Status of RF Accelerating Cavities for SuperKEKB Positron Damping Ring

Tetsuo ABE (KEK)

for SuperKEKB-RF / ARES Cavity Group
(T. Abe, S. Enomoto, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino)

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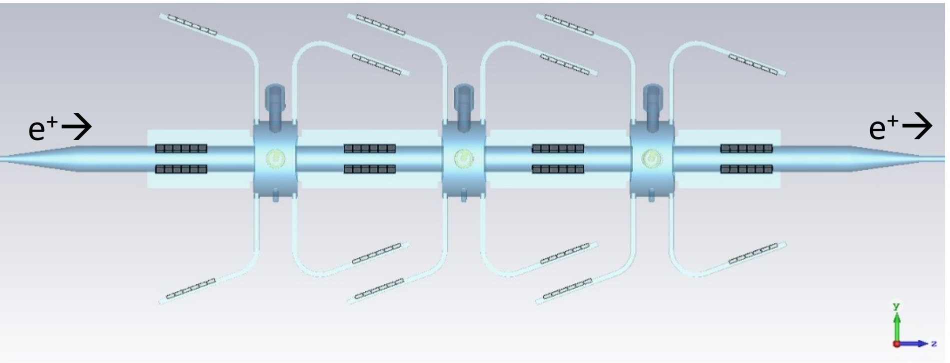
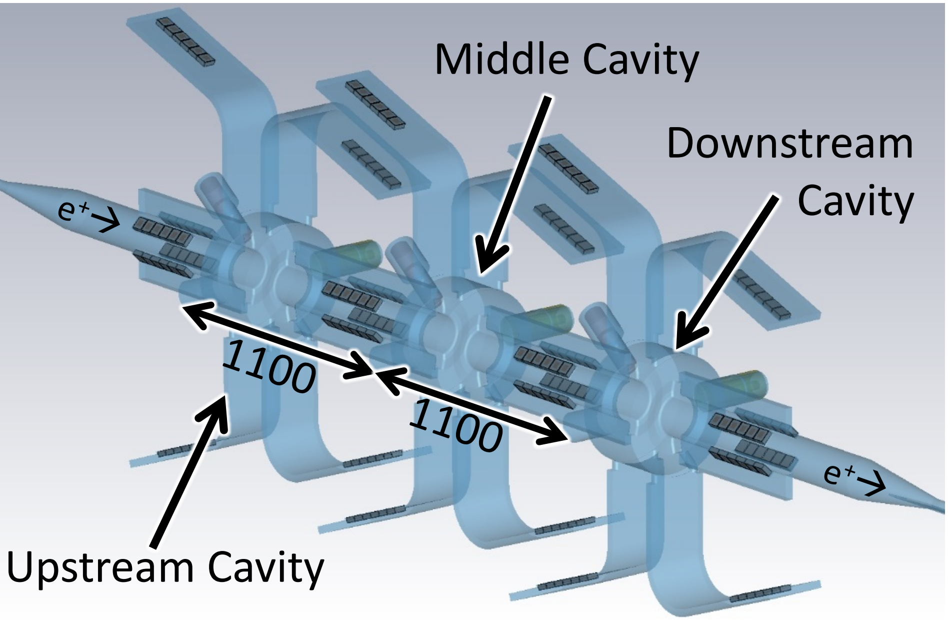
1. Overview and Fundamentals of the RF Accelerating Structure

Overview of the RF Accelerating Structure

✓Blue region: vacuum during operation
✓Gray region: HOM absorbers (SiC ceramics)





- Operational frequency: 508.9 MHz (CW) (same as for the MRs)
- HOM-damped structure based on the successful ARES cavity system
- Max. three cavities to be installed in a space originally designed for one cavity
  - Max. total V_c = 2.4 MV to be supplied to the DR
- "Multi Single Cell" structure
  - Electromagnetic field in each cavity has high independence by the contribution the HOM absorbers between the cavities.
  - Number of cavities is variable; Cavities are replaceable.
  - Assembled in the DR tunnel like LEGO blocks
    - → One big mechanical structure with solid connections of the components
- Vacuum pumps directly attached to each cavity

Design Parameters	
Operational frequency	508.9 MHz
R_{sh}/Q_0	150 Ω
Q_0	~30000
Cavity Voltage (DR spec)	0.7 MV / cavity
Cavity Voltage (Cavity spec)	0.8 MV / cavity
Wall-loss power @ 0.7 - 0.8 MV / cavity	~110 - 140 kW / cavity

MR: Main Ring
HOM: Higher-Order Mode
SiC: Silicon Carbide

Due to predicted CSR effects, the required acceleration voltage was increased fivefold!

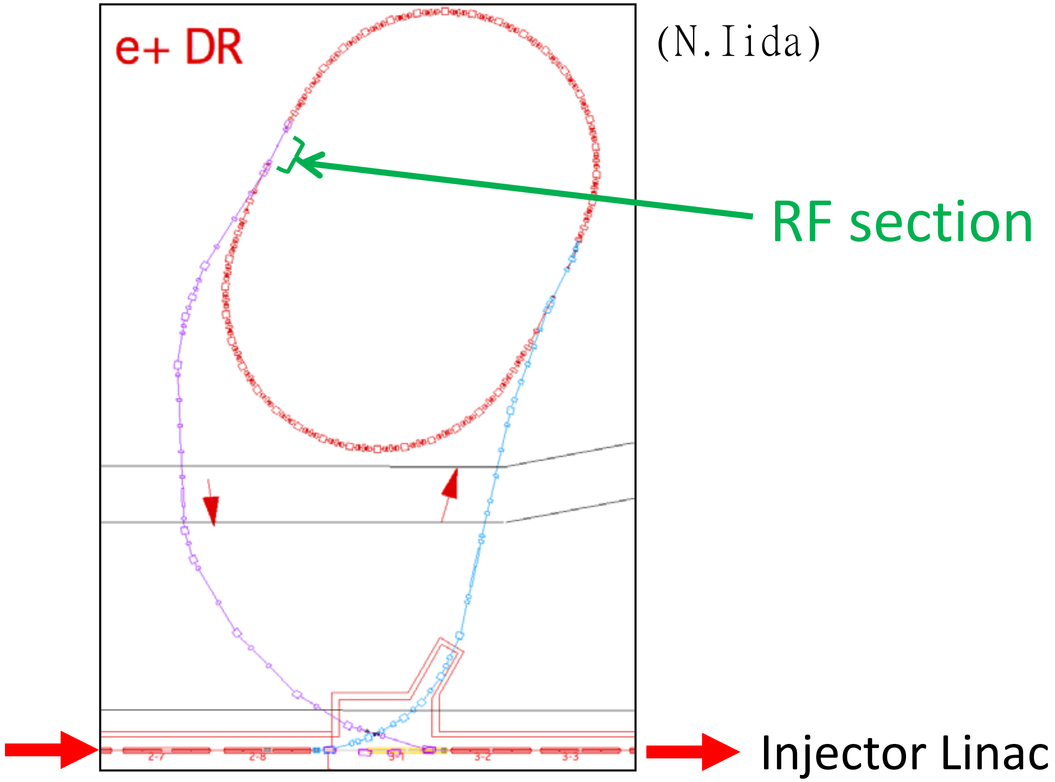
Parameters of the Damping Ring

			MAC10
Energy	1.1	GeV	1.0
No. of bunch trains/ bunches per train	2 / 2		
Circumference	135.5	m	
Maximum stored current*	70.8	mA	
Energy loss per turn	0.091	MV	
Horizontal damping time	10.9	ms	12.7
Injected-beam emittance	1700	nm	2100
Equilibrium emittance(h/v)	41.4 / 2.07	nm	14 / 1.4
Coupling	5	%	10
Emittance at extraction(h/v)	42.5 / 3.15	nm	17.6 / 5.1
Energy band-width of injected beam	± 1.5	%	
Energy spread	0.055	%	
Bunch length	6.5	mm	5.4
Momentum compaction factor	0.0141		0.0019
Number of normal cells	32		
Cavity voltage for 1.5 % bucket-height	1.4	MV	0.26
RF frequency	509	MHz	
Inner diameter of chamber	32	mm	
Bore diameter of magnets	44	mm	

* 8 nC/bunch

CSR

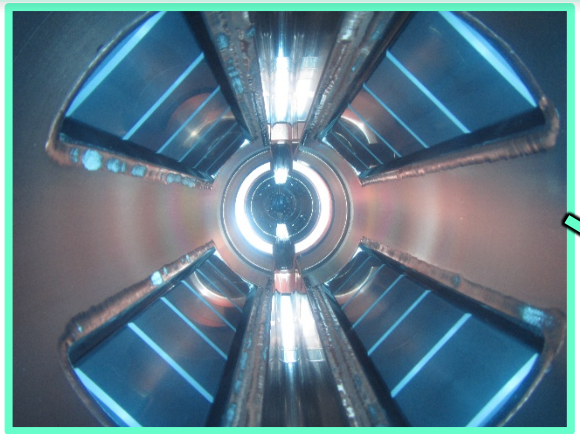
(CSR : Coherent Synchrotron Radiation)



To supply an accelerating voltage higher than 1.4 MV to the DR in the limited space of a sole RF section, which was originally designed for one cavity, this RF accelerating structure has unique space-saving features (→ next page).

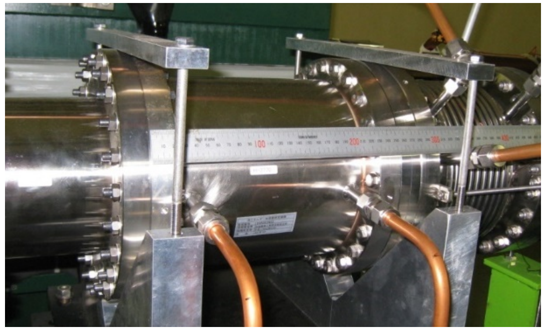
Space-Saving Features

The HOM absorbers in the grooved beampipes absorb not only TE modes but also higher-order TM modes.

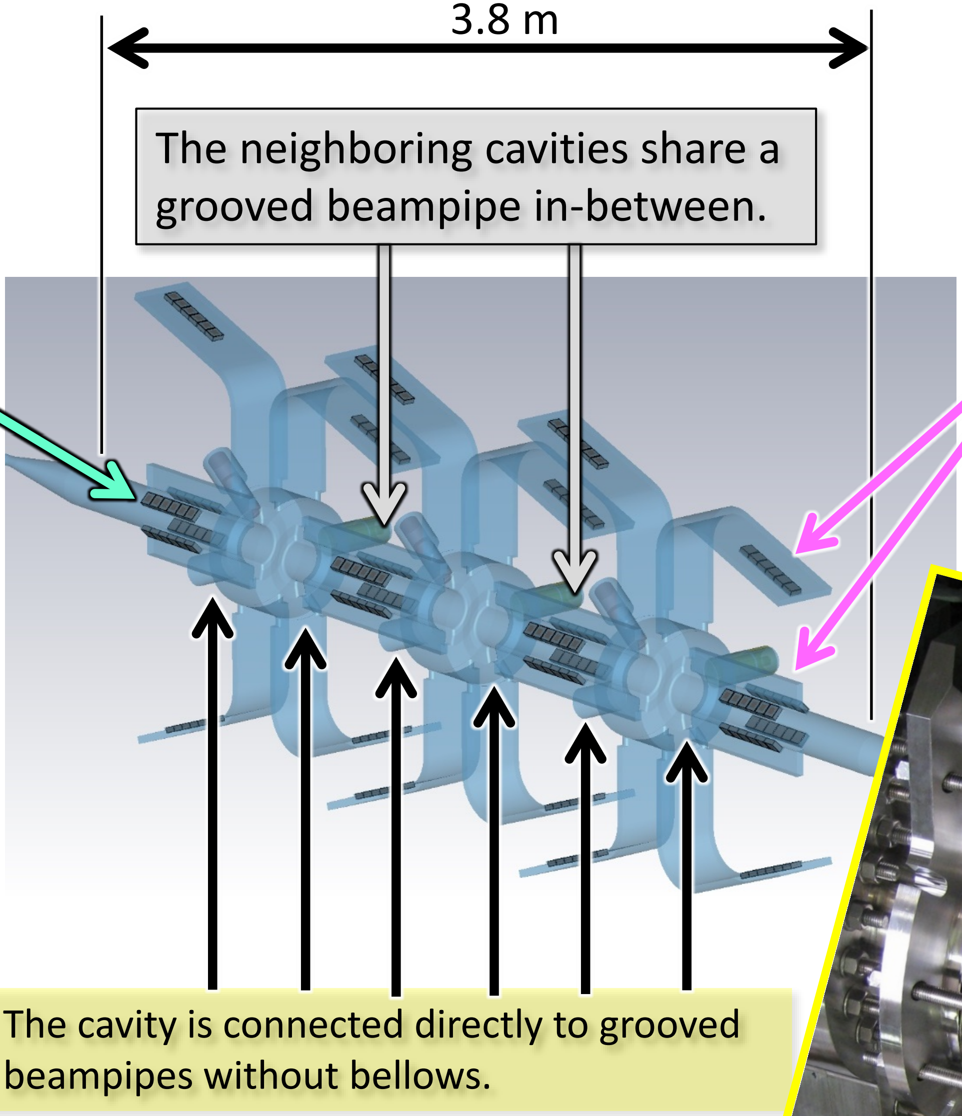


No additional HOM absorbers (such as SiC ducts) needed

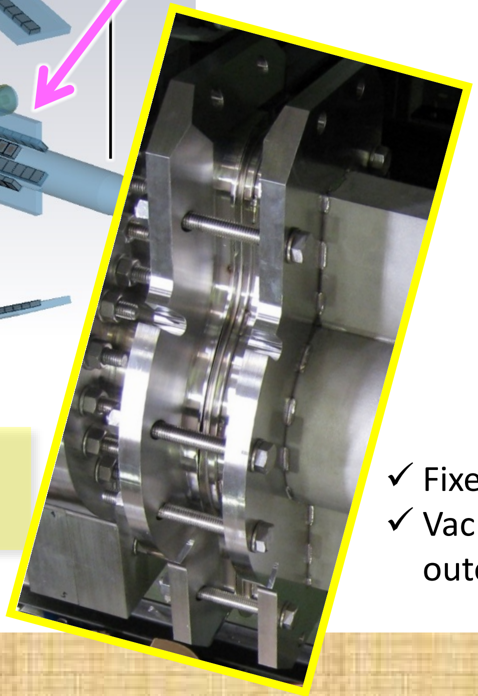
E.g. SiC duct used at the MR / RF section



(280 mm long)



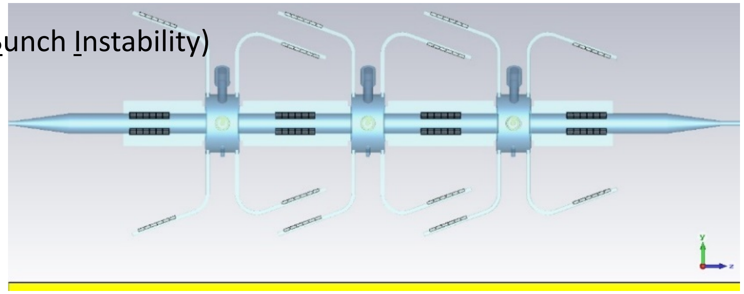
The HOM absorbers are all ***compact*** tile-shaped SiC ceramics (48 x 48 x 20 mm^3).



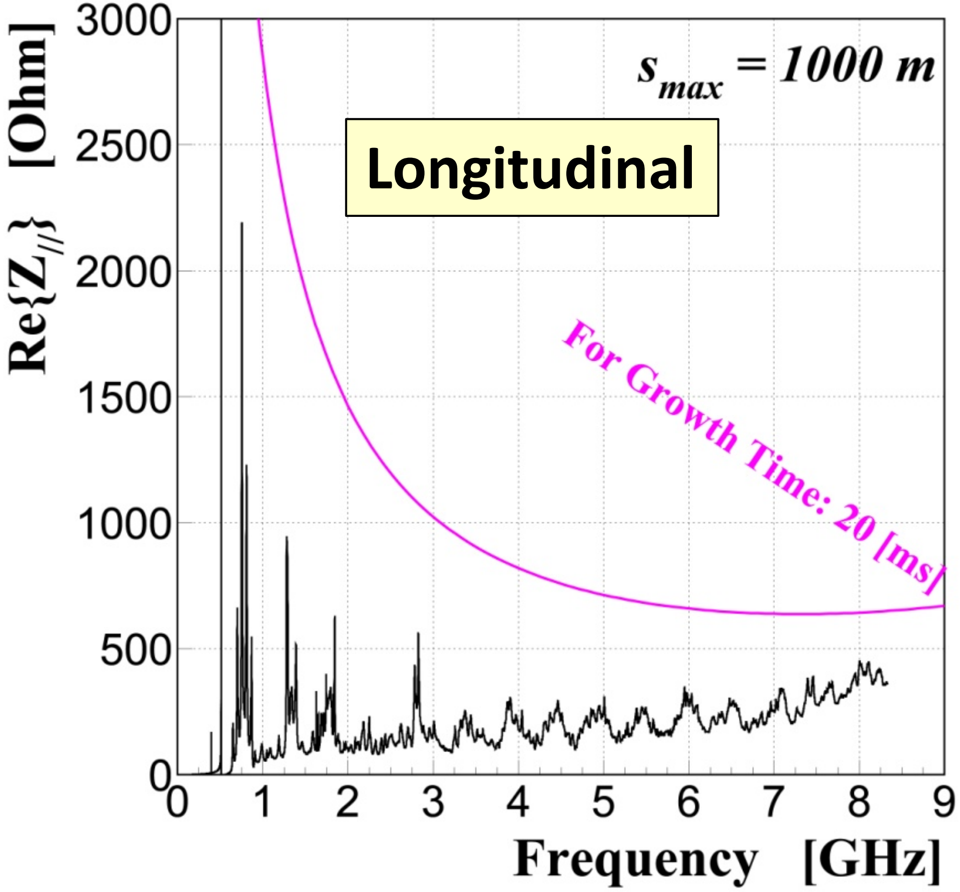
- ✓ Fixed with 16 M12 bolts
- ✓ Vacuum-tight lip welding at the outer periphery (“weld ring gasket”)

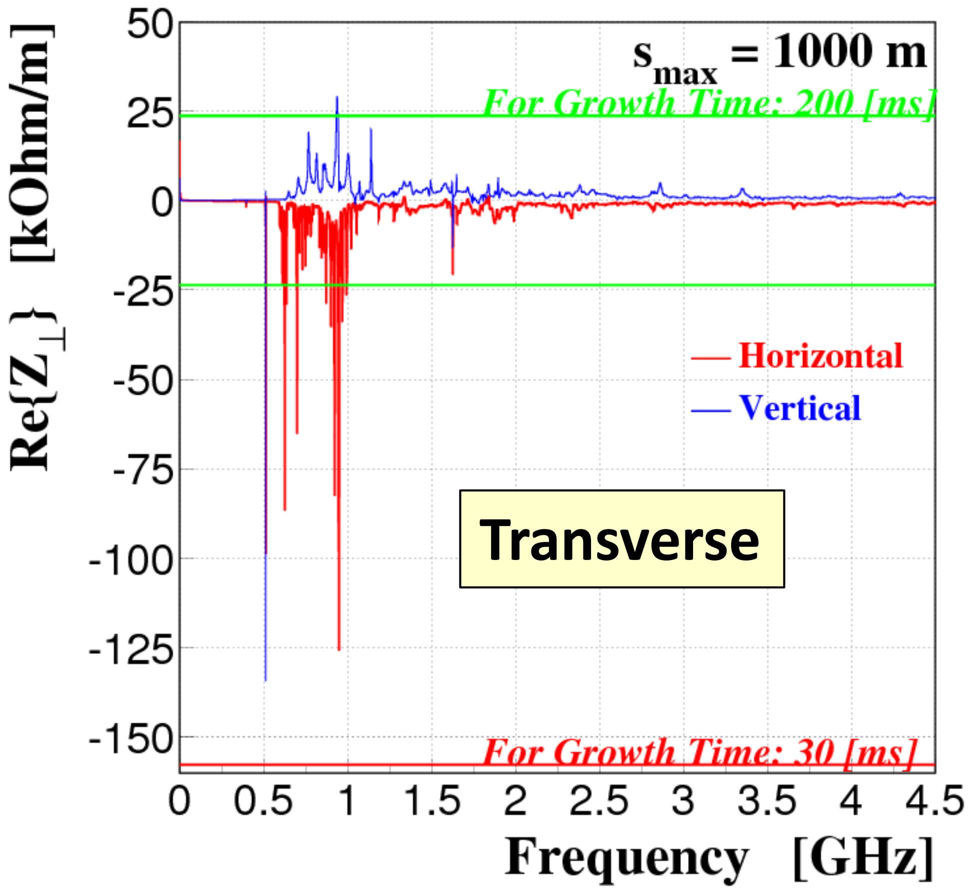
HOM impedances of the RF section are low enough below CBI thresholds.

(CBI: Coupled Bunch Instability)



- ✓From wakepotentials calculated, using GdfidL, for the whole RF section→
- ✓CBI thresholds were calculated for the DR design (8 nC / bunch).

