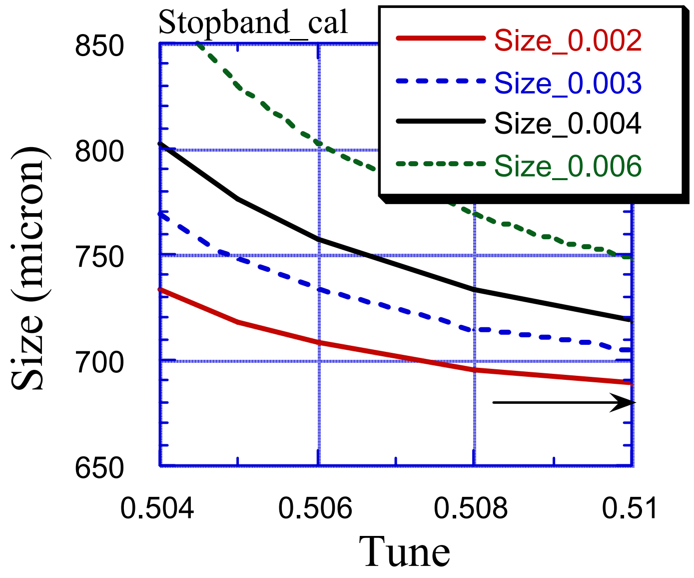
- Gradient errors cause the half-integer stopband and beta beat.
- The beta beat changes the beam size.

$$\frac{\Delta\beta_{ge}}{\beta_0} = -\frac{\nu}{4\pi}\sum_p \frac{J_p e^{i\nu\phi}}{\nu^2 - (p/2)^2}$$

$$\nu \approx \frac{p}{2} \qquad p \text{ : integer}$$

$$\frac{\Delta\beta_{ge}}{\beta_0} \approx -\frac{1}{2}\frac{|\Delta\nu_{sb}|}{(\nu - p/2)}\cos(p\phi + \delta)$$

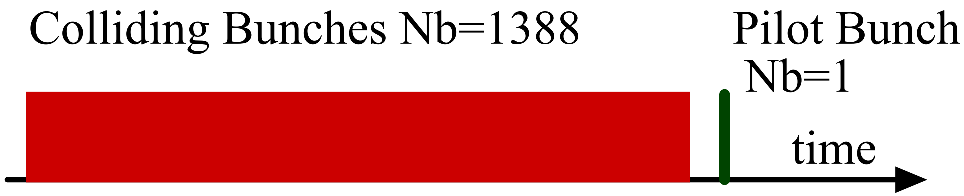
$|\Delta\nu_{sb}| \approx |J_p|/2\pi$: Stopband Width

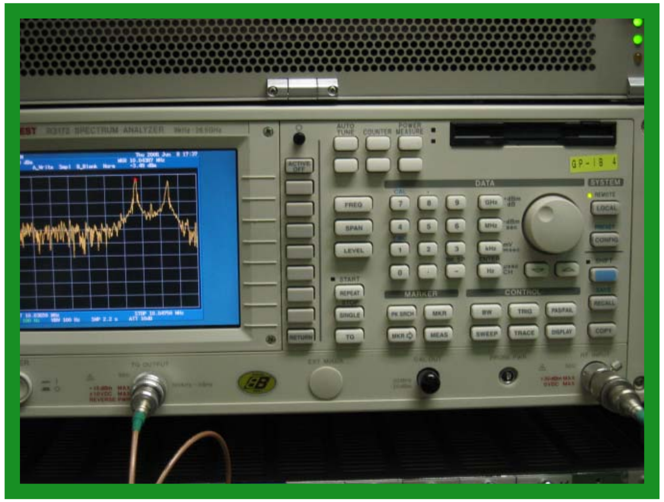


$$\phi = \int \frac{ds}{\nu\beta}$$

Measurement 1: Tune Spectrum

A Gated Tune Monitor is equipped for measuring a pilot bunch tune using a Spectrum Analyzer.



