CRAB CAVITY DEVELOPMENT

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Abstract

Two superconducting crab cavities were installed in the KEKB accelerator. The KEKB (KEK B-factory) is a double-ring, asymmetric-energy, high luminosity electron-positron colliding accelerator with a finite angle beam crossing. A purpose of the crab cavities is to deflect the beam-bunches with time-varying RF fields, and to provide the head-on collision at the interaction point (crab crossing scheme). The head-on collision will drastically increase the luminosity. The crab cavity is required to have high RF fields (kick voltage) to provide beam-bunch deflection. The operating mode (crab mode, 509 MHz) is not the lowest order mode (LOM) of the cavity. In order to sufficiently damp the LOM as well as the HOMs for high beam currents in KEKB, a coaxial coupler is attached along the beam pipe. Two crab cavities have been fabricated and tested in a vertical cryostat. The cavities were recently tested with high RF power in cryostats. We have achieved required kick voltage.

INTRODUCTION

The crab crossing was first proposed by R. B. Palmer for linear colliders to increase the luminosity [1]. K. Oide and K. Yokoya suggested that this crossing scheme is applicable for ring colliders such as KEKB [2]. KEKB is a B-meson factory which consists of two storage rings with a finite angle beam crossing at the collision point. One ring is a 3.5 GeV low energy positron ring (LER) and the other is an 8 GeV high energy electron ring (HER) [3]. Main parameters of KEKB are summarized in Table 1. The crab crossing needs an RF deflector which provides transverse kicks for the beam bunches. Consequently, the beam bunches tilt at the interaction point and collide head-on. After the collision, the beam bunches are kicked back by compensating RF deflectors. Fig. 1 shows the crab crossing scheme.

K. Akai invented a beam deflecting RF cavity (Crab Cavity) [4]. His design is the base of the crab cavity for KEKB. This cavity has several unique characteristics. One is a coaxial coupler to damp the lowest order mode (LOM). Another is a not-round cavity cell (squashed cell) for separating unwanted higher order modes (HOMs). The required RF fields are high for KEKB accelerator. The kick voltage is 1.4 MV corresponding to the surface peak electric field of 21 MV/m.

Superconducting cavity is suitable for the high field requirement. To develop superconducting crab cavity, R&D program started in 1994. Using 1/3-scale Nb model cavities, fabrication methods and surface treatments were studied. In 1996 a full-scale Nb prototype cavity was fabricated and tested intensively. We achieved the required kick voltage after several tests. The second prototype cavity was fabricated for a reproducibility check. The cavity exceeded the required voltage and reached almost 3 MV. This cavity was installed in a prototype cryostat for a cool-down test.

In 2003 K. Ohmi suggested the crab crossing would improve the luminosity [5]. Using a beam-beam simulation method, he concluded that the luminosity would increase two times as much as the present one. Two crab cavities were decided to be installed in both KEKB rings. In this scheme there are no compensating crab cavities. The beam bunches wiggle in the ring. The location of crab cavities was chosen at the straight section 1 km away from the collision point, where superconducting accelerating cavities and a large He refrigerator already exist. This scheme helped to reduce the construction costs. Fabrication of two crab cavities started in 2005.

Table 1: Main parameters of KEKB

	LER	HER
Beam Energy (GeV)	3.5	8.0
Beam Current (A)	1.7	1.3
Crossing angle (mrad)	11 x 2	

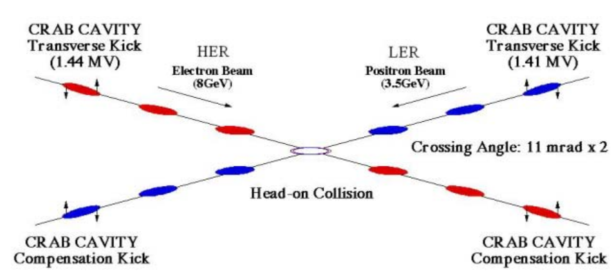

Figure 1: Crab crossing scheme.