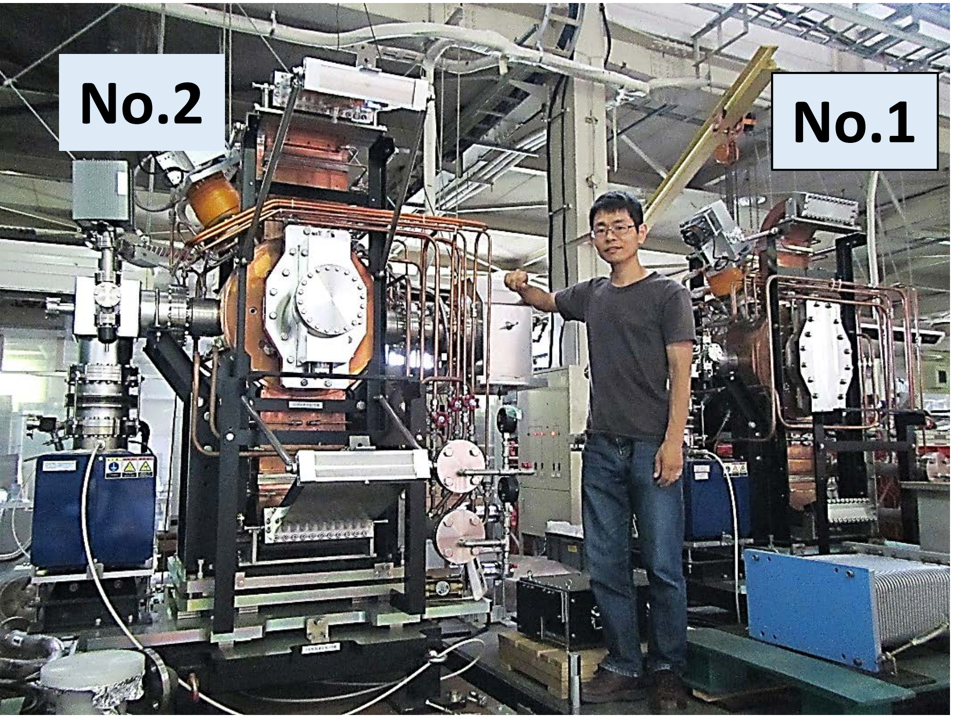




Growth Time > 20 ms
> 5 ms (radiation damping time)

Growth Time > 30 ms
> 10 ms (radiation damping time)

DR Cavities



0. Cavity No.0 (prototype) developed in JFY2011
   - Surface protection of the endplates: acid cleaning followed by chromating
1. **Cavity No.1** fabricated in JFY2012
   - Surface protection of the endplates: Electropolishing (EP)
2. **Cavity No.2** fabricated in JFY2013
   - Surface protection of the endplates: Electropolishing (EP)

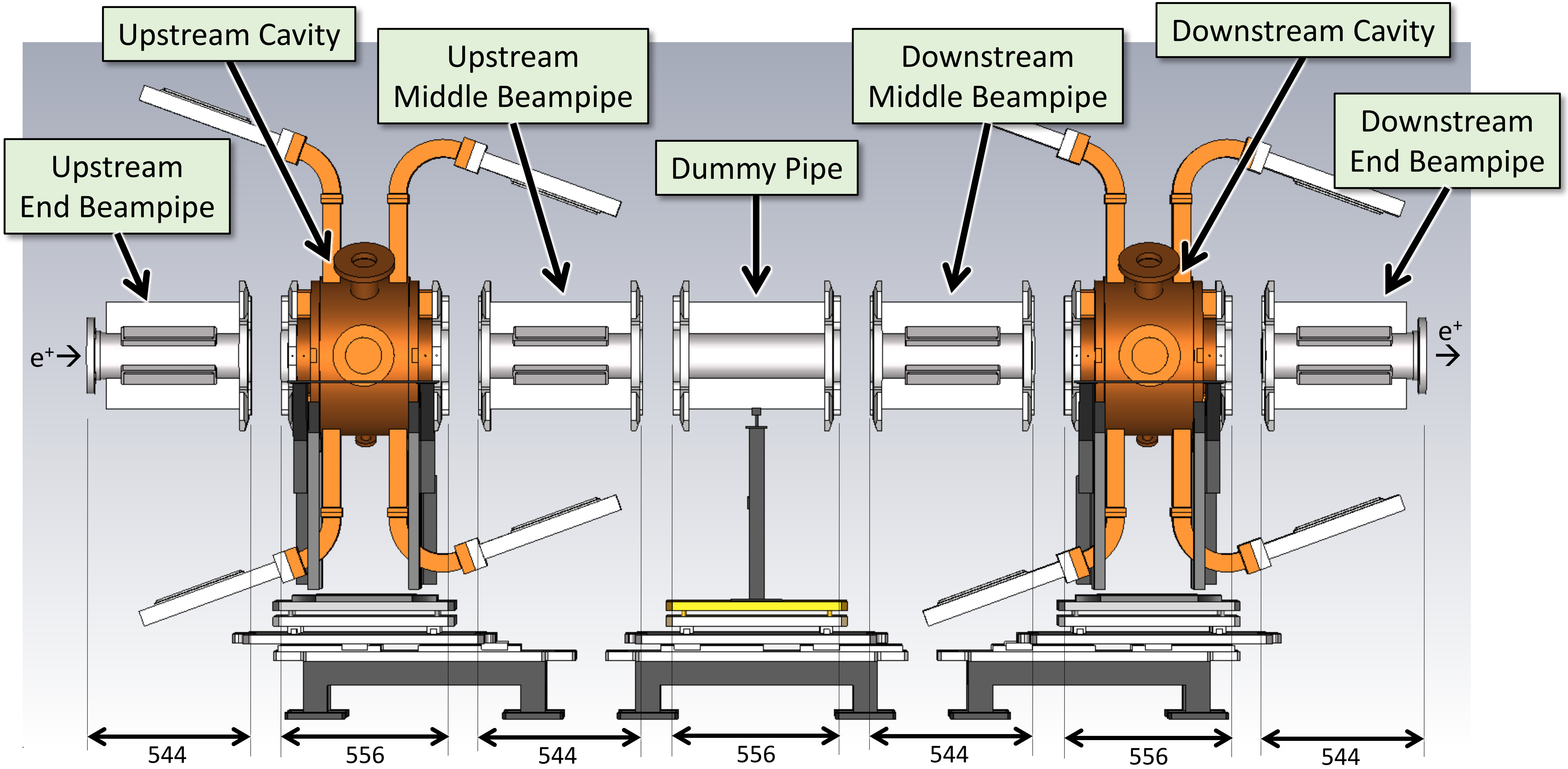
No difference between No.1 and No.2 in the:

- ✓ **Electric design**
- ✓ **Mechanical structure**
- ✓ **Fabrication method**
- ✓ **Low-power performance**
- ✓ **High-power performance**

2. Installation to the DR Tunnel

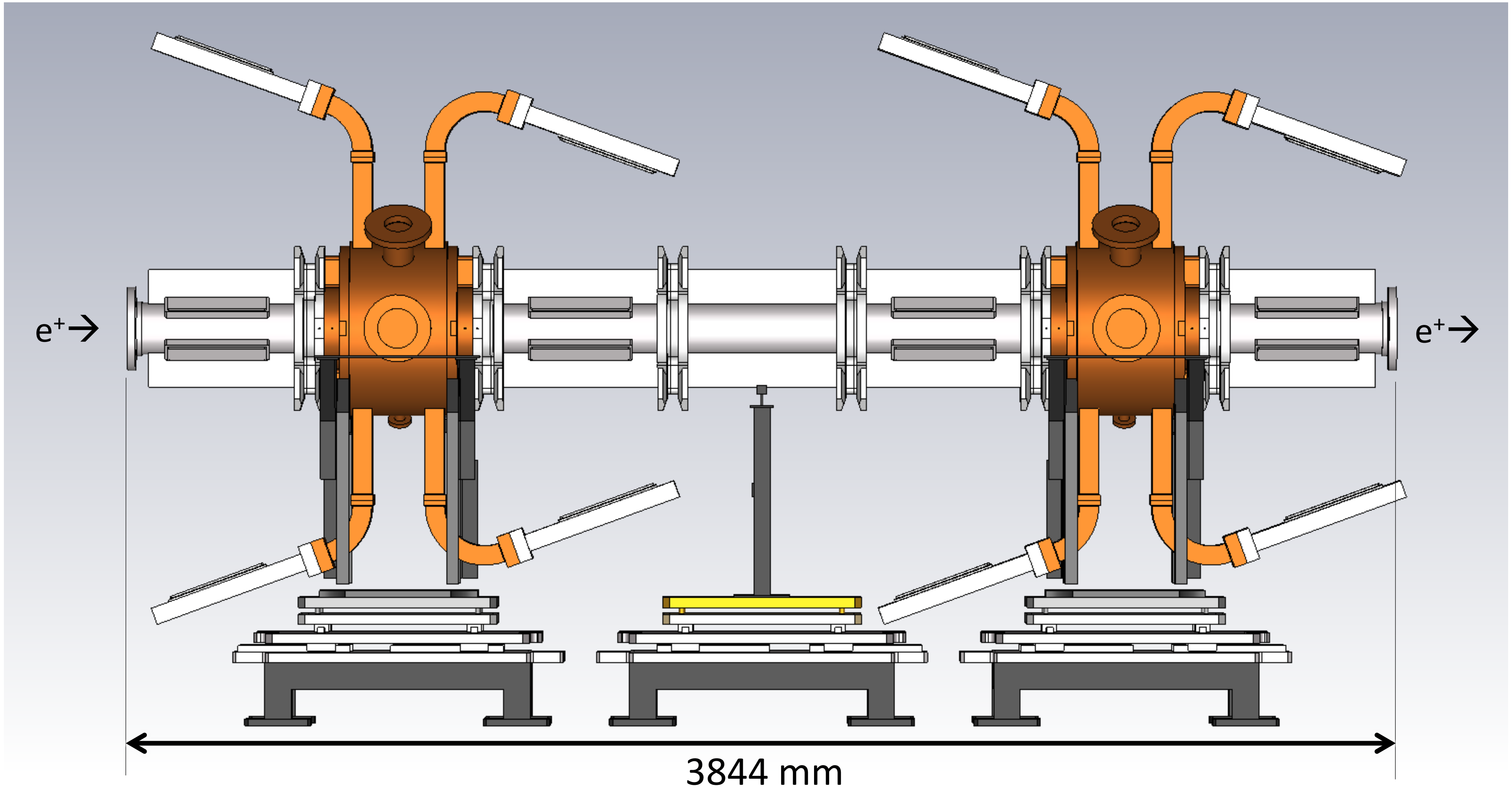
(November, 2016)

Components of the RF Accelerating Structure for the DR



Seven components (= two cavities + five beampipes) to be aligned ➔

Into one big mechanical structure (3.8 m long)



Seven components (two cavities and five beampipes) to be aligned ➔Connected

Alignment Policy

- **Accuracy**
  - 0.3 mm in the transverse directions
    - Same as for the ARES cavities at the MRs
  - (1.0 mm in the longitudinal direction)
- **What to be aligned**: beam-port flanges (not cavities)
- **Beam axis** defined by the quadrupole magnets next to the RF section (upstream and downstream)
- Position measurement of the Beam-port flanges ***prior to the installation***

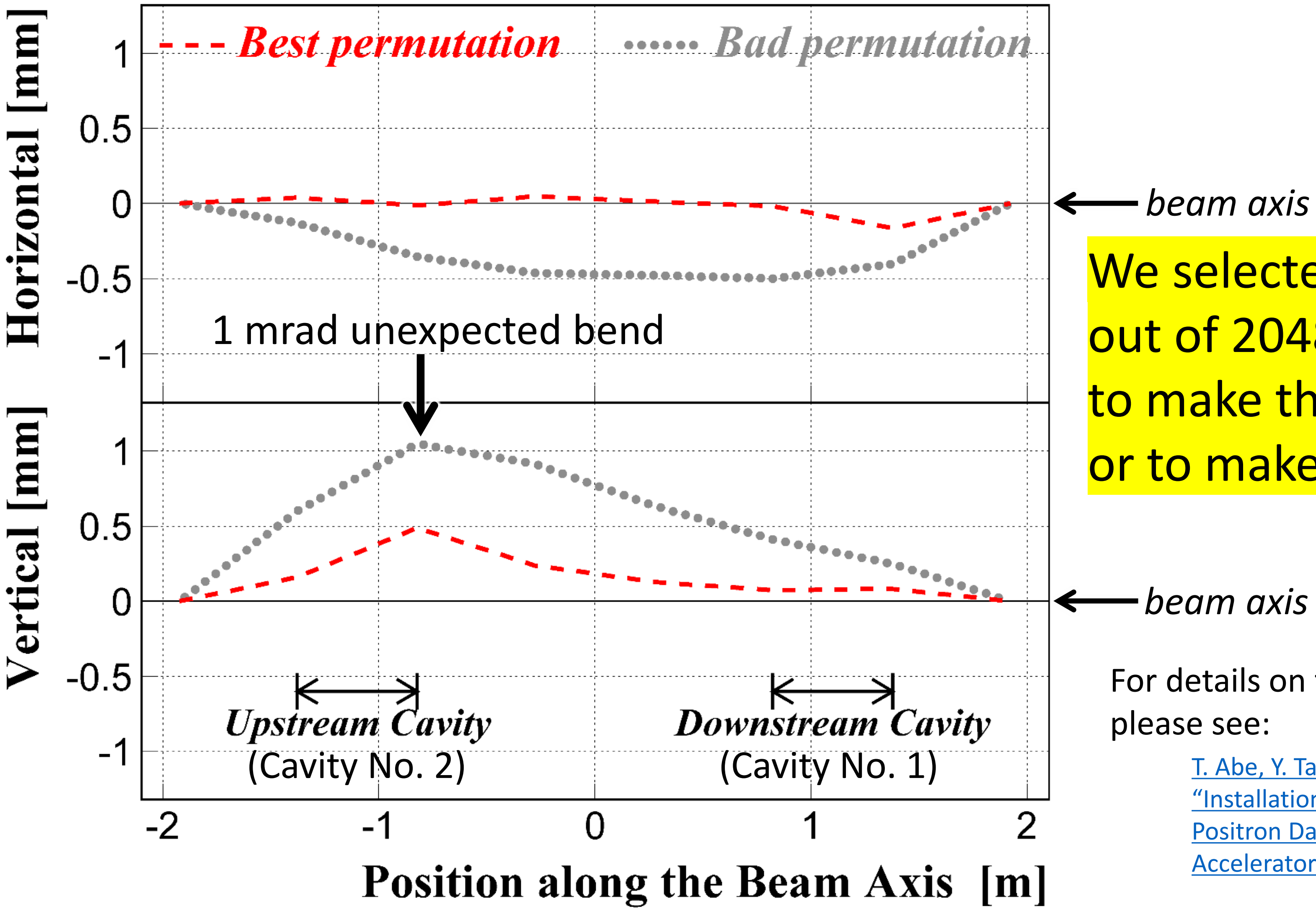
Position measurement of the beam-port flanges

using **FaroArm Edge** (portable CMM):

- ✓ Measurement range: 1.8 m (in diameter)
- ✓ Five axes
- ✓ Precision at a fixed point: 0.024 mm (spec)

FaroArm Edge
from KEKB monitor group →

Offsets of the component centers predicted from the measurement results using FaroArm Edge

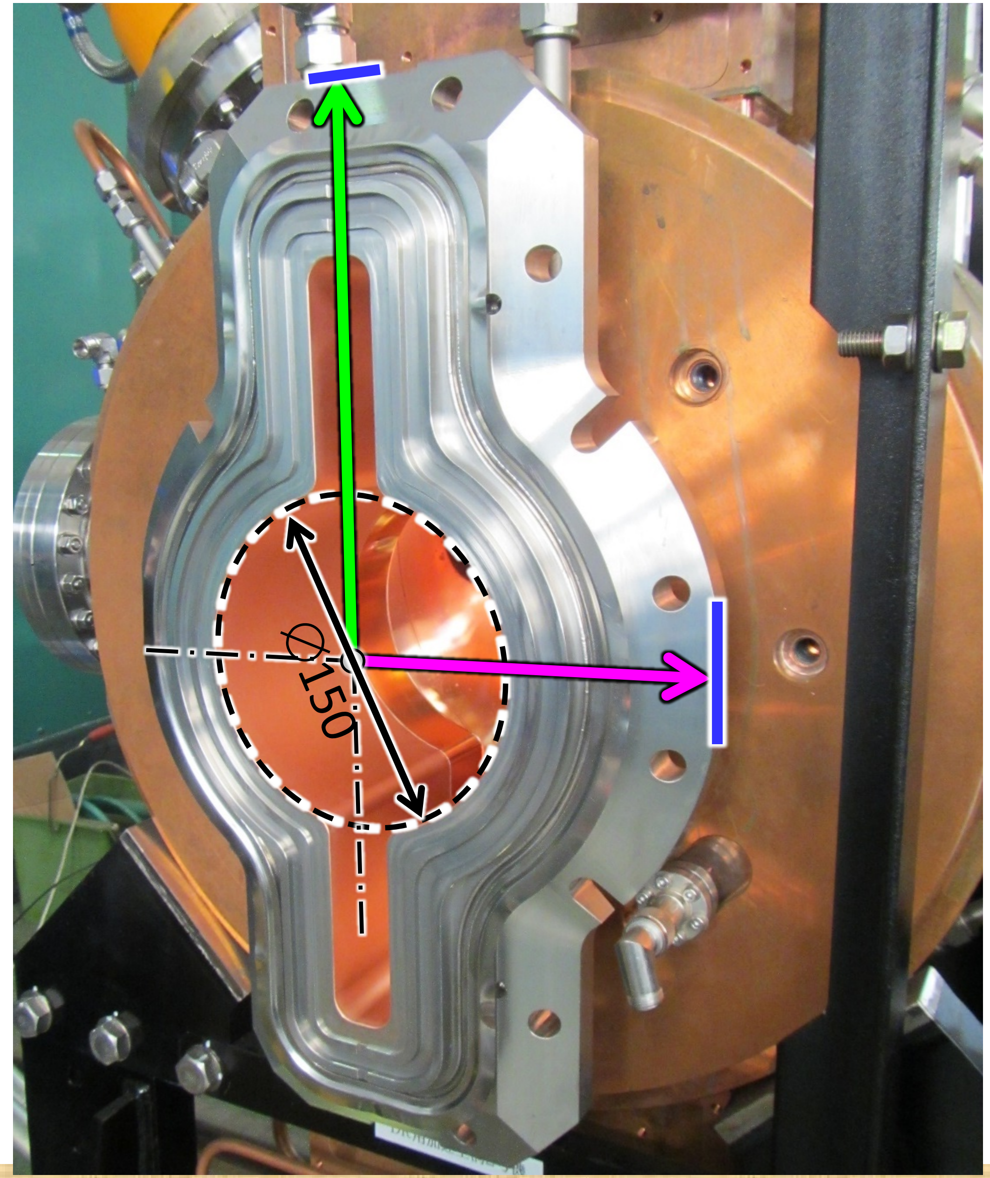


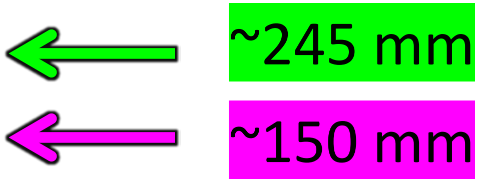
We selected the ***best permutation***
out of 2048 permutations of the components
to make the offsets as small as possible,
or to make the structure as straight as possible.

For details on the algorithm to select the best permutation, please see:

T. Abe, Y. Takeuchi, H. Sakai, T. Kageyama, K. Yoshino, M. Masuzawa, T. Kawamoto, "Installation of Normal-Conducting RF Accelerating Cavities into the SuperKEKB Positron Damping Ring", in Proceedings of the 14th Annual Meeting of Particle Accelerator Society of Japan, 2017 (Paper ID: TUOL06).

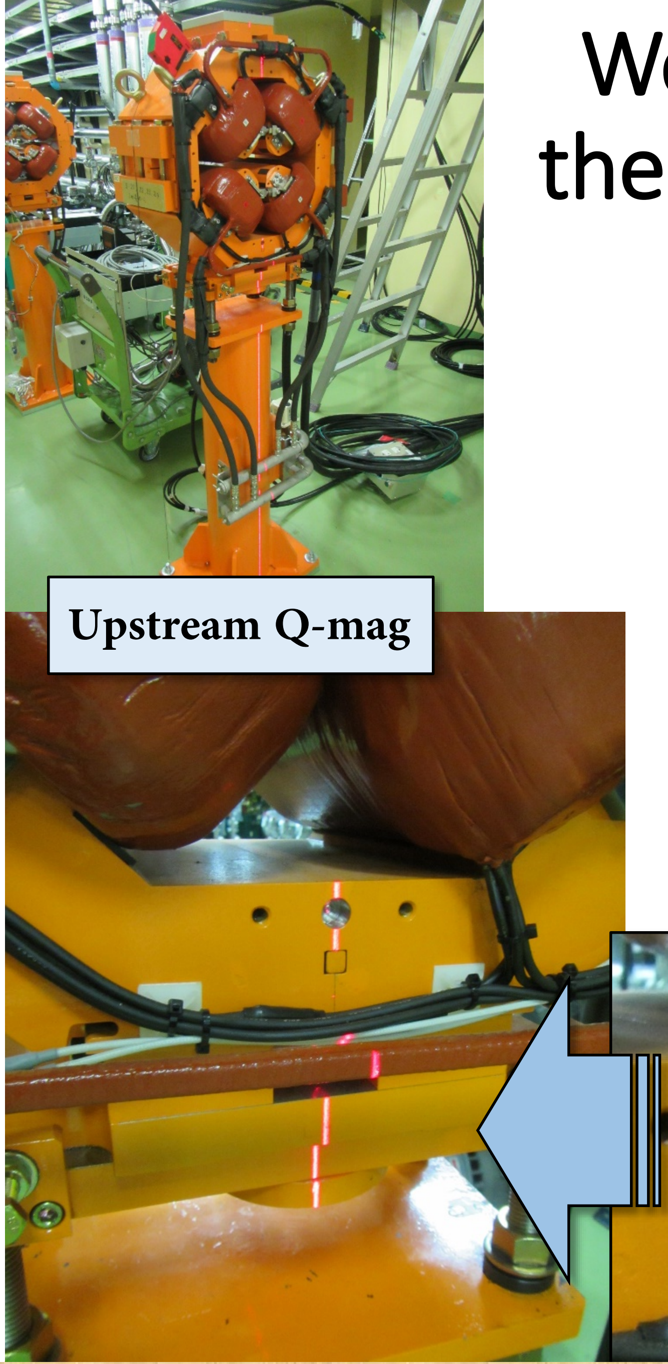
We also measured distances between the ∅150-duct center and the reference planes of the beam-port flanges.

