Development of the KEK-B Superconducting Crab Cavity

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Outline
- KEKB and Crab Crossing
- KEKB Crab Cavity Concept and R&D History
- Fabrication of Crab Cavities
- Cold Test in Vertical Cryostat
- Cryostat for Crab Cavities
- Coaxial Coupler
- Frequency Tuning
- Assembling of Crab Cavity into Cryostat
- High Power Test at Test Stand
- Installation & Commissioning of Crab Cavities
- Summary
Crab Cavities for KEKB

**KEKB**
- **LER** 3.5 GeV
- **HER** 8.0 GeV
- **RF freq.** 508.9 MHz
- **Cross. Ang.** 2 x 11 m rad.

**Collision Point**

**Mt. Tsukuba**
- **Photon Factory**
- **Tsukuba**
- **Nikko**
- **Helium Ref.**
- **1km**

**2 Crab Cavities**

**8 SC-Cavities**

**Oho**

**Fuji**
KEKB Crab Crossing

The crab crossing scheme allows a large crossing angle collision without introducing any synchrotron-betatron coupling resonances. 1, 2)

Original Crab Crossing Scheme

4 Crab cavities scheme    Local crab crossing scheme

Effect of Crab Crossing

(Simulation by Ohmi)

New Crab Crossing Scheme

2 Crab cavities scheme    Global crab crossing scheme

Beam-bunch wiggle around the whole ring!

Advantage: We can use existing cryogenic system for Acc. S.C. cavities

1) R.B.Palmer, SLAC-PUB-4707,1988
2) K.Oide and K.Yokoya, SLAC-PUB-4832,1989
The squashed cell shape cavity scheme was studied by Akai extensively at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell Univ. collaboration.

We adopted this design as “base design”!
KEKB Superconducting Crab Cavity

Mechanical and Fabrication Issues

- Non-axial Symmetric Structure
- Thickness of 4.5 mm Nb Cavity
- Reinforced by Ribs

No Rib

\[ \sigma_{\text{Max}} = 17.6 \text{ kgf/mm}^2 \]

4 - Rib

\[ \sigma_{\text{Max}} = 7.41 \text{ kgf/mm}^2 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>501.7 MHz</td>
</tr>
<tr>
<td>R / Q</td>
<td>46.7 ( \Omega )</td>
</tr>
<tr>
<td>G</td>
<td>220</td>
</tr>
<tr>
<td>Esp / Vkick</td>
<td>14.4 MV / m / MV</td>
</tr>
<tr>
<td>Hsp / Vkick</td>
<td>415 Oe / MV</td>
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# History of KEKB Crab Cavity

<table>
<thead>
<tr>
<th>0) 1/3 scale model 1.5 GHz</th>
<th>1994</th>
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<tbody>
<tr>
<td>3 Nb Cavities</td>
<td></td>
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<tr>
<td>Fabrication &amp; surface treatment of non-axial symmetric cavity</td>
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<table>
<thead>
<tr>
<th>1) Full Scale Prototype Crab Cavity 500MHz</th>
<th>1996</th>
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<tbody>
<tr>
<td>2 Nb Cavities # 1 &amp; # 2</td>
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<tr>
<td>Coaxial Coupler</td>
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<tr>
<td>Prototype Horizontal Cryostat</td>
<td>2003</td>
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<table>
<thead>
<tr>
<th>2) KEKB Crab Cavity 509MHz</th>
<th>2004</th>
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<tr>
<td>Installation of 2 crab cavities in KEKB was decided</td>
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<tr>
<td>2 Nb Cavities for LER, HER</td>
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<tr>
<td>Cold Tested in Vertical Cryostat</td>
<td>2005</td>
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<tr>
<td>Assembling and High power test</td>
<td>2006</td>
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<tr>
<td>Installation and Commissioning</td>
<td>2007</td>
</tr>
<tr>
<td>Jan. ~</td>
<td>1 year</td>
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</tbody>
</table>
## Construction of KEKB Crab Cavity

**collaboration with Industry & build up of infrastructure**

1) Fabrication of the crab cavities and coaxial coupler  
   - MHI

2) Surface treatment
   - Mechanical grinding
   - Cell equator welding part  
     - KEK/MHI
   - Barrel polishing  
     - KEK
   - Electro-Polishing  
     - Nomura Plating
   - Heat Treatment  
     - Kinzoku Giken
   - High pressure rinsing  
     - KEK
   - Clean room for assembling the crab cavity  
     - KEK

