INTENSITY DEPENDENCE OF BETATRON RESONANCES OBSERVED AT THE KEK-PS

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Abstract

An intensity dependent betatron resonance in the tune diagram was observed at the KEK-PS. The strong imperfection resonances were corrected by correction magnets. However with high intensity beam we still observed a big structure of beam loss in the tune diagram. One of possible explanations was a space-charge induced nonstructure resonance.

1 INTRODUCTION

A trial to extend a working area in the tune diagram was performed at the KEK-PS. This study is a part of the intensity up-grading program[1] for the neutrino oscillation experiment combined with Super-KAMIOKANDE. The goal of the program is to double the beam intensity in daily operation, which was 4×10^{12}ppp at that present. The parameters of the KEK-PS is listed in Table 1. A single bunched beam from the 500 MeV Booster synchrotron is injected into the Main Ring (MR) 9 times during the injection period. It takes more than 400 ms because the repetition rate of the Booster is 20 Hz. The beam is accelerated to 12 GeV and is slowly extracted for fixed target experiments or will be extracted in one turn for the neutrino oscillation experiment.

Table 1: Parameters of the KEK-PS

circumference	340 m
lattice type	FODO
periodicity	28
injection energy	500 MeV
harmonic number	9
horizontal physical aperture	$80\pi\mathrm{mm}\cdot\mathrm{mrad.}$
vertical physical aperture	$25\pi\mathrm{mm}\cdot\mathrm{mrad.}$

Among the intensity limiting phenomenon in the MR the space charge tune spread was thought to be responsible for a beam loss at the injection porch. It amounted to about 15% for the injection of 5.5×10^{12}ppp and its rate increased rapidly with the beam intensity. According to the tune diagram survey, the working area in the tune space was believed to be limited by three betatron resonance lines: $2Q_x = 14$, $2Q_x - 2Q_y = 0$ and $4Q_y = 29$. Here Q_x and Q_y are horizontal and vertical betatron tunes. The allowed maximum tune spread was $\Delta Q_y = 0.25$. The best operation point (a set of measured coherent tunes) had been $(Q_x, Q_y) = (7.12, 7.21)$. Our initial plan was to apply resonance corrections and double the working area. However after a careful resonance correction observing low intensity beam, the working area still remained the same for the beam intensity of the daily operation. What we observed was a intensity dependenct structure in the tune diagram. It became clear that the resonance, which we had thought was $4Q_y = 29$, could not be explained by a conventional simple model.

One of our speculations to this resonance was a *space charge induced nonstructure resonance*, which had never been considered in any other synchrotrons. Space charge induced structure resonancs had been pointed out first by B. Montague[3] and later by G. Parzen[4] and S. Machida[5]. Those were resonances in the absence of magnetic field errors. Since the space charge force is modulated according to the beam envelope, it has harmonic components of the superperiod times an integer. Especially when the harmonic number is identical to the periodicity of a focusing function, the resonance becomes very strong and is called a *superstructure resonance*[6, 7]. However in some high intensity proton synchrotrons which take some hundreds of milliseconds for a multi-step injection, much weaker *space charge induced nonstructure resonances* become effective. Quadrupole imperfections modulate the beam envelope function, then to produce other harmonic field components other than the structure number. This effect was analyzed numerically by S. Machida[7] and analytically by Y. Shoji and H. Sato[8]. They calculated the stop-band width of $4Q_y = 29$ of the KEK-PS using experimental data of the magnetic field imperfections. The width of $4Q_y = 29$ was about 40 times that driven by the octupole magnetic field imperfections for the beam intensity of $1 \times 10^{12}\mathrm{ppp} = 1\mathrm{TP}$ per bunch. The calculations also predicted that the width of $4Q_y = 21$ was about 30% of that of $4Q_y = 29$. In this report we show some experimental data on this resonance.

2 EXPERIMENTS

The study started from the correction of normal sextupole resonance $Q_x + 2Q_y = 22$ and two normal octupole resonances: $4Q_y = 29$ and $2Q_x + 2Q_y = 29$. We let the low intensity beam cross a resonance, energized the harmonic correction magnets and optimized them to minimize the beam loss by the crossing. The correction was not applied to skew sextupole and skew octupole resonances, but the beam loss by crossing them was very small compared to those of the normal multipole field resonances.

