RF Accelerating Cavity for SuperKEKB Damping Ring and its Breakdown Study

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on behalf of SuperKEKB-RF / ARES Cavity group
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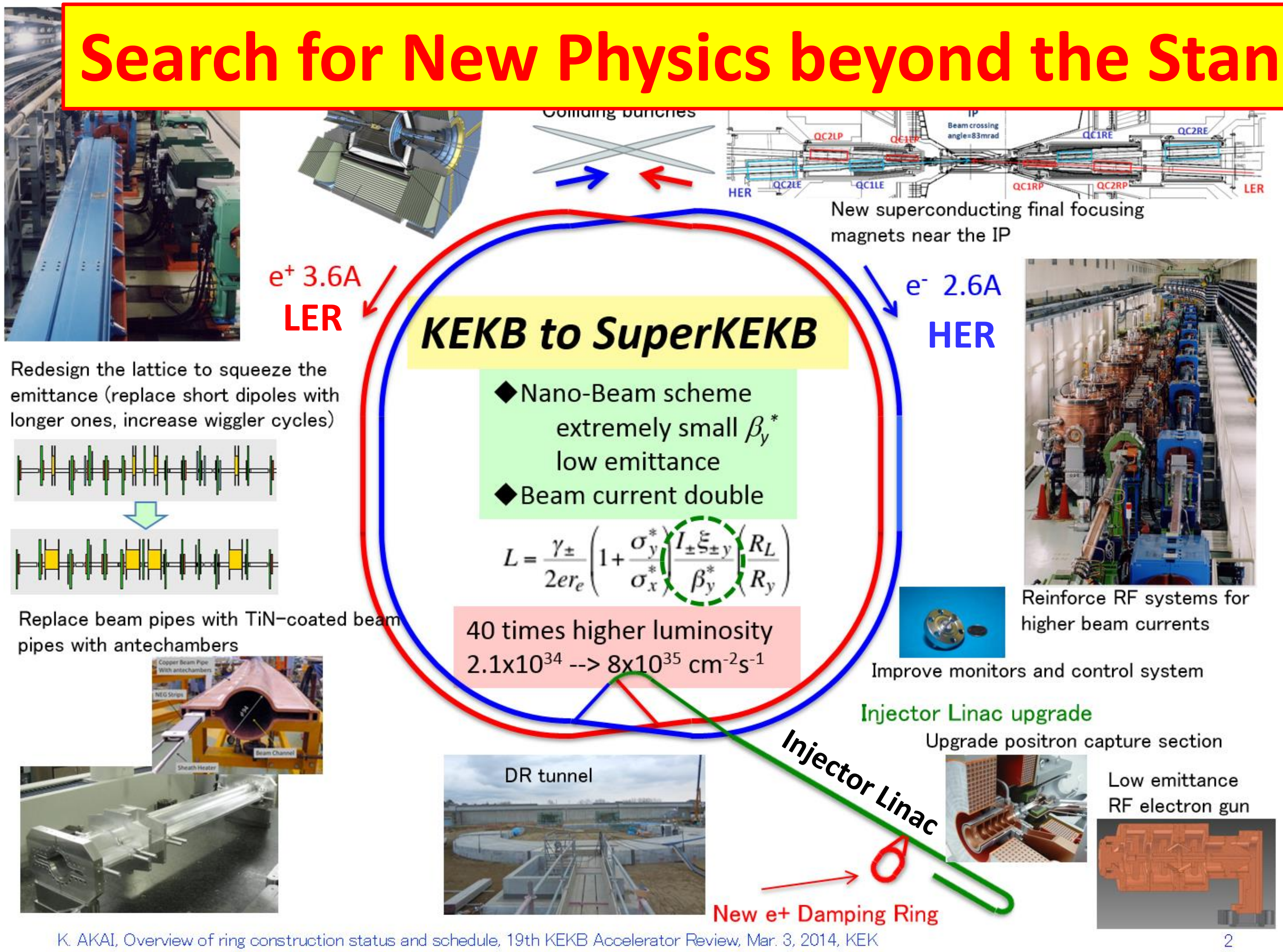
2015-09-02

Asymmetric-Energy e^+e^- Collider Super B-Factory: "SuperKEKB"

Search for New Physics beyond the Standard Model



- ✓ Double ring with a circumference of 3 km
- ✓ e^+e^- Injector Linac
- ✓ The optics is based on the "nano-beam scheme"
- ✓ First beam to be delivered and stored early next year
  - No beam collision in phase 1

New Positron Damping Ring (DR)

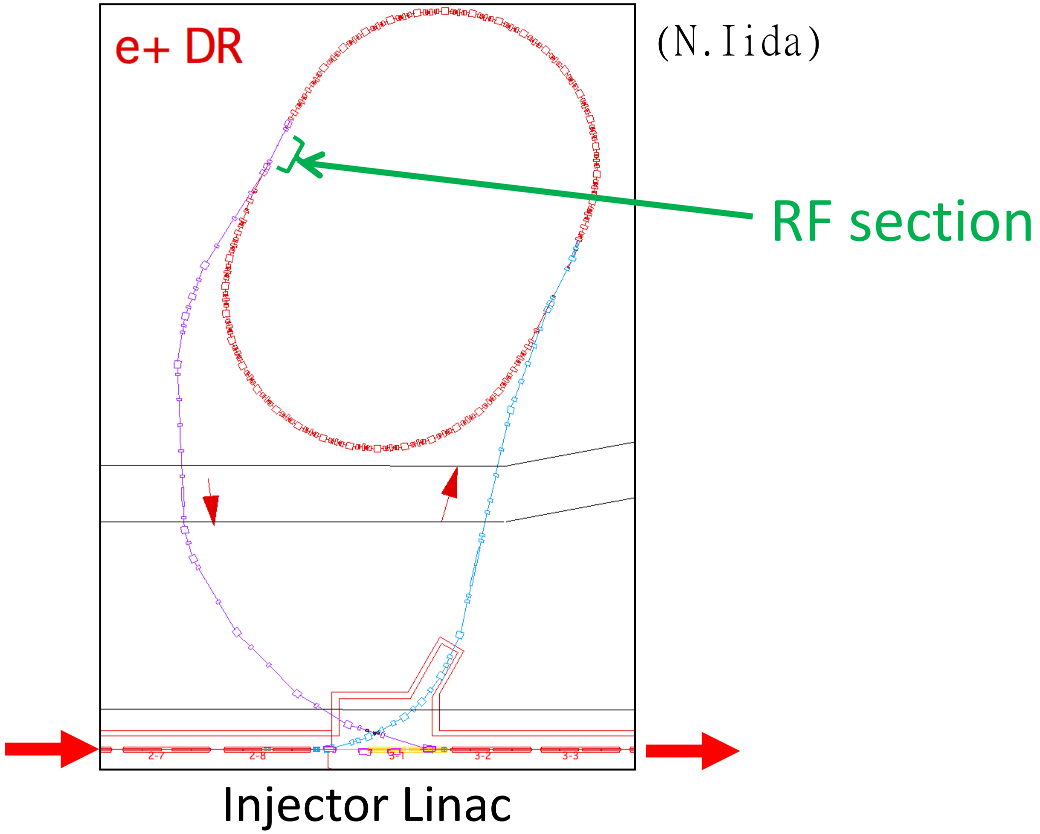
for the low-emittance beam injection to SuperKEKB / LER(e^+)

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	

CSR

* 8 nC/bunch



- ✓Construction of the tunnel and facility finished
- ✓Now installing magnets, followed by vacuum chambers, this year
- ✓Installation of RF cavities next year

