BEAM-INDUCED RF MODES AND RF POWER IN THE CRAB CAVITY FOR KEKB

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Abstract

Two superconducting crab cavities were installed in the KEKB rings and the crab crossing operation started early in 2007. Each crab cavity has two ferrite RF absorbers (HOM dampers), which were developed for the superconducting accelerating cavities of KEKB. One is attached in a beam pipe and the other is attached in a coaxial coupler. The dampers have to damp not only the higher order modes but the lower order modes, since the crabbing mode is not the lowest mode. These parasitic modes should be sufficiently damped for the high current operation. Several antennas were set on the beam pipe to monitor beam-induced RF modes. The most dangerous mode, TM010-like mode, was detected in the RF spectrum. However, its Q-factor was below the instability criterion and consistent with the measured value at the horizontal test before installation. No dangerous modes with high Q-factor were observed in the beam-induced RF spectrum. KEKB stored the beam currents of 1.7A and 1.35 A in the low energy positron ring and the high energy electron ring, respectively. No serious beam instabilities caused by the parasitic modes were observed and the HOM dampers successfully absorbed the beam-induced RF power up to 12 kW. We will present HOM dampers used for the KEKB crab cavities, and measurement results of the beam-induced RF modes and RF power. Simulation results for the beam-induced RF power will be also discussed.

INTRODUCTION

The KEK-B factory (KEKB) is a electron-positron collider consisting of two storage rings [1]. One is an 8 GeV high energy electron ring (HER) and the other is a 3.5 GeV low energy positron ring (LER). Both beams collide with a finite angle at an interaction point. Two crab cavities were recently installed in both rings to increase the luminosity [2]. The cavities deflect beam bunches for the head-on collision (crab crossing [3,4]). To avoid beam instabilities, it is required to sufficiently damp parasitic modes in the cavity for the high current beam operation. For this purpose, the crab cavity for KEKB has several unique structures [5].

The cavity is excited with a TM110-like dipole mode (crab mode, 508 MHz) to kick the beam bunch. This mode has the other polarization which is hardly damped, if the cavity cell has a round shape. The cross section of the crab cavity cell is a race-track shape (squashed cell) to raise the frequency of the other polarization for damping. Since the crab mode is a higher order mode in the cavity, a coaxial coupler is inserted along the beam pipe to extract the lowest order mode (LOM, 408 MHz), which is a TM010-like monopole mode. This mode can propagate in the coaxial coupler as the TEM mode. The cut-off frequency of the TE11dipole mode of the coaxial coupler is set at 600 MHz, which is above the crab mode frequency but below the other higher order dipole mode frequencies. Higher order dipole modes can propagate as the TE mode in the coaxial coupler. A notch filter is attached in the coaxial coupler to reject the TEM-coupled crab mode when the coupler is misaligned. An RF absorber (HOM damper) is attached after the notch filter to damp the LOM and HOMs.

Like a quarter wave resonator, the coaxial coupler has the TEM mode or the TE mode with a quarter wave length and their higher order modes [6]. These modes also cause the beam instability. Especially, the TE modes near 600 MHz have high Q factors, since the stop band of the notch filter for the TE mode is close to this frequency. To damp these modes, the coaxial coupler has a tapered shape to lower the cut-off frequency. The notch filter has partitions in the mid-plane to shift the stop bands of the TE mode away from 600 MHz. The mid-plane of the notch filter tilts 60^{o} to the cavity mid-plane for better damping of the horizontally polarized TE mode.

To monitor these parasitic modes in the beam operation, several pick-up ports using antenna type probes were set on the beam pipe and in the coaxial coupler. We monitored beam-induced RF signals and identified parasitic modes in the cavity and in the coaxial coupler.

The HOM dampers are required to have not only a good mode damping property but also a large power capacity. Total beam-induced RF power (HOM power) in the LER crab cavity becomes 18 kW at a current of 1.7 A, where the bunch length is 6 mm in 1389-bunch operation. The HOM dampers have to absorb such a large HOM power, otherwise the power capacity of the damper limits the beam current. Bench test results of the HOM dampers for the accelerating cavities of KEKB indicate that the HOM power of 18 kW is acceptable for the crab cavity HOM dampers.