CONCEPTUAL DESIGN

The crab cavity is excited with the TM110-like mode (Crab mode, 509 MHz) to kick the beam bunches since this mode has a large R/Q value. However, this mode is not the lowest order mode (LOM). For high current operation, it is important to sufficiently damp the LOM as well as higher order modes (HOMs).

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A coaxial coupler is inserted along the beam pipe to damp the LOM. The LOM (TM010-like mode, 410 MHz) propagates in the coaxial coupler as a TEM mode wave then damps at an RF absorber (HOM damper). Other monopole modes can also propagate in the coaxial coupler. On the other hand, the coaxial coupler has a cut-off frequency for the dipole mode. This frequency is set at 600 MHz, which is above the crab mode but below all dipole HOMs. The dipole HOMs also can propagate and damp.

The cavity cell has a not-round structure (squashed cell) to raise the frequency of unwanted parasitic mode such as the other polarization of TM110-like mode above the cut-of frequency.

Attenuation factor of the crab mode in the coaxial coupler is 60 dB/m. A long coupler, 1 m long at least, is required. A stub support supports the long inner conductor of the coupler.

Although the crab mode is below the cut-off of the coaxial coupler, this mode can propagate in the coaxial coupler as a TEM mode if the coupler is misaligned off the central axis. A notch filter is attached on the coaxial coupler to kick back the TEM-coupled crab mode. The RF parameters of the crab cavity are summarized in Table 2. Schematic diagram of the crab cavity is shown in Fig. 2.

Table 2: RF parameters of the crab cavity

fo	509 MHz
R/Q	46.2 Ω
Geometrical Factor	220
Esp/Vkick	13.5 MV/m/MV
Hsp/Vkick	424 Oe/MV
Required Kick Voltage	1.4 MV

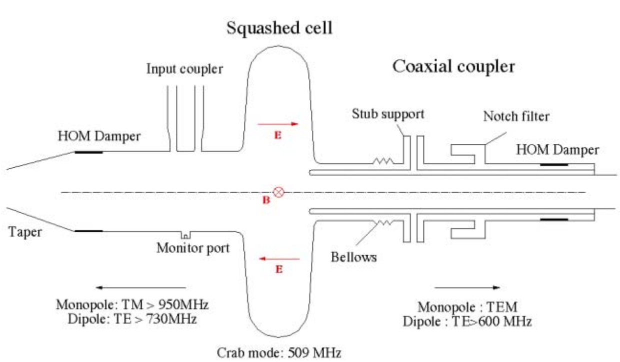

Figure 2: Schematic diagram of the crab cavity.

PROTOTYPE CAVITIES

To realize such a complicated structure of the crab cavity, we established the fabrication method for the squashed cavity cell and surface treatments for high fields [6].

Half cells were hydro-formed from Nb (RRR=180) sheet 5 mm thick and joined by electron beam welding (EBW). Welding seams at the equator of the cell were mechanically grinded. Beam pipes, coupling ports and flanges were also joined by EBW.

The cavity was polished by barrel polishing (100 μm) then electro-polished (EP I, 100 μm). After rinsed with pure water, the cavity was heat treated in a vacuum furnace (700 ^{o}C x 3 hr). Finally the cavity was rinsed by high pressure ultra-pure water rinsing (HPR).

1/3-scale model cavities were fabricated and cold-tested [7]. Then fabrication of full-scale prototype cavities followed. Using the prototype cavity #1, we studied RF performance intensively for high field application. After several modifications of surface treatments, we reached the required surface peak field of 21 MV/m with a Qo value above 10^9 [8].

Fig. 3 shows typical cold test results at 4.2 K. The cavity degraded by a miss-operation of vacuum system. Micro-particles in air contaminated the cavity surface. We tried He processing to this cavity. The RF performance recovered and the peak field exceeded 21 MV/m, however, we observed strong X-ray radiation. After this cold test, cavity was disassembled and rinsed by HPR. The performance recovered completely and no X-rays were observed. HPR is effective to clean up the micro-particles, which may be introduced to the cavity accidentally. The cavity was tested at 2.8 K. The RF fields exceeded 40 MV/m. Lower temperature operation may be an option for high field applications.

