CONSTRUCTION AND COMMISIONING OF KEKB SUPERCONDUCTING CRAB CAVITIES

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Abstract

The superconducting crab cavities for KEKB were constructed and installed into KEKB electron-positron collider in January 2007. After cool-down of the crab cavities, the commissioning of the crab cavities started in February 2007 and continued until end of June. Effective head on collision of electron and positron has been achieved successfully for the first time during this spring operation of the KEKB. A luminosity of above $10^{34}/cm^2/sec$ could be obtained at high beam currents operation (1.3A in the low energy positron and 0.7A in high energy electron).

INTRODUCTION

The electron positron collider KEKB [1] is operating at KEK in 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. 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.

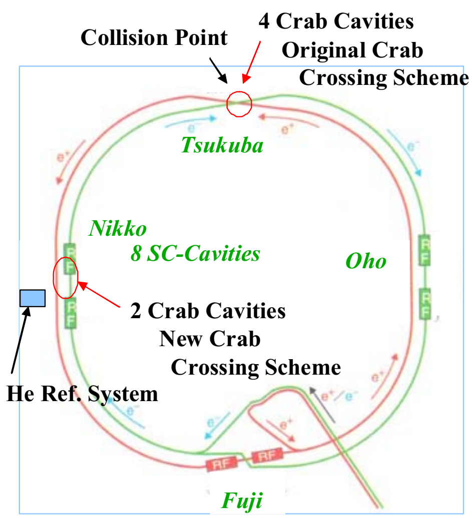

Figure 1: Layout of KEKB.

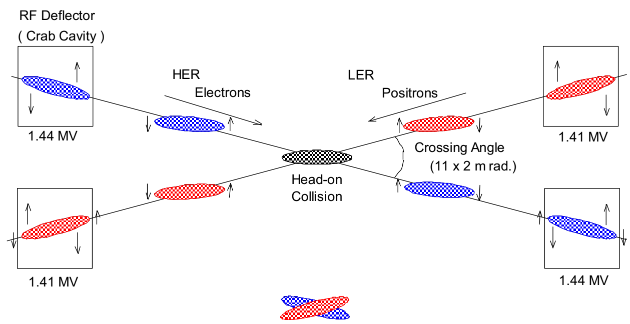

Figure 2: Crab crossing scheme for KEKB and non-crab crossing scheme case (lower).

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 opposite directions with no kick at 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 cooling power of more than 1kW must be constructed in Tsukuba area.