HOM DAMPER

Two HOM dampers were attached for each crab cavity. One is attached in the coaxial coupler (coaxial damper) and the other is attached on the beam pipe (LBP damper). The damper is made of a ferrite material which was developed for the superconducting accelerating cavities of KEKB [7]. The ferrite material was sintered on a copper pipe by the hot isostatic press (HIP) method at 1500 atm and 900 ^{o}C. The size of the ferrite is 240 mm in diameter,

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100 mm in length and 4 mm in thickness. Two stainless steel flanges are electron beam welded to both sides of the copper pipe. A 3/8" copper pipe is wounded on the outer surface of the copper pipe for water cooling. The absorbed RF power is given by the temperature rise of the cooling water. The HOM dampers were high power tested up to 10 kW before installing to the crab cavities. The ferrite surface was inspected by a microscope after the high power tests and no damage was found. Fig. 1 shows a picture of the HOM damper.

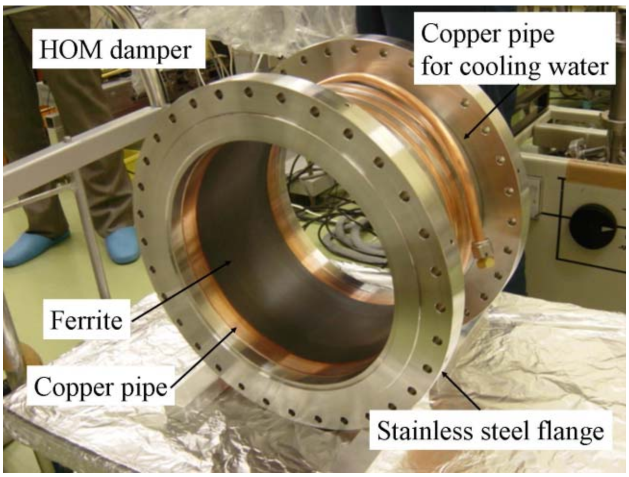

Figure 1: HOM damper for the crab cavity.

BEAM-INDUCED RF MODES

During the commissioning with the crab cavity, various bunch fill patterns were applied. 31-bunch operation with 160-backet spacing was first applied with the bunch current of 1 mA. The beam current was gradually increased as the number of bunches was increased up to 1389.

To monitor the beam-induced modes in the cavity and coaxial coupler, several antennae were attached on the beam pipe and in the coaxial coupler. Four antennae (two ports (Co-H port) in horizontal direction and the other two (Co-V port) in vertical direction) were attached in the coaxial coupler before the notch filter. Four antennae were attached on the beam pipe before the HOM damper (HOM-H/V). Fig. 2 shows layout of pick-up ports. RF signals from these antennae were processed with a spectrum analyzer during the commissioning.

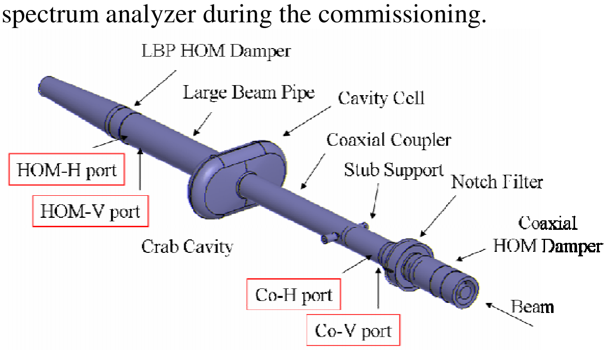

Figure 2: Layout of pick-up ports.