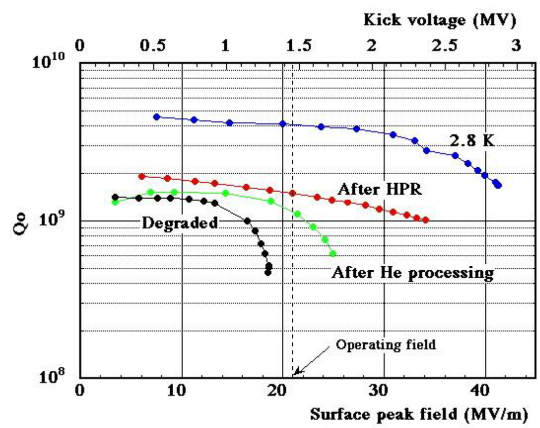

Figure 3: Vertical cold test results after HPR.

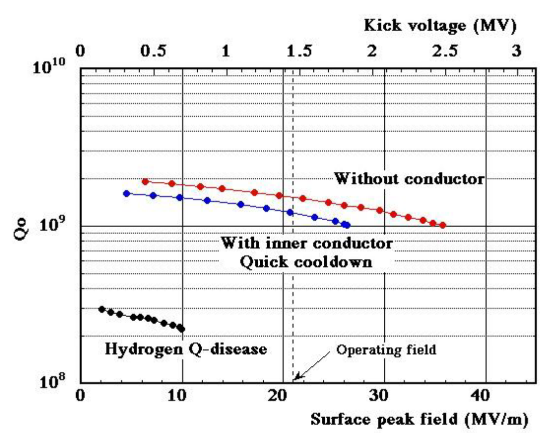

Figure 4: Vertical cold test results with coaxial coupler.

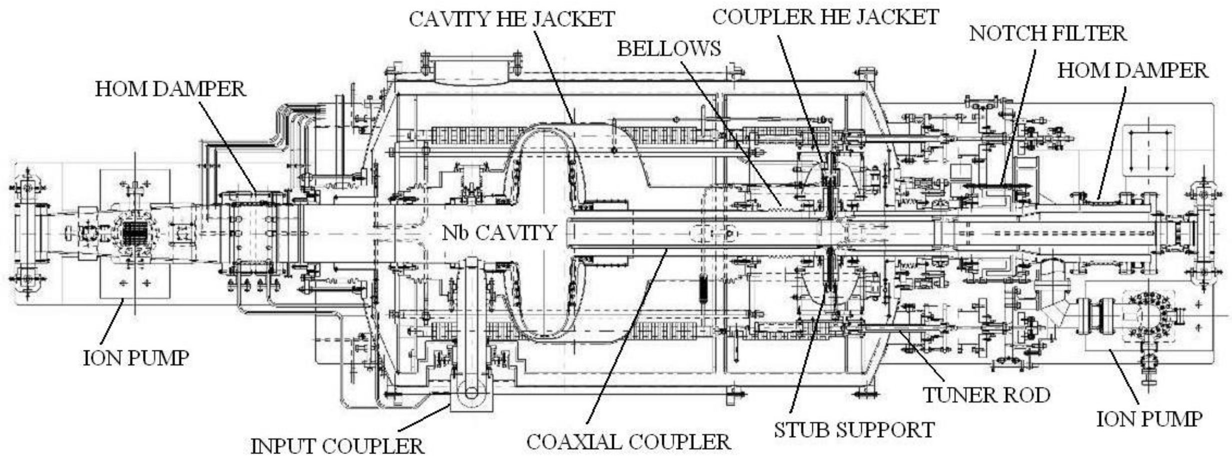

Figure 5: Crab cavity for KEKB (top view).