DR Facility on the Ground

Photos taken on **2015-06-12**

Building facade

Inside the building

Space for the 1.2-MW CW klystron

Local control room

DR Facility on the Ground

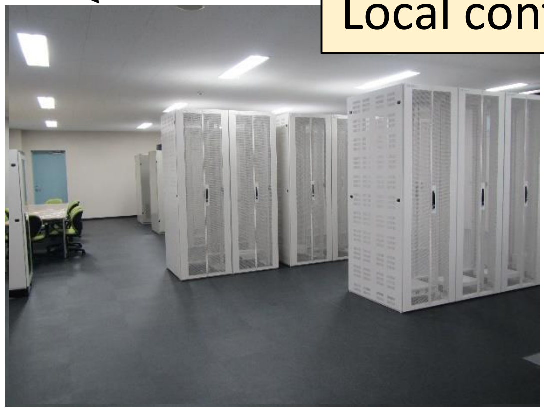
Photos taken on **2015-08-31**

Building facade

Inside the building

Space for the 1MW CW klystron

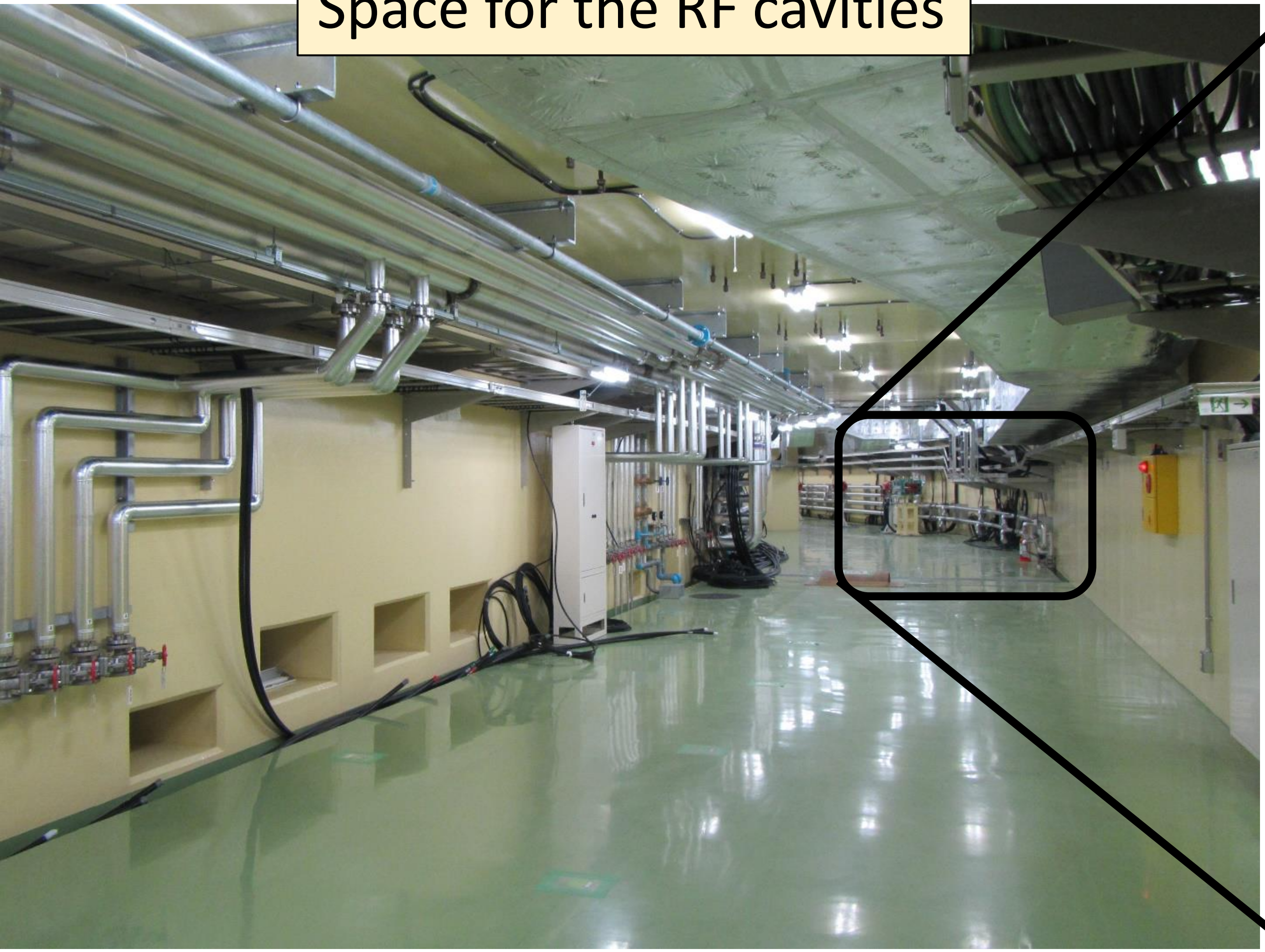
Local control room



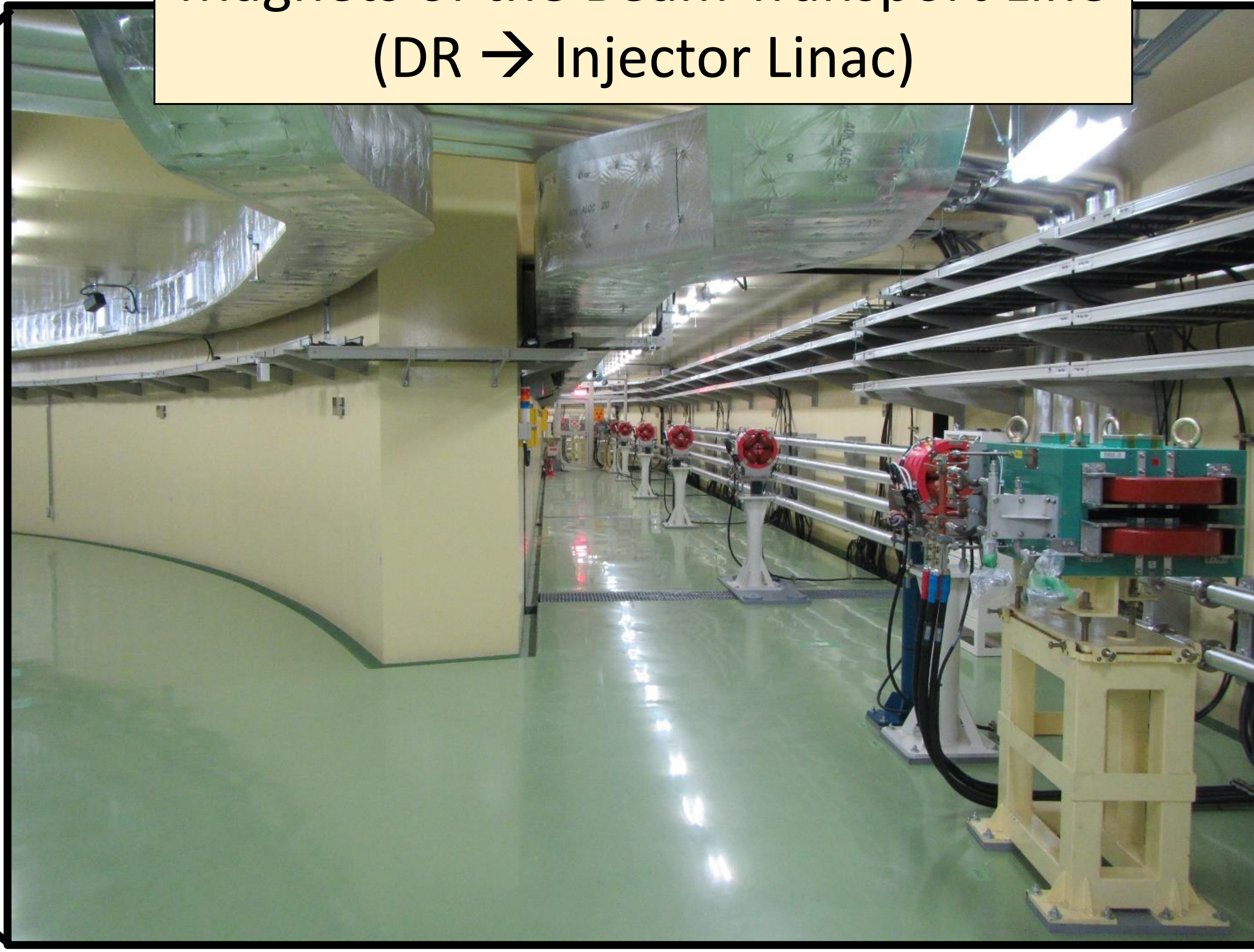
In the DR Tunnel

Photos taken on **2015-06-12**

Space for the RF cavities

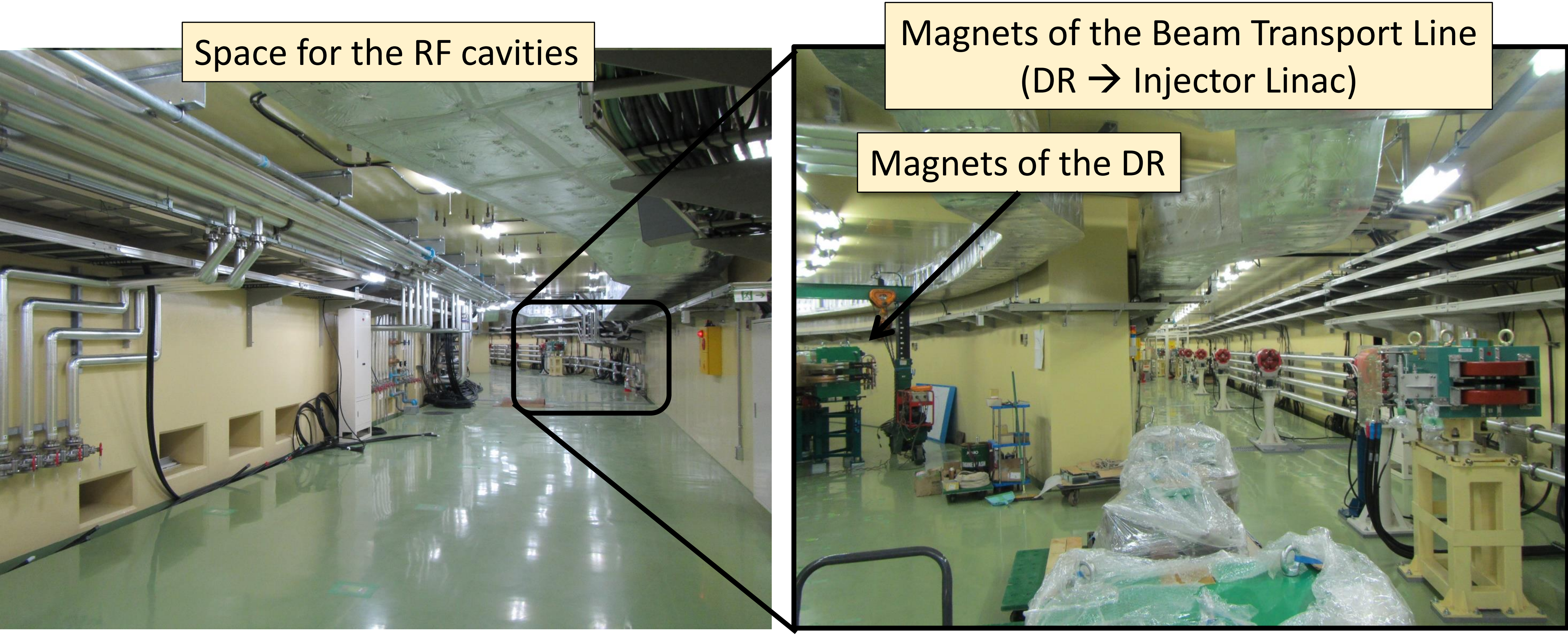


Magnets of the Beam Transport Line
(DR → Injector Linac)



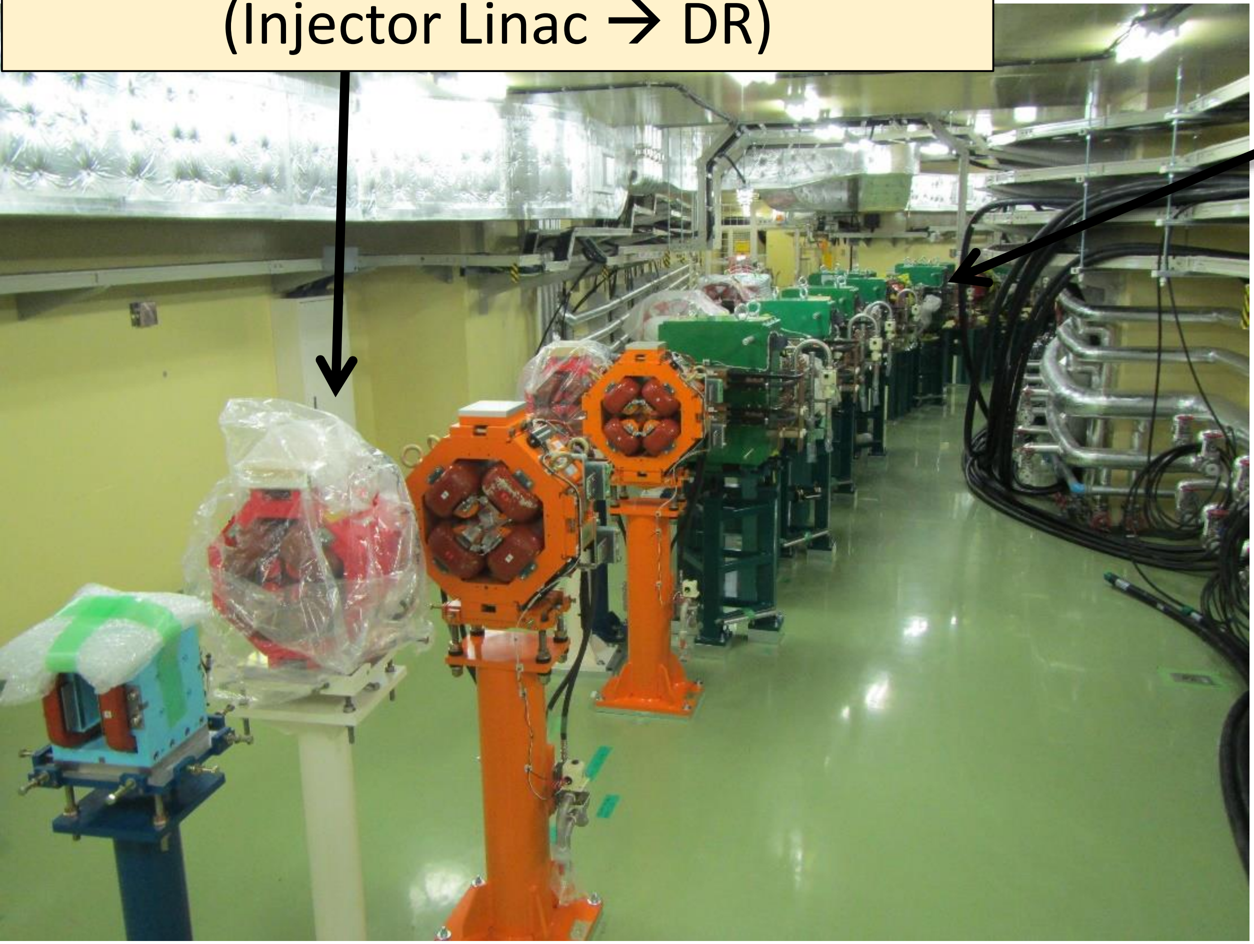
In the DR Tunnel

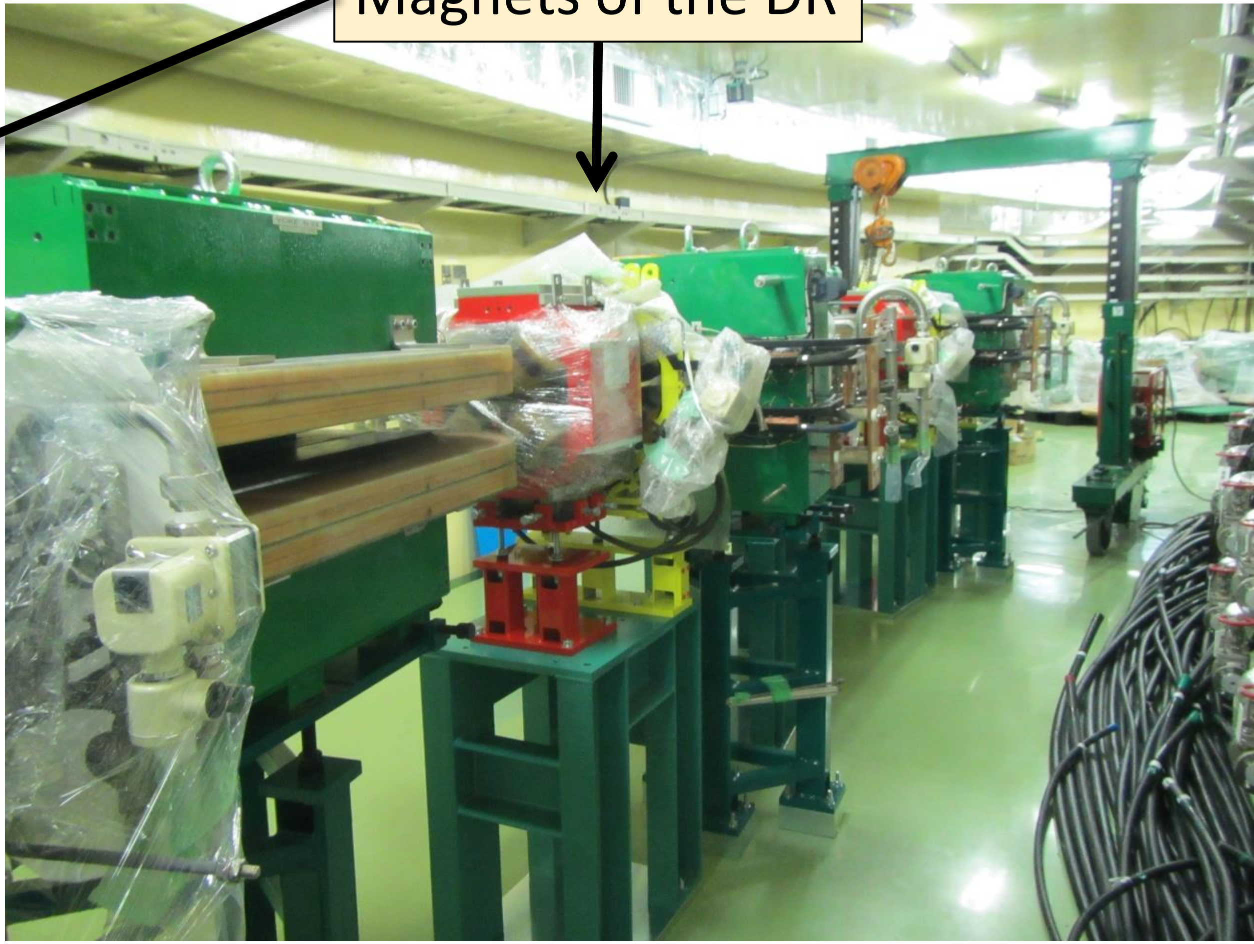
Photos taken on **2015-08-31**



Installing the Magnets in the DR

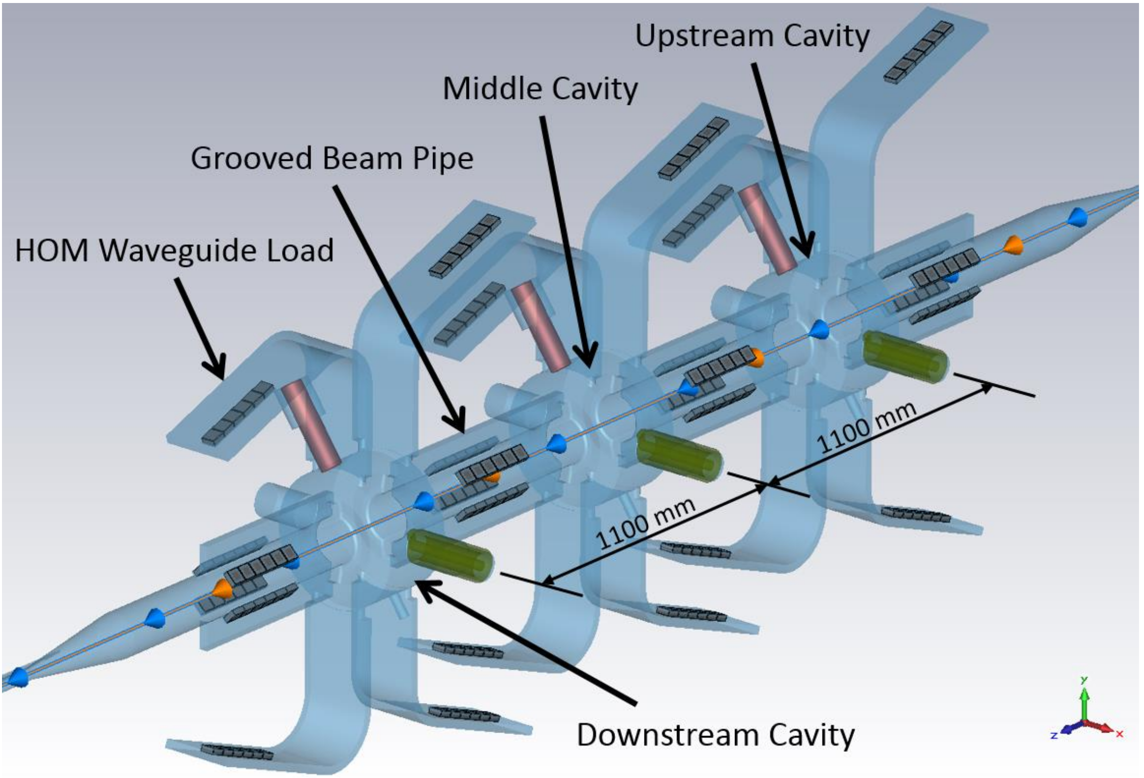
Photos taken on **2015-08-31**

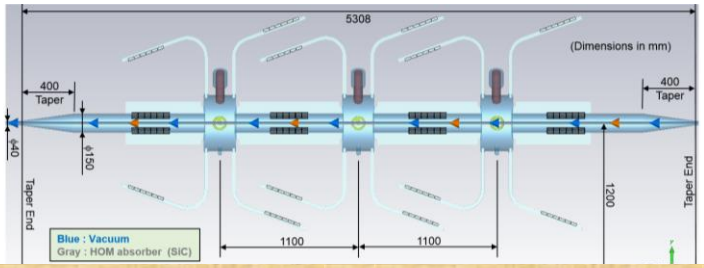




Normal-Conducting (NC) RF Accelerating Structure for the DR

The blue, gray, green, and magenta regions indicate the vacuum, HOM absorbers, coaxial lines of input couplers, and plungers of movable tuners, respectively.
The colored arrows indicate the direction of the positron beam.





- RF operation frequency: 508.9MHz
  - Same as that of the MRs
- Based on the HOM-damped structure of the successful ARES cavity system
- Three cavities at max. to be installed in a space originally designed for one cavity (~3m in the beam direction)
  - Total V_c = 2.4MV at max.
- Apart from the CC and SC of ARES, this DR cavity has the following space saving features that are not included in the ARES:
  - The HOM absorbers are all compact tile-shaped SiC ceramics
  - The neighboring cavities share a GBP in-between
  - The cavity is connected directly to GBPs with lip welding for vacuum sealing at the outer periphery ("weld ring gasket")
- "Multi Single Cell" structure
  - Coupling of the Accel. mode and HOMs among the cavities significantly suppressed by the HOM dampers on the GBPs
  - One big mechanical structure with solid connections of the components
- Loss factor of this structure: 2.3 V/pC (bunch length: 6.0mm)
- Vacuum pumps directly attached to each cavity
- In the DR tunnel, we will assemble the cavities separating them with GBPs similar to LEGO blocks.

