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DAMPING TEST OF THE HIGHER-ORDER MODES OF THE RE-ENTRANT ACCELERATING CAVITY

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Summary

Higher-order modes were studied in a model cavity (500 MHz re-entrant single cell cavity) which was designed for the KEK-PF 2.5 GeV electron storage ring. The longitudinal electric field and the transverse electric and magnetic fields were measured near the beam axis for the higher-order modes. The observed parameters of the TM0-mode resonances were in reasonable agreement with the SUPERFISH calculation. The TM011-like resonance at 758 MHz has the highest shunt impedance of 3.0 MΩ. The observed transverse coupling impedances of the HEM1 modes at 829 MHz (TM110-like) and 1071 MHz (TM111-like) were 12 MΩ/m and 27 MΩ/m, respectively. Damping couplers are being developed to prevent the cavities from driving the coupled-bunch instabilities. The impedances were reduced to less than 0.01 MΩ and 0.2 MΩ/m for almost all of the TM0- and HEM1-mode resonances, respectively, in a low power test.

Introduction

The KEK Photon Factory (KEK-PF) electron storage ring was designed to operate at an energy of 2.5 GeV, and to store current of 500 mA for a multi-bunch mode operation. A system of four re-entrant single cell cavities made of the OFHC copper provides the beam with the energy lost by the synchrotron radiation. Each cavity has inner structure as shown in Fig. 1 to improve the shunt impedance of the 499.99 MHz fundamental (accelerating) mode.[1-3] The detailed RF parameters are presented in Ref. 2.

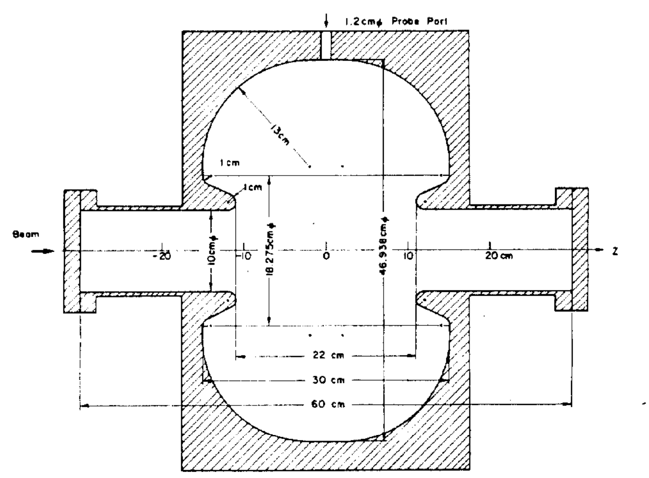

Fig. 1 Inner structure of the KEK-PF cavity.

Possible beam instabilities for the KEK-PF ring were discussed by Takata.[4] It was expected that the wide-band impedances of the cavities and vacuum chamber are small enough to store the designed beam current. However, serious coupled-bunch instabilities may arise from the narrow-band cavity impedances associated with the higher-order mode resonances. Here, the number of the bunches are 312.

We determined the coupling impedances of the higher-order modes in a model cavity made of aluminum. Then, possibility of the coupled-bunch instabilities was studied in terms of the obtained coupling impedances. Devices are being developed to suppress the instabilities by using this information. The results are described here.

Determination of the coupling impedances

Possible resonant modes in an axially symmetric cavity are designated by TM0, TE0 and HEMν (ν≥1). Only the longitudinal field component E_z is present on the symmetric axis z in TM0 modes, while both of the transverse field components $E_\perp$ and $H_\perp$ are present in HEM1 modes. These field components of the TM0 and HEM1 modes were measured with a technique developed by Maier and Slater.[5] Thus, the measured fields are normalized so that the integral of $|\vec{E}|^2$ or $|\vec{H}|^2$ over the cavity is unity: $\int|\vec{E}|^2 dv = \int|\vec{H}|^2 dv = 1$. We are not interested in the ν≥2 modes, which have no field on the beam axis z.