Single-bunch operation

A single beam bunch operation is suitable to observe beam-induced RF modes, since the beam spectrum has a flat structure with the revolution frequency of 100 kHz. To identify beam-induced RF mode, the single beam bunch operation was applied at the machine study. Fig. 3 shows spectra observed at the HOM-H and Co-H ports with a beam current of 0.5 mA. Signals from HOM-H mainly observes beam spectrum, while signals from CO-H observe beam-induced RF modes. Dominant modes below 400 MHz are parasitic modes in the coaxial coupler. These modes are the TEM mode with a quarter wave length (Co-TEM-1/4λ, 57 MHz) and its higher order modes. The LOM was detected at 408 MHz. Several higher order modes of the cavity such as TM310, TM111 and TM130 were detected above 600 MHz. The Q factor of the LOM was evaluated with the spectrum. Fig. 4 shows a beam-induced RF spectrum around 408MHz. A fitting curve in the figure shows that the resonant frequency is 408.3 MHz and Q factor is 140. These are consistent with mode measurement results at the horizontal test. No parasitic mode with the high Q factor was detected.

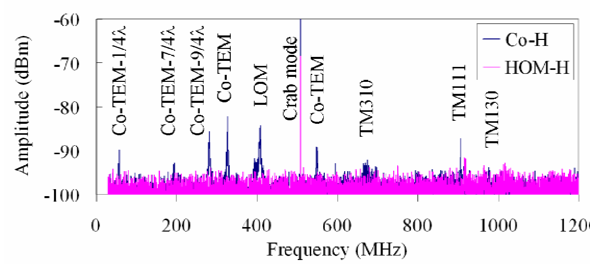

Figure 3: Beam-induced RF spectrum in the single-bunch operation and identified parasitic modes.

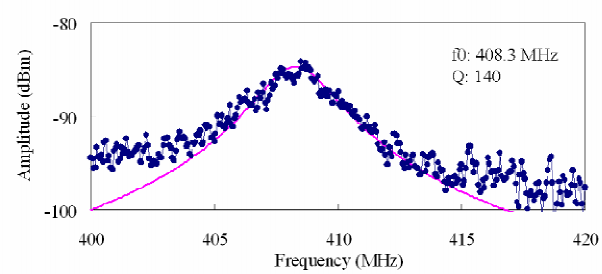

Figure 4: Q and fo of the LOM measured in the spectrum.

Multi-bunch operation

In the multi-bunch operation, beam spectrum shows a structure depending on a bunch fill pattern. Fig. 5 shows the beam-induced spectrum for the 51-bunch beam operation with 98-backet spacing. The beam current was 50 mA. This fill pattern has a structure with 5MHz intervals. The Co-TEM-1/4l mode was intensively excited with this fill pattern. Vacuum pressure rise was observed in the coaxial coupler. On the other hand, 101-bunch beam operation with 49-backet spacing has a structure with 10 MHz intervals. This fill pattern avoided intense excitation of Co-TEM-1/4l mode as shown in the figure, although the beam current was 100 mA. The 51-bunch beam operation also has a spectrum close to the frequency of LOM (Fig. 5b). We observed vacuum pressure rise in the cavity. This type of pressure rise was not observed in multi-bunch operation with a bucket spacing less than 49.

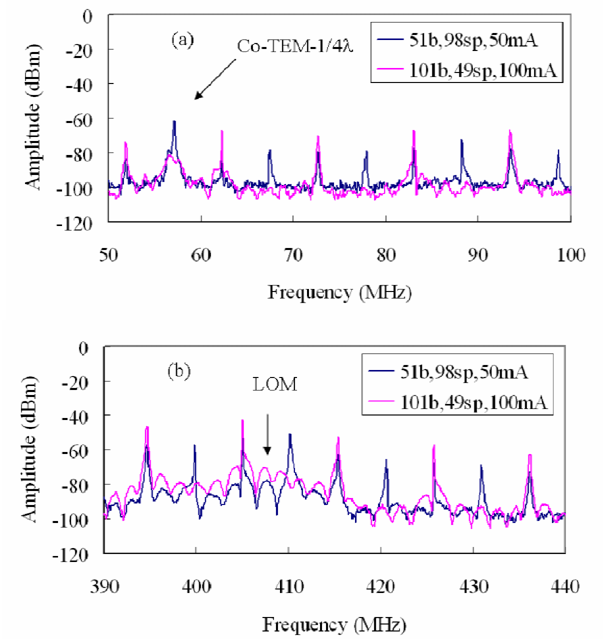

Figure 5: Beam-induced RF spectrum near 50 MHz (a) and 400 MHz (b).