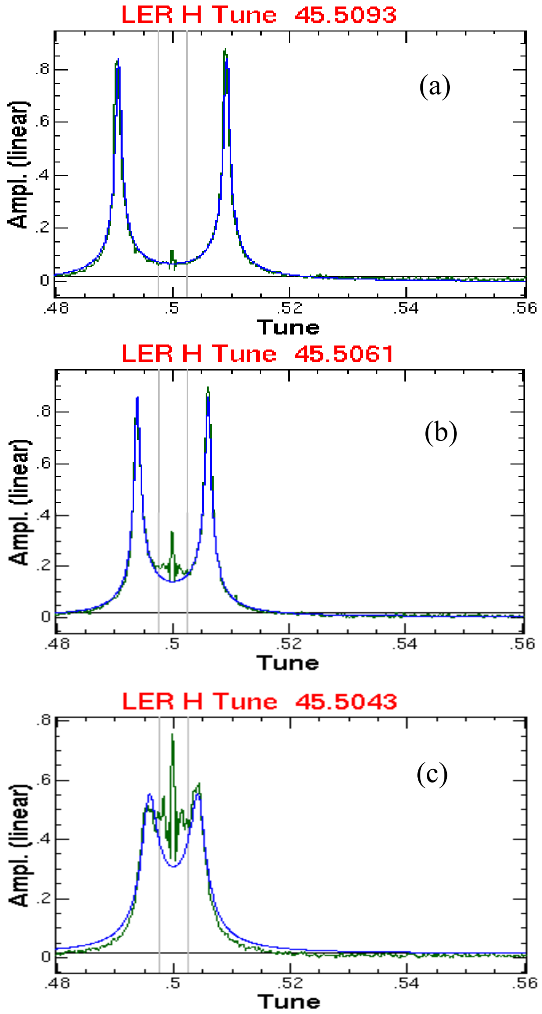


The specifications are:

- Be able to measure bunch-by-bunch tune.
- The measurement (sweep) time is 2.0 sec.
- The resolution of the tune is $\delta\nu=0.0001$.

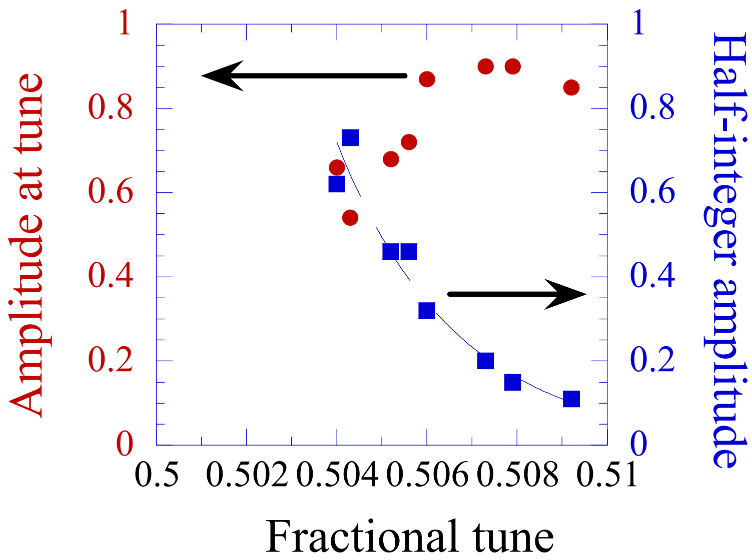
Tune Spectrum (1/3)

We set the tune closer to a half-integer under regular operations, ---



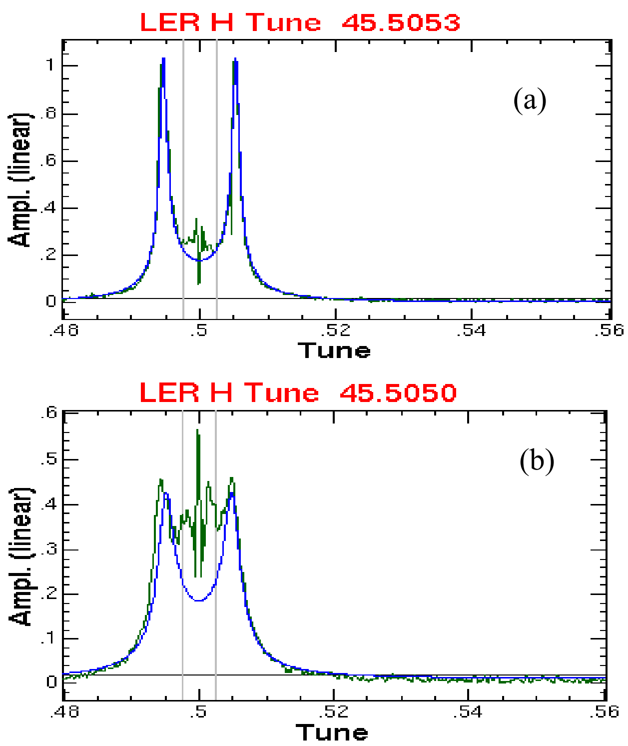
- A sharp spectrum was observed just on a half-integer.
- The amplitude grew exponentially and the betatron amplitude reduced.
- A bunch was lost at ν_x=0.504.

