

# DEVELOPMENT OF THE KEK-B SUPERCONDUCTING CRAB CAVITY

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## Abstract

After more than 10 years of R&D efforts, two superconducting crab cavities for KEKB were constructed and installed into KEKB in January 2007. Effective head on collision of electron and positron has been achieved successfully. The crab cavities are operating stably for more than 1 year under high current operation condition. Design concept and R&D efforts of the superconducting crab cavity will be described. Construction of the crab cavity, including cryostat and tuning mechanism will be also discussed.

## INTRODUCTION

High luminosity electron positron collider KEKB [1] adopted the finite crossing angle scheme, i.e. the beam bunches (height: 2~3 μm, width: ~80 μm, length ~ 7 mm) of electron and positron collide each other in finite angle (2 x 11m rad.) at the collision point. The layout of the KEKB is shown in Fig. 1. In this crossing scheme non-overlapping of the beam bunches at collision point causes beam instability and limit the luminosity. The crab crossing scheme was proposed by R.B. Palmer [2], K.Oide and K.Yokoya [3] to cure this instability.

Strong time-dependent electro-magnetic field in a superconducting crab cavity is used to kick the heads of bunch horizontally and the tails of bunches in opposite directions. Figure 2 shows the concept of the original KEKB crab crossing scheme. Two crab cavities installed near to the collision point are used to kick the bunch of the electrons and positrons. Complete overlapping of the bunch, so-called crab crossing, can be attained at colliding point. After the collision the bunch are kick back to original direction by another crab cavities. In this

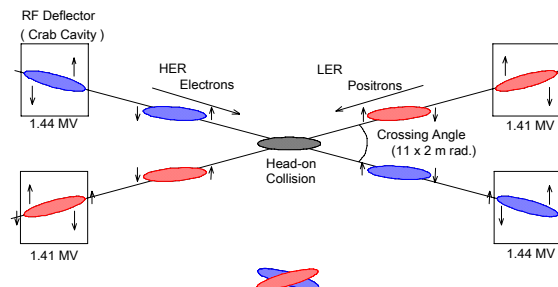


Figure 2: Crab crossing scheme for KEKB and non-crab crossing scheme case (lower)

crab crossing scheme 4 crab cavities are needed in total.

A new crab crossing scheme, so called global crab crossing scheme was proposed and adopted. In this scheme 2 crab cavities, one in HER and other in LER, are installed in the straight section of Nikko and electron and positron bunches wiggle around whole ring and make crab crossing at collision point in Tsukuba. Advantages of the new crab crossing scheme are; number of crab cavity can reduced to 2 and we can use the existing cryogenic system [4] which was constructed for TRISTAN superconducting cavity and is now operating for KEKB superconducting acceleration cavity [5].

## KEKB CRAB CAVITY

### R&D History of KEKB Crab Cavity

The crab cavity R&D study was started at KEK in 1995 and all members of cryogenic group for KEKB superconducting acceleration cavity were involved.

Non-axial symmetric cell type cavity, so called squashed cell shape cavity, was selected for base line design of KEKB crab cavity. The squashed cell type 1/3 scale crab cavity was designed and 3 niobium model cavities were fabricated to establish the fabrication techniques [6]. In parallel with fabrication of the crab cavity, we build up infrastructure for crab cavity R&D, i.e. a test stand for the crab cavity, including a 1.5GHz RF measurement system and a 1.8K cryogenic system.

After we got satisfactory result at cold RF test, we move to design and fabrication of full size 500 MHz crab cavities. A new facility consist of a clean room for assembling and a test stand for cold RF test were constructed near by large helium refrigerator now operating for KEKB superconducting acceleration cavities.