Higher-Order-Mode

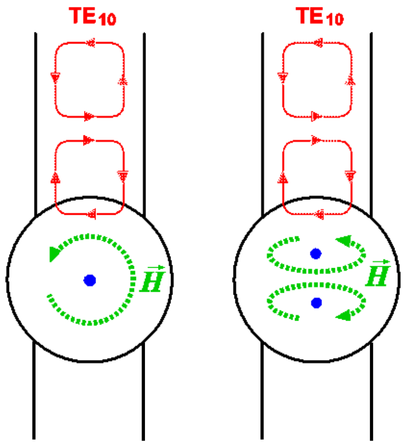
Two Types of HOM Damped Structures

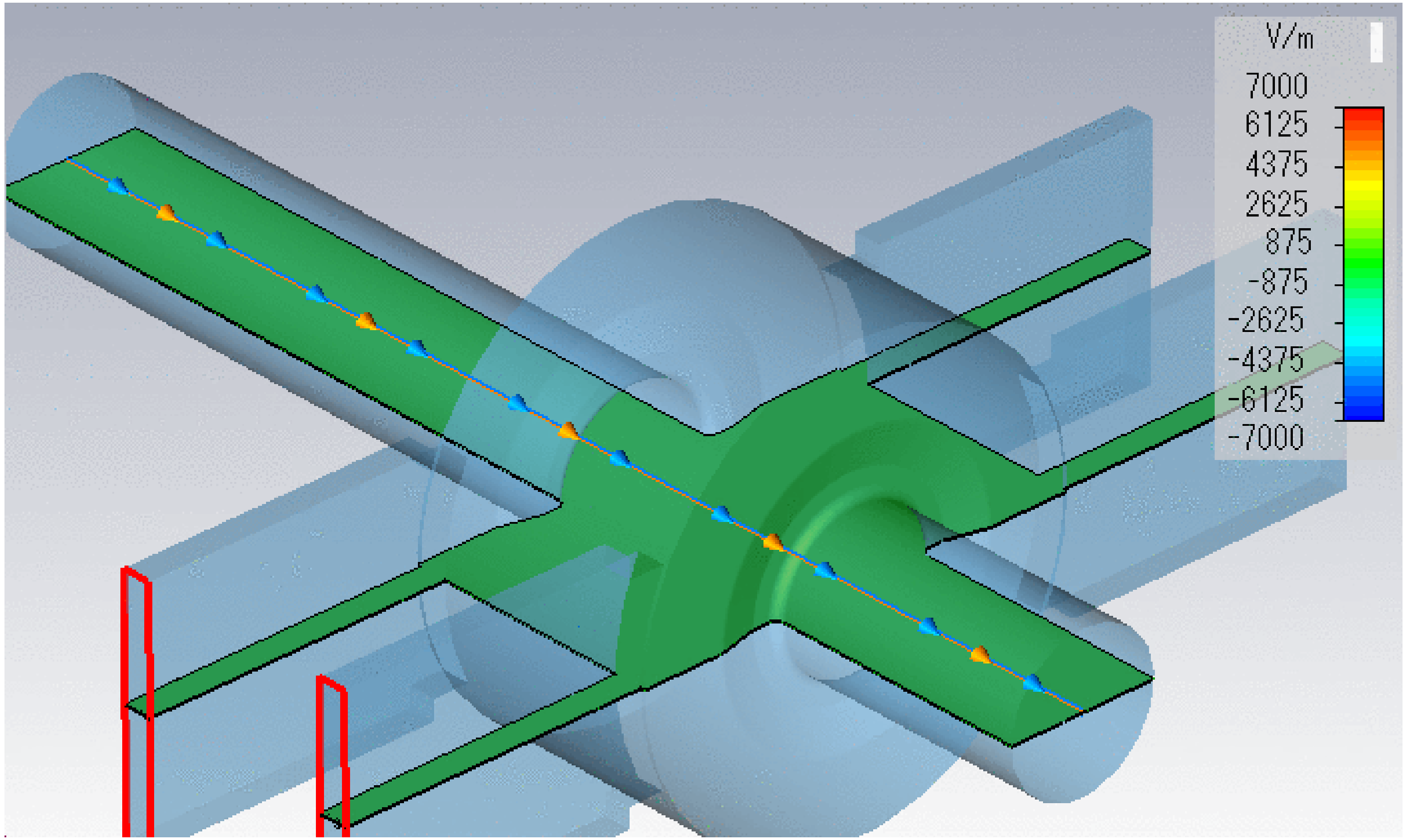
Proven by the long-term successful operation at KEKB

HOM waveguides for damping:

✓Monopole HOMs

✓Vertically-polarized dipole modes





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✓Monopole HOMs
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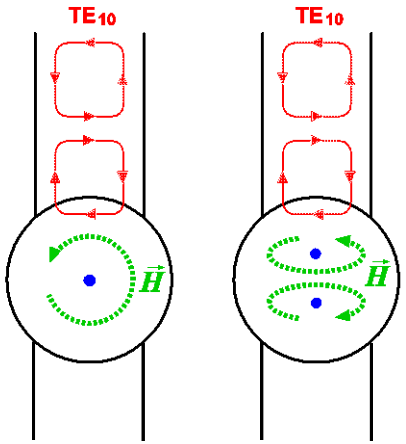
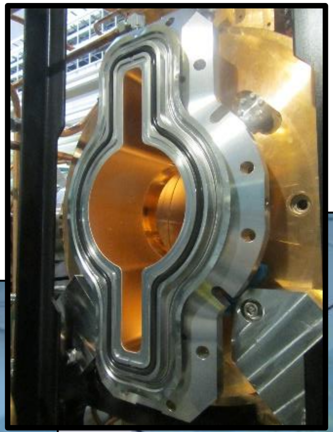
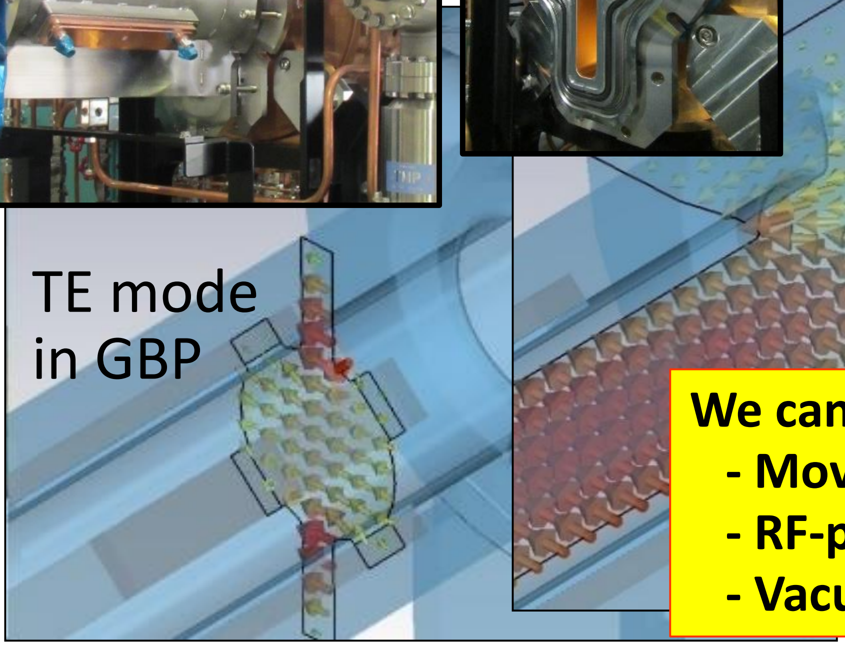
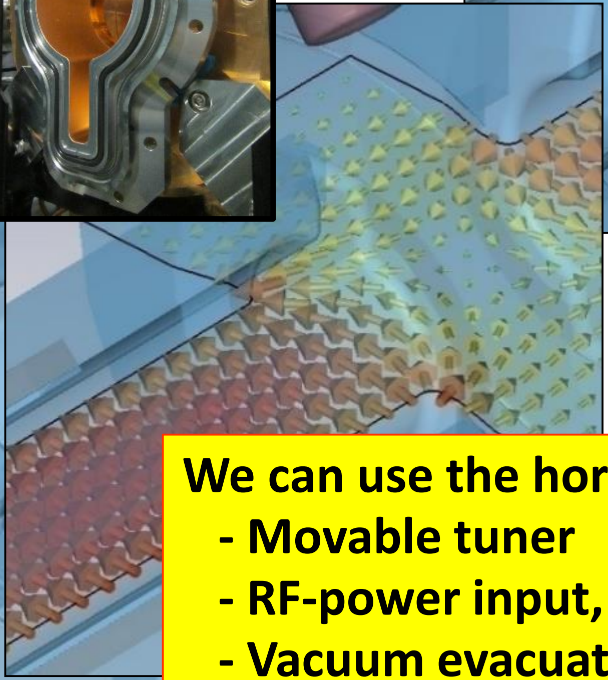


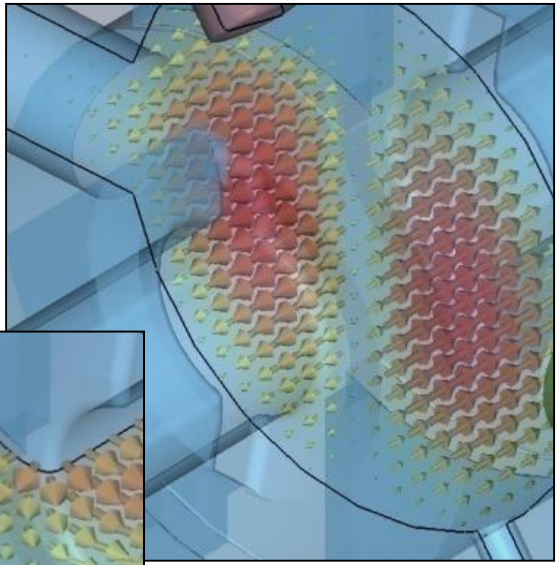
Grooved Beam Pipe (GBP) for damping:
✓Horizontally-polarized dipole modes







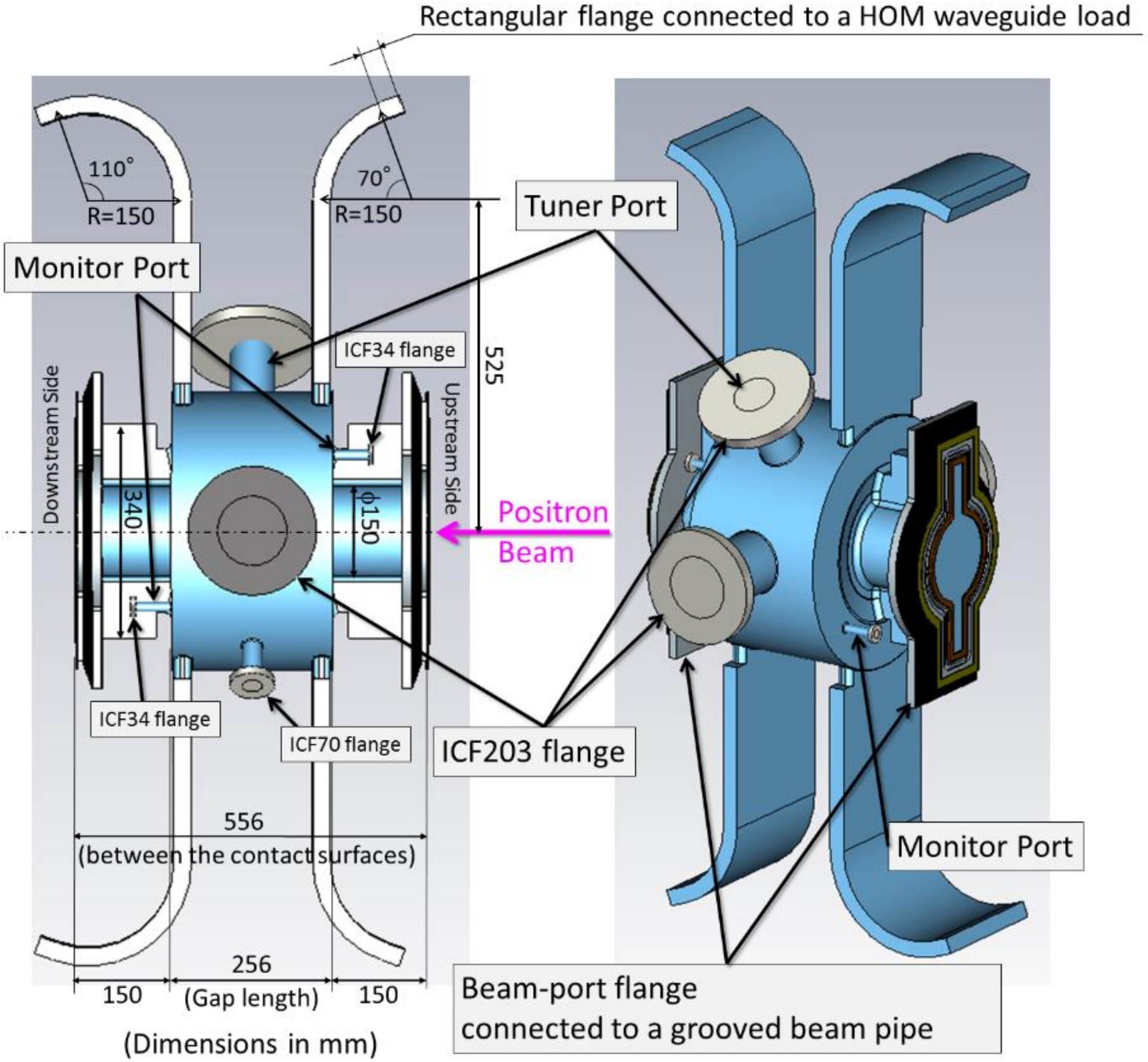
TM_{110} in Cavity



We can use the horizontal space for
- **Movable tuner**
- **RF-power input, and**
- **Vacuum evacuation**

T. Kageyama, "Grooved Beam Pipe for Damping Dipole Modes in RF Cavities," KEK-PREPRINT- 91-133, 1991.

RF Cavity for the DR (DR Cavity)



508.9MHz CW Pillbox NC Cavity

RF operation frequency	508.9 MHz
R_{sh}/Q_0 [a]	150 Ω
Q_0	≈ 30000 (97%IACS[b])
Gradient required in operation	$V_c = 0.70$ MV
	($E_{acc} = 2.7$ MV/m)
Gradient of the specification	$V_c = 0.80$ MV
	($E_{acc} = 3.1$ MV/m)
Wall loss power at $V_c = 0.70$ MV	≈ 110 kW
Wall loss power at $V_c = 0.80$ MV	≈ 140 kW

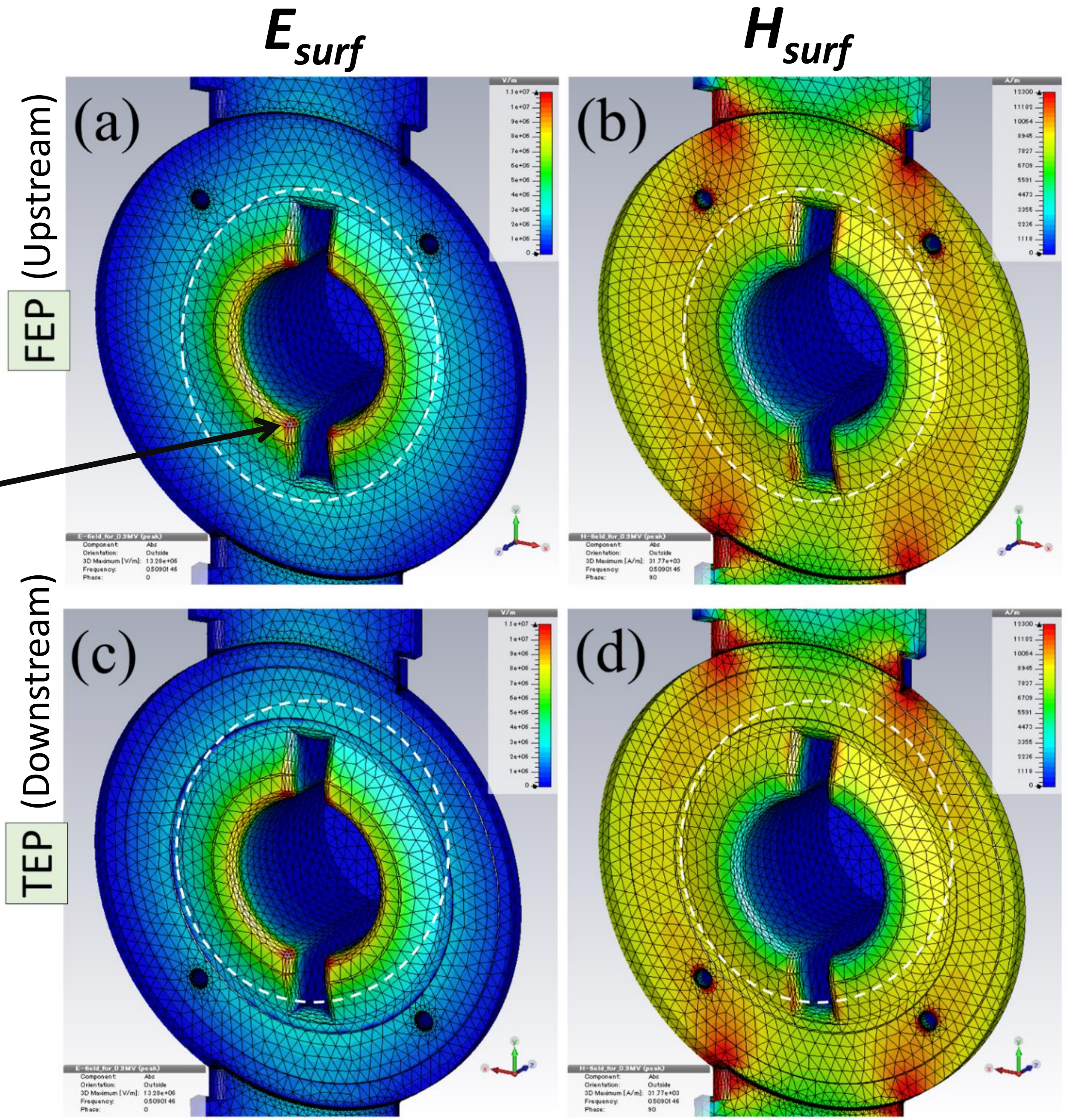
- Made of High Purity Copper (class1)
- Gap length: 256 mm
- E_{surf}/E_{acc} = 3.8 (max)