ξ_x=0.94

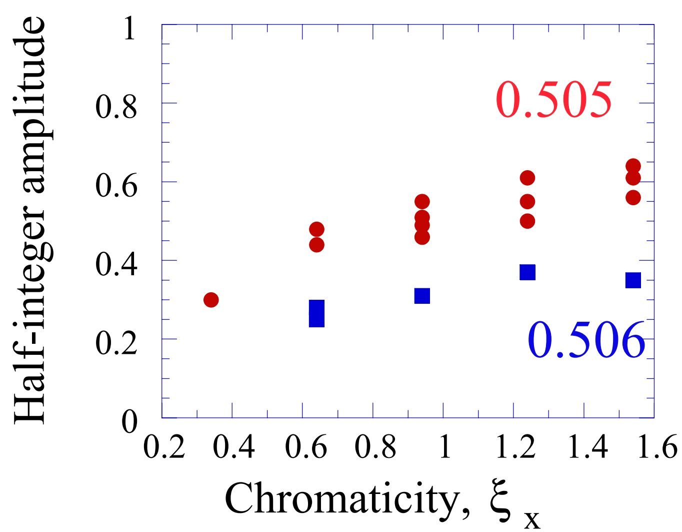


Tune Spectrum (2/3)

- The half-integer amplitude depended on chromaticity under a fixed tune.
- The monitor is sensitive to tune spread.

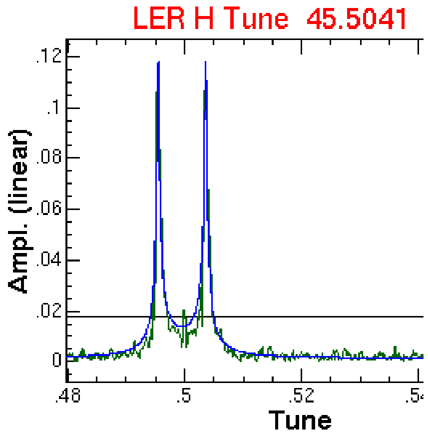


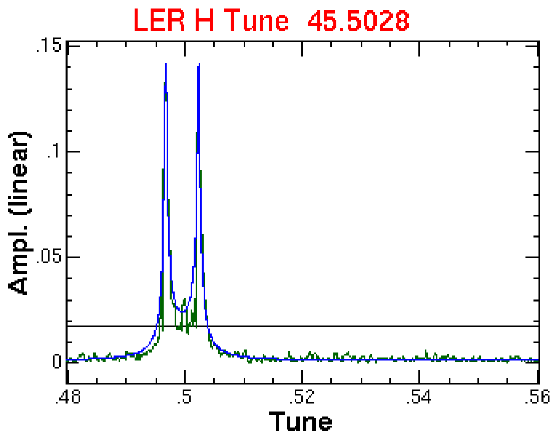
Chromaticity Dependence



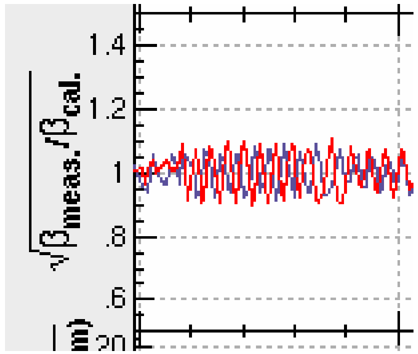
Tune spectrum at low current under non-collision (3/3)

- The tune reached to ν_x= 0.502 **without beam loss**.
- Distortion is weak.
- Beta beat increased from $(\Delta\beta/\beta_0)_{\square\square\square}$=0.10 to 0.25, when ν_x= 0.504 moved to 0.502.
- Beta beat is consistent with linear theory.