If we use the normalized fields, the longitudinal shunt impedance of a specific TM0 mode resonance a is expressed in the form ($Z_o = \sqrt{\mu/\varepsilon}$)

$$R_{sh}/Q_a = 2Z_o\,[\int E_z e^{jkz}dz]^2/k \quad , \qquad (1)$$

where Q_a and $k = 2\pi f_a/c$ are the Q-value and the wave number of the resonance, respectively. We use the same transverse coupling impedance $Z_\perp(\omega)$ as defined by Ref. 6. If we define the transverse shunt impedance by $R_\perp = Z_\perp(\omega{=}\omega_a)$, the $R_\perp$ is given by

$$R_\perp/Q_a = Z_o\, v_\perp^{\,2} \qquad (2)$$

with a parameter

$$v_\perp = j\int E_\perp e^{jkz}dz - \int H_\perp e^{jkz}dz. \qquad (3)$$

These equations were used to determine the shunt impedances empirically. In the derivation of eq. (2), note a relation

$$v_\perp = -\int(\mathrm{grad}\ E_z)_\perp\, e^{jkz}dz/k \qquad (4)$$

which holds for any cavity with reflection symmetry for the planes x=0 and y=0. The derivations of eqs. (2) and (4) are given in Ref. 7.

Seventy four resonances were observed below the cut-off frequency (2,295 MHz) of the 100 mmφ vacuum chamber. Mode assignments were made for all of the resonances. Among them the TM0 and HEM1 mode resonances are shown in Fig. 2. Measured field distributions are shown in Fig. 3 and the obtained parameters are summarized in Table I for the TM0 and HEM1 resonances below 1,300 MHz. The experimental procedure is detailed in Ref. 7. The parameters of the TM0 mode resonances were calculated with the computer program SUPERFISH.[8] The calculation was in reasonable agreement with the experiment for all of the TM0 mode resonances below the cuf-off frequency.

Coupled-bunch instabilities

If the spread of the synchrotron frequency f_s is

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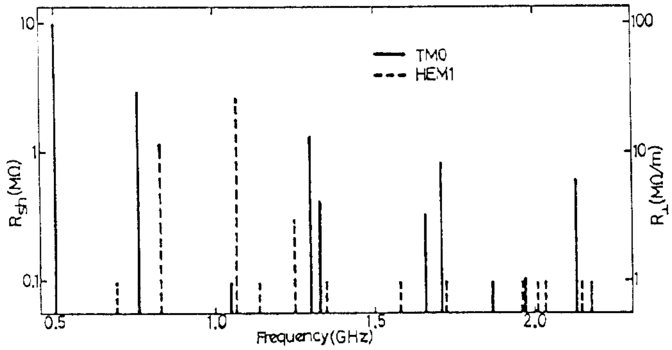

Fig. 2 The TM0 and HEM1 mode resonances observed below the cut-off frequency in the KEK-PF cavity. Small or unknown impedances (HEM1 above 1.3 GHz) are represented as R_{sh} = 0.1 MΩ or $R_\perp$ = 1 MΩ/m.

neglected inside the point-like bunch, the growth-rate of the coupled-bunch longitudinal instability is given by[9-10]

$$\Delta\omega_{/\!/} = \frac{eI_of_o}{2E_o} \cdot \alpha \frac{f_a}{f_s} \cdot \frac{R_{sh}}{2} \qquad (5)$$

in the case of $f_a = nf_o - f_s$. Here, I_o, f_o, E_o and α are the average beam current, revolution frequency, beam energy and momentum compaction factor, respectively. Also, the growth-rate of the coupled-bunch transverse instability is given by[11]

$$\Delta\omega_\perp = \frac{eI_of_o}{2E_o}\, \beta\, R_\perp \qquad (6)$$

in the coincidence case of $f_a = nf_o - f_\beta$. Again, the point-like bunch and zero-chromaticity are assumed. The β is the betatron amplitude function at the cavity and f_β is the betatron frequency.

