SC cavity design and production

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KEK

SC cavity design and production

- Crab cavity design for KEKB
- Crab cavity production and assembly
- High power tests

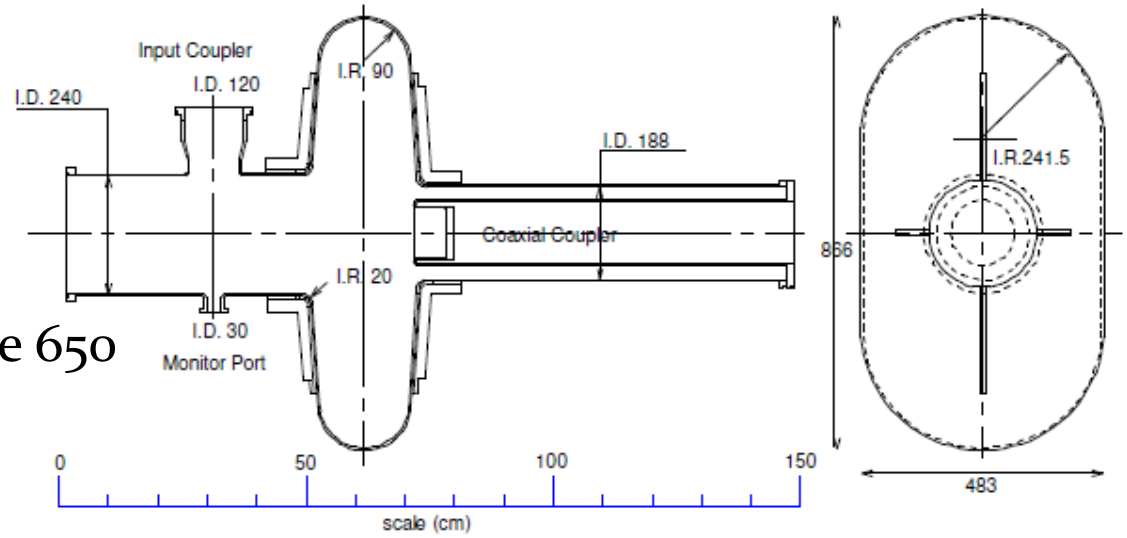
Requirements for KEKB Crab cavity

- Original two crab scheme
  - Two crab cavities in one ring
- High kick voltage: 1.4MV
- Heavily damped cavity
  - Q of FM~100
- Superconducting cavity designed for KEKB
  - Operating frequency: 509 MHz
  - Operating temperature: 4.4K
  - Using the existing cryogenic system and HP stations

	LER	HER
Beam energy (GeV)	3.5	8.0
RF frequency (MHz)	508.887	
Crossing angle (mrad)	±11	
βx,IP (m)	0.33	0.33
βx,Crab (m)	20	100
Kick voltage (MV)	1.41	1.44

Cell type

- Pill box type
  - Squashed cell
    - 866mm x 483mm
    - Separate SOM above 650 MHz
  - Coaxial coupler
    - OD: 130 mm, ID: 100 mm
    - BP diameter: 188 mm
    - Damp FM, SOM, HOMs
    - fc of TE11: 600MHz
  - Beam pipe
    - Diameter: 240 mm

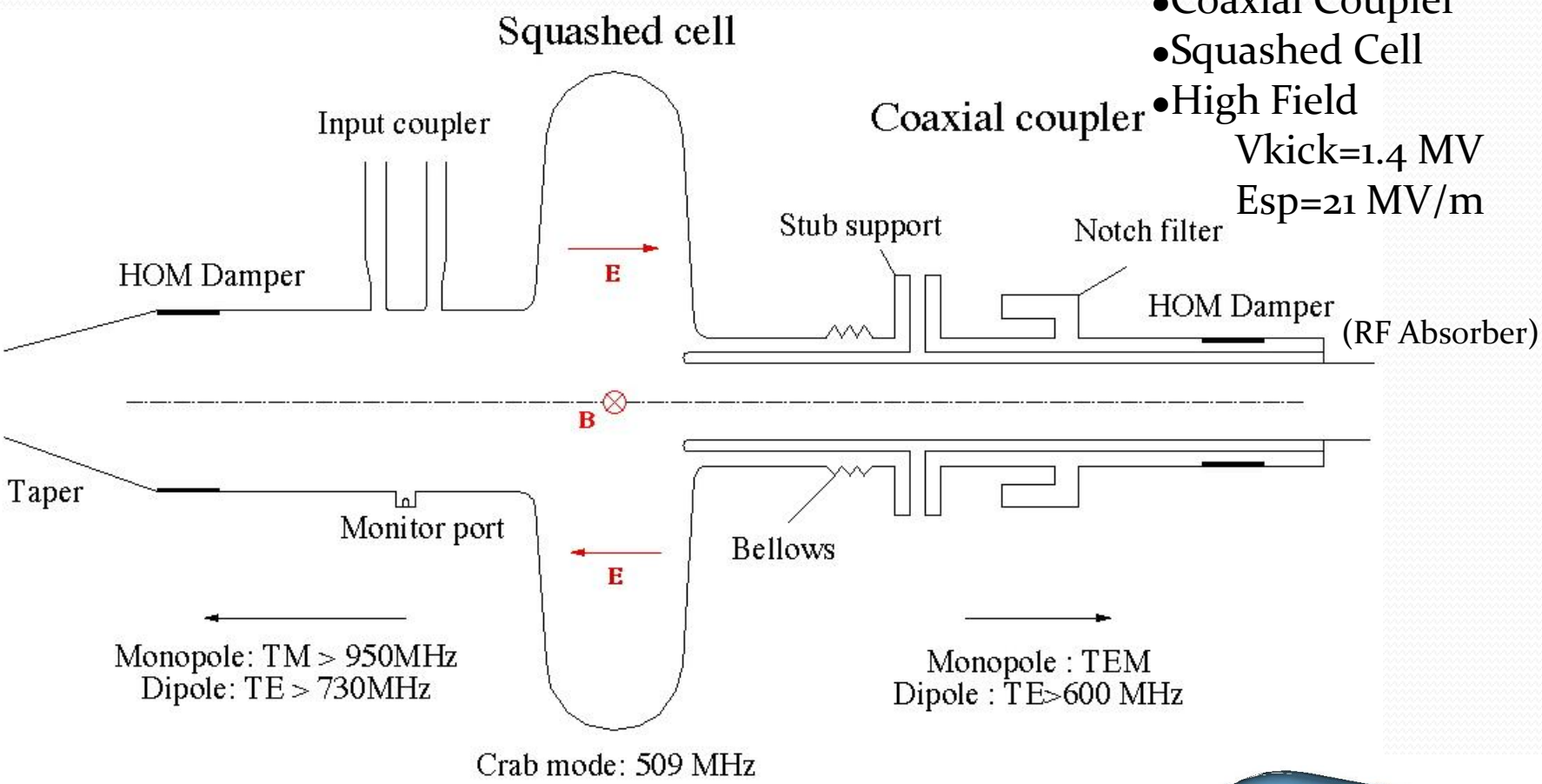


Frequency: 509 MHz

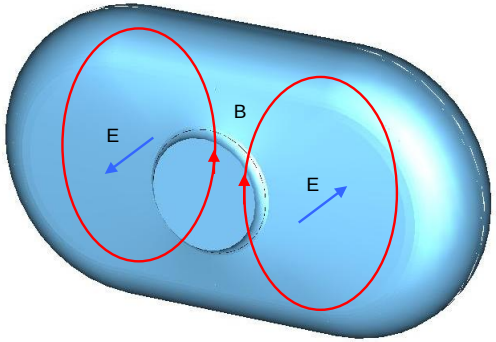
R / Q	46.7 Ω
Γ	220
Esp / Vkick	14.4 MV / m / MV
Hsp/ Vkick	415 Oe / MV

Conceptual design for KEKB

K. Akai
Unique characteristics
- Coaxial Coupler
- Squashed Cell
- High Field
  Vkick=1.4 MV
  Esp=21 MV/m



Crab Mode: TM210-like mode (R/Q:46)
Squashed cell: SOM, 682 MHz > fc of TE11, 600 MHz
Coaxial coupler
Notch filter: TEM-coupled Crab mode rejection when misaligned
Stub support: support for inner conductor and channel for he cooling
Bellows: coaxial coupler alignment
HOM damper: RF absorber

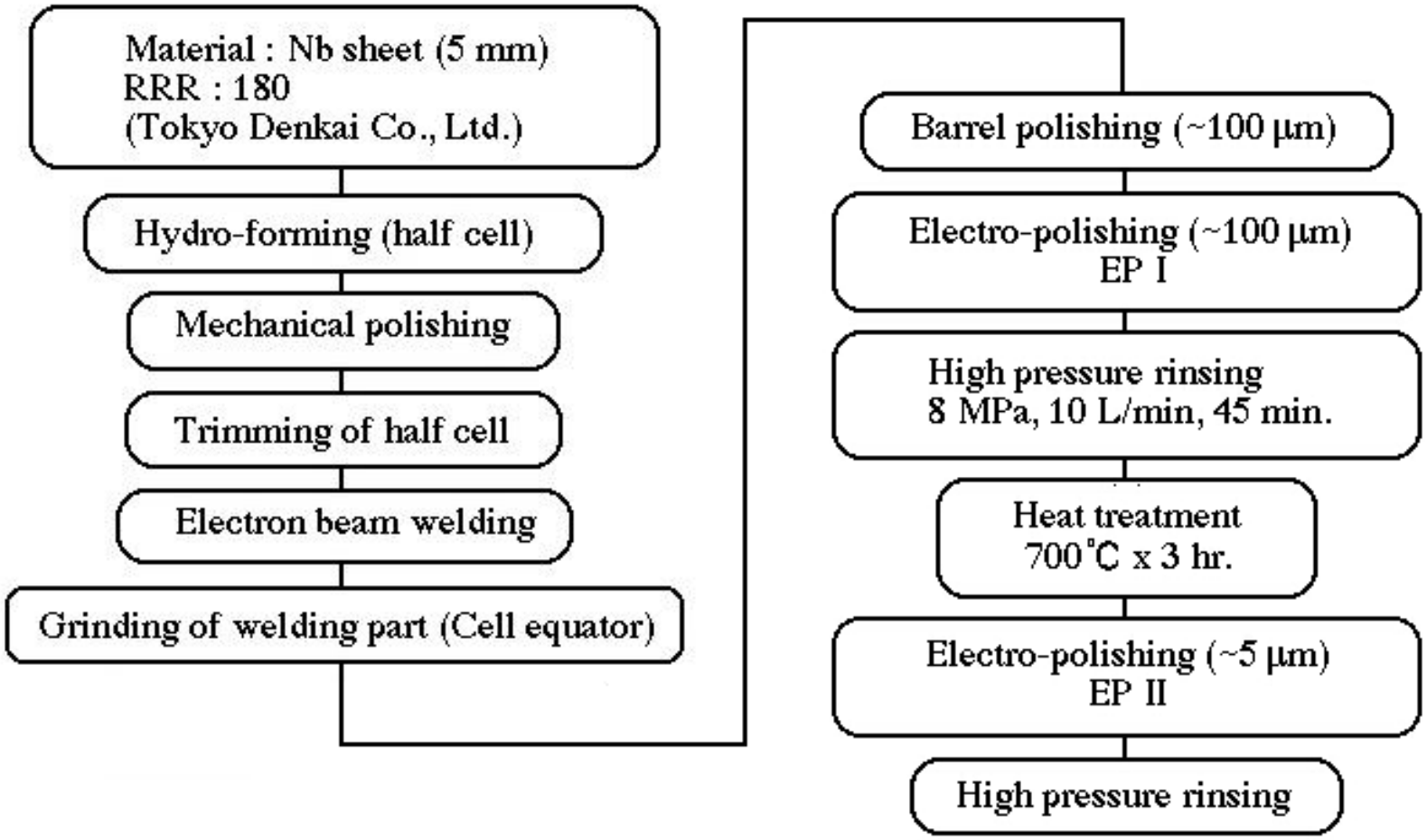


R&D

- 1994 1/3-scale models
- 1996 Full-scale prototype cavities
  - To establish fabrication method for the squashed cell structure
  - To establish surface treatments for high fields
  - Fabricated a model coaxial coupler to study its effect on the cavity performance and multipacting in the coaxial structure

