Status of the Normal Conducting Accelerating Cavities for the MRs and DR of SuperKEKB in JFY2013

(JFY2013 starts on April 1st in CY2013 and ends on March 31st in CY2014.)

Tetsuo ABE

For SuperKEKB-RF / ARES-Cavity Group

(T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino)

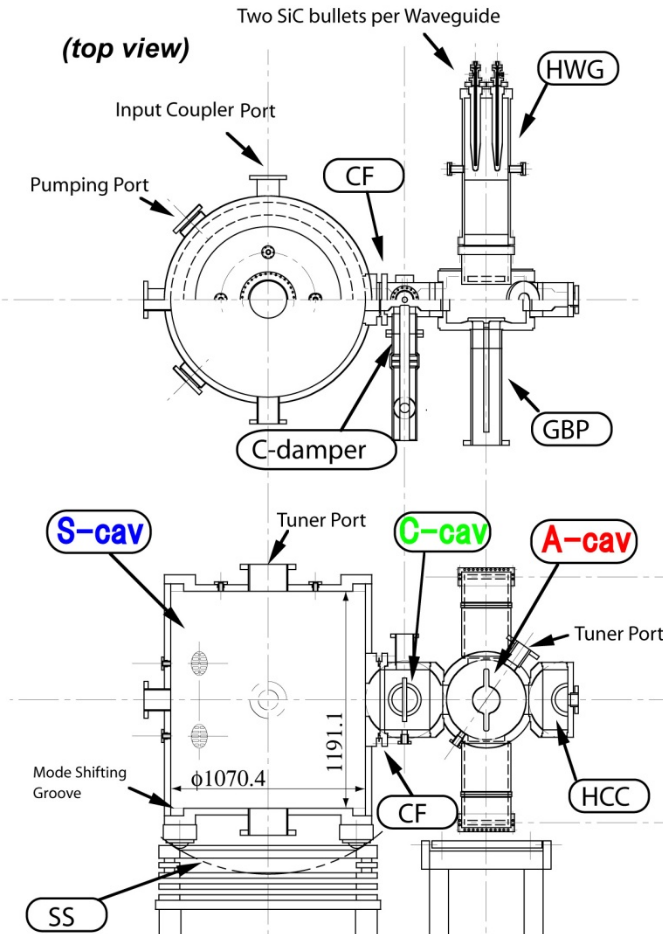
The 19th KEKB Accelerator Review Committee Meeting

March 4, 2014

Main Ring (MR) Cavities

Accelerator Resonantly-coupled with Energy Storage

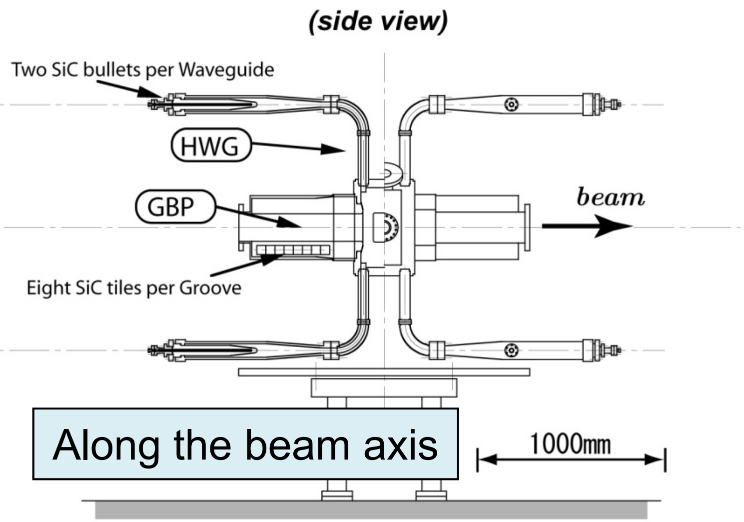
3-cavity system stabilized with the π/2-mode operation



Perpendicular to the beam axis

consists of

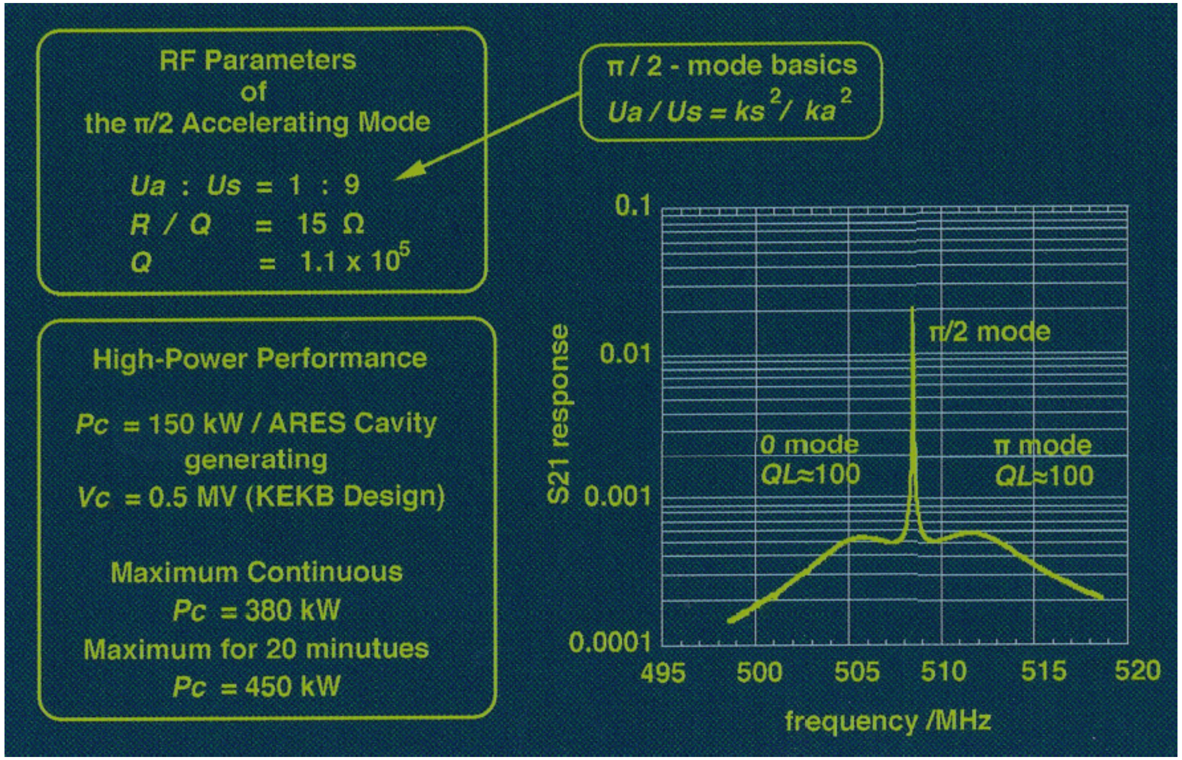
- HOM-damped accelerating cavity (**A-cav**),
- Energy-storage cavity with TE_{013} (**S-cav**),
- Coupling cavity (**C-cav**)
  with a parasitic-mode damper.

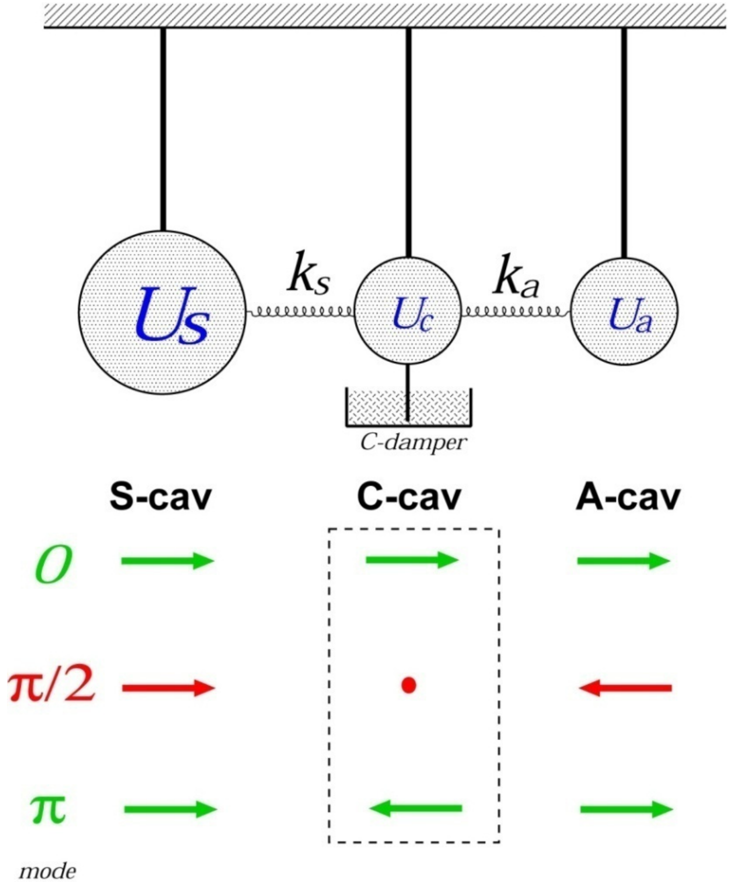


Along the beam axis

Successful Operation of the 32 ARES Cavities at KEKB

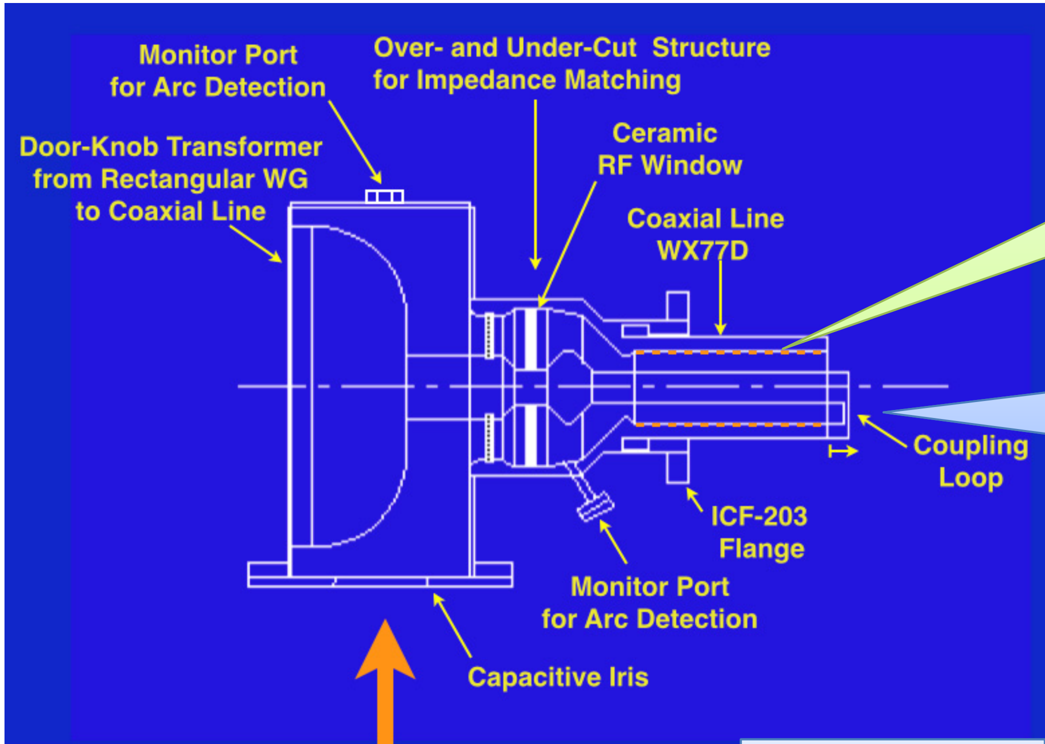
Fundamentals of the ARES Cavity System





Detuning against beam loading: $\Delta f_{\pi/2} = \dfrac{\Delta f_a}{1 + Us/Ua}$ $= \Delta f_a / 10$

ARES Cavity System / Input Coupler / Performance Upgrade



Input Coupler

Fine grooving inside the outer conductor of the coaxial line to suppress multipactoring discharge.

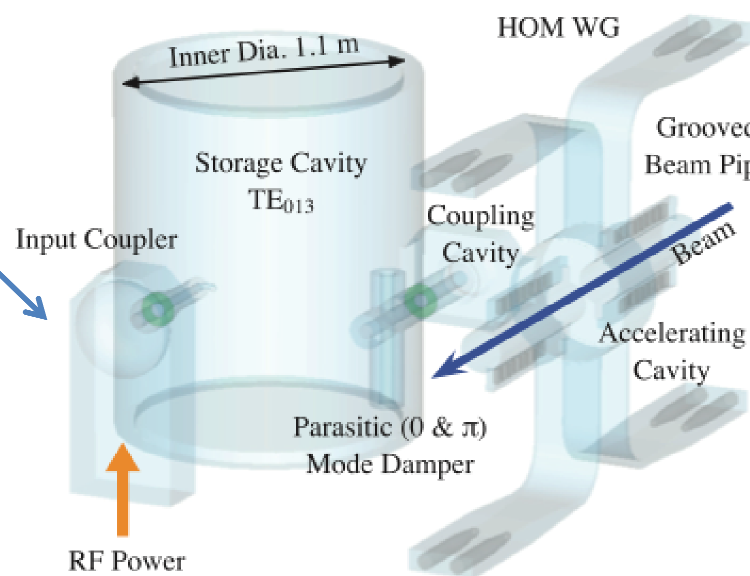
The coupling loop is extended to increase the input coupling factor.

The optimum input coupling factor β_{opt} is given by $\beta_{opt} = 1 + P_{beam}/P_c$.

Power Handling Capability (Spec.)

	P_{input}		P_c		P_{beam}
SuperKEKB	: 750 kW	=	150 kW	+	600 kW
KEKB	: 350 kW	=	150 kW	+	200 kW

P_c = 150 kW generating V_c = 0.5 MV per ARES cavity.

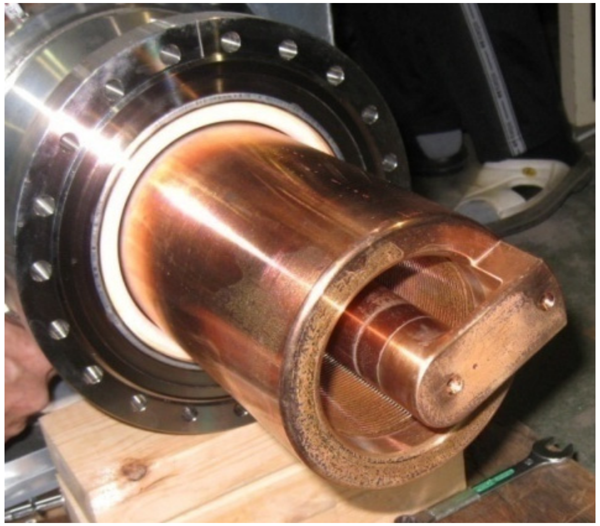


3D Transparent View of ARES Cavity System

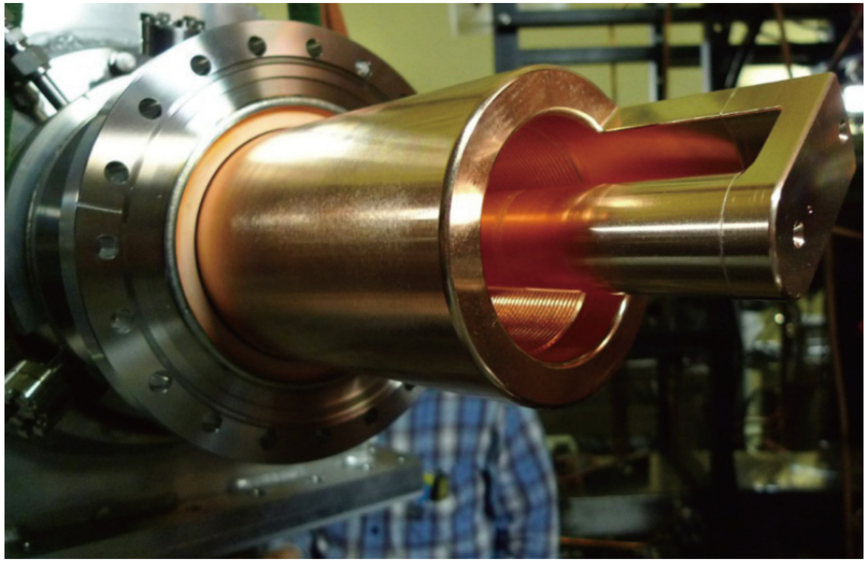
T. Kageyama

Increasing the Input Coupling Factor

Input couplers with increased input coupling (β_{max} = 5→6) needed for the stations with the Klys:Cav=1:1 configuration to accelerate beams with the design currents (Appendix A).



Used at the KEKB-MRs



With increased input coupling for the SuperKEKB-MRs

Typical cycle time of RF conditioning for one coupler

Includes:

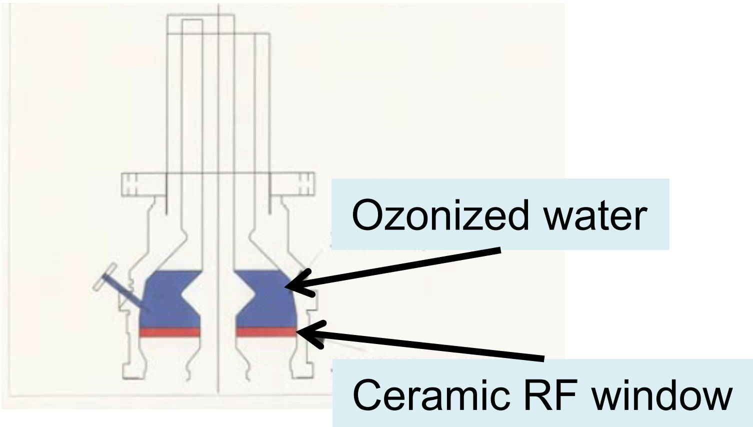
1) Setup & low-level measurements : 2 days (net time: 8x2 = 16 hours),
2) Vacuum evacuation : 4-5 days (about 100 hours), and
3) RF conditioning up to P_{in}= 750 - 800 kW : 15 days (weekdays only, net time: 8x15 = 120 hours),

so that the cycle time is 1) + 2) + 3) + weekends = **4 weeks**.