Using the KEK-PF ring parameters I_o = 500 mA, f_o = 1.6 MHz, E_o = 2.5 GeV, f_s = 61 kHz, α = 0.035 and $\beta \sim 10$ m, the growth-rates of the instabilities arising from the 758.4 MHz TM0 modes and 1070.8 MHz HEM1 modes were estimated to be about 1,500 times larger than the radiation damping rates. Here, the radiation damping times of the synchrotron and betatron

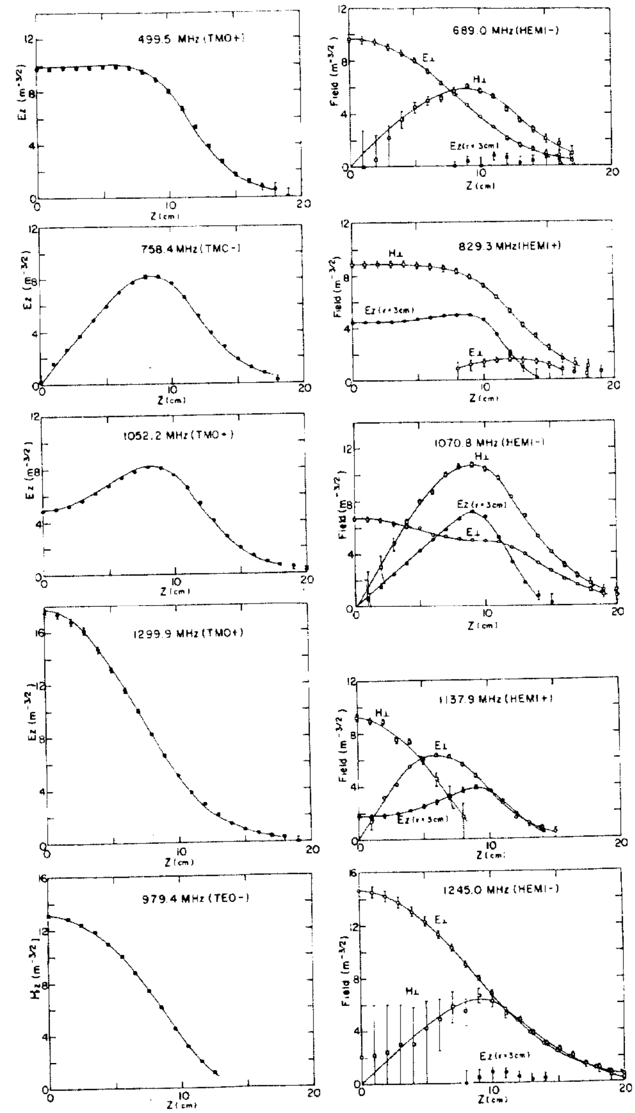

Fig. 3 Field distributions of the TM0, TE0 and HEM1 modes. The solid curves for the TM0 modes are the results of the calculation by SUPERFISH. Those for the other modes are drawn to connect the experimental points smoothly.

Table I Properties of the observed TM0 and HEM1 mode resonances in the KEK-PF cavity. Comparison is made with the calculation by SUPERFISH. The experimental unloaded Q-values were obtained by assuming that the ratios of $Q_{Cu}/Q_{A\ell}$ are the same as that of the fundamental mode.

Mode and Parity	Frequency (MHz) Exp.	Calc.	Unloaded Q Exp.	Calc.	R_{sh}/Q or $R_\perp/Q$ (Ω or Ω/m) Exp.	Calc.	Threshold Q	External Q Type I	Type II
TM0+	499.5	499.5	(44,000)	44,000	220(6)	222	-	-	-
TM0-	758.4	758.6	37,000	37,000	82(2)	81	100	80	< 50
TM0+	1052.2	1052.3	34,000	38,000	0.34(11)	0.19	15,000	600	600
TM0+	1299.9	1299.7	112,000	97,000	10.9(8)	12.0	400	3000	1000
HEM1-	689.0		45,000		< 22		< 4,000	50 300	< 50 < 50
HEM1+	829.3		56,000		207(35)		300	200 1000	300 600
HEM1-	1070.8		40,000		666(31)		100	600 2000	300 300
HEM1+	1137.9		45,000		6(3)		9,000	300 2000	900 1000
HEM1-	1245.0		95,000		< 34		< 2,000	900 7000	< 50 < 50

oscillations are $\tau_\varepsilon \cong 4$ ms and $\tau_\beta \cong 9$ ms, respectively. Furthermore, the growth of the instabilities for almost all of the observed TM0 and HEM1 mode resonances is faster than the radiation damping. Clearly, it is necessary to develop a device to avoid the instabilities.

