CRAB CAVITY DEVELOPMENT

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Abstract

The high luminosity KEKB electron positron collider adopted the finite angle crossing scheme. In this crossing scheme non-overlapping of the beam bunches at collision point causes beam instability and limit the luminosity. The complete overlapping of the electron and positron bunches at colliding point, so-called crab crossing, can be attained by superconducting RF crab cavities. After R&D study of 1/3 scale niobium model cavities to establish the fabrication techniques two full size niobium 509MHz cavities have been fabricated and cold tested so far. The surface peak electric field E_{sp} exceeded the design value of E_{sp} = 21 MV/m and reached to 38 MV/m with Q_0 values is higher than 10^9. In parallel with fabrication of the crab cavities we have started design and fabrication of the horizontal cryostats. A prototype horizontal cryostat is now under construction in KEK.

The fabrication of two crab cavities and cryostats have been started in 2004 and these crab cavities will be installed into Nikko straight section of the KEKB ring in February of 2006 for beam test.

INTRODUCTION

The electron positron collider KEKB [1] is operating at KEK at the highest luminosity in the world [2]. The layout of the KEKB is shown in Fig. 1 and its selected parameters are listed Table 1. The KEKB 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.

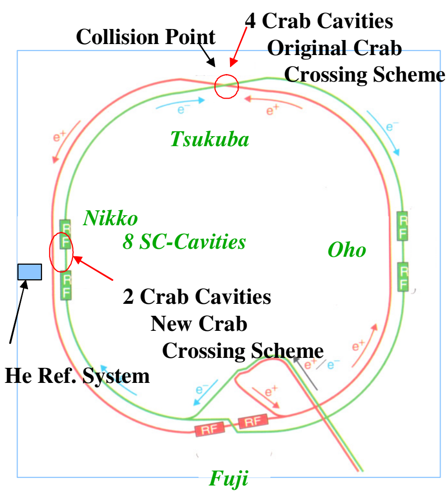

Figure 1: Layout of KEKB.

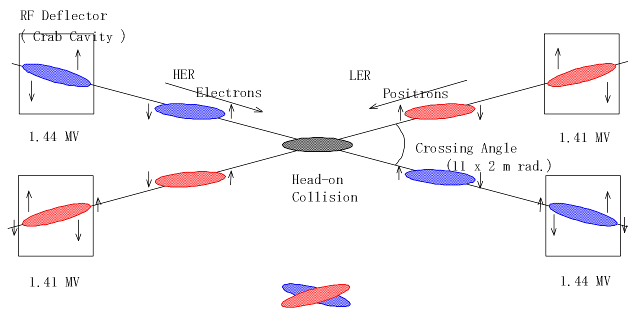

Figure 2: Crab crossing scheme for KEKB (original).

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 [3], K.Oide and K.Yokoya [4] to cure this instability.

Figure 2 shows the concept of the original KEKB crab crossing scheme. Strong time-depending electro-magnetic field in a superconducting crab cavity installed near to the collision point is used to kick the heads and the tails of the bunches in opposite directions with no kick in the centre and can make the bunches to start oscillation. Complete overlapping of bunches of electron and positron, so-called crab crossing, can be attained at colliding point. After the collision the beam bunches are kick back to original direction by another crab cavities. We need four crab cavities in total and a new cryogenic system with a large cooling power must be constructed in Tsukuba area.

A new crab crossing scheme, two crab cavities are installed, one in HER and other in LER, in Nikko straight section, has been proposed to reduce the construction cost. We can use the existing cryogenic system [5] which was constructed for TRISTAN superconducting cavity and is operating for KEKB superconducting acceleration cavity [6]. In the new crab crossing scheme the electron and the positron bunches, kecked by the crab cavities at Nikko straight section, wiggle around the whole ring and make crab crossing at collision point in Tsukuba.

Table 1: Main parameters of KEKB.