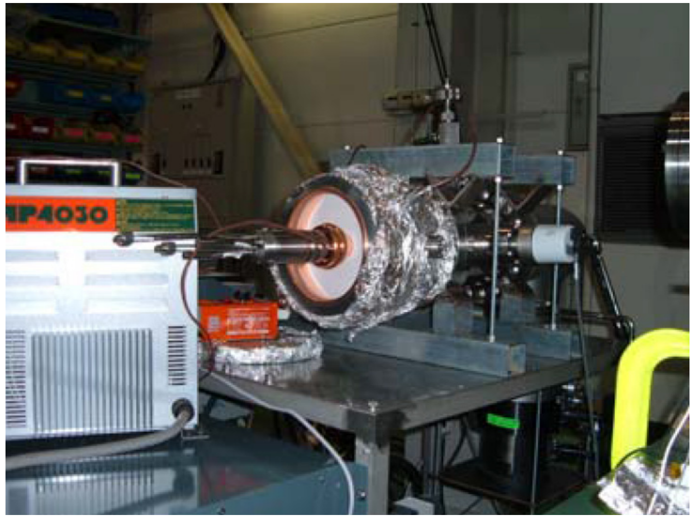
We have applied ozonized water rinsing (OWR) of ceramic RF windows, followed by Baking

✓*Based on the recipe for the SCC couplers*
✓*In parallel to HTP*

1. Ozonized water rinsing (5 – 10 min)



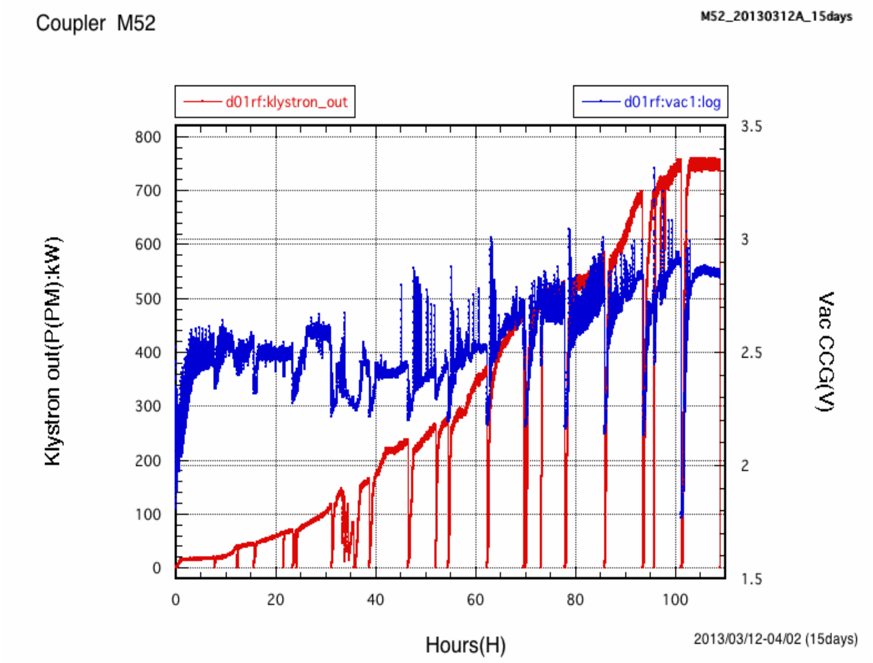
2. Baking (150degC x one week)

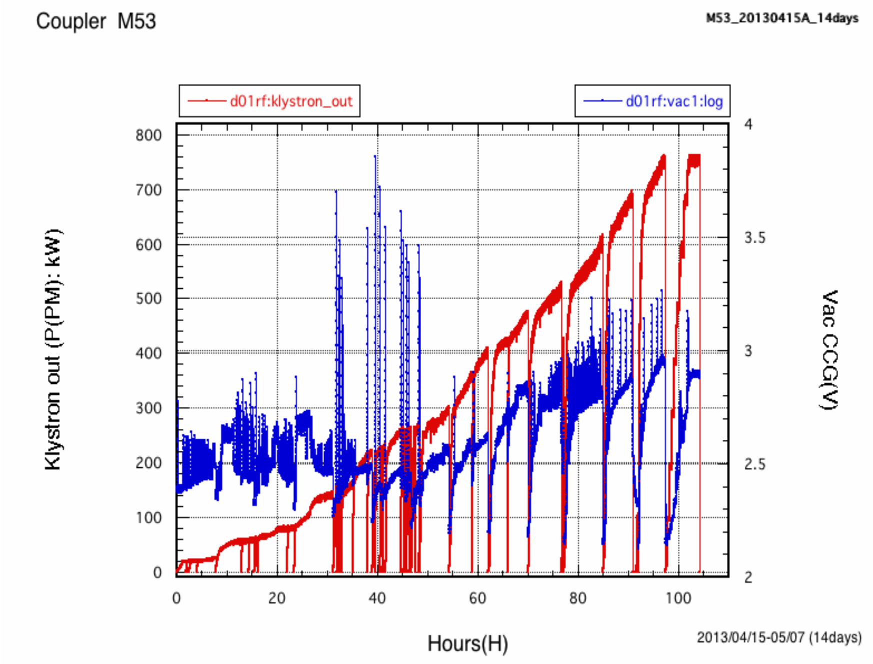


HTP

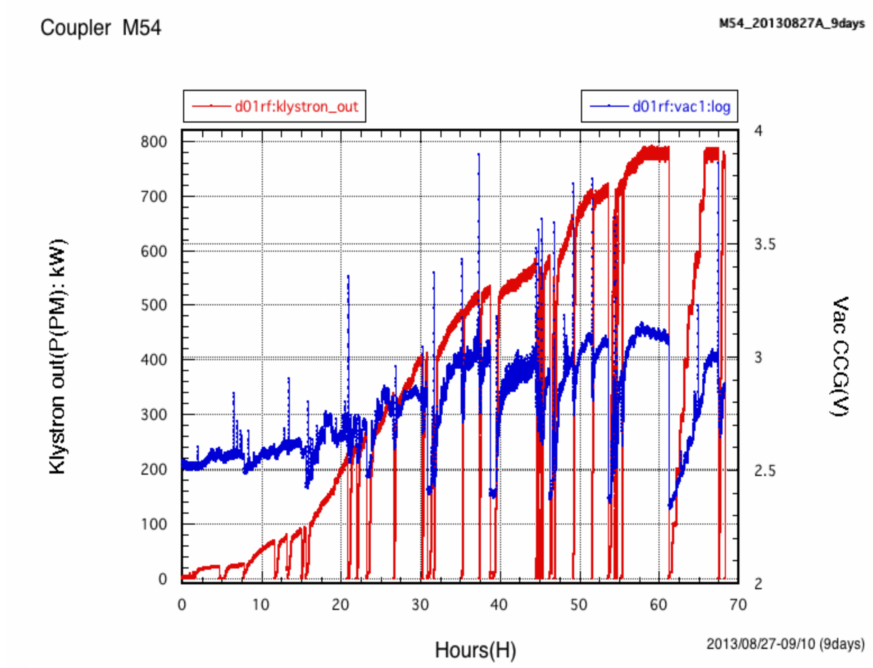
For more details, see
H. Sakai et al., "Ozonized Water Rinsing of RF Windows" (Japanese),
in the Proceedings of the 4th Annual Meeting of Particle Accelerator Society of Japan
and the 32nd Linear Accelerator Meeting in Japan (August 1-3, 2007, Wako, Japan).

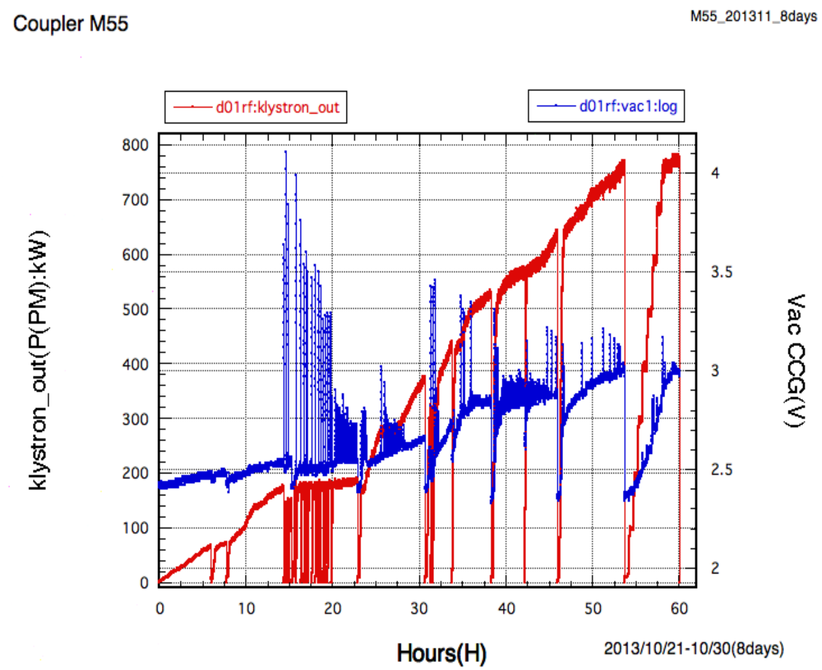
Without OWR+Baking





With OWR+Baking





Typical cycle time of RF conditioning for one coupler

Includes:

1) Setup & low-level measurements : 2 days (net time: 8x2 = 16 hours),
2) Vacuum evacuation : 4-5 days (about 100 hours), and
3) RF conditioning up to P_{in}= 750 - 800 kW : 15 days (weekdays only, net time: 8x15 = 120 hours),

so that the cycle time is 1) + 2) + 3) + weekends = **4 weeks**.

← **OWR+Baking**

Includes:

1) Setup & low-level measurements : 2 days (net time: 8x2 = 16 hours),
2) Vacuum evacuation : 4-5 days (about 100 hours), and
3) RF conditioning up to P_{in}= 750 - 800 kW : 8 days (weekdays only, net time: 8x8 = 64 hours),

so that the cycle time is 1) + 2) + 3) + weekends = **3 weeks**.

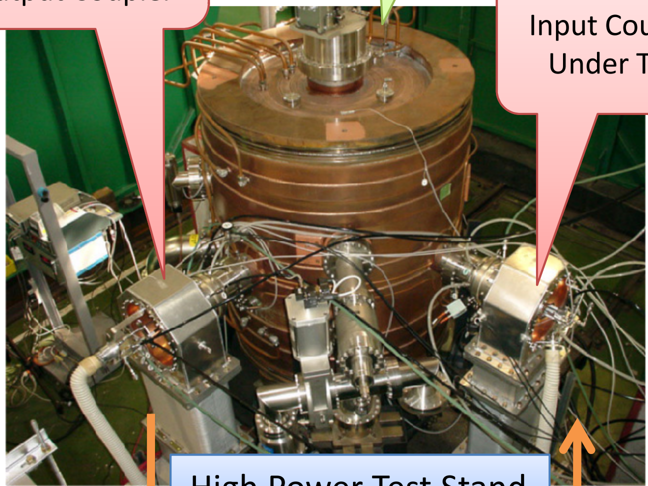
ARES Cavity System / Input Coupler / Production & Processing

T. Kageyama (updated by T. Abe)

ARES Storage Cavity

Input Coupler used as Output Coupler

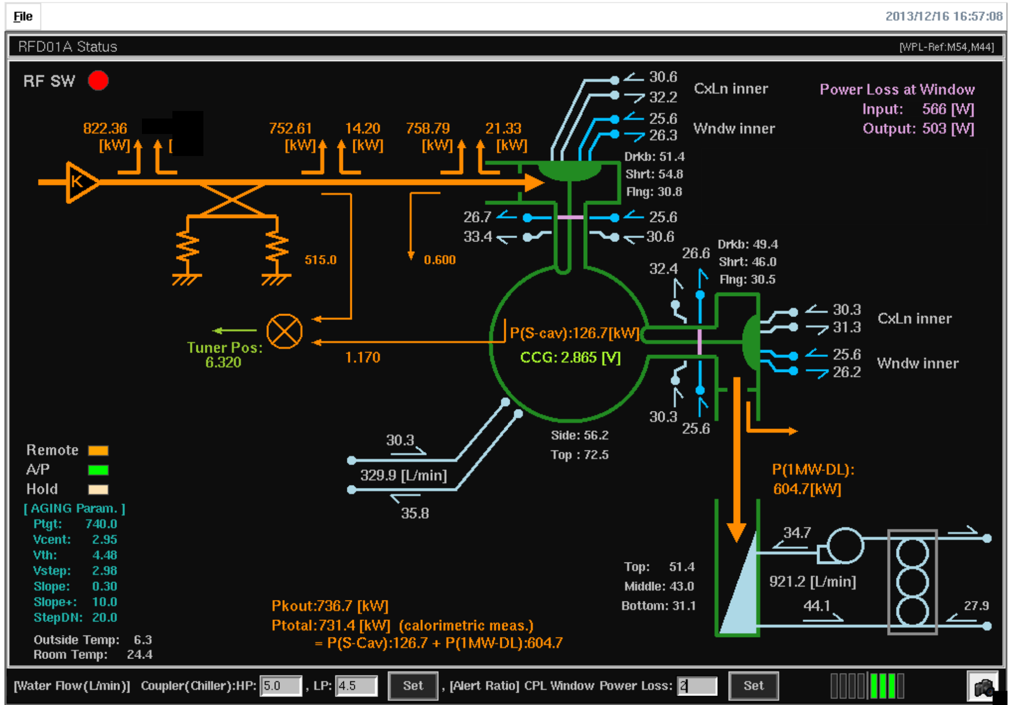
Input Coupler Under Test



High Power Test Stand

To 1MW Water Load

RF Power from 1MW CW Klystron (TOSHIBA E3786)



Snapshot of Status Monitor for RF Processing

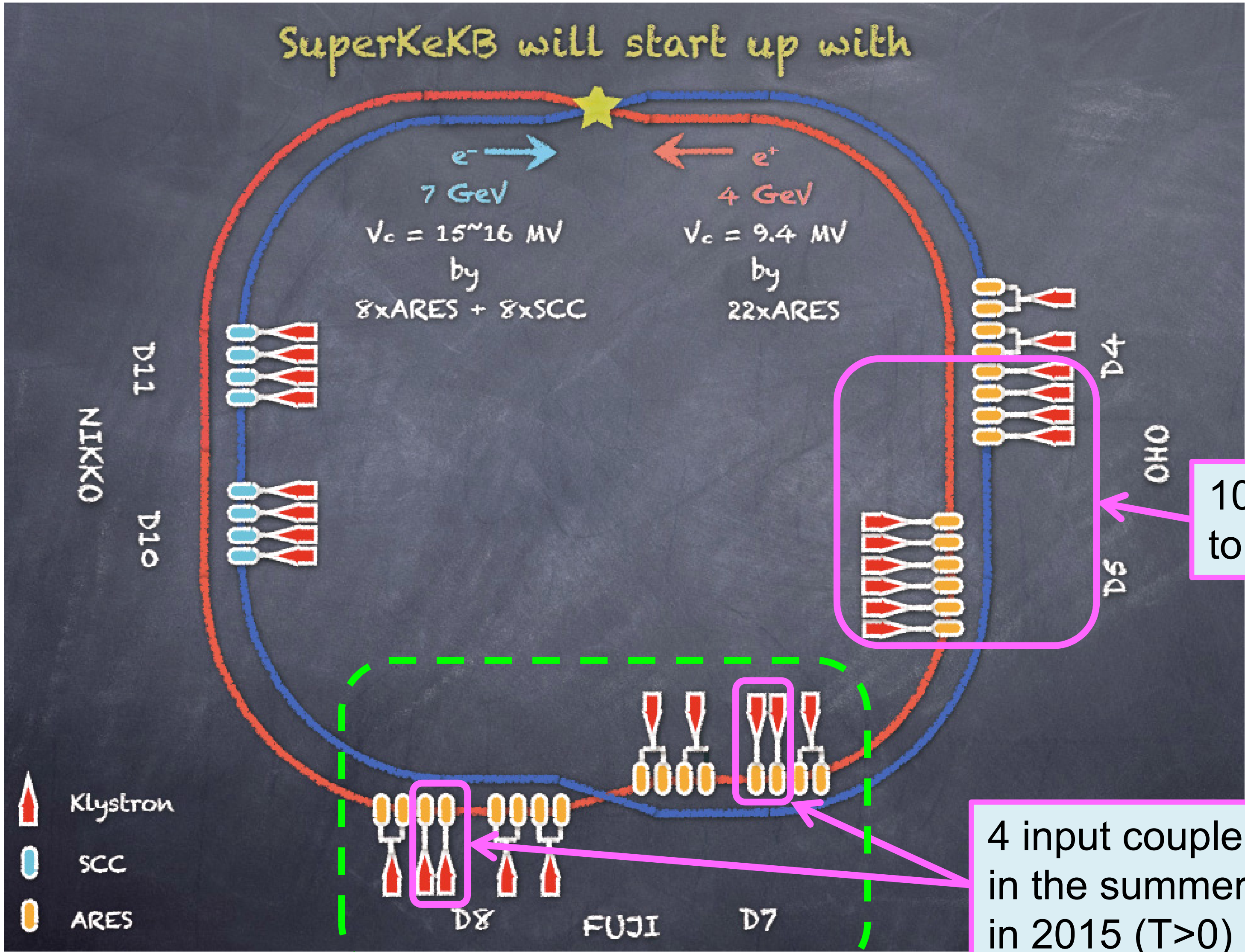
Created by Mikio Tanaka (Mitsubishi SC) under the supervision of T. Kageyama

Status & Plans

- So far, 11 couplers have been processed up to 750-800 kW.
- Now, one coupler being processed.
- By this March, one more coupler to be processed.
- Couplers existing in the MR tunnel will be replaced with new ones for the stations with Klys:Cav=1:1 configuration.

For “T=0” in the 4th Quarter of JFY2014

JFY2014 starts on April 1st in CY2014, and ends on March 31st in CY2015.



10 input couplers to be replaced in T<0

4 input couplers to be replaced in the summer shutdown in 2015 (T>0)

No vacuum break since the KEKB operation ended.

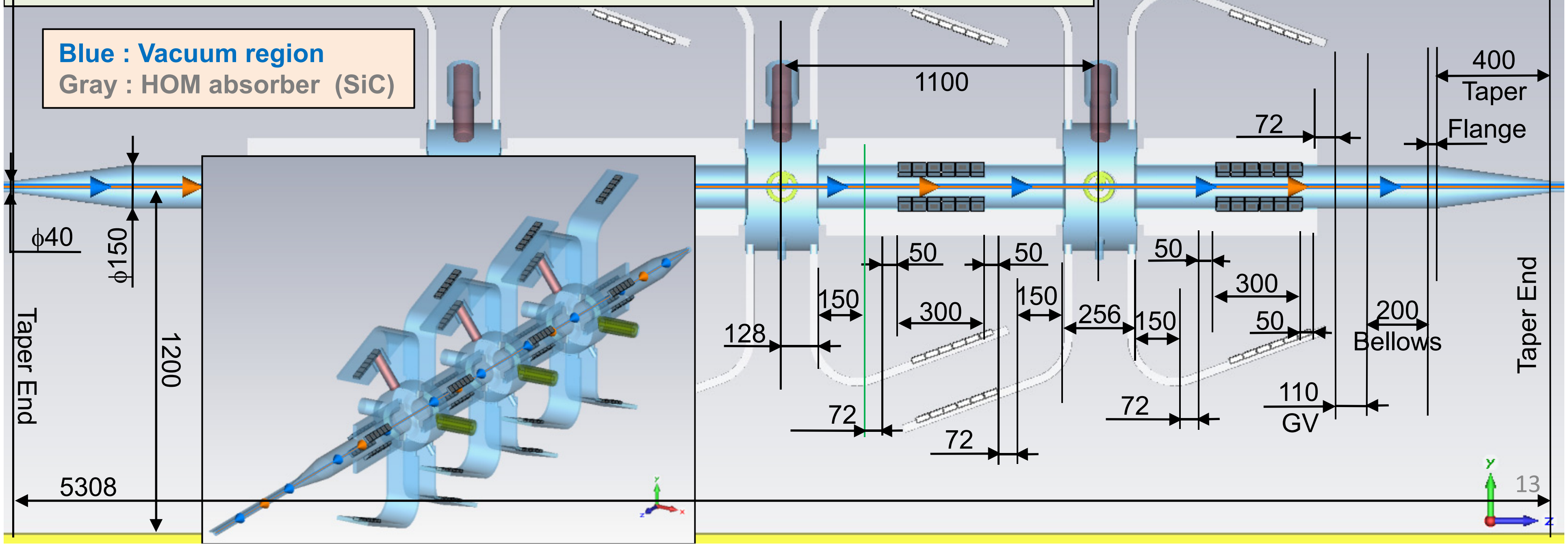
Damping Ring (DR) Cavities

RF Accelerating Structure for the DR

Based on the ARES cavity with the long successful operation at KEKB

1. Accelerating-Mode Frequency: 508.887[MHz] (same as for the MRs)
2. ~~Cavity Voltage (spec.): 0.7[MV/cav] (→Wall-loss power: ~120kW/cav)~~
3. Cavity Voltage (spec): 0.8[MV/cav] (→Wall-loss power: ~150kW/cav) → We can supply total V_c : 2.4MV at maximum.
4. Max. stored beam current: 70.8[mA] → Very low compared to the (Super)KEKB-MRs
5. HOM absorbers: Silicon Carbide (SiC) tiles (Appendix B) → More compact than the SiC bullets
6. Grooved Beam Pipe (GBP) common between cavities
7. Cavity-GBP Joint with a weld-ring gasket (not using a usual flange)
8. *"Multi Single Cell"* structure
9. Reuse of high-power input couplers and tuners proven at KEKB-MRs/ARES
10. Good vacuum in cav. (~10^-6[Pa]) needed for high-power input couplers → Pumping port on each cavity
11. Loss factor (incl. the taper sections): 2.4 [V/pC] (for σ_z=6.0mm)
12. No coupled bunch instabilities (CBIs) due to this structure occur (Appendix C).