Damping test of the higher-order modes

Two damping couplers will be radially introduced through the 100 mmϕ windows from the outside into the cavity to extract the energies of the higher-order modes. One window is placed at 90° from the other in the z=0 plane. The odd-parity modes have strong electric fields on this plane, while the even-parity modes have strong magnetic fields. Thus, a rod antenna and loop were used to suppress the odd- and even-parity modes, respectively. Since the loop also couples with the fundamental mode, a half-wavelength coaxial resonator with an adjustable shorting plunger was attached to the plane of detuned short to stop the fundamental mode. We concentrated ourselves on the high impedance resonances, and tested a number of couplers with different shapes. Some examples are shown in Fig. 4. Figure 5 shows the experimental set-up.

The band-stop filter mechanism worked well stopping the fundamental mode by more than 40 dB. Some examples of the measured external Q-values are shown in Table I. The type I system consists of two couplers, each of which is equipped with either of the loop or antenna. This system suppressed only one of the degenerate HEM1 modes as seen from Table I. In the type II system each coupler is equipped with both of the antenna and loop as shown in Fig. 4. The obtained Q-values are compared with the threshold Q-values in Table I, which were estimated by equating $\Delta\omega_{\parallel}$ and $\Delta\omega_{\perp}$ to $1/\tau_\varepsilon$ and $1/\tau_\beta$, respectively. Here, the growth-rates were calculated for one cavity, since the insertion of the damping couplers with slightly different shapes easily gives rise to a spread of the mode frequencies among the four cavities. It is expected that the Landau damping is factor two or three faster than the radiation damping. Therefore, the type II system attenuated the higher-order modes below 1,300 MHz well enough to avoid the instabilities.

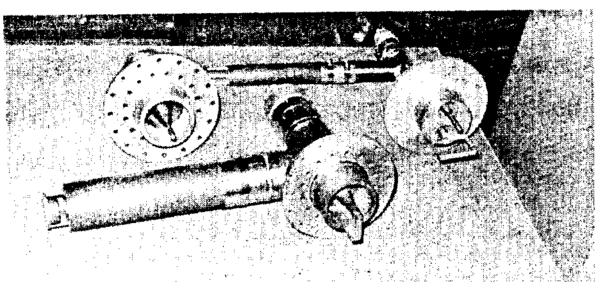

Fig. 4 Examples of the damping couplers used for a low-power test.

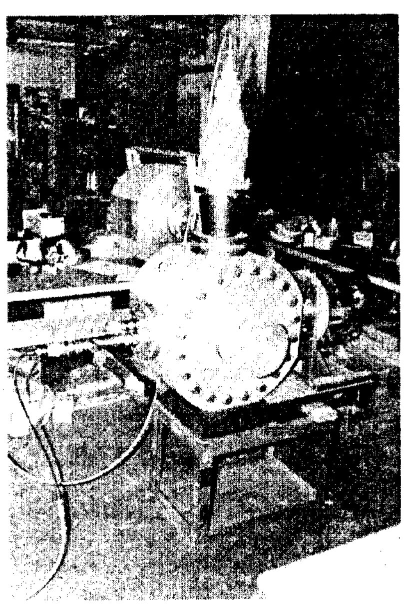

Fig. 5 The experimental set-up for a low power test of the damping couplers.

The damping couplers shifted the resonant frequencies and broke the axial symmetry of the cavity, giving rise to admixtures among different ν modes. These effects became the larger for the higher frequency. Also, the low Q-values of the resonances with the couplers made it almost impossible to measure the field distributions. Since the density of the resonances increases as the frequency becomes higher, it was very difficult to identify the resonant modes higher than typically 1,300 MHz, if the damping couplers are introduced. Also, the precise determination of the shunt impedances was difficult for the high frequency, because the rapidly varying factor e^{jkz} in eqs. (1) and (3) has cancellation effect. For these reasons, the results for the resonances higher than 1,300 MHz are not listed in Table I. However, the above cancellation effect will make the shunt impedances relatively small for the high frequency resonances, and the damping couplers will have some attenuation effect on these resonances. Thus, it is hard to expect that the high frequency resonances drive the instabilities.

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