	Beam Energy	Beam Current
LER (positron)	3.5 GeV	1.8 A
HER (electron)	8.0 GeV	1.3 A
RF frequency	508.9 MHz	
Crossing Angle	11 m rad. x 2	

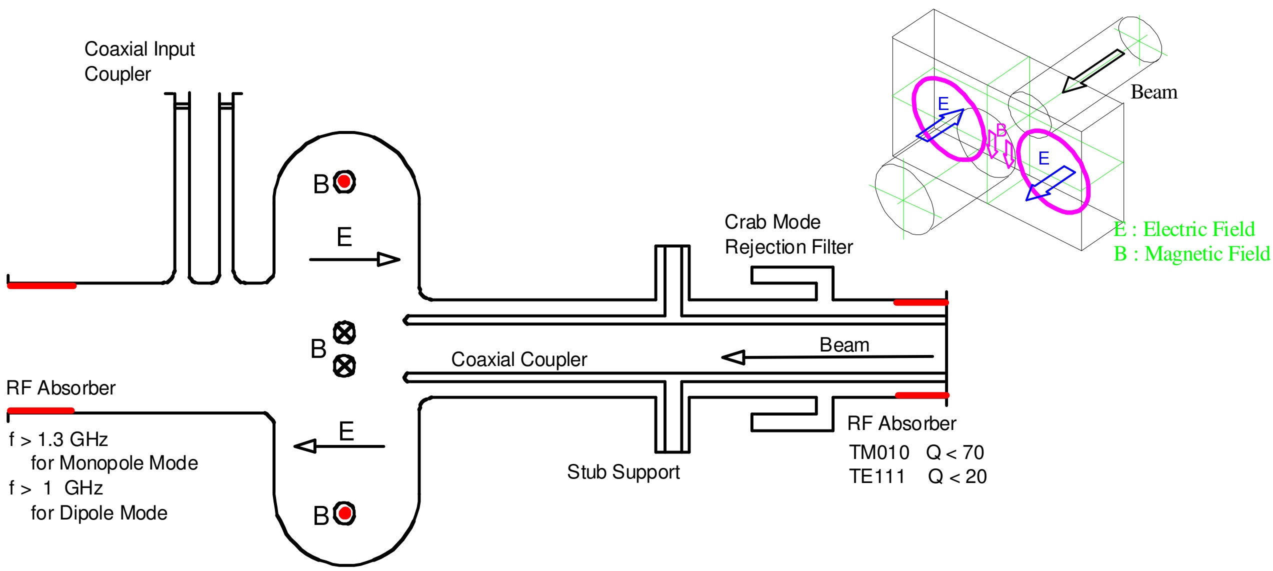

Figure 3: Conceptual design of the KEKB crab cavity (Top view) and schematic drawing of squashed cell shape cavity is shown upper right.

KEKB CRAB CAVITY

R&D History of KEKB Crab Cavity

The R&D study of the KEKB crab cavity has been started at KEK in 1995. At the first stage of the R&D, three 1/3 scale model niobium cavities with resonance frequency of 1.5 GHz were designed and fabricated to establish the fabrication techniques, including forming the cell, assembling the cavity with electro-beam welding and electro-polishing of no-axial symmetric cavity [7]. Then we started design and fabrication of full size 500 MHz crab cavities. Two full size prototype niobium crab cavities have been fabricated and cold tested successfully so far [8].

In parallel with fabrication of the crab cavities we have started the design and the fabrication of the coaxial coupler and horizontal cryostats.

In 2004 we have decided to install two crab cavities into Nikko straight section of the KEKB ring to increase the luminosity and ordered two crab cavities from Mitsubish Heavy Industry Ltd. The forming of the cavity cells and fabrication of the beam pipes have been finished, and assembling and electro-polishing of the cavities will start soon, the cold tests in vertical cryostat will be scheduled in October of 2005. In parallel with fabrication of the crab cavities we have started design and fabrication of niobium coaxial coupler and the horizontal cryostats.