3) RF Measurement system at vertical cryostat  
   - KEK
   - Test Stand in vertical cryostat  
     - 1.5 GHz
     - 500 MHz

4) Horizontal cryostat
   - Design and assembling of prototype  
     - KEK/Koike/Hitachi Oxygen
   - Design and assembling of horizontal cryostat  
     - MHI
   - Clean Room for Installation of the crab cavity into cryostat  
     - KEK

5) Input coupler and HOM damper  
   - MHI/Kinzoku Giken

6) Design and construction of cryogenic system  
   - KEK/Hitachi

7) Test Stand for high power RF test  
   - KEK
Fabrication & Surface Treatment

Forming of Half-Cells

- Crab Cavity Cell
  - Nb Sheet
  - Tokyo Denkai
  - Hydro-forming
  - Mechanical Polishing & Trimming
  - Electron Beam Welding
  - Grinding of Welding Part
  - Cell Equator
  - Barrel Polishing ~ 100 µm
  - Electro-Polishing EP 1 ~ 100 µm
  - High Pressure Water Rinsing
  - Annealing 700 °C × 3 hr
  - Electro-Polishing EP 2 ~ 5 µm
  - High Pressure Water Rinsing 80 bar, 60 min.
  - Assembling for Cold Test
  - Cold Test in Vertical Cryo.

- Beam Pipe
  - Nb Sheet
  - Rolle
  - Barrel Polishing 312Hr

Electro Polishing
Annealing
Assembling
Grinding Machine

Crab cavity was assembled; full penetration, defocused electron beam welding. Inner surface of welding part along the equator of cell has line-like bump. By using grinding machine we must remove it!
Effect of High Pressure Rinsing

1/3 Scale Model
1.5 GHz

By breaking the vacuum and introducing air into the cavity, the $Q_0$ degrade and increase the radiation of X-ray. High pressure rinsing can recover the performance of the cavity.
Clean Room for Assembling Cavity and Cryostat

Clean Room (Class 100) for Cavity Assembling

High Pressure Pure Water Rinsing

Clean Room for Cryostat Assembling

HPS: Coaxial coupler

HPS: Jacketed crab cavity
Set Flanges of Beam Pipes and Ports in Class 100 Clean Room

High Pressure Water Rinsing by 80 bar Ultra-Pure water

Rotation & Up-Down Motion
Cold Test Stand for KEKB Crab Cavity

The crab cavity is taken out from clean room to install into the vertical cryostat.

He Refrigerator for KEKB superconducting Acc. cavities

Liq. He Dewar 12,000 L

Clean room

Vertical cryostat

Inner Dia. 1100 x 0.8 t
Depth 3500

Heat Loss ~ 3W
Test Result of KEKB Crab Cavity Prototype #1

Design Esp

Fabrication and Surface Treatment
RF Performance Test with a Coaxial Coupler Good!
Multipacting could be overcome by RF process.

Crab Cavity #2
Same Performance!
Multipacting in Crab Cavity with Coaxial Coupler
Test Result of KEKB Crab Cavity for LER

Test result could not satisfy the design value!
Back to EP II processing.
Inspection in the cavity

A Whisker Like Foreign Material was found at the heating spot!

Lint of Cotton Wiper?

Picture of electron microscope

Small Beam Pipe

Trace of Rib

Input Coupler Port

A Whisker Like Foreign Material was found at the heating spot!
Conceptual Cryostat Design for KEKB Crab Cavity

Characteristics

• Frequency Tuning   Coaxial Coupler   ~30 kHz / mm
• Stub-Support -- Mechanical Support & Cooling of Coaxial Coupler
• Jacket-type Helium Vessel (Main He Vessel and Sub He Vessel)
• Jacket-type Magnetic Shield

RF Absorber
~ 18 kW

I.D. 240

Input coupler

Magnetic Shield (Jacket Type)

RF Absorber
~ 8 kW

I.D. 100

Monitor Port

80 K LN2 Radiation Shield

Bellows

Main He Vessel

Crab Mode Reject Filter

Sub Liq. He Vesse

Stub Support

Frequency Tuning by Adjusting Distance

at LER 1.6 A
1300 bunch
Design and Fabrication of KEKB Crab Cavity Cryostat

- No design and construction examples
- Easy to assemble and disassemble under clean condition
- Compact and light weight for transportation
- Leak tight for long period operation stress free at In seal

