HEAD-TAIL INSTABILITY IN THE KEK-PS MAIN RING

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Abstract

A horizontal head-tail instability has been observed at the beginning of acceleration in the KEK-PS main ring. The instability occurs due to a large change in chromaticity produced by the sextupole component of the eddy-current induced field in the dipole beam-pipe. The horizontal chromaticity increases up to a positive value around 80 ms after the beginning of acceleration. The longitudinal mode 0, 1 and 2 have been observed. The impedance model, including resistive wall impedance, kicker impedance and broad band impedance, explains the instability for a single bunch operation very well.

1 INTRODUCTION

The beam loss had emerged around 80 ms after the beginning of acceleration (P2) in recent machine operations[1][2]. The observation using the position monitor revealed that the beam loss is caused by a horizontal coherent dipole motion, which was identified as the Head-Tail Instability (HTI) of longitudinal mode, mainly, $\ell = 0$. Chromaticity control using one of the two sextupole families has been the most effective cure to suppress the instability. The beam loss around 80 ms after P2 has almost vanished by properly exciting sextupoles, although sometimes the instability occurs during operation in these months, which could be nearly suppressed by octupole magnets.

In this paper an analysis using the Sacherer's formula and recent operation experience are presented.

2 ANALYSIS

The qualitative feature of the observed HTI was well explained by a multi-particle simulation code, although a constant wake was used[1].

In order to obtain more quantitative feature, the growth rate is calculated using the Sacherer's formula[3][4][5] along with an impedance model.

The growth rate normalized by ω_0 is

$$\mathrm{Im}[\Delta\nu_\ell^\perp],$$

where

$$\Delta\nu_\ell^\perp = \frac{-\mathrm{i}}{\ell+1}\frac{ecN_b}{4\pi\nu_x\omega_0\tau_b E/e}(Z_\perp)_{\mathrm{eff}},$$

$$(Z_\perp)_{\mathrm{eff}} = \frac{\sum_{p=-\infty}^{+\infty} Z_\perp(\omega_p^\perp)h_m(\omega_p^\perp-\omega_\xi)}{\sum_{p=-\infty}^{+\infty} h_m(\omega_p^\perp-\omega_\xi)},$$

Table 1: Beam and machine parameters.

ω_0	$2\pi\times 767$ kHz
ω_s	$2\pi\times 4$ kHz
N_b	5.8×10^{11} protons/bunch
ν_x	7.15
τ_b	75 ns
E	$700+938$ MeV
η	-0.22

$$\omega_p^\perp = (p+\nu_x)\omega_0 + \ell\omega_s,$$

p = integer, ℓ is the azimuthal mode number, ω_0 the revolution frequency, ω_s the synchrotron frequency, e the electron charge, c the light speed, N_b the bunch intensity, ν_x the horizontal betatron tune, τ_b the total bunch length, E the total energy, $\omega_\xi = \xi\omega_0/\eta$ the chromatic frequency, ξ = $\Delta\nu_x/(\Delta p/p)$ the chromaticity, and η the slippage factor. The parameters used for the calculation are summarized in Table 1.

For coupling impedances a resistive wall impedance, a kicker impedance and a broad band impedance are assumed. The resistive wall is considered to comprise two parts, one from almost rectangular beam pipes[6] in the bends and quads ($Z^{(m)}_{\mathrm{RW}\perp}$) and one from almost cylindrical beam pipes in straight sections ($Z^{(s)}_{\mathrm{RW}\perp}$), i.e.

$$Z^{(m)}_{\mathrm{RW}\perp} \approx (\mathrm{sgn}(w)-\mathrm{i})\frac{R_{(m)}}{b^3_{(m)}}\frac{\pi^2}{24}\sqrt{\frac{2\rho}{\epsilon_0|\omega|}},$$

and

$$Z^{(s)}_{\mathrm{RW}\perp} \approx (\mathrm{sgn}(w)-\mathrm{i})\frac{R_{(s)}}{b^3_{(s)}}\sqrt{\frac{2\rho}{\epsilon_0|\omega|}},$$

where $2\pi R_{(m)}$ and $2\pi R_{(s)}$ are the total length of the magnet section and the straight section, respectively, ρ the vacuum chamber resistivity, $b_{(m)}$ the half height of the beam pipe and $b_{(s)}$ the pipe radius. The relevant parameters are summarized in Table 2.

There are five identical kickers for injection in the 12GeV PS[7]. Its impedance (real part) is[8]

$$\mathrm{Re}[Z_\perp^{(k)}] = \frac{Z_{T0}}{k\ell_k}[\sin(k\ell_k + k'\ell'_k) - \sin(k'\ell'_k)]^2,$$

where a and b are the half height and the half width of the kicker aperture, $Z_{T0} = Z_s\ell_k/(4ab)$, $k = \omega/v_{kicker}$, $k' = \omega/v_{cable}$, ℓ_k and ℓ'_k the length of the kicker and cable, respectively, Z_s is the vacuum impedance, $v_{kicker} =$

Table 2: Parameters for the resistive wall impedance.