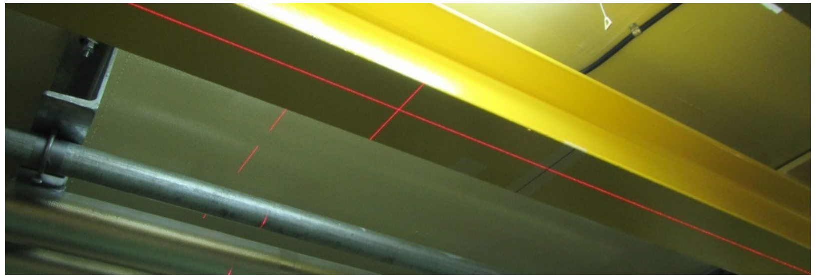


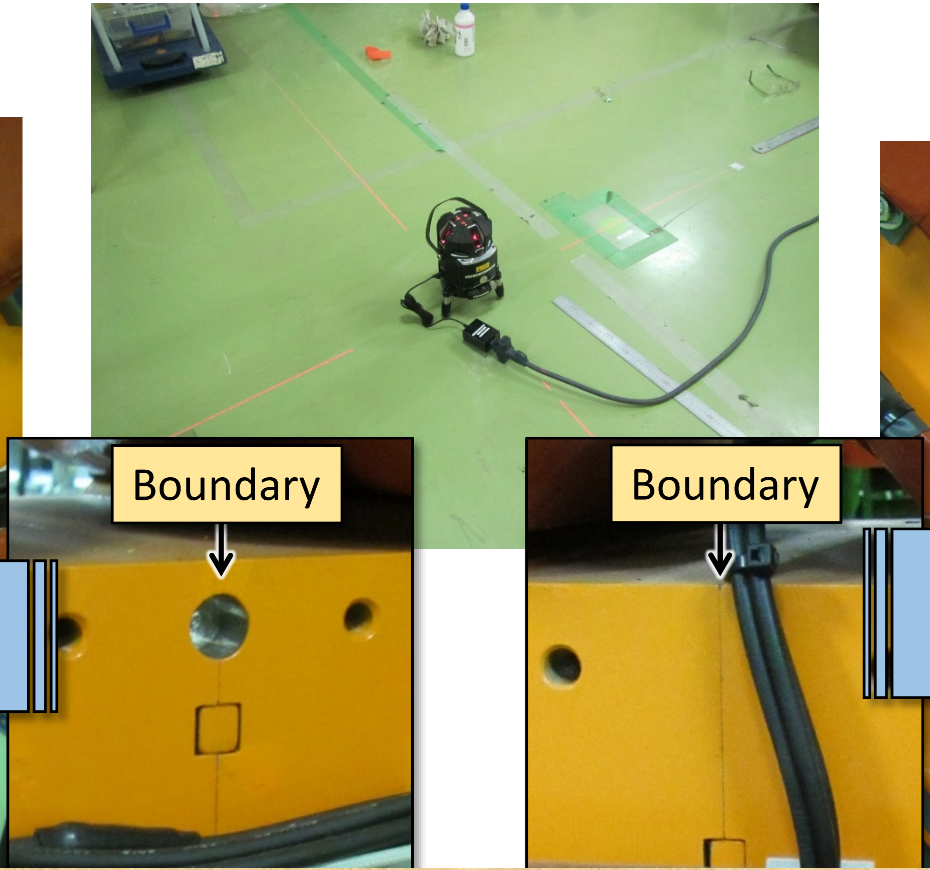


To be used in the position measurement after the installation

We defined and marked the beam axis (horizontal).

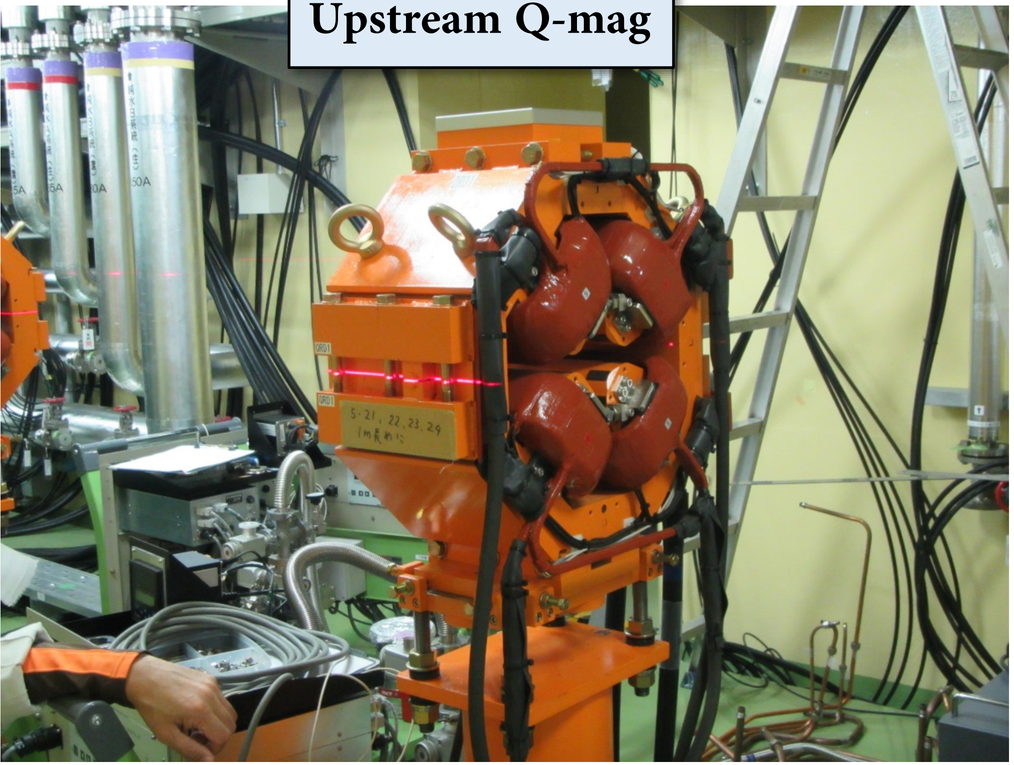




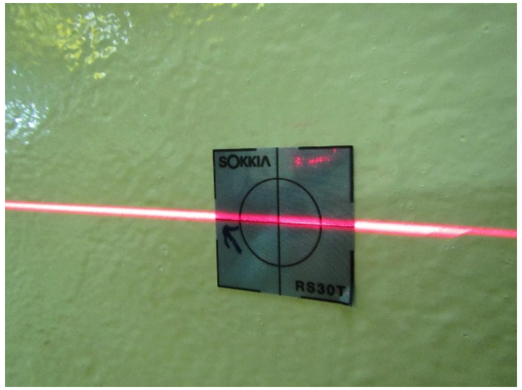


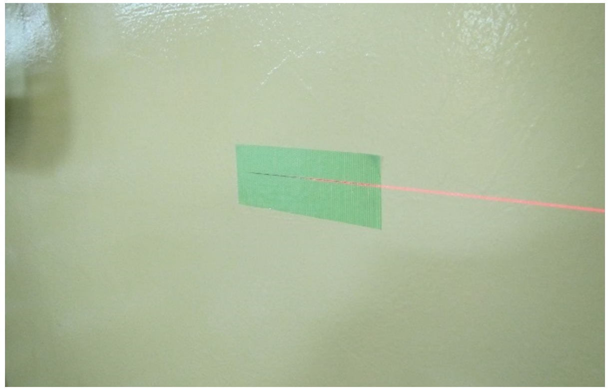
We defined and marked the beam axis (level).

Upstream Q-mag

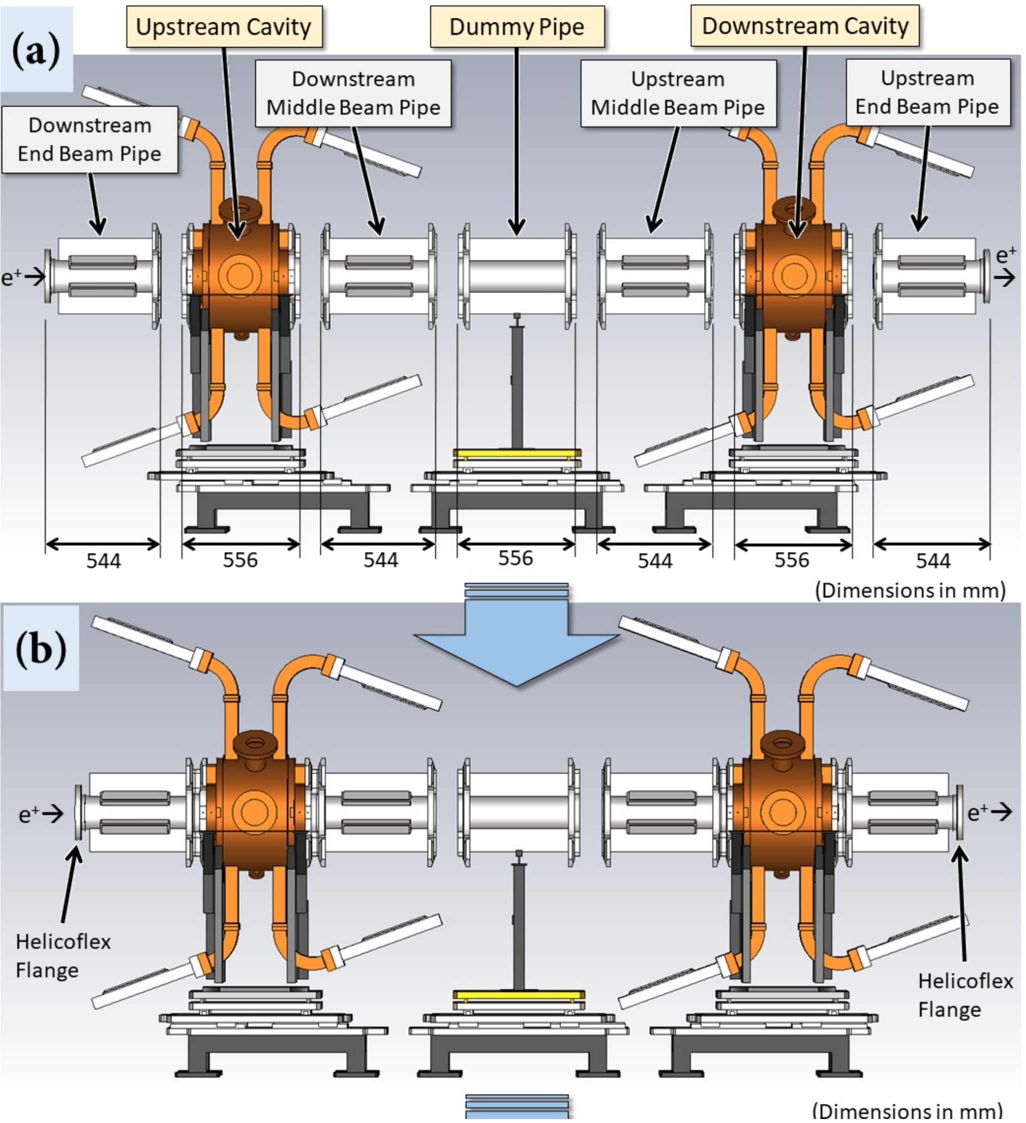


Downstream Q-mag





Connecting the grooved beampipes to the cavities



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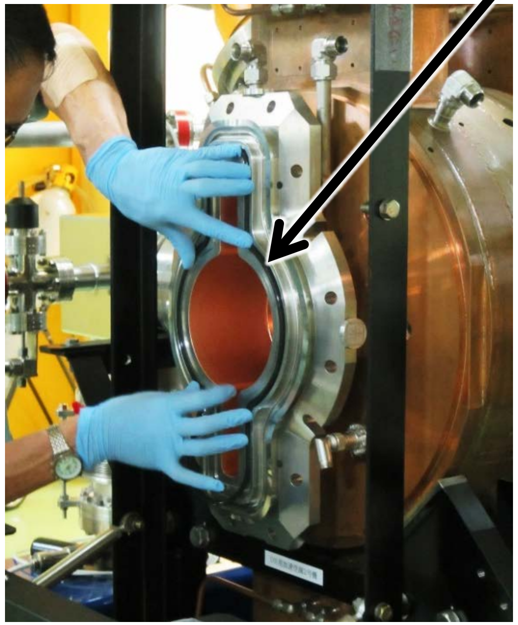

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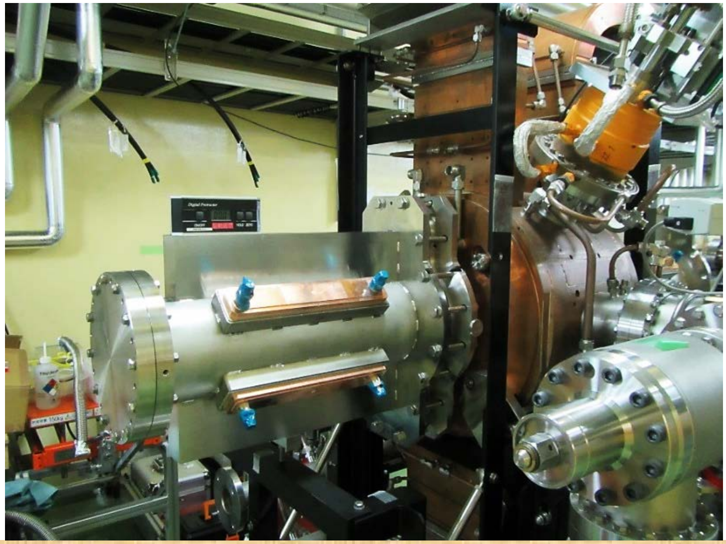
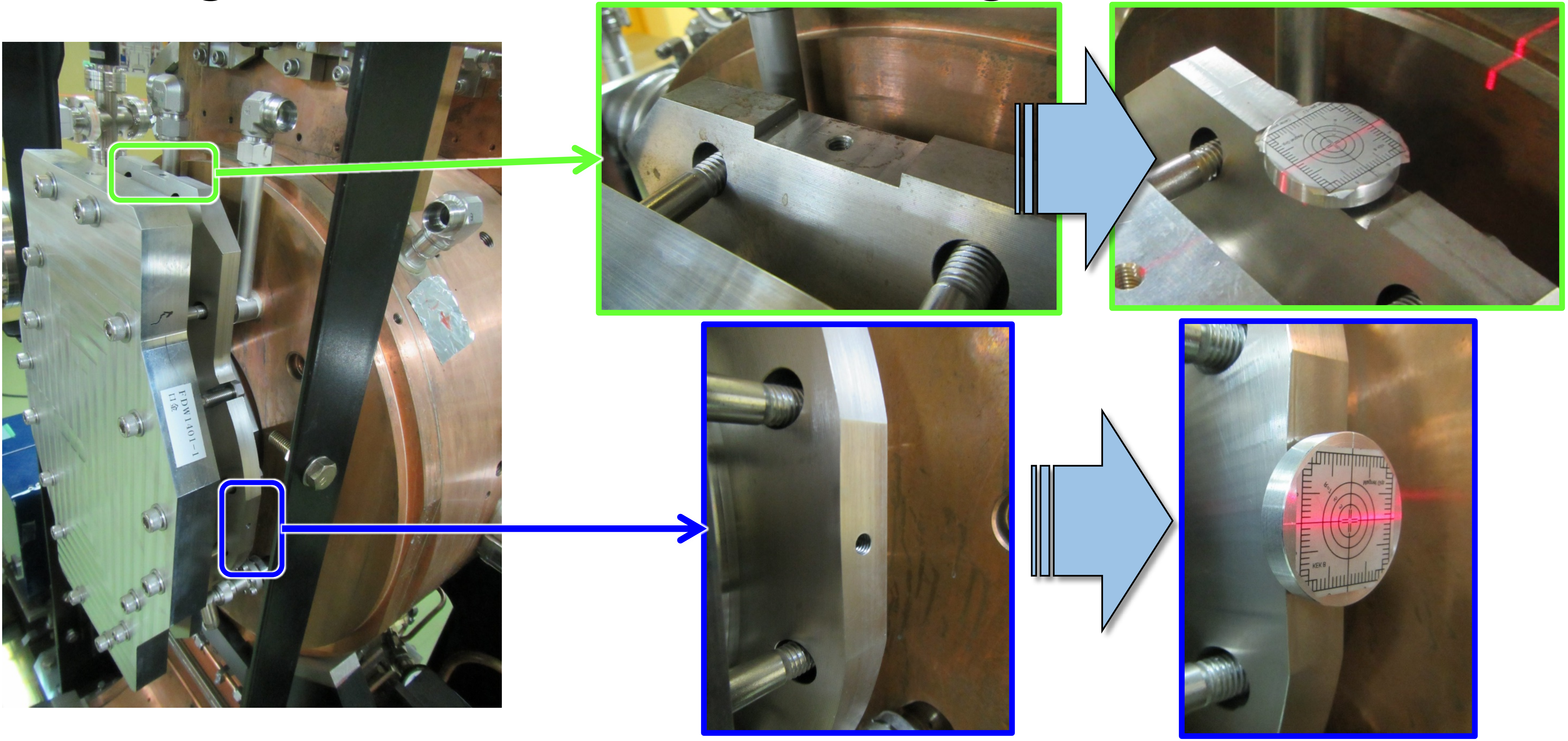
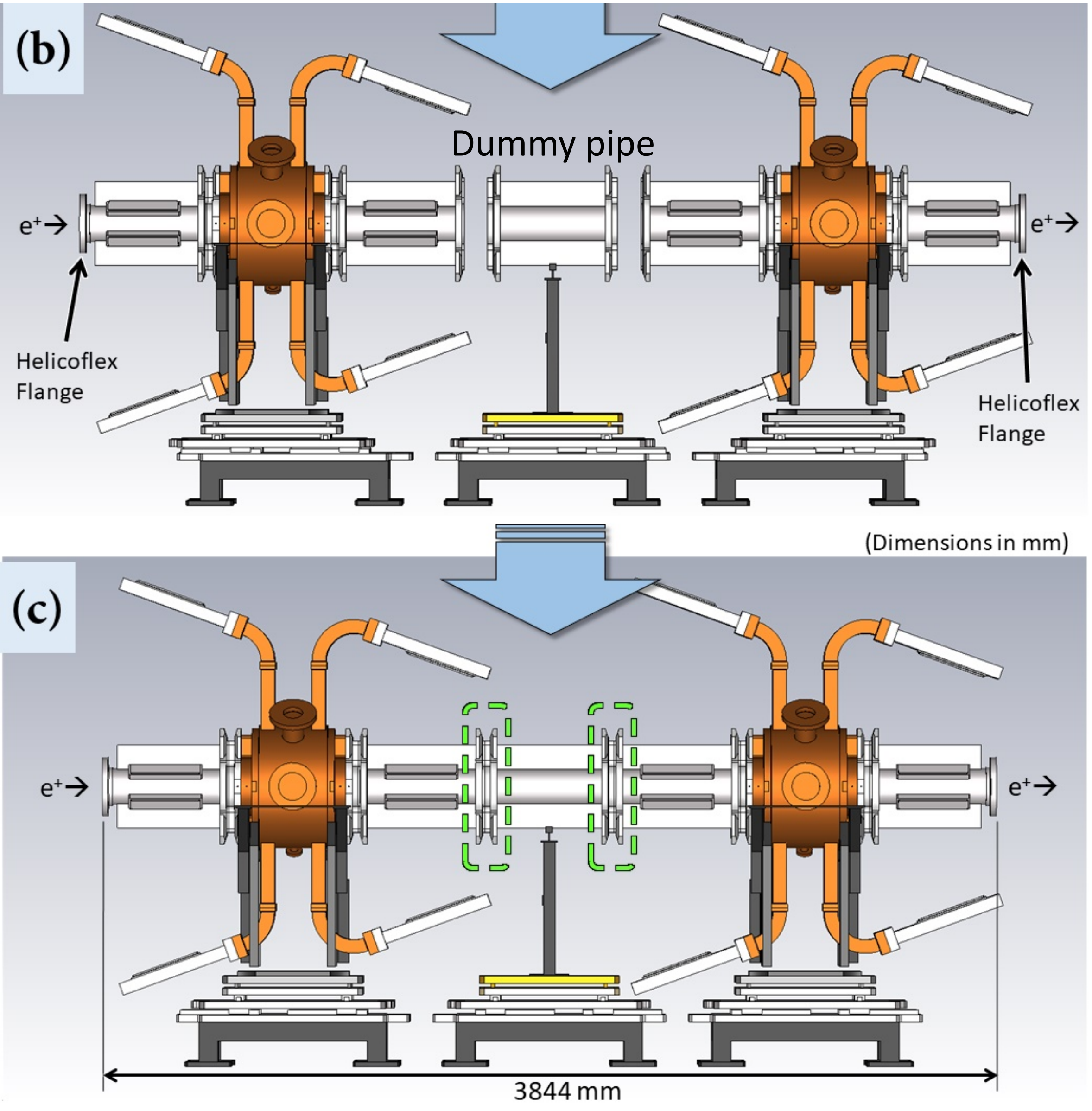
→

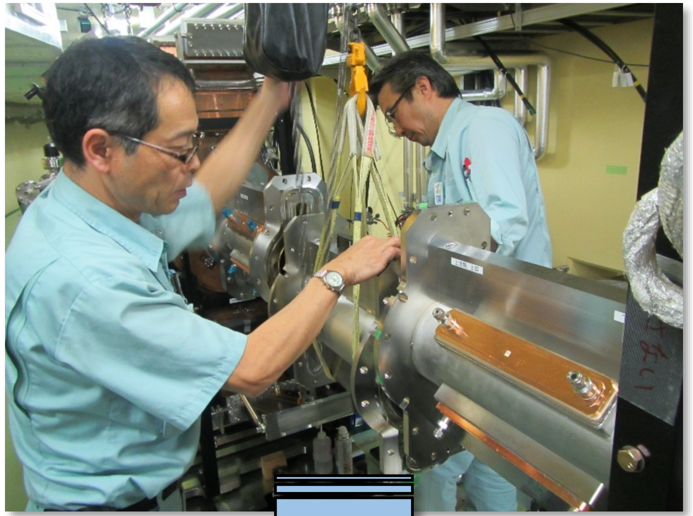


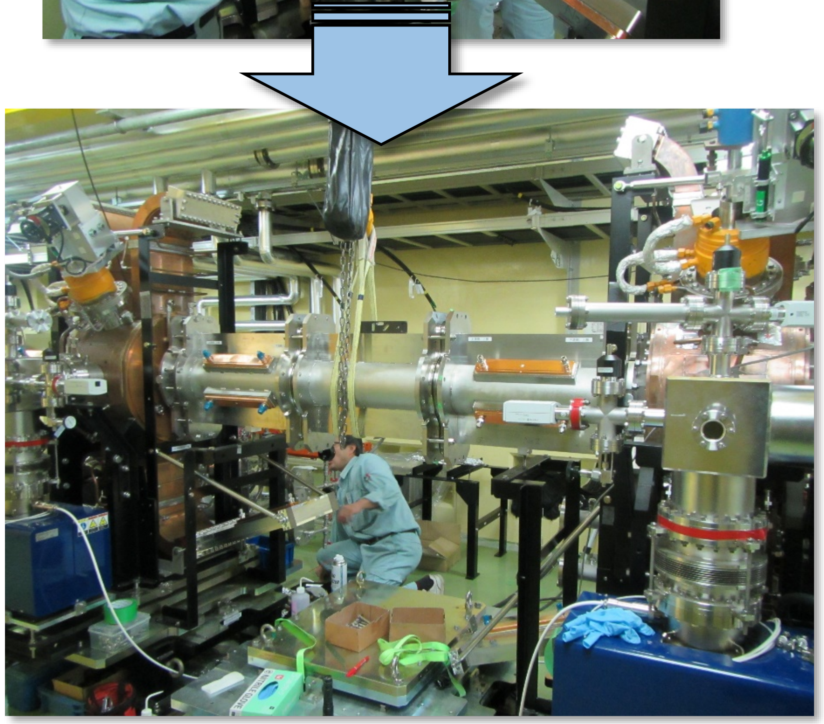
Alignment of the Beam-Port Flanges of the Cavities

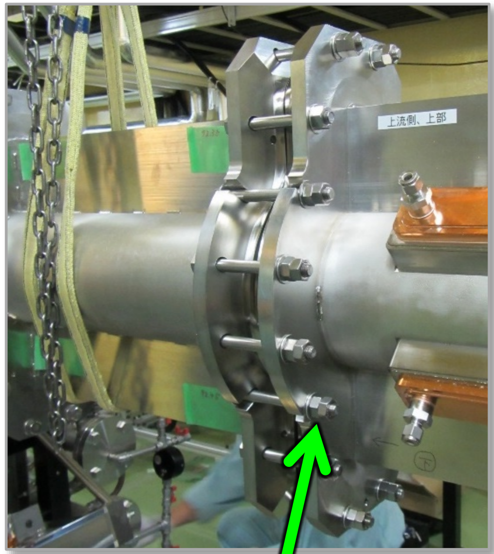


Then, we connected the dummy pipe.