Frequency tuning by coaxial coupler
Jacket type helium vessel
Main-Helium Vessel for Crab Cavity
Sub-Helium Vessel for Coaxial Coupler

Complex structure and challenging design

A prototype cryostat was designed, constructed and cold tested at KEK.
R&D efforts for important components
Bellows, End cell, Input coupler, HOM damper
Crab Cavity & Coaxial Coupler in Cryo-module

1) Crab Cavity is hanged by 4 invar support rods.
2) Coaxial coupler is hanged by 4 stainless rods which are supported by 2 support arms.
3) Head position of the coaxial coupler is controlled by 2 tuning rods.
4) Head of coaxial coupler is cooled by liq. helium supplied from stub support.
Cryostat for KEKB Crab Cavity

Total Weight ~5ton

Beam

Gate Valve

RF Damper

Input Coupler

5 m
Forming of Helium Vessel End Shell

<table>
<thead>
<tr>
<th>Vessel</th>
<th>φ</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Helium Vessel</td>
<td>920</td>
<td>2</td>
</tr>
<tr>
<td>Sub Helium Vessel</td>
<td>600</td>
<td>1.5</td>
</tr>
<tr>
<td>Cryostat Vacuum Vessel</td>
<td>1200</td>
<td>2</td>
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φ 920 x 2 t
Main helium vessel end shell

φ 600 x 1.5 t
Sub helium vessel end shell
Bellows

Pitch 17.9 mm  R = 3 mm  t = 0.4 mm

I.D. 188

Press Unit and Pressure Water Pump

Female Die and Outer Guide Pipe

To Increase the tuning range change to stainless steel with copper plating bellows!

Thickness  t = 0.3 mm
Assemble & Cold Test of Prototype Cryostat

1) Jacket Type Helium Vessel       to Check the Leak Tight
2) Input Coupler                   to Check Thermal Contraction
3) Without Coaxial Structure

Design and assembled in KEK

Leak at In-Seal of Beam Pipe Flange! Nov. 29, 2005

Disassemble and Reassemble

Cool Down Test OK! Feb. 6-10, 2006
What cause the Leakage?

Transition Flange
Niobium – SUS by Indium Seal
Beam Pipe Nb

Welding
SUS Jacket
SUS Transition Flange
Helicoflex

In - Seal

The tip of volt touched to the bottom!
Input Coupler for KEKB Crab Cavity

High Power Test Stand

Tw: 200kW
Sw: 100kW

Crab test coupler (05/06/09 ~ 05/06/13)

Cooling Water
RF Window

4.4 K 300 K

Cooling Water
HOM Damper     Ferrite RF Absorber

Same design used in KEKB Acc. SC cavity

Cavity   0.7 V/pC
Taper    0.04 V/pC
Damper   0.3 V/pC
Total:   1.04 V/pC
HOM power: 20.5 kW
(1.6 A, 1300-bunch)
Magnetic Shield (Jacket Type)

Permalloy 3t

Segmentation

Large Beam Part

Cell Part

Small Beam Part
Frequency Tuning Mechanism

Main Tuner:
- Frequency Tuning: ~30 kHz / mm

Sub Tuner:
- Adjust Position of Coaxial Coupler

Load Cells

Beam

RF Monitor

Bellows

Coaxial Coupler

Stub Support

Sub Liq. He Vessel

Main Liq. He Vessel

Driving Rod

Support Pipe

Driving Plate

Pick up Probe

Load Cells

Main Tuner:
- Mechanical + Piezo
- 6 mm + 200 mm

Cryostat Vacuum End Cell
Frequency Tuner

- Resonance frequency can be controlled by main tuner.
- Coaxial coupler position can be controlled by sub-tuner.