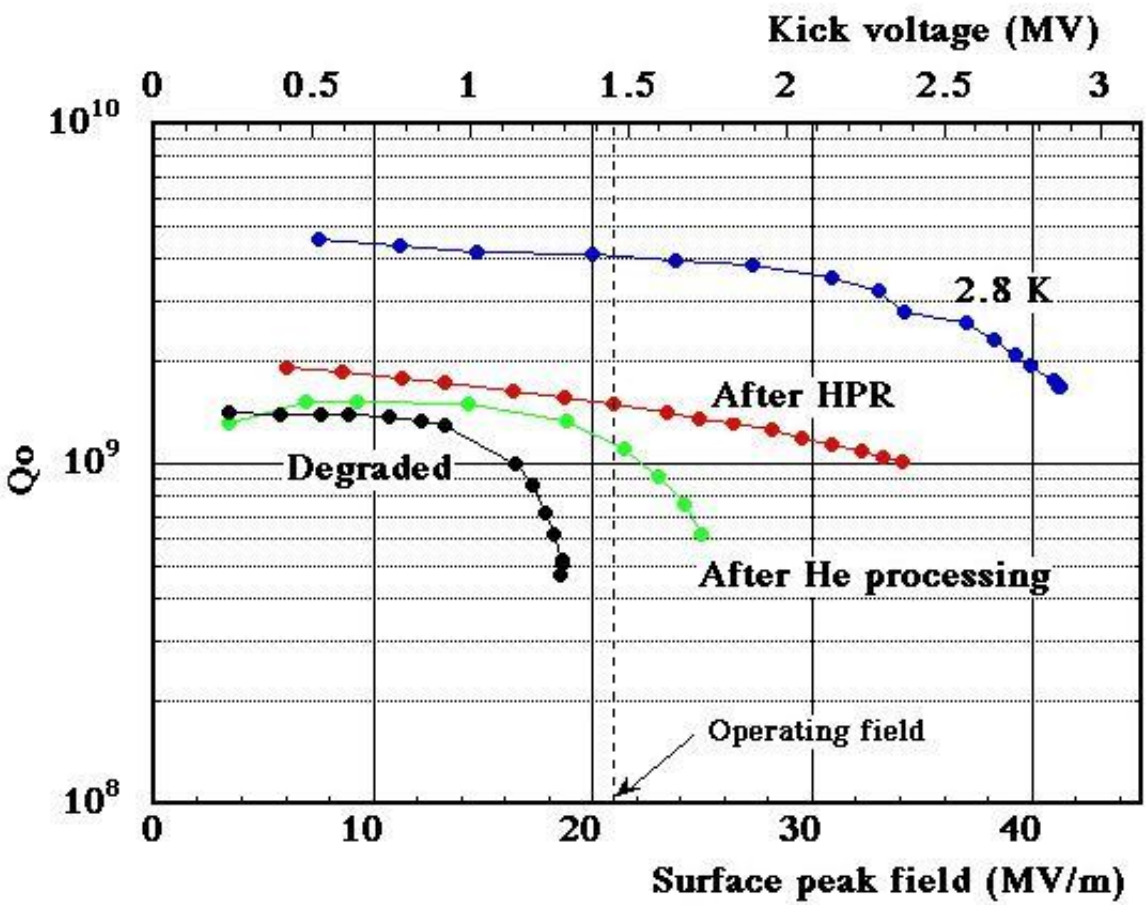
Fabrication and surface treatments

Intensively studied using prototype cavities



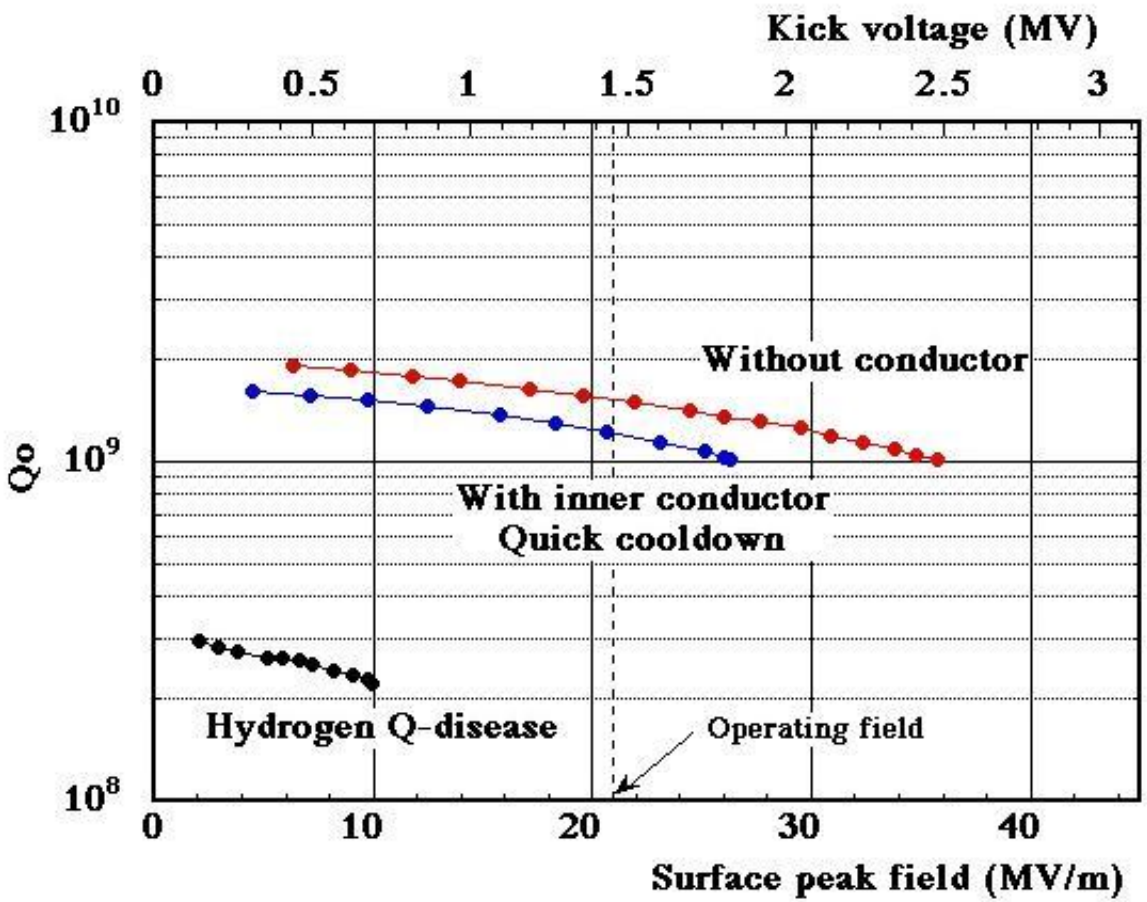
Vertical Cold Test (prototype cavity)

The prototype cavity reached the required kick voltage of 1.4 MV

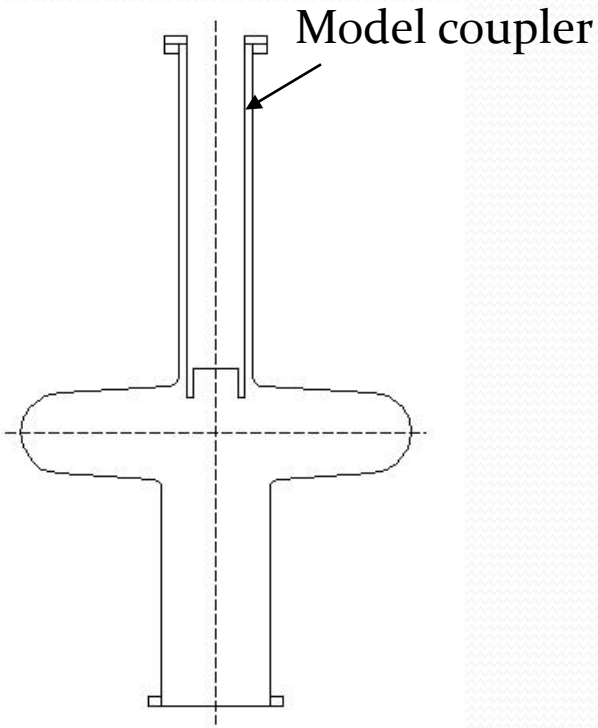


Degraded by micro-particles
He processing tried
Performance recovered by HPR
Low Temperature operation tried, ~3MV reached

Vertical Cold Test (with a model coupler)



Effect of coupler tested with a short model coaxial coupler.
Multipacting occurred at low fields, but it was processed in an hour.
Hydrogen Q-disease occurred.
It could be avoided by quick cooling.
Required voltage achieved with the coaxial coupler



Fabrication of KEKB crab cavities

- Established fabrication method and surface treatments of the cavity cell
- Investigated effects of the inner conductor of the coaxial coupler
- Required voltage reached
- Confirmed performance recovery by HPR
- After the R&D, we started fabrication of two crab cavity modules in 2005

Milestone of Crab Cavity for KEKB

After the R&D, we started fabrication of two crab cavity modules in 2005

2005

Jan. **Start the Fabrication of 2 Crab Cavities**

Dec. RF Test of Crab Cavity HER in Ver. Cryostat V_{kick} = 1.9 MV

2006

Jan. RF Test of Crab Cavity LER in Ver. Cryostat V_{kick} = 2.7 MV

Feb. Cool-down Test of Prototype Cryo-module

Feb. **Start the Assembling of Cryo-module for Crab Cavity HER**

Mar. Insertion Failure of Coaxial Coupler

Apr. Improved the Insertion Tool

Finished the Assembling Crab HER

May. **Cool-down & High Power Test at Test Stand** V_{kick} = 1.65 MV

July Dismantle the Cryo-module

Improved RF Contact of Coaxial Coupler and Bellows

Aug. Reassemble the Cryo-module

Sep. **Cool-down and High Power Test of Crab HER at Test Stand** V_{kick} = 1.8 MV

Oct. Assembling the Cryo-module for Crab LER

Nov. **Cool-down and High Power Test of Crab LER at Test Stand** V_{kick} = 1.93 MV

2007

Jan. 8,11 **Installation of Crab Cavities for HER and LER into KEKB Ring**

Jan.29,31 Start the Cool-down of Crab Cavities for HER and LER

Feb. 9,10 Start of RF Aging V_{kick} = 1.7 and 1.43 MV for HER and LER

Feb. 19 **Crab Kick**

Fabrication Procedure of Crab Cavity

Crab Cavity Cell | **Beam Pipe & Flange**

MHI Kobe

- **Nb Sheet** — Tokyo Denkai, 5 mm t RRR = 180
- **Half Cell Hydro-forming**
- **Mechanical Polishing & Trimming**
- **Electron Beam Welding**
- **Grinding of Welding Part** — Cell Equator

KEK Tsukuba

- **Barrel Polishing** — ~ 100 μm

Nomura Plating Kanuma

- **Electro-Polishing** — EP 1, ~ 100 μm
- **High Pressure Water Rinsing**

Kinzoku Giken Mito

- **Annealing** — 700 °C x 3 hr

Beam Pipe & Flange

- **Nb Sheet**
- **Rolle**

Nomura Plating Kanuma

- **Electro-Polishing** — EP 2, ~ 5 μm
- **High Pressure Water Rinsing** — 80 bar. 60 min.

KEK Tsukuba

- **Assembling for Cold Test**
- **Cold Test in Vertical Cryo.**

Forming and Barrel Polishing

Forming of 4 Half-Cells for Crab Cavity for LER and HER

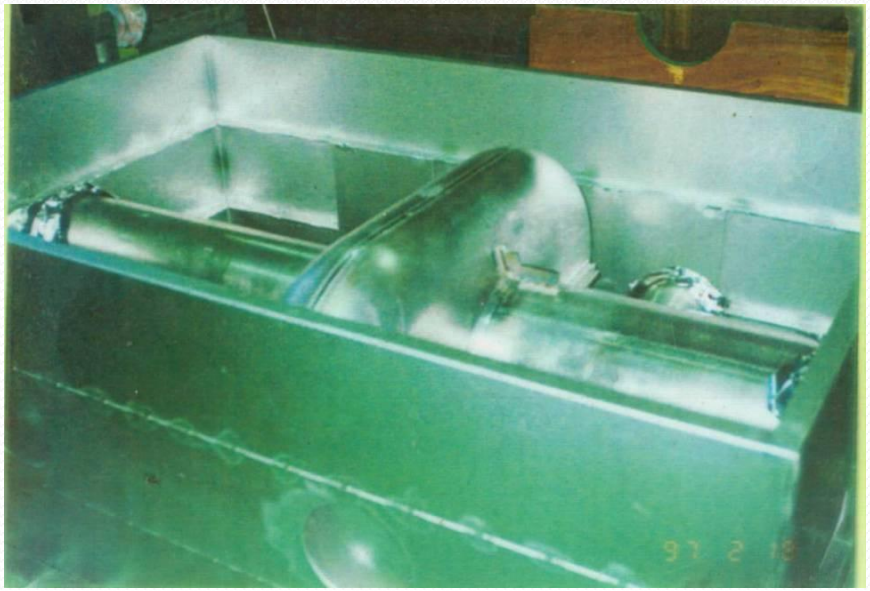
Barrel Polishing
Polishing Time 312 Hr
Average ~100μm
Equator ~150μm

Electro Polishing & Annealing

Electro Polishing at Nomura Plating Ltd.

Rotation speed: 1RPM
Cathode: Aluminum pipe
EP 1 ~ 100 μm
EP 2 ~ 5 μm

Annealing at 700°C for 3 hours at Kinzoku Giken Ltd.



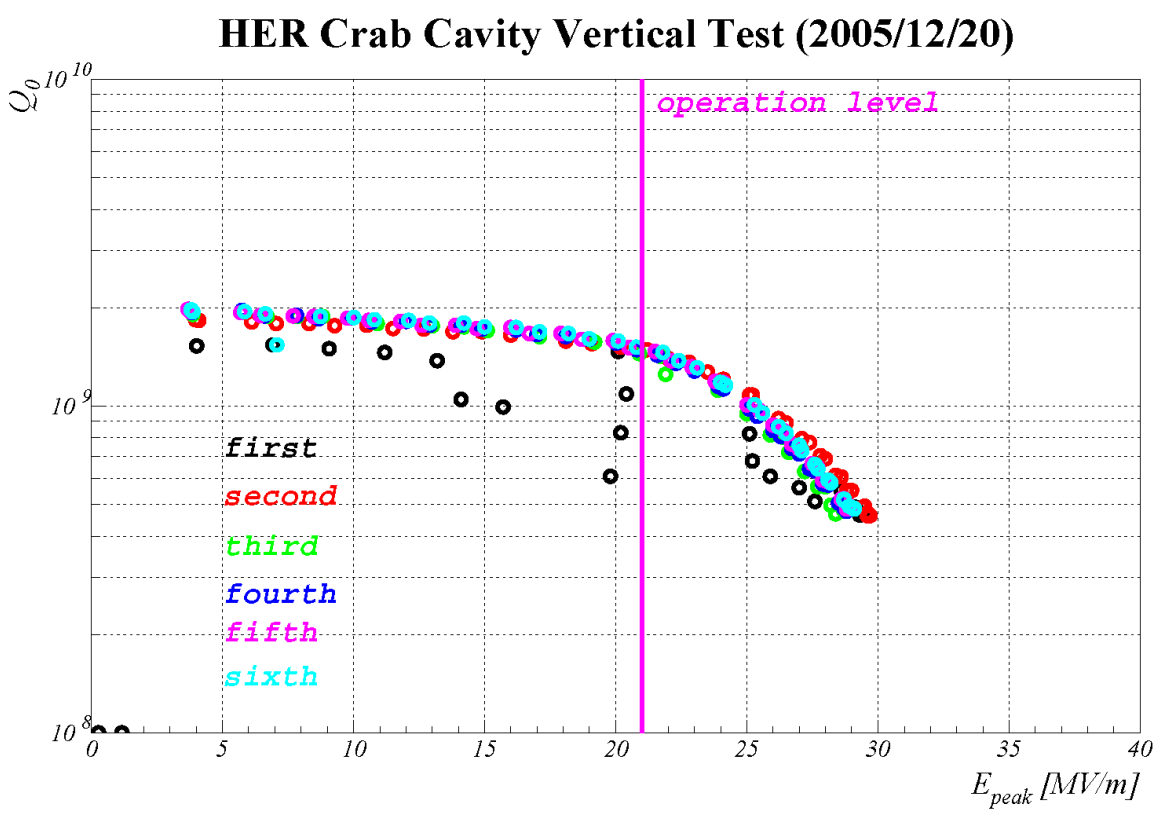
High Pressure Rinsing and Assembling for RF Cold Test

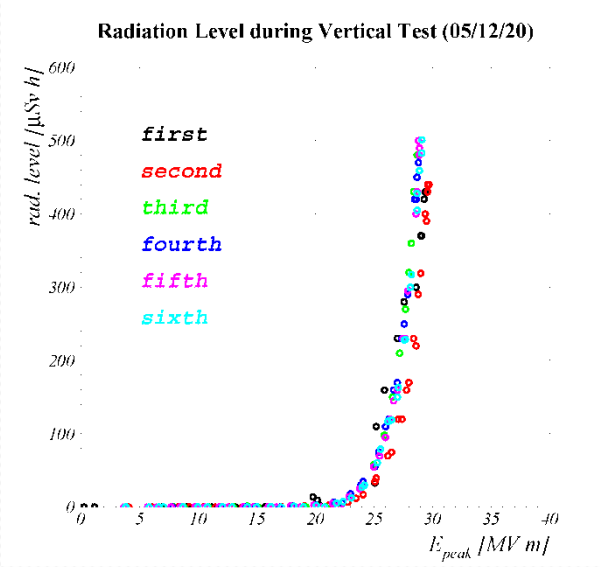
Set Flanges of Beam Pipes and Ports
in Class 100 Clean Room