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

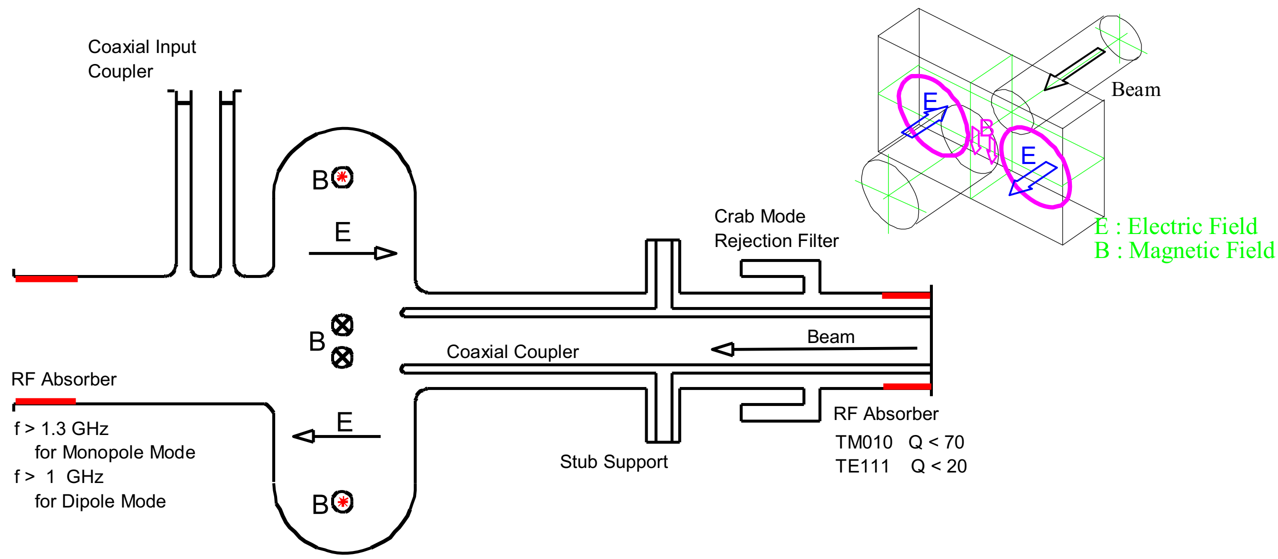

Figure 3: Conceptual design of the KEKB crab cavity (Top view) and schematic drawing of squashed cell shape cavity is shown upper right.

KEKB CRAB CAVITY

R&D History of KEKB Crab Cavity

The R&D study of the KEKB crab cavity was started at KEK in 1995. At the first stage of the R&D, three 1/3 scale 1.5 GHz model niobium cavities 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 were fabricated and cold tested successfully [8].

Installation of the two crab cavities into Nikko straight section of the KEKB ring was decided and fabrication of two crab cavities was started in 2004. In parallel with fabrication of the crab cavities designing and fabrication of niobium coaxial coupler and the horizontal cryostats were started.

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 from the cavity.

This crab cavity scheme was proposed and studied extensively by K. Akai [9] at Connell University under KEK and Connell 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 are very difficult due to large in size and non-axially symmetric in shape. Head part of the coaxial coupler must be set accurately in the center of the cavity to prevent the crab mode 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

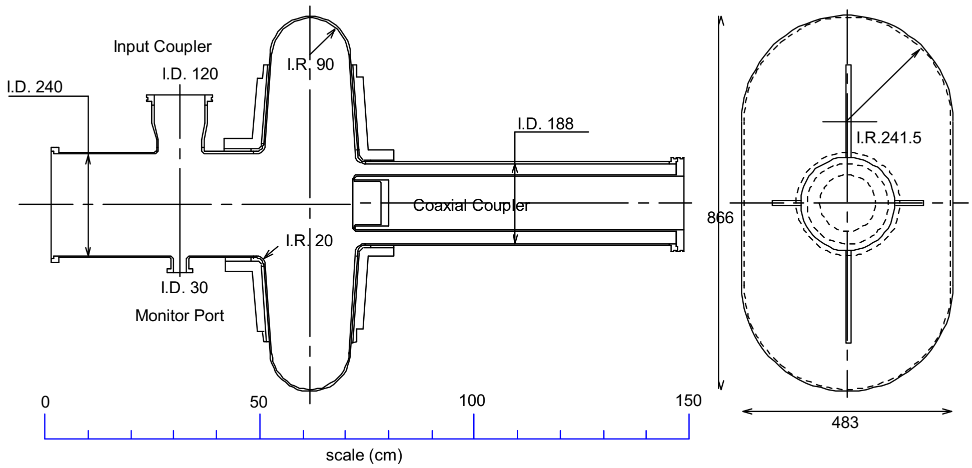

Figure 4: KEKB crab cavity with a model coaxial coupler.

A long niobium coaxial coupler is 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 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.

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. 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 simplified model coaxial coupler is inserted in the cavity as 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 multipactoring phenomena under the cold test in vertical cryostat.

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. The 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^{o}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, again to remove surface layer about a few μm and then carried out high pressure water rinsing about 1 hour. Figure 5 shows the crab cavity under high pressure rinsing

Figure 5: High pressure water rinsing.

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 cooling test. After assembled into the test set up, the crab cavity was baked for about 1 day at 100^{o}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.

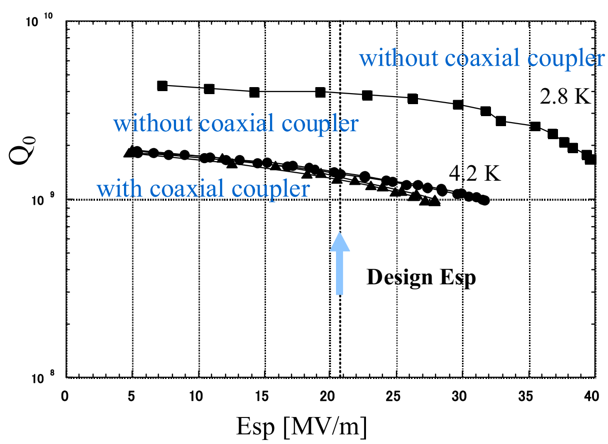

Figure 6: Measured Q_0 crab cavity #1 without and with coaxial coupler.