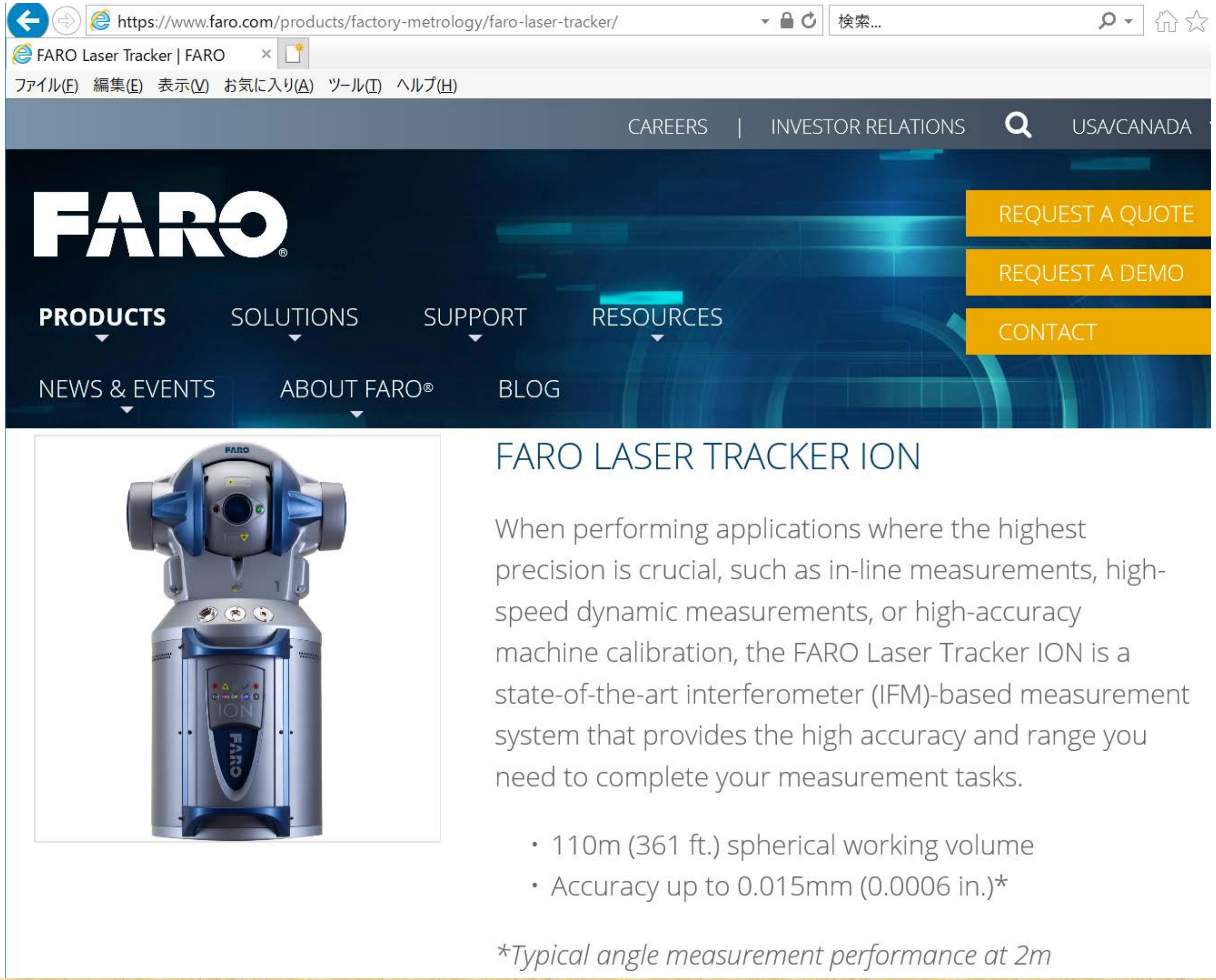


Fixed with double nuts to avoid too much stress

Position Measurement of the Beam-Port Flanges *after the Installation*

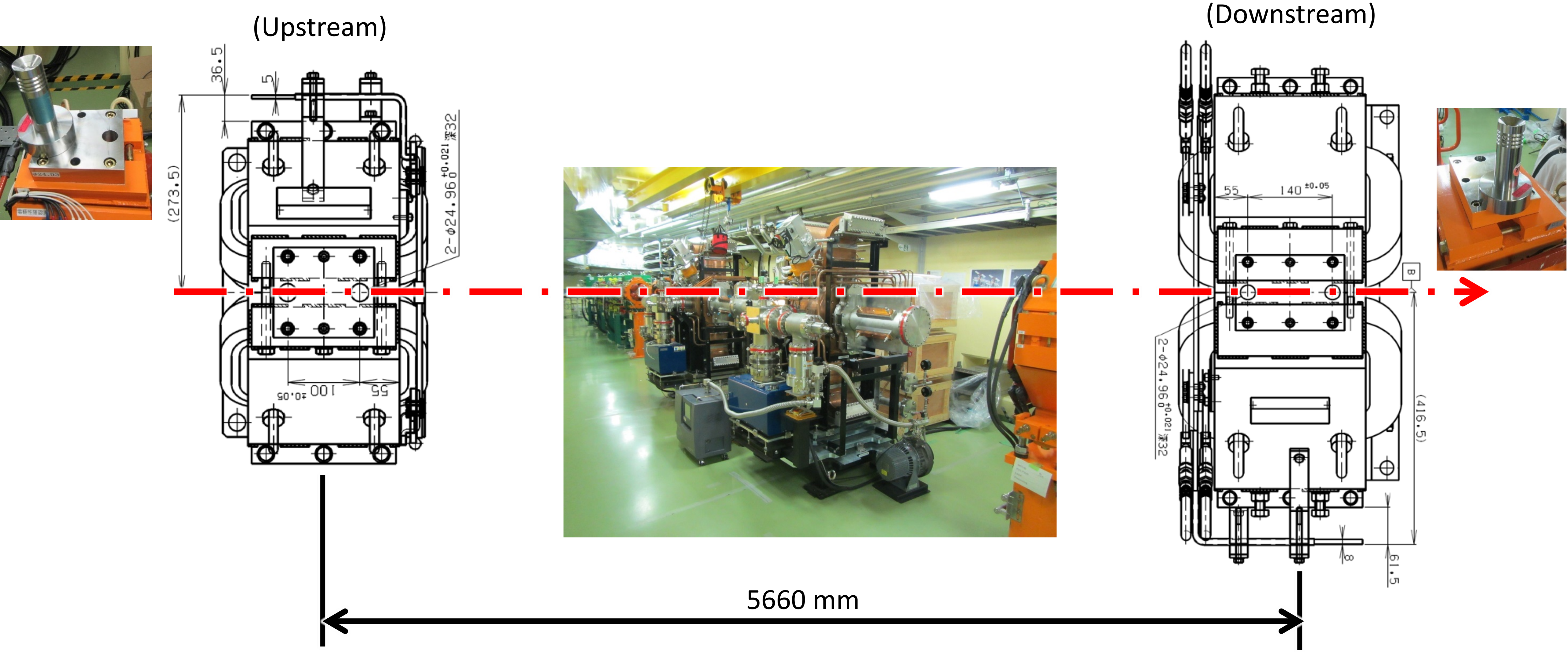
to check the installation accuracy

Using FARO Laser Tracker ION

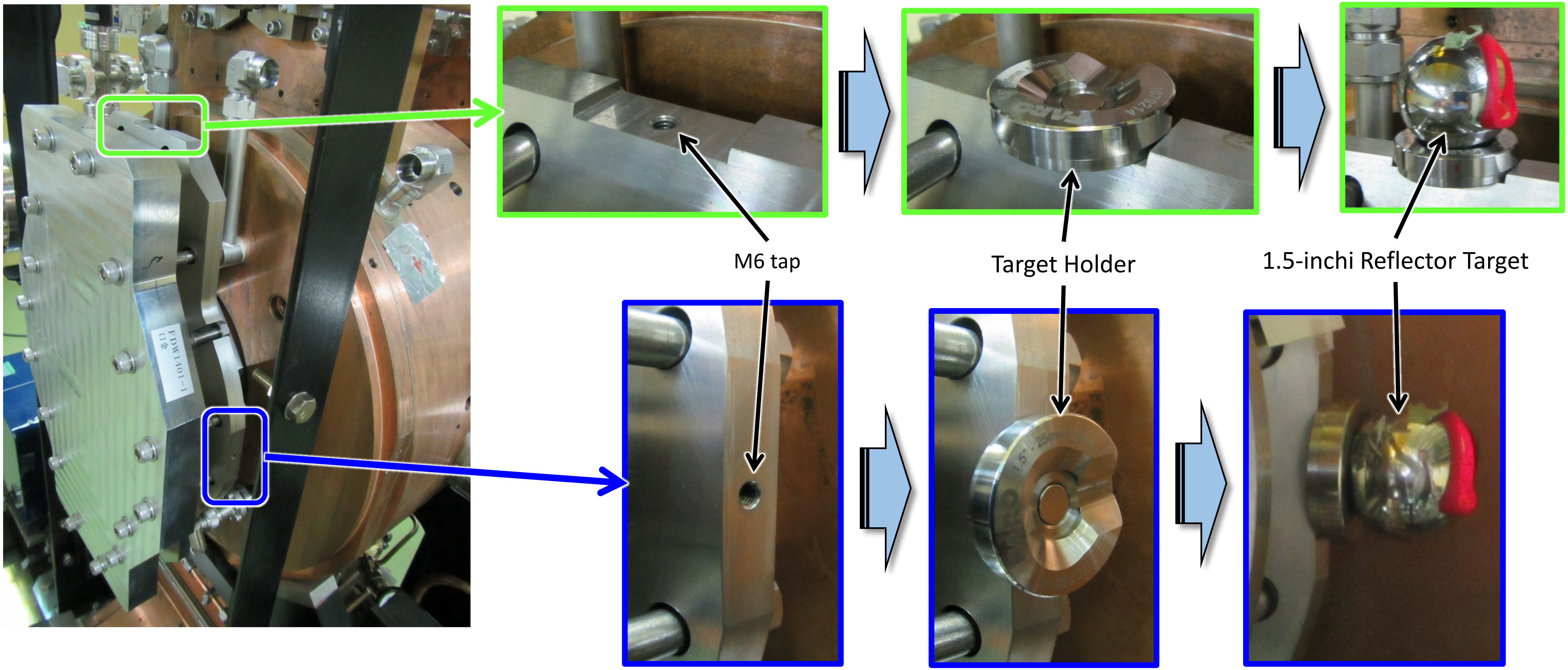


From KEKB Magnet Group

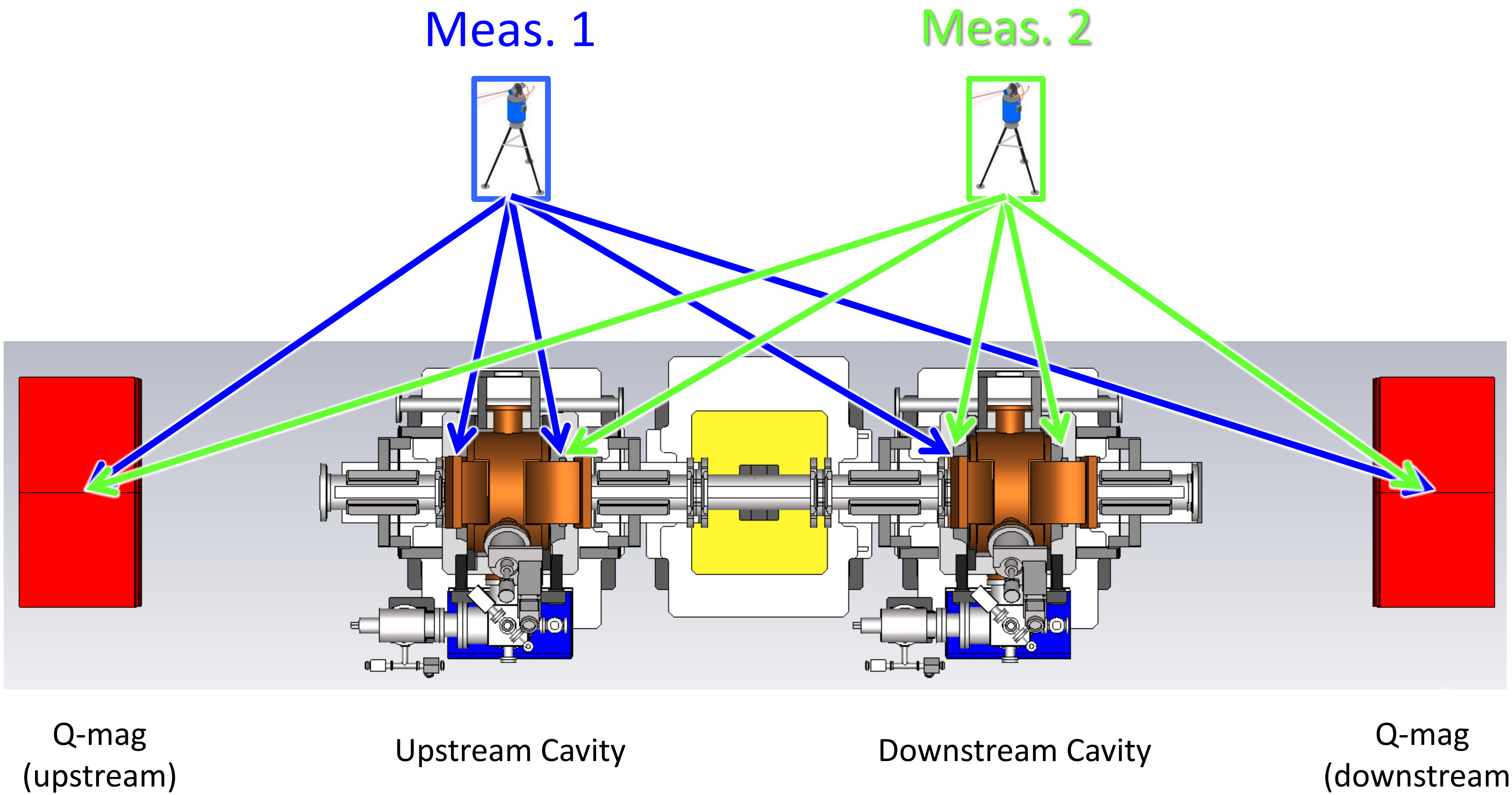
Redefined the beam axis based on the reference base plates of the Q-magnets



Position Measurement using the laser tracker

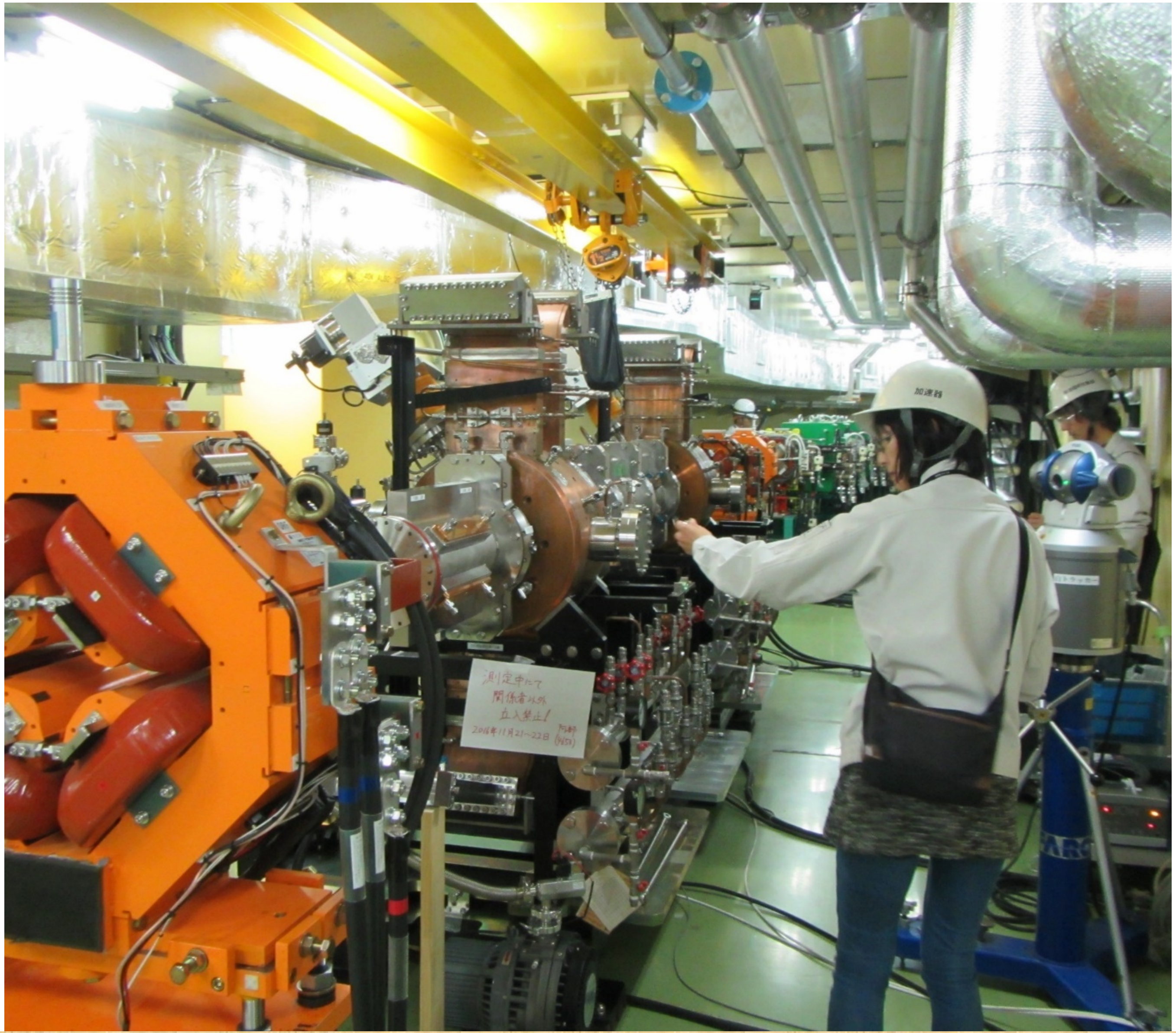


Two-step measurement

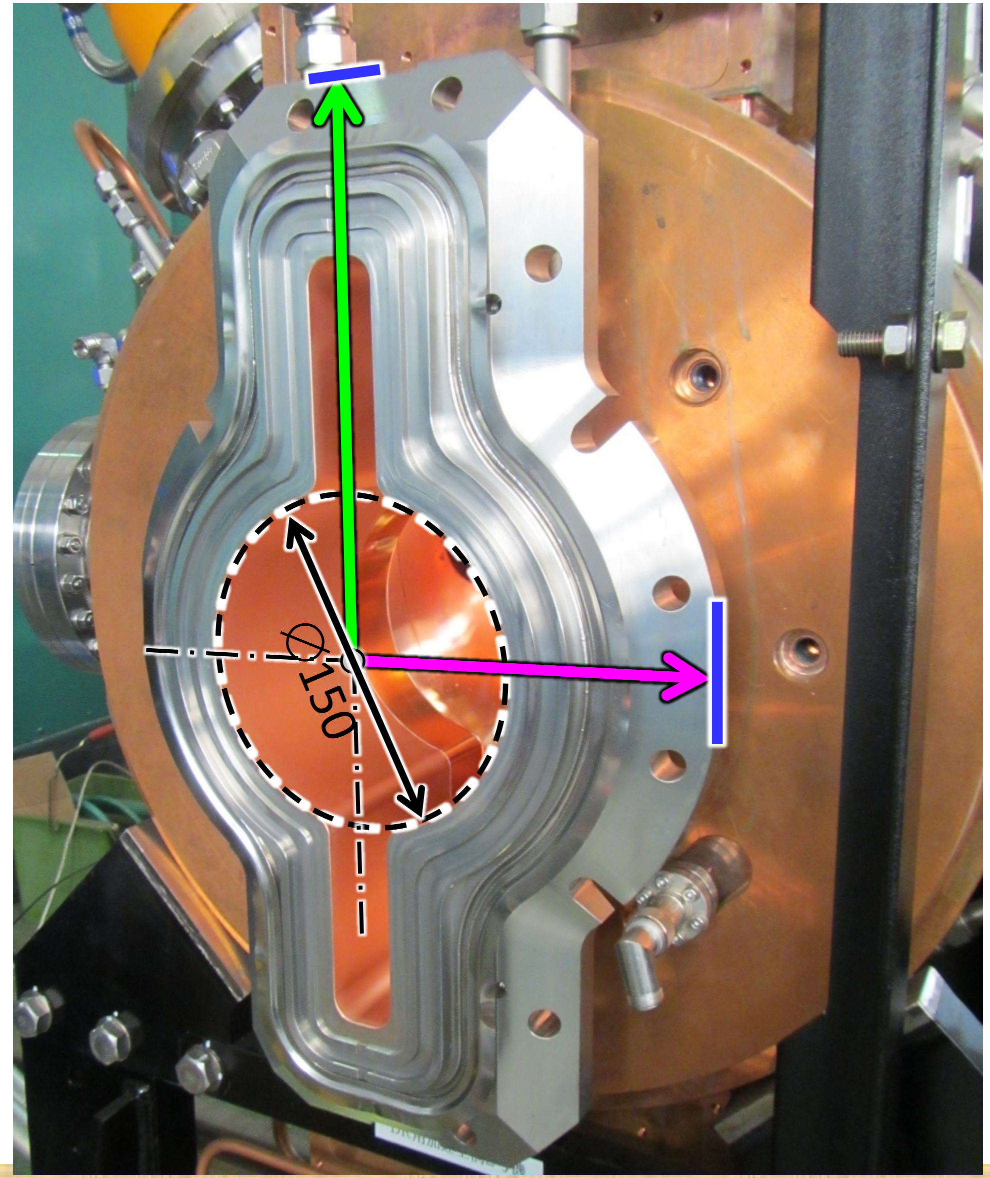


Measurement using the laser tracker by Masuzawa-san and Kawamoto-san

(From KEKB Magnet Group)