E_{surf}(max) < 13 MV/m

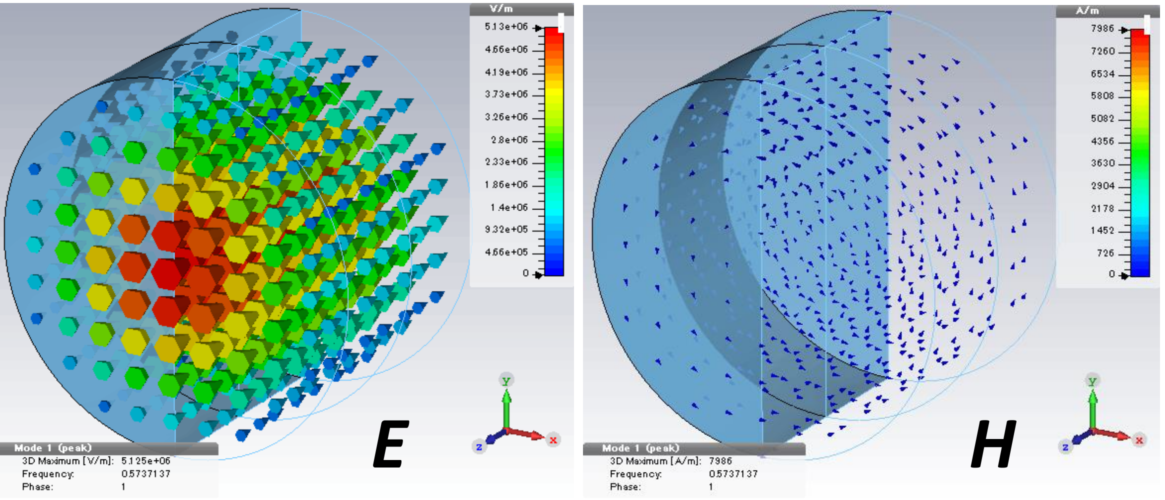
Surface field on the Endplates

Scaled for V_c = 0.90 MV
(E_{acc}=3.5 MV/m)

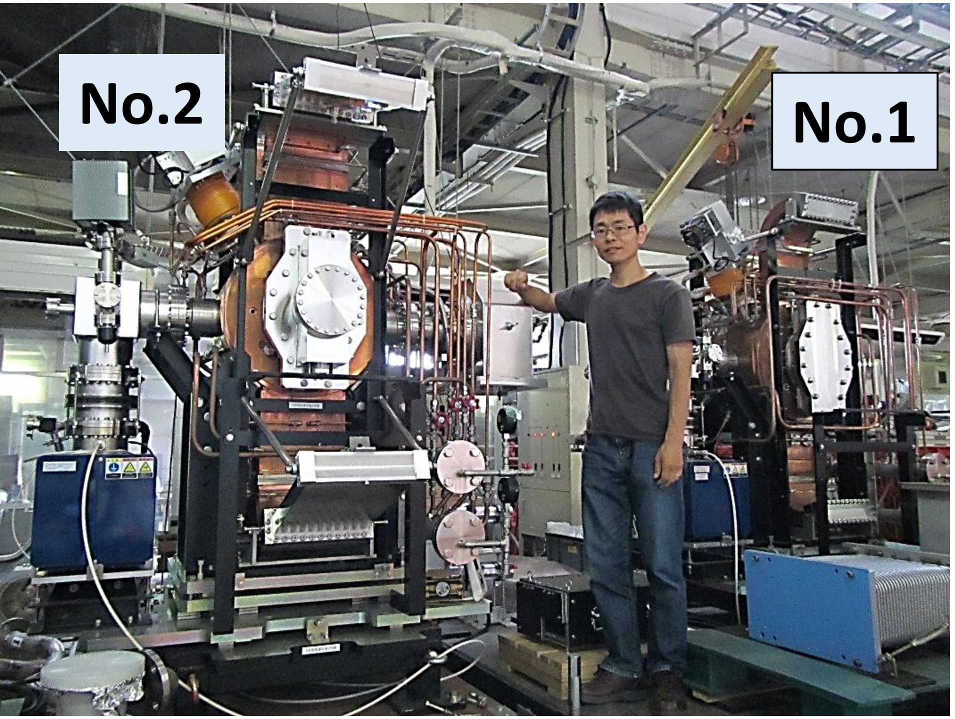
E-field_for_0.9MV (peak)	
Component:	Abs
Orientation:	Outside
3D Maximum [V/m]:	13.28e+06
Frequency:	0.5090146
Phase:	0



Accelerating mode: TM_{010}



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, and**
- ✓ **Fabrication method**

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

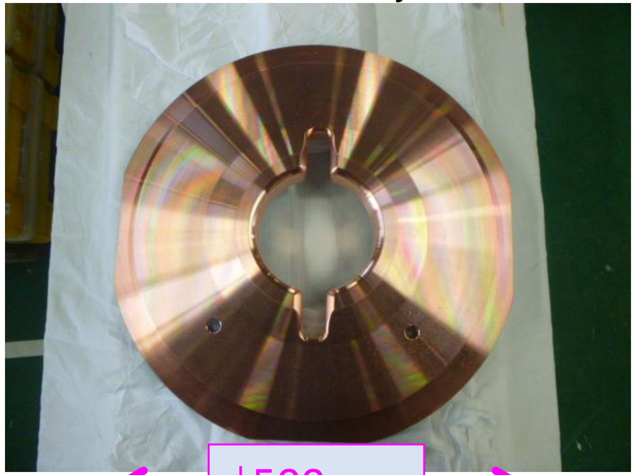
R_a=1.5μm, R_y=8μm

After EP

R_a=0.2μm, <u>R_y=1μm (< δ = 3μm)</u>

(Upstream)

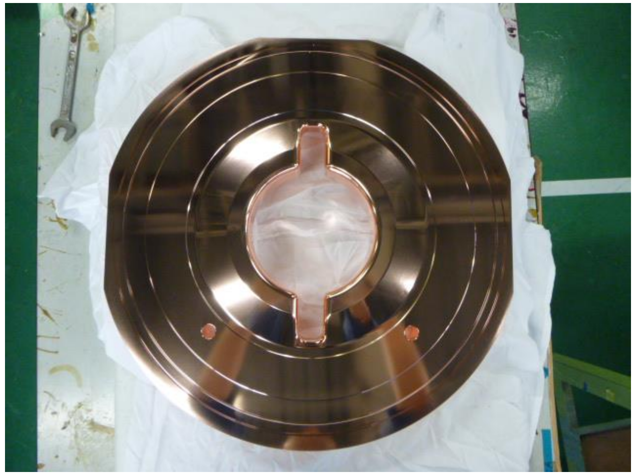
<u>F</u>ixed <u>E</u>nd <u>P</u>late (<u>FEP</u>)
w/o tuning bump



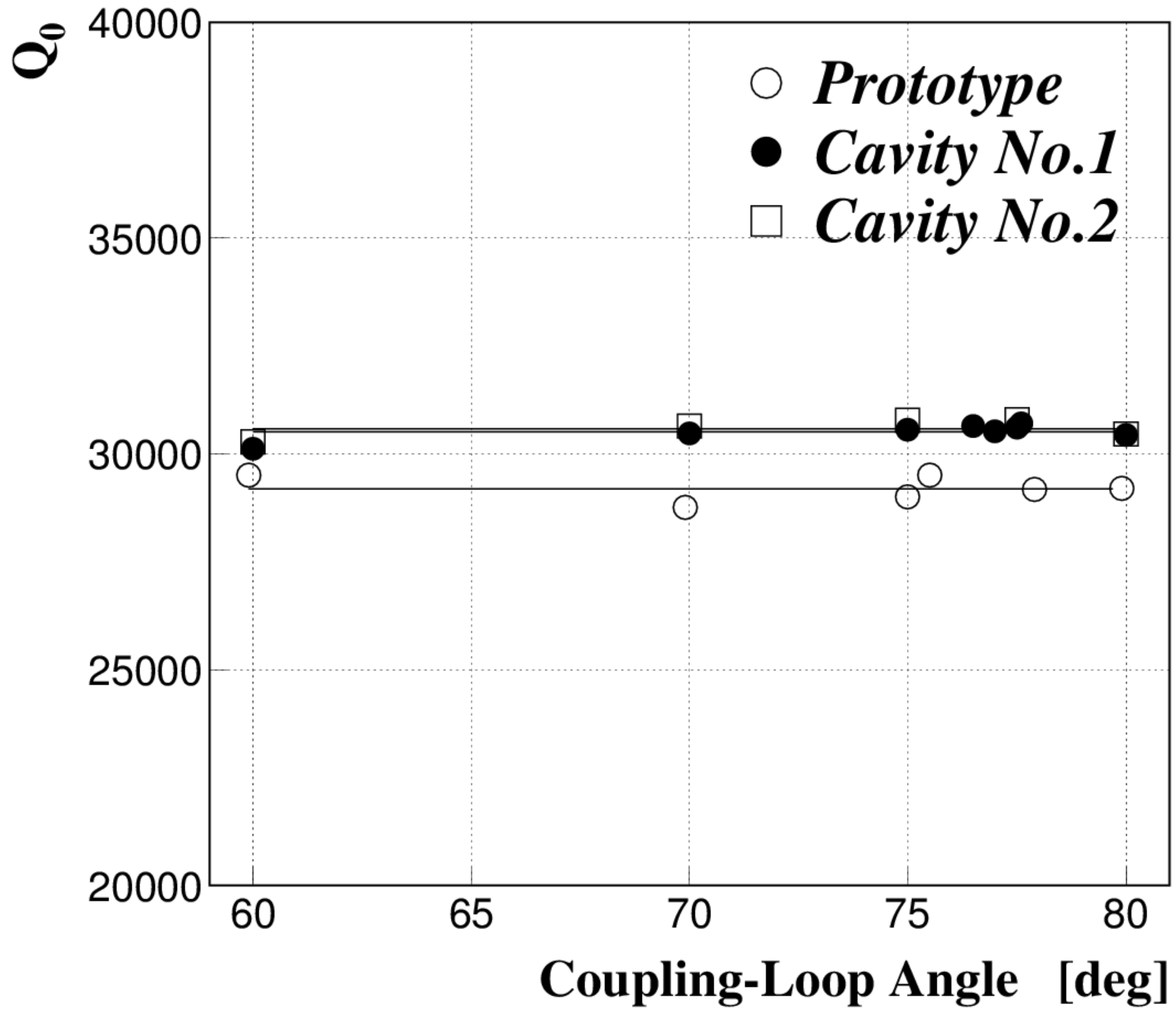
ϕ500mm

(Downstream)

<u>T</u>uning <u>E</u>nd <u>P</u>late (<u>TEP</u>)
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

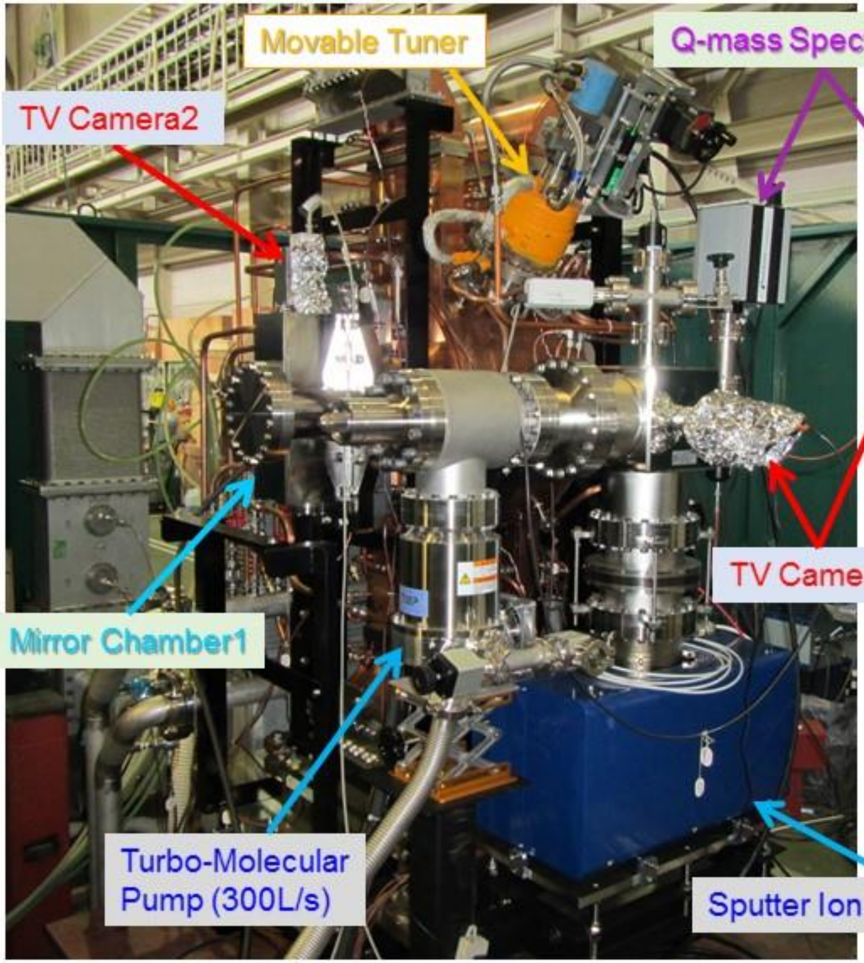
(Note: No EP applied to the barrel)

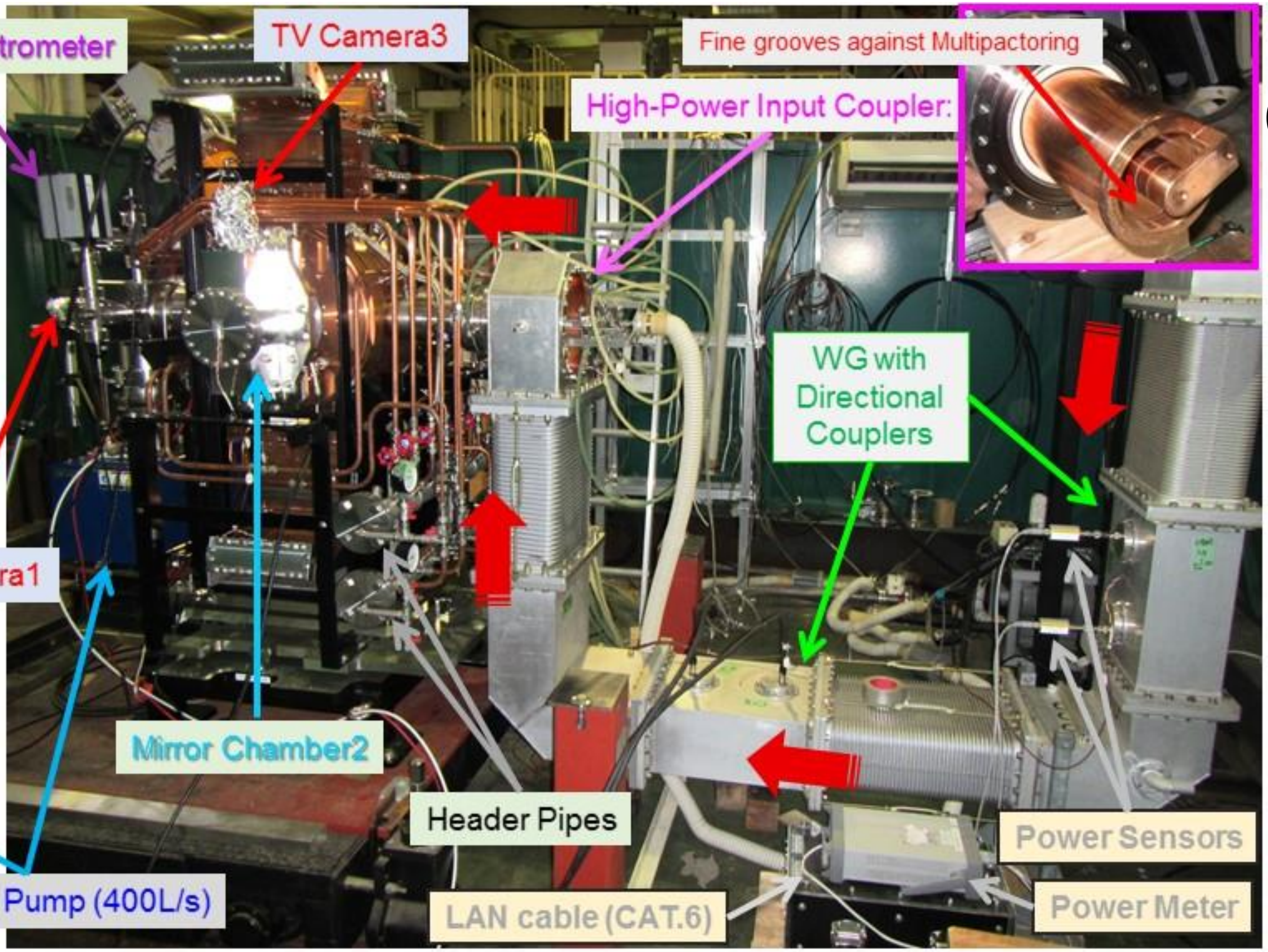
Breakdown Study based on Direct In-Situ Observation of Inner Surfaces of the DR Cavity No.2

which has the following 3 characteristics:

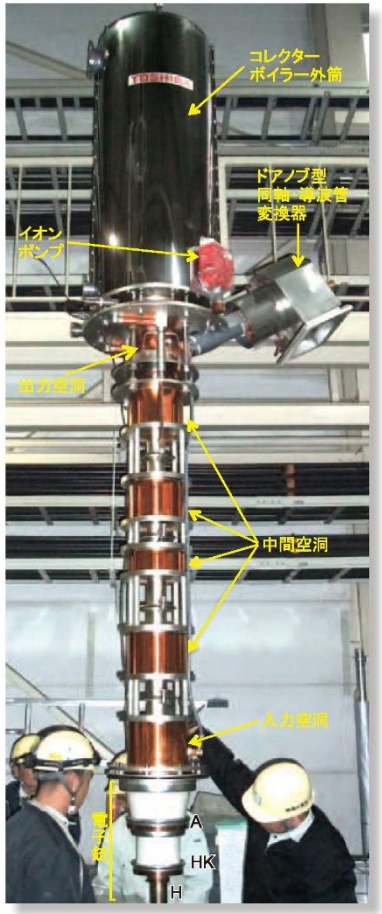
1. **Exhaustive** observation
   - To capture all of cavity breakdowns
2. **Multi-directional** and **wide-field** observation
   - To observe the origin of the cavity breakdown
3. **Quantitative** data analysis
   - What is majority and significant?