RF Characteristics of Crab Cavity

Figure 3 shows conceptual design of the KEKB crab cavity. The magnetic field of the TM_{110} mode with the resonance frequency of 508.9MHz 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 inserted into the cavity cell is used to extract the lowest 430MHz TM_{010} acceleration mode and the higher TE mode outside the cavity.

This crab cavity scheme was proposed and studied extensively by K. Akai [9] at Cornell University under KEK and Cornell collaboration program. We have decided to choose this crab cavity scheme as the base line design of the KEKB crab cavity. Selected parameters of the KEKB superconducting crab cavities are listed in Table 2.

Mechanical design and fabrication of the crab cavity is difficult due to its large size and non-axially symmetric shape, and the head part of the coaxial coupler must be in super-conducing state and set accurately on beam axis to prevent coupling with the crab TM_{110} mode and propagate out to RF absorber by TEM mode.

Table 2: Selected parameters of KEKB crab cavity.

R / Q	46.7 Ω
Γ	220
Esp / Vkick	14.4 MV / m / MV
Hsp / Vkick	415 Oe / MV

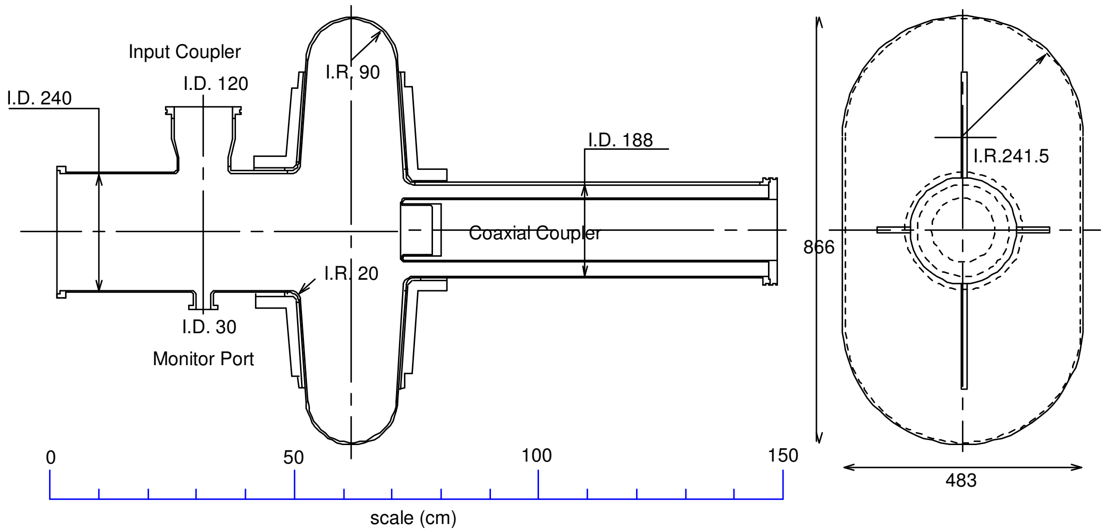

Figure 4: KEKB crab cavity with a model coaxial coupler.

The long coaxial coupler is made from niobium and supported at the midpoint by stub structure which provides mechanical support and the access port of liquid helium for cooling. A notch filter set in the end of coaxial coupler rejects the crab mode flow out from the cavity. Higher order modes induced in the cavity by high current beam bunch are extracted through the large beam pipe and the coaxial coupler and damped at RF absorbers outside the cavity.

Mechanical Characteristics of Crab Cavity

The design of the KEKB superconducting crab cavity is shown in Fig. 4. The cavity is large in size, about 1m by 0.5m of cross section, because higher excitation mode of TM_{110} is used for crab kick. 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. A model coaxial coupler is also shown in Fig. 4. This coaxial coupler made from niobium was used to check the performance of the crab cavity with coaxial coupler, especially to investigate multipacting phenomena under the cold test in vertical cryostat. The multipacting phenomena caused by the insertion of the coaxial coupler will be discussed later.