Combined with the measurement results using FaroArm Edge on the distances between ∅150-duct center and the reference planes of the beam-port flanges,

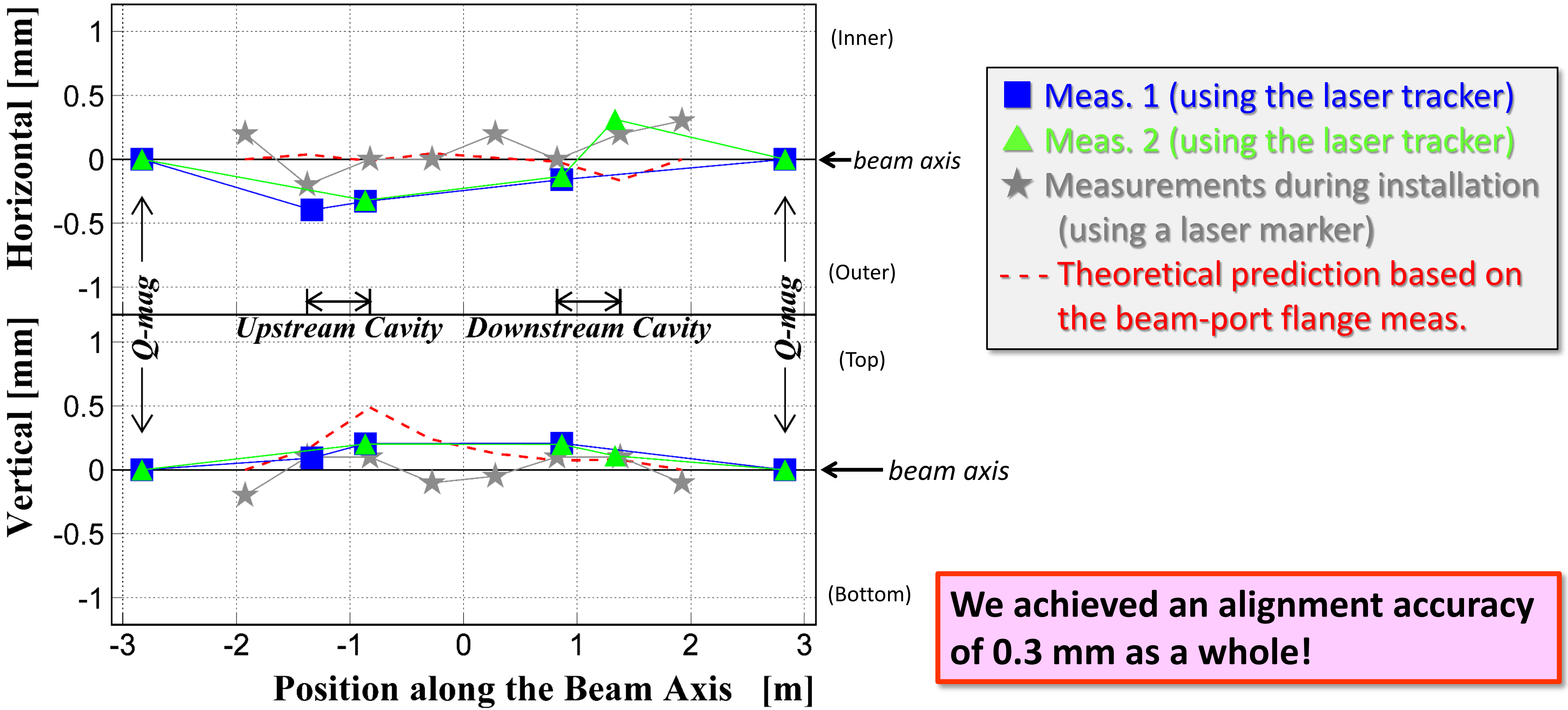


Using FaroArm Edge

~245 mm

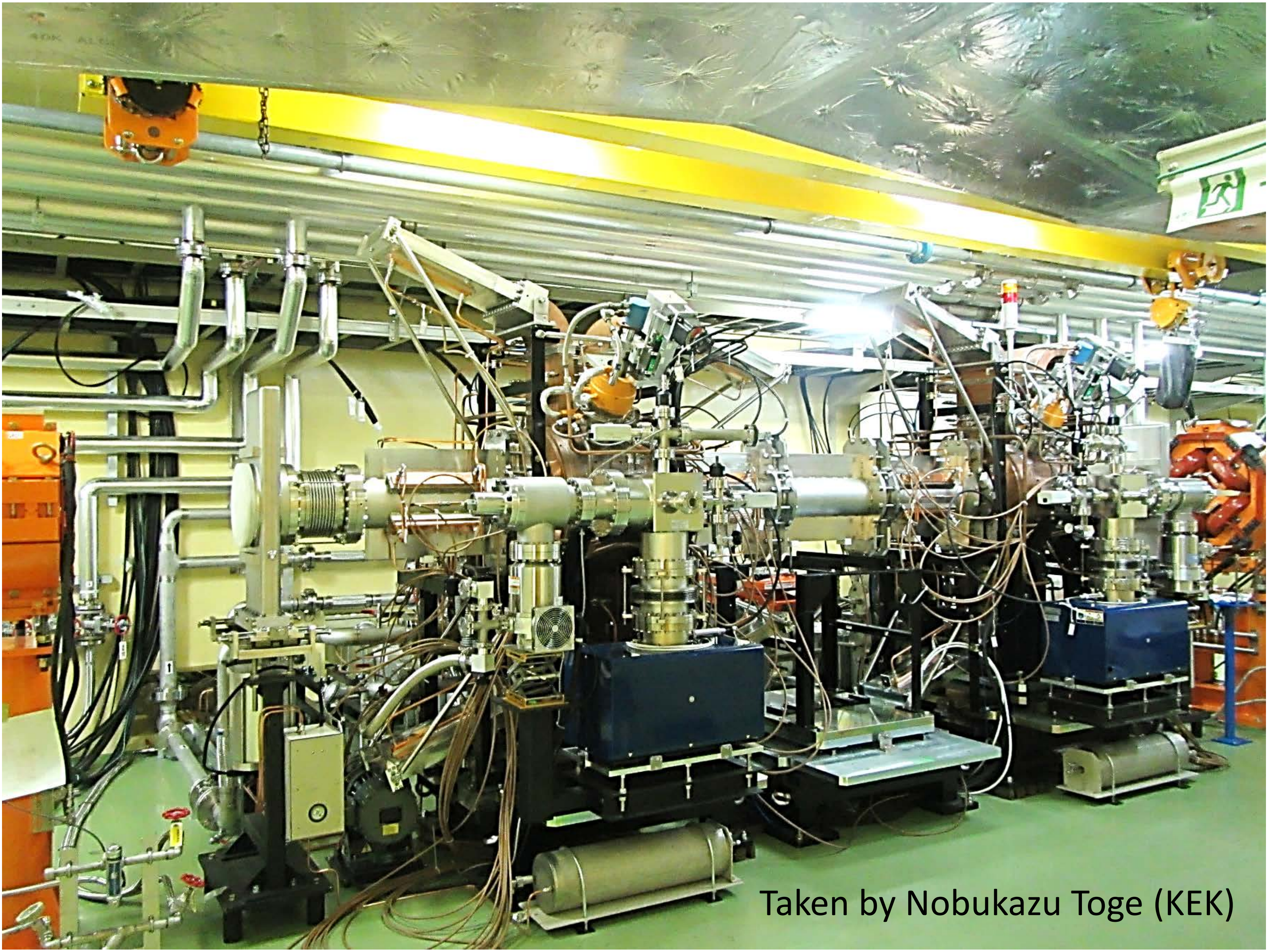
~150 mm

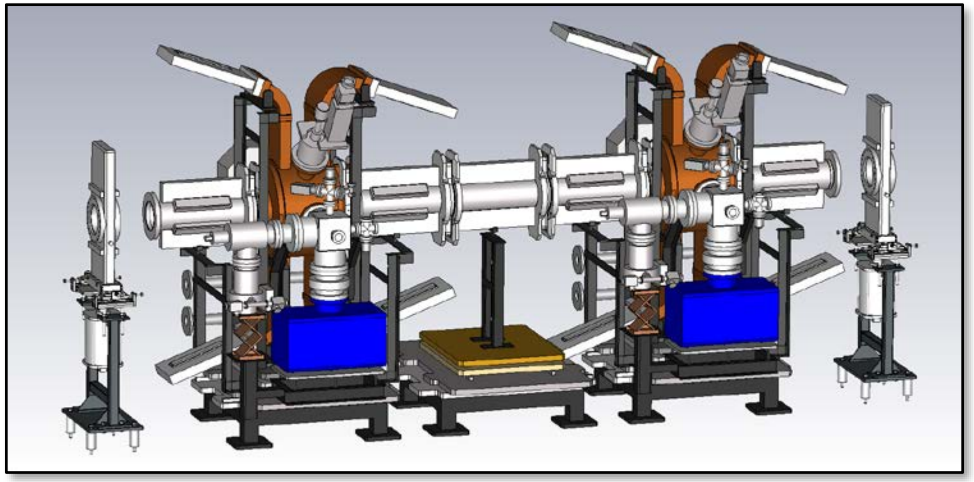
We obtain deviations of the beampipe center from the beam axis.



We achieved an alignment accuracy of 0.3 mm as a whole!

After all the installation works

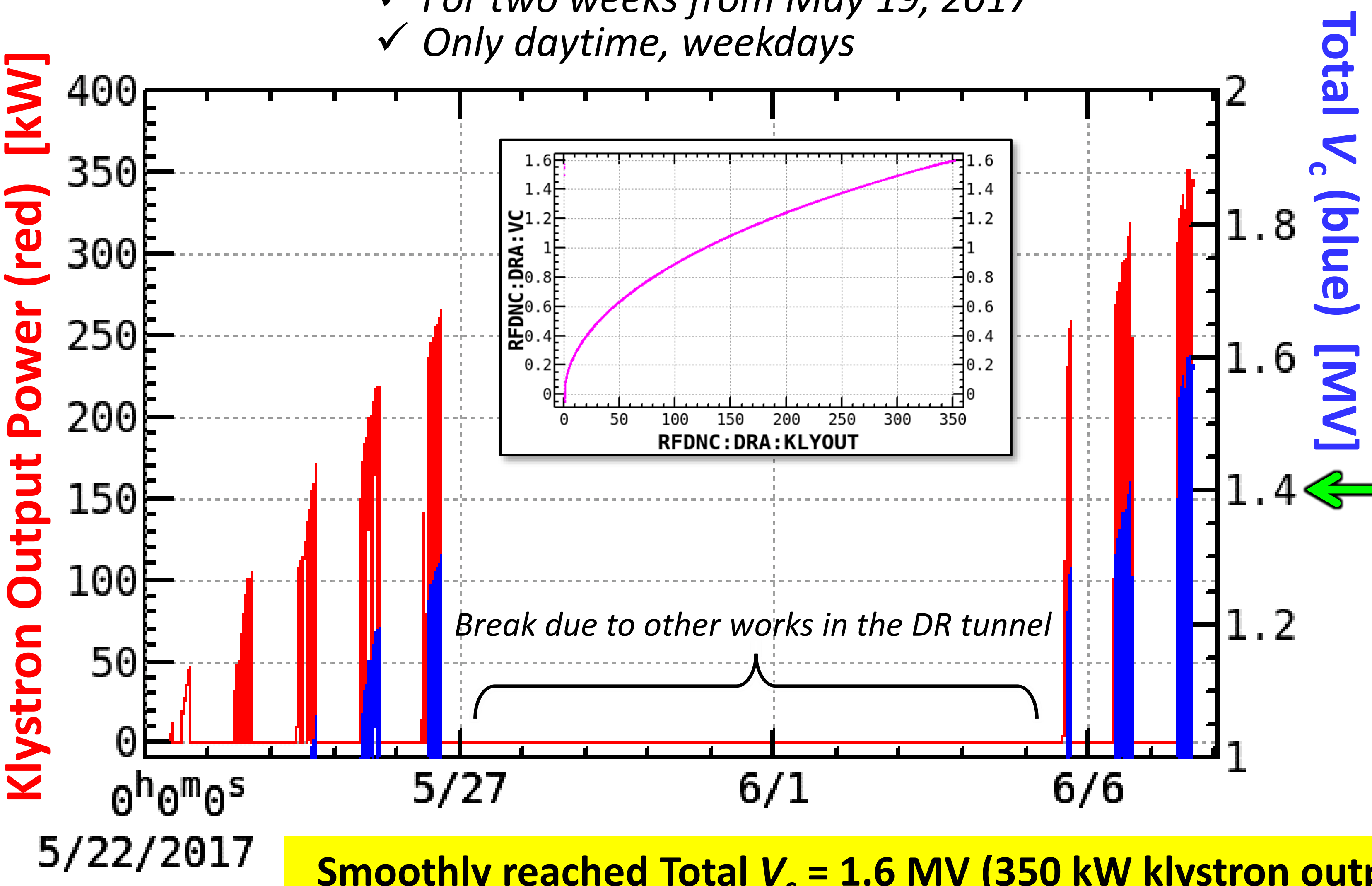




High-Power RF Conditioning after the Installation

- ✓ *For two weeks from May 19, 2017*
- ✓ *Only daytime, weekdays*

Note: High-power RF conditioning of each cavity was completed at a test stand beforehand.



Smoothly reached Total V_c = 1.6 MV (350 kW klystron output) over the DR spec: total V_c = 1.4 MV

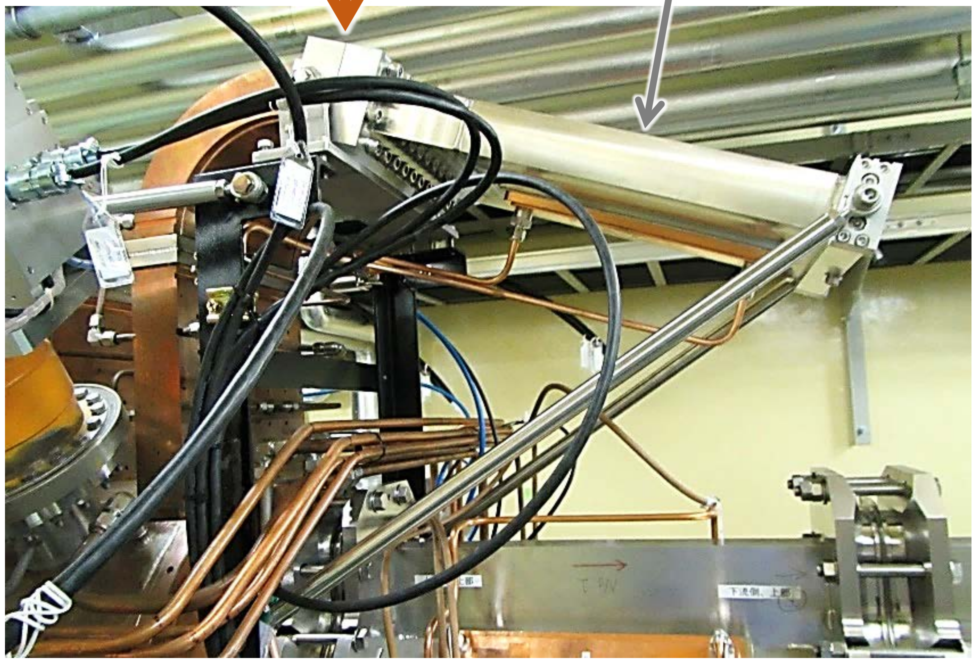
However,

After maintaining total V_c = 1.6 MV (350 kW klystron output) during the conditioning,
small vacuum leaks (10^{-9} to 10^{-8} Pa m^3/sec)
occurred at the 7 rectangular flanges of the HOM waveguides .

Possible cause is a thermal cycle accompanied by high temperature at the rectangular flanges
(~50 degC at max. for total V_c = 1.6 MV)

The vacuum leaks stopped by increasing the clamping torque except for one waveguide flange*.

(*The gasket was replaced, and then no leak)

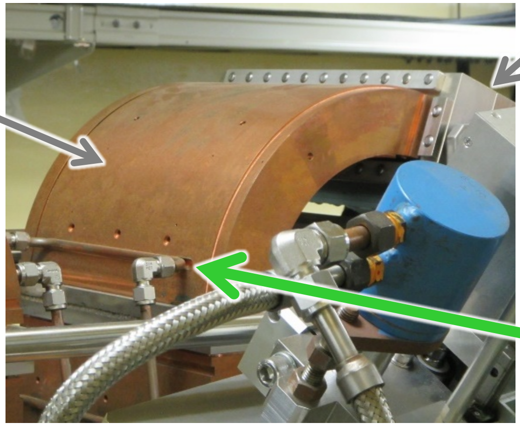


Measures against thermal cycles (taken in Oct., 2017)

1. We added more cooling pipes on the E-bends of the HOM waveguides to suppress the thermal cycle at the rectangular flanges.

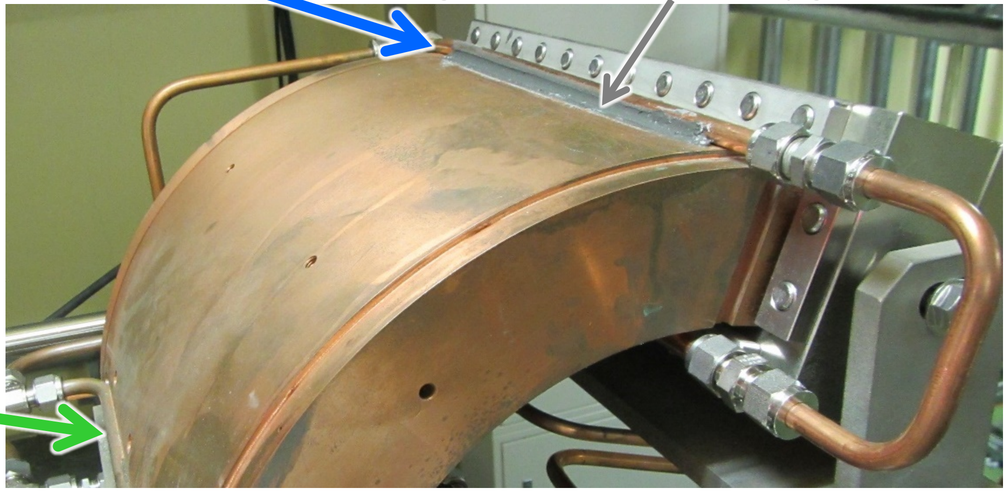
E-bend

Cavity



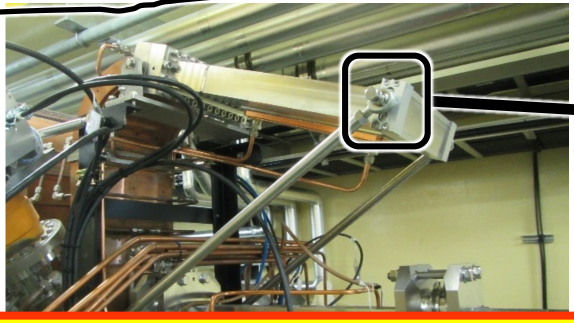
Cooling pipe brazed on the E-bend during the fabrication of the cavity

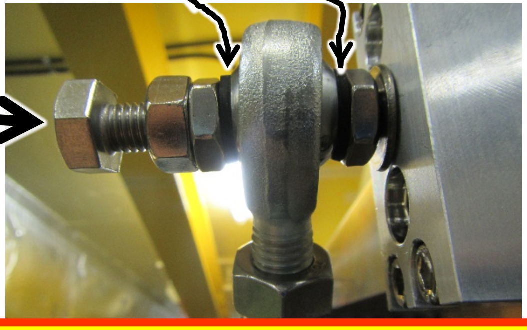
High thermal-conductivity glue (Devcon)



2. We inserted rubber bushes at the end of the support bars to make small degree of flexibility.

(EPDM)





No vacuum leak since we took these measures

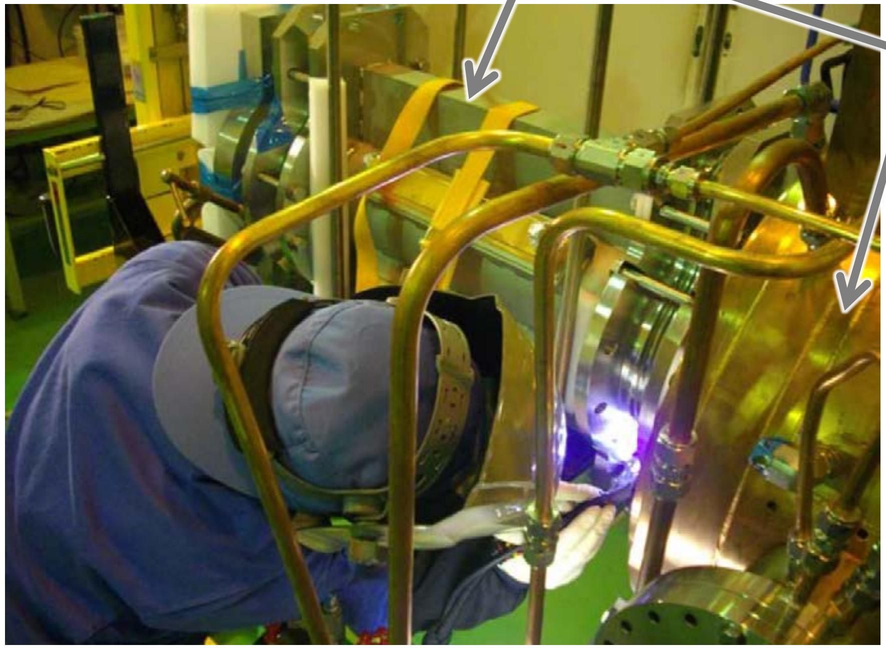
(last leak test performed on Feb.22, 2018)

3. Status of Cavity No.0 (prototype)

Cavity No.0 was used for Lip Welding Test in 2012.