Setup of High-Gradient (HG) Test



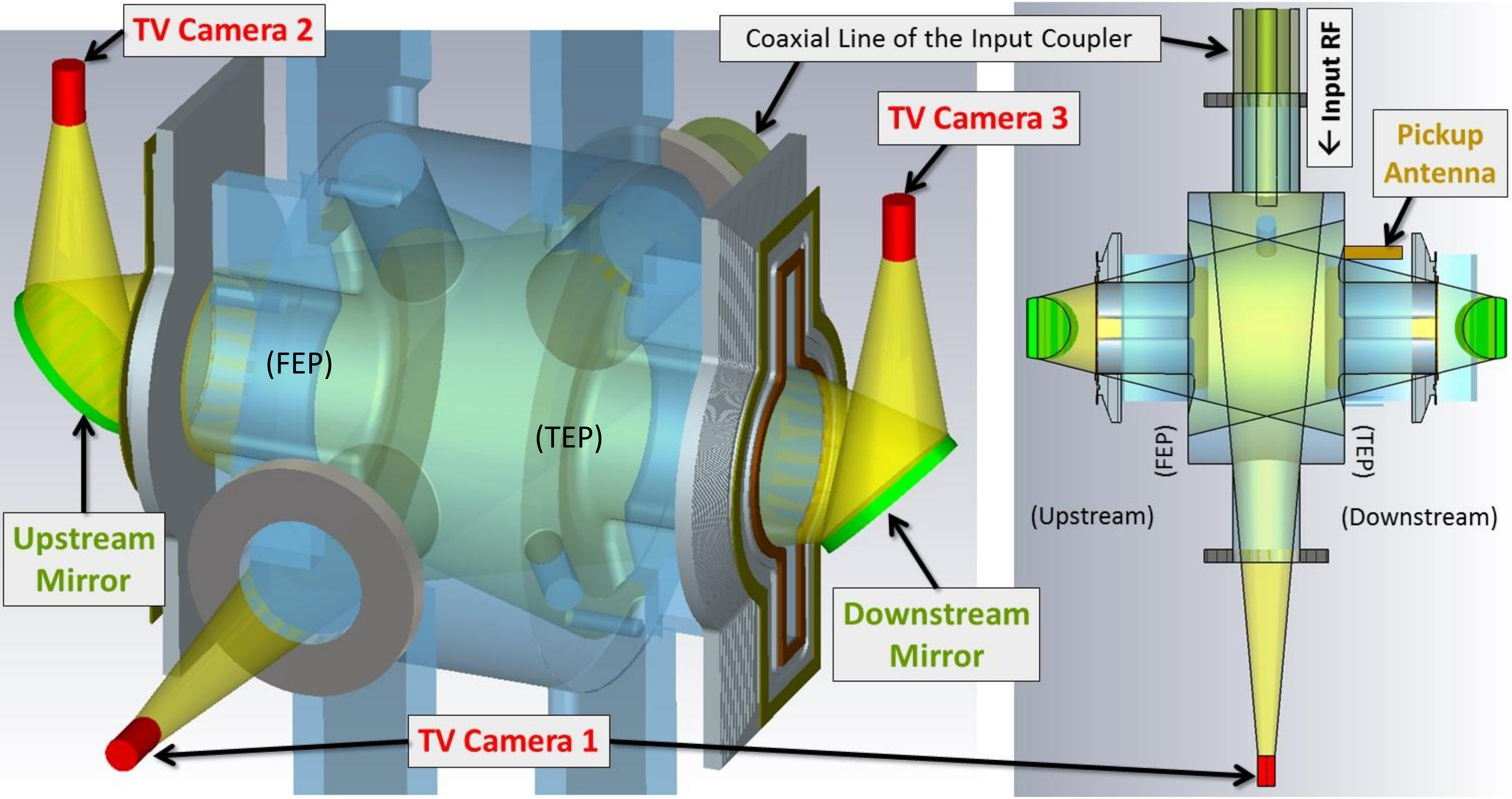


Toshiba
CW Klystron
E3732
(1MW, 508.9 MHz)

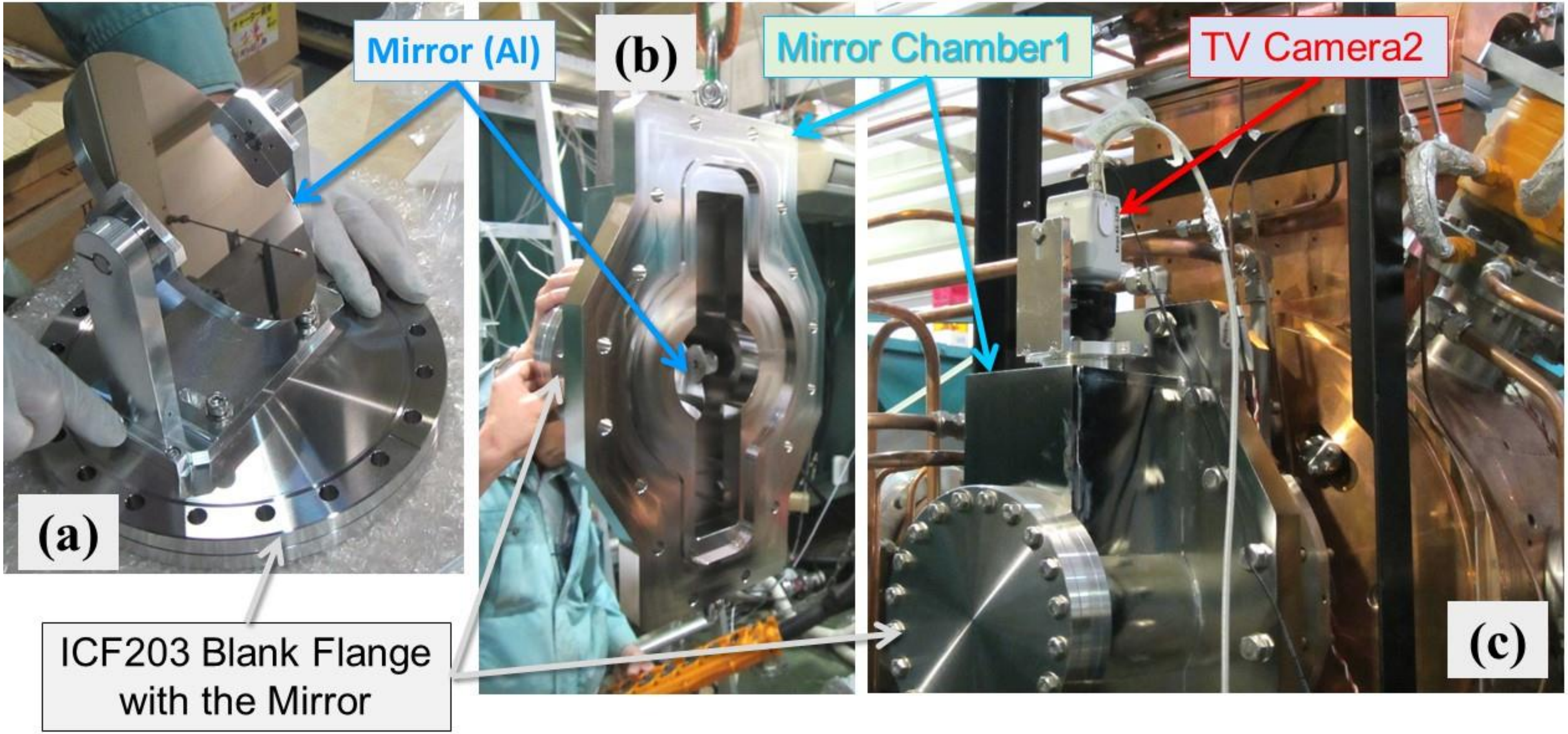


(No beam injected into the cavity during the HG test)

3 TV cameras for **Multi-directional and wide-field** observation



Mirror Chamber



TV Camera

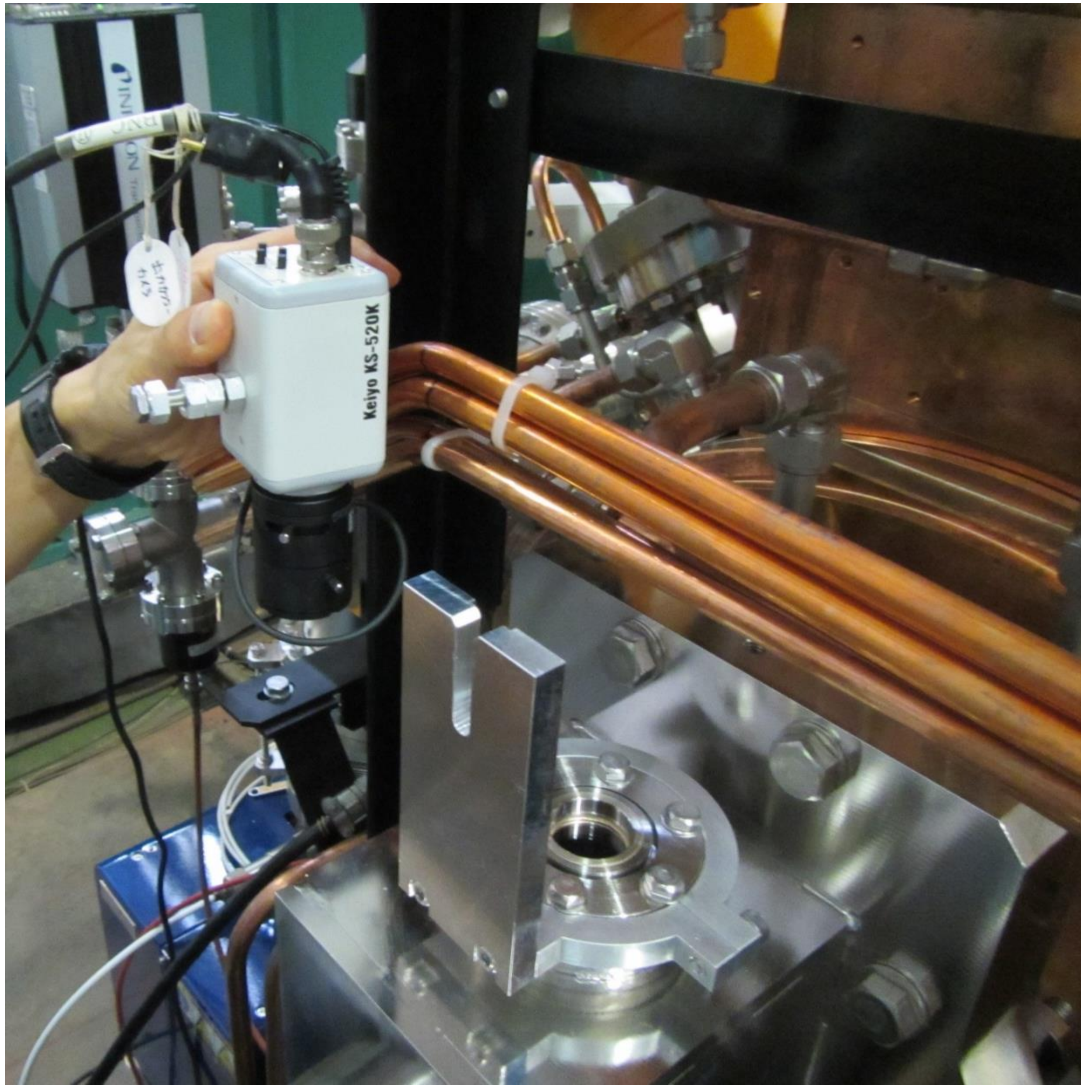
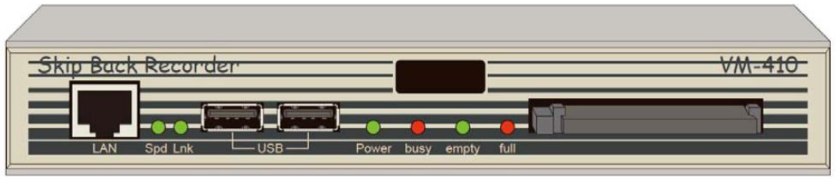


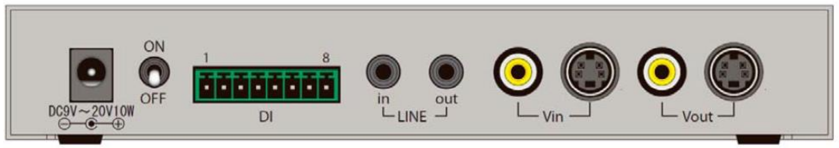
Image Sensor	1/3-inchi CCD
Minimum illuminance of object	0.05 lux (color)
S/N	> 52 dB
Gross Sensor Resolution	52×10^4 pixels
Output format	NTSC
Frame rate	30 fps
Price	20,000 YEN

