VERTICAL INSTABILITY CAUSED BY ION-TRAPPING IN KEK-PF STORAGE RING

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ABSTRACT

The vertical instability observed in PF storage ring has been considered as the effect of the ion-trapping since its first appearance about one year and half ago. This instability would be explained by the model of two-stream instability. The stabilization by exciting RF knockout system will also be reported here.

INTRODUCTION

The vertical instability has been observed in PF storage ring with improving the vacuum pressure. However, this instability can be cured with the large negative value of vertical chromaticity made by exciting the sextupole magnets in opposite direction to usual correction of chromaticity. In routine operations of ring, this instability is avoided by partially filling the RF-buckets and with positive chromaticity[1]. There are many measurements on this instability since its appearance. However, it was not clear what gives rise to this instability, although there were some indications that it would be caused by ion-trapping on the electron orbit: tune shift, tune spread, increase of vertical height, lifetime shortening and so on.

The threshold current of the vertical instability has been measured by changing the vertical betatron tune over a wide range. To clear the complicated phenomena, the sextupole magnets have been turned off and the measurement has been made for uniform-filling of RF-buckets. The results imply that one of the possible explanations of the mechanism of the instability would be so-called two-stream instability: one is electron beam and another trapped ion.

We have also found that the vertical instability is stabilized by exciting RF knockout system at a frequency within certain range, the preliminary results of which will be given together with its plausible explanation.

A MODEL OF VERTICAL INSTABILITY

The single particle behavior and mechanism of ion-trapping are analyzed in Ref. 2, and the critical mass number A_c for the vertical motion is,

$$A_c = \frac{N_e}{n}\frac{r_p}{n}\frac{\pi R}{\sigma_y^2(1+\sigma_x/\sigma_y)} \qquad (1)$$

where N_e is the electron number of beam, r_p the classical radius of proton, R the average radius of ring, n the number of bunches and σ_x and σ_y are the beam width and the beam height. The rough estimation of A_c for uniform-filling with 312 bunches in PF ring gives the order of magnitude 10^{-3} even at the beam current of 500 mA. Therefore, according to Eq. 1, any ion can be trapped on the electron orbit.

The ionization time τ_i is given by

$$\tau_i = \frac{1}{d_m \sigma_i c} \qquad (2)$$

with d_m the number density of molecule, σ_i the ionization cross-section, c the velocity of light. At the vacuum pressure of 10^{-9} Torr, we have the ionization times,

$$\tau_{H_2} \sim 1.3\ \mathrm{sec}, \quad \tau_{CO} \approx \tau_{N_2} \sim 0.2\ \mathrm{sec}$$

for the beam energy 2.5 GeV, using the cross-section $\sigma_{H_2} \sim 0.7\times10^{-18}\,\mathrm{cm}^2$ and $\sigma_{CO} \approx \sigma_{N_2} \sim 4.6\times10^{-18}\,\mathrm{cm}^2$. From these value together with $d_{H_2}/d_{CO} \sim 5/3$, the CO^+ ion would be trapped about four times as many as H_2^+. As the ionization times are nearly same as the repetition rate of injection 1 Hz or less, the ion tends to neutralize the electron beam, unless the ion has very fast mechanisms escaping from inside the beam. Therefore the single particle instability of ion caused only by the forces of the bunches of electron beam and the following drifting between the passages of bunches would not occur.

Keil and others studied the e-p instability in coasting proton beam where the electrons from ionized molecules are trapped in the electric potential of beam[3]. Their analysis for the coasting beam can be applied to our case of bunched beam, because we have many bunches: 312 bunches in PF ring, and the result of the analysis shows that the dangerous mode number of the instability is an integer near the betatron tune ($\nu_y \approx 4\sim5$).