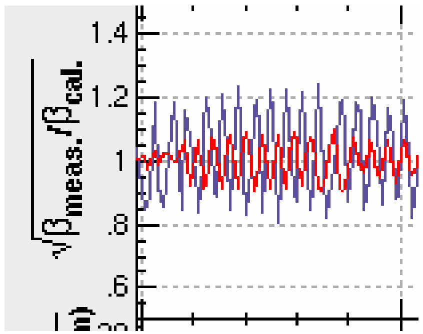




ν_x= 0.504

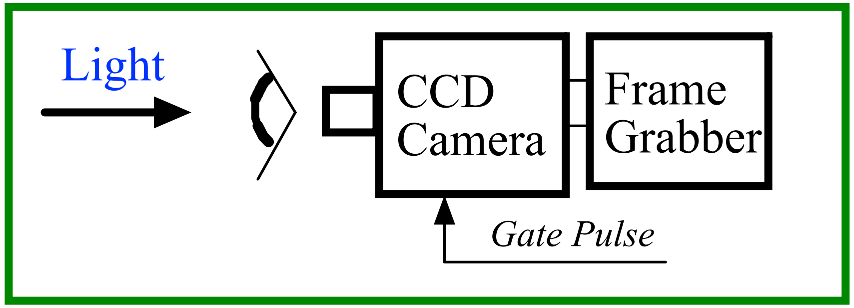


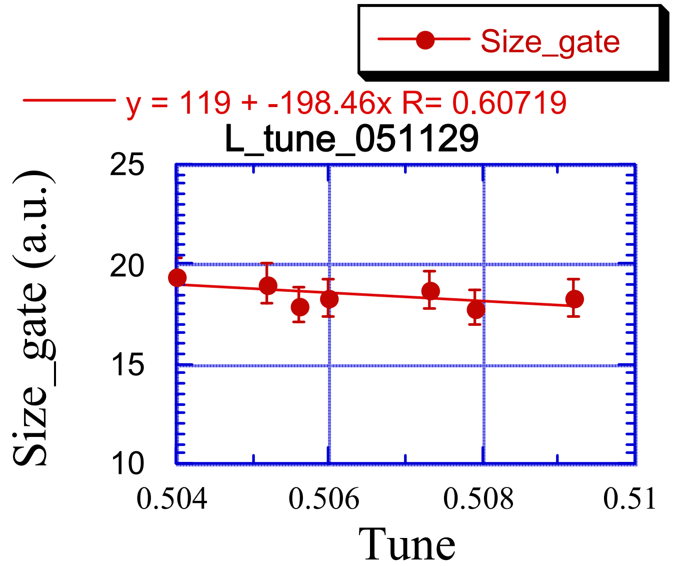
ν_x= 0.502



Measurement 2: Beam size of a non-collision bunch

Horizontal size of a pilot bunch was measured using a gated CCD camera under collisions.