Skip Back Recorder

4-1 前面と名称



4-2 後面と名称



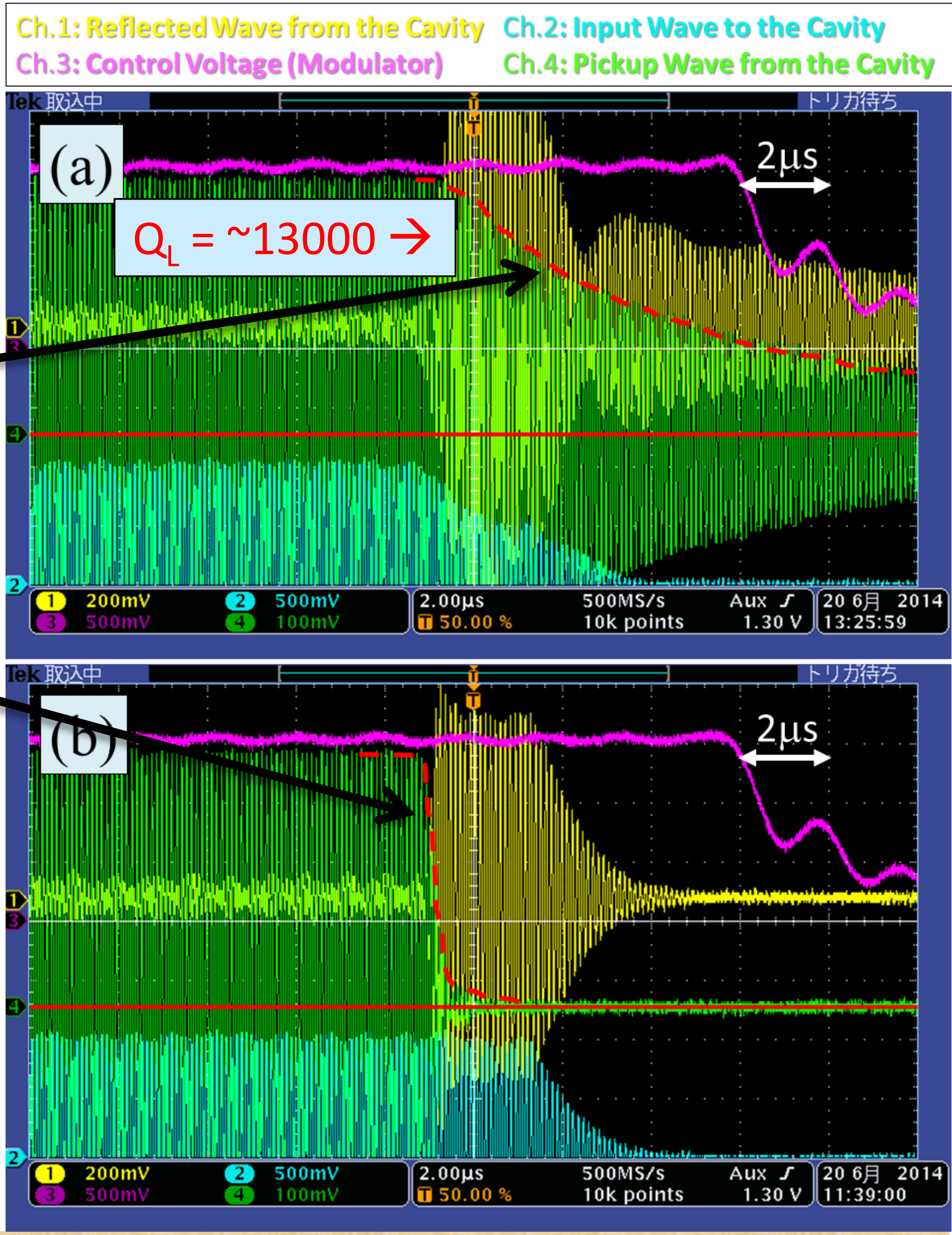
- ✓OS: Linux
- ✓**Input video: NTSC**
- ✓**<u>Trigger: RF switch "ON → OFF"</u>**

All of the cavity-breakdown events recorded *automatically*
(5 seconds before, until 1 second after this trigger)

Exhaustive observation

Identification 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
   - ~8 μs ➔ Not cavity breakdown
   - << 8 μs ➔ Cavity breakdown



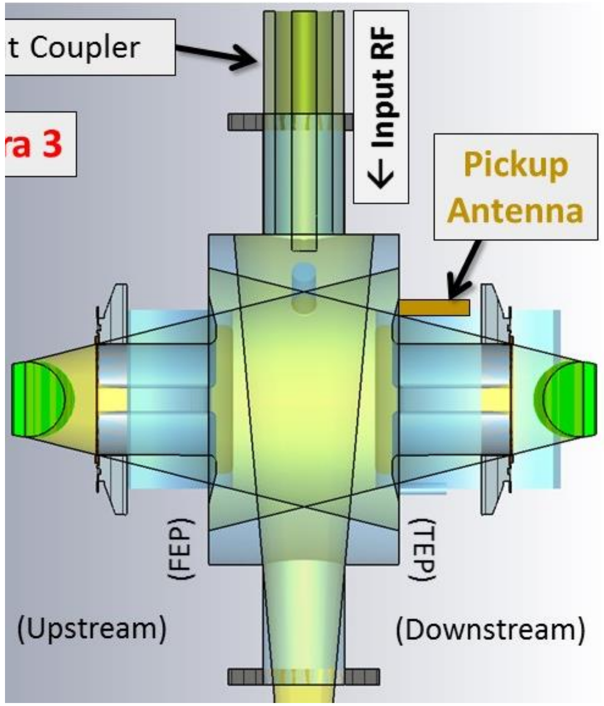
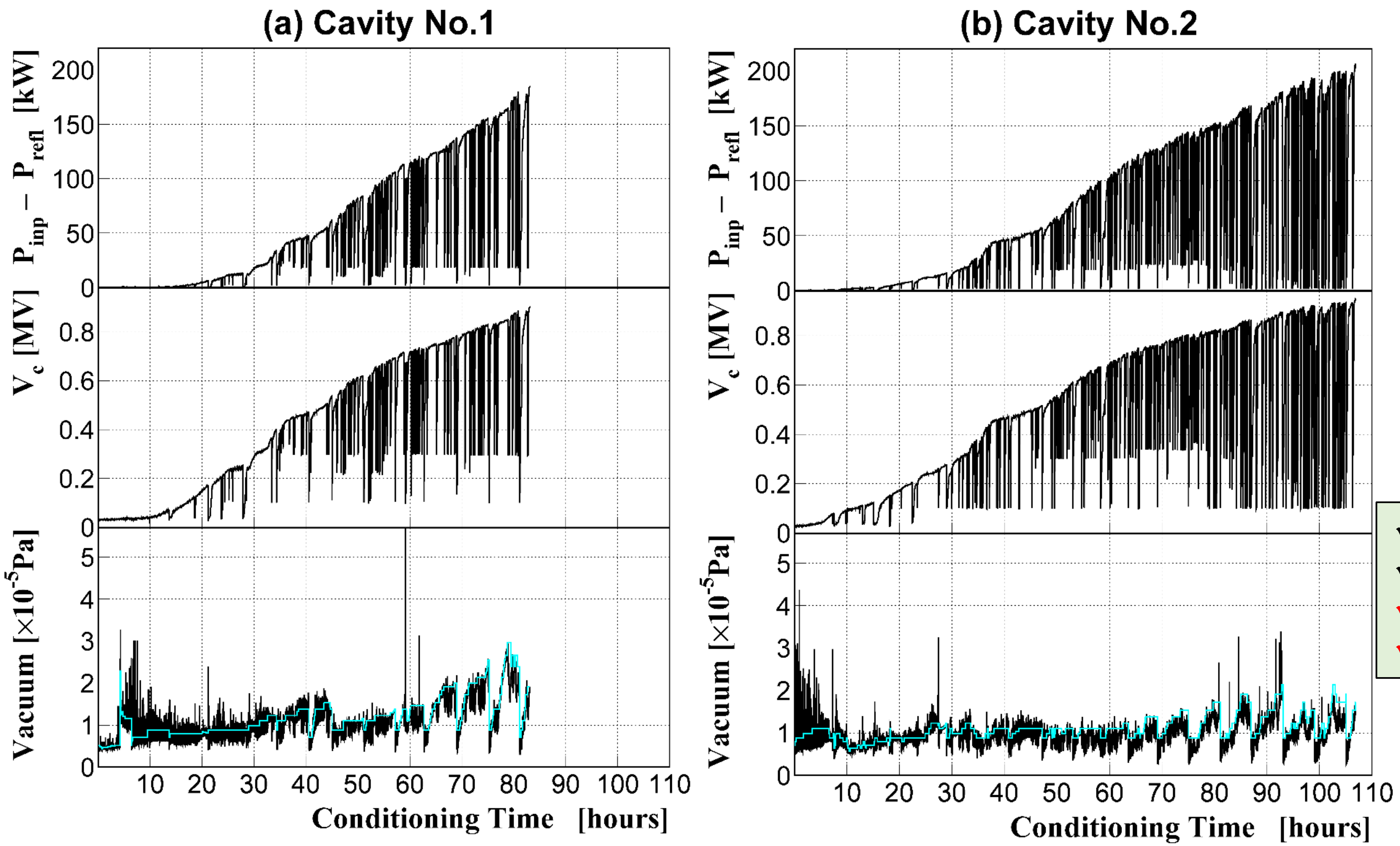


FIG. 6: Waveforms of the oscilloscope displayed for a time span of 20 μs (= 2 μs/div) when the interlock system was activated. The red dashed curves indicate the envelope of the 508.9-MHz pickup signal from DR Cavity No. 2, and the red solid lines indicate its zero level. (a) The RF switch was turned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

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



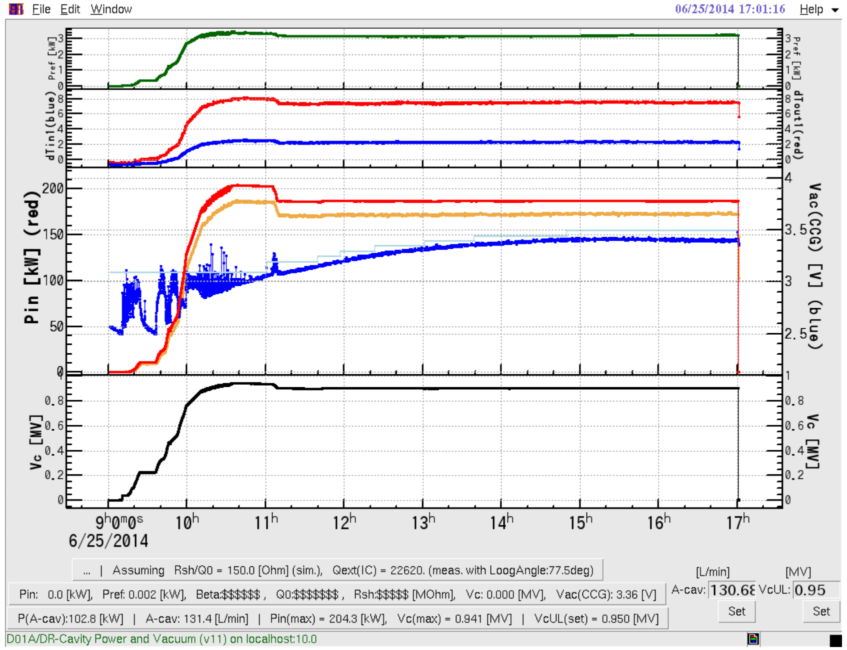
The light blue lines indicate the reference vacuum pressure specified by the computer controlled automatic aging.
If the vacuum pressure is higher than the reference, P_{in} is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{in} is slightly stepped up as 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: $P_{wall} = P_{in} - P_{refl} = \sim 0.99 \times P_{in}$
- ✓ **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 $\underline{V_c = 0.90\ \mathrm{MV}}$

> V_c = 0.70 MV
> (required for DR operation)

Example of the daily histories →



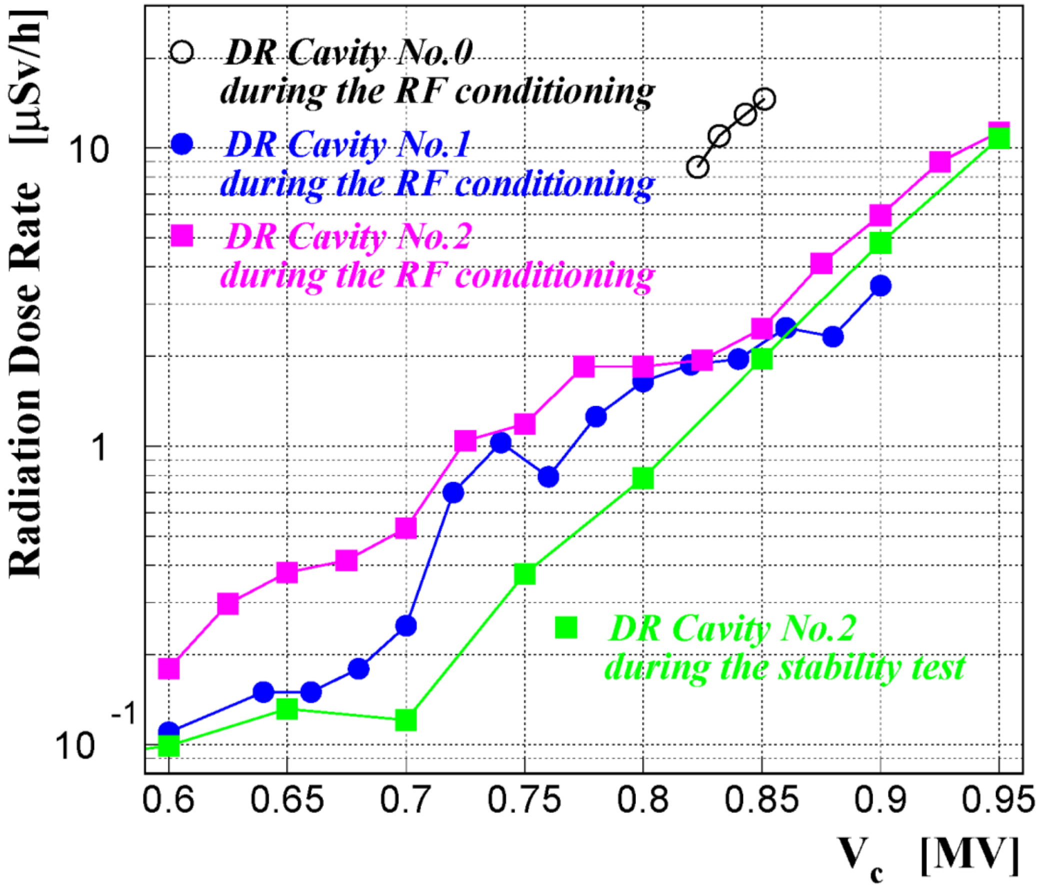
- Cavity No.1: 3 breakdowns for 14.5 hours in total = **$5.0^{+4.8}_{-2.7}$ /24hrs**
- Cavity No.2: 11 breakdowns for 80 hours in total = **$3.3^{+1.3}_{-1.0}$ /24hrs**

Same stability between the DR Cavities No. 1 and No. 2 within the statistics

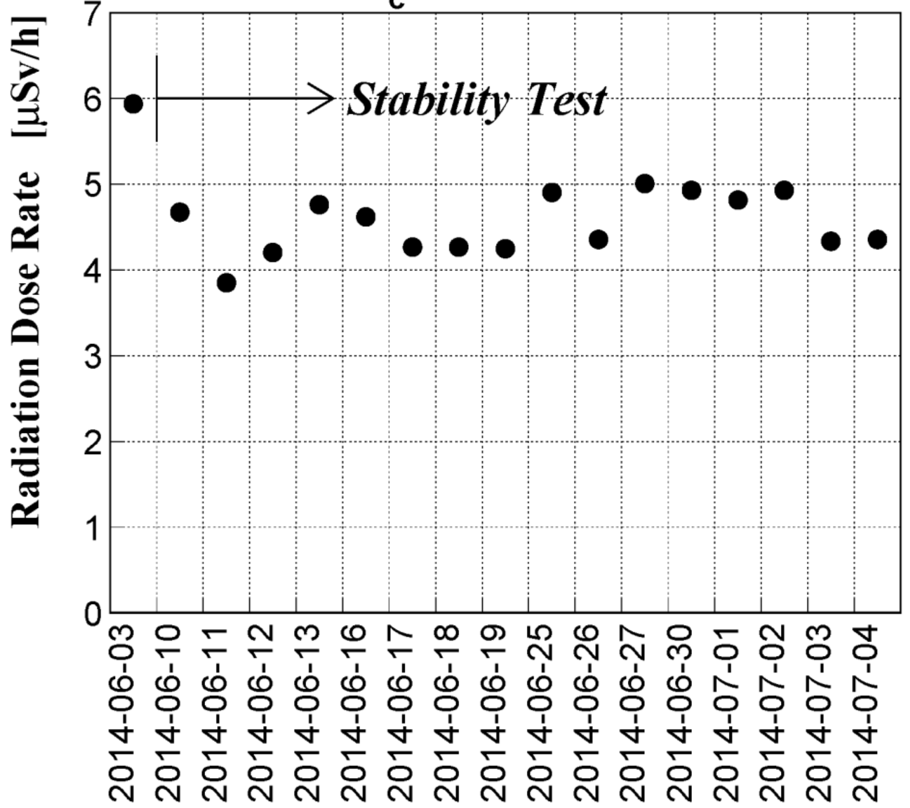
Radiation Dose Rate

= Indirect observation of the dark current:

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



V_c = 0.90 MV for the DR Cavity No.2



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

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

No significant difference between DR Cavities No.1 and No.2 found in:

- ✓ Q_0
- ✓ RF conditioning speed
- ✓ Vacuum performance
- ✓ HG performance, including BDR
- ✓ Radiation dose rate (dark current)