Fabrication of Crab Cavity

A half cell of the crab cavity was hydro-formed from 5mm thick niobium sheet with RRR 200 purchased from Tokyo-Denkai Ltd. Inner surface of the half cells were buff polished, the welding part was trimmed by machining, and a full cell was assembled by electron beam welding. The rough surface of welding part along the equator line was made smooth by using specially designed grinding machine developed at KEK. Inner surface of the crab cavity, especially welding part of equator, was barrel polished about 400 µm. The inner surface was electro-polished about 100 µm using the rotary type electro-polishing machine with straight shape cathode made of pure aluminium pipe, and then high pressure 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 electro-polished again to remove surface layer slightly about a few µm and then carried out high pressure rinsing 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 next 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 cooling test. After assembled into the test set up, the crab cavity was baked for about 1 day at 100ºC, and set into the vertical cryostat (1.1m in diameter and 3.5m in height). The cavity was cooling down from room temperature to 150 K under cooling speed of about 17 K per hour to prevent vacuum leakage and then quickly cool down to liquid helium temperature in about 1 hour.

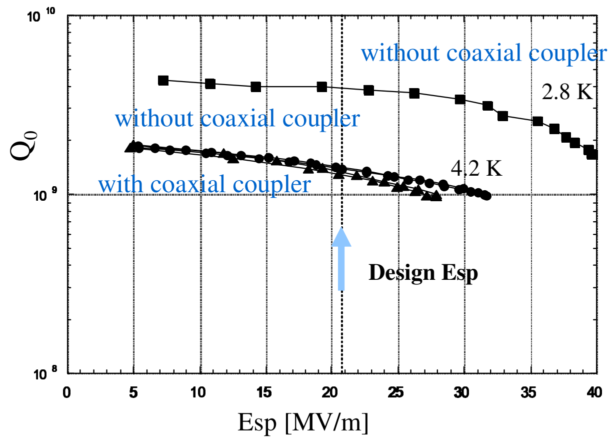

Figure 5: Measured Q_0 of KEKB crab cavity #1 without and with coaxial coupler.

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 simplified niobium coaxial coupler.

Without coaxial coupler, E_{sp} of the cavity #1 reached to 30MV/m keeping Q_0 values higher than 10^9 at 4.2 K.

By lowering the bath temperature to 2.8 K by pumping, E_{sp} could reached to 40 MV/m.

The E_{sp} of the cavity with coaxial coupler could exceed the design value of E_{sp} = 21 MV/m and reach 27 MV/m.

Multipacting in Crab Cavity

During the first cold RF test with coaxial coupler very strong multipacting was observed [10] at very low RF field. This multipacting could be overcome by about 1 hour long RF processing. We kept this processed cavity cold at 4.2 K for a few days and carried out the RF test again, in this case we could not observe the multipacting. In the cold RF test without coaxial coupler we did not observed multipacting.

Crab Cavity #2

The full scale crab cavity #2 was fabricated to check the reproducibility of fabrication and surface treatment methods developed at the crab cavity #1. Figure 6 shows the Q_0 values of the KEB crab cavity #2. The cold RF test results without coaxial coupler are satisfactory and almost same to the crab cavity #1 as shown in Fig. 5. After the cold test this cavity was disassembled and replaced by the new flanges, so called transition flanges, for further installation into horizontal cryostat and then carried out cold test in vertical cryostat. The measured Q_0 values was very bad and start deteriorate at E_{sp}= 12 MV/m accompanied by outbreak of X-ray emission.

We have concluded that the degradation was caused by micro-particles introduced into the cavity during