In the coasting beam approximation, the coherent dipole motions of the electron beam and the ion in the vertical direction are given by

$$\begin{aligned} \ddot{y} + \omega_y^2 y &= -\omega_e^2 (y - z) \\ \ddot{z} &= -\omega_i^2 (z - y) \end{aligned} \qquad (3)$$

where y and z are the vertical position of the center of the electron beam and that of the ion, ω_y is the vertical betatron frequency, and ω_e and ω_i are

$$\omega_e^2 = \frac{2\rho_i r_e c^2}{\gamma}\frac{1}{q(p+q)}$$

$$\omega_i^2 = \frac{2\rho_e r_p c^2}{A}\frac{1}{b(a+b)}$$

with ρ_i, ρ_e the ion and electron numbers per unit length, γ the Lorentz factor, r_e the classical radius of electron, A the mass number, p, q the rms width and height of ion, and a, b the rms width and height of electron beam. Assuming the density of ion to be uniform, we have from Eq. 3,

$$(\Omega^2 - \nu_i^2)\left[(\Omega - m)^2 - (\nu_y^2 + \nu_e^2)\right] - \nu_e^2 \nu_i^2 = 0 \qquad (4)$$

where ν_i is ω_i/ω_0 with ω_0 the angular revolution frequency, m the mode number and Ω the eigen-frequency corresponding to m. The coherent quadrupole instability caused by ion-trapping can be analyzed in almost same method as the dipole case. The detail analysis and calculation for both dipole and quadrupole coherent instabilities will be presented elsewhere. Examples of the calculations are shown in Figs. 1 and 2.

The analysis shows that for the dipole instability the most dangerous mode number is the nearest integer above the tune ν_y: m=5 for the present operation of PF ring, and for the quadrupole instability the nearest integer above 2 : m=9 for PF ring. It also shows that the frequency of the dipole oscillation excited by the instability is near $(m - \nu_y)\omega_0$ when measured at a certain location in the ring.

It should be noted here that the magnetic field in bending magnets together with the electric field induced by the beam tends to remove the ion from the bending magnets, i.e. the effect of drift velocity. This effect and the different densities of neutral molecules along the ring cause the density of ion to vary with the location. It should be also noted that

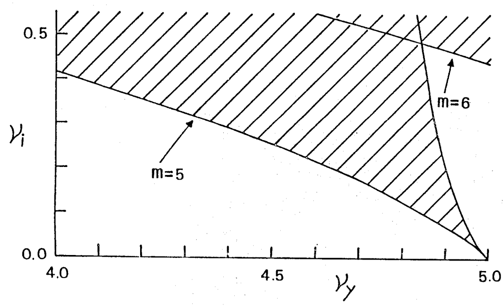

Fig. 1 Dipole instability for A=28 and fully neutralized beam with a=1.5 mm and the aspect ratio b/a=0.25

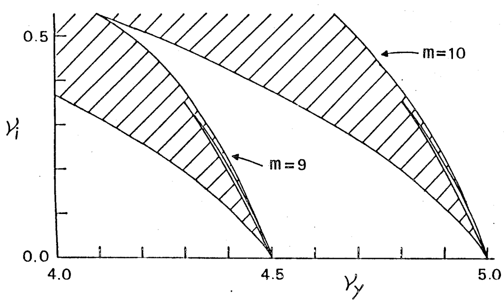

Fig. 2 Quadrupole instability for $_x$=5.35, A=28 and fully neutralized beam with a=p=1.5 mm and the aspect ratio b/a=q/p=0.25

the coherent quadrupole motion is disturbed in the bending magnets due to the cyclotron motion, the effect of which is not included in the calculations of Figs. 1 and 2.

EXPERIMENTS

As we had not enough time to study the vertical instability, only preliminary results are presented here. When the beam profile fluctuates due to the vertical instability, we always observe the spectrum $f_r - \Delta f_y$ on the spectrum analyzer of RF knockout system and also on the spectrum analyzer of the signals from position monitors. Here f_r and Δf_y are the revolution frequency and the fractional betatron frequency, respectively.

Even when it is difficult to see the fluctuation of the beam profile as the instability is weak, we can still observe the spectrum $f_r - \Delta f_y$. We have sometimes observed the other spectra: $\Delta f_y, \Delta f_x$, $f_r - \Delta f_x$ near the threshold current at which a large part of the beam was abruptly lost. After the beam loss, we usually got the wavelike beam-filling on the current monitor as shown in Fig. 3. The shapes of the filling depend on the circumstances, but generally we have five or six peaks per one revolution in the shape, or almost double number of peaks. These observations indicate that the coherent motion of the vertical instability is a dipole motion, although we can not discard a possibility that the coherent quadrupole motion would be also excited because we have not any method measuring the quadrupole motion.