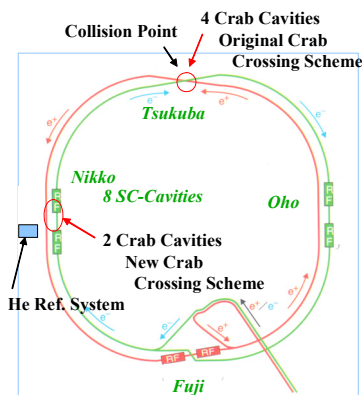


Figure 1: Layout of KEKB

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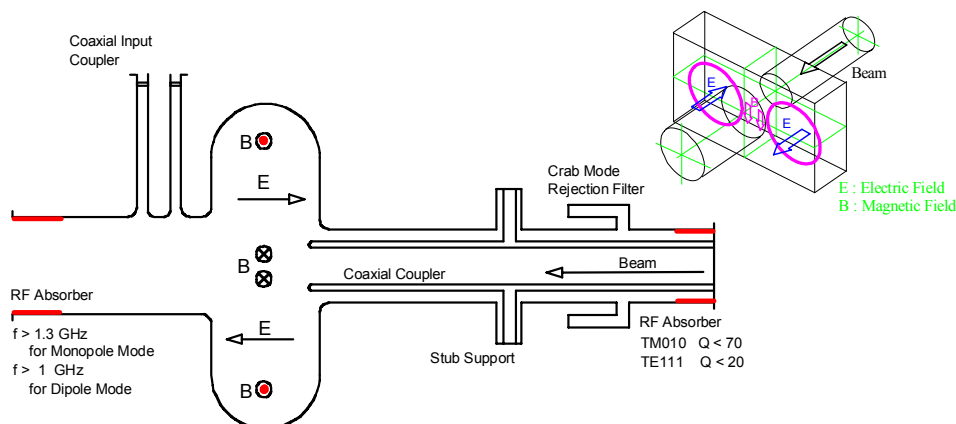


Figure 3: Conceptual design of the KEKB crab cavity (Top view) and schematic drawing of squashed cell shape cavity is shown upper right.

Two full scale 500MHz prototype niobium crab cavities were fabricated and cold tested. One of the prototype cavities was cold tested with coaxial coupler in vertical cryostat to investigate multipacting phenomena at coaxial structure of the crab cavity. We observed severe multipacting phenomena at low RF level, but could overcome by about 1hour RF processing. The kick voltages of the crab cavities exceed the design value. [7].

Design study of the prototype cryostat and the frequency tuner for KEKB crab cavity were started. Fabrication of the prototype cryostat and R&D of its key components were also started at KEK.

Installation of the two crab cavities into Nikko straight section of the KEKB ring was decided and fabrication of two KEKB crab cavities was started in 2004. The designing and fabrication of key components of the crab cavity, i.e. niobium coaxial coupler and the horizontal cryostats were also started in parallel. The final assembling of the crab cavities were carried out in KEK.

### RF Characteristics of Crab Cavity

Figure 3 shows conceptual design of the KEKB crab cavity. The magnetic field of the  $TM_{110}$  mode is used to kick the beam bunch horizontally as shown in Fig. 3.

We have adopted non-axially symmetric cavity, so called squashed-cell shape cavity, which has the cross section of racetrack shape to push up the resonance frequency of unwanted degenerate  $TM_{110}$  mode to 700MHz, higher than the cut-off frequency of large beam pipe of the cavity. A coaxial coupler which is inserted deep into the cavity cell is used to extract the lowest 430MHz  $TM_{010}$  acceleration mode and the higher TE mode from the cavity. The coaxial coupler must be set accurately in the centre of the cavity to prevent the crab mode propagate out to the RF absorber by TEM mode. A notch filter set in the end of coaxial coupler rejects the crab mode flow out from the cavity. Higher order modes induced by high current beam bunch are extracted from

the cavity through the large beam pipe and the coaxial coupler and damped at RF absorbers outside the cavity.

This crab cavity design scheme was proposed and studied by K. Akai [8] extensively at Connell University under KEK and Connell collaboration program. We have decided this design scheme for the base line design of the KEKB crab cavity. Selected parameters of the KEKB superconducting crab cavities are listed in Table 1.

### Mechanical Characteristics of Crab Cavity

Mechanical design and fabrication of the crab cavity are difficult due to large in size and non-axially symmetric in shape. The design and size of squashed-cell shape KEKB superconducting crab cavity is shown in Fig.4. The cavity is made from niobium and both iris part of the cavity cell are reinforced by 4 ribs to prevent stress concentration due to non-symmetric cell shape.

### Fabrication of Crab Cavity

A half cell of the crab cavity was hydro-formed from 5mm thick RRR 200 niobium sheet purchased from Tokyo-Denkai Ltd. The inner surface of the half cell was buff polished, the welding part was trimmed by machining, and a full cell was assembled by electron beam welding. The rough surface of welding line along the equator was made smooth by using specially designed grinding machine developed at KEK. Inner surface of the crab cavity, especially welding line of equator, was barrel polished about 400  $\mu\text{m}$ . The inner surface was electro-polished about 100  $\mu\text{m}$  using straight shape cathode made of pure aluminium pipe. The cavity