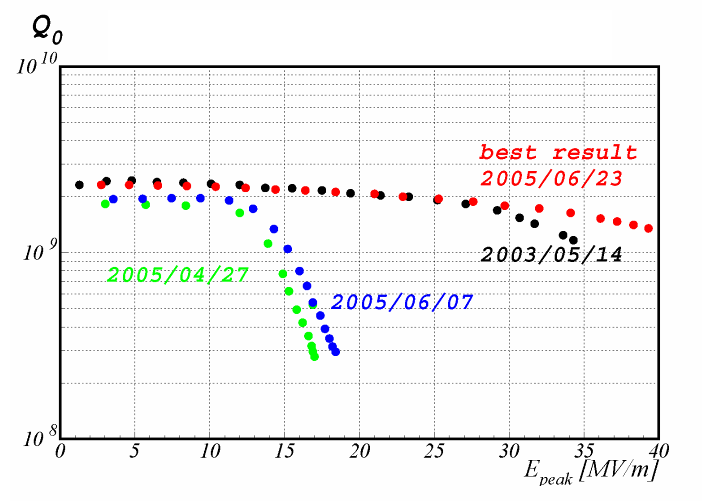

Figure 6: Measured Q_0 of KEKB crab cavity #2.

disassemble and assemble the flanges. We carried out the high pressure rinsing with ultra pure water to remove micro-particles. Figure 7 shows the crab cavity #2 with transition flange under high pressure rinsing. The RF performance was recovered and E_{sp} reached to about 38 MV/m with Q_0 is higher than 10^9.

Figure 7: High pressure rinsing; KEKB crab cavity #2 with transition flange under high pressure rinsing.

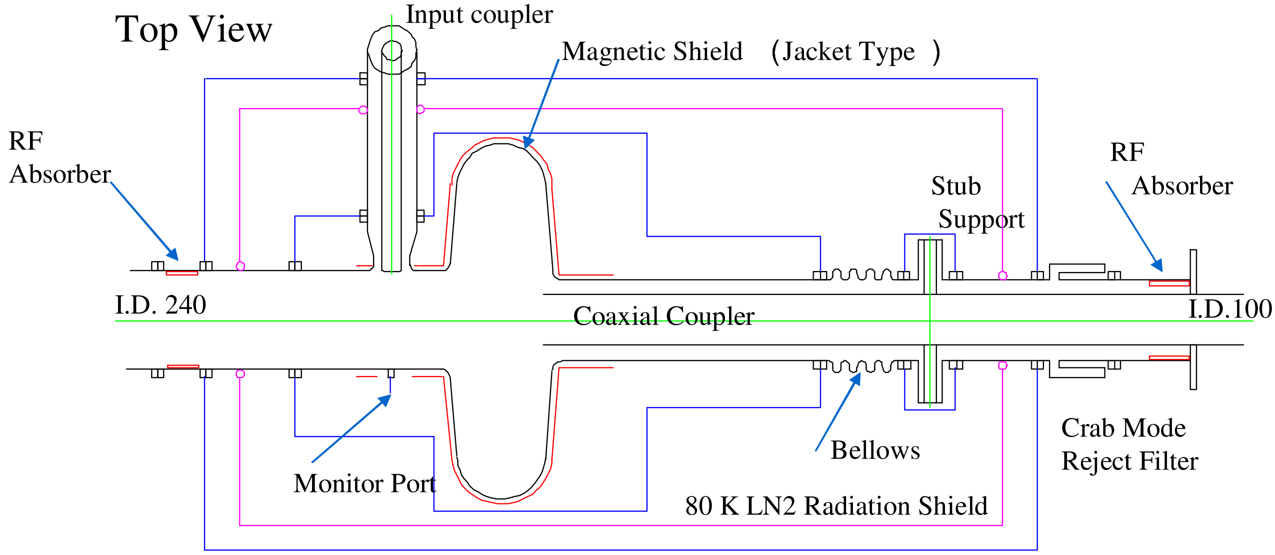

Figure 8: Conceptual design of the KEKB crab cavity in the horizontal cryostat.

CRYOSTAT FOR CRAB CAVITY

Jacket Type Helium Vessels

Figure 8 shows the conceptual design of KEKB crab cavity in the horizontal cryostat. 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 and to install into the limited space of the tunnel. The jacket type cryostat has a big advantage to be able to make the cavity clean by high pressure rinsing after jacketing the cavity.