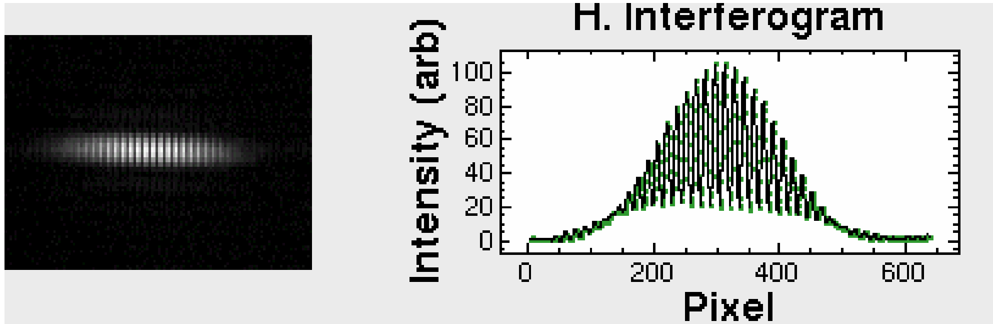


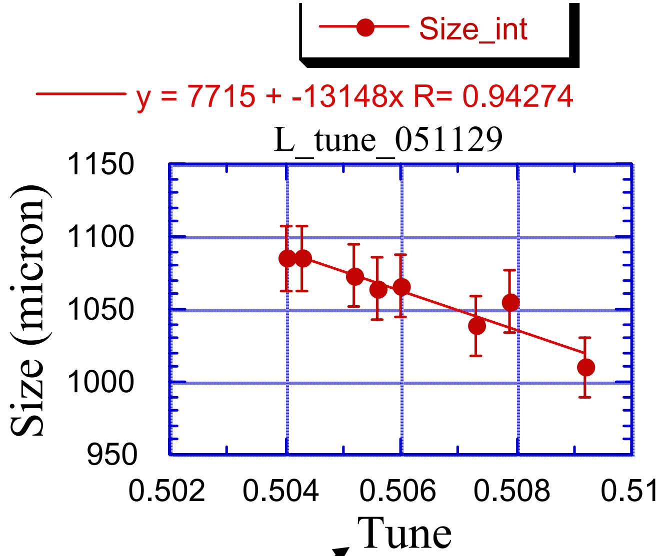


- Linearly fitting line shows horizontal size slightly increases by 6.4% with large error bars, when the tune changed from ν_x= 0.510 to 0.504.
- Linear fitting may suggest an **effective stoband** of $|\Delta\nu_{sb}|\cos(p\phi+\delta) = 0.002$ to 0.003.

Size Measurement of Colliding Bunches

Horizontal size of colliding bunches were measured using an interferometer.





Non-collision bunch

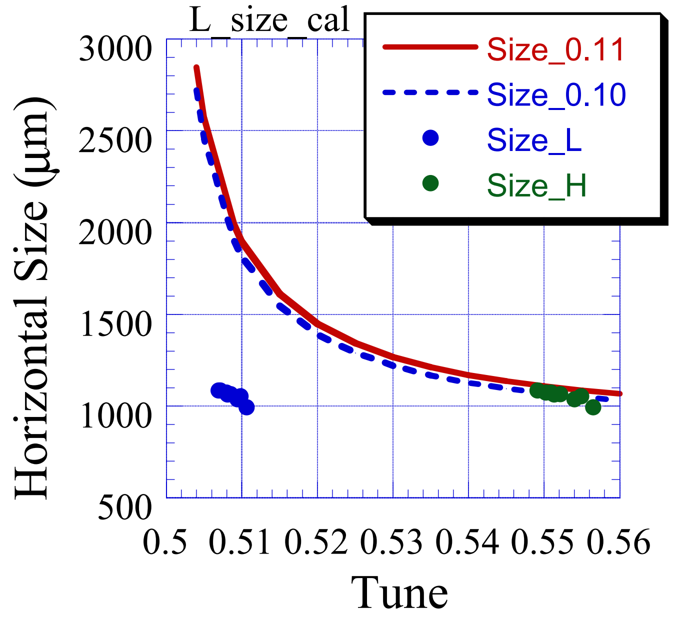
- Horizontal size increased by 7.6% when tune changed from $\nu_x = 0.510$ to 0.504.
- The size might be affected by both effects of dynamic beam-beam and stopband.

Note:
Tune of colliding bunches is different from that of pilot bunch.

Consideration for Size Measurement in Collision

- Colliding bunches have two modes of tune: L-mode and H-mode.
- Two tunes can be estimated, assuming ξ_x=0.11.
- By using the H-mode tune, measured size agrees with calculated one.