Cavity No.0

Grooved beampipe (prototype)



We have demonstrated:

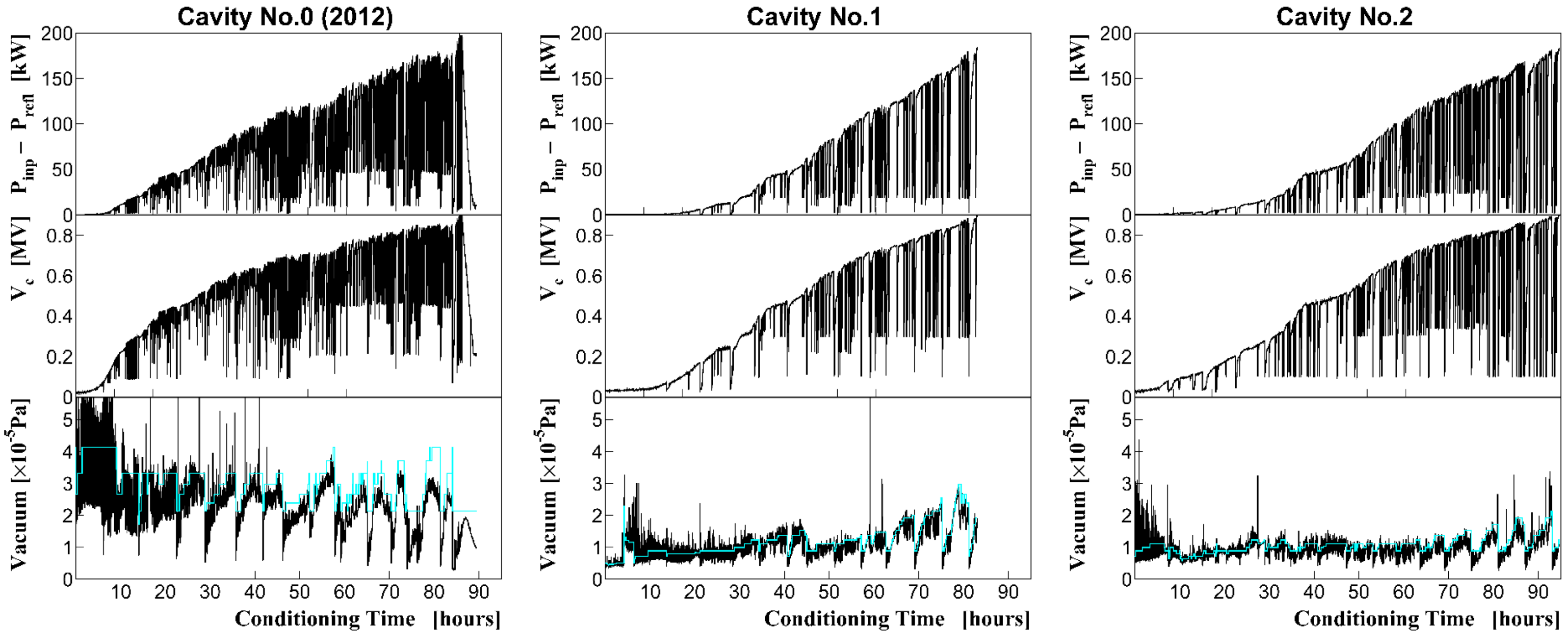
(1) It is possible to perform vacuum-tight lip welding in the DR tunnel after the installation of the cavities, and

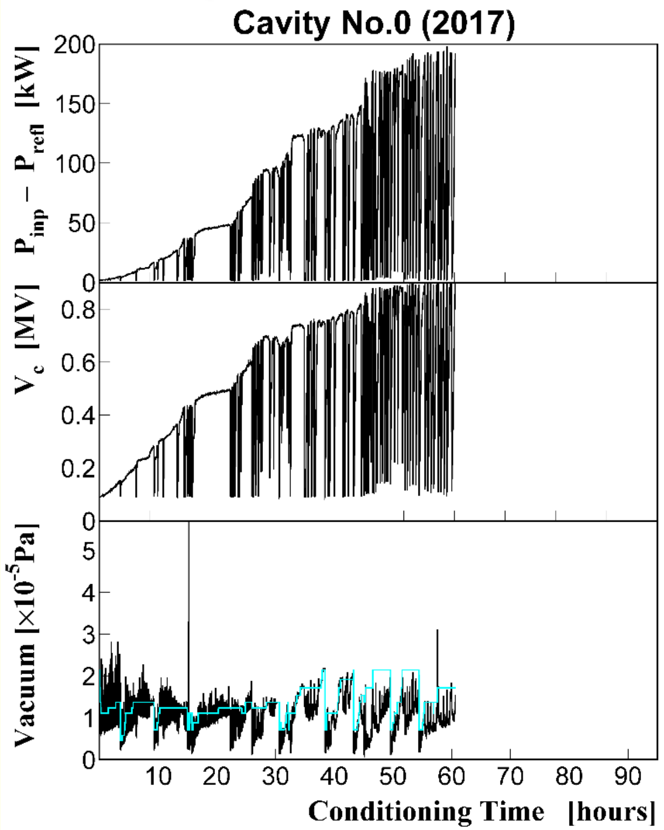
(2) Lip welding → Leak test: OK → Disassembly -> Re-welding → Leak test: OK → Disassembly

Cavity No.0 was re-tested on its high-power performance.

March, 2017

Conditioning Histories up to V_c = 0.90 MV/cavity





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, the input RF power (P_{inp}) is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{inp} is slightly stepped up as long as the vacuum pressure is lower than the reference. P_{refl} and V_c indicate the reflected RF power and cavity voltage, respectively.

(1) Reached V_c = 0.90 MV (radiation limit) smoothly.
(2) Maintained V_c = 0.90 MV for six hours.
→ **Comparable performance with Cavity No.1 and No.2.**

We decided to promote Cavity No.0 to be a spare cavity for DR operation.

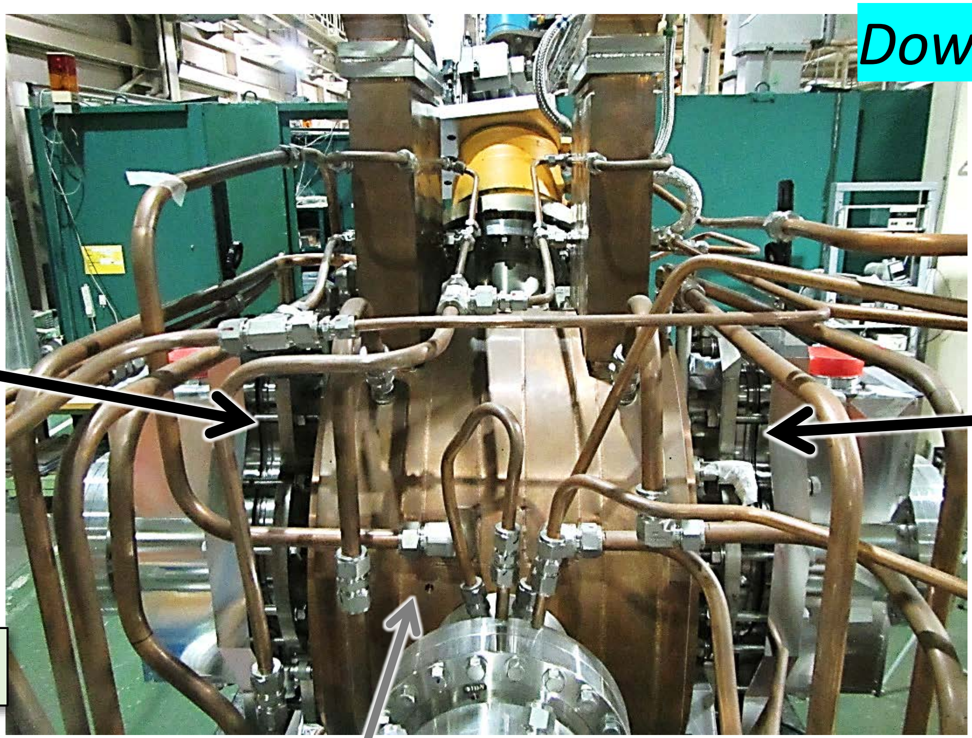
- Enough high-power performance
- Four HOM waveguide loads to be made soon
- Bellows for vacuum-tight lip welding to be replaced

Status of the Bellows of Cavity No.0

To be replaced by new one!

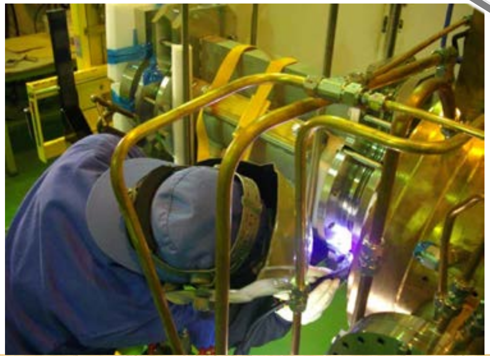
Upstream side

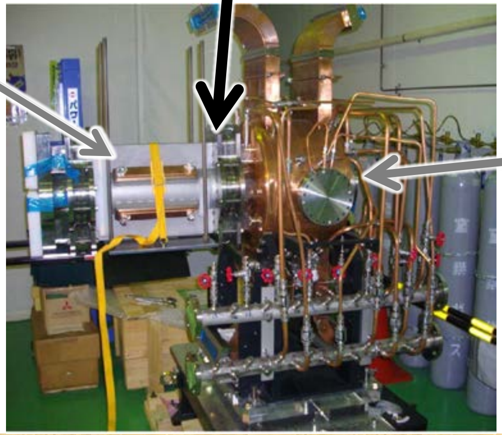
Downstream side



Used in the lip welding test performed in 2012

Grooved beampipe (prototype)





Cavity No.0

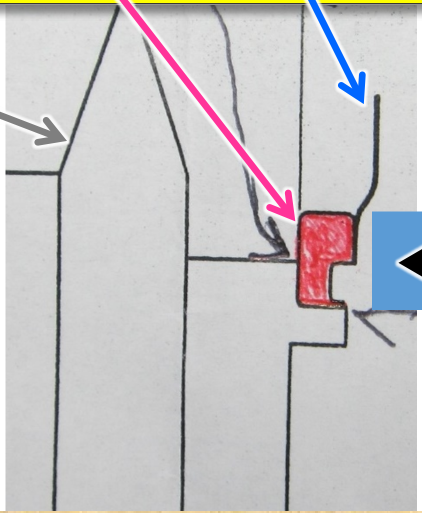
Replacement Test of Bellows

Using the grooved beampipe prototype

(performed in 2017)

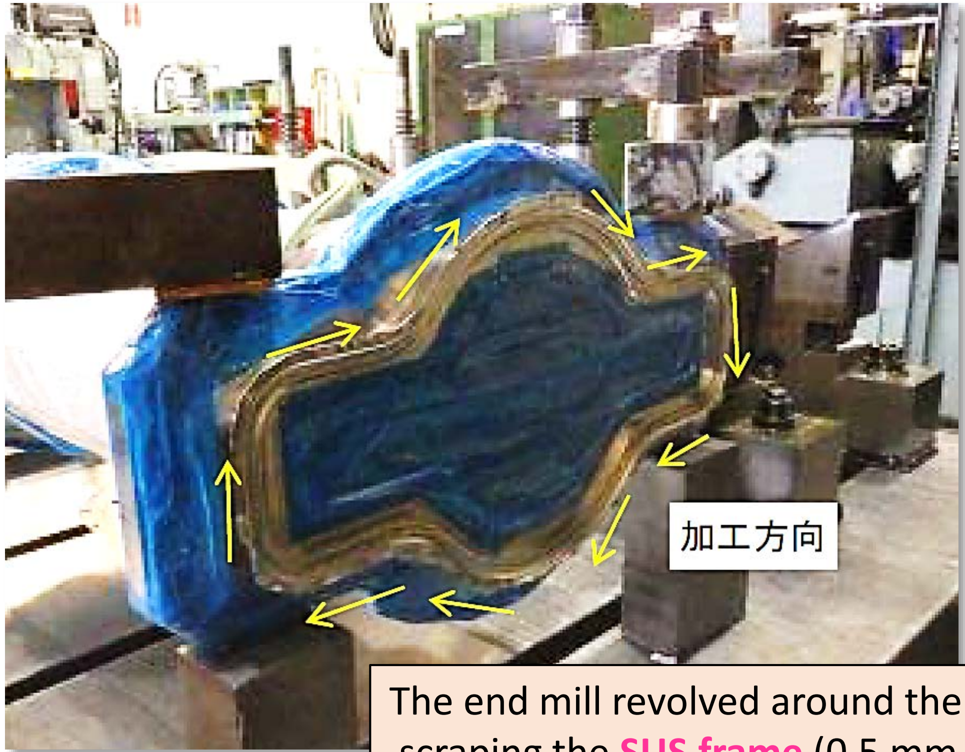
Bellows for vacuum-tight welding is welded on a **SUS frame**.

Flange



End mill

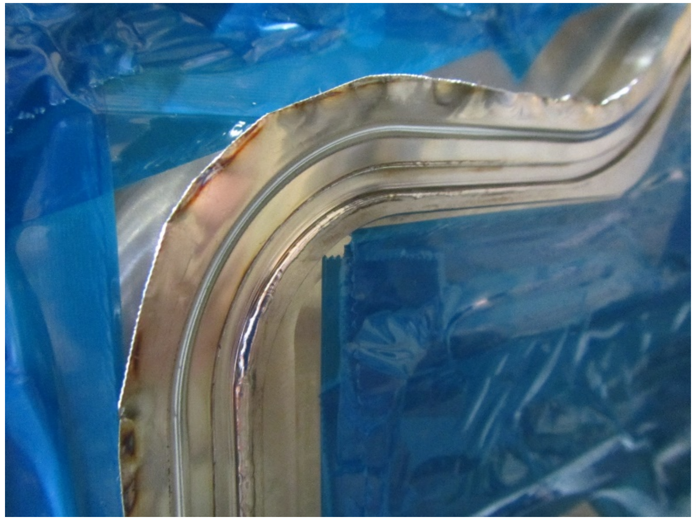
(0.5 mm / round)



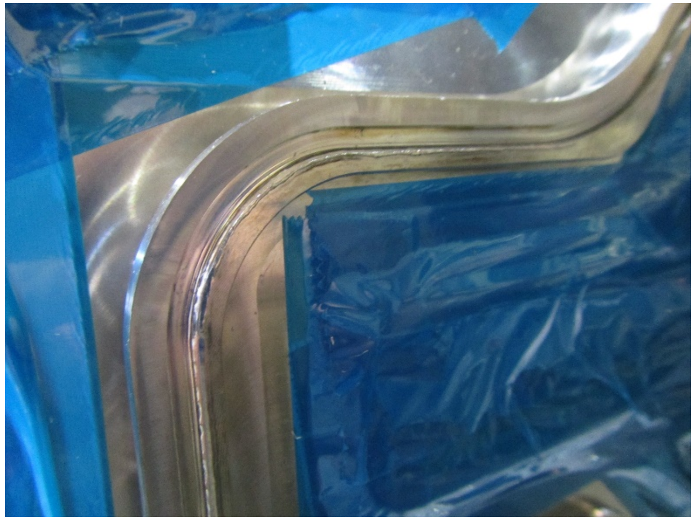
The end mill revolved around the beam axis (14 rounds), scraping the **SUS frame** (0.5 mm / round).

By End Milling

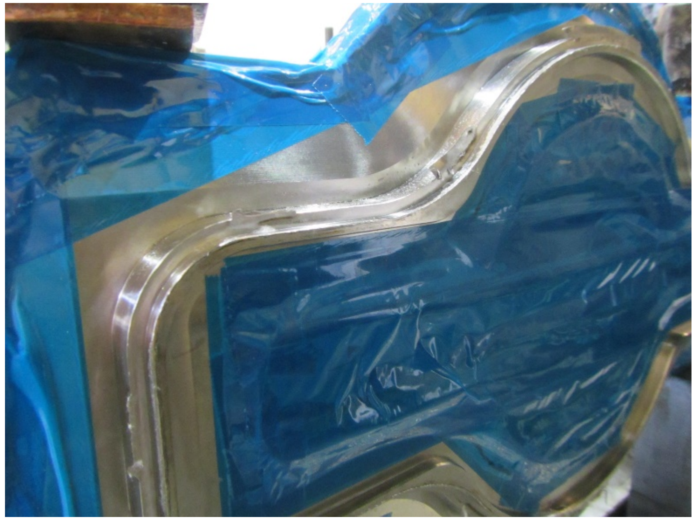
Before

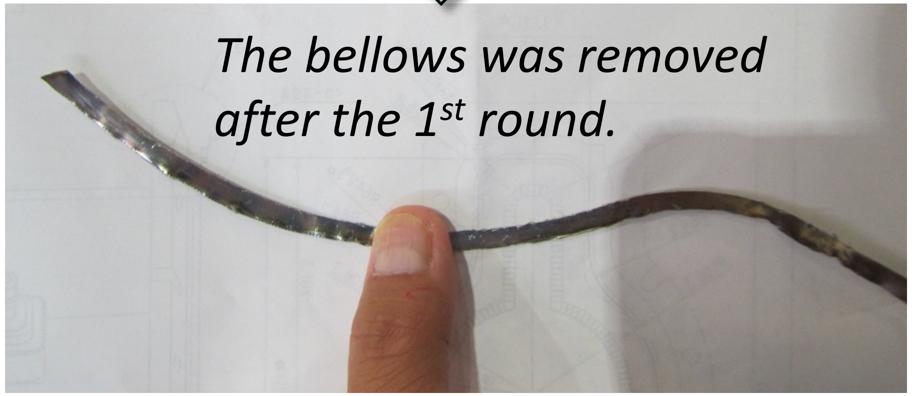


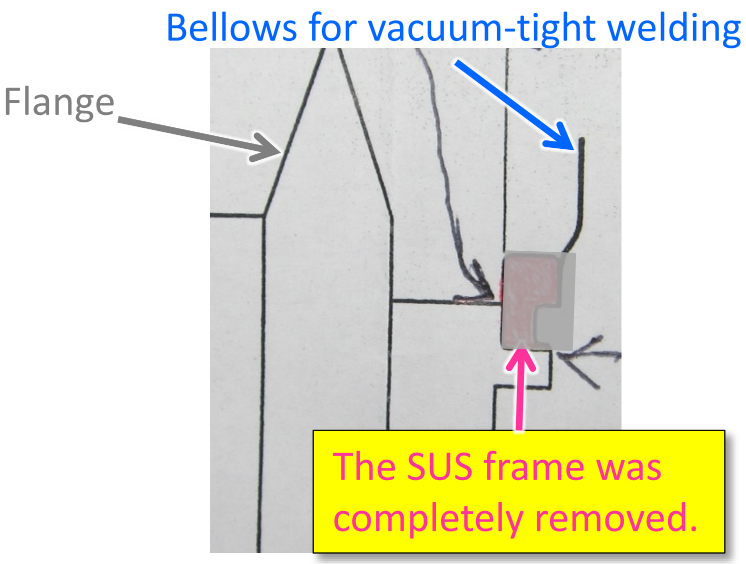
After the 4th round



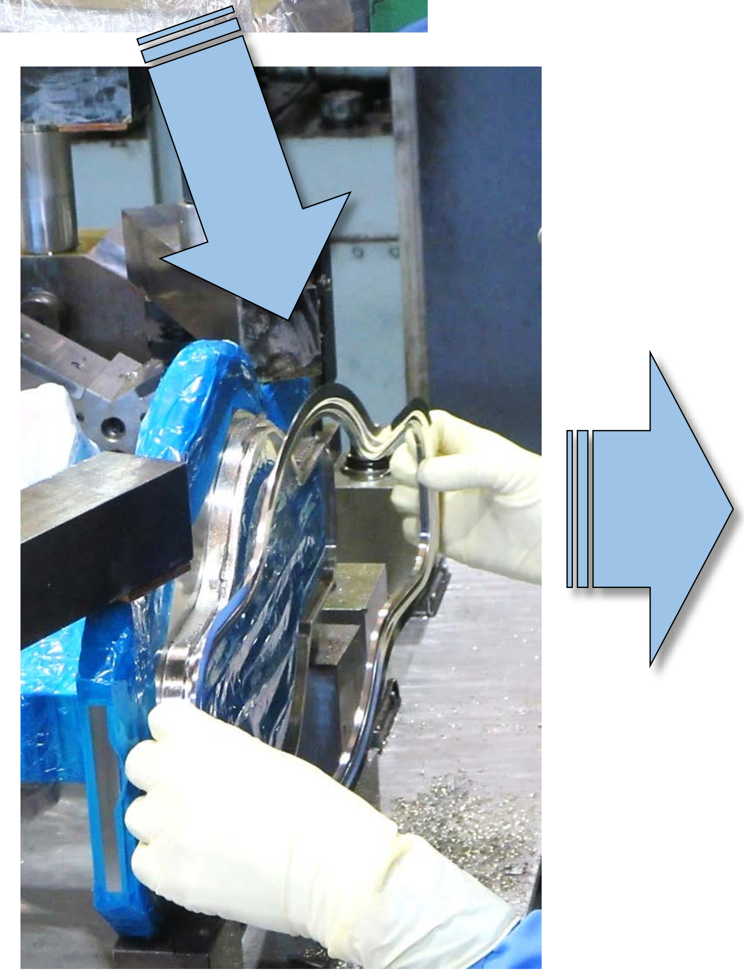
After the 14th round (last)