High Pressure Water Rinsing
by 80 bar Ultra-Pure water

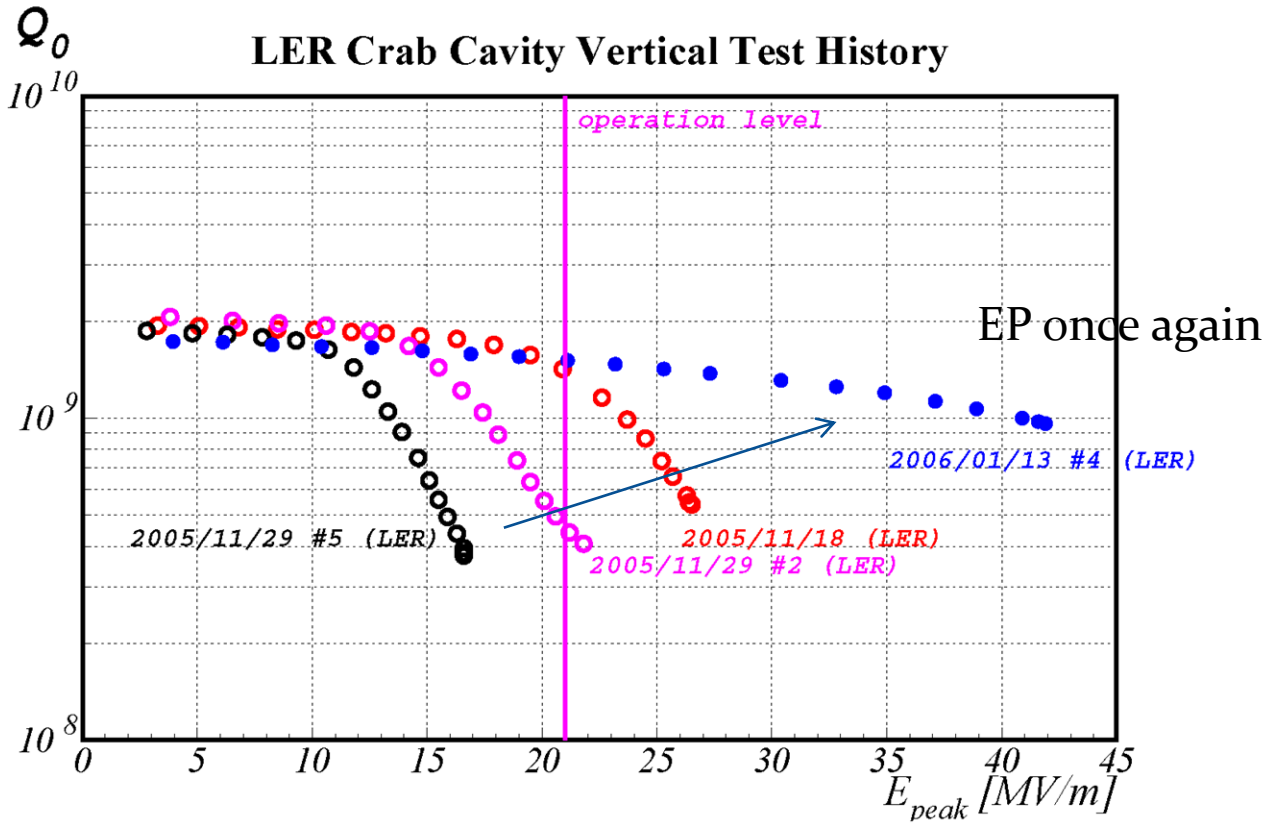
Rotation & Up-Down Motion

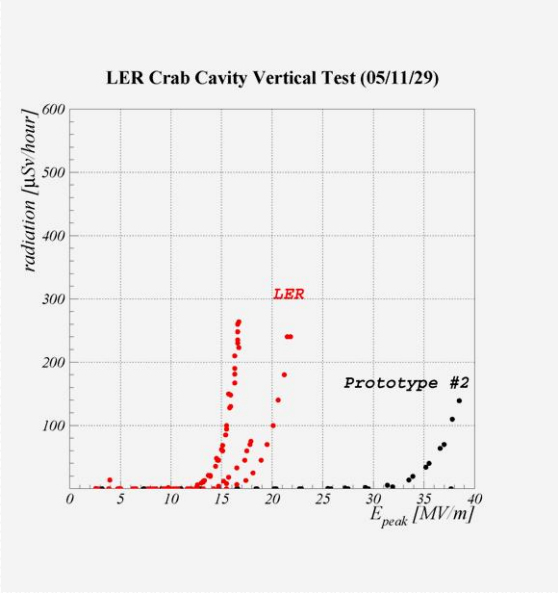
Cold test results of HER crab



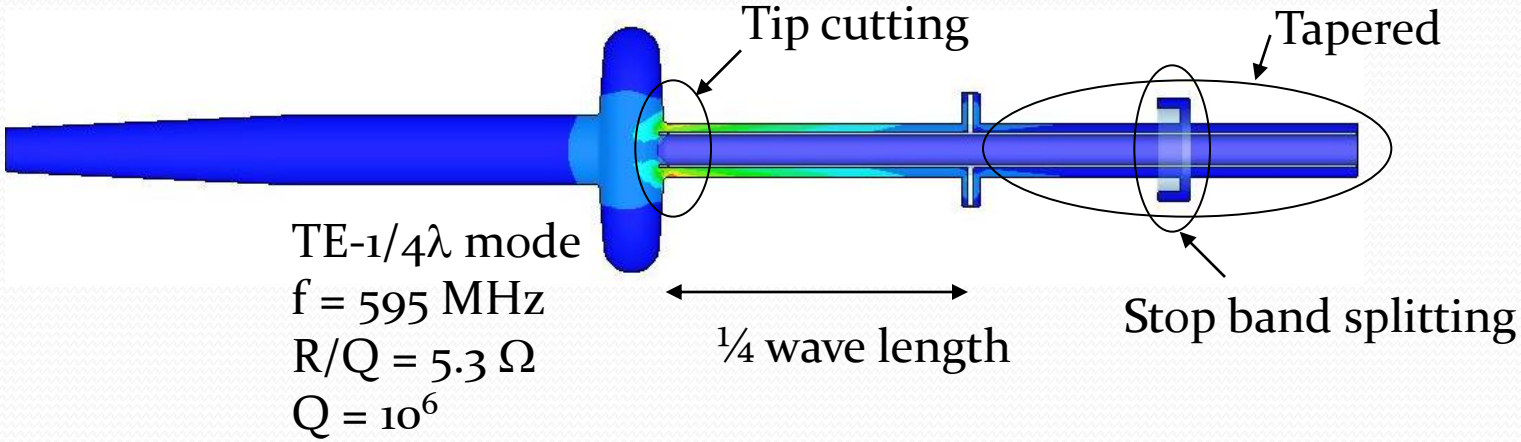


Cold test results of LER crab





Coaxial coupler design
Parasitic modes in the coaxial coupler



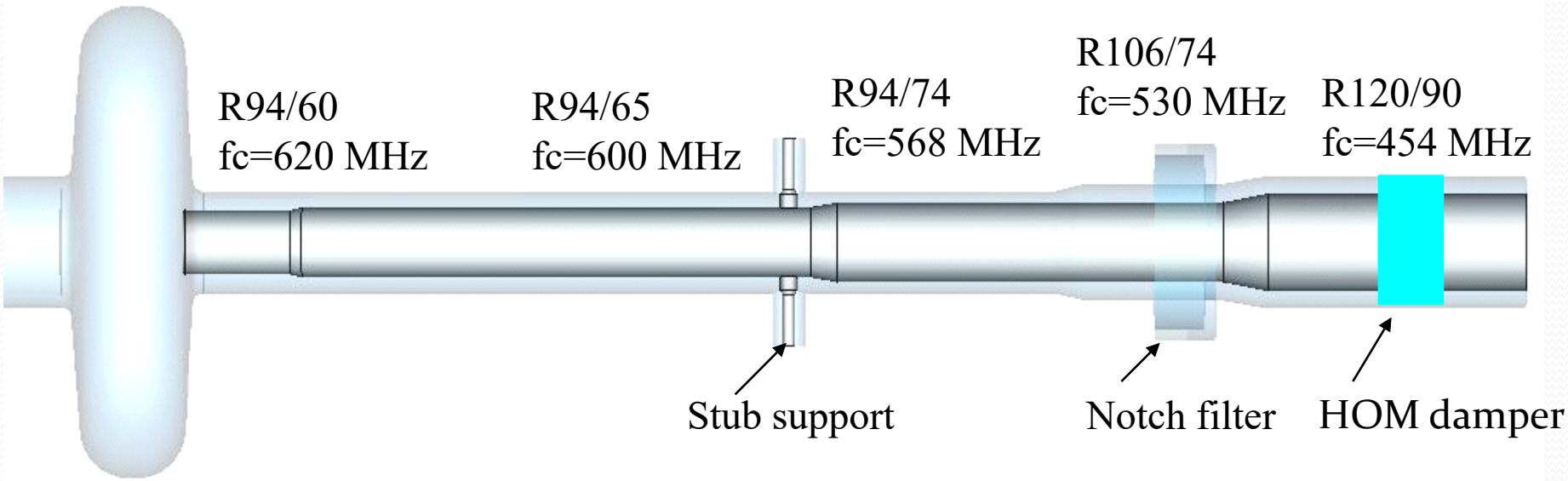
Coaxial coupler has parasitic modes.
The most dangerous mode is the TE-1/4λ mode.
High R/Q (5.3Ω) and frequency lower f than cut-off.
Can not propagate to HOM damper.
This mode remains with high Q factor and gives high impedance.

Three modifications were applied to extract this mode.

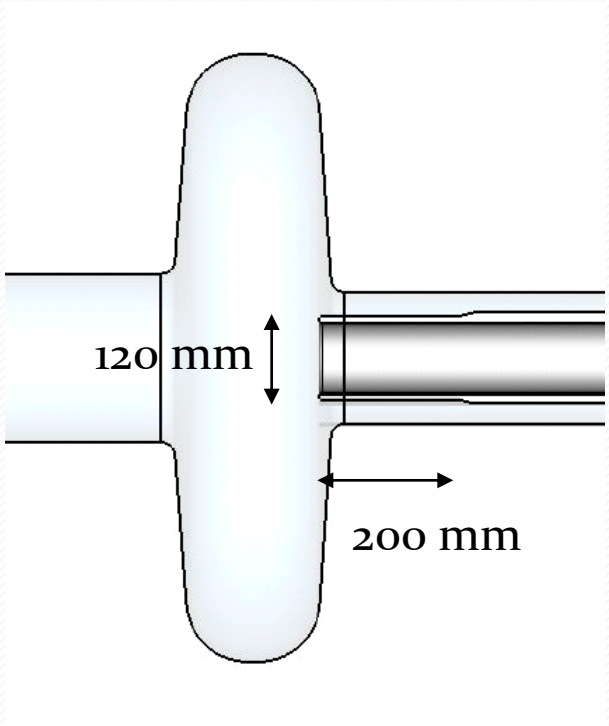
1. Tapered coupler design for lower cut-off.
2. Tip cutting design for raising f of TE-1/4λ mode.
3. TE stop band splitting of notch filter.

Tapered coaxial coupler design

Coaxial coupler has several tapered sections
Decrease cut-off frequency (fc) for TE-mode propagation
Tip cutting at the tip of the inner conductor, fc=620 MHz



Tip cutting design



To raise the frequency of TE-1/4λ mode, outer diameter of the inner conductor is adjusted to 120 mm, which gives the cut-off of 620 MHz.

This modification makes TE-1/4λ mode above 600 MHz and lower R/Q.

Effect of tip cutting design

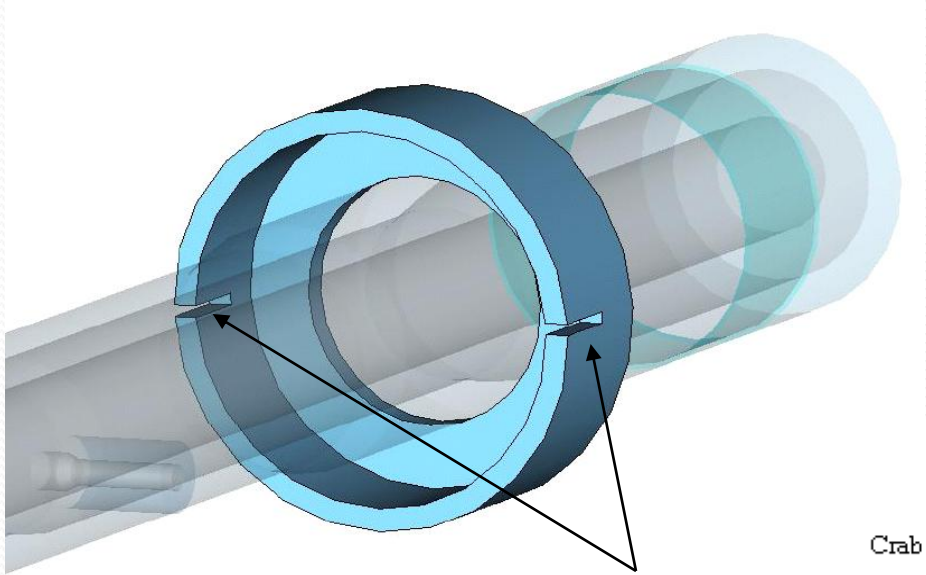
Δf, Δf/ΔL, Qext and R/Q

Frequency shift of the crab mode
Tuning parameter Δf/ΔL
External Q factor of the TM110 mode (LOM)
R/Q of TE-1/4λ mode

The coupler has to be inserted 5 mm into the cavity to compensate frequency shift of crab mode.

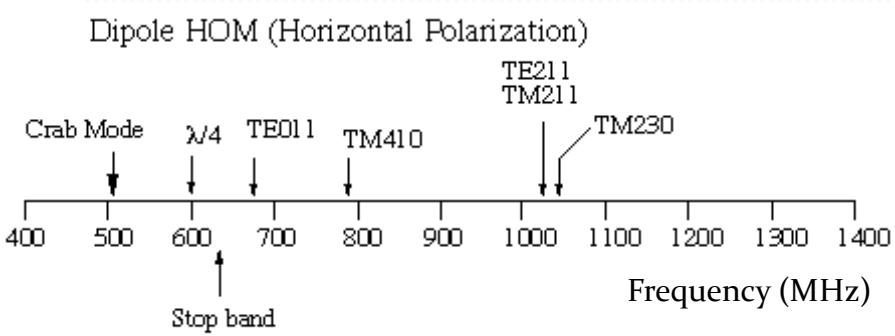
	Δf(crab)	Δf/ΔL	Qext(LOM)	R/Q(TE-1/4l)
No cutting		30 kHz/mm	69	5.2 Ω
Tip cutting	-145kHz	30 kHz/mm	58	2.1 Ω

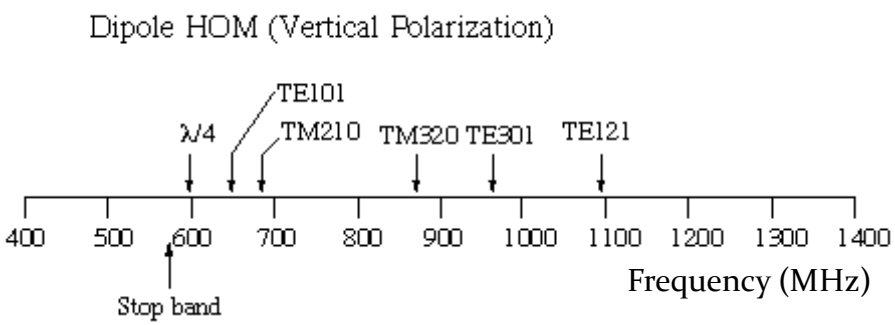
Stop band splitting design of the notch filter



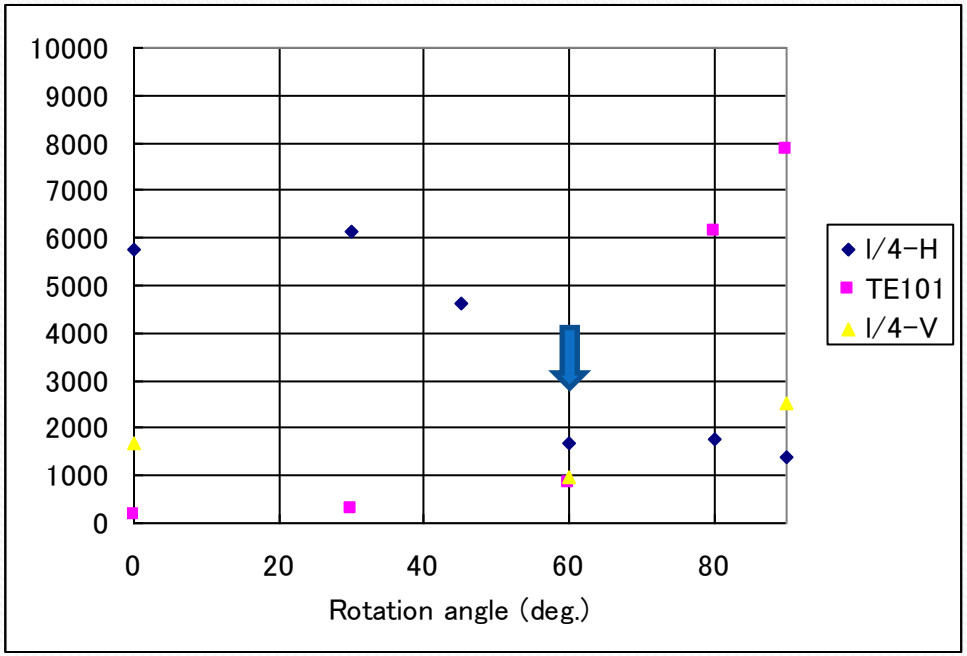
Previous design has a stop band at 630 MHz for TE mode. This band is close to the TE-1/4λ mode.
A stop band splitting notch filter is designed. It has partitions in the mid-plane to separate stop bands for horizontally polarized TE mode (650 MHz) and vertically polarized one (570 MHz).