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 without 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

Multipactoring in Crab Cavity

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

KEKB Crab Cavity for HER & LER

The KEKB crab cavity 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 cold RF test results of the KEB crab cavity for LER. At the 1st test, the Q_0 values start deteriorate at about E_{sp}=15MV/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 tried to inspect the inside the cavity carefully and 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 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.

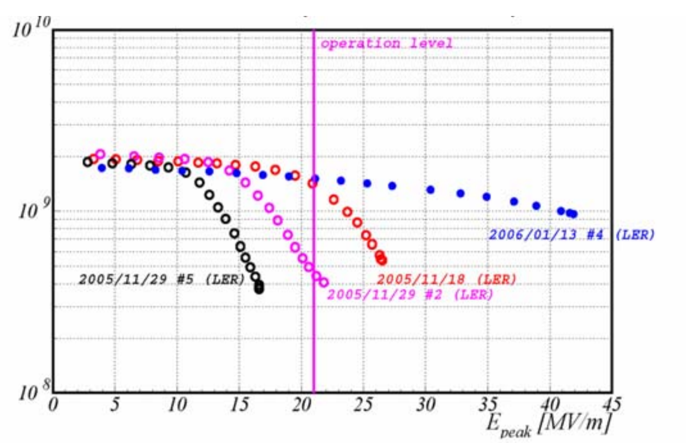

Figure 7: Measured Q_0 of KEKB crab cavity for LER.

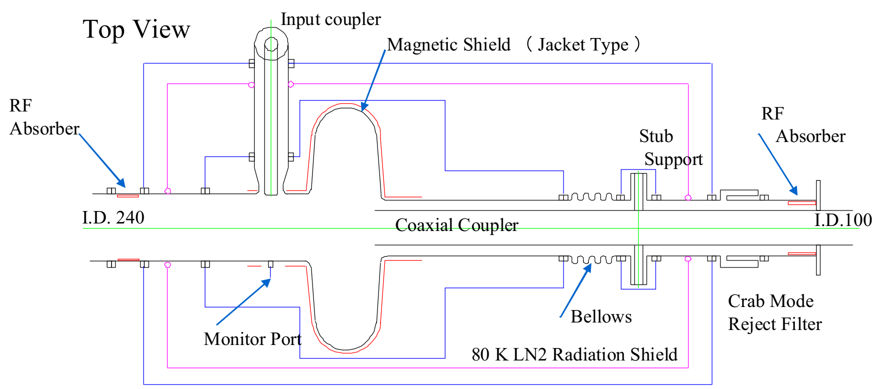

Figure 8: Conceptual design of the horizontal cryostat for KEKB crab cavity.

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.

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 38kHz/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.

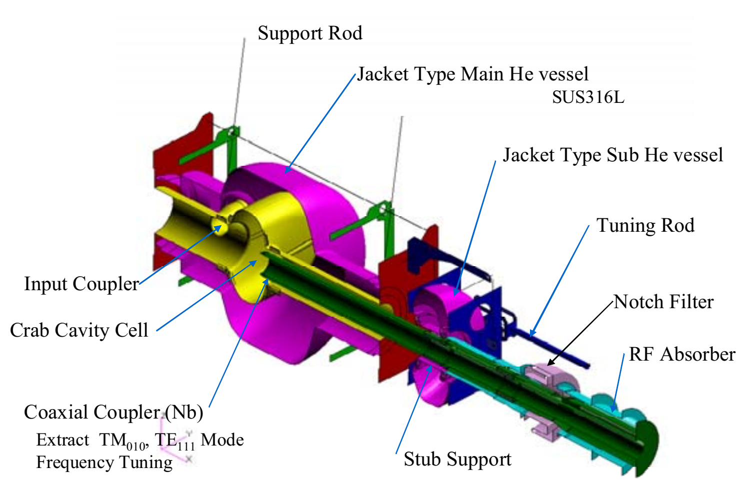

Figure 9: Configuration of the crab cavity in jacket type helium vessels and stub structure.

