

## BEAM DYNAMICS MEASUREMENTS IN THE VICINITY OF A HALF-INTEGERS RESONANCE

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### Abstract

The operating point of the betatron tune set near to a half-integer is a crucial parameter to produce high luminosity in electron/positron ring colliders. Dynamic beam-beam effects change the optics parameters, depending on the betatron tune and the beam-beam parameter. On the other hand, the existence of the half-integer stopband affects the beam stability. Therefore, the beam behavior near a half-integer might provide interesting issues from the viewpoint of beam dynamics. We measured the frequency response of the beam across a half-integer for measuring the betatron tune at KEKB. A sharp spike just at a half-integer was observed in the tune spectrum. We believe the spectrum to be a nonlinear resonance caused by some off-momentum particles in a bunch. The horizontal beam size measured using a synchrotron radiation monitor indicated a slight increase when the tune approached a half-integer. The variations of the size due to dynamic beam-beam effects should be evaluated using an  $H$ -mode tune not an  $L$ -mode.

### INTRODUCTION

KEKB [1] is a multibunch, high-current, electron/positron collider. The collider consists of two storage rings: the Low Energy Ring (LER) for a 3.5-GeV positron beam and the High Energy Ring (HER) for 8-GeV electrons. The maximum luminosity achieved so far is  $1.6 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ , where the horizontal beam-beam parameter of the LER reaches a high level of  $\xi_{bbx} \approx 0.1$ .

The operating point of the betatron tune is crucial to raise the luminosity and to maintain a sufficient beam lifetime. The horizontal betatron tune is set just above a half-integer, especially in the LER. The tune should be kept constant during physics experiments by feedback control. Thus, the tune of a non-colliding pilot bunch, which is placed just after a train of colliding bunches, is always monitored. The charge or the current of the pilot bunch is about 10 nC or 1 mA.

The operation tune setting very close to a half-integer under a high beam-beam parameter produces strong dynamic beam-beam effects. The dynamic beam-beam effects result in a distortion of the optics: an emittance growth and a beta beat. On the other hand, approaching a half-integer, we would encounter effects of the half-integer resonance. The existence of the half-integer stopband is based on machine errors. KEKB has internal errors in the optics parameters, as in all storage rings, and in addition, suffers from variations due to external fields. The power supplies for some quadrupole magnets of

KEKB were influenced by variations of the magnetic field of the KEK-PS (Proton Synchrotron) [2]. Thus, the betatron tune varied synchronized with a cycle of KEK-PS. Although precise adjustments of the power supplies reduced the variations, a distortion in the tune spectrum was still observed as the tune approached a half-integer. The horizontal beam size of the LER was measured as a function of the tune.

### BEAM DYNAMICS NEAR A HALF-INTEGERS

The beta function is modified by the additional field gradient due to the beam-beam interaction. A beta beat is produced around the ring. Especially, when the tune is set near to a half-integer, the beta beat causes significant effects. Figure 1 shows the expected horizontal beta function at a radiation point for a synchrotron radiation monitor (SRM) [3] installed in a weak bending magnet of the LER and also shows the horizontal emittance as a function of the fractional tune, assuming a beam-beam parameter  $\xi_{bbx} = 0.11$ . Both the emittance and the beta function increase, as the tune approaches a half-integer. Thus, the horizontal beam size observed by the SRM is expected to increase.

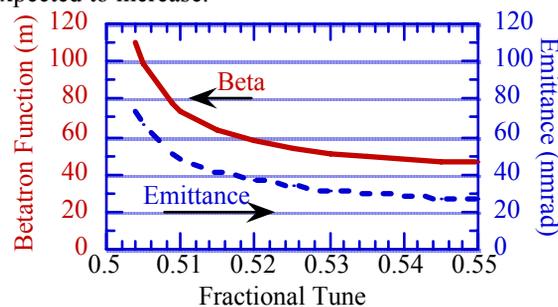


Figure 1: Calculated beta function at a radiation point for the SRM and the horizontal emittance in the LER as a function of the horizontal tune, assuming  $\xi_{bbx} = 0.11$ . Without collisions, the beta function is  $\beta_{x0} = 21.4 \text{ m}$  and the emittance is  $\epsilon_{x0} = 17.8 \text{ nmrad}$ .

The operation near a half-integer is very sensitive to machine errors. Gradient errors of a machine produce the beta beat around a ring and also yield the stopband around a half-integer [4,5]. Since no machine exists without error, this issue would be common for all machines. The stopband width depends on the intensity of errors. The stability of a beam generally depends on the distance of the tune from a half-integer and the tune spread. A bunch has a tune spread depending on the energy spread and the chromaticity. When the betatron tune approaches a half-integer, the beta beat would be resonantly affected by the

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stopband of a half-integer. A beta beat with a linear theory is approximately given by [4]

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

in the case of  $\nu \approx p/2$ . Here,  $p$  is an integer,  $\phi = \int (1/\nu\beta)ds$  the betatron phase and  $\delta$  a constant. The beta beat would change the beam size as a function of the tune.