Table 1: Selected parameters of KEKB crab cavity

R/Q	46.7 $\Omega$
$\Gamma$	220
Esp / Vkick	14.4 MV / m / MV
Hsp / Vkick	415 Oe / MV

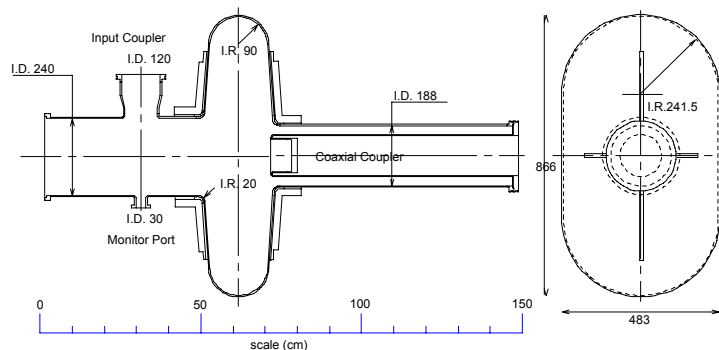


Figure 4: KEKB crab cavity with a model coaxial coupler

was high pressure water rinsed by the spray of 70 bar ultra-pure water to remove the chemical agent and micro-particle remained on the cavity inner surface. The cavity was installed in titanium box and annealed at 750°C for about 3 hours in vacuum furnace to remove hydrogen gas absorbed during the electro-polishing. Before assemble the cavity into the pumping station for cold RF performance test, the cavity was slightly electro-polished, so called EP2, to remove surface layer about a few μm and high pressure rinsed about 1 hour.

*RF Performance Test in Vertical Cryostat*

We have constructed a test stand of the KEKB crab cavity for cold test in vertical cryostat near to large helium refrigeration system which is operating for KEKB superconducting cavity, because a large amount of liquid helium, more than 5,000 L, is required for one batch of cold test. After assembled to the test set up and pumping, the crab cavity was baked for about 1 day at 100°C, and set into the vertical cryostat (1.1m in diameter and 3.5m in height). The cavity was cooling down from room temperature to 150K under cooling speed of about 17K per hour to prevent vacuum leakage and then quickly cool down to liquid helium temperature in about 1 hour.

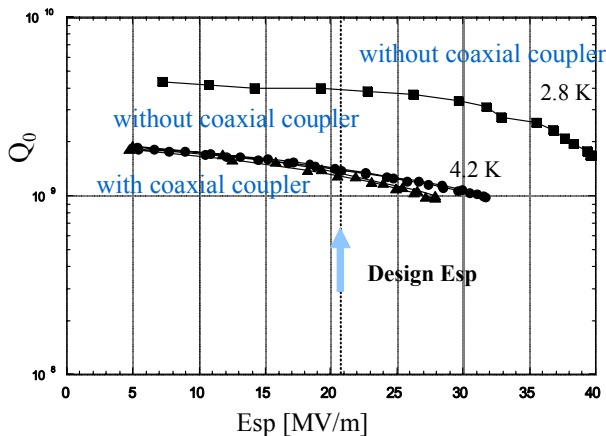


Figure 6: Measured  $Q_0$  crab cavity #1 without and with coaxial coupler

Figure 5 shows measured  $Q_0$  values of the crab cavity #1 as a function of the surface peak electric field  $E_{sp}$  with and without coaxial coupler. The  $E_{sp}$  of the cavity #1 with no coaxial coupler reached to 30MV/m keeping  $Q_0$  values higher than  $10^9$ . By lowering the bath temperature to 2.8K by pumping,  $E_{sp}$  could reached to 40MV/m. The  $E_{sp}$  of the cavity with coaxial coupler could exceed the design value of  $E_{sp} = 21$  MV/m and reach to 27MV/m.

The full scale crab cavity #2 was fabricated and cold tested to check the reproducibility of fabrication and surface treatment procedures developed at the crab cavity #1. The cold RF test results without coaxial coupler are satisfactory and almost same to the crab cavity #1.

*Multipacting in Crab Cavity*

We set a simplified niobium coaxial coupler to the cavity as shown in Fig. 4 and carried out the cold RF test in vertical cryostat to check the RF performance with coaxial coupler. At the first RF test after cool down, a strong multipacting was observed [9] at very low RF field level. We could overcome the multipacting by about 1 hour long RF processing. We did not observe the multipacting if the cavity was kept at liquid helium temperature.

*KEKB Crab Cavity for HER & LER*

The KEKB crab cavities for LER and HER were cold tested in vertical cryostat to check the RF performance before assembling into the horizontal cryostat. Figure 7 shows the test results of the KEB crab cavity for LER.

