TRANSVERSE COHERENT INSTABILITY IN THE KEK BOOSTER

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INTRODUCTION

Recently the KEK booster beam intensity has been raised to $3\sim5\times10^{11}$ protons per pulse[1)] and a coherent transverse instability has been induced in the horizontal plane. Beam behaviours including the bunch motion were surveyed about the instability and the effects of sextupole and octupole magnets were studied. It was found that the kicker magnets for the beam extraction are responsible for the instability.

So far many experimental[2)] and theoretical[3)] studies about the transverse instabilities have been reported in many laboratories. They have been explained by the head tail effect and ascribed to the interaction of the beam with the vacuum chamber and with ferrite magnets inside the chamber. The experimental results observed in the KEK booster are also explained by the head tail effect.

FEATURES OF THE INSTABILITY

In the KEK booster the beam injected from a linac with a multi-turn process is accelerated from 20 MeV to 500 MeV in a period of 25 msec. The transverse instability occurs around $12\sim20$ msec after the injection as seen from a beam intensity monitor and a horizontal ΔR signal in Figs.1-a and b. A grow-up of a coherent transverse betatron oscillation is observed around the instability. The instability is induced at a beam intensity above 3×10^{11} ppp. It occurs around 20 msec at lower intensities. The instability depends on the beam size just after the injection. Narrower beams are liable to induce the instability than wider beams. A wide and intense beam could be accelerated up to 5×10^{11} ppp without inducing the instability.

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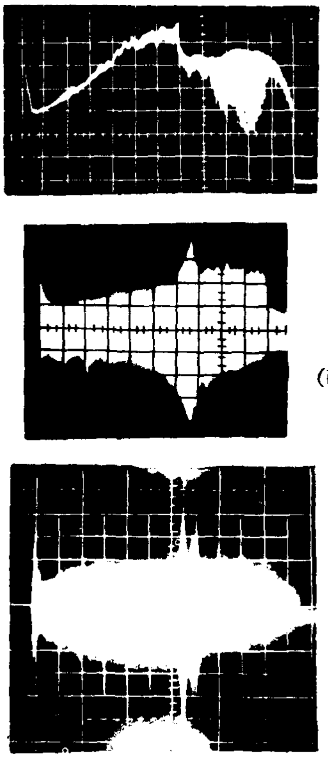


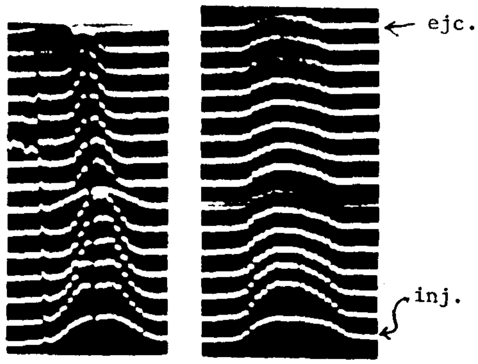
(a)

ΔR

(b)

ΔR

(c)



(d) (e)

Fig.1.

(a) Beam intensity (1×10^{11} ppp/div. 5 msec/div)
(b) Horizontal ΔR signal (5 ms/div)
(c) Horizontal ΔR signal without the terminator at the kicker magnet
(d) Horizontal non-destructive profiles during acceleration (1.7 ms step)
(e) Vertical non-destructive profiles

In spite of the fact that the betatron oscillation amplitude greatly increases with the instability, the normalized emittance of the extracted beam is nearly equal to that at the injection. Beam profiles in the acceleration period can be seen with non-destructive beam profile monitors as shown in Figs.1-d and e.The horizontal profiles indicate that the horizontal beam size accumulated for 30 μs suddenly increases and decreases at 12.5 msec within a time about 3 ms and that the beam size damps adiabatically during all the acceleration period. This explains the no-emittance blow-up and also suggests that the coherently increased betatron amplitude decreases coherently just after the instability.

In the vertical plane the beam size is nearly constant from the injection to the ejection as shown in Fig.1-e. The normalized emittance estimated with an extracted beam is twice larger that that at the injection. The vertical ΔZ signal shows no coherent oscillations. The reason of the emittance blow-up is not yet known.