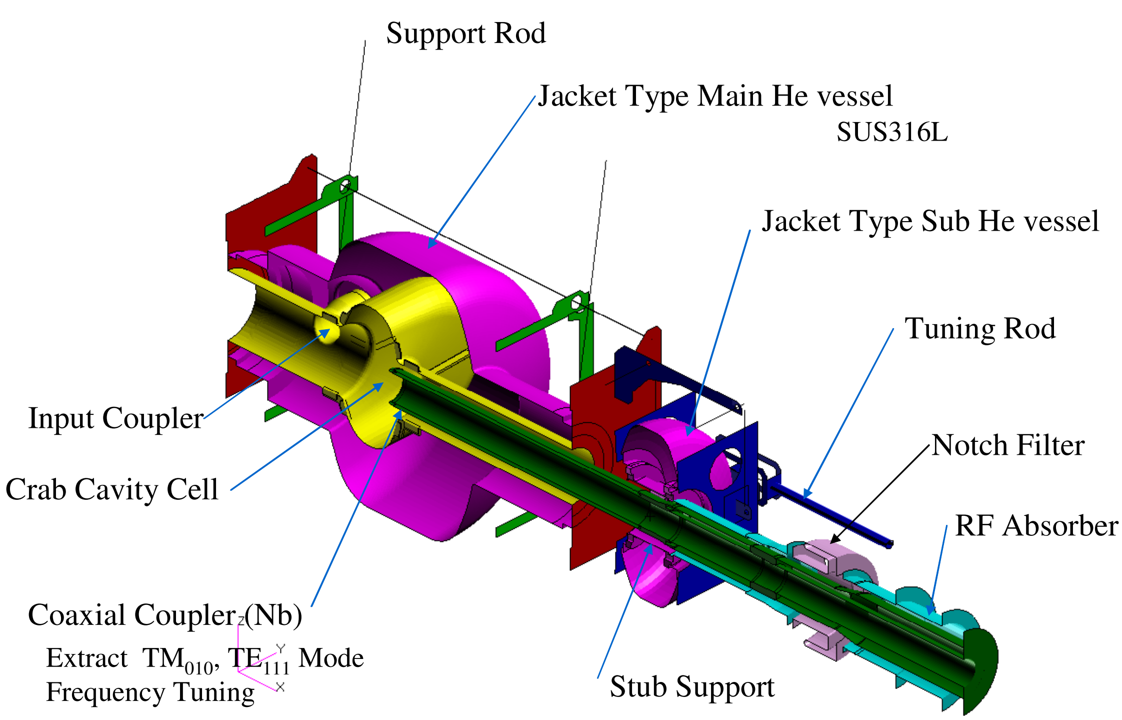

Figure 9: Configuration of the crab cavity in jacket type helium vessels and stub structure.