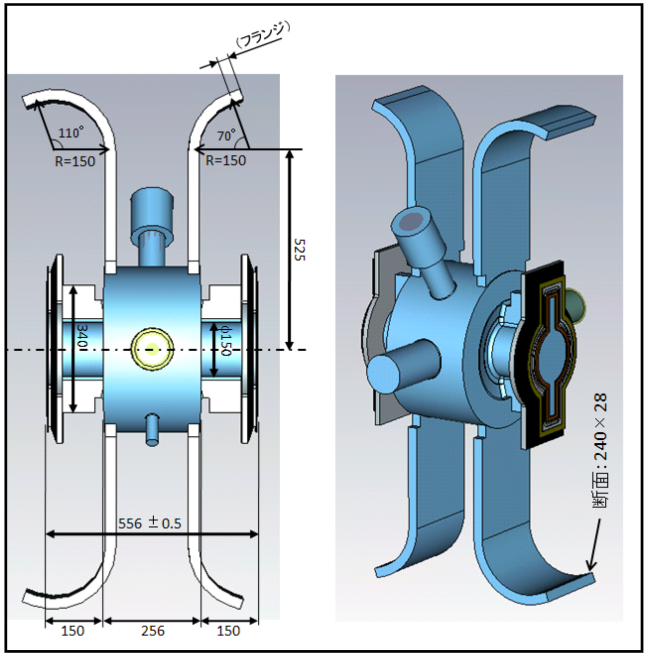
(Dimensions in mm)



Cavity No.1

Low- and High-Power Test Results

✓Made in JFY2012
✓Tested in JFY2013



f_a = 508.887 MHz
R_{sh}/Q_0 = 150 Ω
Q_0 ≈ 30000

←Appendix D

← Just after the delivery,
Cooling pipes not yet attached

The Endplates of Cavity No.1 Electro-Polished (EP)

✓Material: OFHC(class1)

✓Etching: 40μm

(Skin depth@500MHz: 3μm)

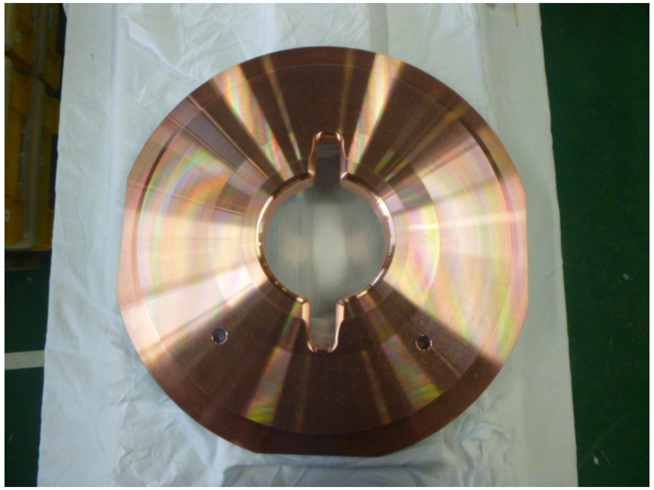
Before EP

R_a=~1.5μm

After EP

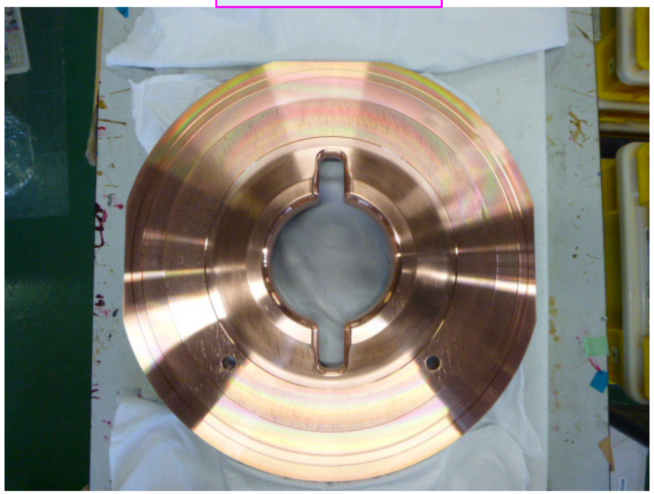
R_a=~0.2μm

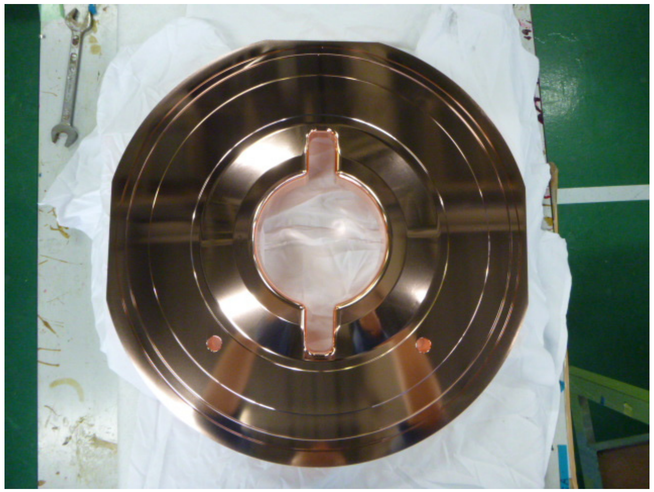
Endplate
w/o the tuning bump



ϕ500mm

Endplate
w/ the tuning bump

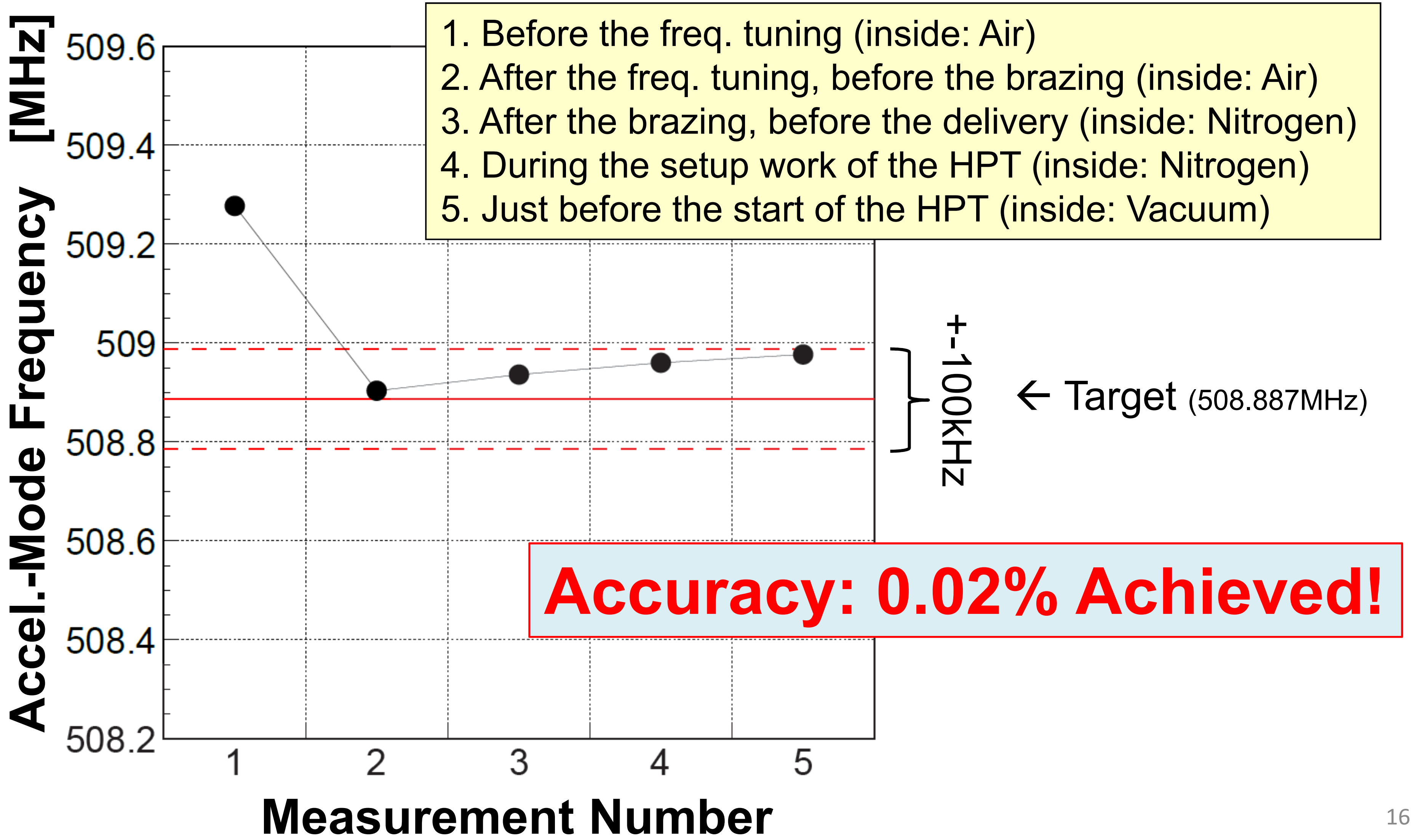




Low-Power Measurements (1/2)

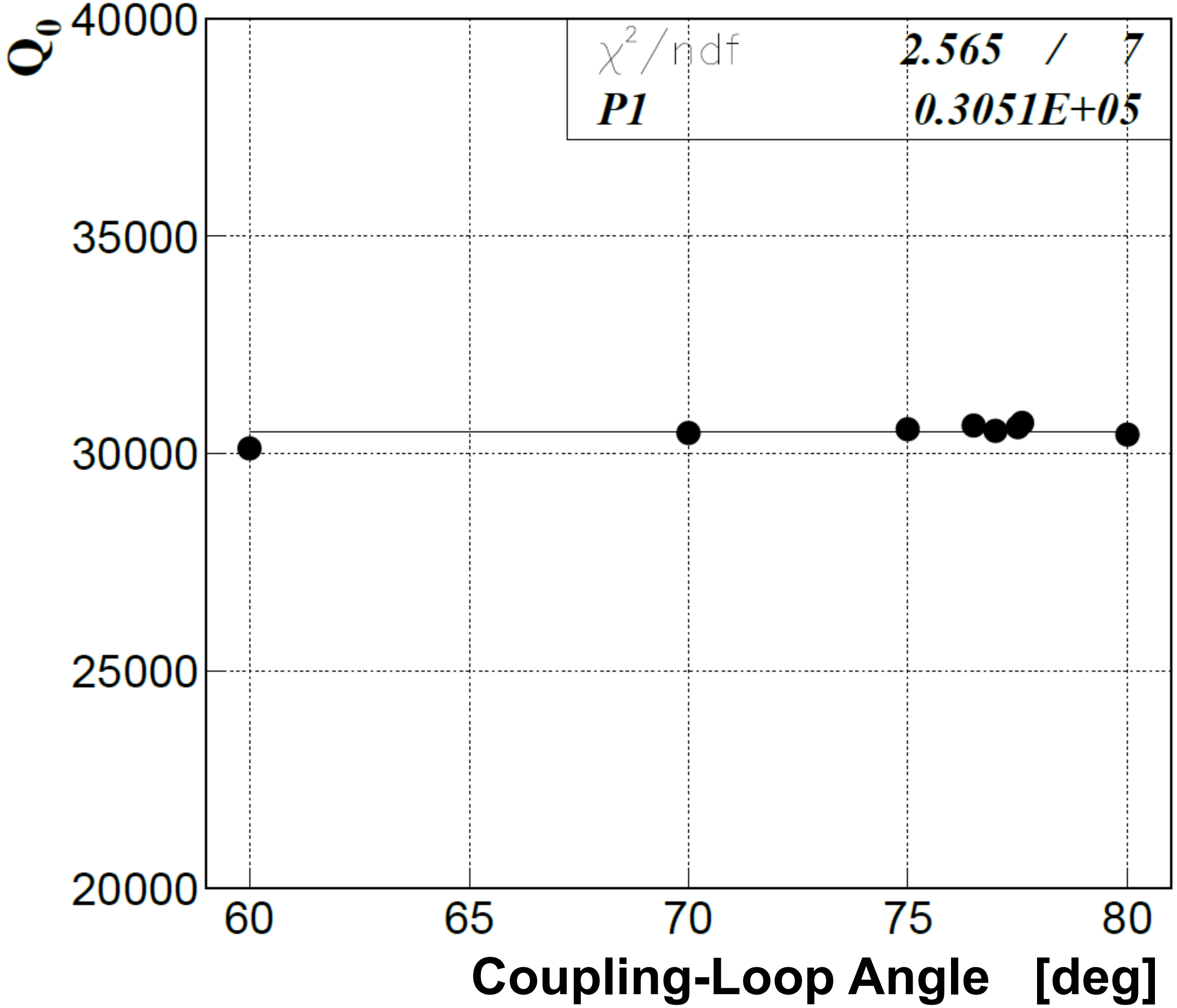
Accel.-Mode Frequency

(converted to one with 30degC & vacuum inside)



Low-Power Measurements (2/2)

Unloaded Q-factor (Q_0)



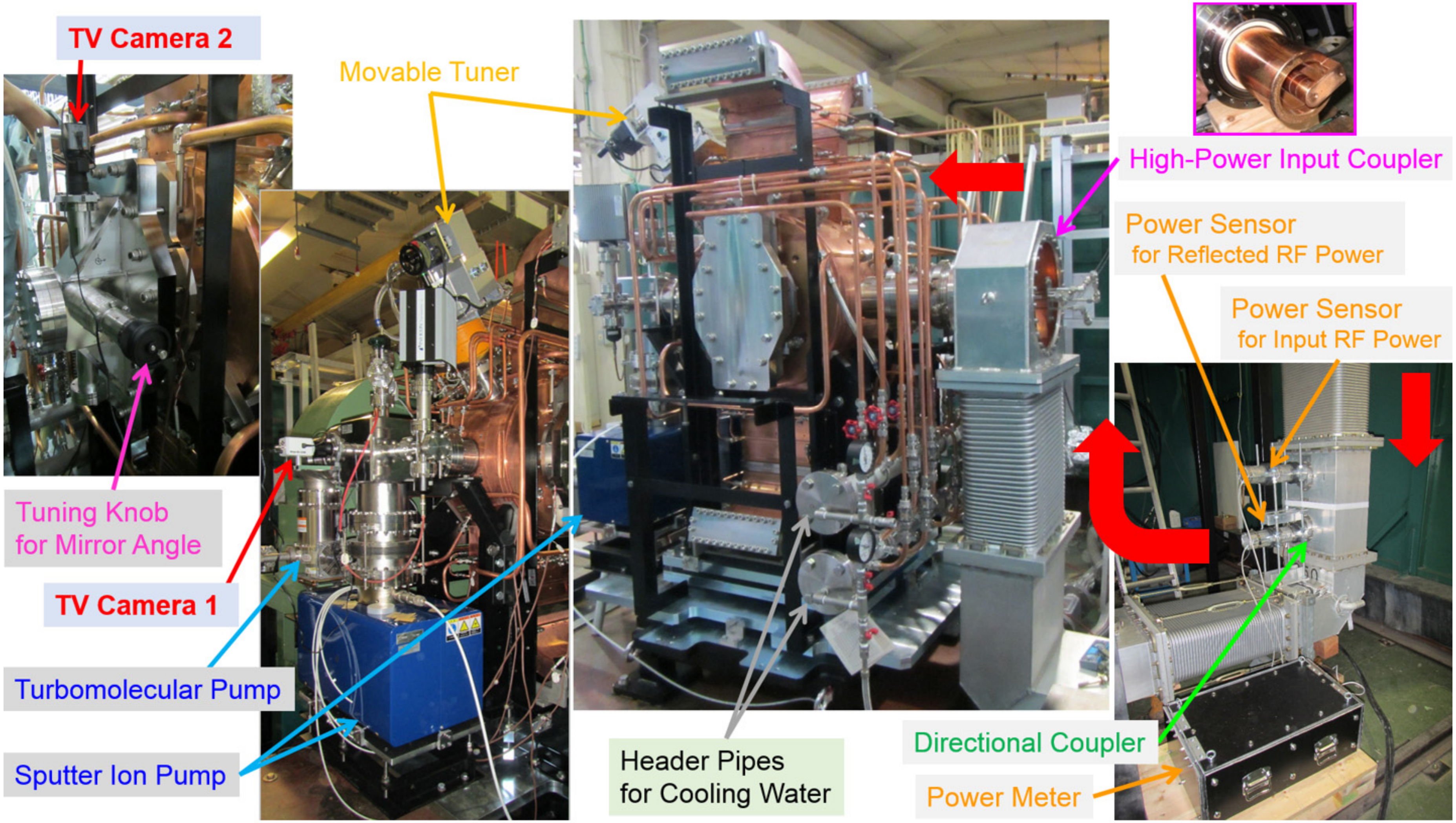
(Tuner Pos.:15mm)

←97%IACS

(Cf. 93%IACS for Prototype)

Setup of the HPT

is the same as that of the prototype (Cavity No.0)
except for the control system improvements



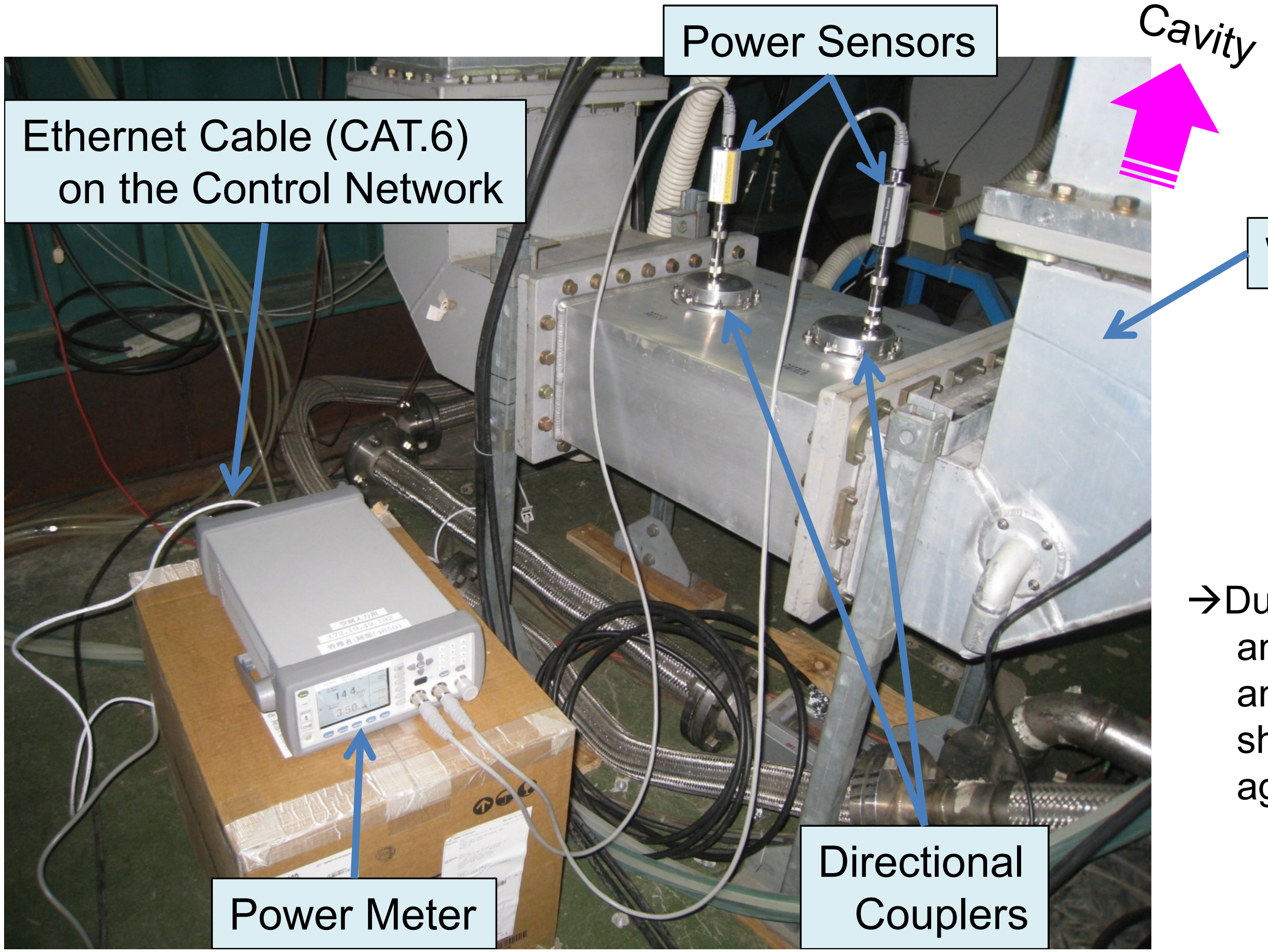
Control System Improvements to solve the RF Power Fluctuation Problem(Appendix E)

(I) We measured P_{in} and P_{refl} with power sensors directly connected to the directional coupler in the radiation shield,
then transmit the values via the LAN to the D1 control room in digital.