⇓

No cavity's particular problems or unusual characteristics found

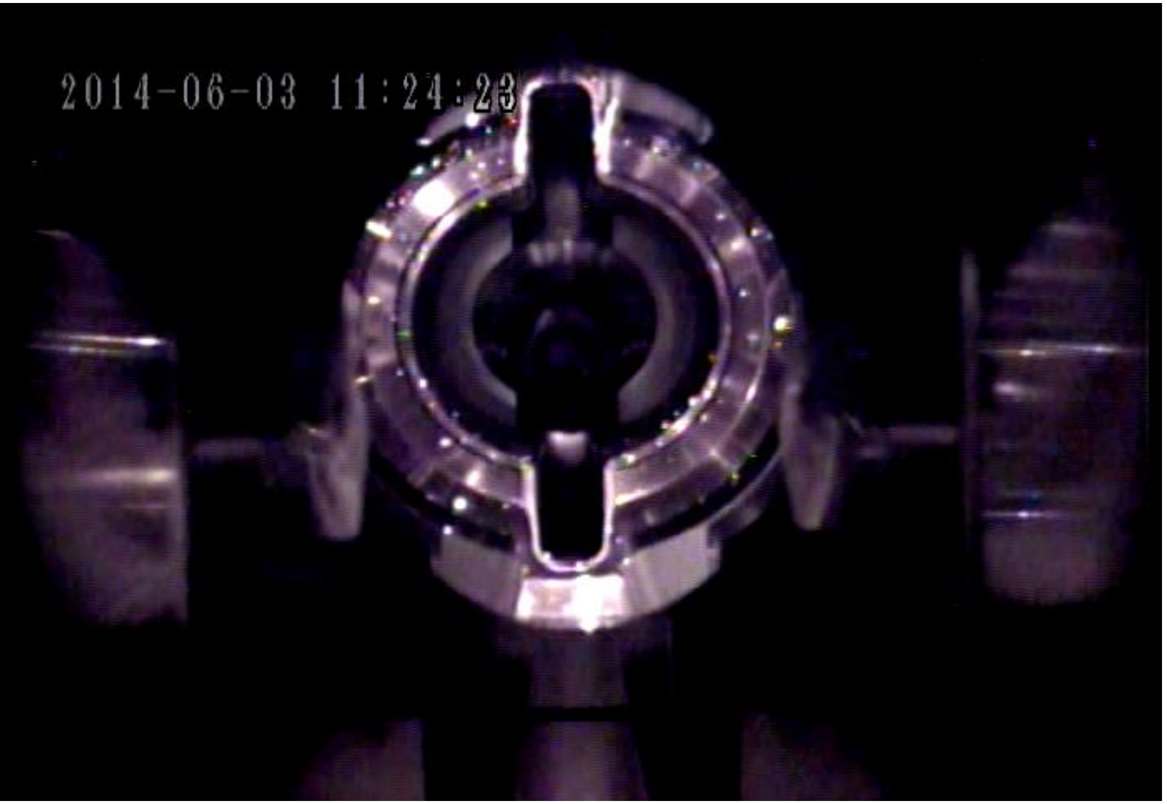
⇓

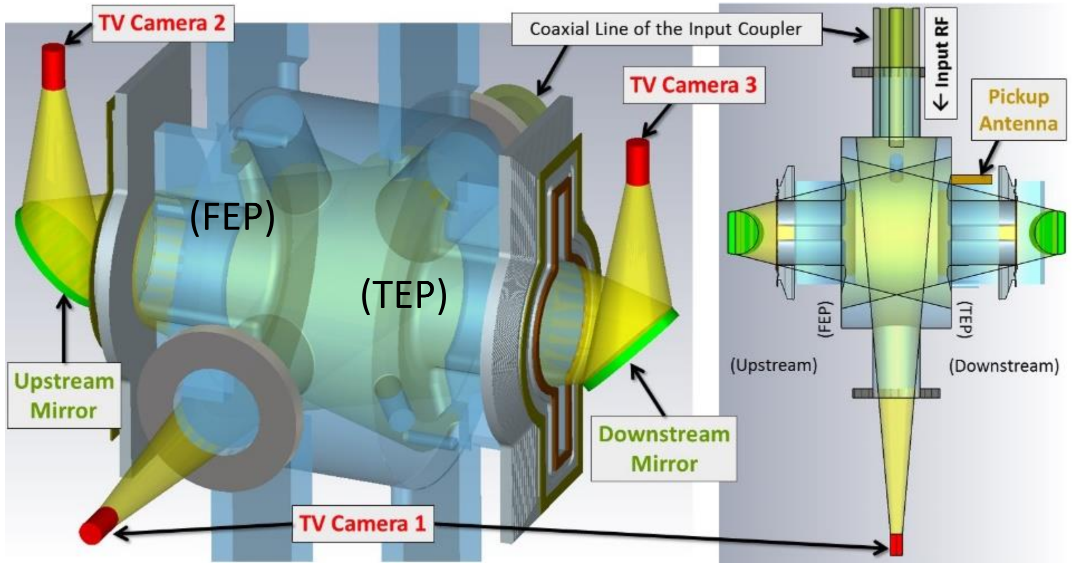
We can perform breakdown study only for the DR Cavity No.2 without a loss of generality.

Statistical Data Analysis of Cavity Breakdown Events for DR Cavity No.2

Example of the Recorded Videos

Upstream Endplate





- ✓ By TV camera 3
- ✓ During HG operation with V_c = 0.90 MV (Eacc = 3.5 MV/m)
- ✓ Non-breakdown status

Clear and stable bright spots observed on the endplates during the HG operation

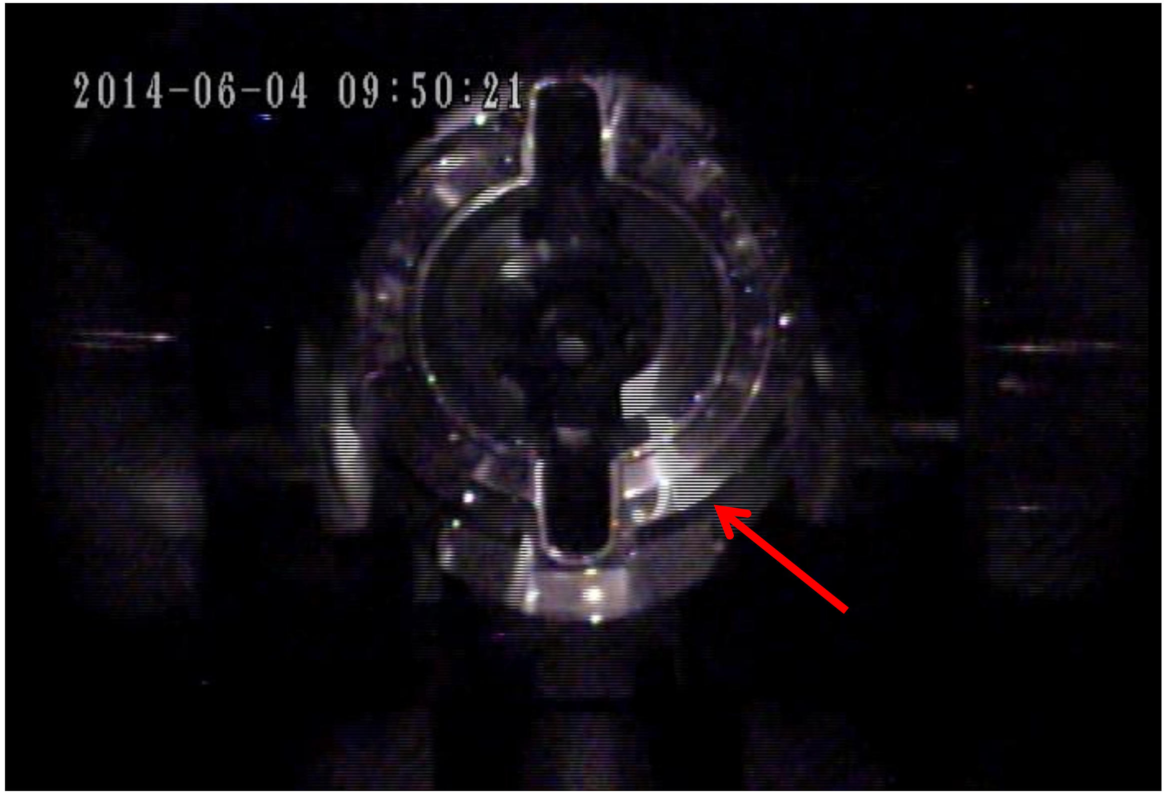
- ➢ **Maintained their intensity**
- ➢ **Giving no significant effects on the HG operation as long as they remained stable**

Example of Cavity-Breakdown Events (1)

Flash(1)

T < 0

T = 0



Cavity Breakdown!

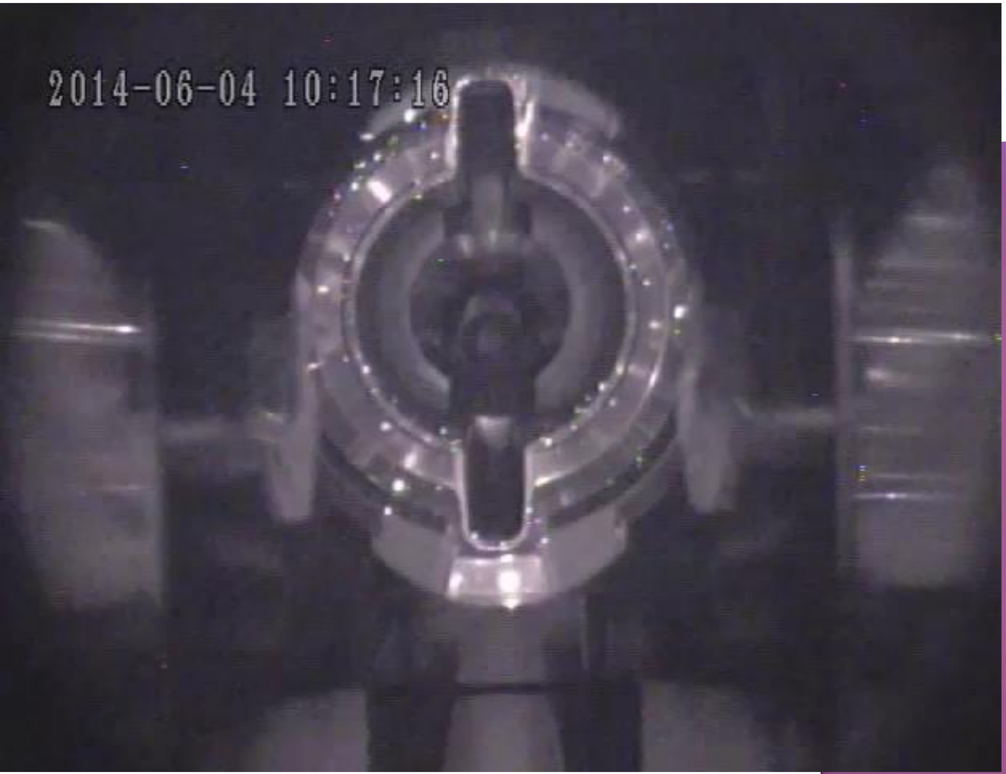
at V_c=0.76MV (E_{acc} = 3.0 MV/m)

Example of Cavity-Breakdown Events (2)

Flash(2)

V_c=0.89 MV (E_{acc} = 3.5 MV/m)

Upstream Endplate

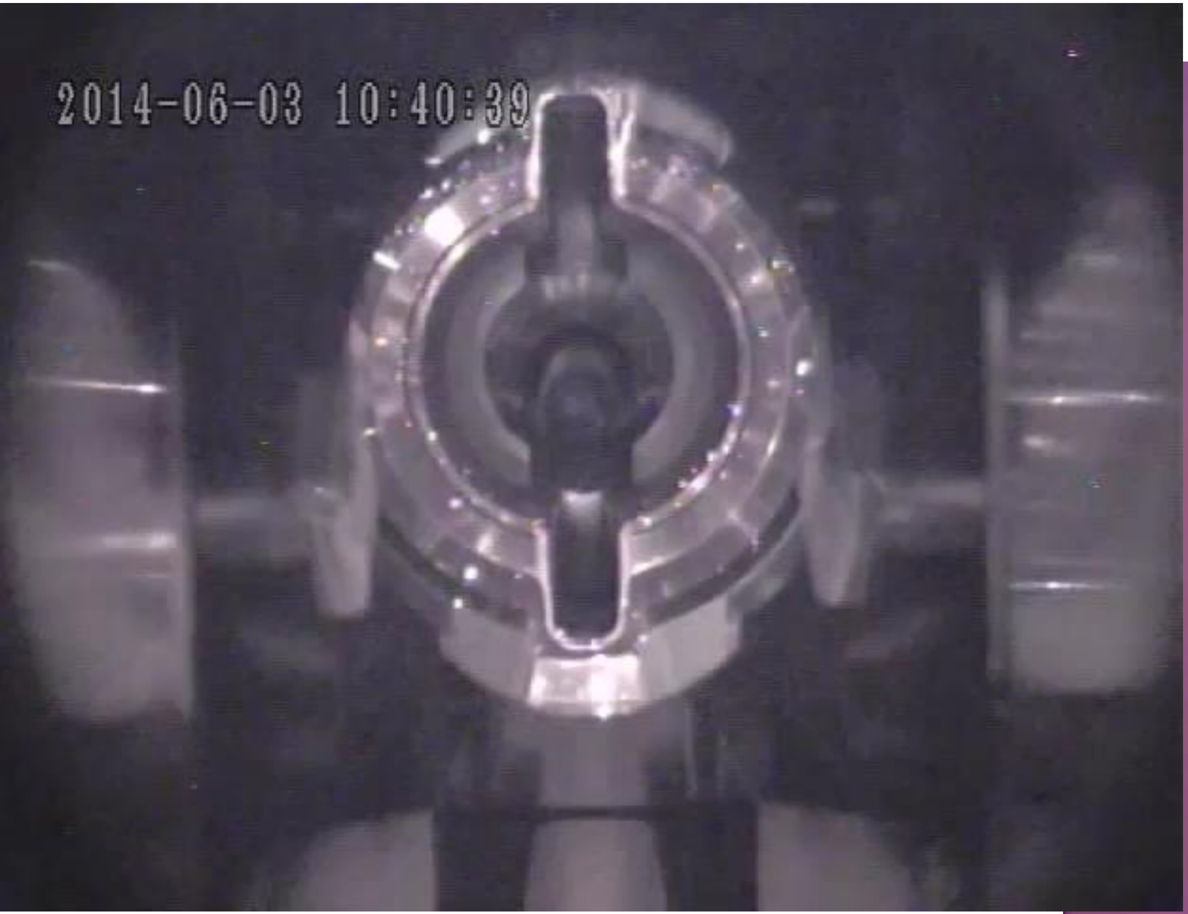


Coaxial Line of the Input Coupler

Downstream Endplate

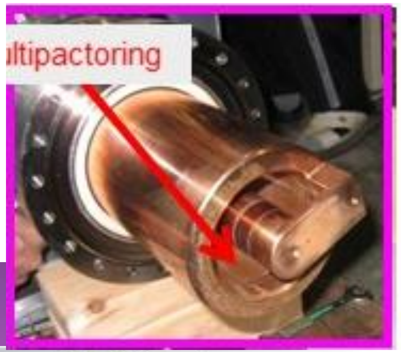
Example of Cavity-Breakdown Events (3)

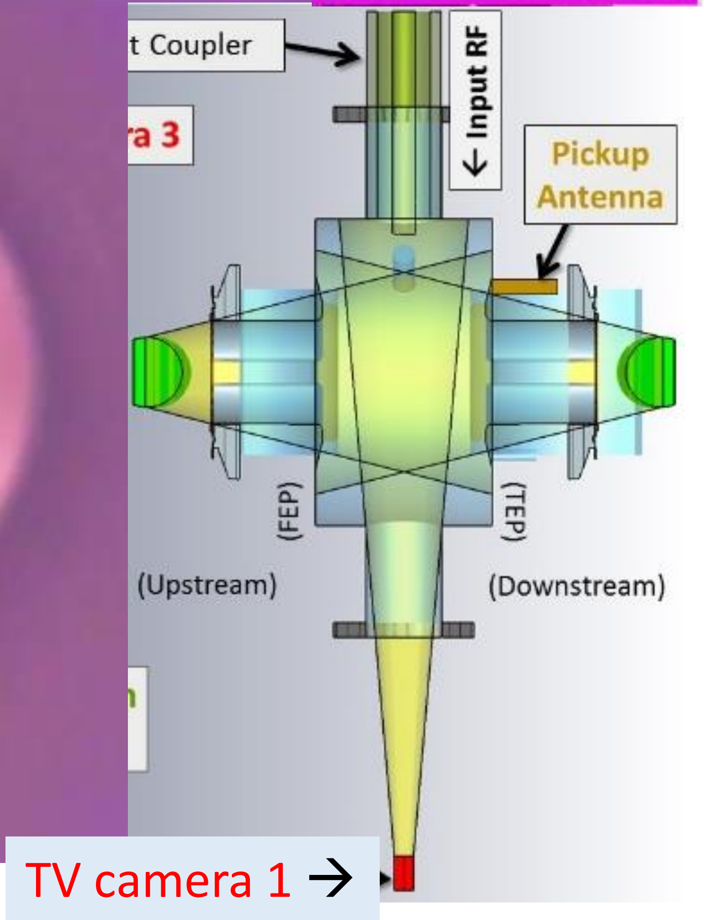
Upstream Endplate



Lightning!