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.

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 10kW, 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.

ASSEMBLING & HIGH POWER TEST OF KEKB CRAB CAVITY

Assembling the cavity into Horizontal cryostat

In parallel with fabrication of the KEKB crab cavities, assembling of their cryostats progressed smoothly in the factory of Mitsubish Ltd. The cryostats were brought in KEK. And the final assembling of crab cavity for HER was started in March 2006 in KEK. The coaxial coupler could not connect to the crab cavity beam pipe which was installed in the cryostat due to poor assembling setup. By improving of its assembling tools we could finish the assembling of the crab cavity for HER in April 2006.

First Cool-down and High Power Test

The crab cavity was brought to test stand and installed in the pit of the test stand and cool-down of the cavity was started on May 29, it took about 1 week to ready for high power test. The whole system was cooled down without leakage and the control of liquid helium level in the helium vessel of the cryostat and cooling gas for coaxial coupler worked well. We keep the system cold about 1 month. After RF process kick voltage of the crab cavity reach to 1.67 MV exceed the nominal operation voltage of 1.44 MV.

During 1 month operation period of the crab cavity, we found following problems; 1) narrow dynamic range of frequency tuner, 2) slow response frequency tuner.

We decided to disassemble the cavity to improve the problems. The KEKB crab cavity for HER was sent back to assembling building and carried out following modifications; 1) the copper bellows which used for connection between cavity beam pipe and coaxial coupler was changed to stainless steel bellows with copper plating to increase the movable range. 2) Increase the strength of tuner driving structure. 3) The RF contacts were attached to the connection part of coaxial coupler to improve the RF connection. The cavity was assembled again after high pressure water rinsing. It took about 4 months to modified and reassemble crab cavity for HER.

The crab cavity was brought back to test stand and high power tested. We confirm the kick voltage of 1.8 MV. The dynamic range of the tuner increase up to about 100 kHz and phase stability was improved.

After confirm the performance of the crab cavity for HER was satisfactory. We started assembling of the crab cavity for LER into the cryostat. By the high power test 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.

Figure 10: KEKB crab cavity for HER installed in KEKB

COMMISSIONING OF KEKB CRAB

Installation and Beam commissioning of the KEKB crab cavities

The crab cavities for HER and LER were installed in to the KEKB on January 2007. Figure 10 shows the crab cavity for HER installed into the KEKB. Cool-down of the cavities was started on January 29 with cooling speed of about 3 K per hour. The cavities cooled down without trouble. RF operation of the cavities was started from February 9. The kick voltage of 1.5 and 1.43 MV were obtained for crab cavities for HER and LER respectively.

High current beam operation with crab cavities

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 very good. The tilt of the beam bunch was measured by streak camera to check the crab kick.

By adjusting the beam operation conditions of the KEKB, beam currents were increased to 1.2 A for LER and 0.67 A for HER with crab crossing and the peak luminosity of 10.5 x 10^{33}/ cm^2/s was obtained.

The beam currents were also increase up to 1.7A for LER and 1.35 A for HER under crab cavities were detuned. During this high current operation the HOM dampers which were attached to beam pipe and end part of coaxial coupler absorbed about 10 kW and 2kW respectively. Cooling system of the coaxial coupler worked very well during the high beam current operation. This looks like very promising for further high current future operation.

During operation, the crab cavities were tripped by the sudden degradation of vacuum at input coupler and cavity. This was caused by release of the gas condensed on cold surface of the cavity and coupler part. The trip rate could be reduced by warm up the cavity up to 80K and remove the condensed gas.

SUMMRY

After more than 10 years of R&D efforts, we could establish the fabrication techniques of the KEKB crab cavity and the very complicated cryostat. The crab cavities for HER and LER were assembled into the cryostats and 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. A luminosity of above 10^{34}/cm^2/sec could be obtained at high beam currents operation (1.3A in the low energy positron and 0.7A in high energy electron). These results show the potential of the crab cavities and encourage the application of the crab cavities to other filed.

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