(II) We laid new coaxial cables from the radiation shield to the D1 control room for P_{in} and P_{pickup} (used in the feedback) and P_{refl} (used in the I/L).

(I) RF Power Measurements of P_{in} and P_{refl} close to the Cavity in the Radiation Shield of D1-A Test Stand

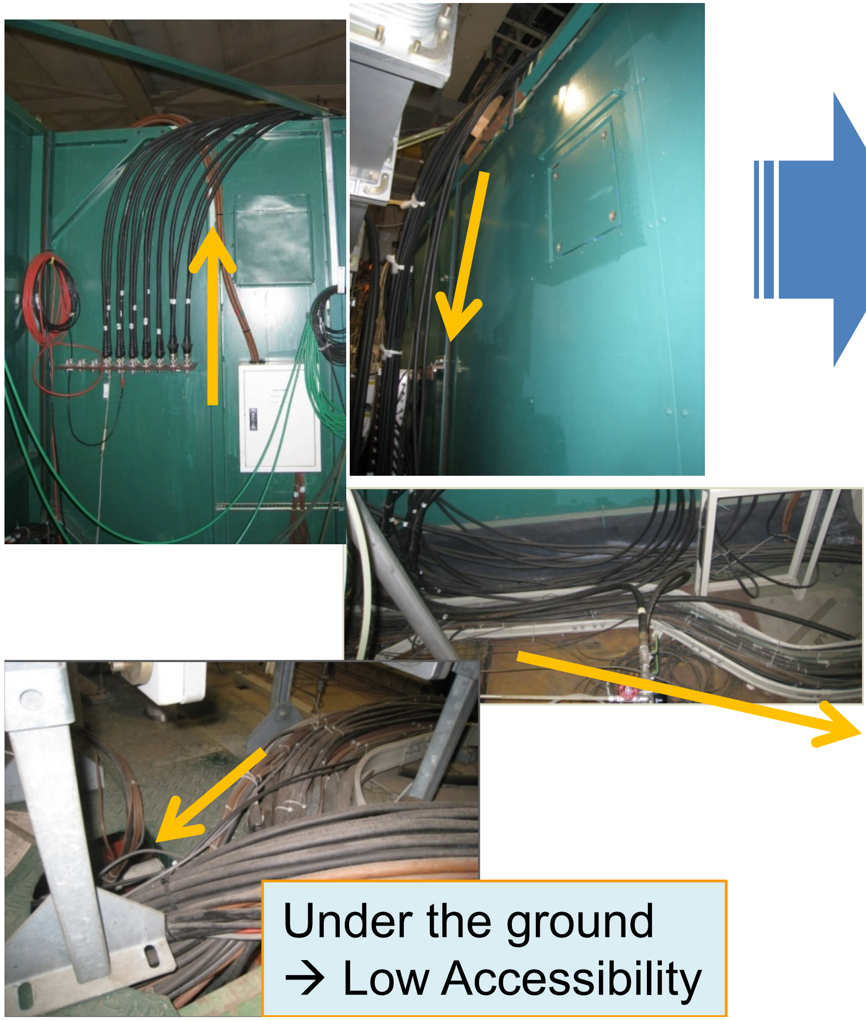
- ✓ The power sensors are directly connected to the directional coupler.
- ✓ The power meter is also put in the shield with its ethernet interface connected to the control network.



→During this HPT, the sensors and meter were surrounded and protected with lead sheets (5-10mm thickness) against radiation.

(II) Coaxial Cables:
Radiation Shield <-> D1 Control Room

OLD
✓Laid ~30 years ago
✓~70m-long cables of 10D-WF-H50-S4
✓Total cable loss (meas.) : ~5.2dB (> spec.: ~3.6dB)



Under the ground
→ Low Accessibility

NEW
✓Laid in Jan., 2013
✓91m-long cables of 10D-WFLEX-FR
✓Total cable loss (meas.) : 4.4dB (< spec.: 5.5dB)

Above the ground
→ High Accessibility

Control System Improvements to solve the RF Power Fluctuation Problem(Appendix E)

(I) We measured P_{in} and P_{refl} with power sensors directly connected to the directional coupler in the radiation shield,
then transmit the values via the LAN to the D1 control room in digital.

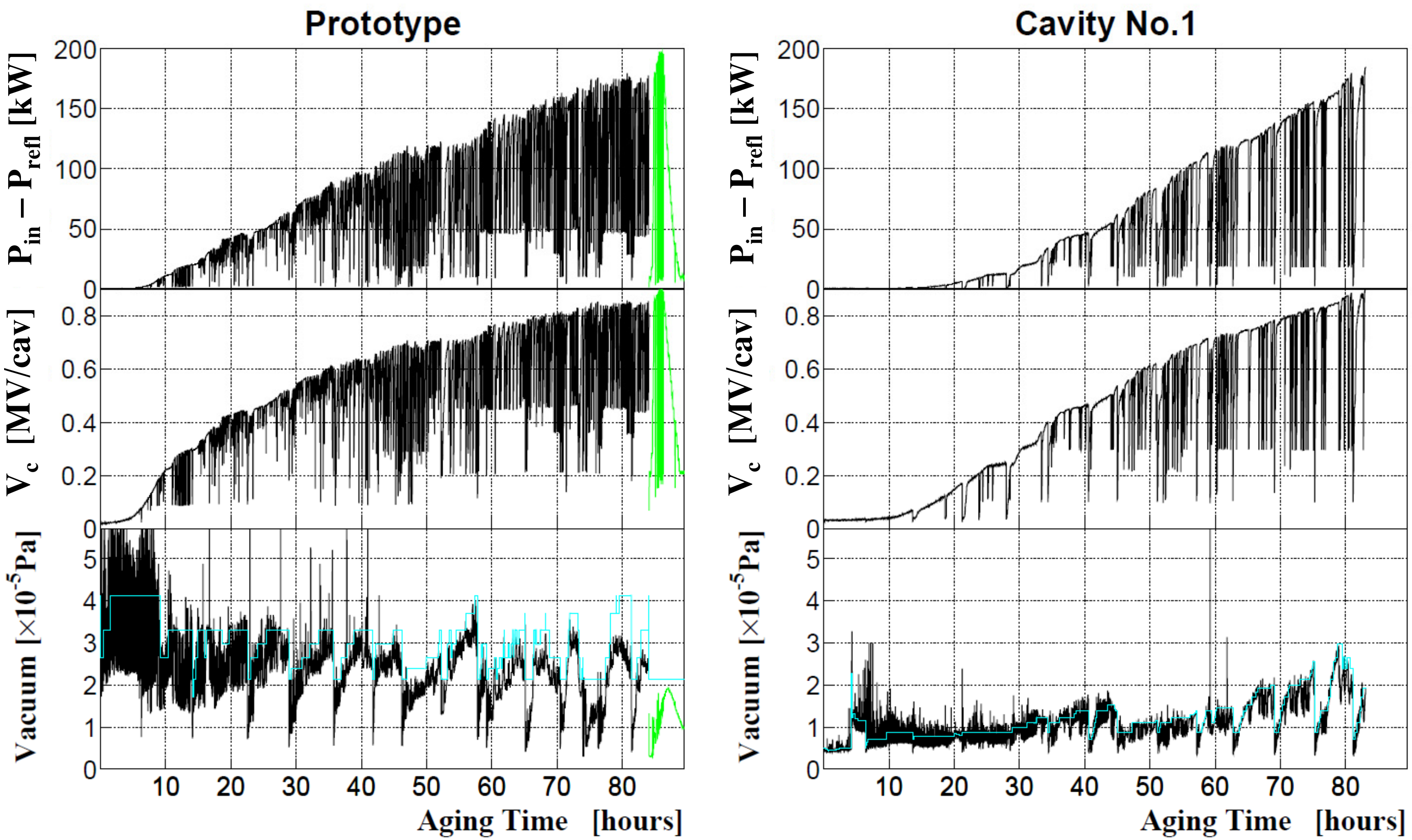
(II) We laid new coaxial cables from the radiation shield to the D1 control room for P_{in} and P_{pickup} (used in the feedback) and P_{refl} (used in the I/L).

No RF Power Fluctuation During this Test!
→ Ready for V_c-holding endurance tests with this improved environment

Just before the start of the HPT

Almost Full Radiation Shield

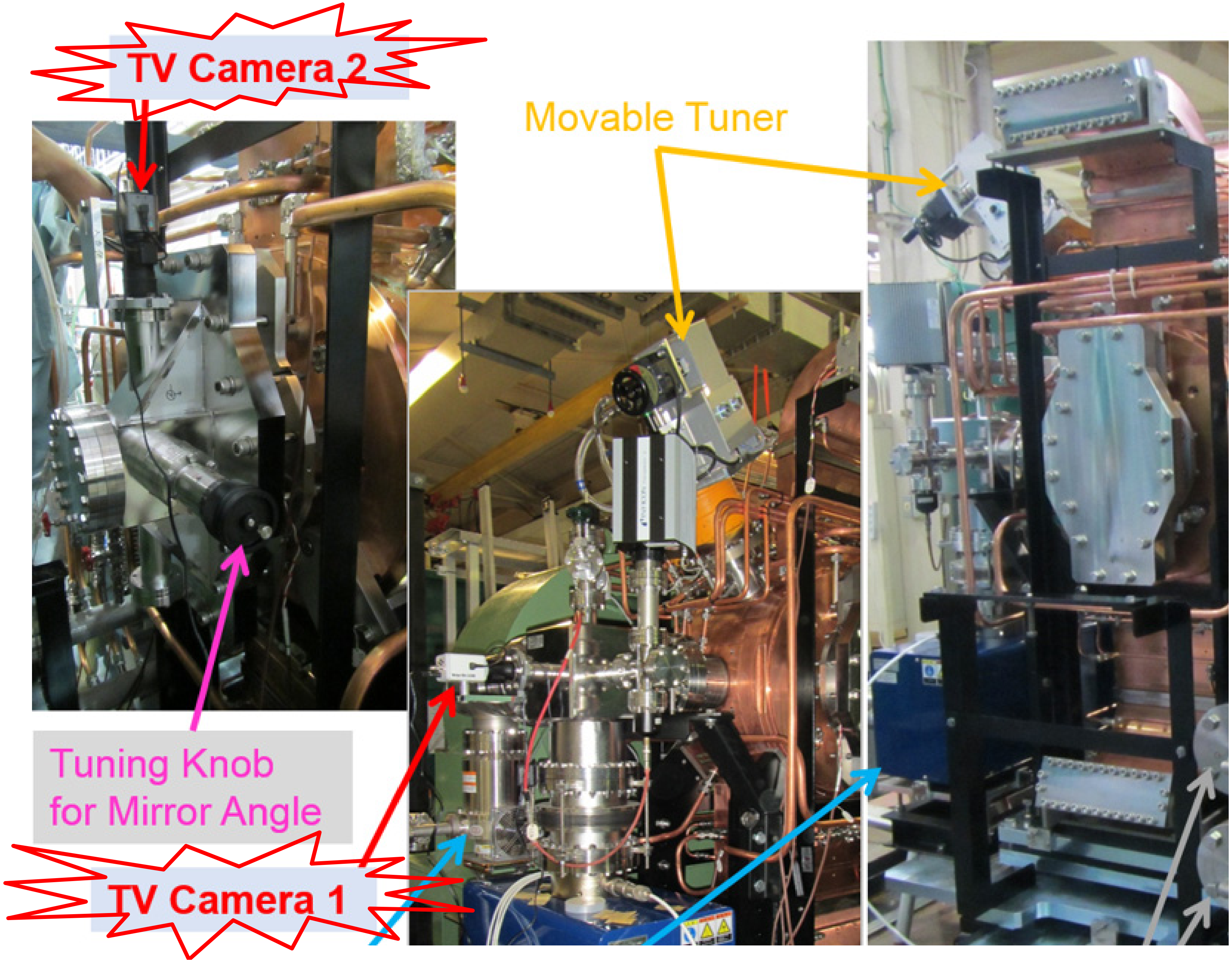
Aging Histories up to V_c=0.9MV/cav



The light blue lines indicate the reference vacuum pressure specified by the computer controlled automatic aging. If the vacuum pressure is higher than the reference, P_{in} is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{in} is slightly stepped up as long as the vacuum pressure is lower than the reference.

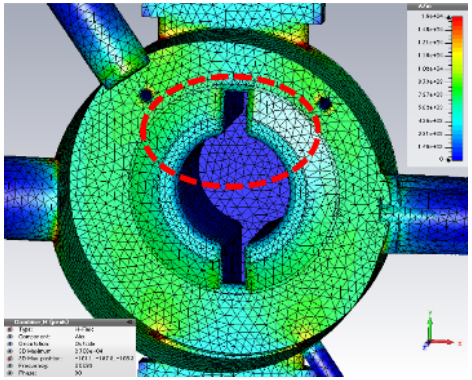
- ✓ P_{in} (P_{refl}) : input power to (reflected power from) the cavity
- ✓ Wall-loss power: $P_{wall} = P_{in} – P_{refl}$ = ~0.99 x P_{in}
- ✓ V_c calculation described in Appendix F
- ✓ The prototype cavity was not electro-polished.
- ✓ Better performance with electro-polishing for Cavity No.1
  → Lower vacuum pressure and lower trip rate
- ✓ **Smooth conditioning for Cavity No.1**

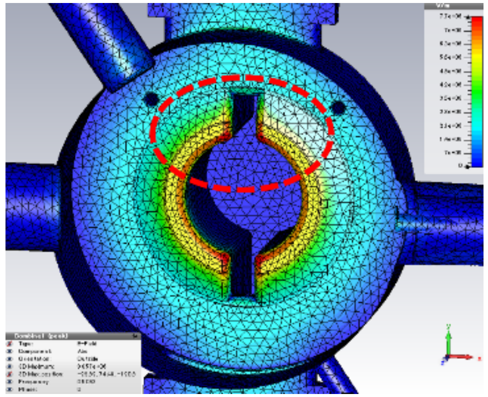
Setup of the HPT



TV Camera Footages
when the I/L with P_{refl} worked

Time series: T1 → **T2** (I/L) → T3 → **T4** (I/L)


Surface Magnetic Field

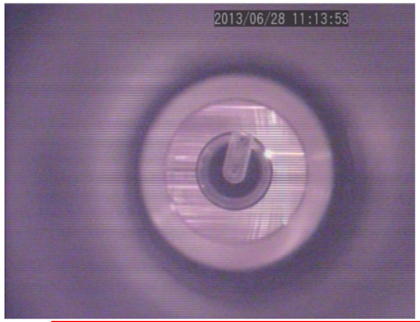

Surface Electric Field

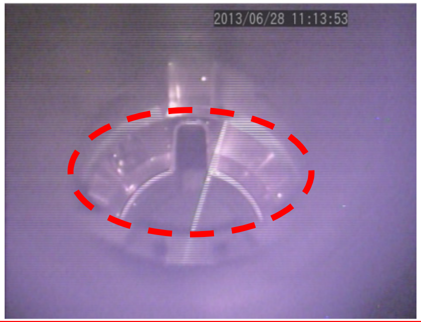
(V_c=0.82MV/cav) Lightning!