Beam offset

As the beam passes though off the centre of the cavity, dipole modes were induced. The most sensitive mode for this beam offset is the crab mode. The field centre of the cavity was determined as the crab mode has the minimum beam-induced power with the crab cavity detuned. Higher order dipole modes were also induced in the beam offset operation. Fig. 6 shows an RF spectrum taken for a horizontal offset of 5 mm in the 51-bunch operation with 98-backet spacing. RF spectrum without beam offset is shown in the same figure for comparison. RF spectrum at 1069 MHz was identified with the TM230 mode.

RF signals in a vertical beam offset operation was also taken in the same bunch fill pattern. An RF spectrum is shown in Fig. 6. Vertically polarized dipole mode excitations are not so clear with a vertical offset of 5 mm.

RF mode in the input coupler

The input coupler is inserted to the crab cavity in a horizontal direction. To support an inner conductor, the coupler has a stub-type structure. The stub structure has a parasitic mode from the terminated part of the stub support to the tip part of the inner conductor. This mode can propagate in the beam pipe as a horizontally polarized TE mode. Fig. 7 shows beam-induced spectrum taken at the HOM-H and HOM-V ports on the beam pipe. Mode excitation at 916 MHz is observed in the 51-bunch operation with 98-backet spacing.

The frequency of this mode is above the cut-off of the beam pipe. The LBP damper sufficiently damps this mode. In the multi-bunch operation with a bucket spacing less than 49, amplitude of this mode excitation is small.

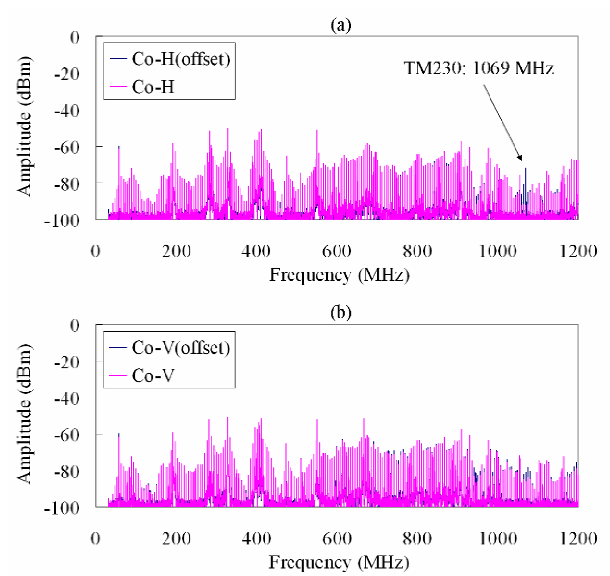

Figure 6: Beam-induced RF spectrum in the horizontal beam offset (a) and in the vertical beam offset (b).

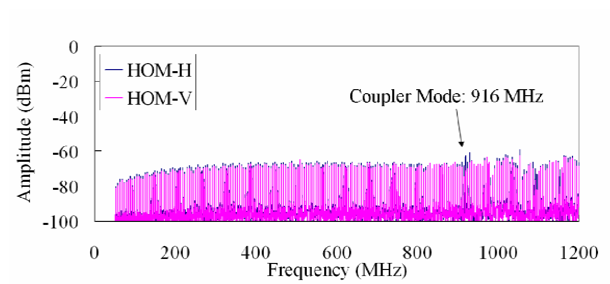

Figure 7: Beam-induced RF spectrum in the beam pipe.