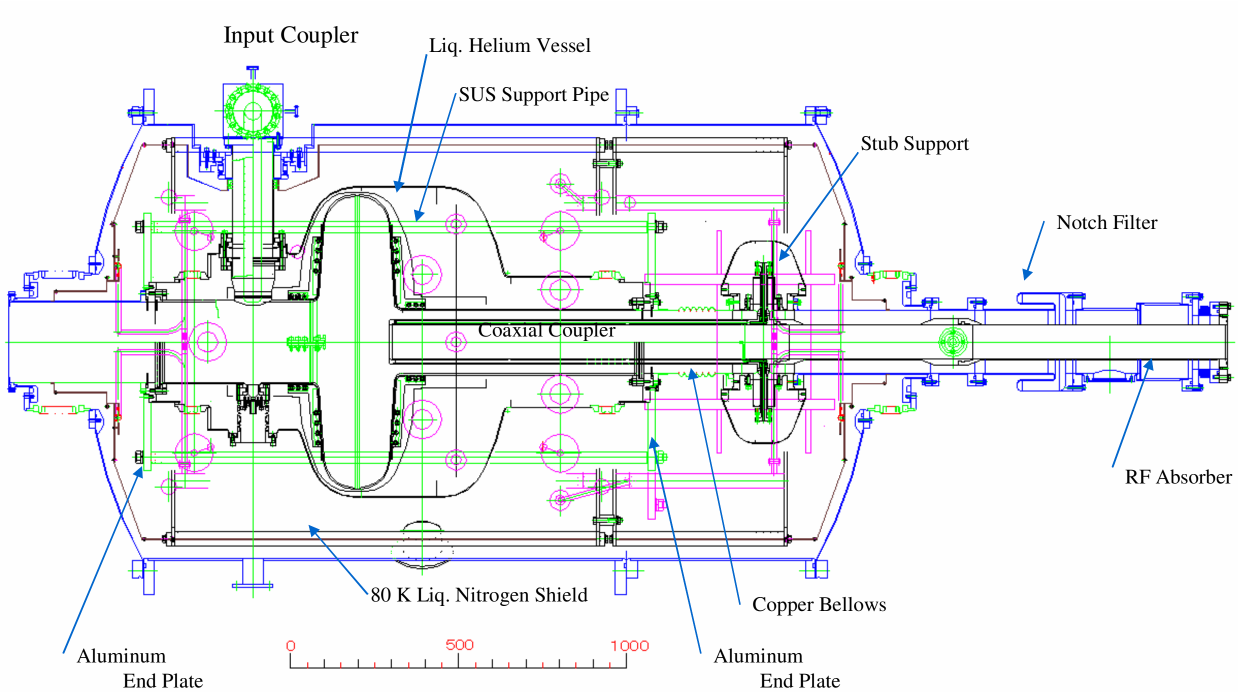

Figure 10: Detailed design of the KEKB crab cavity (Top view).

Coaxial Coupler

A coaxial coupler installed into cavity cell along beam axis is supported horizontally at the mid point by the stub supports to prevent vibration. The stub supports are also used for cooling the coaxial coupler, i.e. access ports to supply liquid helium and recover return gas. 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 bellows.

Frequency Tuner

The coaxial coupler is also used for frequency tuner. The resonance frequency of the crab mode is controlled by adjusting the insertion depth of coaxial coupler to the cavity cell. The head position of the coaxial coupler is controlled by two driving rods connected to stub support horizontally in parallel. The sensitivity of the resonance frequency against the position is 38 kHz/mm. The rods are driven by Piezo and motor drive mechanical actuators set outside the cryostat.

The axis of the coaxial coupler must precisely coincide with and cell axis to prevent coupling to the crab mode through TEM mode. The position of the axis of coaxial coupler can adjust by changing the relative length of the driving rods.

Jacket Type Magnetic Shield

A jacket type magnetic shield, tight fitted to the cavity in the helium jacket, is used for KEKB crab cavity because it is difficult to shield the magnet field penetrated from both end of large crab cavity by using the simple cylindrical shape. Two half cell shape jackets made form 3 mm tick permalloy are put on the crab cavity and assembled into the full cell shape by screws.

Cryostat Design of KEKB Crab Cavity

Figure 10 shows the detailed drawing of the jacket type cryostat for KEKB crab cavity. The helium vessels are thermally guarded by aluminium 80 K radiation shield cooled by liquid nitrogen, and beam pipes are thermally anchored to 80 K radiation shield to reduce the static heat loss to helium vessel lower to 15 W. The helium vessel and the 80 K thermal shield are lapped by 30 layers aluminized multi-layer insulator.

Input Coupler

An antenna type input coupler is connected horizontally to large beam pipe 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.

RF Damper

Ferrite type RF absorbers, 240 mm in inner diameter and absorbing power of 10 kW, are set at large beam pipe and the end part of the coaxial coupler outside the cryostat, to damp the higher modes and the lowest mode.

Transition Flange

In our jacket type cryostat design, we use so called "transition flanges" at beam pipes and input coupler ports, to connect the cavity and the helium vessel. The transition flanges made from stainless steel are connected to the niobium cavity using indium seal and then the cavity is assembled into the jacketed form by welding. U-tight seal are used to assemble the jacketed cavity into the cryo-module.