T3

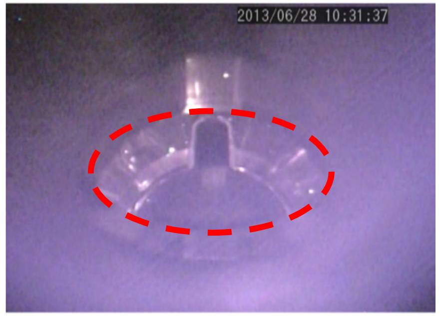
TV Camera1 TV Camera 2

T4





Explosion! (V_c=0.82MV/cav)



T1

TV Camera1 TV Camera 2

T2

As the conditioning progressed, these phenomena disappeared.
→Conditioning progress confirmed also visually

V_c-Holding Endurance Test

V_c [MV/cav]	Wall-Loss Power [kW]	Total Holding Time [hours]	Number of Cavity Trips (Appendix G)
0.80	144	30.5	1
0.85	164	18	0
0.90	186	14.5	3
0.95	210	8	1

Time series ↓

(No vacuum-pressure spikes during this test)

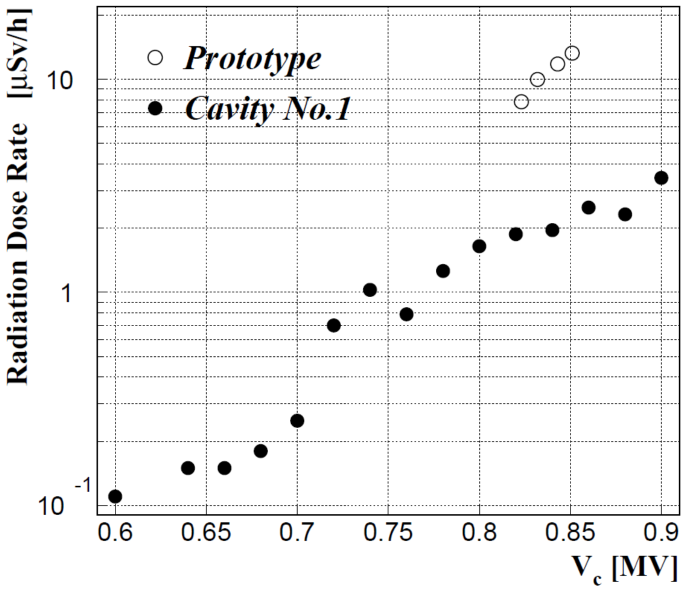
⇒ **Stable operation with V_c=0.8MV/cav verified**

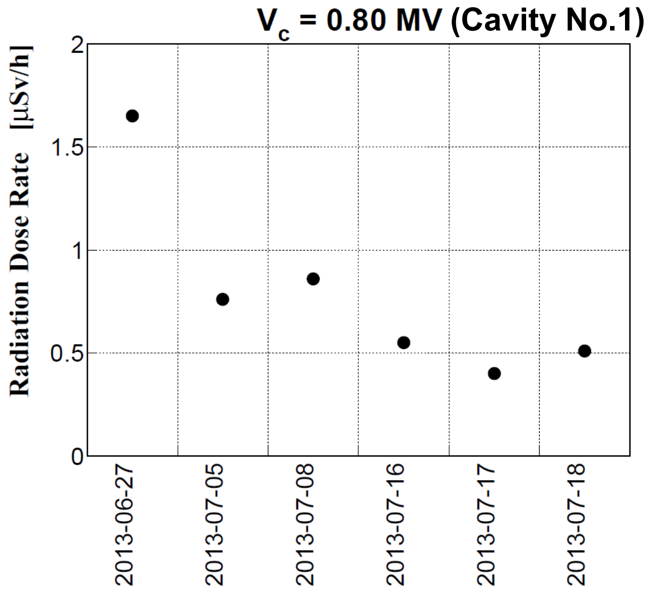
- ☐ **Further conditioning effect expected**
- ☐ **No performance limit observed during this test**

Effects of EP Observed

Comparing the results between the Prototype and Cav.No.1

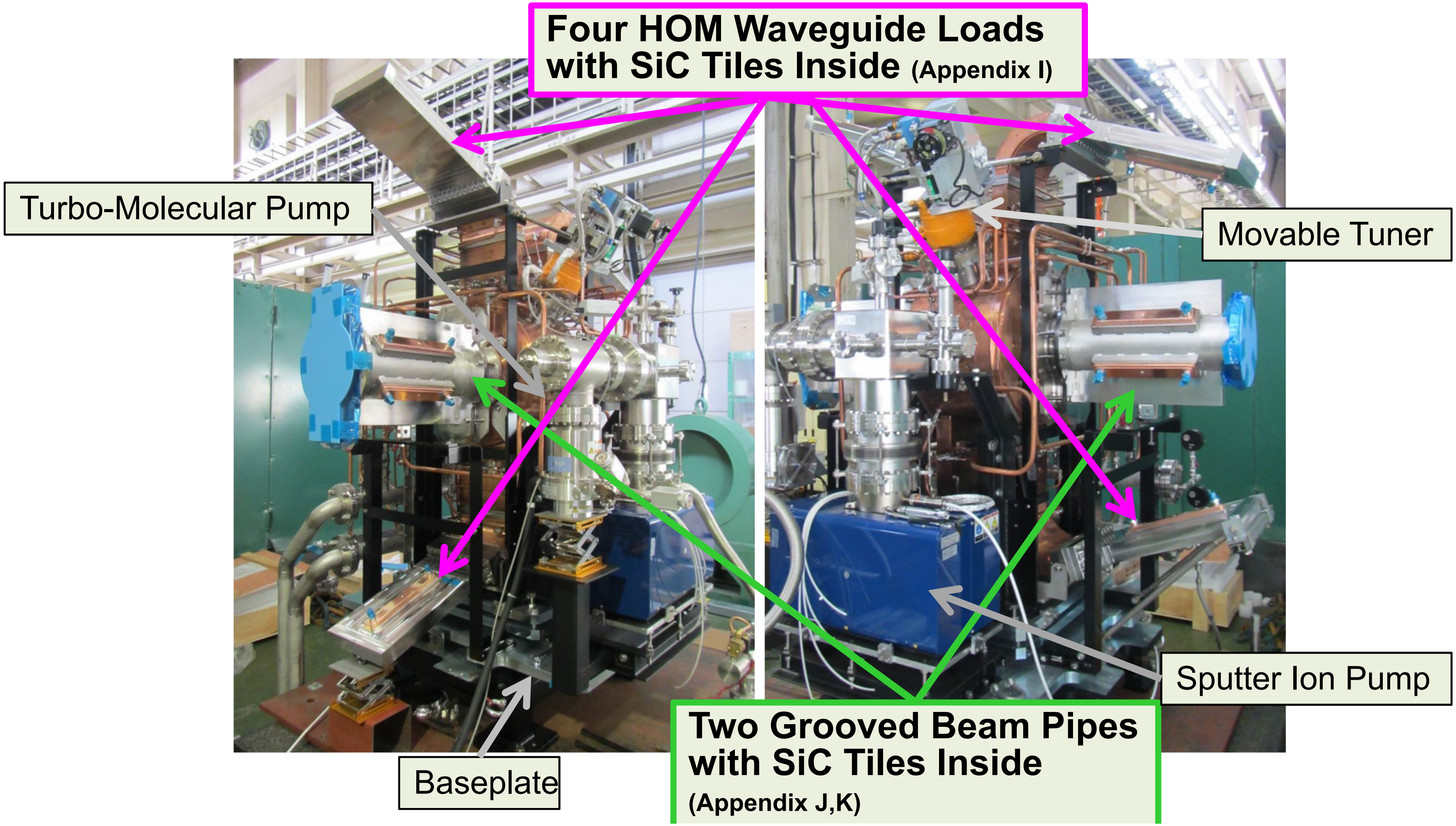
1. Higher Q_0
2. Lower vacuum pressure during the HPT
3. Lower cavity trip rates
4. Lower radiation
   - Less field emission
   - Smaller local-field enhancement factors



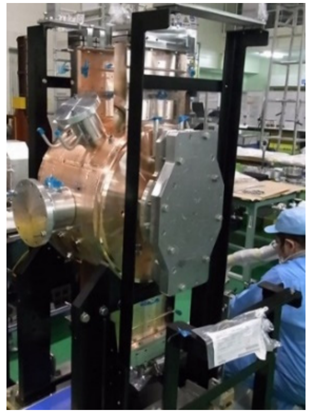


(Measured, in the radiation shield, at the same position about 2m away from the cavity)

Mounting Test with the HOM Waveguide Loads and Grooved Beam Pipes has been Performed Successfully with Vacuum Sealing.



Status of Cavity No.2



- Passed a final vacuum leak test after the brazing
- RF performance (low-power) after the brazing: OK

	Cavity No. 2 (preliminary)	Cavity No.1 (published)
f_a	509.007MHz ($=f_0$+120kHz)	508.977 MHz ($=f_0$+90kHz)
Q_0	30792（98%IACS)	30506 (97%IACS)

(f_0=508.887MHz)

- Being fabricated almost in the final stage
- To be High-Power Tested in May-June, 2014.

Summary on the DR Cavities

1. **The accelerating structure for the DR**
   - Based on the KEKB-MR/ARES cavity with the long successful operation at KEKB
   - Cavity No.0 (prototype) made in JFY2011, and tested in JFY2012
   - Cavity No.1 made in JFY2012 based on the prototype, and tested in JFY2013
   - Cavity No.2 being made in JFY2013
2. **Results of the High Power Test of Cavity No.1**
   - Smooth conditioning up to V_c=0.95MV/cav (P_{wall}=210kW)
     - ✓ V_c limited by the radiation regulation for this test stand
   - Clear effects of EP observed
   - Stable operation with V_c=0.8MV/cav verified
   - No performance limit observed up to V_c=0.95MV/cav

   →"Pass"
3. **High-Power Test of Cavity No.2**
   - To be performed this coming spring

Schedule of the MR and DR Cavities
in JFY2014

MR cavities related
DR cavities related

- **CY2014**
  1. **Apr.**
     - **Setup change of the test sand (D1-A): coupler → DR cavity**
     - **Installation of two "new" cavities (kept as spares) to the beam line in the OHO D4 RF section, including lip welding and alignment**
  2. **May**
     - **Installation of six used cavities (moved HER→LER) to the beam line in the OHO D5 RF section, including lip welding and alignment**
  3. **May – June : HPT of DR Cavity No.2 @D1-A**
  4. **June – Oct. : Preparation works in the MR tunnel to (re)boot the 30 MR cavities**
  5. **Nov. – Dec. : RF conditioning of the 30 MR cavities**
- **CY2015**
  6. **Jan. – Feb. : Installation of the DR cavities, including lip welding and alignment**
  7. **Mar. : Check of the RF system for the DR, including the digital LLRF**
  8. **Apr. : RF conditioning of the DR cavities**

Fin

Appendices

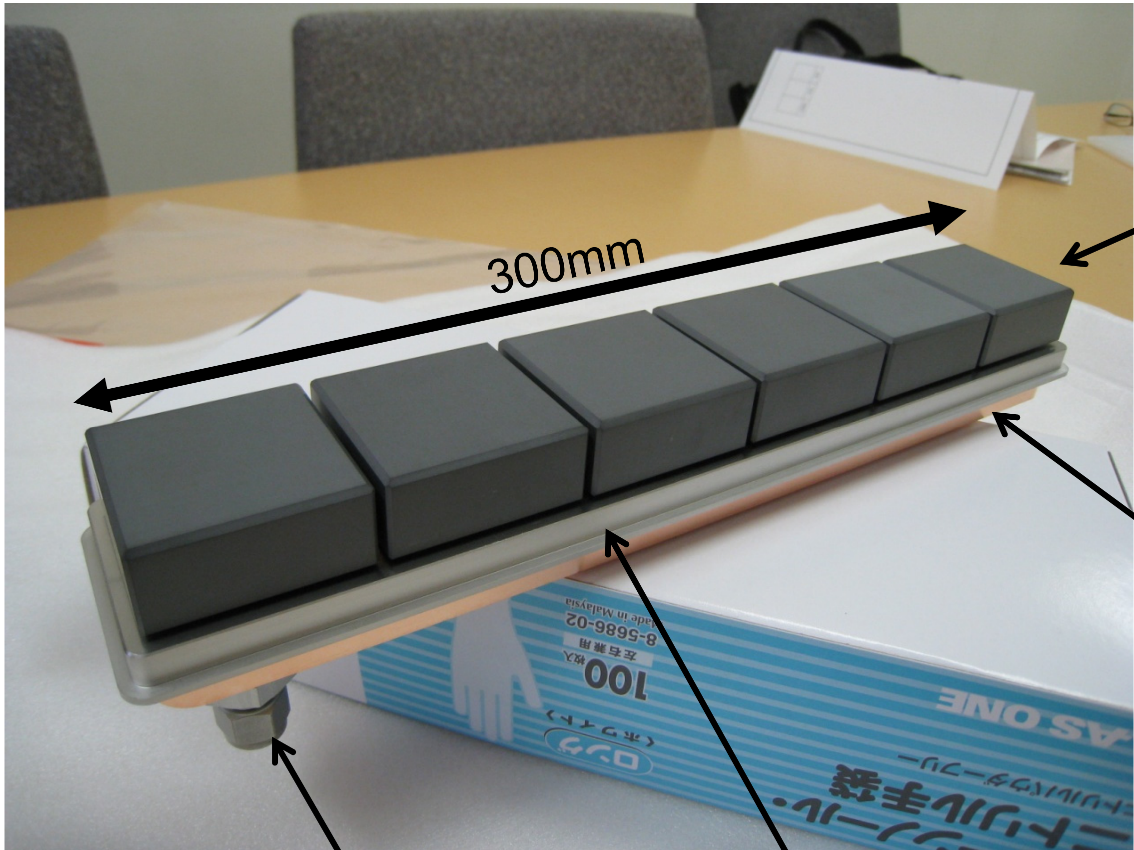
Appendix A

22 ARES Cavities operated for SuperKeKB LER (I_{beam} = 3.6 A)

RF frequency	508.869 MHz	
Flywheel Energy Ratio U_S / U_A	9	unchanged
Cavity Voltage V_C	0.48 MV	P(wall) = 140 kW
Detuning Frequency $\Delta f_{\pi/2}$ / Δf_{AC}	-28 kHz / -280 kHz	P(beam) = 460 kW
Input Coupling Factor β	5.0	β (optimum) = 4.3
CBI (-1 mode) due to the Acc. mode	τ = 4 ms	RF feedback
CBI due to the 0 and π modes	τ = 21 ms	bunch-by-bunch FB

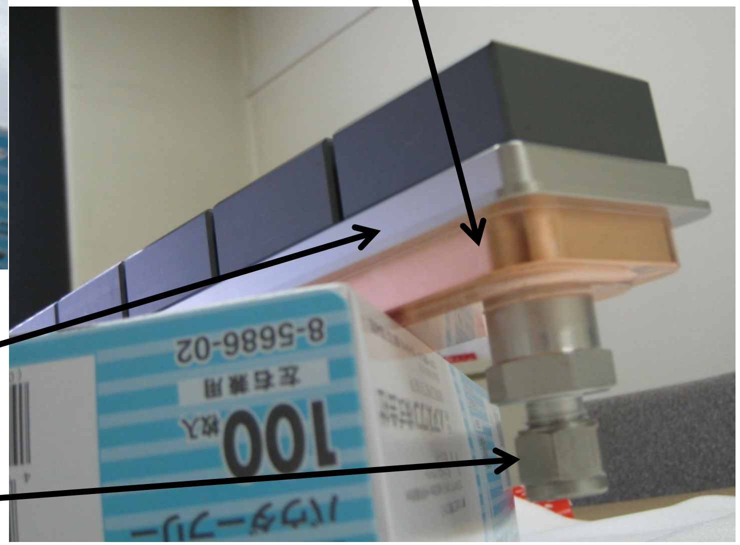
(T. Kageyama, MAC'11)

Appendix B:
A Set of SiC Tiles for the DR Cavity/HOM-WG or GBP



6 SiC Ceramic Tiles
Brazed on a Copper Plate

Copper Plate with a Cooling Channel

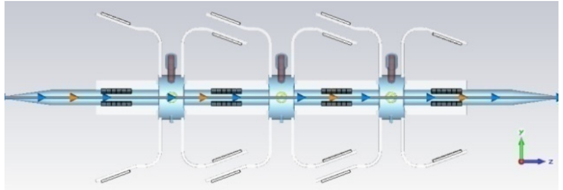


(Y. Takeuchi)

SUS Frame for Welding

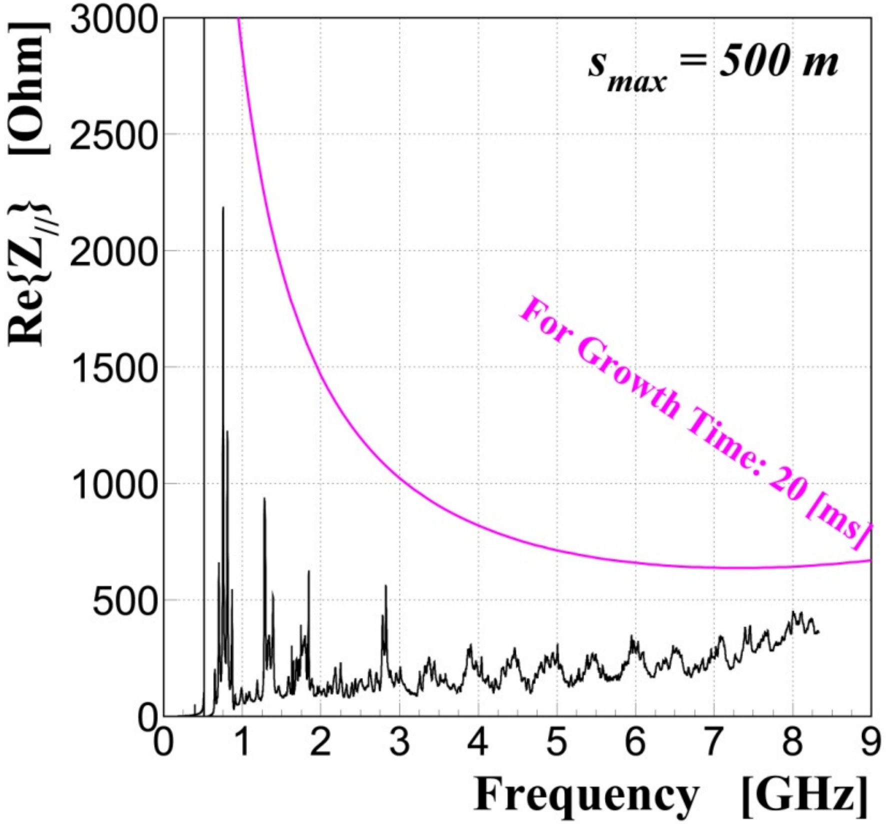
Cooling-Water Pipe Joint

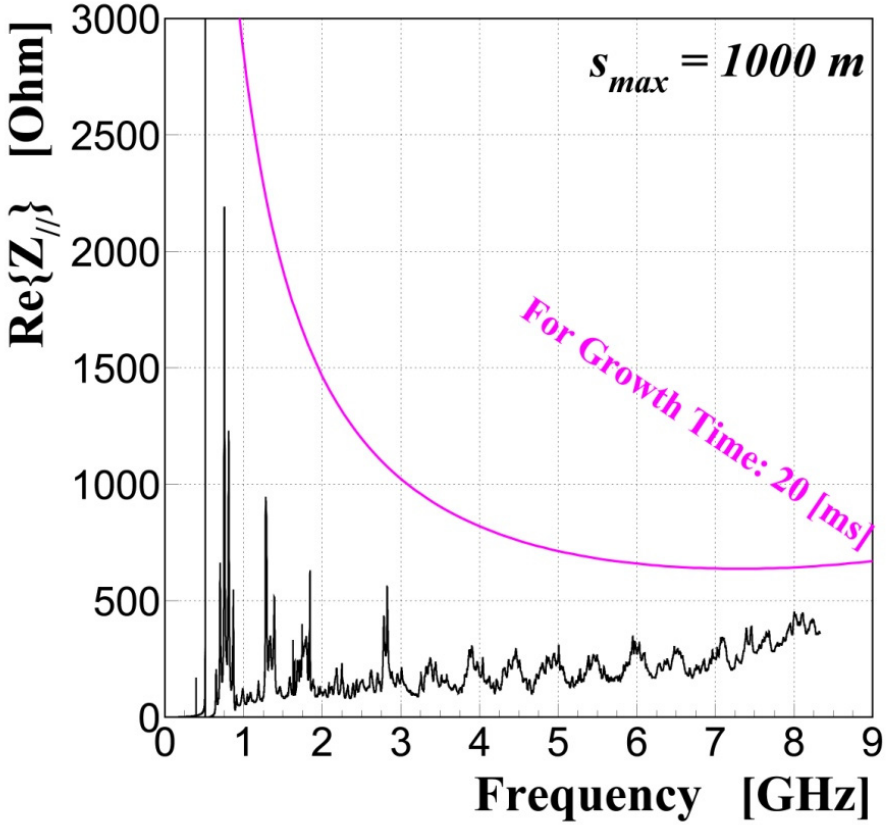
Appendix C (1/2): Longitudinal Impedance of the RF section: and CBI



Estimated from Finite-Difference Time-Domain parallel computations of GdfidL with the PC cluster