Tune Dependence of the Threshold Current

We measured the dependence of the threshold current on the vertical betatron tune. The working points we took the measurements are shown as the hatched region in Fig. 4. A typical working line in the tune diagram is also shown as an arrow in Fig. 4. The measured data are plotted in Fig. 5 with the theoretical threshold current of the dipole instability.

Fig. 5 implies that the vertical instability can be explained by two-stream instability, although the data are scattered on Fig. 5. However, the scattered data would be understood as due to the injection conditions and the vacuum circumstances.

A difference resonance was excited in the region hatched in Fig. 5, and the beam became round as we had experienced it many times before (see Fig. 4). We skipped the measurement because it was difficult to take the data efficiently at the difference resonance. We also crossed a line of third resonance. However we encountered no difficulty to take the measurements because the sextupole magnets were turned off.

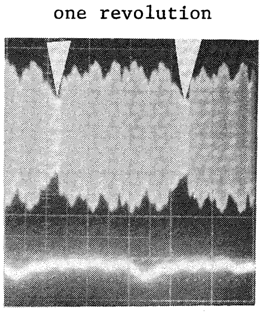

Fig. 3

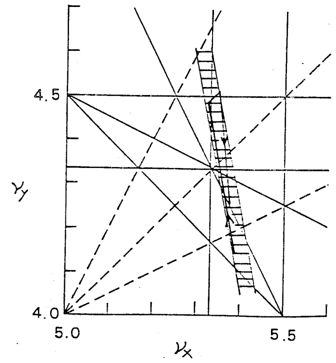

Fig. 4

Fig. 3 A shape of beam-filling after the abrupt beam loss.

Fig. 4 The working points where the threshold current has been measured.

Stabilization by RF Knockout

We found that the vertical instability can be suppressed by exciting RF knockout system[4]. The spectra on the spectrum analyzer of RF knockout before and after the suppression of the instability are shown in Fig. 6 and Fig. 7. The driving frequency able to suppress the instability has a relatively wide range ~ ±100kHz around 1.2MHz for uniform-filling, but for partial-filling its frequency range is very narrow, a few kHz. The frequency range also depends on the driving power of RF knockout, and when some operation--point is chosen and some power level is set for RF knockout, the frequency range stabilizing the instability is split into two or three parts for the uniform--filling.

Whether the instability is suppressed or not depends on the direction of changing the driving frequency. Fig. 8 shows this hysteresis of stabilization. We also measured the current dependence of the driving frequency that can suppress the instability, and the tune dependence of the frequency. From the preliminary measurement, we could not clearly find their dependence, but it seems that the driving frequency decreases as the vertical tune increases. Further we could not suppress the instability above the line of difference resonance (see Fig. 4). For uniform--filling, we sometimes failed to stabilize the instability for a long time only by using RF knockout. However, we did not try to use sextupole magnets along with RF knockout.

In routine operations of machine with partial-filling, more sharp partial-filling gives more higher threshold current, although we does not usually need this filling pattern of RF-buckets. This indicates that the vertical instability is not related to the single bunch instability at least directly.

DISCUSSION

When the vertical instability is not so strong, the amplitude of its growth is limited, and the beam is in a stationary state with the "notch"[1]. This implies that some amplitude-dependent mechanism stabilizing the