## MEASUREMENTS

### Tune Spectrum

The betatron tune of the pilot bunch was measured using a swept-frequency method, where a spectrum analyser with a tracking generator was used. When the tune approached closer to the half-integer, we observed a distortion in the spectrum of the pilot bunch, where a sharp spike appeared just at the half-integer. We call the amplitude with a sharp spike in the spectrum the half-integer amplitude. The tune spectrum was recorded as a function of the fractional tune under a fixed chromaticity as shown in Figs. 2(a) and 2(b). When the tune was less than 0.504, the approach was stopped, because the measured bunch was partly lost due to a short lifetime. Although the tune spectrum was symmetrical for a half-integer, the peak amplitude at the tune slightly decreased with a wider spectrum as shown in Fig. 2(b). Figure 3 shows the half-integer amplitude as well as the tune amplitude, as a function of the fractional tune. We found an exponential growth in the half-integer amplitude. The tune spectrum was observed again while changing the horizontal chromaticity under a fixed betatron tune of  $\nu_{x0}=0.505$ . The horizontal chromaticity controlled by sextupole magnets varied over a range of  $\xi_{chx} = 0.9 \pm 0.6$ . It was confirmed that the tune spectrum became wider as the chromaticity increased, which suggests that the tune spectrum would somewhat reflect the tune spread of a bunch. We found that the half-integer amplitude tended to increase together with an increase in the width of the distorted tune spectrum when the horizontal chromaticity was increased. Note that these measurements were carried out at the same excitation amplitude as under the regular collisions.

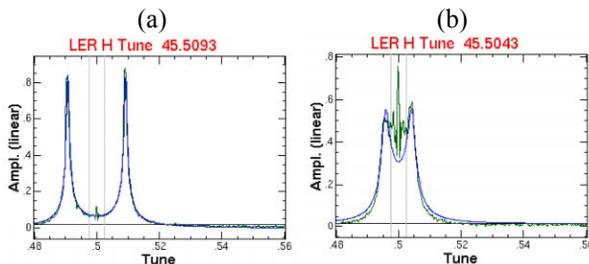


Figure 2: Horizontal tune spectra under a fixed chromaticity of  $\xi_{chx}=0.94$ . The green lines indicate the measured spectra and the blue lines the fitted ones with the Lorentzian function. The horizontal axis is the fractional tune and the vertical is the amplitude. Fitted

fractional tunes indicate  $\nu_x=0.5093$  (a) and  $\nu_x=0.5043$  (b). The sweep time was 1.9 s. During the measurement, the PS was operative.

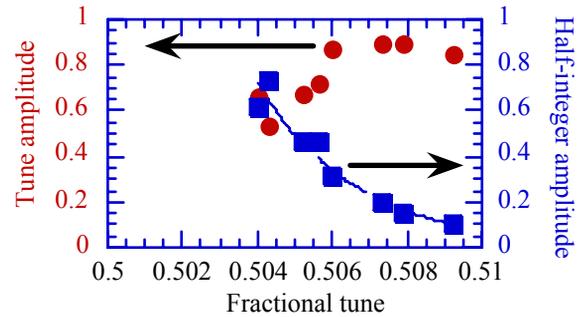


Figure 3: Half-integer amplitudes (blue squares) and the tune amplitude (red dots) as a function of the fractional tune.

### Beam Size Measurement

First, the horizontal beam size of a non-colliding pilot bunch was measured. The horizontal profile of the synchrotron radiation was obtained using a gated CCD camera. The measured size is a relative value and is plotted as a function of the fractional tune as shown in Fig. 4. The size tended to increase as the tune approached a half-integer. The effect of diffraction was considered due to using visible light, which resulted in a small value of about 3% for the beam size measurement. The effect would be negligibly small. However, the width of the error bars was larger than the slope of a linear fitting.

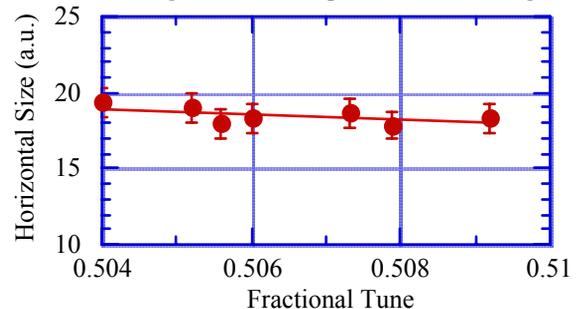


Figure 4: Horizontal beam size of a non-colliding bunch as a function of the fractional tune. The size is relative value, where the calculated size is  $660 \mu\text{m}$ . Plotted is an averaged size of 10 times measurements for each tune.

Next, the averaged horizontal beam size of all bunches was measured using an interferometer equipped with retro-focus optics [3]. The horizontal rms beam size can be obtained from the visibility of an interferogram. The measured size was around  $1050 \mu\text{m}$  under collision; on the other hand, the size under non-collision was  $650 \mu\text{m}$ , which agreed with a calculated value of  $660 \mu\text{m}$ . The measurement shows that the size increased by 7.6% when the tune approached a half-integer, as shown in Fig. 5. It is noted that the measured tune is not the tune of a colliding bunch, but that of the non-colliding pilot bunch. Both effects due to the dynamic beam-beam and the beta beat are considered to be sources of the change in size.