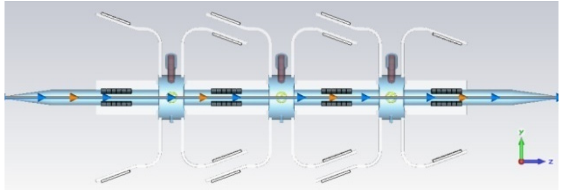
– CBI threshold for Total V_c: 1.4MV





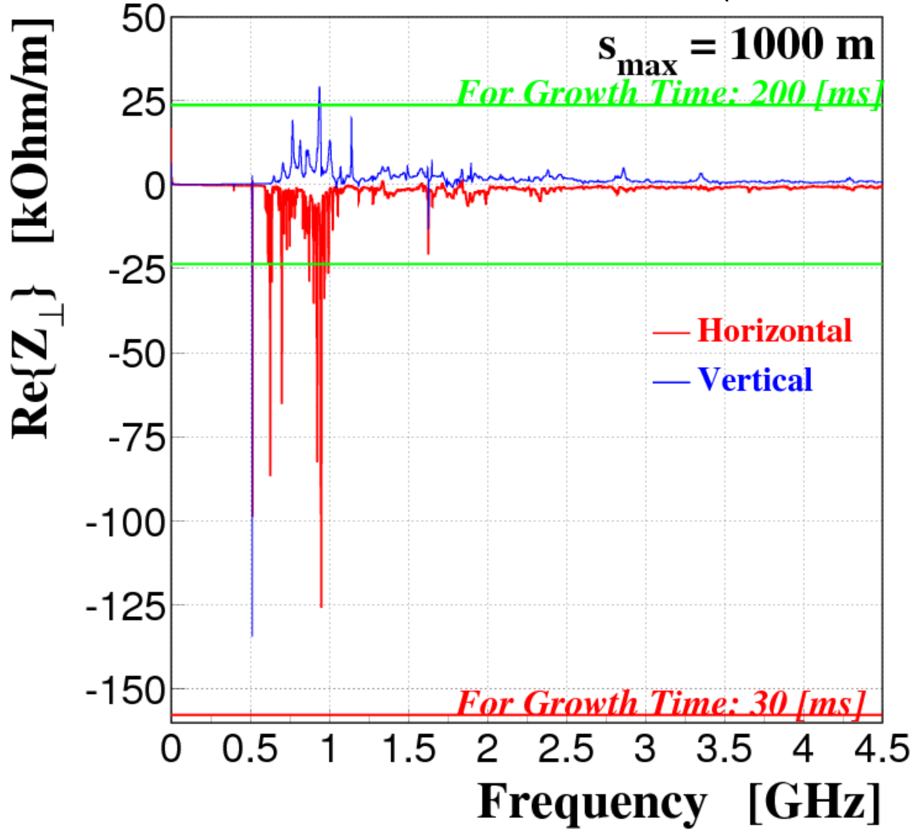
Growth Time > 20ms
> 5ms (rad. damping time)

Appendix C (2/2) : Transverse Impedances of the RF section: and CBI

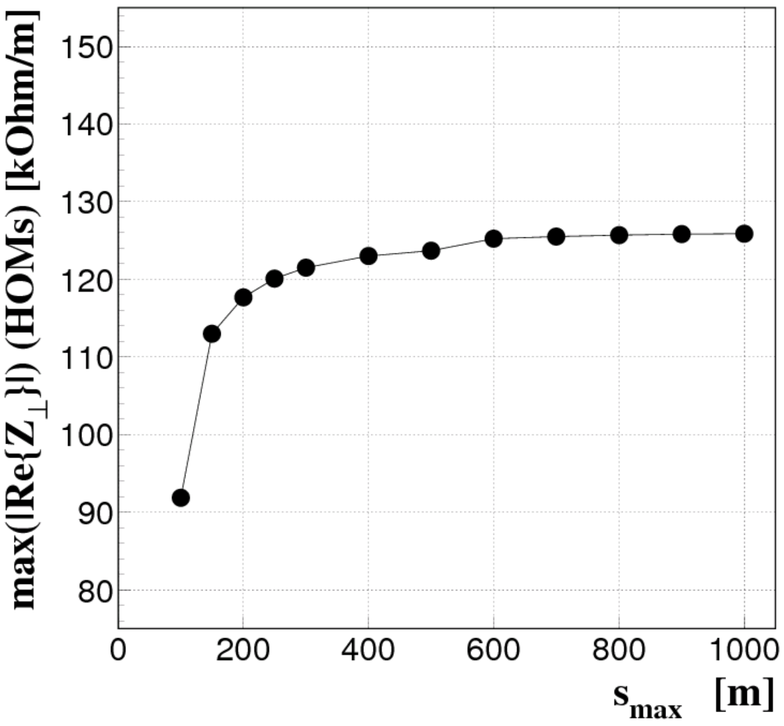


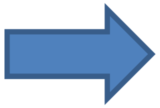
Estimated from Finite-Difference Time-Domain parallel computations of GdfidL with the PC cluster

(Tuner Position: 30mm inside)



CBI threshold for Total V_c: 1.4MV and a growth time of 30ms or 200ms



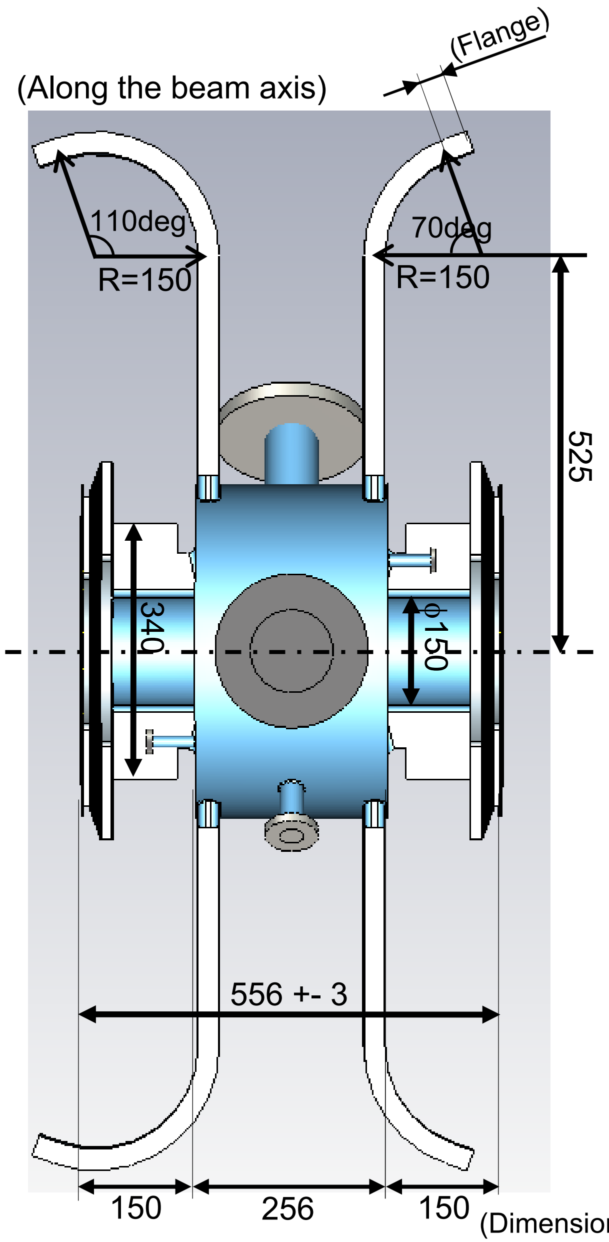


Growth Time > 30ms

> 10ms (rad. damping time)

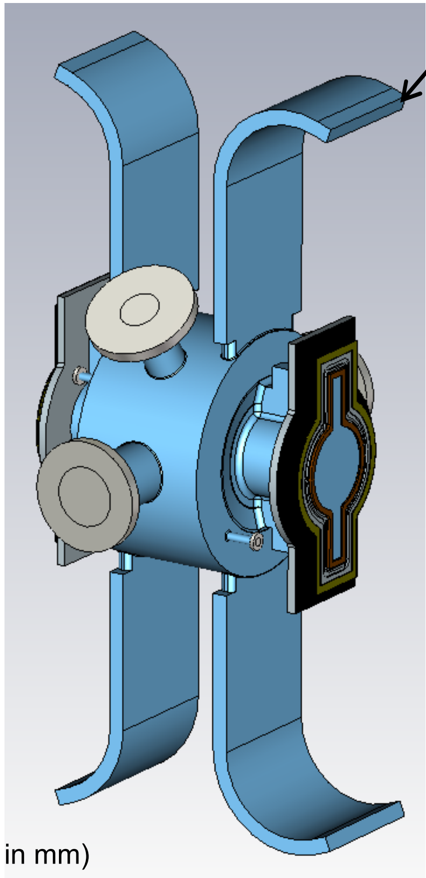
Appendix D (1/2): Cavity (main body)

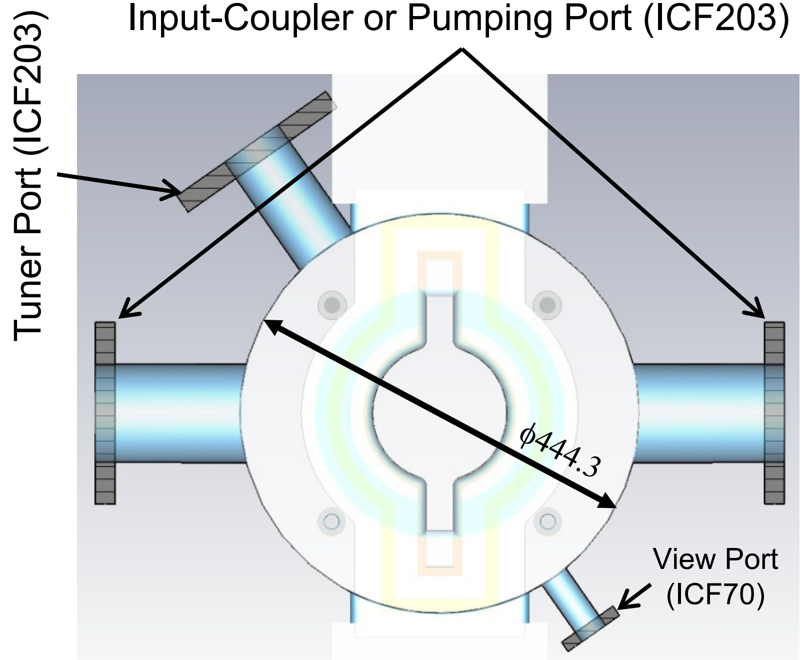
✓Material: OFHC (Class1)
except for the flanges, ports, GBPs, and HOM-WGs
✓Mirror symmetry except for the E-bends, tuner, and monitor ports.
✓Two input-coupler ports, one of which is to be used as a pumping port



(Dimensions in mm)

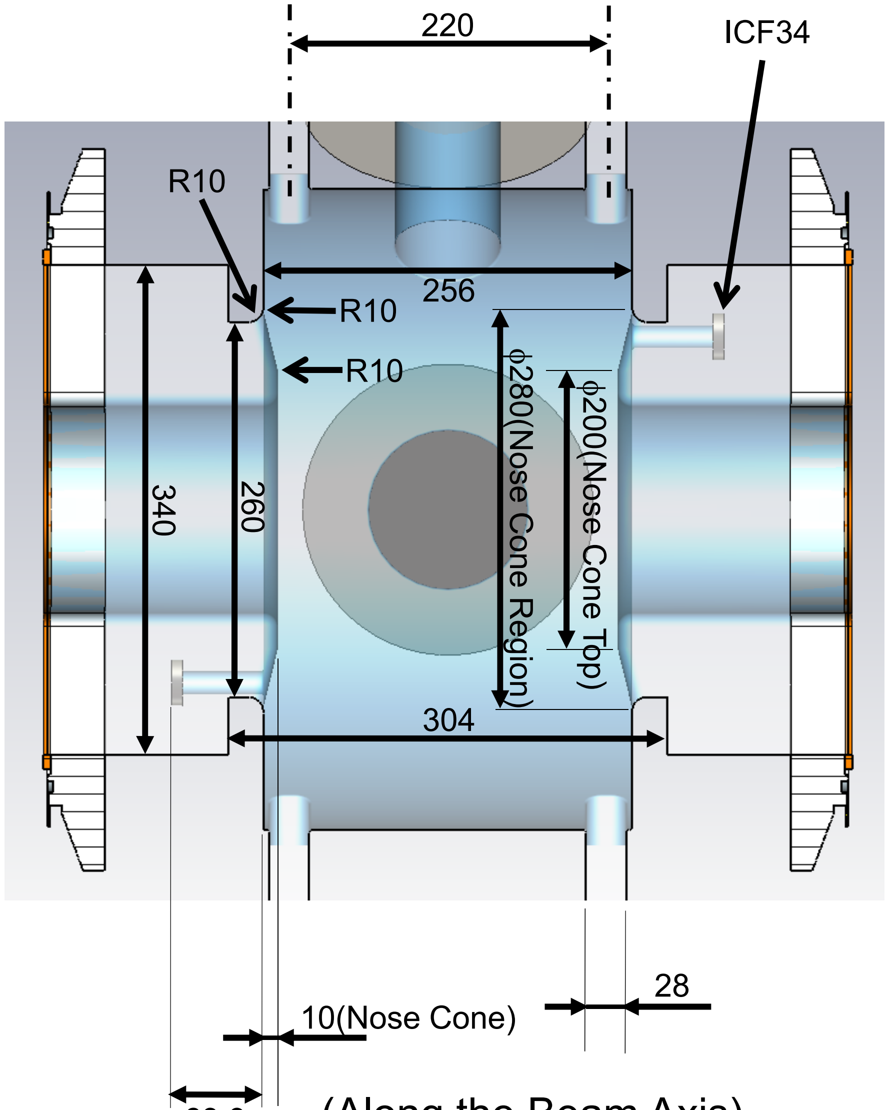
Cross-section: 240mm x 28mm



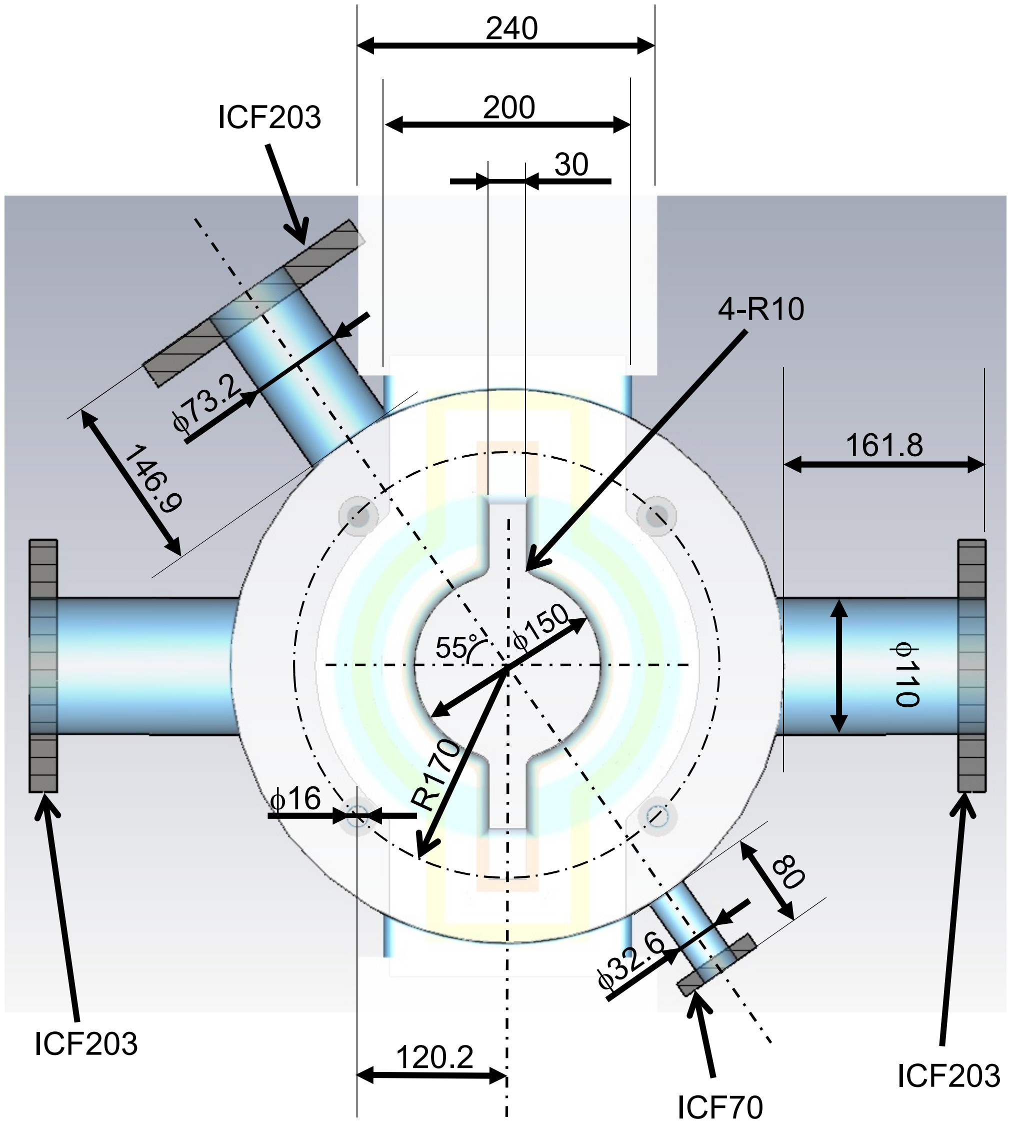


(Cross-section perpendicular to the beam axis)

Appendix D (2/2): Cavity (Main Body)



(Along the Beam Axis)

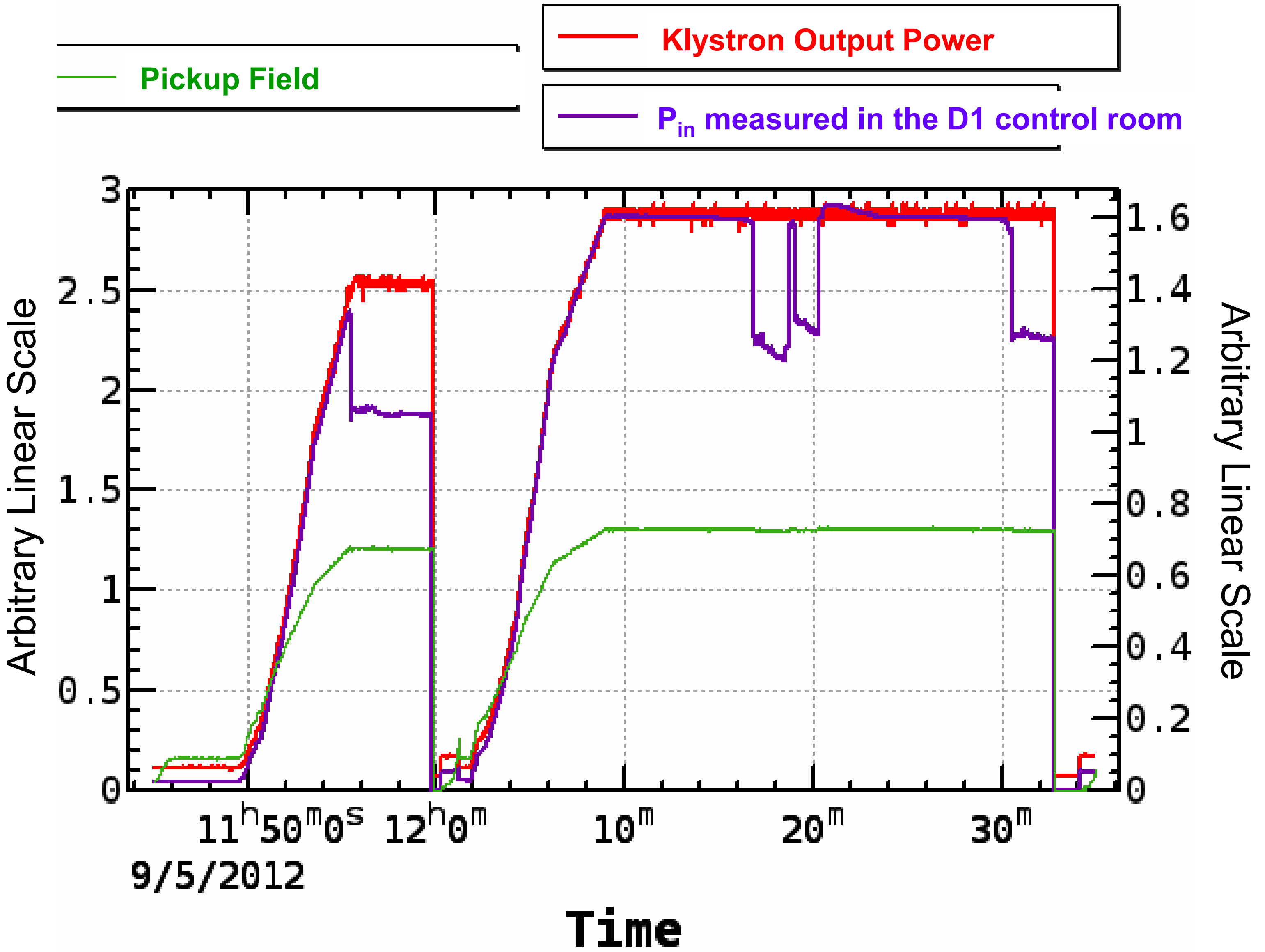


(Perpendicular to the Beam Axis)