EXPERIMENTS

According to the theory of the head-tail effect, the instability depends on the bunch mode number m and the signs of chromaticity ξ and dispersion η of revolution frequency. The mode $m = 0$ is unstable when $\xi > 0$ below the transition energy, which is the case in the KEK booster. Figure 2 shows the coherent beta-

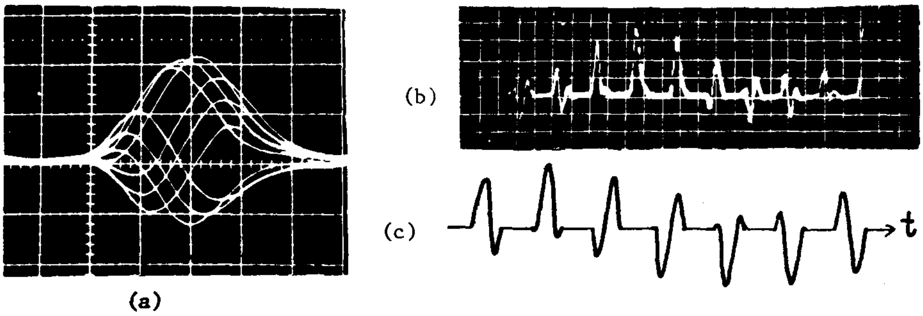


Fig.2. a) ΔR signal of a single bunch consecutively traced every 15 μsec.
b) ΔR signal of a bunch successively traced.
c) ΔR signal calculated with equation (1). (χ=-5.1 rad and Q=2.150)

tron oscillation. The ΔR signal of the bunch in Fig.2-a indicates m = 0. The phases of the successive bunches shift backward (Fig.2-b) so that the phase shift between the head and tail in the bunch is negative.

The chromaticity was obtained by measuring the horizontal tune as a function of radial beam position. As shown in Fig.3 the chromaticity is about +0.4, gradually decreases owing to the magnetic field saturation and then changes sign at 20 msec after the injection. This value is in good agreement with the tune spread measured by an RF knock-out.[4] It is noted that the grow-up of the ΔR signal so far has been observed before 20 msec. The chromatic frequency ω_ξ (= $\frac{\xi}{\eta}$ Q ω_0) and the phase shift χ (= $\omega_\xi \tau_L$) were estimated with the observed data ξ, Q and τ_L, where Q is the betatron frequency per revolution, $\omega_0/2\pi$ the revolution frequency and τ_L the bunch length. At 17 msec $\omega_\xi/2\pi$ = -11 MHz and χ = -5.1 radian. As shown in Fig.2-c, the ΔR signal of the k-th revolution is well expressed by

$$\Delta R \propto P_0(t)e^{j\omega_\xi t + 2\pi kQ} \quad (1)$$

where $P_0(t)$ is a bunch shape function of $\cos(\pi\frac{t}{\tau_L})$ $(-\frac{\tau_0}{2} \le t \le \frac{\tau_0}{2})$ for a sinusoidal mode m = 0.

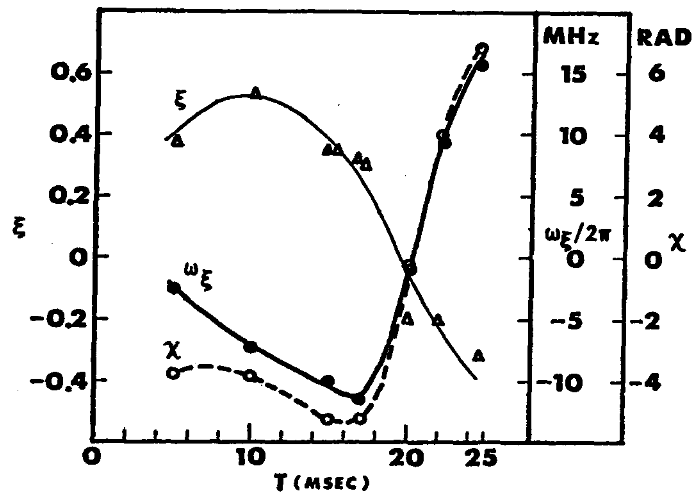


Fig.3. Measured chromaticity ξ, chromatic frequency $\omega_\xi/2\pi$ and phase shift χ between the head and tail in a bunch.

In the usual operation the instability occurs at 12∿20 msec depending on the accelerating conditions, but when the terminator of the kicker magnet is removed, it occurs only at 17 msec and two sharp peaks in the ΔR signal are observed as shown in Fig.1-c. From this it is inferred that the interaction between the beam and the kicker magnet causes the instability. The resonant frequency ω_k of the magnet without the terminator is given by[5]

$$\omega_k^j = 2\omega_0 \sin\left(\frac{j}{N+1}\frac{\pi}{2}\right), \qquad j = 1 \sim N \tag{2}$$

$$\omega_0 = 1/\sqrt{L_0 C_0} = 2\pi \times 36.7 \text{ MHz}$$

where L_0 and C_0 are the inductance and capacitance of a unit cell of the magnet and N is the number of cells. The impedance of the magnet was measured. Without the terminator the strong peak appeared at 10.2 ($= \frac{\omega_k^1}{2}$) MHz with the full width at half maximum 1.1 MHz and a low peak around 18 MHz. The damping time of the strong peak is about 0.3 µsec, which is comparable to the period of the revolution (0.18 µsec at 17 ms). With the terminator the measured impedance has no peaks as a function of frequency and the damping time is much shorter. Therefore the beam will interact between the head and tail almost within a bunch through the kicker magnet. Induced voltage by the beam at the kicker magent without the terminator has several peaks at the time when $\omega_k^1 = \omega_p = (p + Q)\omega_0$, where p is integer. There appeared two strong peaks at about 17 ms.