Dynamic Size at SRM



σ_{x0}=656 μm

Summary on Beam Size

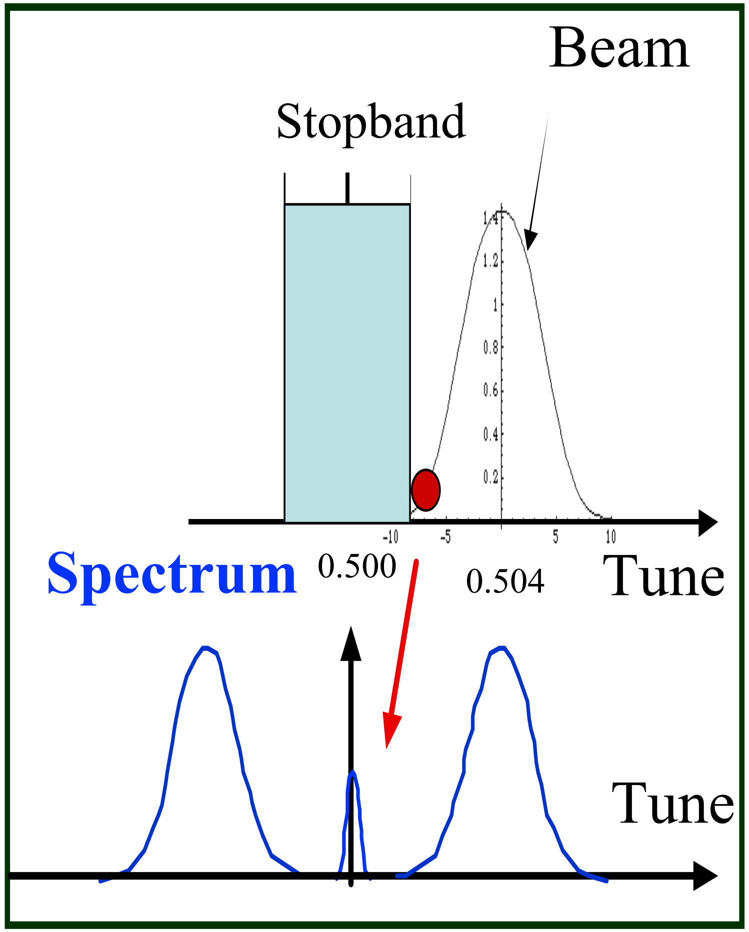
- Horizontal size slightly increased when the tune approached to a half-integer.
- Non-collision bunch would be affected by beta beat.
- However, quantitative evaluation is difficult due to large error bars in size measurement, needs more precise measurement.
- Colliding bunches is mainly caused by dynamic beam-beam effects.
- The tune in the *H-mode* should be used to evaluate the dynamic beam-beam effects, not that in the *L-mode*.

Summary on Tune Spectra

- We observed a resonance at a half-integer in tune spectrum.
- The amplitude of the half-integer resonance depended on detuning and tune spread (chromaticity).
- The stopband width depended on the beam conditions.
- Beta beat measured in low current was consistent with linear theory.
- The half-integer resonance might be caused by off-momentum particles of a bunch.

My Imagination for Half-integer Resonance

- Stopband is made by machine errors.
- The width depends on beam conditions.
- Some off-momentum particles of a bunch jump into stopband and are trapped there.
- Trapped particles appear as a resonance at a half-integer.
- Need to consider dynamics of off-momentum particles in simulation.



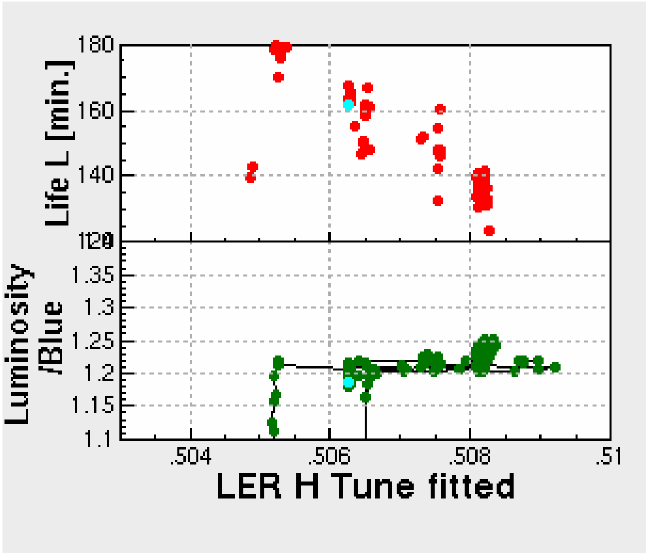

Thank you for your attention!