Appendix E (1/2)

RF Power Fluctuation (1)

~~ Fast ~~



Appendix E (2/2)

RF Power Fluctuation (2)

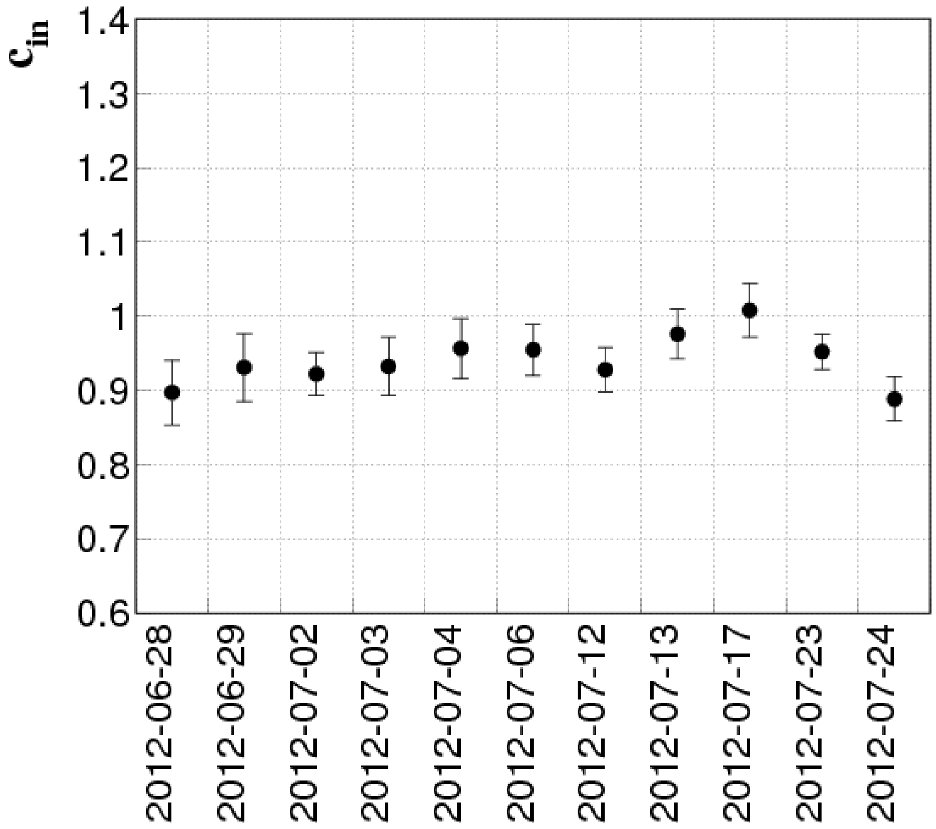
~~ Slow ~~

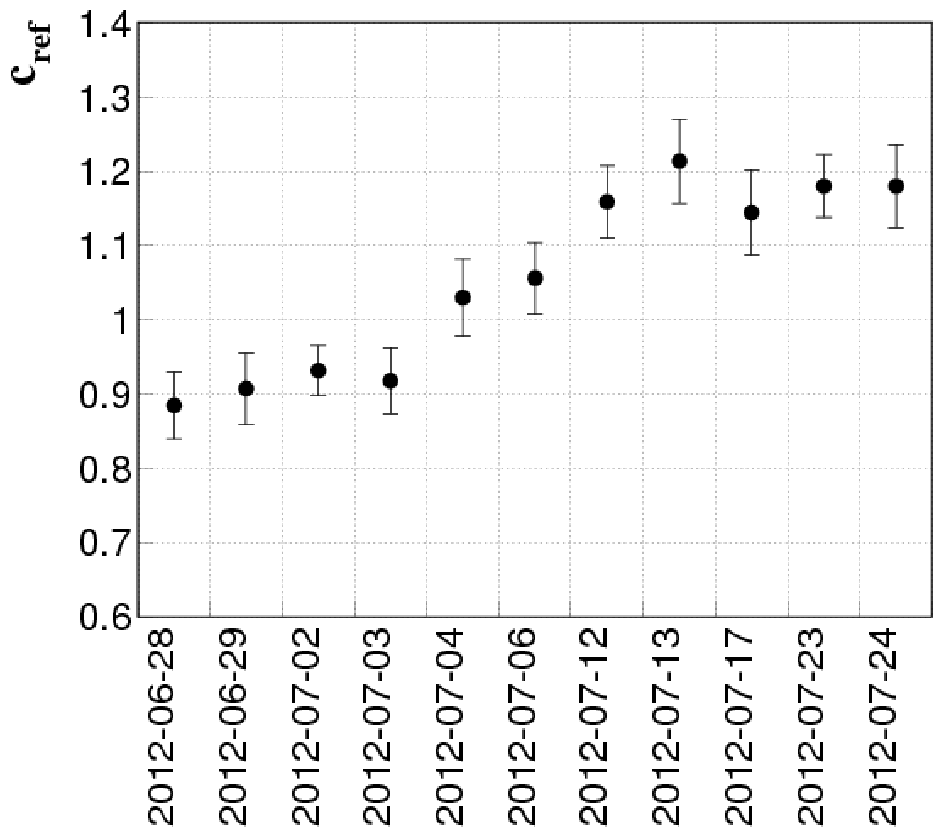
Recalibration Constants

$P_{in}(corr) = c_{in} \times P_{in}(meas)$

$P_{refl}(corr) = c_{refl} \times P_{refl}(meas)$

Recalibrated for calorimetric powers and powers measured in the radiation shield





Appendix F
How to Calculate Cavity Voltage (V_c)

✓P_{in} , P_{refl}: Input and Reflected RF powers measured, respectively
✓Assuming the cavity to be tuned

Input Coupling Factor : $\beta^{(HP)} = \dfrac{1+\sqrt{P_{refl}/P_{in}}}{1-\sqrt{P_{refl}/P_{in}}}$ (over-coupling)

(HP: High Power)

Unloaded Q : $Q_0^{(HP)} = \beta^{(HP)} \times Q_{ext}$ (We use Q_{ext}= 21814 from the LP meas.)

(LP: Low Power)

Shunt Impedance : $R_{sh}^{(HP)} = (R_{sh}^{(HP)}/Q_0^{(HP)}) \times Q_0^{(HP)}$

(We use $R_{sh}^{(HP)}/Q_0^{(HP)} = R_{sh}^{(cold)}/Q_0^{(cold)}$ =150Ω from the simulation.)

Cavity Voltage : $V_c = \sqrt{R_{sh}^{(HP)} \times \underline{(P_{in} - P_{refl})}}$

$(P_{in} - P_{refl}) = P_{wall}$

For more details, see
T. Abe et al., “Development of RF Accelerating Cavity for the Positron Damping Ring at SuperKEKB” (Japanese), in the Proceedings of the 9th Annual Meeting of Particle Accelerator Society of Japan, 2012 (Paper ID: THLR06).

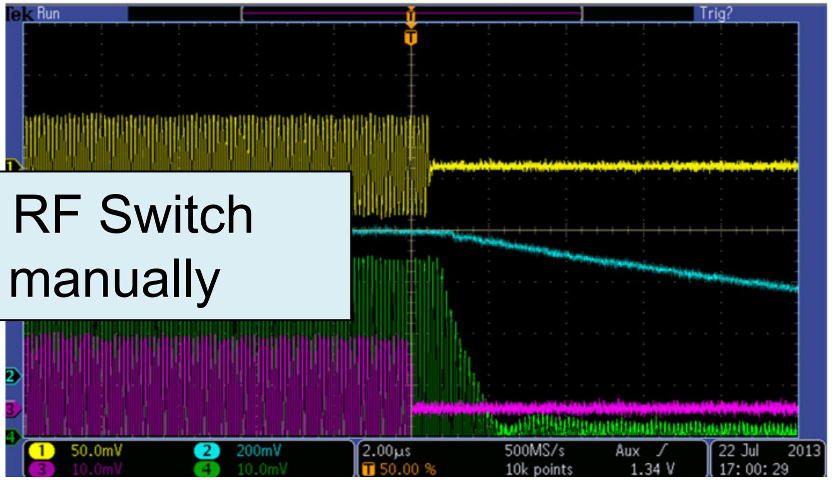
Appendix G : How to Identify "Cavity Trip" (1/2)

If the cavity pickup signal decays with a decay time constant of 10μm (← Q_L=15000), it is NOT "Cavity Trip".

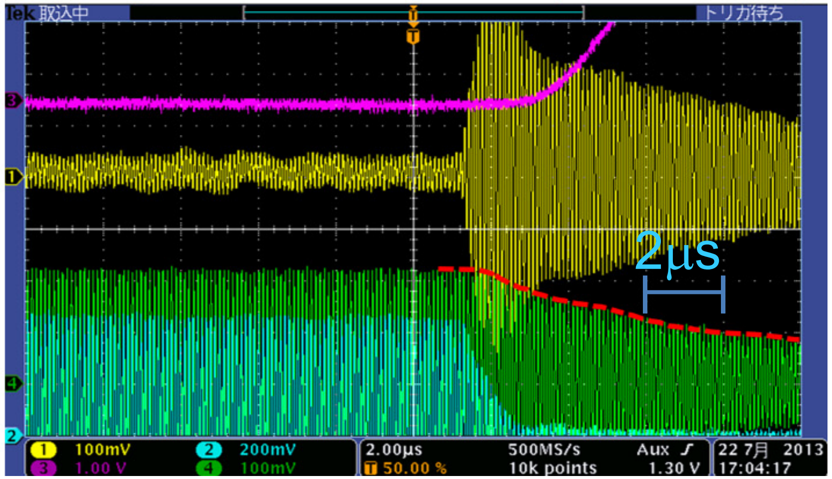
- - - Envelope of the Cavity Pickup Signal (508.9MHz) (Appendix H)

When the RF Switch turned off manually

Ch.1: Input Wave to the Klystron Ch.2: Output Level from the Klystron
Ch.3: Output Wave from the LLRF Ch.4: Output Wave from the Circulator

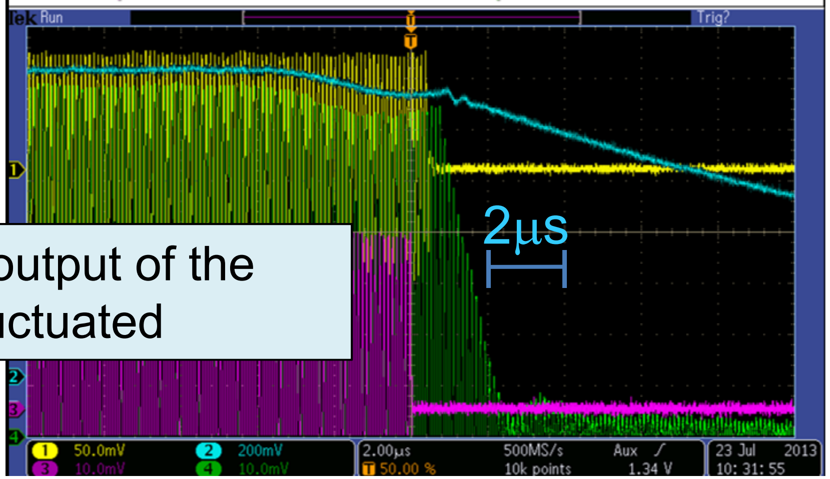


Ch.1: Reflected Wave from the Cavity Ch.2: Input Wave to the Cavity
Ch.3: Tuning Phase Ch.4: Pickup Wave from the Cavity

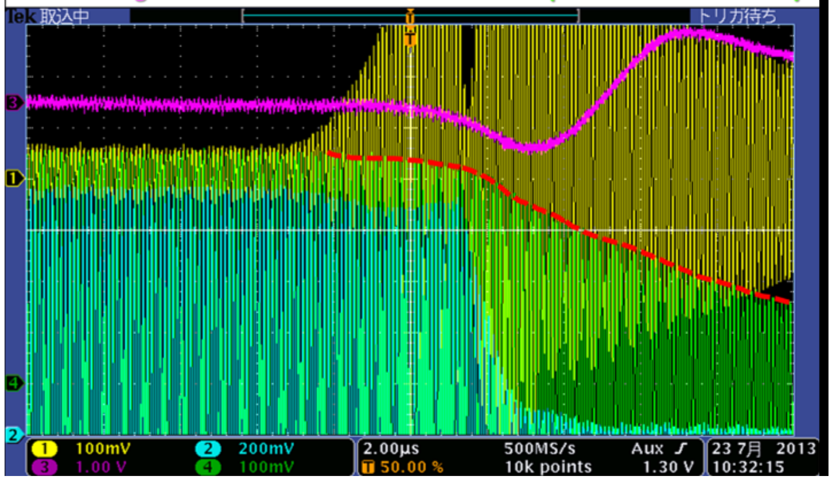


When the output of the Klystron fluctuated

Ch.1: Input Wave to the Klystron Ch.2: Output Level from the Klystron
Ch.3: Output Wave from the LLRF Ch.4: Output Wave from the Circulator



Ch.1: Reflected Wave from the Cavity Ch.2: Input Wave to the Cavity
Ch.3: Tuning Phase Ch.4: Pickup Wave from the Cavity

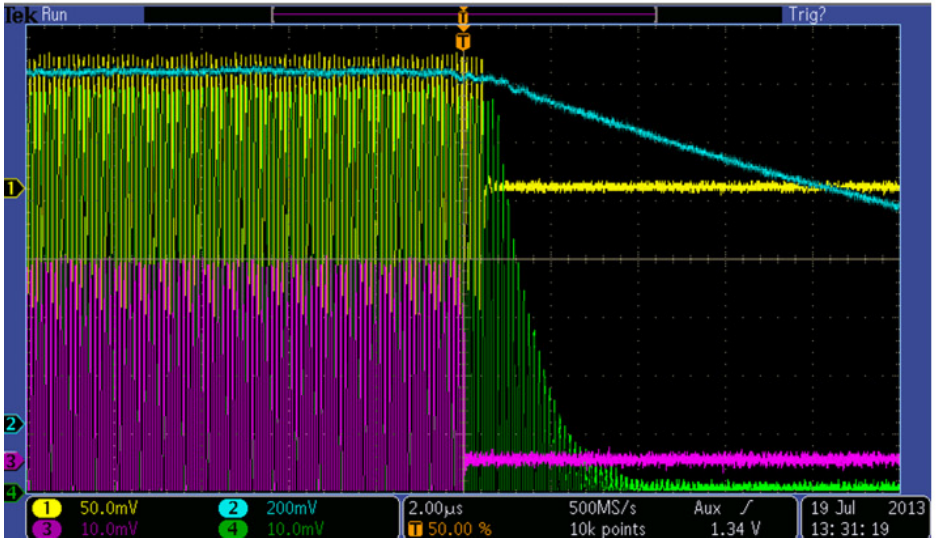


Appendix G : How to Identify “Cavity Trip” (2/2)

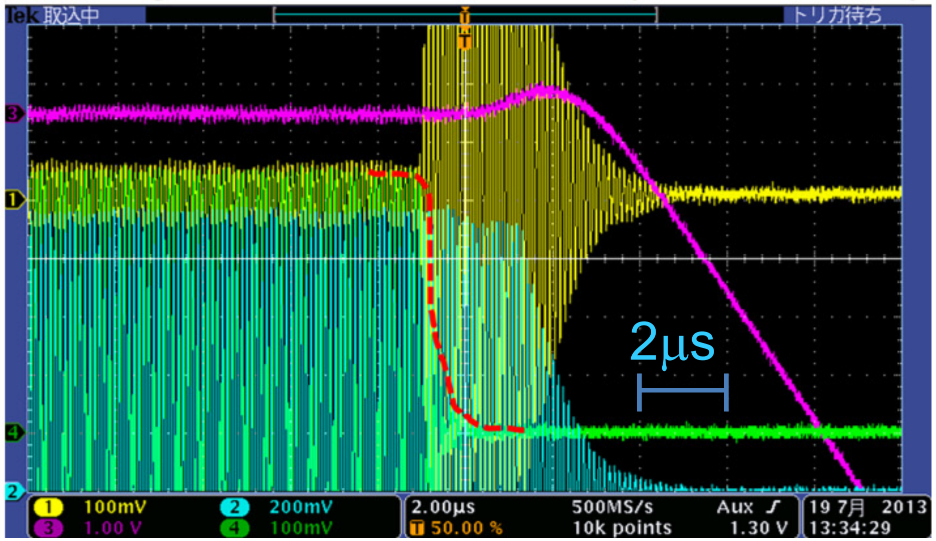
If the cavity pickup signal decays much faster than 10μm (← Q_L=15000), it is “Cavity Trip”.