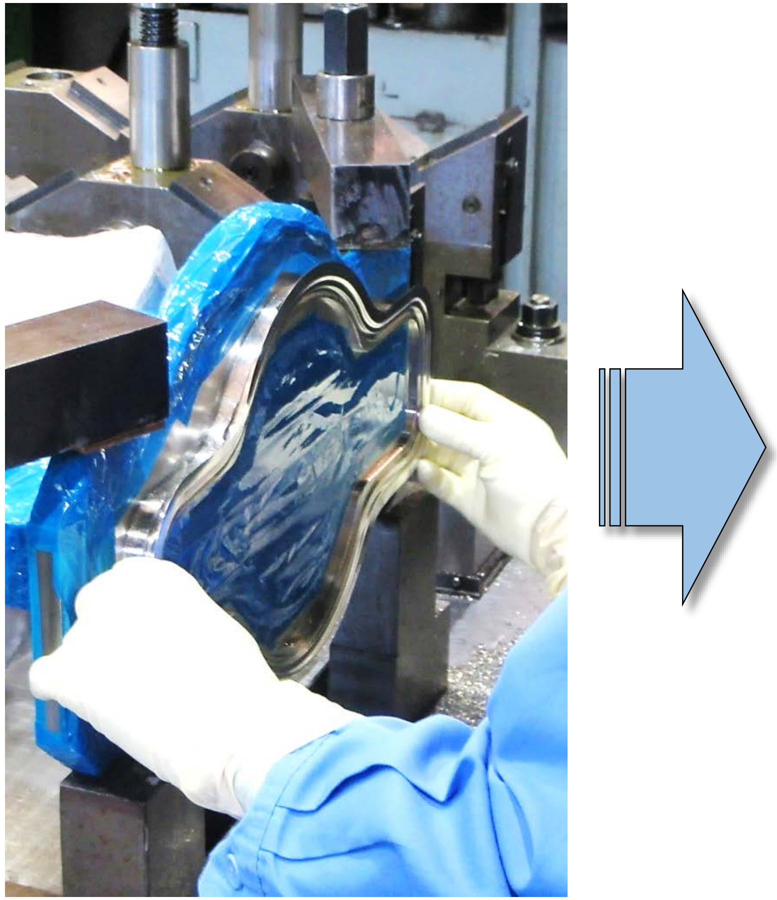




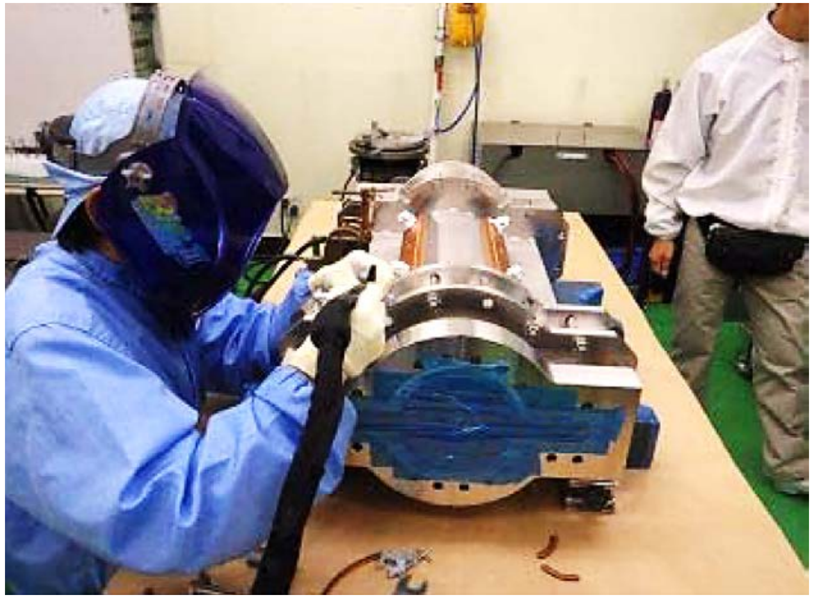


← New bellows (0.2mm-thick bellows welded on a SUS frame)





Lip welding test



➔ No leak detected

Summary

- **Cavity No.1 and No.2**
  - Were successfully installed to the DR tunnel / RF section
    - ~0.3 mm accuracy in the transverse directions achieved
  - Position measurement of the beam-port flanges prior to the installation was successful and useful.
  - High-power performance re-checked: OK
  - Now accelerating positrons without any serious problems

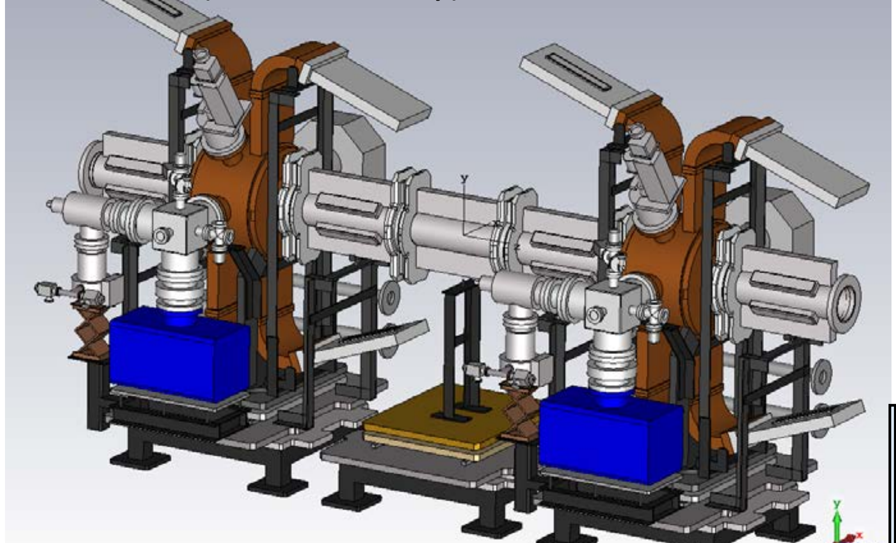
- **Cavity No.0**
  - To be promoted to be a spare cavity for DR operation
  - High-power performance re-checked: OK
  - Its bellows for vacuum-tight lip welding to be replaced by new ones this coming spring
  - Will be a spare cavity during Phase II

Thank you for your attention!

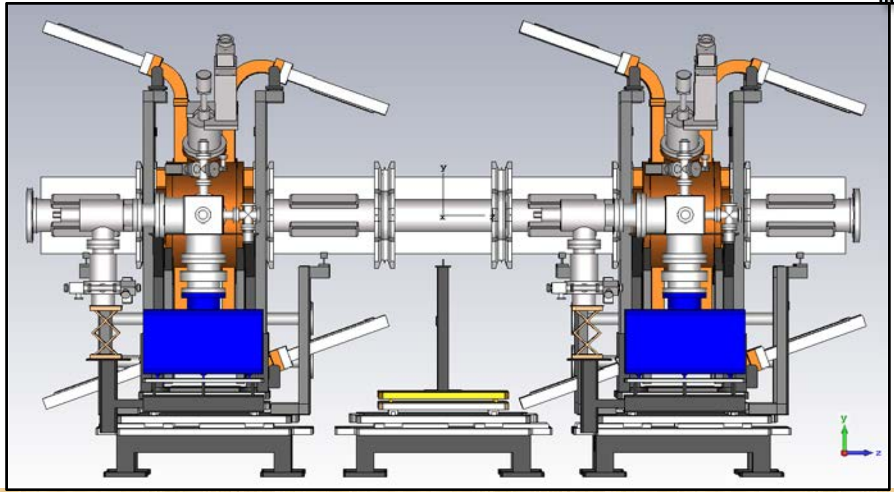
Backup Slides

2 → 3 Cavity Configuration

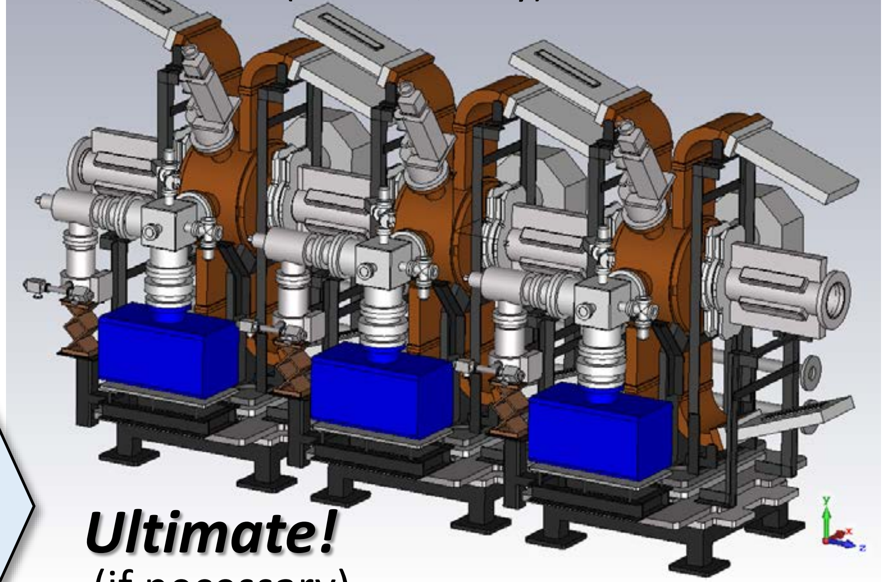
Total V_c = 1.4 MV for nominal DR operation @ Phase II
(0.7 MV/cavity)



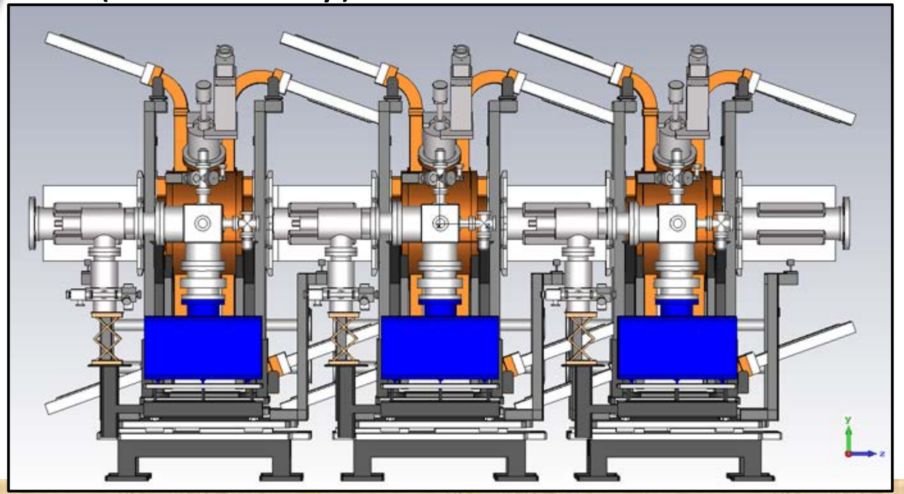
Starting with 2 cavities



Total V_c = 2.4 MV at max. @ Phase III?
(0.8 MV/cavity)



Ultimate!
(if necessary)



The Endplates of DR Cavity No.1 and No.2 were Electropolished (EP).

Material: OFC (class1), 40μm etching, Skin depth(δ)@500MHz: 3μm

Before EP

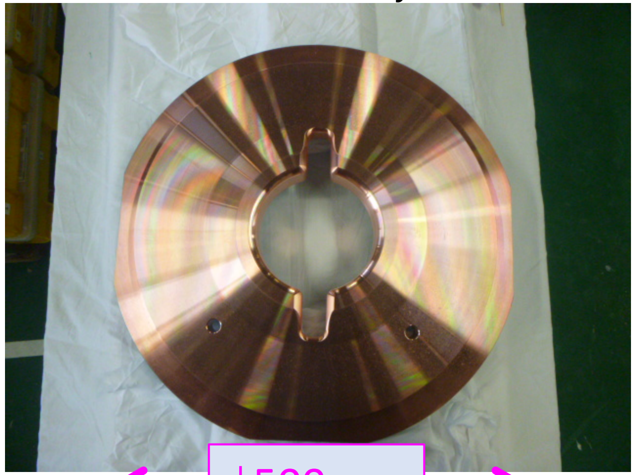
R_a=1.5μm, R_y=8μm

After EP

R_a=0.2μm, R_y=1μm (< δ = 3μm)

(Upstream)

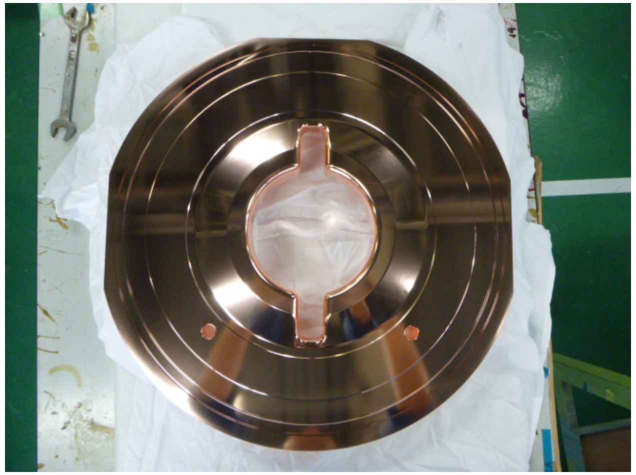
Fixed **E**nd **P**late (**FEP**)
w/o tuning bump



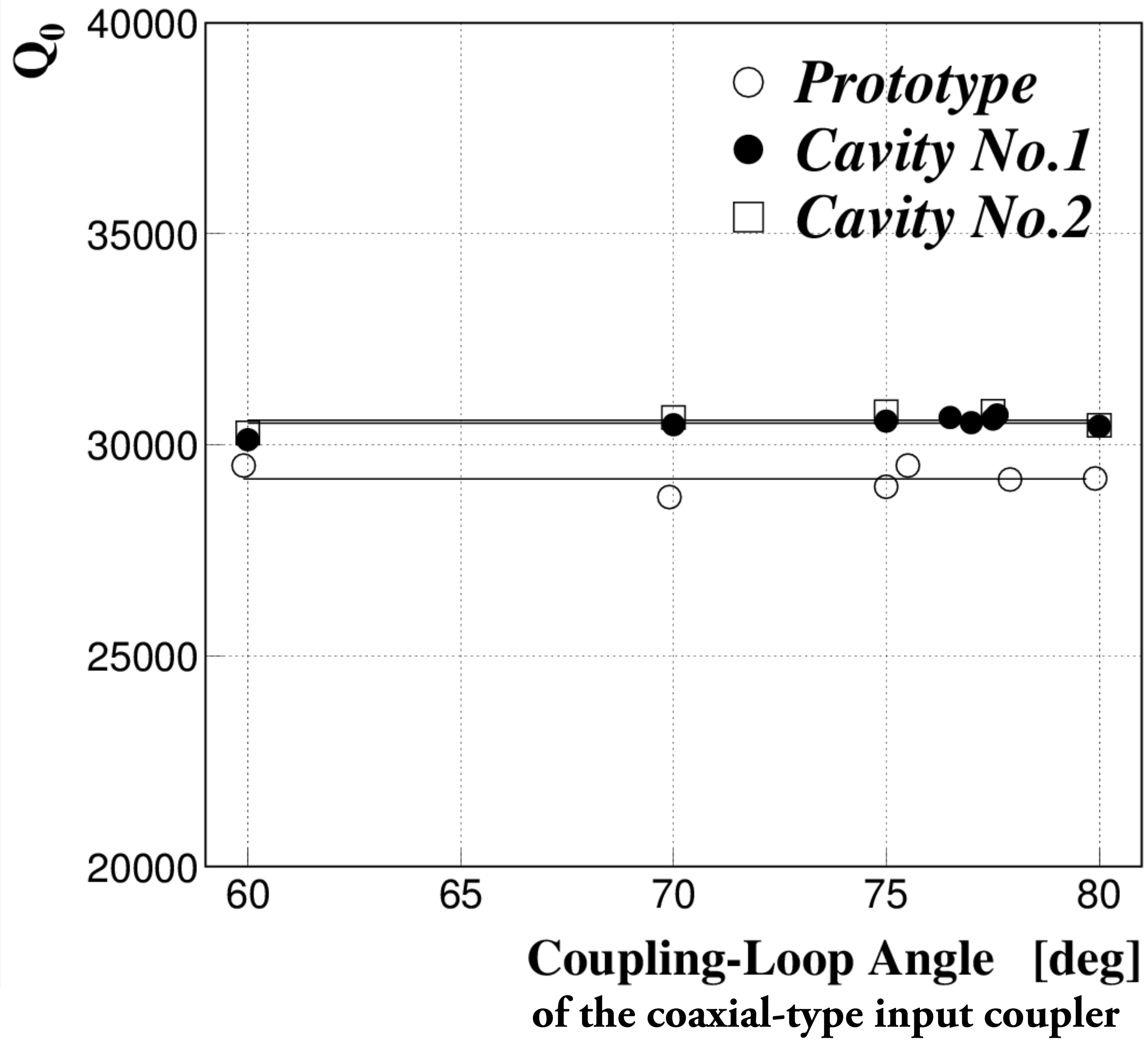
ϕ500mm

(Downstream)

Tuning **E**nd **P**late (**TEP**)
w/ tuning bump



Low-Power Measurements of Unloaded Q-factor (Q_0)

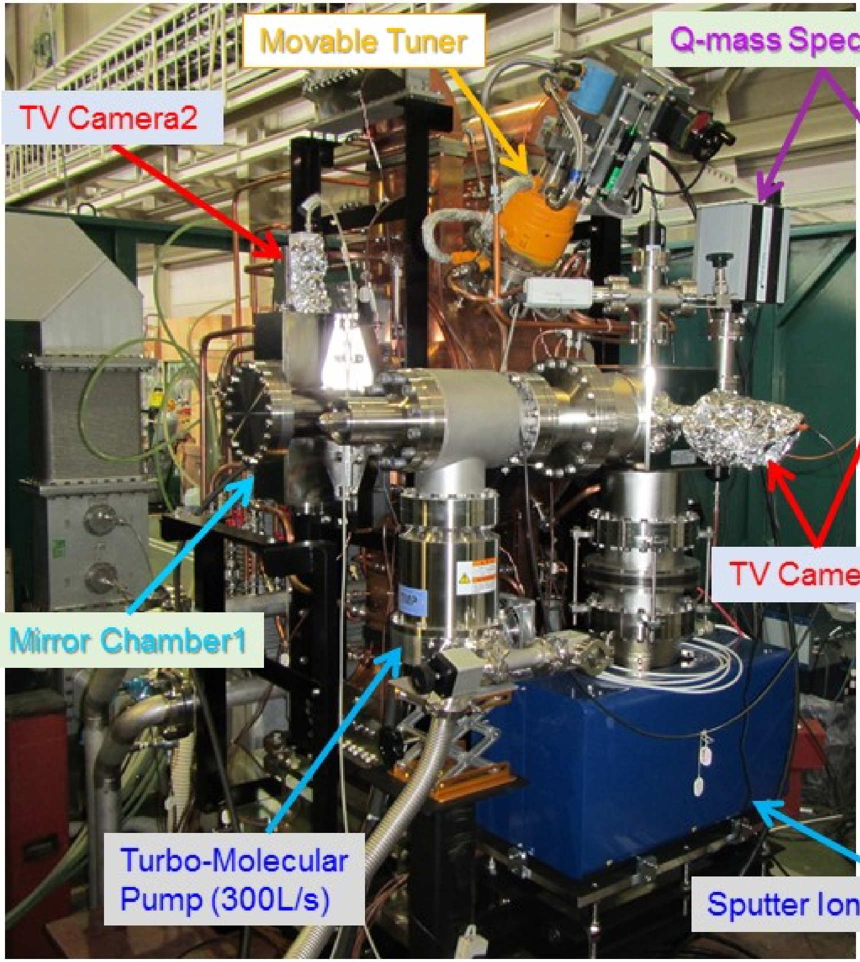


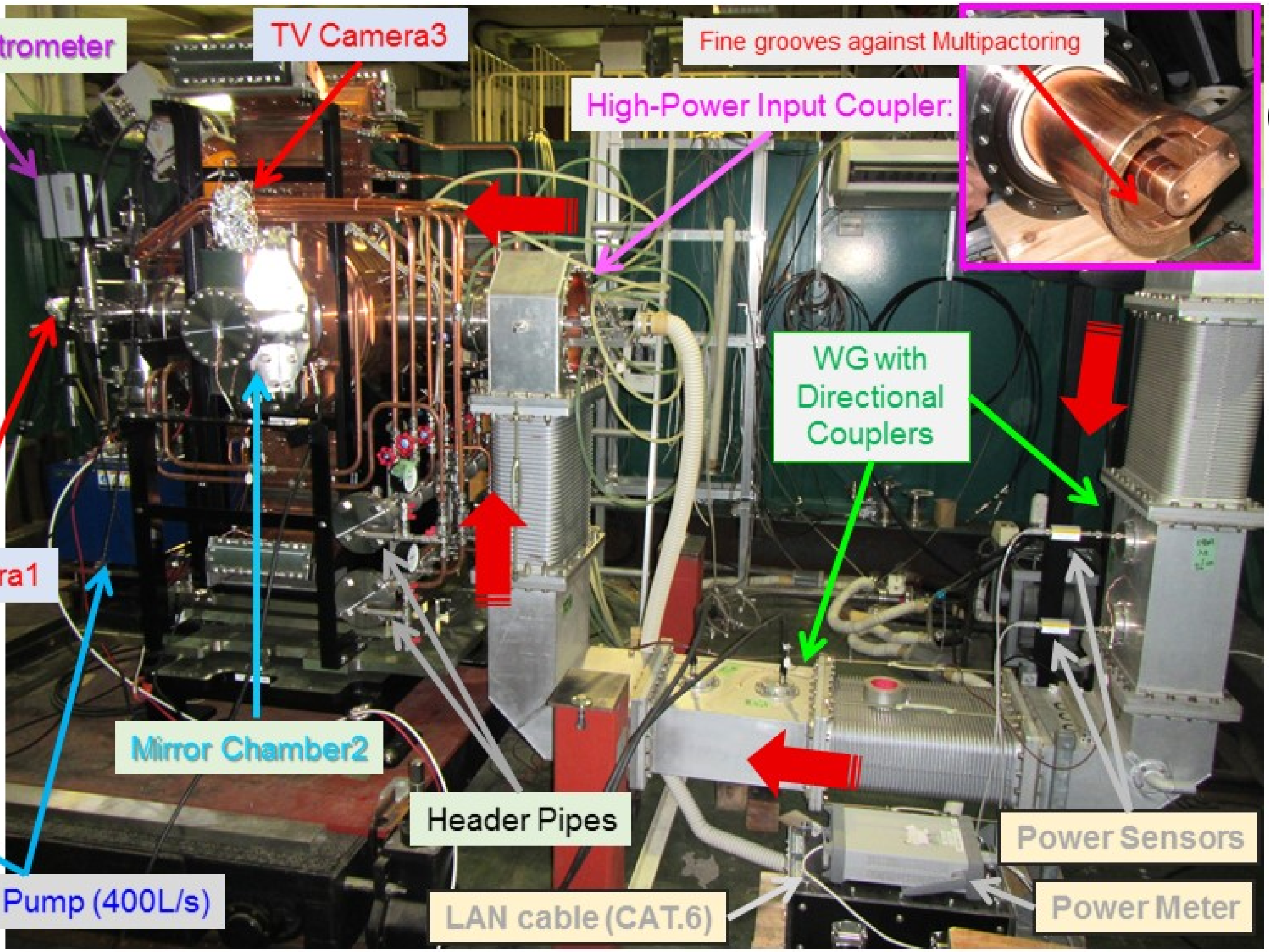
	Q_0(meas) / Q_0(sim)
Prototype	92.9%IACS
Cavity No.1	97.1%IACS
Cavity No.2	97.3%IACS

4% improvement with EP

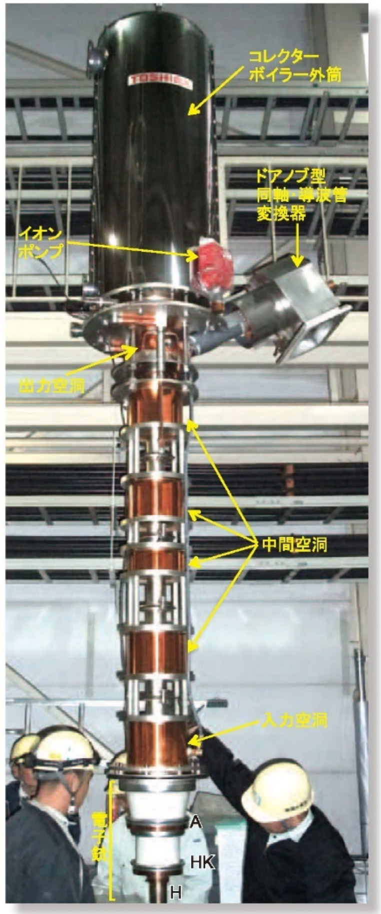
(Note: No EP applied to the barrel)