$R_{(m)}$	200 m
$R_{(s)}$	140 m
$b_{(m)}$	25.5 mm
$b_{(s)}$	60 mm
ρ	$9 \times 10^{-7}\Omega{\cdot}\mathrm{m}$

Table 3: Kicker parameters (for one module).

Z_s	377 Ω
Z_0	25 Ω
a	25 mm
b	62.5 mm
v_{kicker}/c	0.028
v_{cable}/c	0.67
$\ell_{(k)}$	250 mm
$\ell'_{(k)}$	55 m

$Z_0 a/(\mu_0 b)$ velocity in the kicker, v_{cable} velocity in the cable and Z_0 is the characteristic impedance of the kicker. Each kicker is matched at one end and connected with a cable at the other end which is approximately open at the end of the cable. The parameters used in the calculation are summarized in Table 3[7].

For the broad band impedance

$$Z_{\mathrm{BB}\perp} = \frac{\omega_r}{\omega}\frac{R_T}{1+\mathrm{i}Q(\omega_r/\omega-\omega/\omega_r)},$$

the parameters listed in Table 4 are assumed.

The real part of the total impedance mentioned above which contributes the growth rate is depicted in Fig.1.

The form factor, $h_m(\omega)$ for parabolic distribution is

$$h_\ell(\omega) = (\ell+1)^2\frac{1+(-1)^\ell\cos(\omega\tau_b)}{[(\omega\tau_b/\pi)^2-(\ell+1)^2]^2}.$$

The calculated results are depicted with the measured data for the mode $\ell = 0$ in Fig.2 and Fig.3. In Fig.2 the growth rate for the mode $\ell = 0, 1$ and 2 are plotted by a solid line, a dashed line and a dotted line, respectively.

These results agree with the measured values very well. It should be noted that three impedances contribute almost equally to the growth rate.

Table 4: Broad band impedance.

R_T	3 MΩ/m
ω_r	$2\pi \times 1.4$ GHz
Q	1

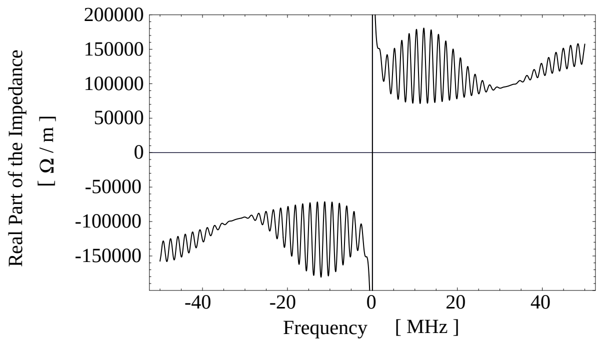

Figure 1: Real part of the total impedance (calculated).

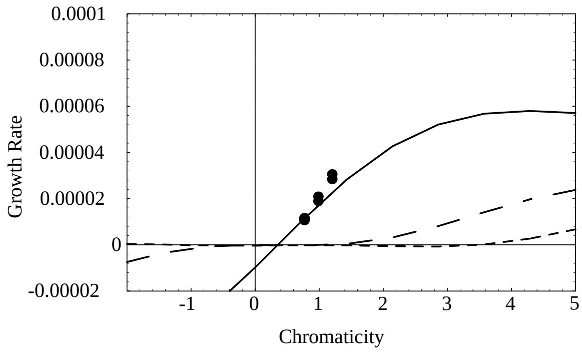

Figure 2: Growth rate as a function of horizontal chromaticity.

3 CURE WITH OCTUPOLE MAGNETS

The instability sometimes occurs in usual accelerator operation in which nine bunches are accelerated, although the chromaticity is made just below zero. To suppress the instability, two presently available octupoles which are asymmetrically located in the ring are excited in addition to the chromaticity optimization.

We should trade off the Landau-damping effect against a dynamic aperture. We have examined the dynamic aperture by our own two dimentional simulation code (transverse motion) capable of including nonlinear elements, such as sextupole and octupole magnets[1]. In the simulation, a phase space vector (x, x', y, y') is multiplied by the transfer matrix in the linear field components and x' and y' are

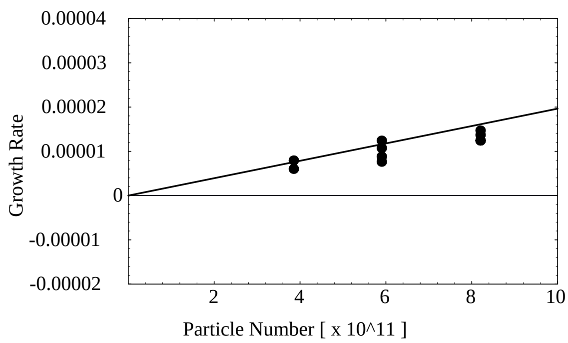

Figure 3: Growth rate as a function of bunch intensity.