To test the effect of coaxial coupler, we made a model inner conductor, which is a short version of full size coupler to meet space restrictions of our vertical test stand. Fig. 4 shows cold test results with the inner conductor. At low fields, multipacting was observed around the tip of inner conductor [9]. This type of multipacting was processed in an hour. At the same time serious degradation was observed [10]. This is so-called hydrogen Q-disease of the inner conductor. Nominal surface treatments of the inner conductor involve heat treatment for degassing of hydrogen but we skipped this procedure. As is well known, the hydrogen Q-disease happens if the cavity stays at temperatures around 100 K for several hours. To prevent this disease we cooled down the cavity quickly below 150 K. We achieved the required field even with the coaxial coupler.

The prototype cavity #2 was fabricated for confirmation of our fabrication method. Electro-polishing of 5 μm surface removal (EP II) was added before HPR in standard surface treatments. The cavity exceeded 21 MV/m and reached 35 MV/m. We have established the fabrication method and surface treatments. After the vertical cold tests, this cavity was installed in a prototype cryostat and cooled down to confirm the cool-down procedures.

CRAB CAVITIES FOR KEKB

Engineering designs of the crab cavity for KEKB started in 2004 including a cryostat, coaxial coupler, etc [11]. Fig. 5 shows a cryostat assembly of the HER crab cavity.

Cryostat

We applied a jacket-type He vessel for the squashed cell crab cavity. The jacket is directly welded on stainless steel transition flanges which are connect to the cavity with indium seals. The cavity can be cleaned with HPR without breaking indium seals. The vessel provides 400 L of liquid helium. In the jacket, a permalloy magnetic shield jacket surrounds the cavity. A heater, a liquid helium level sensor, temperature sensors, and PIN diode X-ray sensors are set for monitoring.

The coaxial coupler also has a jacket-type He vessel at the stub support to cool the Nb inner conductor. The inner conductor has a cooling channel which is connected to the He vessel through the cooling path in the stub support. The vessel is connected to the cavity vessel with stainless steel tubes.

Large-size bellows, which is made from Cu-plated stainless steel 240 mm in diameter and 0.2 mm thick, connects the cavity and the coaxial coupler. This bellows is used for adjusting the coupler position for frequency tuning. The bellows has cooling channels at both flanges.

80 K thermal shields made of Al plates and Cu strips surround both jackets. A vacuum vessel made of stainless steel contains this assembly.

Coaxial Coupler

The coaxial coupler consists of three parts. These are a Nb inner conductor and stub support assembly, a tapered section part made of Cu-plated stainless steel, and a notch filter assembly part including a HOM damper. Each part is joined with RF contacts made of BeCu rings.

First the inner conductor part and the tapered section part are connected and installed in the cryostat. Then the notch filter assembly part is connected outside the vacuum vessel.

Frequency Tuner

The resonant frequency of the cavity shifts with displacement of the coaxial coupler by 30 kHz/mm. We use this shift for frequency tuning. The coaxial coupler assembly is connected to a tuning system by tuner rods. The tuner system consists of a main tuner and two sub-tuners. The main tuner is set at the central position of a movable plate to adjust insertion length of the inner conductor, while two sub-tuners are set at both sides of the plate to adjust its alignment. The main tuner consists of a motor driving jack and a Piezo tuner. One sub-tuner is a motor driving jack and the other is a manual jack.

HOM damper

The HOM damper is a ferrite RF absorber which was developed for the KEKB accelerating damped cavities. The ferrite material is sintered on an inner surface of a copper pipe by the HIP (Hot Isostatic Press) method with 1500 atm and 900 ^{o}C. The size of ferrite material is 120 mm in diameter, 120 mm in length and 4 mm in thickness. Copper tube is wound on the outer surface of the copper pipe for water cooling. One damper is set at the end part of the coaxial coupler and the other is set at the beam pipe. These dampers were RF tested up to 10 kW before installation.

Input coupler

The input coupler is a coaxial-type one which is horizontally inserted into the cavity beam pipe to couple the crab mode. The coupler has a stub support to support the inner conductor. This coupler is required to handle about 100 kW of RF power. The couplers were RF tested up to 200kW before installation.