Setup of High-Gradient (HG) Test





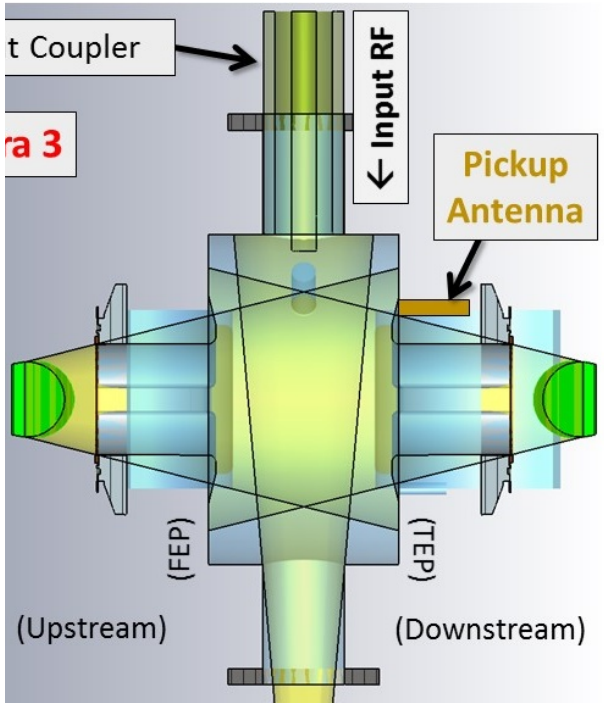
Toshiba
CW Klystron
E3732
(1MW, 508.9 MHz)



(No beam injected into the cavity during the HG test)

Detection of Cavity Breakdown by the Decay Time in Pickup Signal

1. The interlock system was activated with a reflection level over the threshold.
2. Check the decay time of the pickup signal of the accelerating mode
   - ~8 μs ➔ Not cavity breakdown
   - << 8 μs ➔ Cavity breakdown



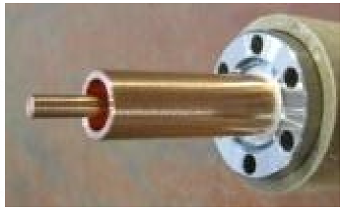
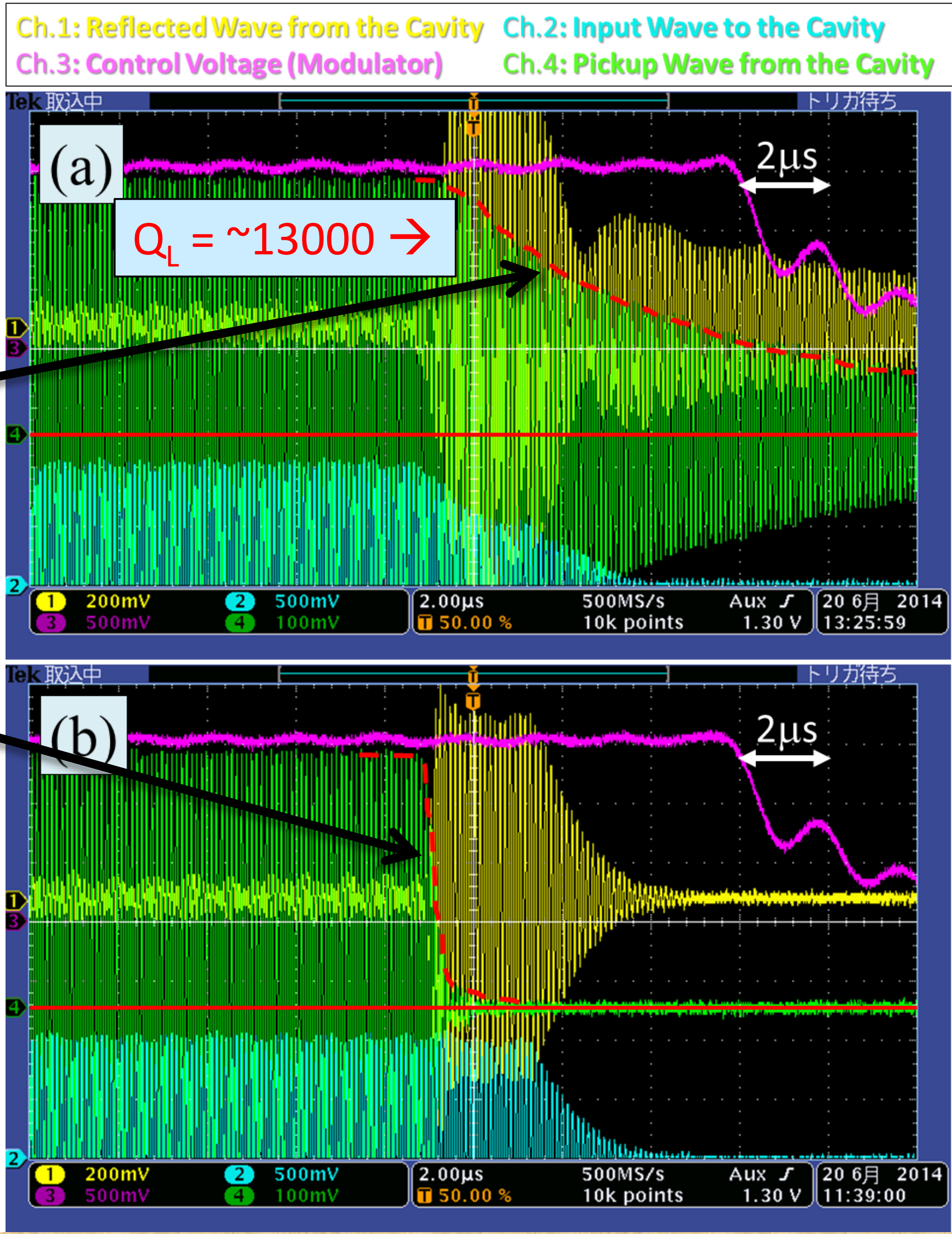


FIG. 6: Waveforms of the oscilloscope displayed for a time span of 20 μs (= 2 μs/div) when the interlock system was activated. The red dashed curves indicate the envelope of the 508.9-MHz pickup signal from DR Cavity No. 2, and the red solid lines indicate its zero level. (a) The RF switch was turned off for a reason related to the klystron. (b) Example of the cavity breakdown events.

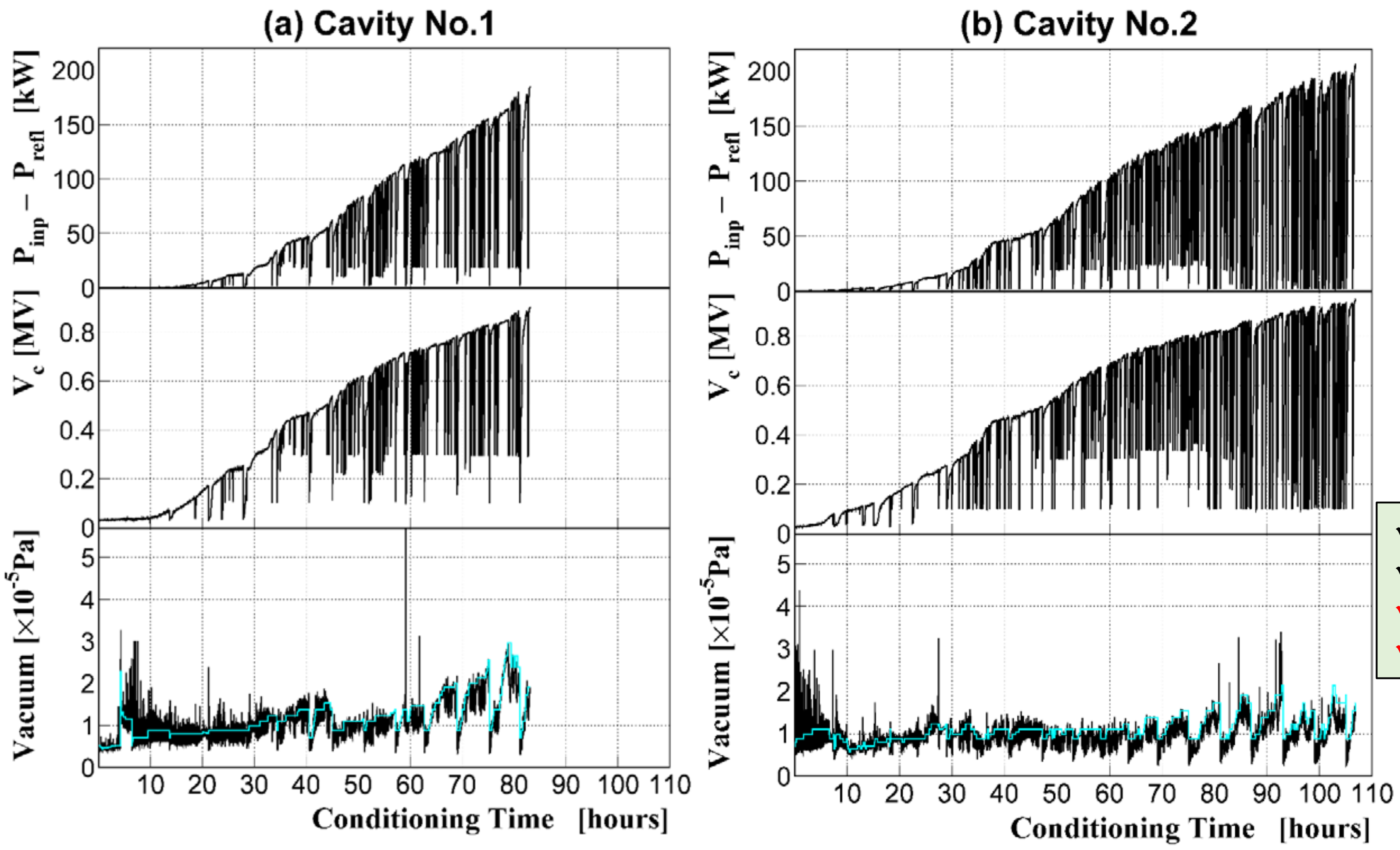
[T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino, "Breakdown Study based on Direct In Situ Observation of Inner Surfaces of an RF Accelerating Cavity during a High-Gradient Test", Phys. Rev. Accel. Beams **19**, 102001 (2016).]



Histories of the RF Conditioning

✓ 83 hours to reach Vc=0.90 MV

✓ 95 hours to reach Vc=0.90MV
✓ 107 hours to reach Vc=0.95MV



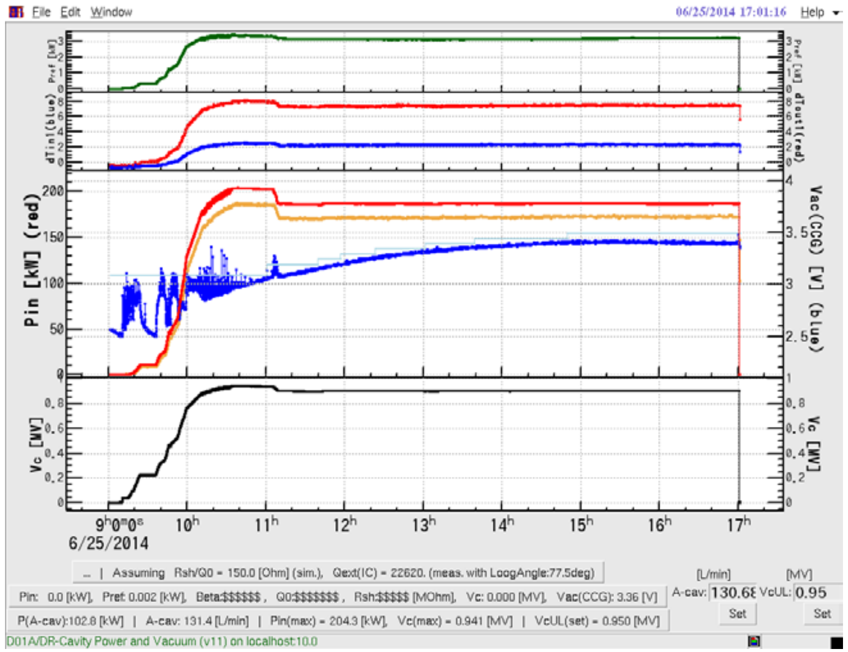
The light blue lines indicate the reference vacuum pressure specified by the computer controlled automatic aging. If the vacuum pressure is higher than the reference, P_{in} is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{in} is slightly stepped up as 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}
- ✓ **Cavity No.2 reached 0.95MV/cavity successfully.**
- ✓ **Comparable conditioning speeds btwn Cavity No. 1 and 2**

After the RF Conditioning (up to V_c=0.95MV) completed,
Stability Test with Holding V_c = 0.90 MV

> V_c = 0.70 MV
(required for DR operation)

Example of the daily histories →



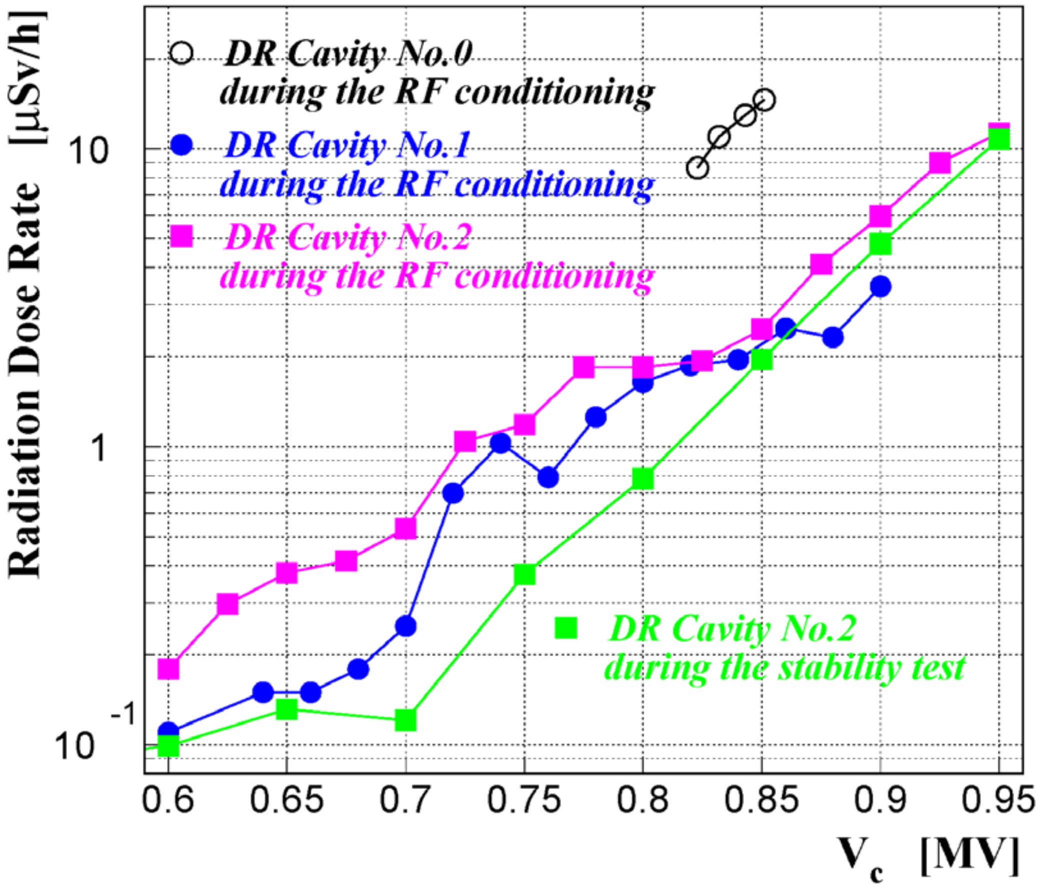
- Cavity No.1: 3 breakdowns for 14.5 hours in total = **$5.0^{+4.8}_{-2.7}$/24hrs**
- Cavity No.2: 11 breakdowns for 80 hours in total = **$3.3^{+1.3}_{-1.0}$/24hrs**

Same high-power performance between DR Cavities No. 1 and No. 2 within the statistics

Radiation Dose Rate

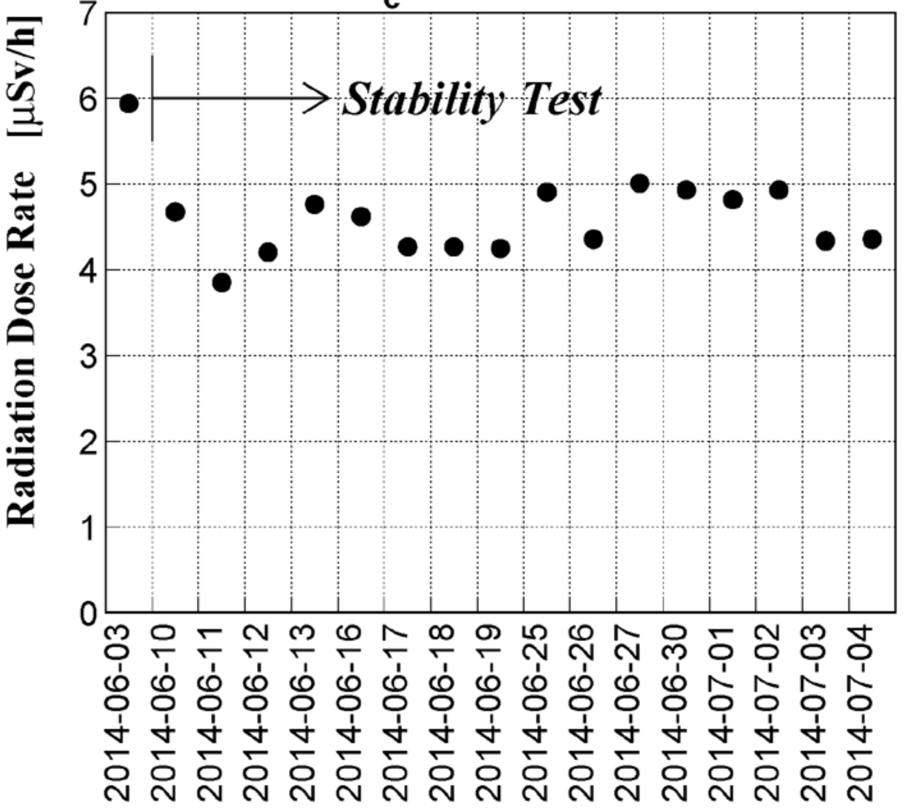
= Indirect observation of the dark current:

Field emission
→Acceleration
→Impact on the inner surface
→Emission of X-ray



No significant difference between DR Cavity No. 1 and No.2

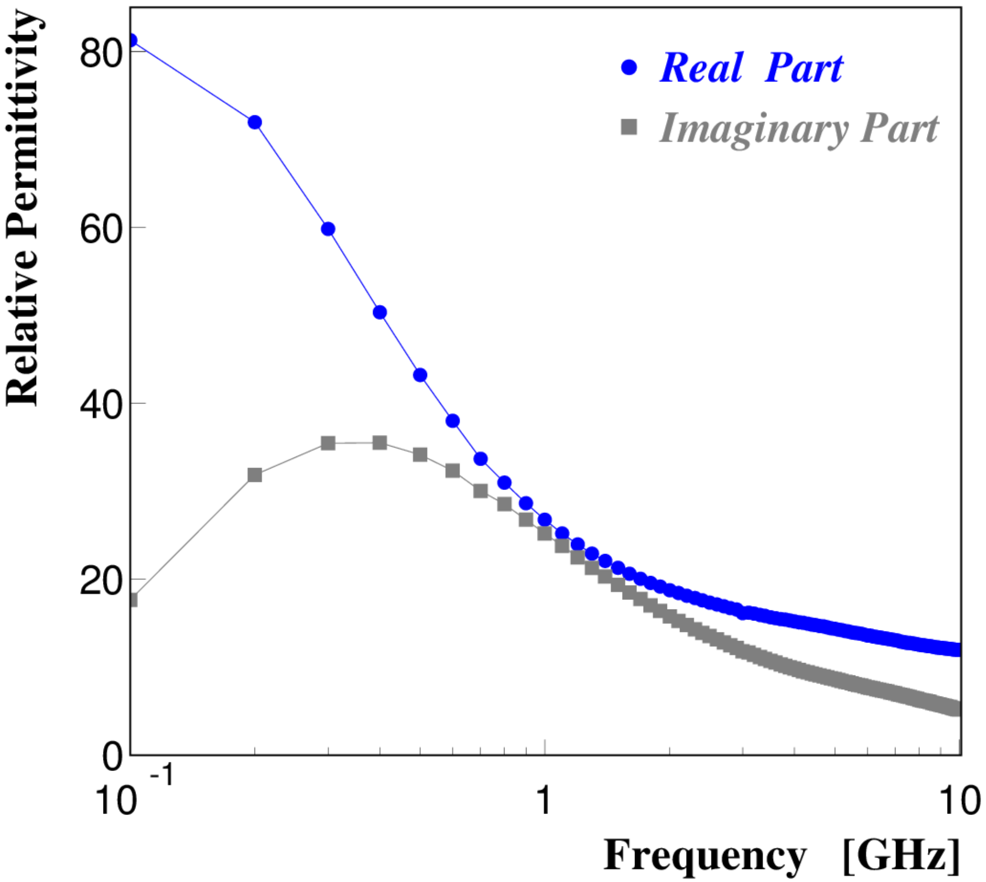
V_c = 0.90 MV for the DR Cavity No.2



Constant during the stability test (20 cavity breakdowns in this period)

Permittivity of the SiC ceramic tiles

Typical Measurements of SiC ceramics



Relative permittivity of the SiC ceramics (CERASIC-B), as a function of frequency, used in designing this accelerating structure.
These permittivity values are typical measurements on the SiC ceramic tiles used for the GBPs of the ARES.

Permittivity of SiC ceramics largely depends on

- Source SiC powders
- Sintering conditions of SiC ceramics

We aggressively controlled the permittivity by changing the amount of aluminum contained in the SiC powder so that the permittivity should be close to that used in designing the accelerating structure.

Y. Takeuchi, et al., "Control of RF Dielectric Properties of SiC Ceramics for HOM Absorbers", in Proceedings of the 8th Annual Meeting of Particle Accelerator Society of Japan, Aug. 2011 (Paper ID: TUPS137)

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