Prototype Cryostat

Before construction of two horizontal cryostats for the KEKB crab cavities, which will be installed in the KEKB ring for beam operation, we have decided to construct a prototype cryostat to establish fabrication and assembling techniques of complicated jacket type cryostat, especially forming the cell shape with wall thickness of 2 mm stainless steel helium vessel and jacketing it on crab cavity. This prototype cryostat will also be used for test stand of the crab cavity R&D in future, especially for the development of new coaxial coupler. The cryostat is now under construct at KEK. Figure 13 shows the complete vacuum vessel.

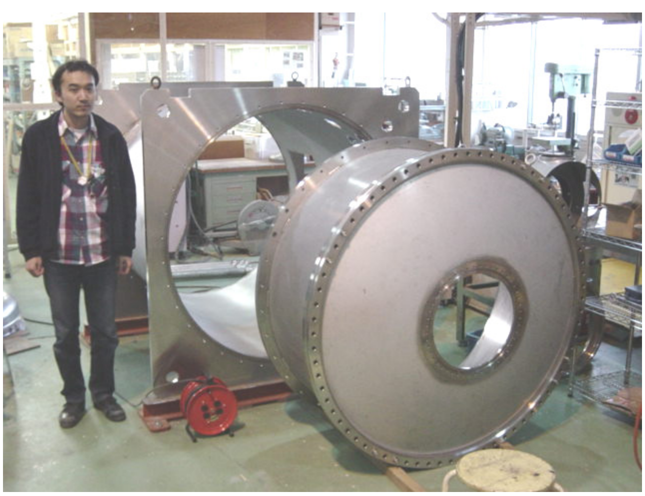

Figure 13: Vacuum vessel for KEKB crab cavity.

SUMMARY

After about 10 years of R&D efforts, we could establish the fabrication techniques of the KEKB crab cavity and its cryostat. The E_{sp} of the cavity with coaxial coupler could exceed the design value of E_{sp} = 21 MV/m which corresponds to the kick voltage of 1.44 MV and reach to 27 MV/m.

We have decided installation of the two crab cavities into KEKB ring in 2004. We have ordered two niobium cavities from Mitsubish Heavy Industry Ltd. in 2004. The fabrication of the cavities and cryostats is now underway on schedule. These crab cavities will be installed into Nikko straight section of the KEKB ring in February of 2006 for beam test.

SUMMARY

The authors wish to express their gratitude to Professors, K. Oide, S. Kurokawa, Y. Kamiya and Y. Totsuka for their continuous support. Thanks are also due to the member of KEKB upgrading group for their devoted and useful suggestions and comments.

REFERENCES

[1] KEKB B-Factory Design Report, KEK Report 957, June 1995.

[2] KEKB B-factory, July 2003-July 2004, KEK Annual Report http://www-acc.kek.jp/KEKB

[3] R. B. Palmer, SLAC-PUB-4707,1988

[4] K. Oide and K. Yokoya, SLAC-PUB-4832, 1989

[5] K.Hosoyama et al, "Design and performance of KEKB superconducting cavities and its cryogenic system", Advances in Cryogenic Engineering, Vol. 43, p.123, Edited by P.Kittel, Plenum Press, New York, 1998

[6] T. Furuya et al, "Achievements of the superconducting damping cavities in KEKB accelerator", Proc. of the 11th Workshop on RF Superconductivity, Germany Sept. 2003

[7] K. Hosoyama et al, "Crab cavity for KEKB", Proc. of the 7th Workshop on RF superconductivity, p.547 (1998)

[8] H. Nakai et al, "Research and development program on superconducting crab cavities for KEKB" Proc. of the 11th Workshop on RF Superconductivity Germany, Sept. 2003

[9] K. Akai et al, Proc. IEEE Part. Accel. Conf. p.757 (1993)

[10] Y. Morita et al, "Multipacting in the crab cavity", Proc. of the 11th Workshop on RF Superconductivity Germany, Sept. 2003