HIGH POWER TEST

Two crab cavities were fabricated with the same procedure as the prototype cavities. Those cavities were cold tested in a vertical cryostat. Nb inner conductors of the coaxial coupler were also fabricated. The inner conductors were heat treated to prevent hydrogen Q-disease.

The HER crab cavity was first assembled in a clean room and high power tested in July 2006. Several modifications were needed such as the tuner mechanism, limited stroke of the coaxial coupler, etc. After the high power test, the HER crab cavity was disassembled and several modification were done. The tuner rods were replaced by more rigid ones. The large-size bellows, connecting the cavity and coaxial coupler, were made from stainless steel pipe 0.2 mm thick. In the first test, we used bellows made of Cu pipe 0.4 mm thick. This modification made its stroke wider (+/-10 mm). The coaxial coupler part outside the vacuum vessel was set on a movable base for smooth displacement.

The HER crab cavity was tested again in Nov. 2006. The LER crab cavity, which was modified in the same way, was tested in Dec. Details of the high power tests are described below.

Cool-down

The crab cavity was set in a high power test stand and connected to the 8 kW NIKKO helium refrigerator. The refrigerator cooled down the cavity at the rate of 2 K/h to avoid vacuum leakage. The Nb inner conductor of coaxial coupler was also cooled down by adjusting the helium gas flow. During the cool-down, the resonant frequency and shrinkage of the cavity were monitored. The frequency shifted 400 kHz at the end of cool-down.

Tuner Test

After the cool-down, the resonant frequency was adjusted to the operating frequency of 509 MHz by deforming the cavity cell then the tuner adjustment followed. The alignment of the coaxial coupler was set by the sub-tuner by monitoring the RF power leakage at the coaxial coupler. We set the coupler at the position where the RF power leakage is minimized. The main tuner was tested and a frequency shift of 30 kHz/mm was obtained. The main tuner was connected to the tuner feed back system and the resonant frequency was maintained at the operating frequency.

High Power Conditioning

The crab cavity was connected to a 1 MW klystron. Several interlocks were set to protect the cavity. These were vacuum interlocks, an arc sensor at the input coupler, RF power detectors at the coaxial coupler, and a break-down detector of the cavity. We gradually increased the input RF power as the cavity was being processed. Pulse conditioning was used frequently. Fig. 6 shows a conditioning state of the HER crab cavity. We reached 1.4 MV that is the operating voltage of this cavity. After that, the kick voltage slightly degraded because of high vacuum pressure. The pressure was getting higher during the conditioning. We decided to warm the cavity up to 85 K to evacuate condensed gases on the cavity surface. Temperatures and the vacuum pressure during this warm-up are shown in the same figure. We observed hydrogen and nitrogen/carbon mono-oxide out-gassing. We re-cooled the cavity and the vacuum pressure decreased below 10^{-7} Pa. After the evacuation we reached 1.8 MV.

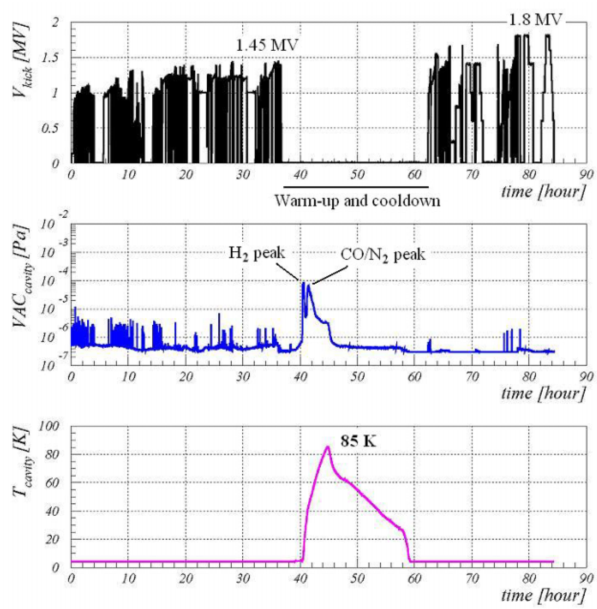

Figure 6: Kick voltage, vacuum pressure and temperature of the HER crab cavity during conditioning.