According to the theory, the instability is induced when the product of the transverse impedance $Z_\perp(\omega_p)$ and the bunch spectrum $h_m(\omega_p - \omega_\xi)$ for the mode m shifted by the chromatic frequency becomes large. At 17 msec the chromatic frequency is $\omega_\xi/2\pi = -11$ MHz and so the bunch spectrum $h_0(\omega_p - \omega_\xi)$ for $m = 0$ has the strongest peak at $\omega_0 = (p + Q)\omega_0 = -2\pi \times 10.2$ MHz with $p = -4$, which coincides with the resonant frequency ω_k^1 of the kicker magnet. When the magnet is terminated the band width spreads up to ∿30 MHz, thus the instability may be induced at 12 ∿20 msec.

A sextupole correction magnet was excited around 17 msec with a pulse current of a half sinusoidal shape. The chromatic frequency $\omega_\xi/2\pi$ is -11 MHz without the sextupole field and changed in the range -14 ∿ +0.3 MHz with the sextupole magnet. The instability was gradually depressed with the increase of the sextupole field and suppressed at the both ends. From this fact it is inferred that the bunch spectrum $h_0(\omega_p - \omega_\xi)$ for mode $m = 0$ has small components at the frequency $(\omega_p - \omega_\xi)/2\pi \simeq 4$ or -10.5 MHz, where $\omega_p/2\pi = -10.2$ MHz $= -\omega_k^1/2\pi$ as before. These values are small compared with the expected half width of the spectrum $h_0(\omega_p - \omega_\xi)$ which is given by $1/\tau_L \simeq 13$ MHz at 17 msec.

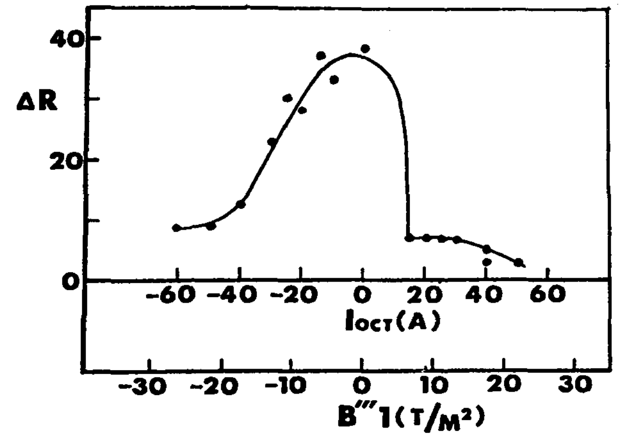


Fig.4. Amplitude dependence of ΔR signal at the instability on the octupole current when the kicker magnets are terminated. (ΔR: peak to peak in an arbitrary scale)

An octupole correction magnet was excited. The dependence of the ΔR signal (peak to peak) on the octupole current was obtained as shown in Fig.4. In order to suppress the instability an octupole field of $B'''\ell \simeq 20$ T/m^2 is sufficient. The tune spread induced with this octupole field is given by

$$\Delta Q_x = \frac{1}{32\pi}\frac{B'''\ell}{B\rho}(\beta_x^2\varepsilon_x - 2\beta_x\beta_y\varepsilon_y) \qquad (3)$$

$$\simeq 2 \times 10^{-5}$$

where ℓ is the length of the octupole magnet, $B\rho$;the magnetic rigidity, β;the betatron amplitude function and ε;the emittance. As a rule of thumb, the stability criterion with the octupole field is given by[7]

$$\Delta Q_x \gtrsim \frac{4}{1+m}|\Delta Q_{ic} - \Delta Q_c| \qquad (4)$$

for mode m, where ΔQ_{ic} and ΔQ_c are incoherent and coherent Q shift, respectively. They are estimated as $\Delta Q_{ic} \simeq -0.015$ and $\Delta Q_c \ll \Delta Q_{ic}$. Therefore the octupole field for the stabilization is 300 times smaller than the field required by equation (4). The growth rate of the instability was measured as a function of the octupole current without the terminator at the kicker magnet. The time is about 4 msec without the octupole field and gradually decreases with the field. The second peak of the ΔR signal shown in Fig.1-c is more easily depressed than the first peak with the octupole field.

CONCLUSION

Though all the phenomena observed here have not been understood in detail, it can be concluded that the instability is damped by the incorporation of small sextupole and octupole correction magnets. Further theoretical and experimental investigations of the phenomena are still in progress.

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