At the 1<sup>st</sup> test, the  $Q_0$  values start deteriorate at about  $E_{sp}=15$ MV/m accompanied by outbreak of X-ray emission. We have concluded that the degradation was caused by micro-particles in the cavity. We tried the RF processing and high pressure water rinsing, but we could not improve the performance as shown in Fig. 7. We decided to disassemble the cavity and return to EP2 process. We found the black whisker like foreign material (15 micron mm in diameter x 0.6 mm in length) adhered on the surface near to the heating spot. It was a

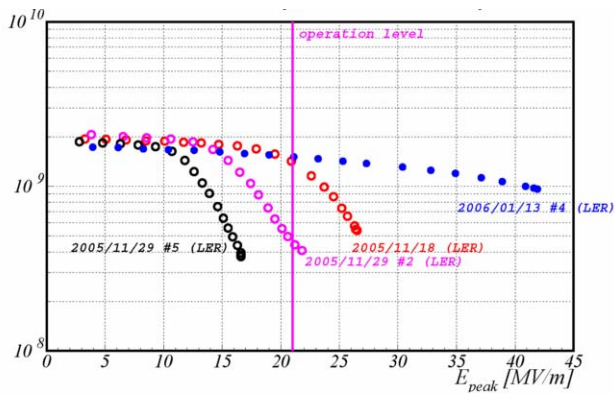


Figure 7: Measured  $Q_0$  of KEKB crab cavity for LER

fragment of lint of cotton wiper, presumably contaminated during assembling of flange to the cavity.

After the EP2 the RF performance was recovered and  $E_{sp}$  could exceed 40MV/m with  $Q_0$  is higher than  $10^9$ .

Cold test results of the of the KEB crab cavity for HER was satisfactory.

## CRYOSTAT FOR CRAB CAVITY

The conceptual design of horizontal cryostat for the KEKB crab cavity is shown in Fig. 8.

We have adopted the jacket type helium vessel for the KEKB crab cavity, because the cryostat must be designed as compact and less weight as possible easy to handle in the limited space in the KEKB tunnel.

In this jacket type cryostat design, we used “transition flanges” to connect the cavity to the helium vessel. The stainless steel transition flanges are connected to niobium cavity flanges using indium seal and then the stainless steel jacket is welded to assemble the jacketed cavity. U-tight seal are used to assemble the jacketed cavity into the cryostat.

Main jacket type helium vessel which contains the crab cavity is installed in the horizontal cryostat and supported by 4 invar rods to keep centre position of the cavity unchanged during cool-down.

The coaxial coupler which is contained in sub jacket type helium vessel is supported by 4 stainless steel rods.

These rods are hanged by cantilever type arms connected to the end plate of the main jacket. By this supporting scheme we can adjust the head position of the coaxial coupler in the crab cavity.

The helium vessels are guarded by 80K aluminium thermal shield pipe cooled by liquid nitrogen.

The coaxial coupler is supported at the midpoint by the stub support to provide the mechanical strength. This support is used the access port of liquid helium for cooling.

The configuration of the crab cavity in jacket type helium vessels and the coaxial coupler and the stub support in the cryostat is shown in Fig. 9. The crab cavity and the stub support structure are covered by the jacket type liquid helium vessels made from stainless steel and connected by copper plating stainless steel bellows.

The resonance frequency of the crab cavity is controlled by adjusting the insertion depth of coaxial coupler to the cavity cell. The insertion depth is changed by two tuning rods connected to stub support in parallel using main tuner. The sensitivity of the resonance frequency against the insertion depth is 38kHz/mm. The head position of coaxial coupler can be adjusted to centre of the cell by changing offset of the driving rods using sub tuner. The main tuner is driven by Piezo and motor actuators set in tandem outside the cryostat. The sub tuner is driven by motor actuator.

A jacket type magnetic shield is adopted for KEKB crab cavity, because it looks difficult to shield the magnet field penetrated from both beam pipes by using the simple cylindrical shape. Two half cell shape jackets made from 3 mm tick permalloy are put on the crab cavity cell and to assemble into the full cell shape by screws.