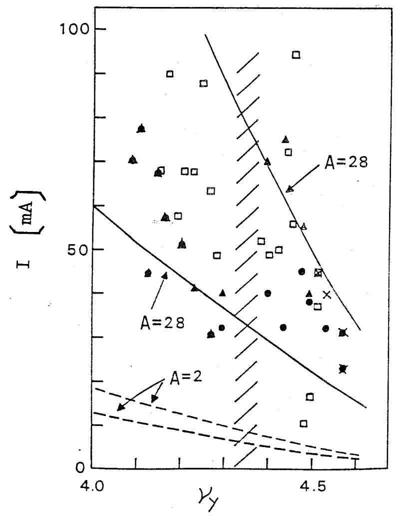

Fig. 5 The dependence of the threshold current on the vertical betatron tune. The lines denote the theoretical lower limit of the threshold for the dipole instability: the thick lines are for 100% neutralization and the thin lines for 10% neutralization.
Case A ● --- threshold at injection with kicker being excited.
△--- threshold after injection.
×--- abrupt loss of a large part of beam.
Case B same as in Case A.
In Case A, the thresholds were measured after the remaining beam was once dumped. In Case B, the remaining beam was generally used for the next measurement.

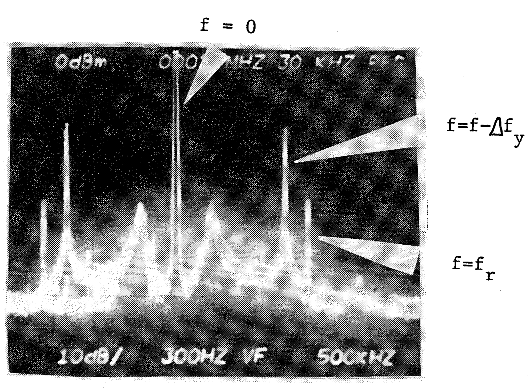

Fig. 6 Spectra before the instability is suppressed.

instability exists ,i.e. nonlinear effect. From this, we may assume that the vertical instability is phenomenologically described by van der Pol equation,

$$\ddot{y} - (\alpha - \beta y^2)\dot{y} + \omega^2 y = F(t) \qquad (5)$$

where the rhs of the equation is external force such as RF knockout. We may include the higher order terms in Eq. 5; e.g. nonlinear restoring force.

Although we have not quantitatively analyzed the vertical instability applying Eq. 5 to it , we can infer that the suppression of the instability by RF knockout would be very similar as the dynamic stabilization in plasma physics[5] and also the quenching phenomenon in electric circuits.

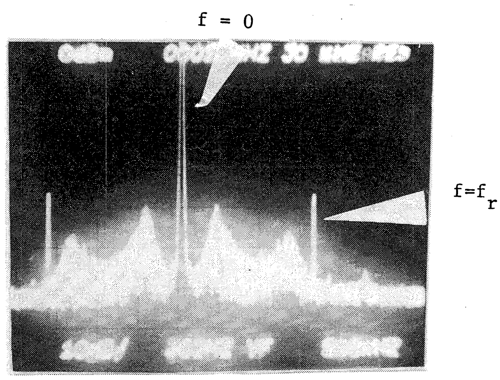

Fig. 7 Spectra after the instability has been suppressed by RF knockout.

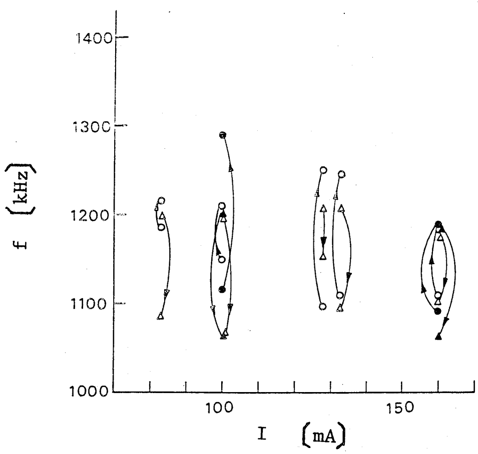

Fig. 8 The range of the driving frequency of RF knockout that stabilizes the instability. The range is denoted by the line between the marks of circle or triangle, and filled and empty marks have different powers. Here the driving power is relatively low.

There are several subjects and questions about the vertical instability: (1) the effect of sextupole magnets should be studied in detail. (2) the Landau damping and the nonlinear effects would play an important role. (3) neutral molecules may give an effect on the motion of ion, specifically at higher vacuum pressure. (4) the interactions between different kinds of ion and their influence on the electron motion should be included in the calculations. (5) the quadrupole component in the field produced by RF knockout would play a role in the suppression.

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