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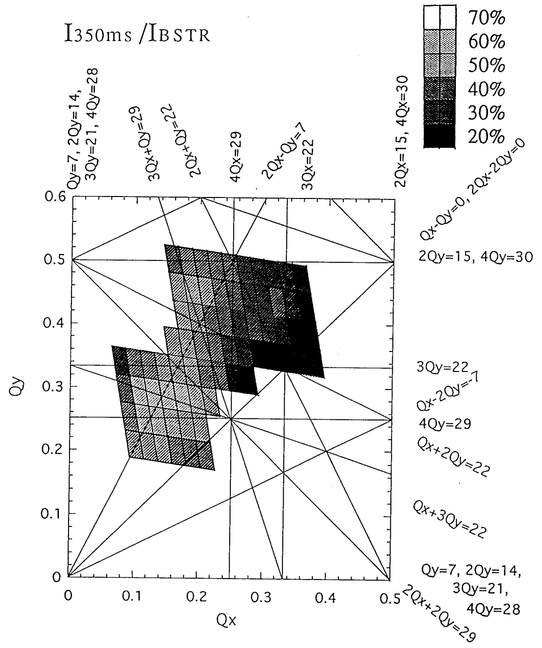

Figure 1: Two dimensional tune diagram survey for high intensity beam of 1.3TP. The frame was a bare tune diagram.

Figure 1 shows the two dimensional tune diagram survey. A single bunched beam of 1.3TP was injected into the ring and stored for longer than 350 ms. The beam survival ratio to the bare machine tune was measured. Here the bare machine tune means the betatron tune with no space charge tune shift. The best operating point (bare machine tune) was $(7.12, 7.25)$. Below that point (lower Q_y) the beam was lost rapidly by the integer coupling $Q_x - Q_y = 0$ or $2Q_x - 2Q_y = 0$ (Montague resonance). On the left of that point (lower Q_x) the beam was lost by $2Q_x = 14$ or $4Q_x = 28$ (superstructure resonance). Above that point the beam was lost slowly by the unknown resonance.

Figure 2 shows the intensity dependence of the beam survival ratio measured along the line in the tune diagram.

With low intensity beam (0.1TP) there was no serious structure in the tune diagram. However with higher intensity (0.3TP) a dip of the beam loss appeared where the space charge shifted tune would be on the resonance $4Q_y = 29$. With higher intensity than the daily operation (more than 0.6TP) the dip became broader and deeper then merged to be a step.

This kind of a dip could be produced intentionally either by a quadrupole perturbation or an octupole perturbation as shown in Fig. 3. Figure 4 showed that for a higher intensity a weaker quadruple perturbation worked. The expected half-integer stop-band width by the quadrupole imperfection was 0.04. The quadrupole magnet (EQ) could excite the same width at 15 A in horizontal and 50 A in vertical.

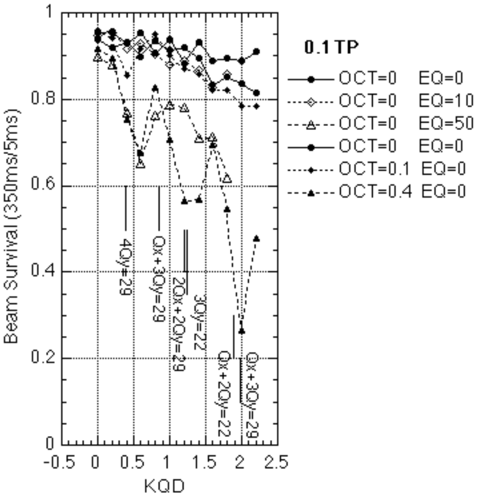

Figure 3: The beam loss dip intentionally produced by an octupole or quadrupole perturbations. As an perturbation quadrupole, a quadrupole for magnet the resonant beam extraction was temporary used.

We tried to optimize the quadrupole perturbations and minimize the beam loss dip. Two quadrupole magnets: EQ1 and EQ2 were originally set for the half-integer resonant extraction. It was fortunate that they were roughly in diagonal positions in $29th$ harmonic phase. However we observed only a tiny improvement by the optimization of two quadrupoles (Fig. 5). The optimized quadrupoles were very much weaker than the expected imperfection.

The other prediction from our speculation was the dependence on the integer part of the tune. Figure 6 shows the beam survival ratio around $4Q_y = 29$ and $4Q_y = 21$. Our speculation was a good explanation of the difference between two at the sub-integer part from 0.23 to 0.35.

3 SUMMARY

We observed the intensity dependent resonance at the injection porch of the KEK-PS. It was possible that this resonance was a space charge induced nonstructure octupole resonance produced by quadrupole imperfections. However we could not prove it by applying the quadrupole correction. The correction scheme could be bad, because it has only one quadrupole magnet for each of sine and cosine component. Different explanations would be possible, such as a mirror charge field induced resonance[8].

4 REFERENCES

[1] H. Sato, Proc. of the 10th Symp. on Accelerator Science and Technology, Hitachinaka, Japan (Oct. 1995) p. 11.

[2] G. Guinard, CERN 76-06 (1976); CERN 78-11 (1978).

[3] B.W. Montague, CERN 68-38 (1968).

[4] G. Parzen, Nucl. Instr. & Meth. A281 (1989) 413-425.

[5] S. Machida, Nucl. Instr. & Meth. A309 (1991) 43-59.