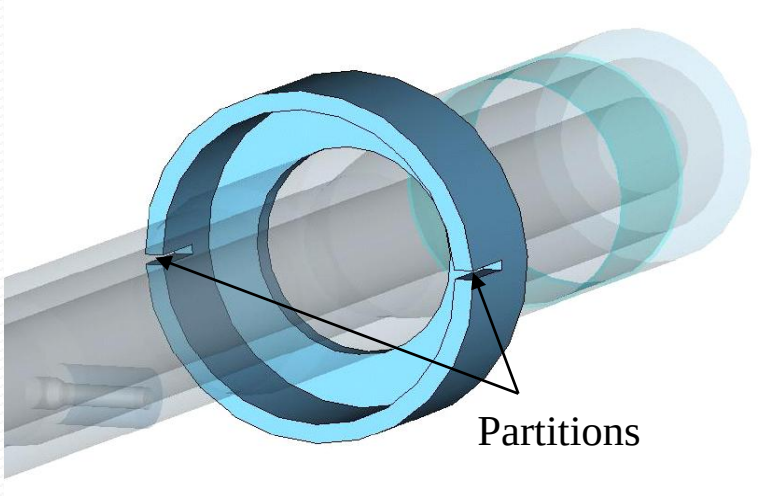
Stop band (H-V splitting)	
TEM	509 MHz
TE(H)	650 MHz
TE(V)	570 MHz





Rotation of notch filter



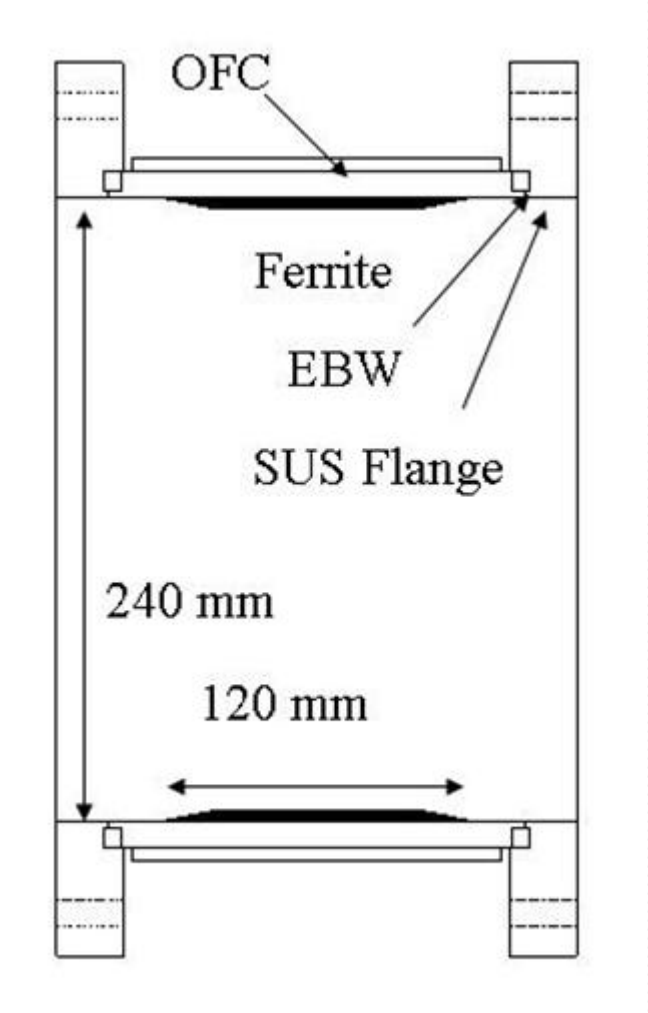


Mode	0 deg.	45 deg.	90 deg.
l/4-H	5.24	5.32	5.36
l/4-V	4.98	5.30	5.17
TE101	10.3	10.1	10.8

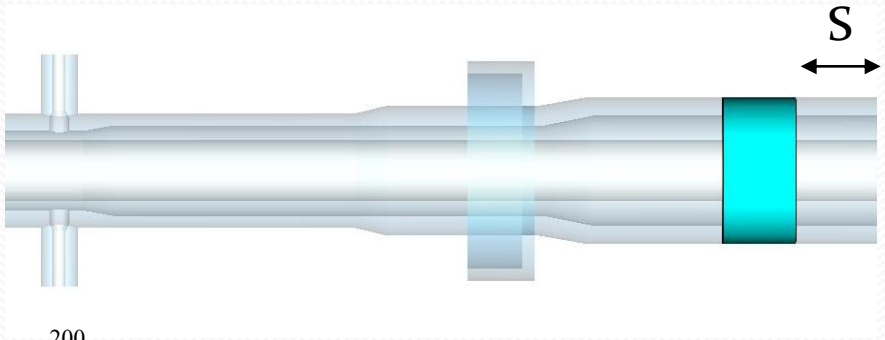
Rotation of notch filter further decreases the Q factor of the horizontal TE1/4 mode. The Q factor of the TE101 cavity mode does not vary until it hits the stop band of the notch filter at the 90 degrees. The vertical TE1/4 mode has no significant variation. We set the rotation at 60 degrees.
R/Q of these tree modes are almost the same against the rotation.

Ferrite HOM damper

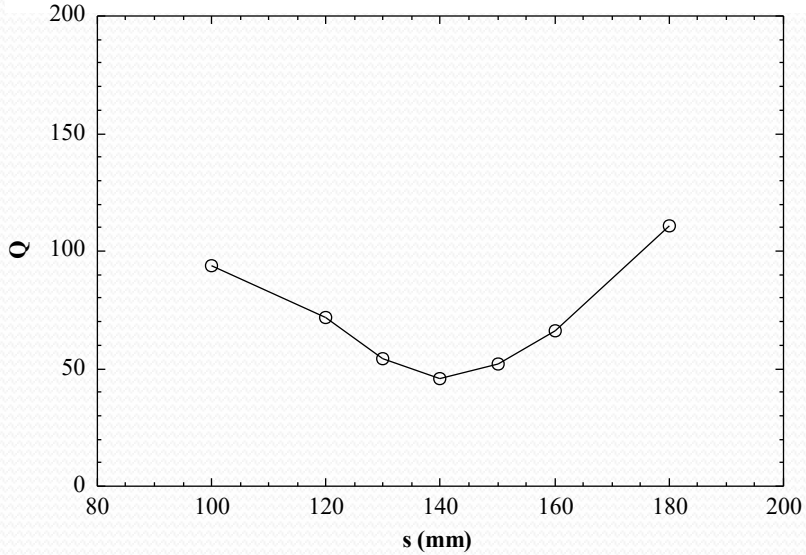
- RF absorber
- Ferrite material
- HIP (Hot Isostatic Press) method
  - 1500 atm, 900℃ for 5h
- Size: 240mm$^{\phi}$ x 120 mm x 4mm^{t}



HOM damper position



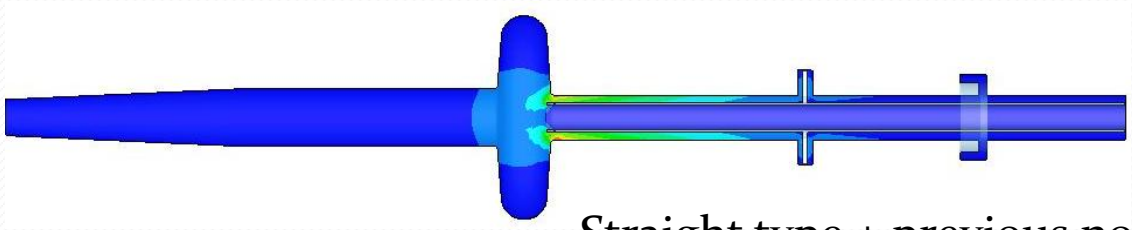
HOM damper
Ferrite RF absorber
Size: 240ϕ x 120 mm



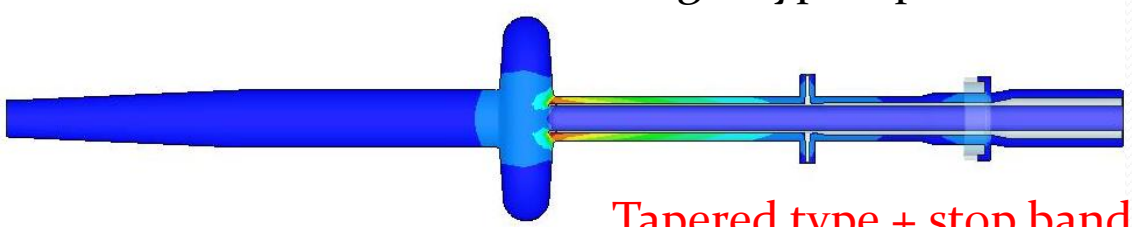
Q factor of the TM110 mode (LOM) as a function of damper position.

Position of the damper was optimized for the minimum Q factor of LOM.

Comparison of TE-1/4λ mode damping

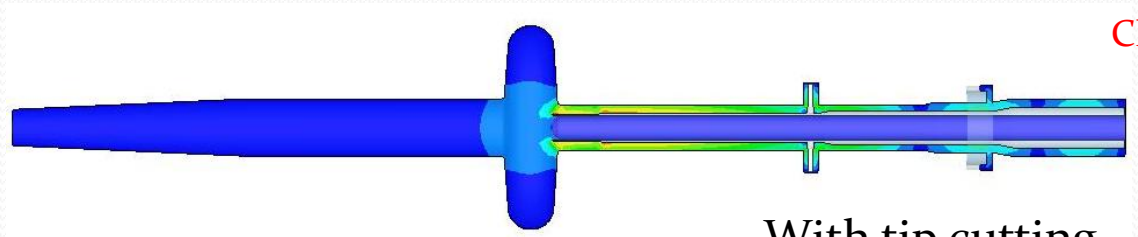


Straight type + previous notch filter



Tapered type + stop band splitting notch

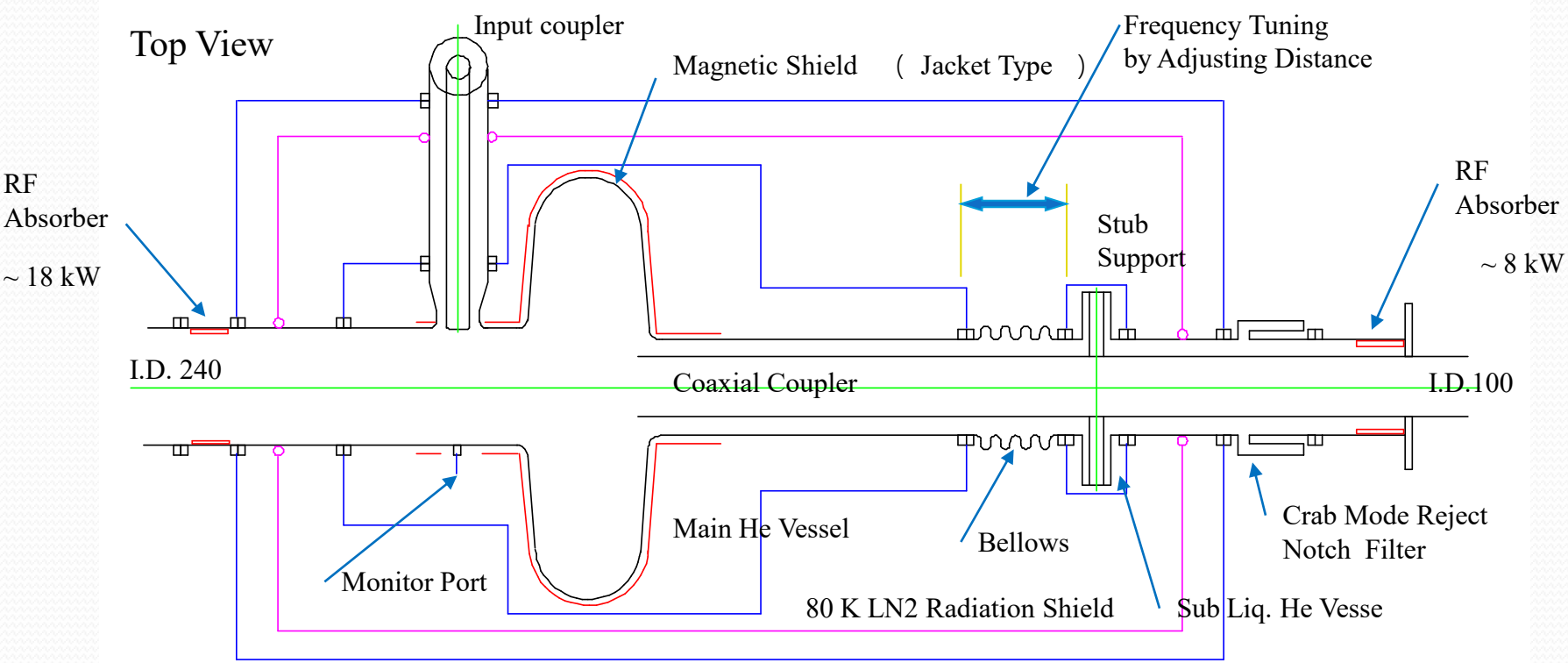
Chosen for KEKB CC



With tip cutting

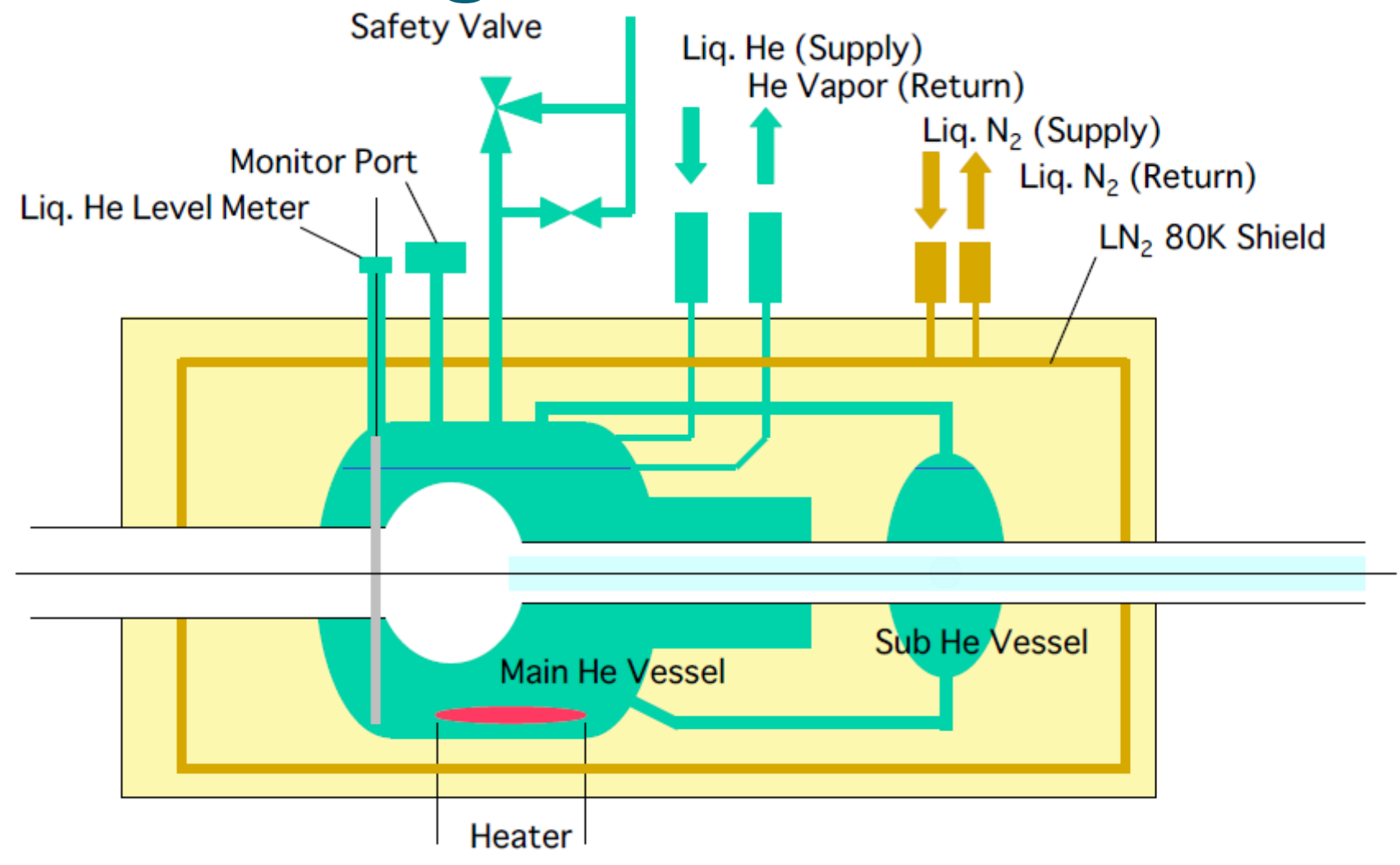
Type	f	R/Q(MWS)	Q(HFSS)
Straight	595 MHz	5.7 Ω	10^6
Tapered	602 MHz	5.2 Ω	5800
Tapered + tip cutting	607 MHz	2.1 Ω	2700