shifted with each nonlinear field component in the way of thin lens. The dynamic aperture is calculated for the case in which two octupole magnets are excited in addition to 16 sextupole magnets, a half of which is used for suppressing HTI. As another nonlinear elements the eddy-current induced sextupole field in the beam-pipe of the bending magnets, remnant sextupole componets in the bending, quadrupole and sextupole magnets are included[1]. Those nonlinear elements are considered to be localized at the center of the magnets. The result is depicted in Fig.4. The number of revolution without loss is indicated by the size of square at a starting point of the tracking. For comparison Fig.5 is shown, which is the dynamic aperture with only chromaticity correction and without octupole excitation. The aperture is drastically reduced by the octupole excitation.

The expected growth rate of the single bunch HTI is in the order of 0.00001 according to the previous disscussion. The horizontal betatron tune spread introduced by the octupole magnets which is required to suppress the instability during nine bunches operation is calculated to be about 0.014 for the typical emittance of $\sim 17\,\pi$ mm mrad. Therefore required octupole strength is too large which suggests multibunch effect.

To increase the dynamic aperture, symmetrically located octupole magnets have been numerically examined. In Fig.6 the dynamic aperture is depicted for eight octupoles with the excitation of one quarter current of the upper case per each magnet. This setting causes the same tune spread as the upper case. The aperture becomes as about three times as large. The installation is planned in the next shutdown period of the PS.

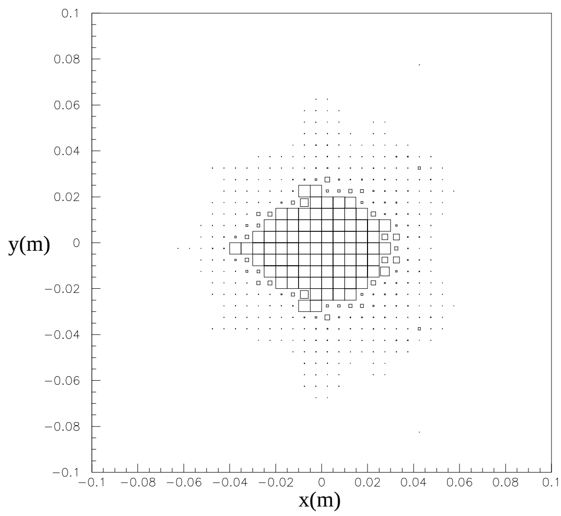

Figure 4: Dynamic aperture with two asymmetrically located octupoles.

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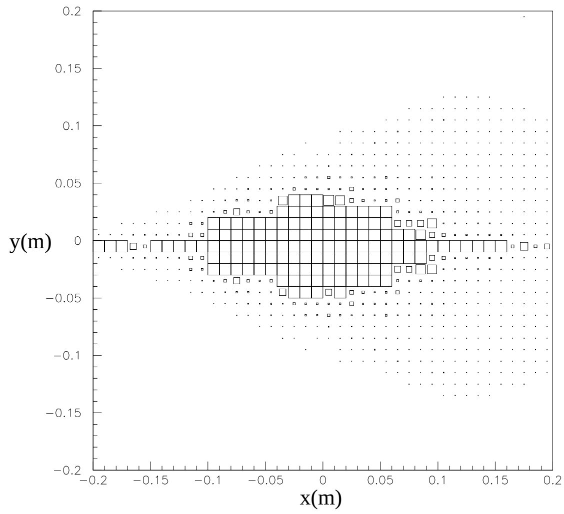

Figure 5: Dynamic aperture with 16 sextupoles and other sextupole fields.

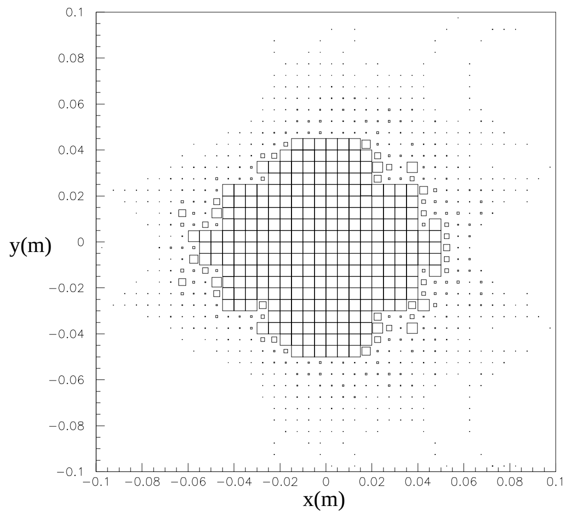

Figure 6: Dynamic aperture with eight symmetrically located octupoles.

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