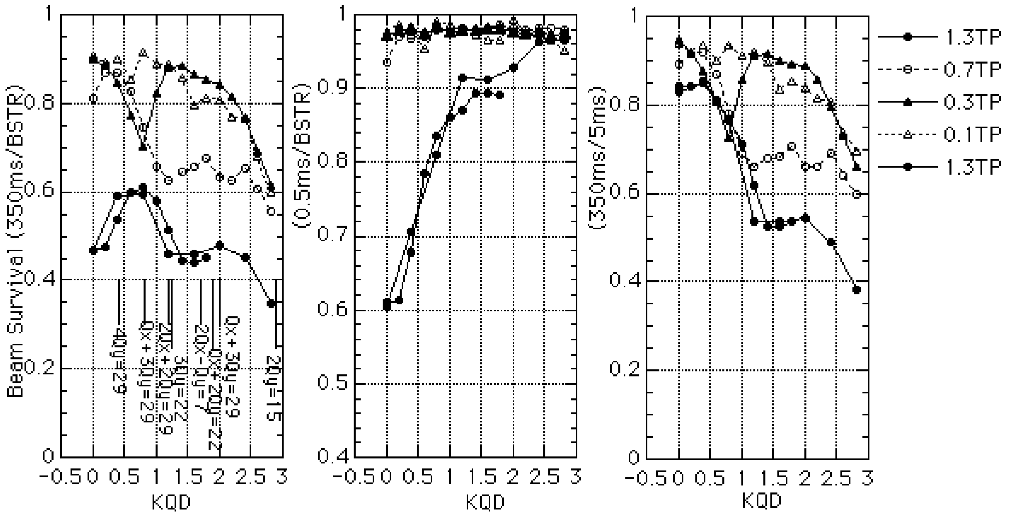

Figure 2: Intensity dependence of the beam survival ratio. The horizontal axis is the strength of the lattice focusing quadrupoles. The plots are the total loss, the initial fast loss and the slow loss, respectively from the left. The positions of the resonances in the figure were calculated from the bare tunes. The surveyed line started from $(7.12, 7.21)$ and ended at $(7.23, 7.49)$ in the tune diagram.

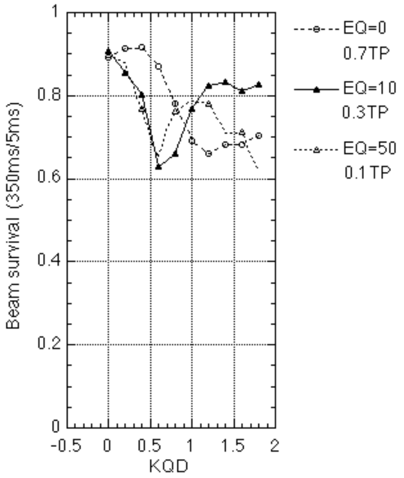

Figure 4: The beam loss dip intentionally produced by the quadrupole perturbations. The shift of the dip was thought to be came from the space charge tune shift.

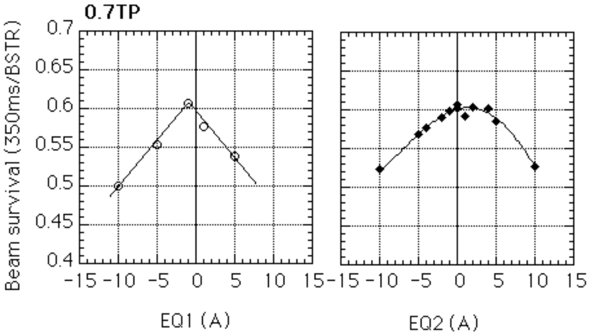

Figure 5: The dip depth vs. quadrupole perturbations.

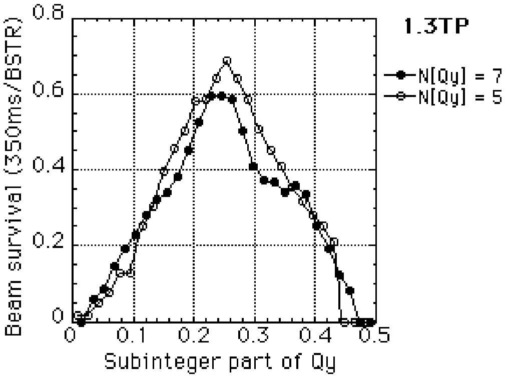

Figure 6: The tune surveys along lines for two different integer part of vertical tunes; 5 and 7. The horizontal tune was fixed to 7.13.

[6] S. Machida and Y. Shoji, Workshop on Space Charge Dominated Beams, Bloomington, Indiana (Sept. 1995) AIP Conference proceedings 377, pp. 160-168.

[7] S. Machida, Nucl. Instr. & Meth. A384 (1997) 316-321.

[8] Y. Shoji and H. Sato, 'An analytical formula for the bandwidth of a strong nonstructure octupole resonance induced by a space charge', to be published in Nucl. Instr. & Meth.