Conceptual Design of Cryostat for KEKB Crab Cavity

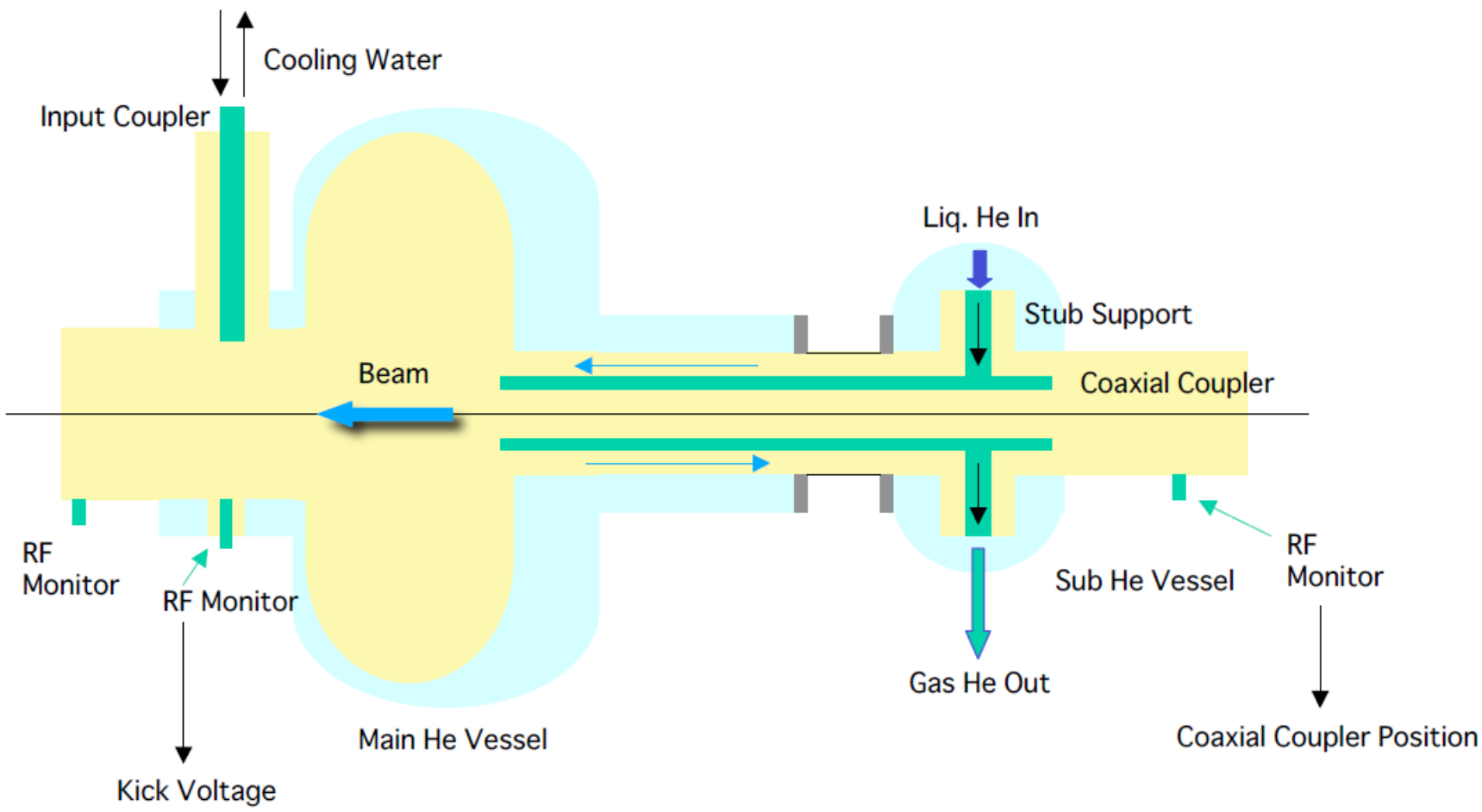


Jacket-type Helium vessel for the large cavity cell
Jacket type sub-Helium vessel for the stub support to provide cooling of the inner conductor
Large size bellows (188ϕ) connects both jackets for alignment of the coaxial coupler and frequency tuning