The LER crab cavity was also conditioned in the same manner. No warm-up of the cavity was needed before we reached 1.8 MV.

The external Q value of the coupler was measured by field decay method. Qext are 1.3 x 10^5 and 2.0 x 10^5 for HER and LER crab cavities, respectively. Those values reasonably agree with the designed one (1.6 x 10^5). We monitored tuner phase during the conditioning. The phase distribution of the HER crab cavity was within 1 degree, which is acceptable for KEKB. On the other hand, that of the LER crab cavity was much larger. We need further investigation.

Qo measurement

RF losses of the cavity were measured calorimetrically at several kick voltages. Heat loads were obtained by adjusting a heater power set in the He jacket so as to keep the liquid He level constant. These heat loads give Qo values. Fig. 7 shows the results for both cavities. Qo measured at the vertical cold tests are shown in the same figure for comparison. These data agree within measurement errors. No significant Qo degradation was observed in these tests.

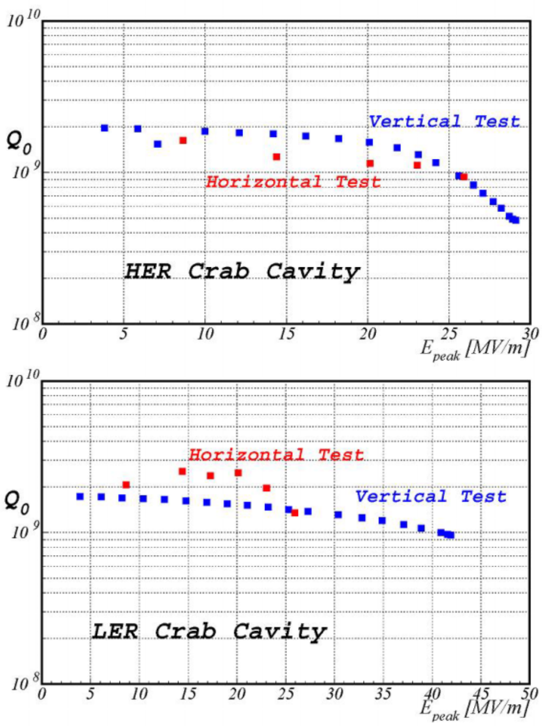

Figure 7: Qo of the HER crab cavity (above) and LER crab cavity (below). Qo obtained in the vertical cold tests are plotted in the same figures.

SUMMARY

The crab cavities for the crab crossing of the KEKB were developed. The fabrication method and surface treatments were intensively studied with prototype cavities. Two crab cavities for KEKB have been fabricated and tested in cryostat. We have achieved the required kick voltage (1.4 MV). Those cavities have been installed in both KEKB rings (Fig. 8). Beam tests will start soon.

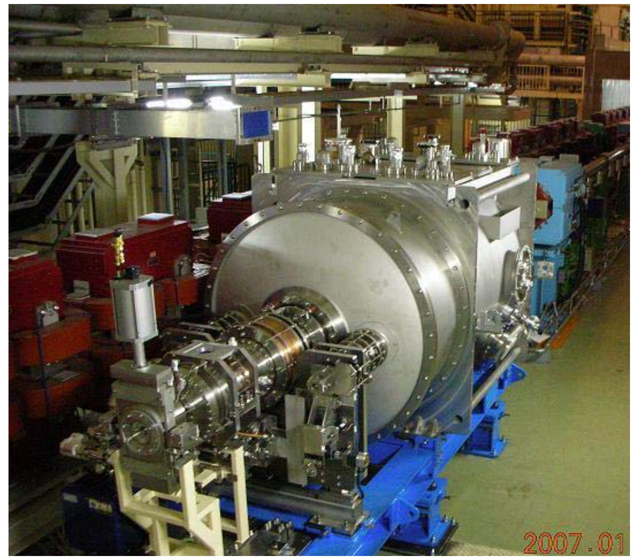

Figure 8: HER crab cavity installed in the KEKB ring.

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