- - - Envelope of the Cavity Pickup Signal (508.9MHz) (Appendix H)

Ch.1: Input Wave to the Klystron Ch.2: Output Level from the Klystron
Ch.3 : Output Wave from the LLRF Ch.4 : Output Wave from the Circulator



Ch.1: Reflected Wave from the Cavity Ch.2: Input Wave to the Cavity
Ch.3: Tuning Phase Ch.4: Pickup Wave from the Cavity

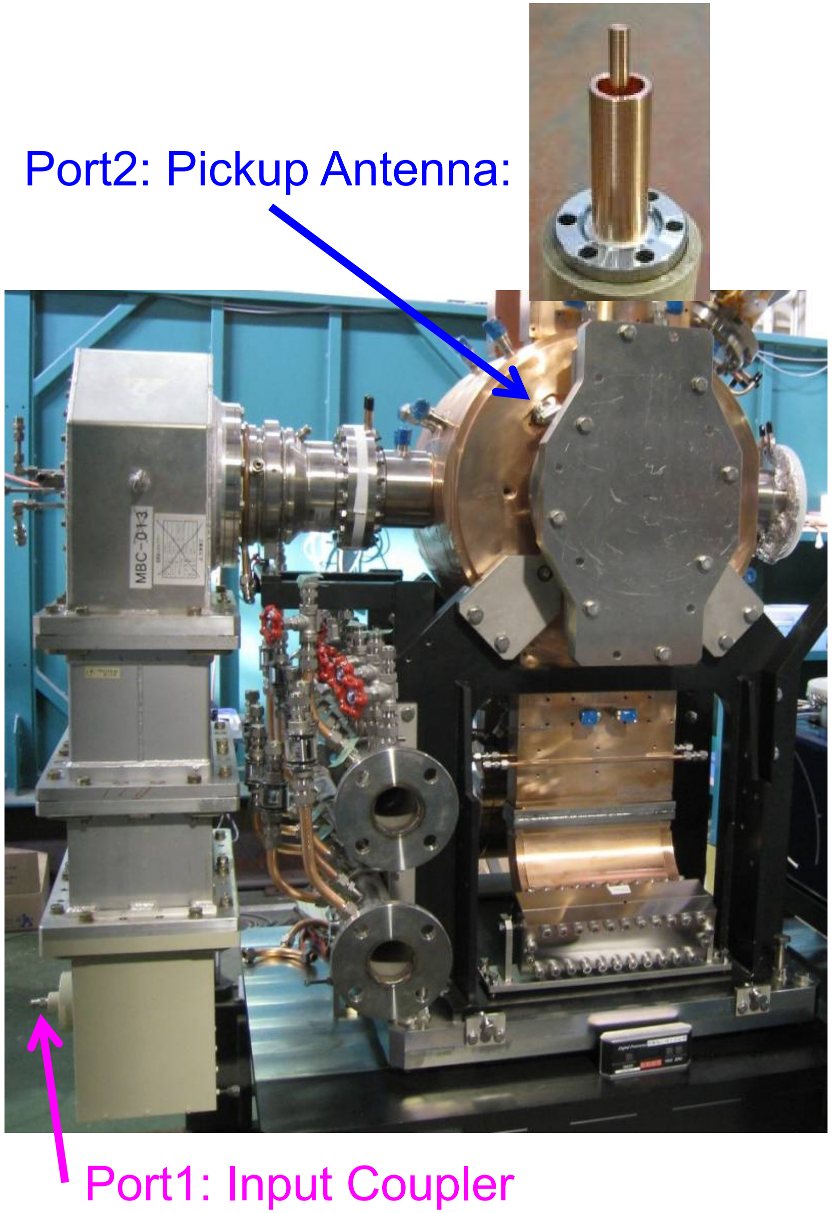


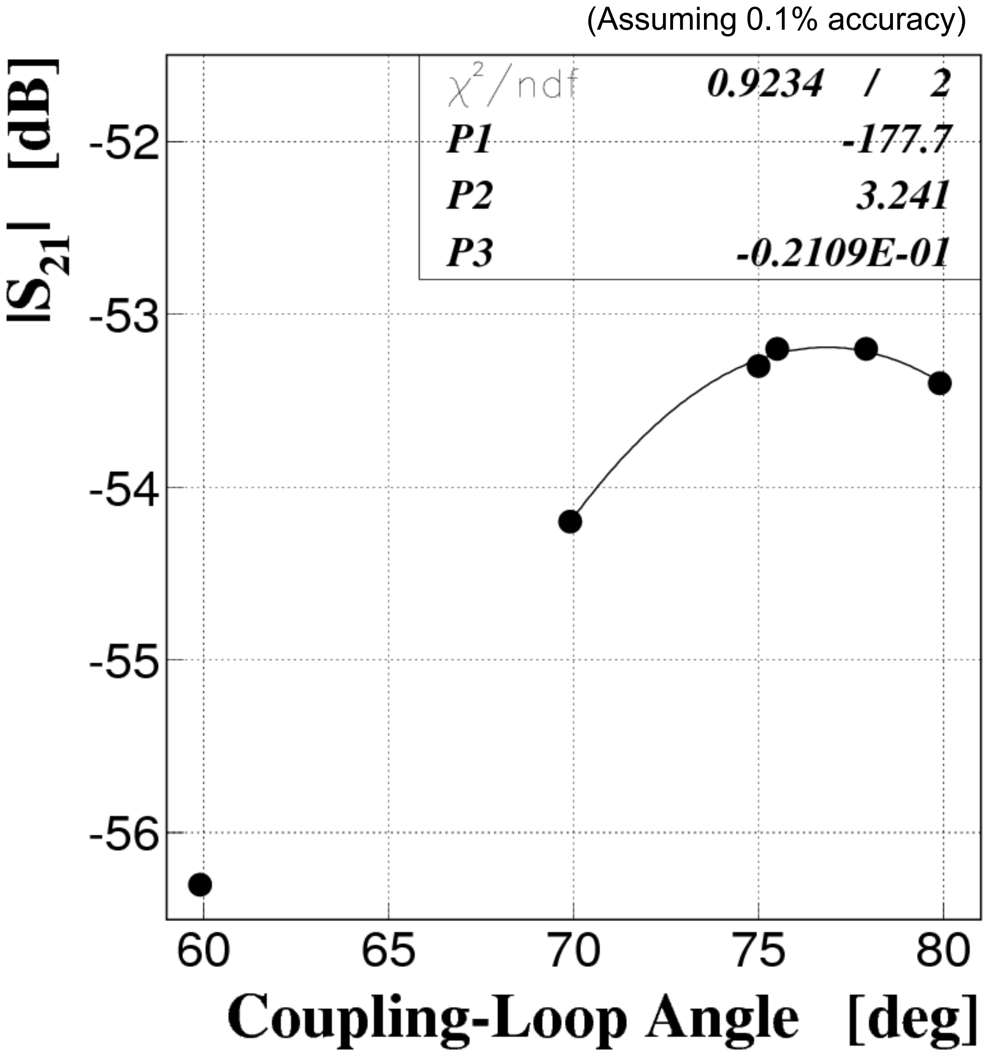
When a discharge occured in the cavity,
(confirmed visually with the TV cameras, and the I/L with P_{refl})

We can count real number of cavity trips.

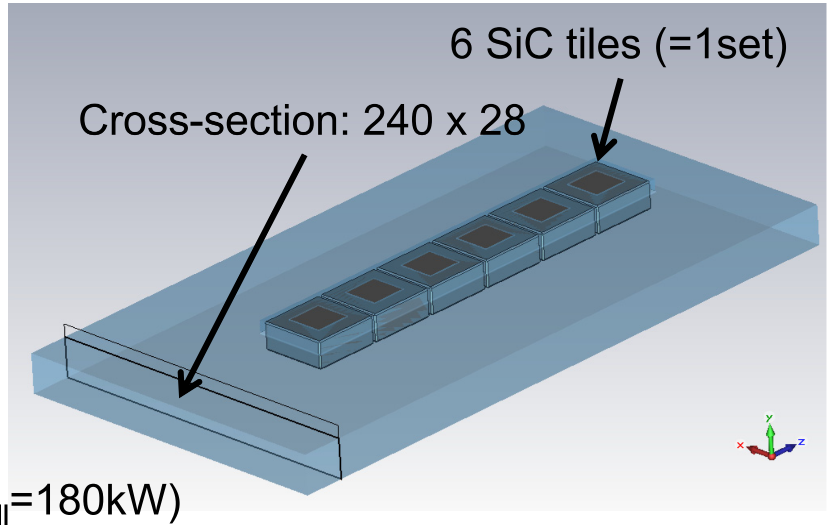
For more details, see
T. Abe et al., "High Power Testing of the RF Accelerating Cavity for the Positron Damping Ring at SuperKEKB“ (Japanese), in the Proceedings of The 10th Annual Meeting of Particle Accelerator Society of Japan, 2013 (Paper ID: SAP057).

Appendix H: High-Power Pickup Antenna

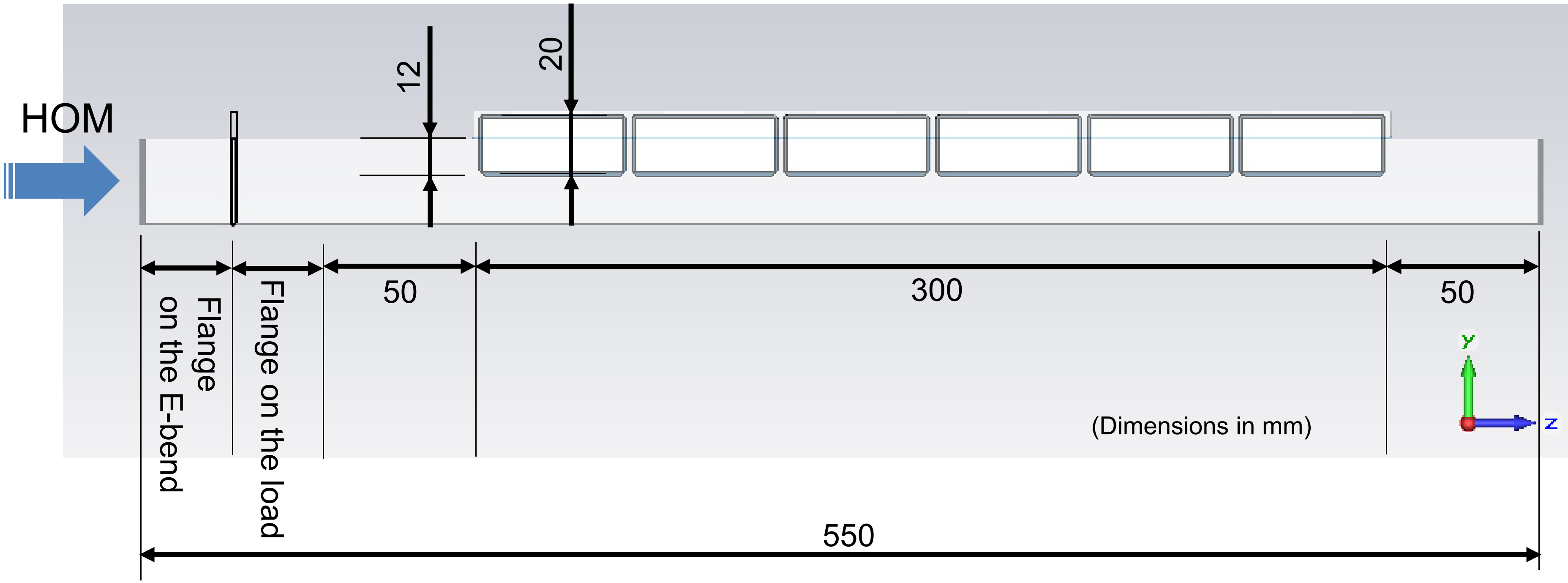




Appendix I: HOM-WG Load

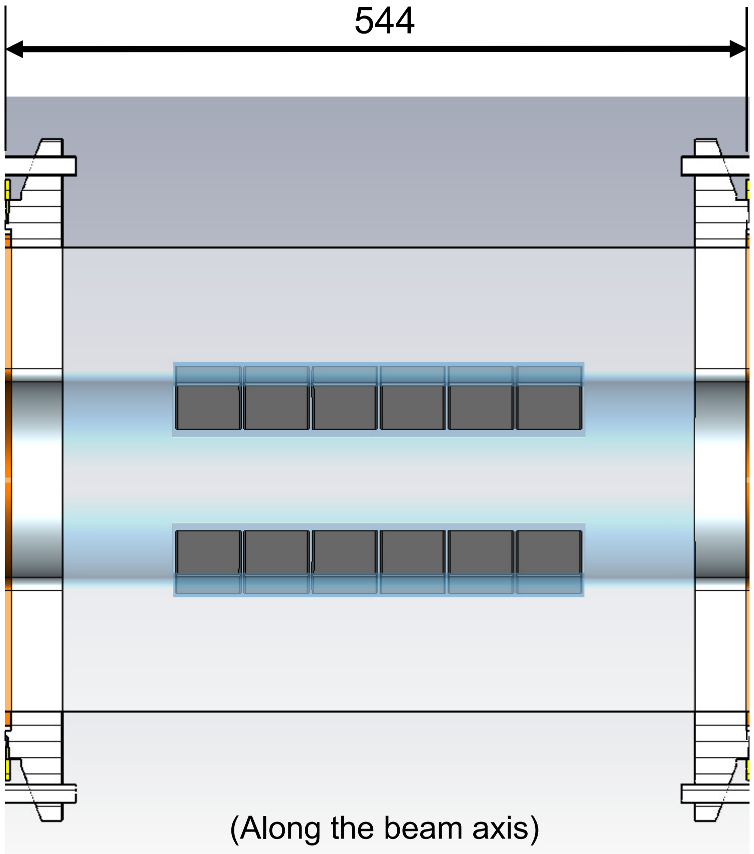


- ✓Material of the WG: SUS
- ✓HOM Absorber: SiC (Silicon Carbide) ceramics
    - •Brazed on a copper plate
    - •Water-cooled via the copper plate
    - •Same as used for the KEKB-MRs/ARES
- ✓Power Capability: 1.2kW/set(@1.3GHz)
- ✓Max. HOM Power absorbed: ~30W/WG
- ✓Max. Accl.-Mode Power absorbed: ~130W/WG (for P_{wall}=180kW)

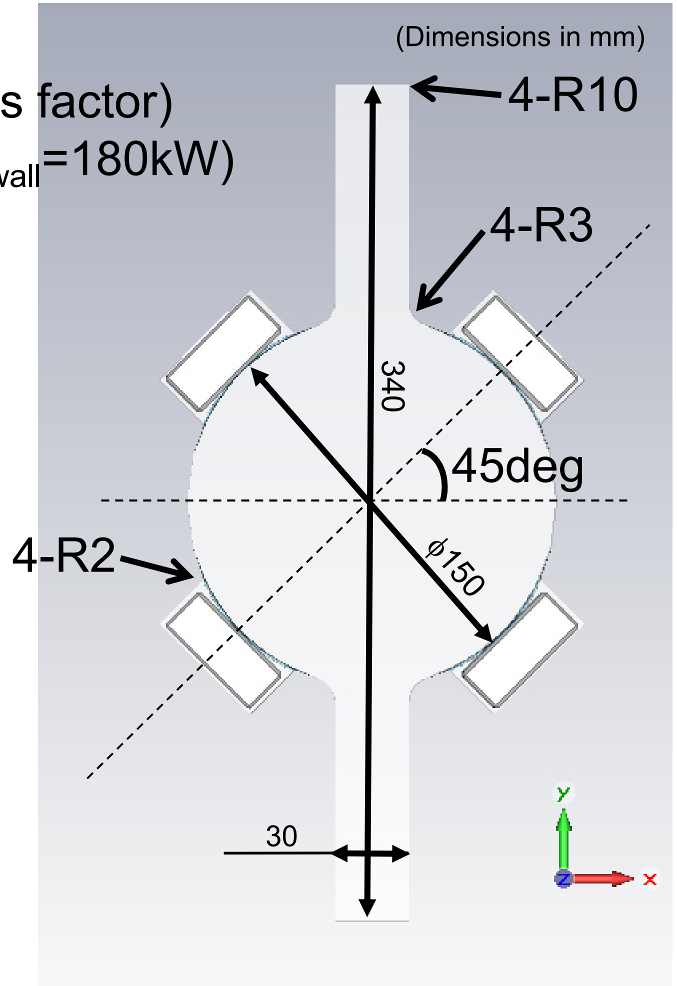


Appendix J: GBP (btwn)

✓Material: SUS
✓4 sets of SiC tiles (same as used for the HOM-WGs)
✓Max. HOM Power absorbed: ~200W/GBP (incl. the loss factor)
✓Max. Accl.-Mode Power absorbed: ~100W/GBP (for P_{wall}=180kW)
✓Loss factor: ~0.2 [V/pC] (for σ_z=6.0mm)



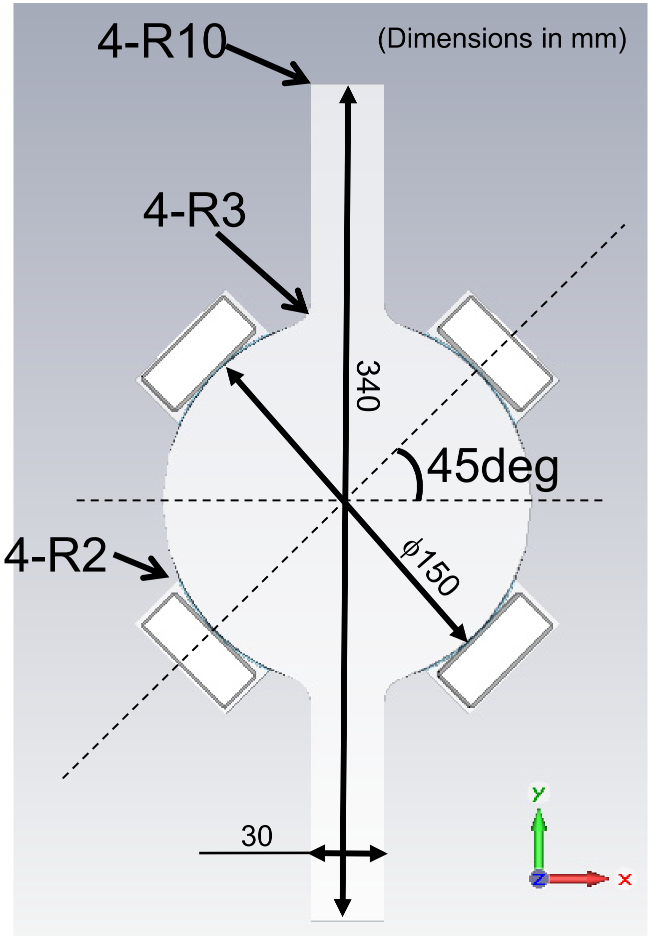
(Along the beam axis)



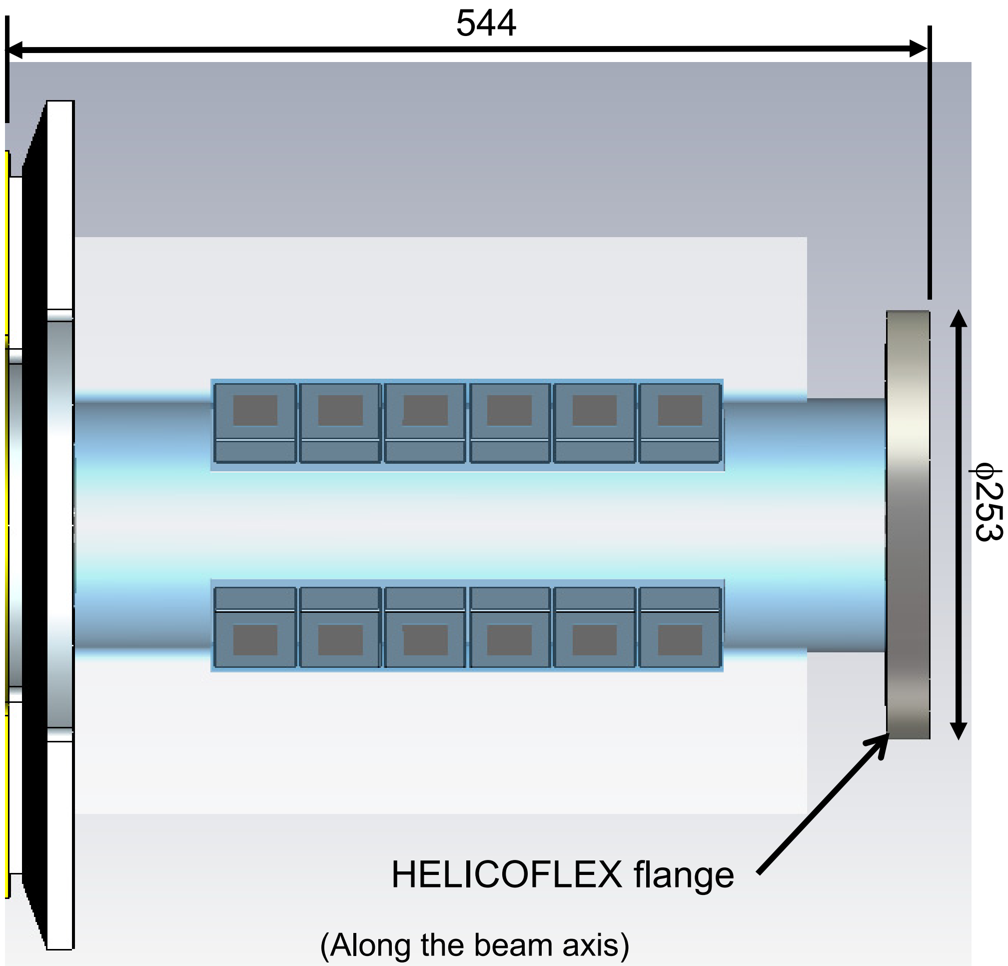
(Cross-section perpendicular to the beam axis)

Appendix K: GBP (end)

✓Material: SUS
✓4 sets of SiC tiles
✓Max. HOM Power absorbed: ~200W/GBP (incl. the loss factor)
✓Max. Accl.-Mode Power: ~100W/GBP (for P_{wall}=180kW)



(Cross-section perpendicular to the beam axis)



(Along the beam axis)

EOF