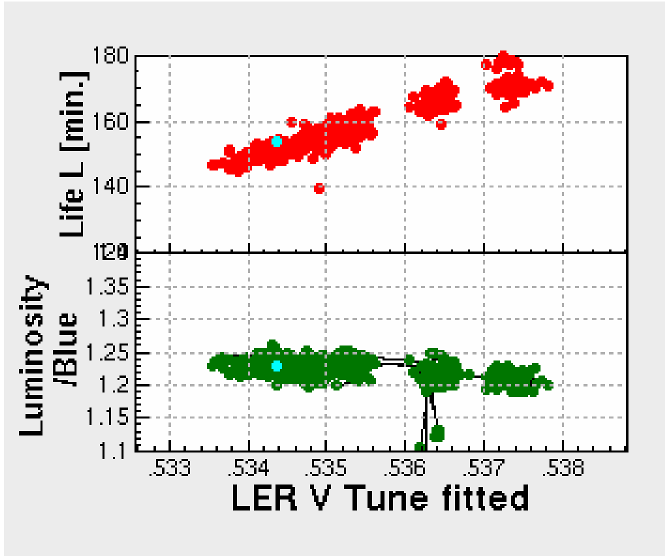
Extra Slides

Tune Survey

An Example

- The luminosity and the beam life are sensitive to the tunes.

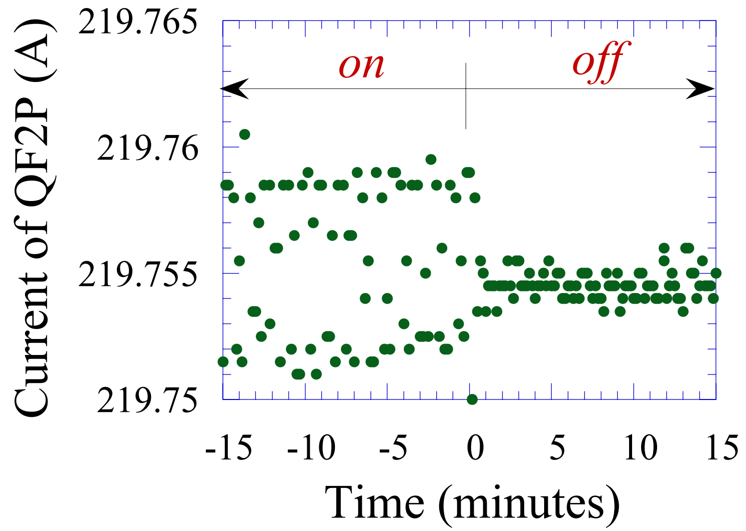


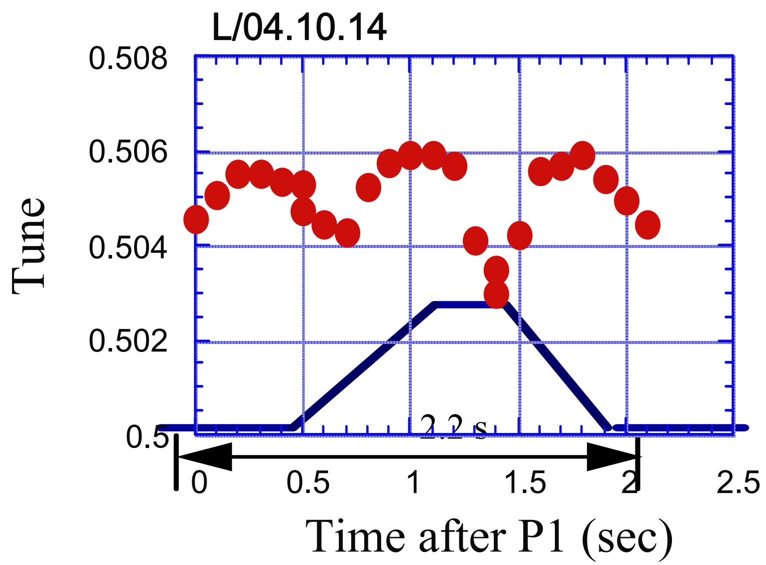


Measurement 1 : Distortions by KEK-PS

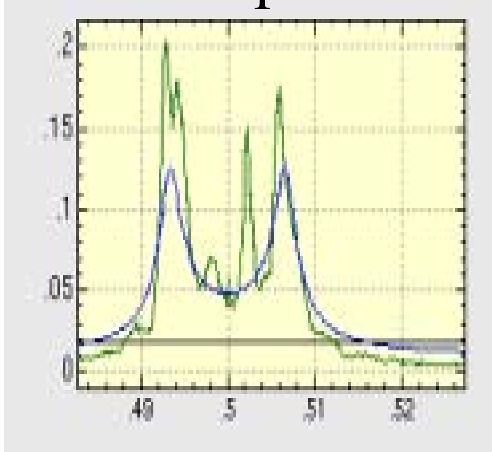
- Power supplies of KEKB was affected by KEK-PS operation.
- Tune spectrum was distorted.
- Tune varied, synchronized with KEK-PS cycle.