An antenna type input coupler is connected to large beam pipe horizontally to excite crab mode. The external  $Q_{ex}$  of input coupler is set to about  $10^5$  to tolerate about 1mm offset of beam position during operation and higher than about 100kW RF power must be handled. The inner conductor is cooled by water and outer conductor is cooled by cold helium gas from helium vessel. Two ferrite type RF absorbers, similar design to KEKB superconducting acceleration cavities, are set at large

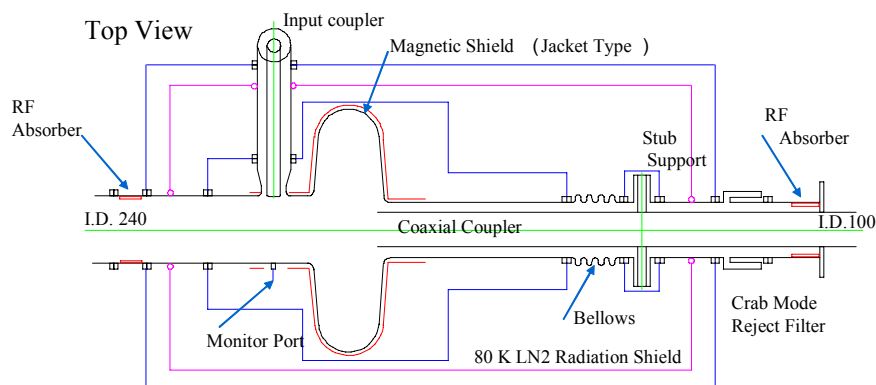


Figure 8: Conceptual design of the horizontal cryostat for KEKB crab cavity

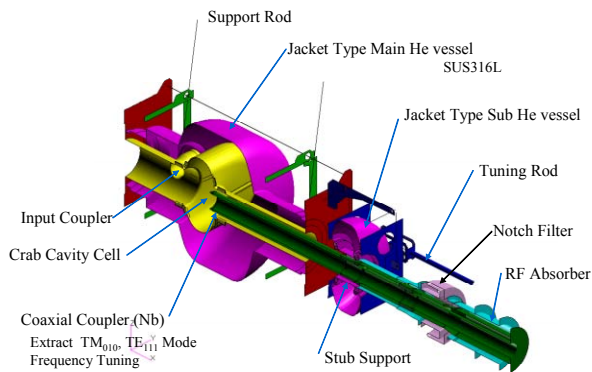


Figure 9: Configuration of the crab cavity in jacket type helium vessels and stub structure.

beam pipe and the end part of the coaxial coupler outside the cryostat, to damp the higher modes and the lowest mode. The RF absorber has 240 mm in inner diameter and absorbing power of 10kW.

### ASSEMBLING & HIGH POWER TEST

The final assembling of crab cavity for HER was started in March 2006. But due to poor assembling setup, the inner conductor of the coaxial coupler could not connect. By improving of its assembling tools, we could complete the assembling of the crab cavity for HER in April 2006. The crab cavity was sent to high power test stand and cool-down of the cavity was started on May 29. The whole system was cooled without leakage and the control of liquid helium level in the helium vessel of the cryostat and cooling gas for coaxial coupler worked well [7]. After RF process the kick voltage of the crab cavity reached to 1.67 MV, exceed the nominal operation voltage of 1.44 MV but found some weak points.

This crab cavity was sent back to assembling facility and copper bellows was changed to stainless steel bellows to increase the dynamic range of frequency tuning, and increase the strength of mechanical structure of the tuner to improve the response of feed back system. It took about 4 months to modified and reassemble the crab cavity. The crab cavity was high power tested again and the kick voltage reach to 1.8 MV. The dynamic range of the tuner increase up to about 100 kHz and phase stability was improved [11]. After we confirmed the performance of the crab cavity for HER, the assembling of the crab cavity for LER was started. The kick voltage of 1.93 MV could be attained, but cavity phase was fluctuate about 30degree. This fluctuation of the cavity phase could be cured by RF feed back system.

### COMMISSIONING OF KEKB CRAB

The crab cavities for HER and LER were installed in to the KEKB on January 2007. The cavities cooled down and kick voltage of 1.5 and 1.43 MV were obtained for crab cavities for HER and LER respectively. The beam operation with crab crossing was started on February 13. The kick voltage of the crab cavities were measured

directly by the measurement of the orbit change of the beam kicked by the crab cavity. Agreement between the estimation and the measurement value was good [12].

### SUMMARY

After more than 10 years of R&D efforts, we could construct the KEKB superconducting crab cavity. The crab cavities for HER and LER were installed in the KEKB after long delay of the construction schedule. Effective head on collision of electron and positron has been achieved successfully for the first time. The crab cavities are operating stably for more than 1 year under high current operation condition. These results show the potential of the crab cavities.

### ACKNOWLEDGEMENT

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