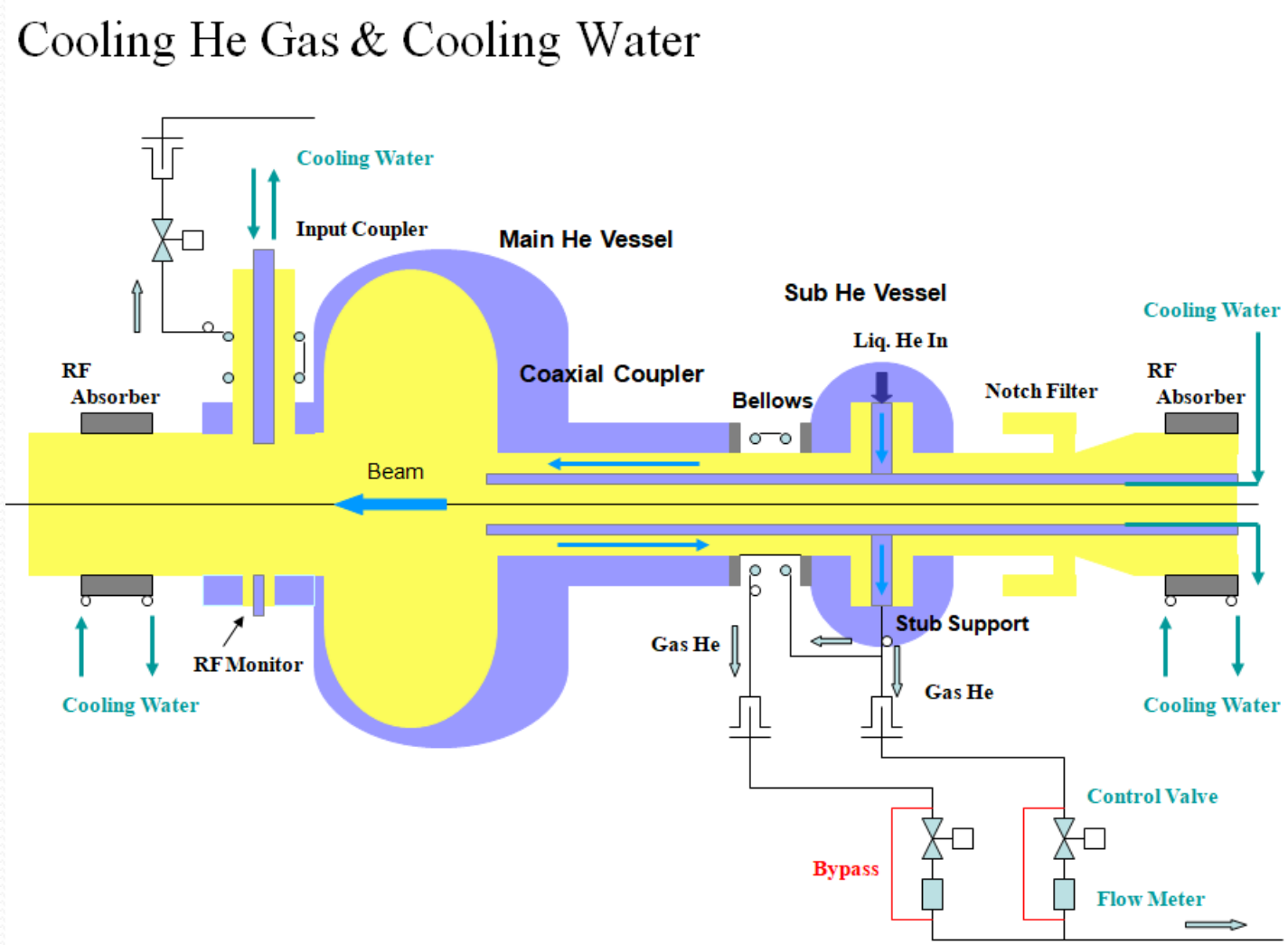
Cell cooling scheme



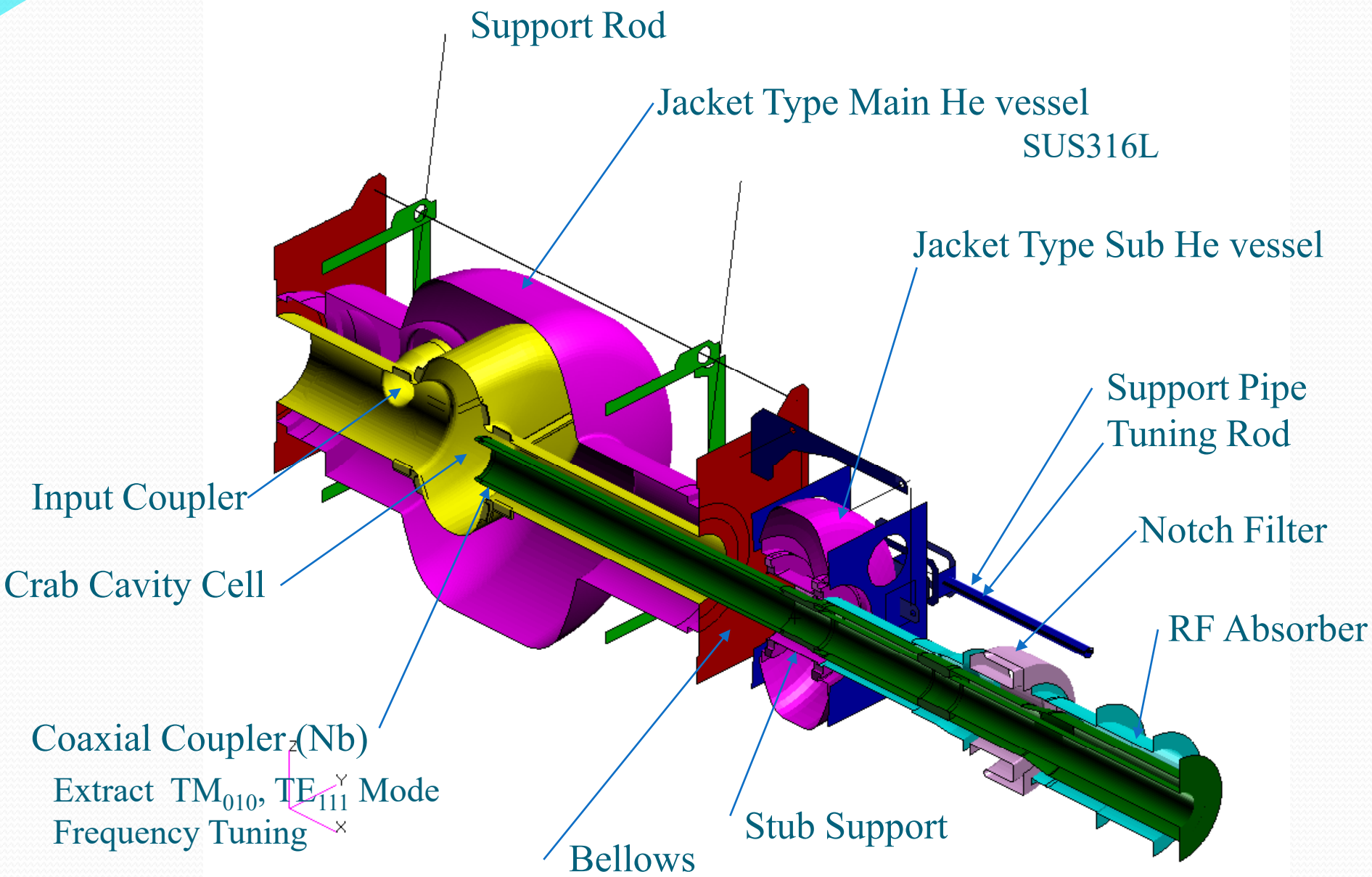
Coaxial coupler cooling scheme



He gas and water cooling

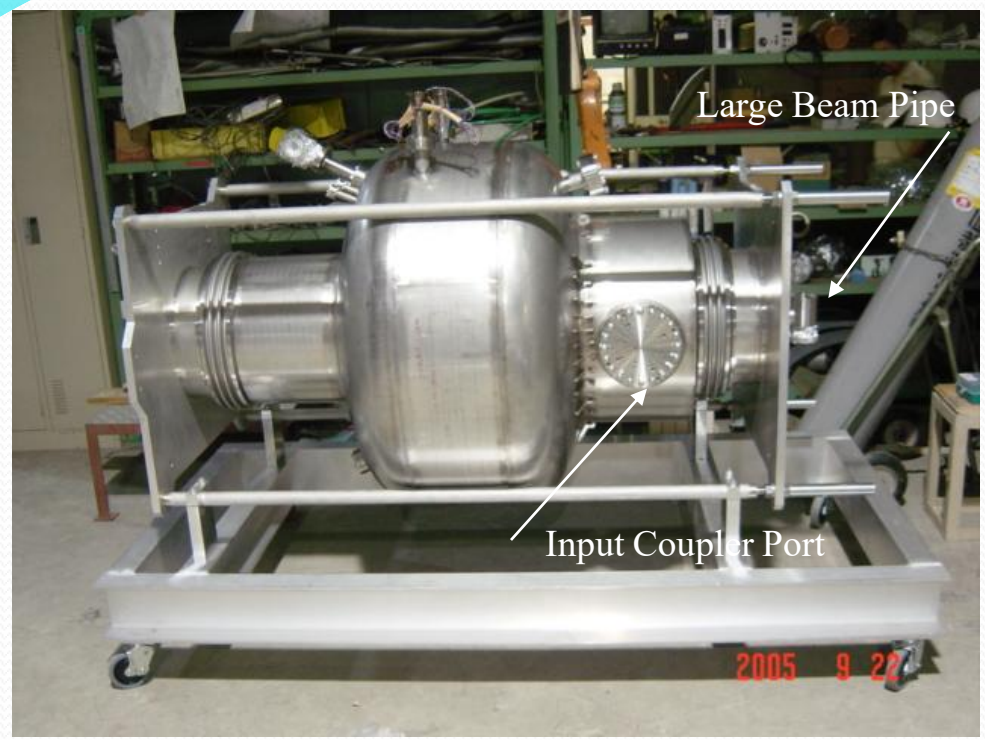


Crab Cavity & Coaxial Coupler in Cryo-module



Jacket Type Helium Vessel

Prototype

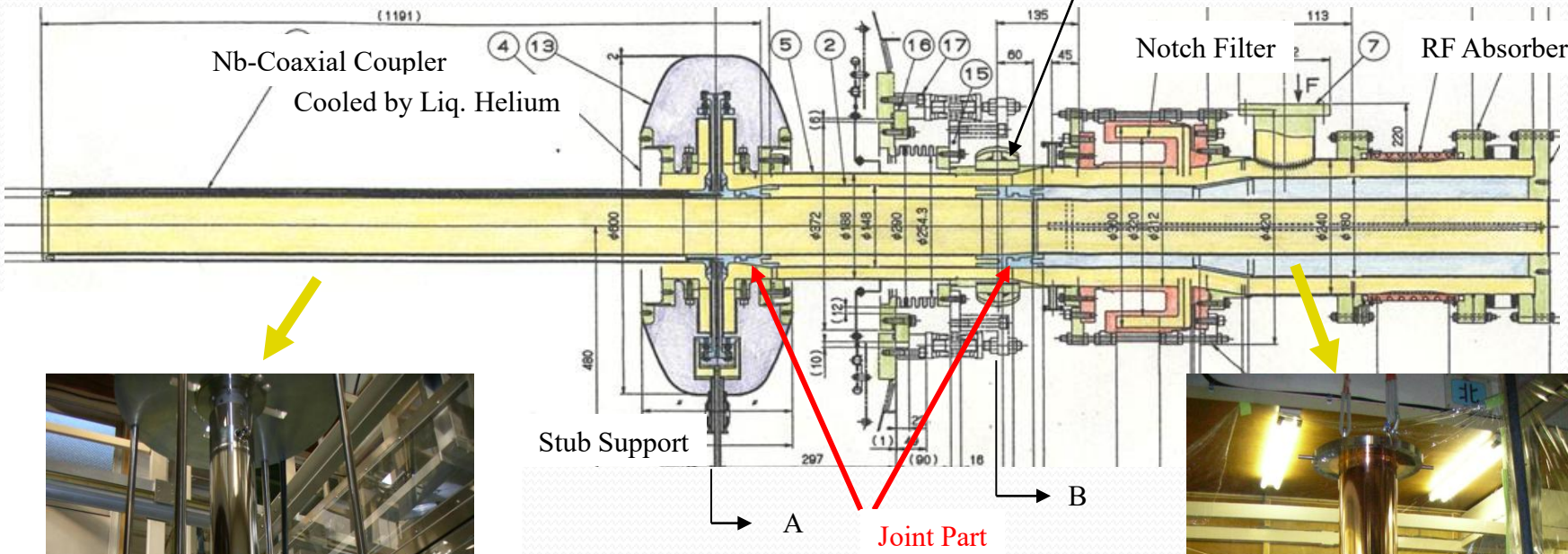


Jacket Type Helium Vessel

Jacket Type Magnetic Shield

Permalloy 3t

Coaxial coupler assembly
Structure detail



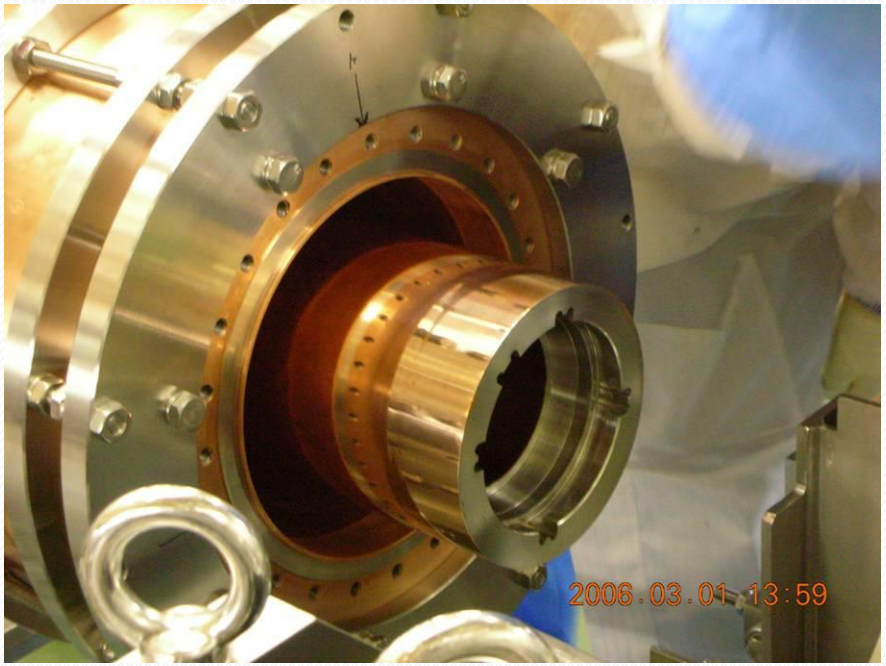
Inner conductor consists of three parts
1 Niobium coupler
2 SS joint conductor
3 SS inner conductor

Nb-Coaxial Coupler
Cooled by Liq. Helium

Copper-plated SS Inner Conductor
Cooled by Water

Assembling of Coaxial Coupler

Crab Cavity (Cryostat) Side



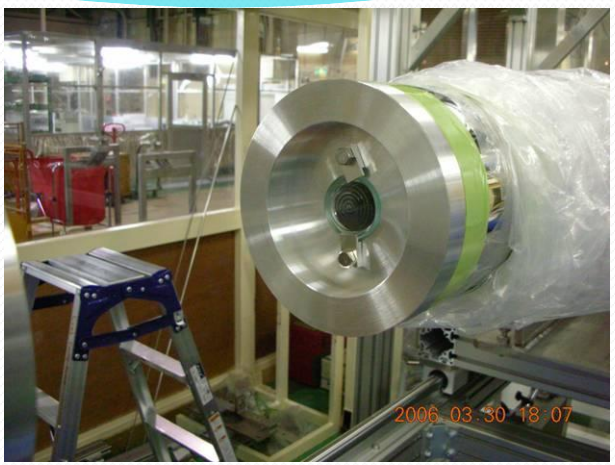
Notch Filter Side

Bayonet Type Connection

Step 1 Insert

Step 2 Rotate Clockwise 30 degree

Alignment of Coaxial Coupler



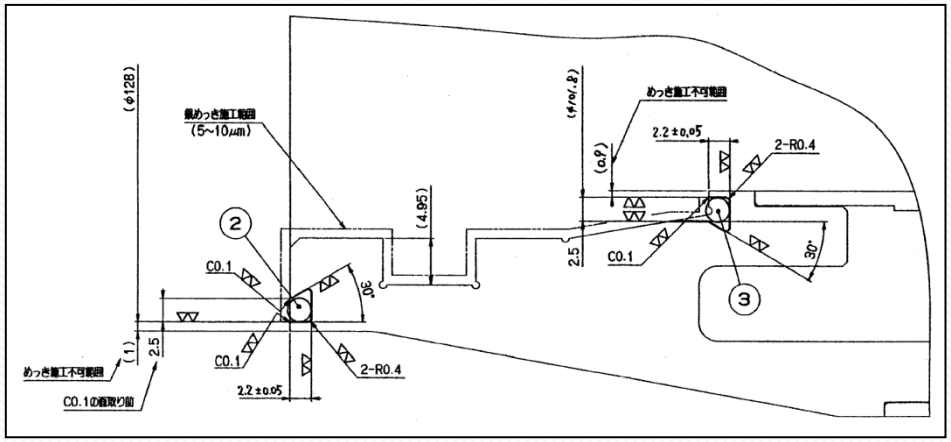
Decide the axis of the coaxial coupler set in the cryostat by using transit.

Align the axis of the coaxial coupler which will be connected to the coaxial coupler of cryostat side.

RF Contact

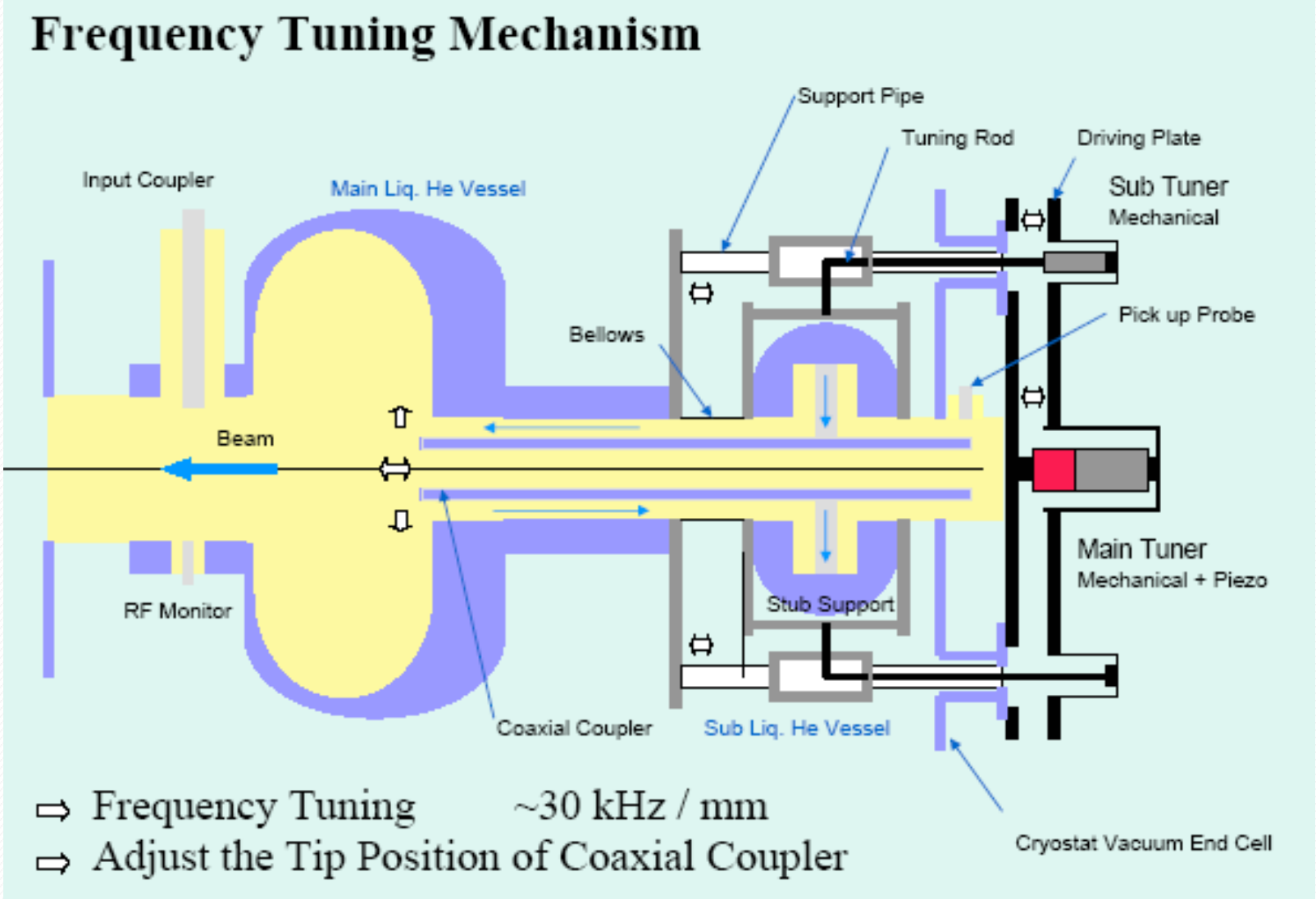
In the joint parts, RF contacts were attached for good electric contact

Type： Spiral
Material： BeCu
Spring Constant： 14kg/ϕ94mm (0.5kg/cm)

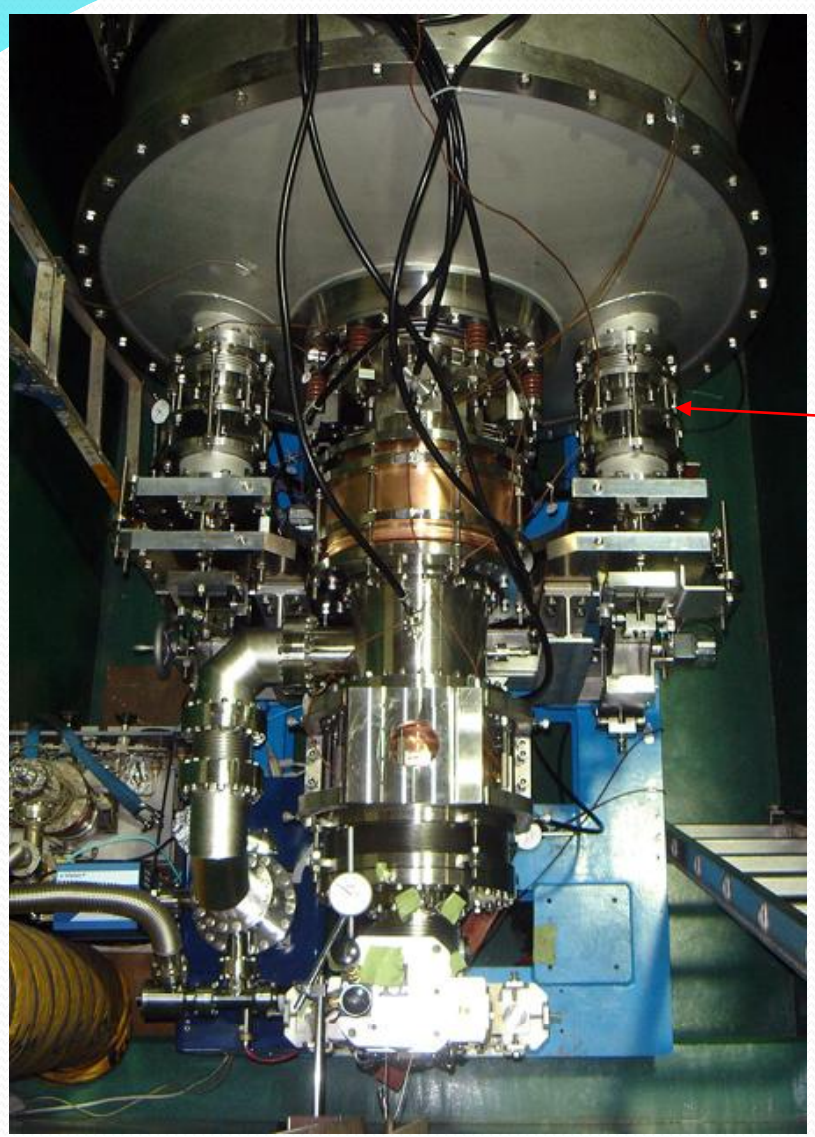


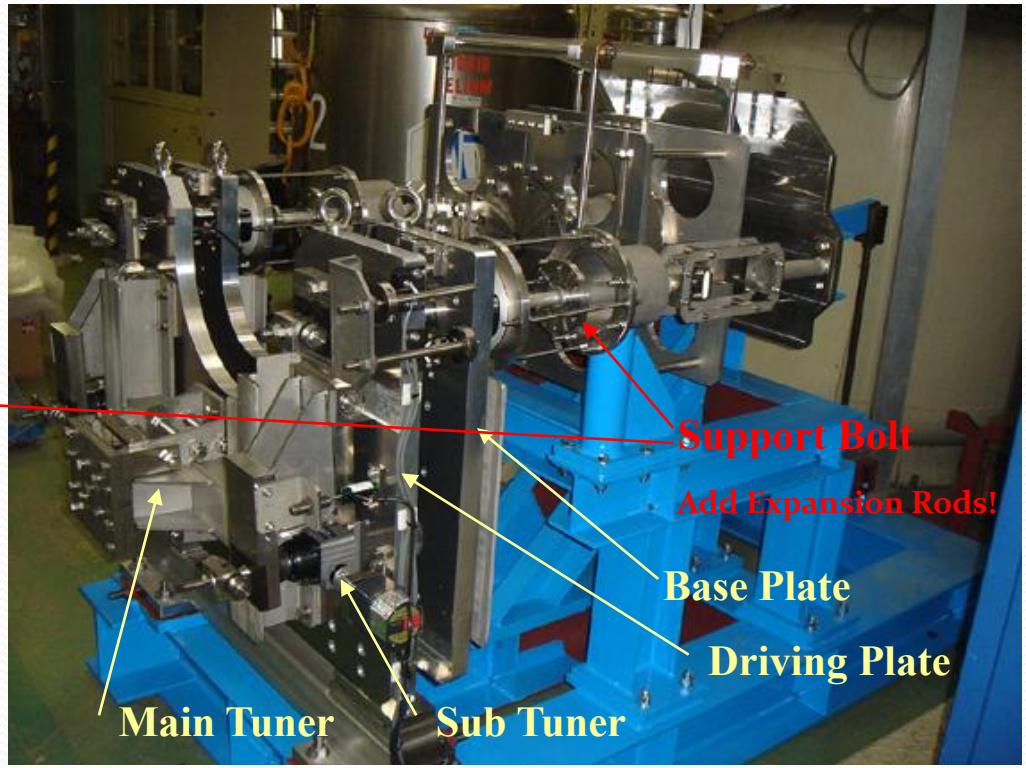
Frequency tuner

Frequency tuner tunes the cavity by the insertion of inner conductor (30kHz/mm)
It consists of main and sub tuners
The main tuner (motor jack and piezo) drive the inner conductor
The sub tuner adjusts its alignment