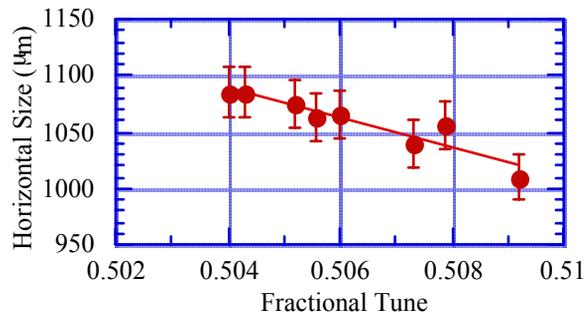


Figure 5: Horizontal beam size under collisions as a function of the fractional tune. During the measurement, the beam current was almost constant at 1730 mA. A calculated horizontal size is 660  $\mu\text{m}$  without collision.

Let us consider the beam-size measurement under collisions. We understand that the beam-beam interaction produces two modes of the betatron tune, the  $L$ -mode and the  $H$ -mode in one plane [6]. Assuming a horizontal beam-beam parameter of  $\xi_{bbx}=0.11$ , the beam size at the SRM can be calculated as a function of the tune, where the horizontal dispersion function is negligibly small. On the other hand, the tunes of the  $L$ -mode and  $H$ -mode are also calculated from the measured tunes. Thus, the measured size is plotted using two values of the tune, which are plotted in Fig. 6. It is clear that the measured size using the  $H$ -mode tune agrees with the calculated size. The dynamic beam-beam effects should be evaluated using the  $H$ -mode tune [6]. Since a tune of the  $H$ -mode is far apart from a half-integer, the effect of the stopband would be negligible.

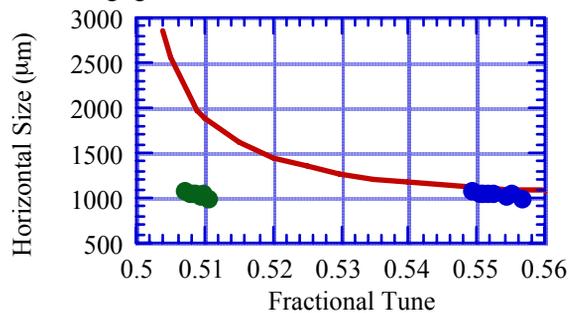


Figure 6: Horizontal beam size observed at the SRM as a function of the fractional tune. Solid line is a calculated size, assuming  $\xi_{bbx}=0.11$ , blue dots are measured size using  $H$ -mode tunes and green dots are measured size using  $L$ -mode tunes.

## DISCUSSION

The tune spectra as shown in Fig. 2 were obtained under the operation of the PS. Since the PS has recently been discontinued, a similar measurement was carried out after the shutdown of the PS. A spike at a half-integer was still observed and the characters of the spike were approximately the same as those measured under the PS operation. Therefore, the source of the spike is caused not by the influence of the PS, but by other effects.

The tune spectrum was measured under a low beam current without collisions. The intensity of the pilot bunch was almost the same as that of the usual operations. In this case, no beam loss was observed even when the tune was set at very near a half-integer,  $\nu_x=0.502$ . We observed a small distortion in the spectrum at a tune of less than  $\nu_x=0.504$ . When the tune moved to a half-integer, the half-integer amplitude slightly increased as shown in Fig. 7. At the same time, the beta beat,  $(\Delta\beta/\beta_0)_{\text{rms}}$ , was increased from 0.10 to 0.25, which was consistent with an expectation with Eq. (1).

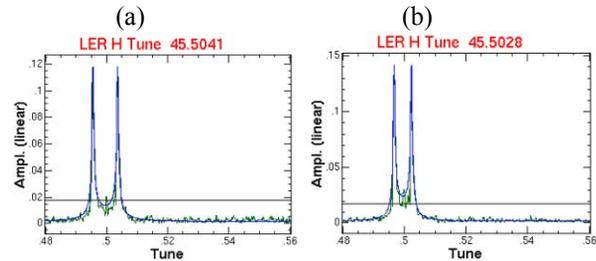


Figure 7: Tune spectrum measured at a low current under non-collision. The measured spectrum (green) was well fitted with the Lorentzian function (blue) except a half-integer, which shows tunes of  $\nu_x=0.5041$  (a) and  $\nu_x=0.5028$  (b).

From these results, we could imagine that the measured spectra were related to a nonlinear resonance at a half-integer, and they might be affected by some off-momentum particles in the bunch, not by a coherent motion of the whole bunch. The observed phenomena could be explained by supposing that some off-momentum particles in a bunch jumped into an unstable region and were trapped in the half-integer resonance. The width of the resonance depends on the beam conditions. The slight increase of the horizontal size as shown in Figs. 4 might contribute to the distortion in the spectrum around a half-integer. To confirm this presumption, a precise simulation with a particle tracking including some machine errors would be desirable.

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