BEAM-INDUCED RF POWER

Loss Factor

Beam-induced RF power (HOM power) is absorbed in the HOM dampers. The loss factor of the crab cavity structure was calculated using the ABCI calculation code. The crab cavity has a squashed cell, however, two-dimensional treatment is reasonably good approximation in case that the cell structure is large compared to the beam pipe radius. The loss factor is 0.88 V/pC for the bunch length of 6 mm (σz=6mm). Although the total HOM power is given from the loss factor, it is important to estimate the HOM power coming to each HOM damper, because, in high current operation, the large power capacity of the HOM damper may limit the beam current. To estimate the power ratio, we simulated RF fields during the beam passage using the MAFIA T2 simulation code. In the simulation, electro-magnetic fields at the coaxial coupler and beam pipe were monitored to calculate the Poynting vector. Summing the Poynting vector on the surface and time gives RF powers coming to each HOM damper. The estimated power ratio is 1(LBP):0.3(coaxial). In addition to the geometrical loss factor, the LBP damper has its own loss factor, because the damper is exposed to the electro-magnetic fields of the beam bunches. This own loss factor was calculated to be 0.25 V/pC for the bunch length of 6 mm. The total loss factor 1.13 is divided into 0.93 and 0.2 for the LBP and coaxial dampers, respectively. The estimated power ratio is 1:0.22.

Absorbed RF power

During the beam operation, we monitored absorbed HOM powers in both dampers. Fig. 8 shows measured HOM power absorbed in the dampers for HER and LER crab cavities. Absorbed powers were measured at several beam currents in the 1389-bunch operation with 3.5-backet spacing up to 1.7A in the LER and 1.35 A in the HER. The cavities were detuned above 0.7 A in the HER and 1.3 A in the LER. The total absorbed powers reached to 12 kW in both rings. The power ratio is about 1: 0.2, which well agrees with the simulation. Lines in the figure are calculated RF powers from the loss factor. Absorbed RF powers in the HER reasonably agree with the simulation. However, absorbed RF power in the LER are about a half of the simulated value. One reason is that the bunch length in the LER is slightly longer than 6 mm [8]. The second reason is that a SiC damper attached after the taper section of the crab cavity contributes to absorb the RF power. The temperature of the SiC damper significantly increased during the high current operation. We plan to measure absorbed RF power in the SiC dampers.

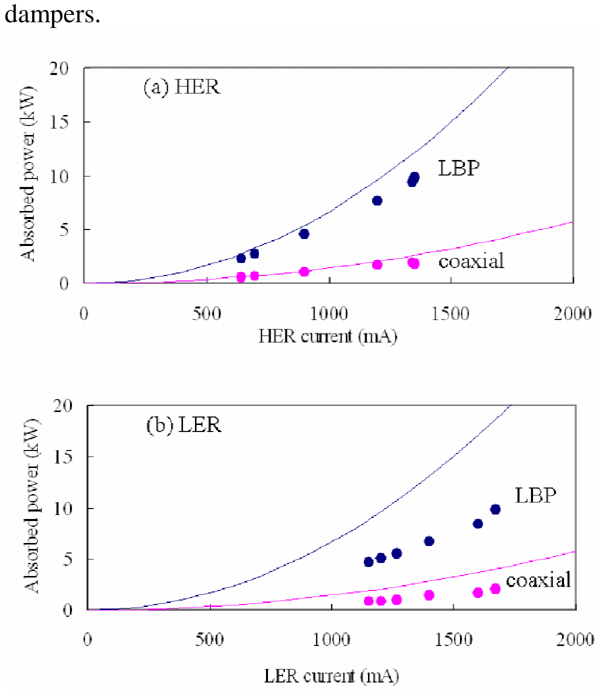

Figure 8: Absorbed HOM power in HER (a) and LER (B). Lines in the figure are calculated power from the loss factor.

SUMMARY

Two crab cavities were installed in the KEKB ring and the commissioning with crab cavities has started. During the beam operation, beam-induced parasitic modes were monitored using pick-up ports on the beam pipe and the coaxial coupler. Parasitic modes were sufficiently damped and the crab cavity accepted the beam current of 1.7 A in LER without beam instabilities caused by the parasitic modes. The HOM dampers successfully absorbed HOM power up to 12 kW (10 kW in the LBP damper and 2 kW in the coaxial damper). The mode damping property and the large power capacity of the HOM dampers enabled the crab cavities to work in the high current operation.

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