Frequency Tuner



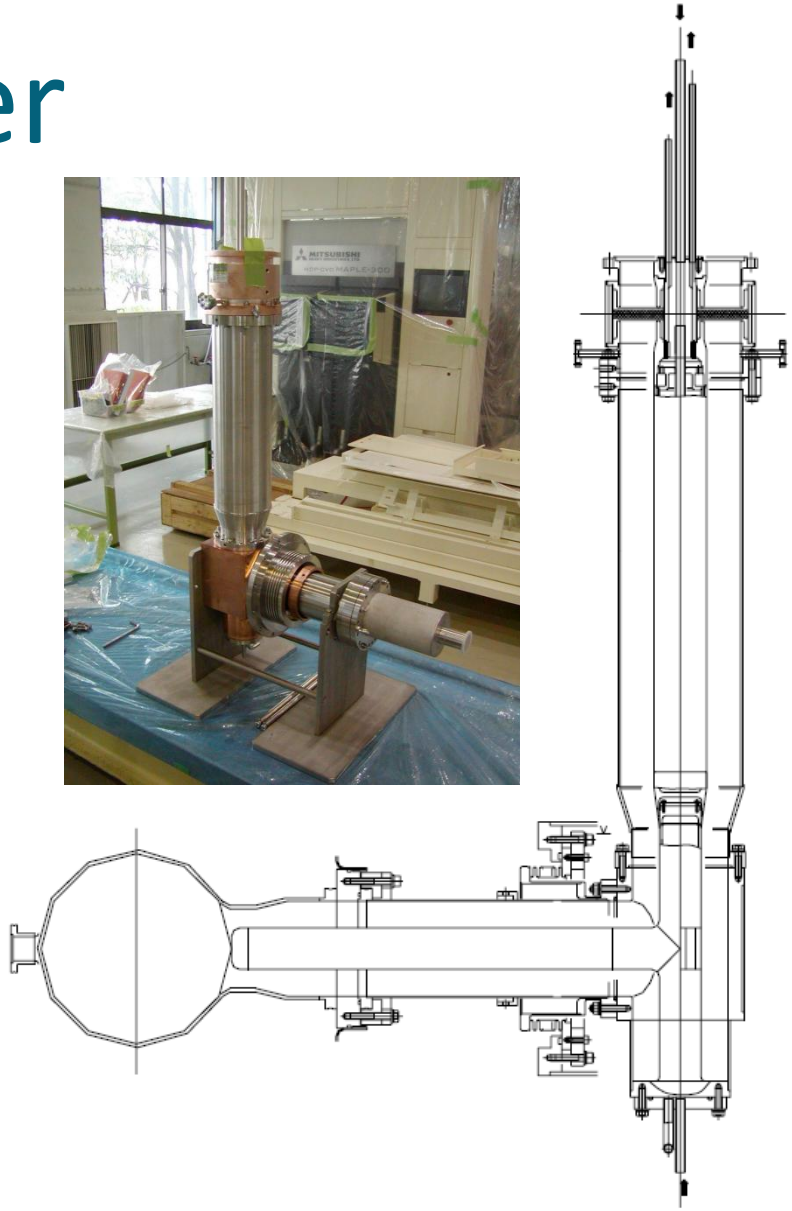


Test Stand for Frequency Tuner

Frequency Tuner of Crab Cavity for HER

High power coupler

- Horizontal insertion
- T-Stub structure
  - VSWR:1.15 at 509 MHz
- Ceramic RF window
- Water cooled inner conductor
- Monitor ports
  - Electron collection probe
  - View port for arc sensor
  - Vacuum gauge port
- Conditioning
  - Up to 250kW (TW) before installation
  - Up to 200 kW (SW) before cool-down
    - Up to 150 kW for LER crab
- Typical RF power
  - 25 kW for LER crab at 0.9 MV
  - 75 kW for HER crab at 1.5 MV



K. Akai et al, EPAC96, p. 2118.

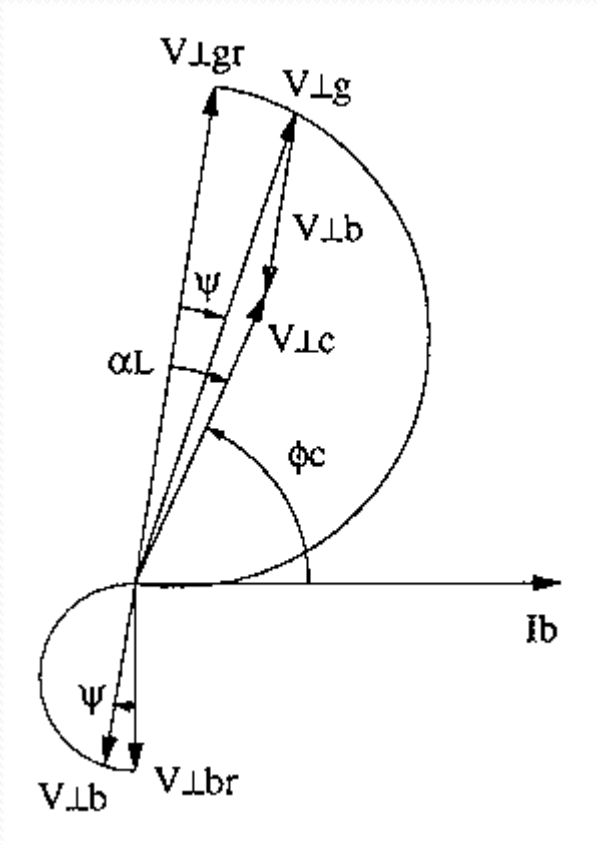
Loaded-Q factor

Choice of Q_L is important
Maximum Pg~100kW
Fluctuation ΔPg~10kW

Generator power

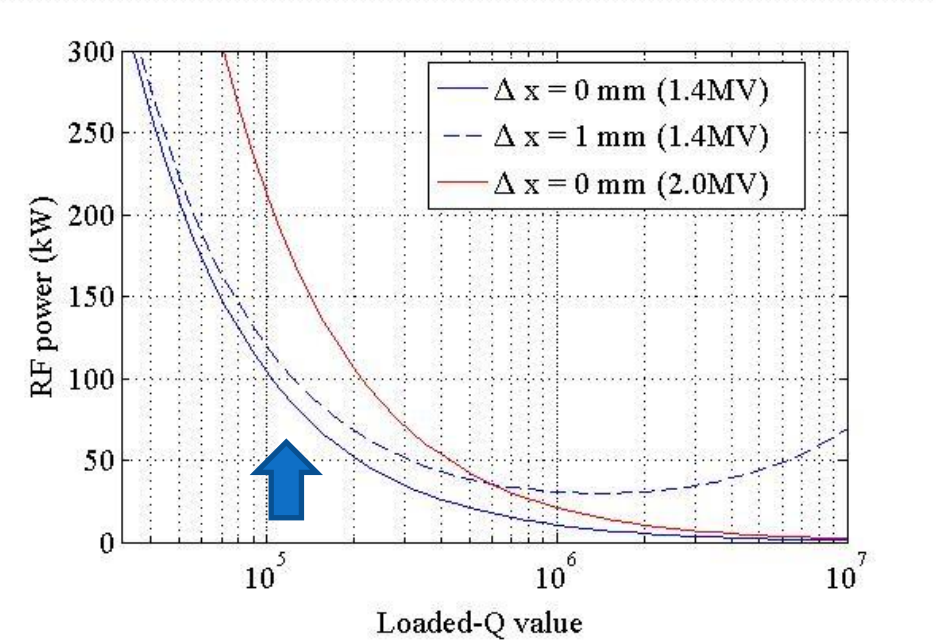
$$P_g = \frac{1}{4\left(\frac{R_\perp}{Q_0}\right)Q_L}\left\{V_c + I_b\left(\frac{R_\perp}{Q_0}\right)Q_L k\Delta x\right\}^2$$

Beam-induced crabbing voltage when the beam shifts Δx



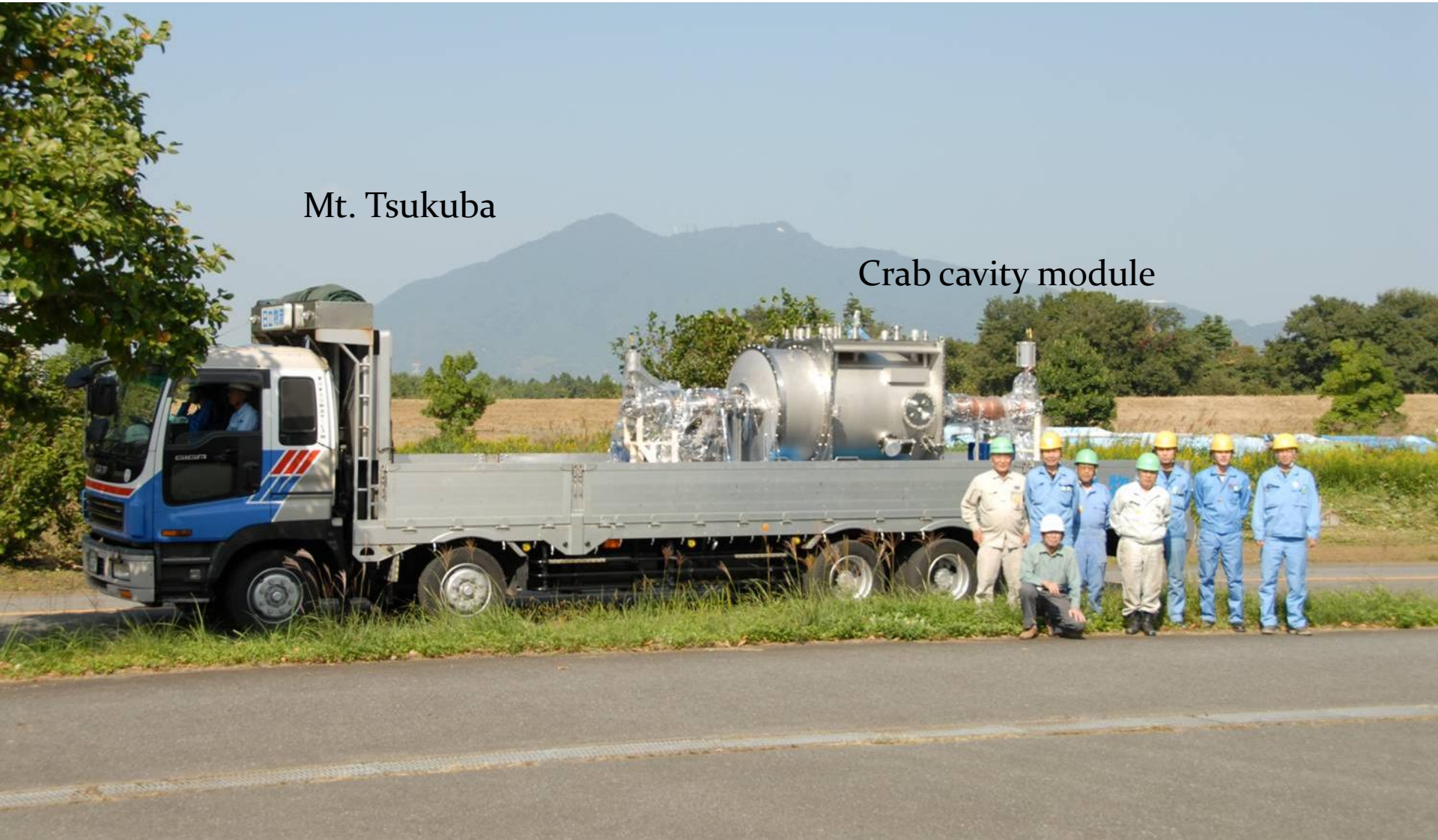
Phaser diagram for the crabbing mode

Required power to maintain the crabbing voltage.
Beam induced voltage (0.2MV for Ib=2 A, QL=2x105, dx=1 mm)



Not to be sensitive to beam orbit change.
Q_L=1-2 x 10^5 is a good choice.
Q_L=1.6x10^5 (HER)
Q_L=2.0x10^5 (LER)

High power tests



High power test

- Adjustment of the resonant frequency
- Alignment of the coaxial coupler
- Optimization of the tuner feedback system
- Conditioning of the cavity
- Qo measurement
- Static loss measurement of the cryostat