Power Supply for Q-Magnets





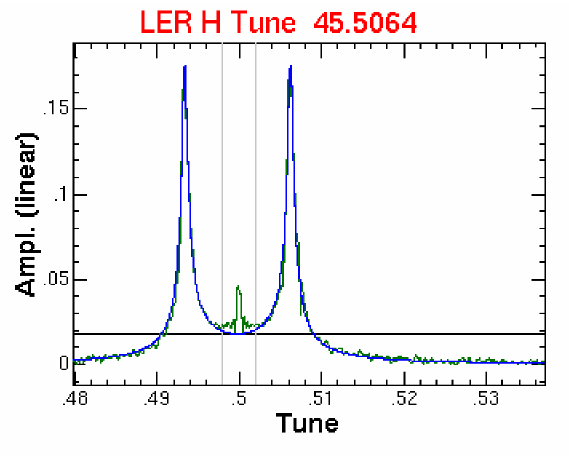
Tune Spectrum



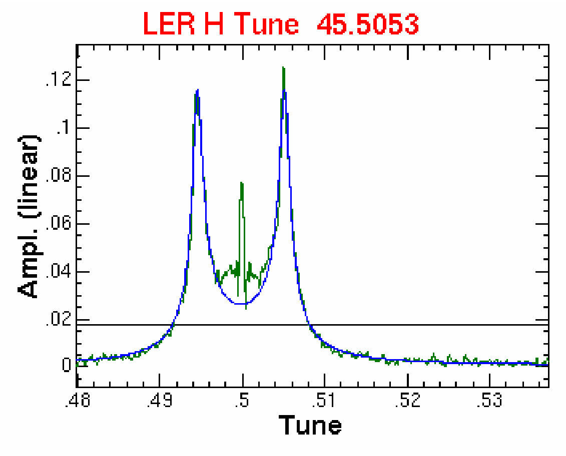
Tune spectrum after PS shutdown

- The distortion is observed regardless of PS.

(a)

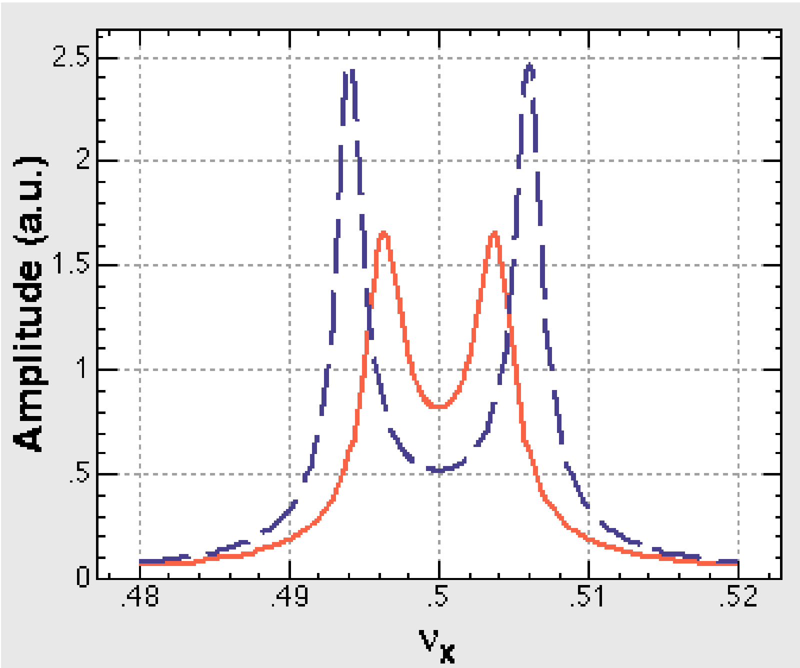


(b)



Simulating the spectrum

- The betatron tune spectrum well simulates the real one.
- But, no distortion can be seen at half-integer.



- Conditions -

- Phase relation is the same
- Assuming a single particle
- No machine error