Frequency Tuner Crab Cavity for HER
Phase stability

Phase Stability by Mechanical Tuner

Phase Stability is improved by RF Feedback
Cooling System for KEKB Crab Cavity

- **Main He Vessel**
- **Sub He Vessel**
- **Liq. He In**
- **Gas He**
- **RF Monitor**
- **Bellows**
- **Notch Filter**
- **Control Valve**
- **RF Absorber**
- **Beam**
- **Coaxial Coupler**
- **Input Coupler**
- **Cooling Water**
- **Operation Pressure of Helium Vessel**: 1.15 bar
- **Compressor**: 1.05 bar
- **Δp = 0.1 bar**

**Cooling Water**

**Room Temperature Water Cooling**
- **Liq. Helium Cooling**
- **Cold Helium Gas Cooling**

**Input Coupler Inner, HOM Damp.**
- **Coaxial Coupler End**
- **Coaxial Coupler Head**
- **Input Coupler Outer, Bellows**

**Compressor Suction**
RF Contact

Type: Spiral
Material: BeCu
Spring Constant: 14kg/φ94mm (0.5kg/cm)
Assembling the Coaxial Coupler

- **Nb Inner Conductor of Coaxial Coupler**
- **Stub Support**
- **Inner Conductor of Stub Support**
- **Leak Check of Assembled Coaxial Coupler**
Insertion Setup for Coaxial Coupler

Notch Filter (~100kg)

Vacuum Pumping

Connect of inner conductor

Step 1  Insert
Step 2  Rotate Clockwise 30 degree
Assembling Coaxial Structure to Crab Cavity

- Inner conductor of the assembled coaxial coupler was high pressure rinsed.
- Head part of the coaxial coupler was installed into the cavity and assembled.
- Coaxial coupler was hung by 4 rods which were connected to 2 support arms.
Assembling Large Beam Pipe

Large beam pipe (HOM damper & taper chamber) was assembled to crab cavity.

Inside crab cavity
Coaxial coupler
Iris of crab cavity
Input coupler
Tapered copper pine
Move to Test Stand for Cool-down & High Power Test

April 26, 2006  1st
Oct. 16, 2006   2nd

Mt. Tsukuba

Crab cavity for HER

Dec. 6, 2006

Crab cavity for LER
Test Stand for Crab Cavity at D10 Station

Control System for RF Test

- High Power RF Station
- Cryogenic System

Acc. Cavity

Sub-transfer Line

Crab Cavity

HER
May 12 – June 16, 2006  1st Test
Oct. 24 – Nov. 17, 2006  2nd Test
LER

Improved the Problems

Sub-transfer Line

Improved the Problems
1st High Power Test for Crab Cavity HER

- Crab cavity for HER was cooled down without leakage.
- $V_{\text{kick}} = 1.67 \text{ MV}$, exceed the design value of $1.44 \text{ MV}$.
- Cavity and coaxial coupler was cooled stably during the high power test.

Cryogenic system worked very well.

Problems & Improvements (Disassemble & Re-assemble)

- Resonant frequency was lower than design value ($\sim 300\text{kHz}$)
  ➔ After cool down, the cavity was pre-tuned
- Narrow tuning range
  Main tuner & Sub tuner
  ➔ Change to thin stainless bellows with copper plating
- Tuner feedback stability is not good
  ➔ Reinforce the tuning structure
- RF contact at the joint part of the coaxial coupler: for high current operation
High Power Test for Crab Cavity HER & LER

Crab Cavity HER

Second Horizontal Test for HER Crab Cavity at 4K

- Input Power: 120kW
- $V_{kick}$: 1.80MV
- Vacuum
- Temperature

Crab Cavity LER

First Horizontal Test for LER Crab Cavity at 4K

- Input Power: 55kW
- $V_{kick}$: 1.93MV
- Vacuum
- Temperature
**Q_0-Measurement**

During high power test at test stand Q_0 were measured by calorimetric method.
Installation & Commissioning of Crab Cavities

Installation of Crab Cavities
for HER Jan. 8, 2007,
for LER Jan. 11, 2007

Carrying the crab cavity using crane track

Crab Cavity for HER

Cool-down of Crab Cavities
Jan. 29, 2007

Vkick = 1.5 MV for LER
Vkick = 1.6 MV for HER

Beam Operation Start
Feb. 13

Crab Cavity for LER
SUMMARY

• After R&D efforts of 1.5 GHz and 500MHz crab cavities: We have constructed facilities for assembling of the cavities & cold RF test.

• 2 KEKB crab cavities have been constructed and installed in KEKB.

• The crab cavities are operating more than 1 year without serious problems.

  Kick voltage of crab cavity LER has decreased to \( V_{\text{kick}} = 1.1 \text{ MV} \)

• \( L_{\text{peak}} = 15 \times 10^{33} \text{ /cm}^2/\text{s} \) attained under crab on operation.

• Potential of superconducting crab cavity could be shown!