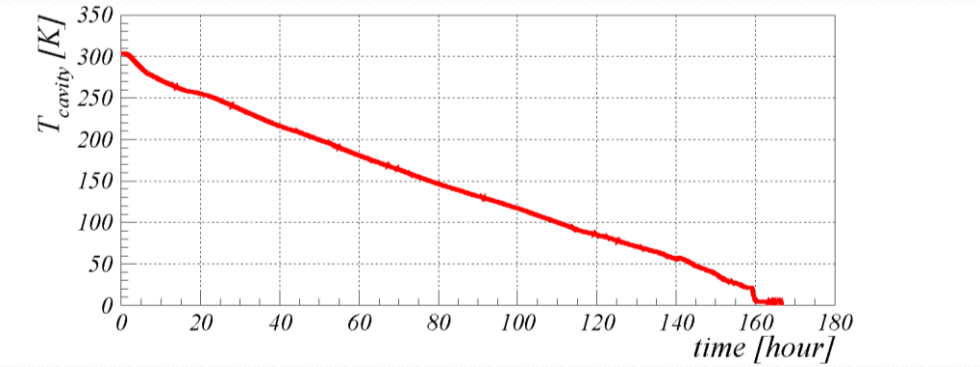
High Power Test Stand

Conducted in a pit of a high power test stand

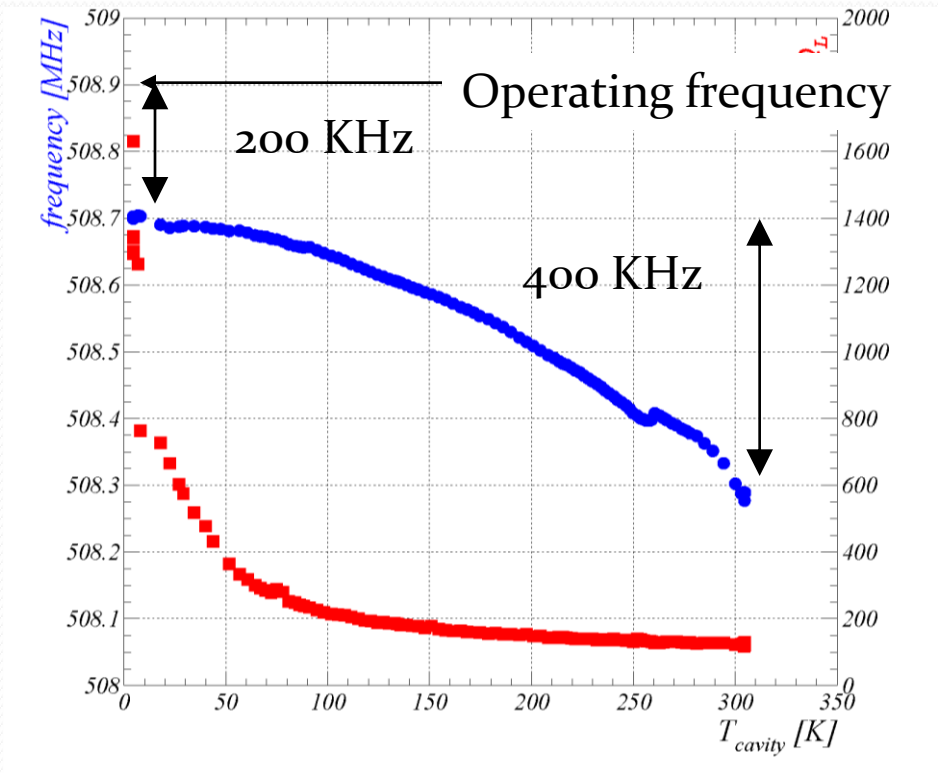
Installed in the pit

He Transfer tubes connected

Cool-down and frequency adjustment of HER crab

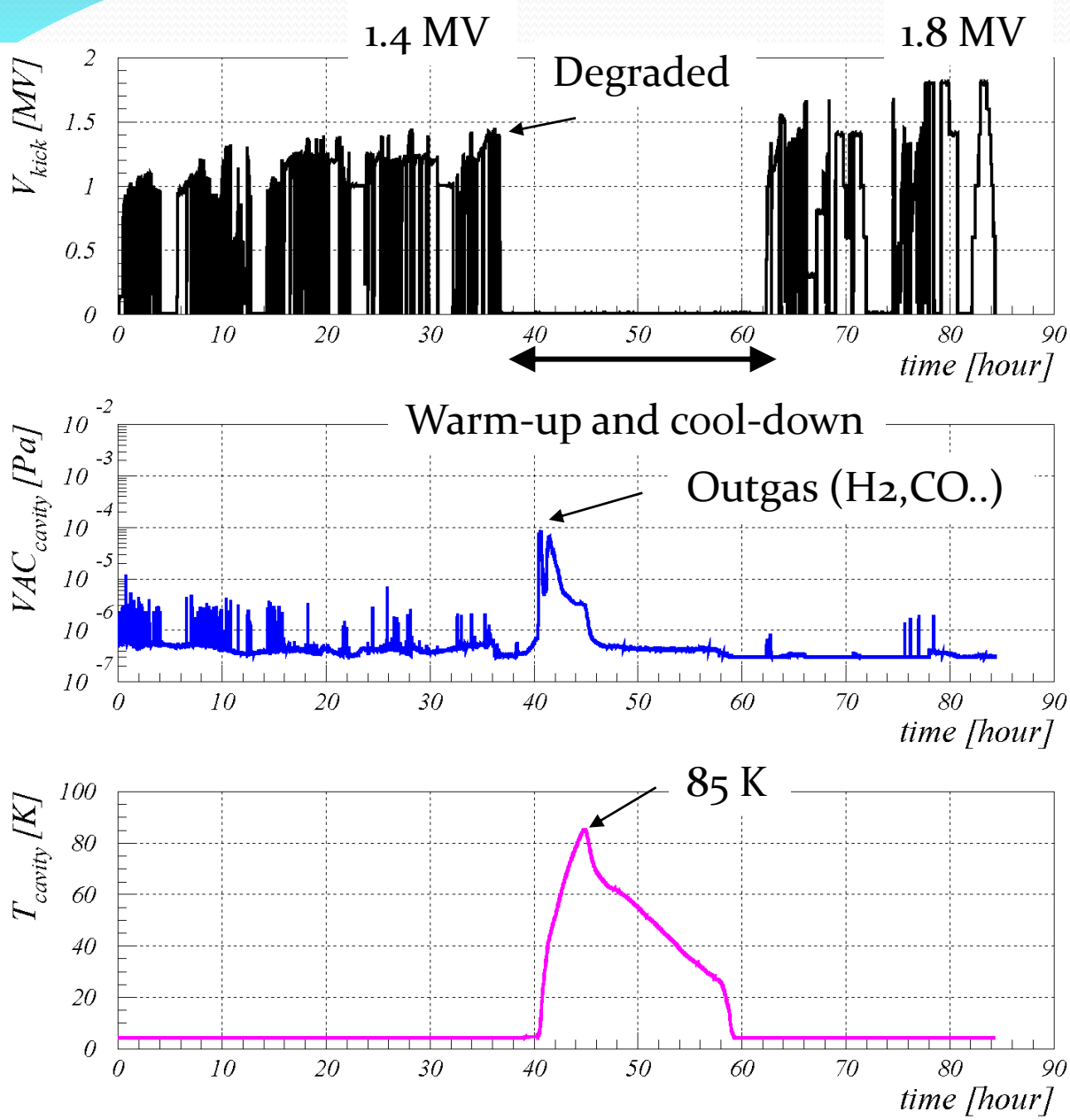


Cool-down rate: 2 K/h
1 week



Frequency shift during cool-down
400 kHz
To the operating frequency,
Cell deformation
100 kHz
Coaxial coupler insertion
100 KHz

Conditioning status of HER crab



Hi power conditioning
The crabbing voltage increased

1.4 MV reached

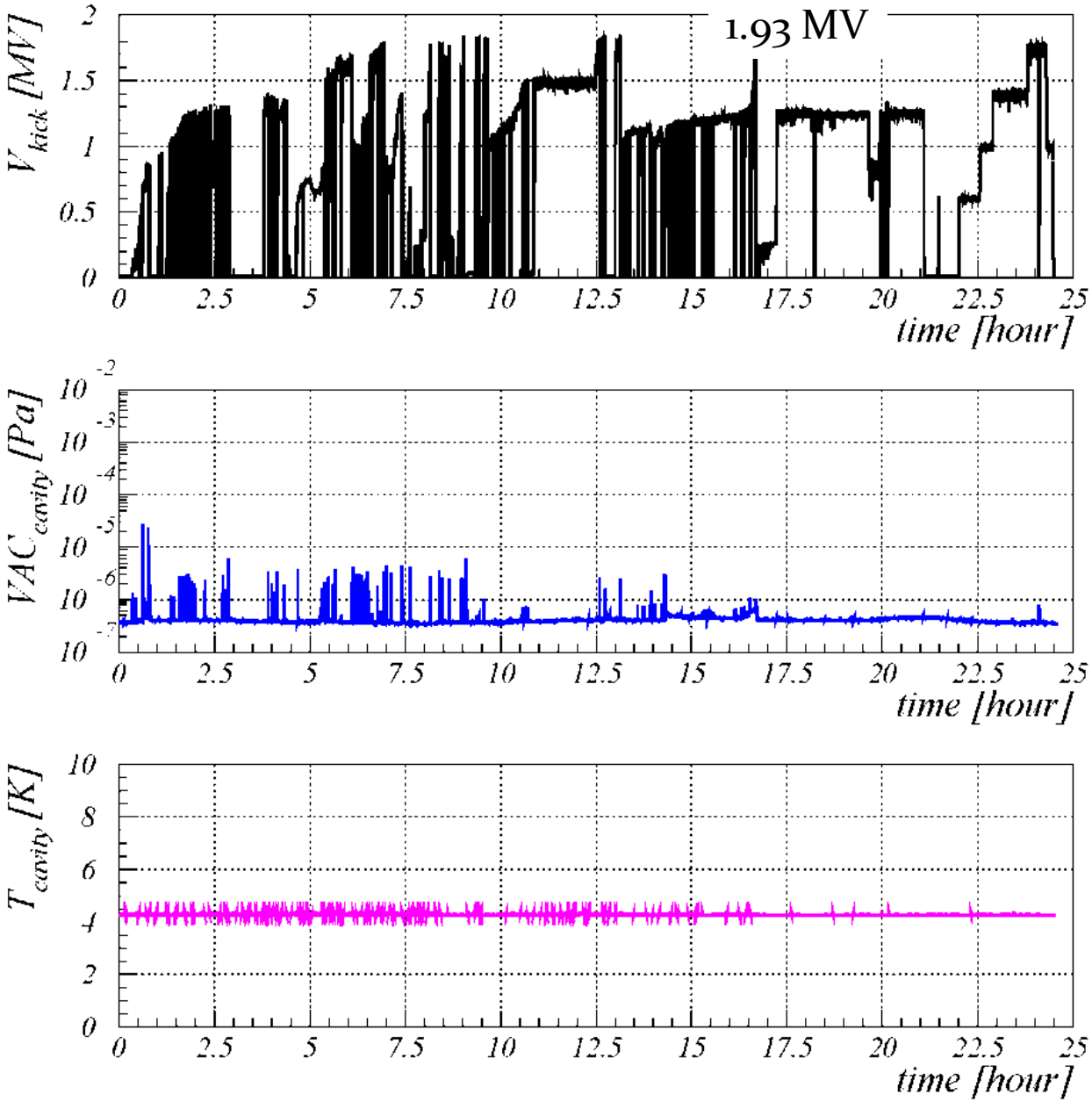
Slightly degraded
due to vacuum pressure increase

Warm-up to 85 K and cool-down for evacuation

High poer conditioning again

1.8 MV reached

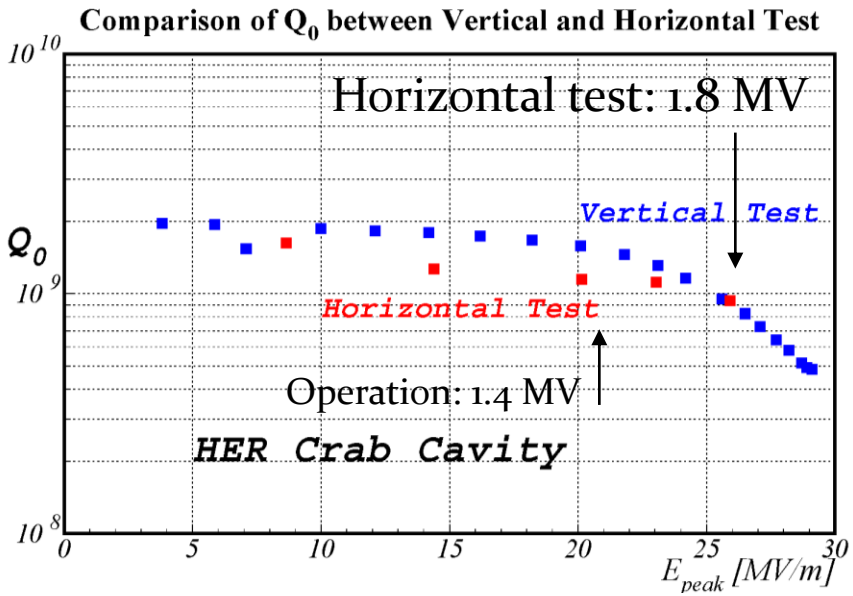
Conditioning status of LER crab

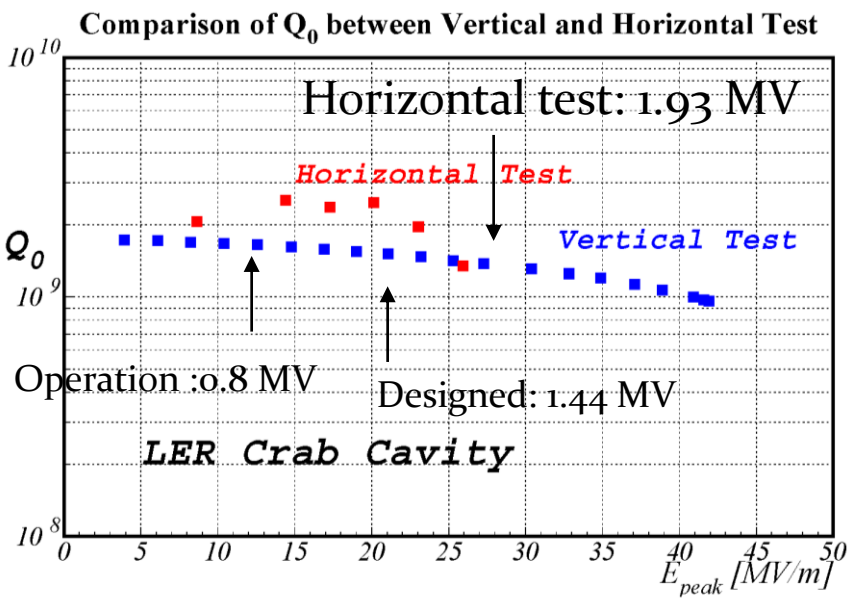


Hi power conditioning

1.93 MV reached

Qo measurement

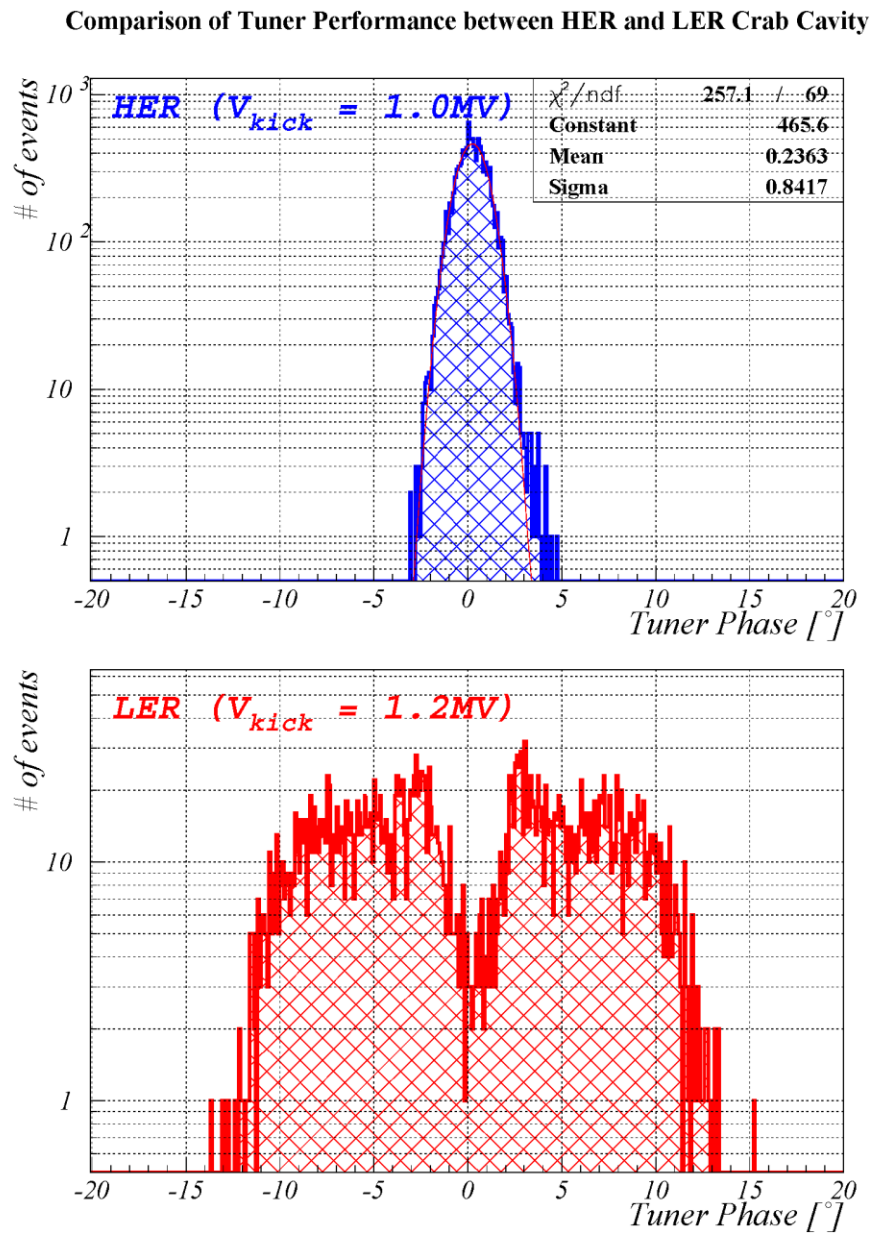




Qo of the cavity measured
Conducted by a heat load measurement method of the cryostat
Consistent with the vertical test results

Tuner phase

- Tuner phase stability
  - HER crab: +/-3 deg.
  - LER crab: +/-15 deg.
- HER tuner operates smoothly
- LER tuner has a large backlash
  - Two peaks observed
  - LLRF compensates this tuner backlash and control the crabbing phase precisely at the beam operation



Two crab cavities installed in KEKB, one for each ring in January 2007

HER (8 GeV electrons)

LER (3.5 GeV positrons)