Coaxial Line of the Input Coupler





Cavity Breakdown at V_c = 0.89 MV (E_{acc} = 3.5 MV/m)

By the Statistical Analysis

- We have found that such pyrotechnical phenomena are minority in the cavity-breakdown events using the TV cameras.

- What is majority?

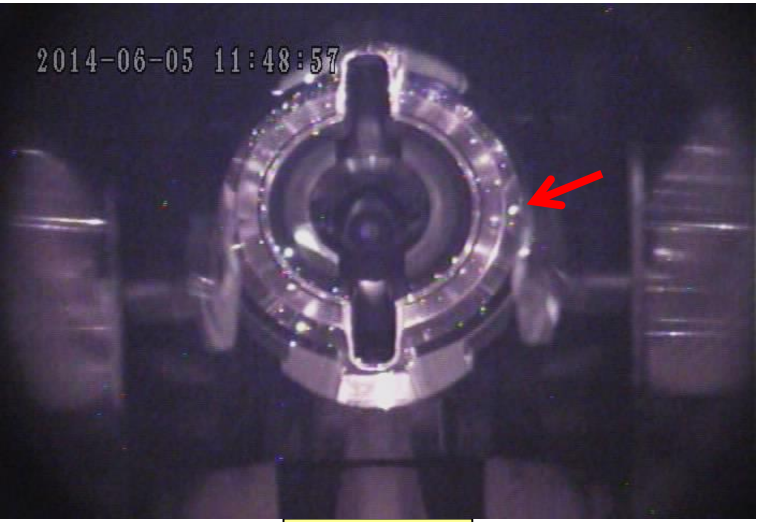
Example of Cavity-Breakdown Events (4)

Spot-type explosion of a stable bright spot
which had maintained its intensity until the explosion,
followed by disappearance

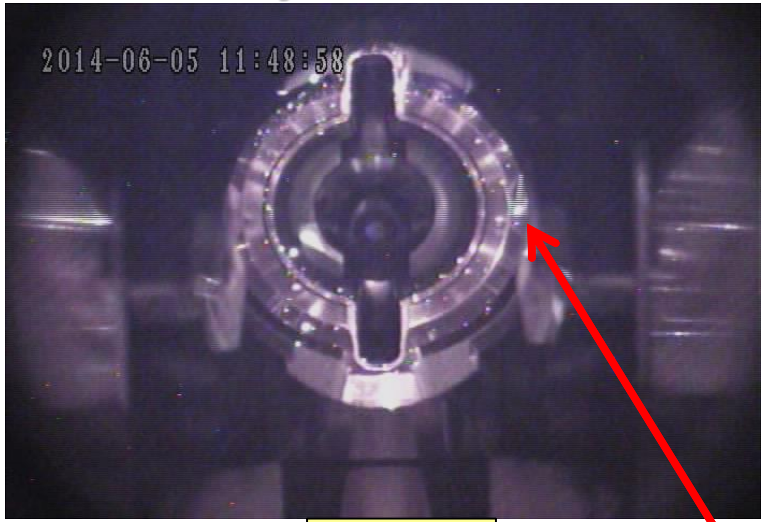
V_c = 0.95 MV (E_{acc} = 3.7 MV/m)

Cavity Breakdown!

No bright spot there!

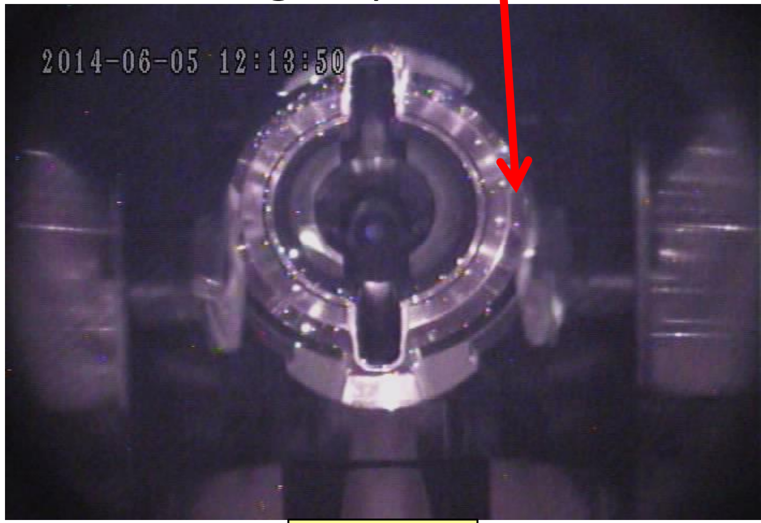


T < *0*



T = *0*

Mini-Supernova

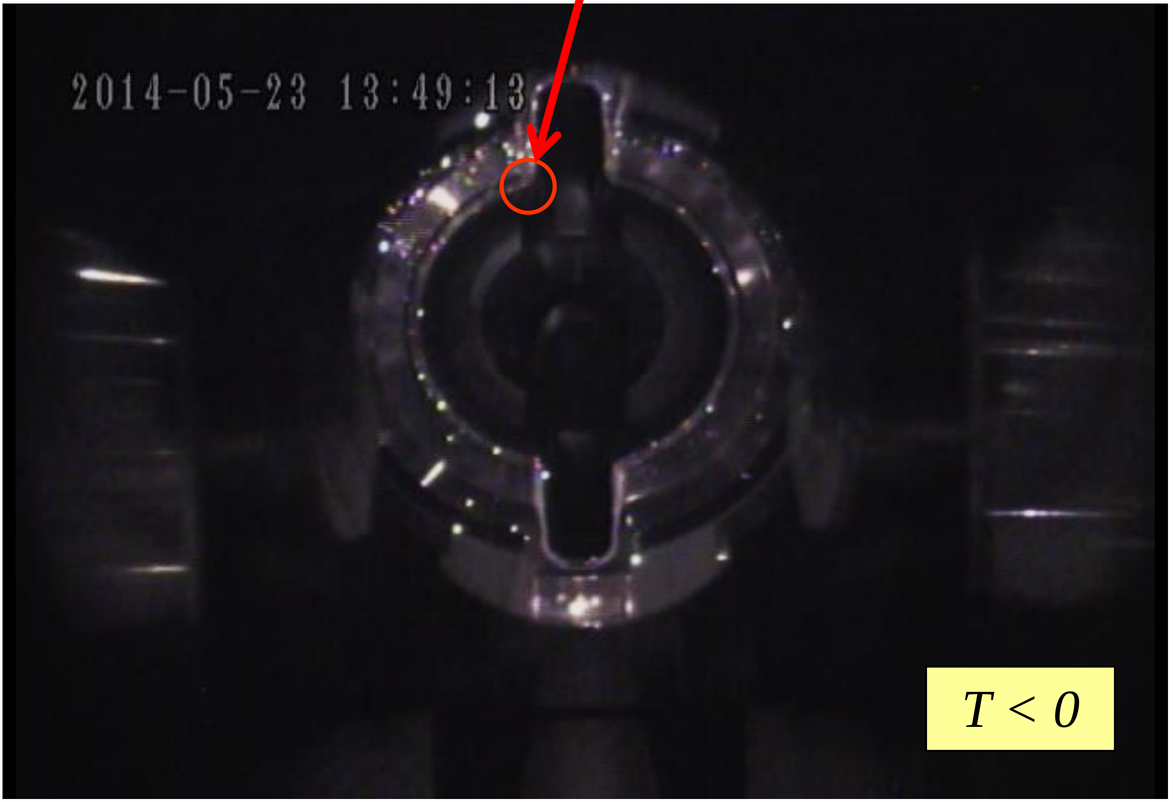


T > *0*

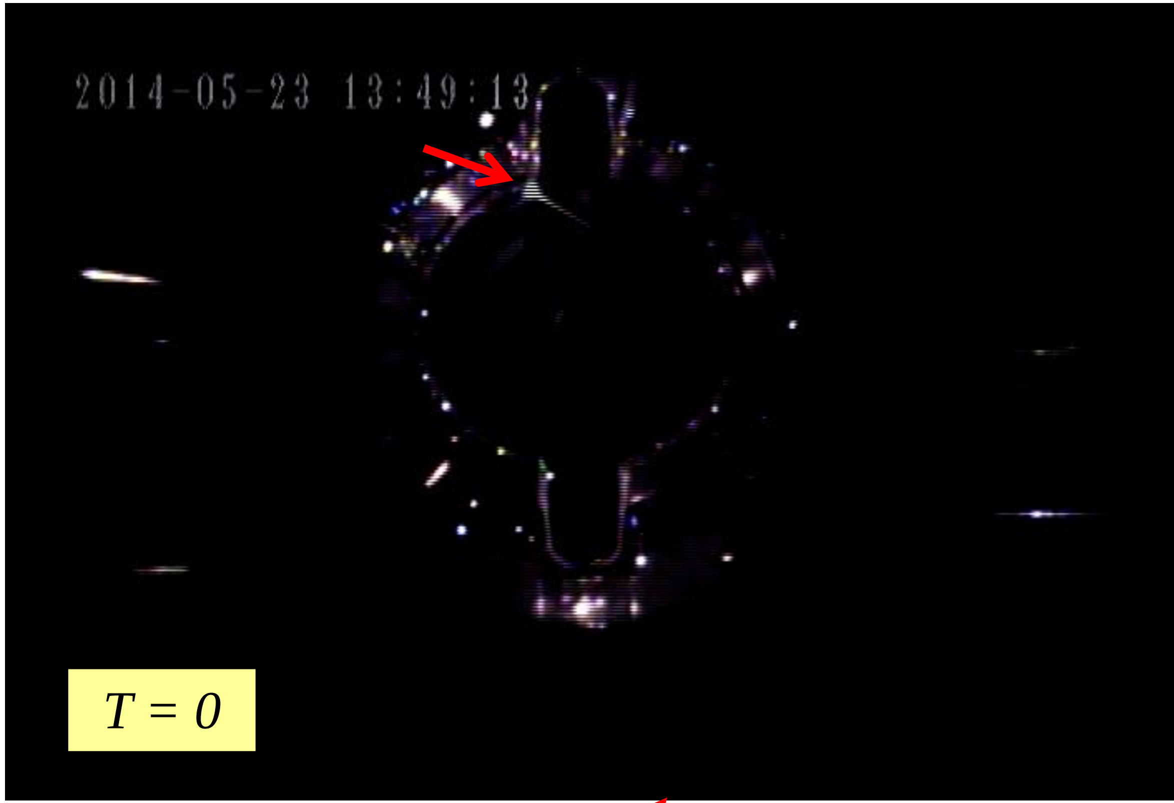
Example of Cavity-Breakdown Events (5)

Spot-type explosion without a stable bright spot

No bright spot here



Cavity Breakdown!



V_c = 0.65 MV (E_{acc} = 2.5 MV/m)

Explosion!

Counting Cavity-Breakdown Events for each Category

TABLE IV: Classification of the cavity breakdown events. Numbers enclosed in square brackets (parentheses) are percentages of the total numbers of cavity breakdown events (with any observed abnormalities).

Period	Spot-type explosion with a BS[a]	Spot-type explosion with no BS	Non-spot-type flash	Non-spot-type lightning only	Others
RF Conditioning	44	72	4	14	9
	[24.4%] (30.8%)	[40.0%] (50.3%)	[2.2%] (2.8%)	[7.8%] (9.8%)	[5.0%] (6.3%)
Stability test (total)	7	9	3	1	0
	[28.0%] (35.0%)	[36.0%] (45.0%)	[12.0%] (15.0%)	[4.0%] (5.0%)	
Stability test	5	2	1	1	0
($V_c = 0.90$ MV)	[45.5%] (55.6%)	[18.2%] (22.2%)	[9.1%] (11.1%)	[9.1%] (11.1%)	

[a] BS indicates bright spot.

60% or more of the cavity-breakdown events are spot-type explosions.

Counting Cavity Breakdown Events for each Category

(BS: Bright Spot)

Period	BS disappeared
Conditioning	36
	[20.0%] (25.2%)
Stability test (total)	7
	[28.0%] (35.0%)
Stability test ($V_c = 0.90\,\mathrm{MV}$)	5
	[45.5%] (55.6%)

TABLE V: Number of spot-type explosion events with BSs, where the BSs disappeared after the explosions. The numbers enclosed in square brackets (parentheses) indicate proportions to the total number of the cavity-breakdown events (events with any abnormality observed).

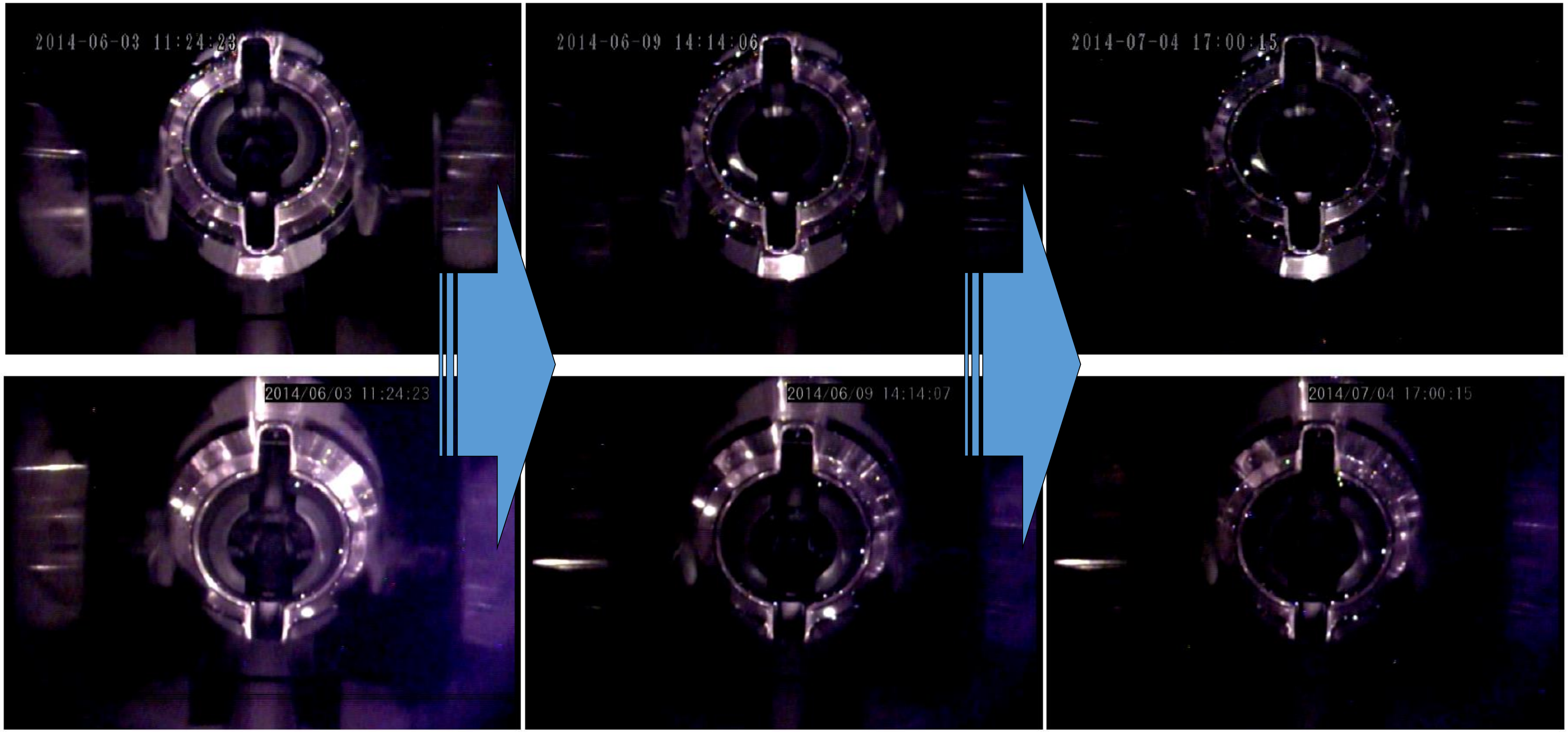
In 20% or more of the cavity-breakdown events, the bright spots exploded, and then disappeared.

Bright Spots @ V_c = 0.90 MV (E_{acc} = 3.5 MV/m)

During RF Conditioning → At the beginning of the stability test → At the end of the stability test

Upstream Endplate

Downstream Endplate

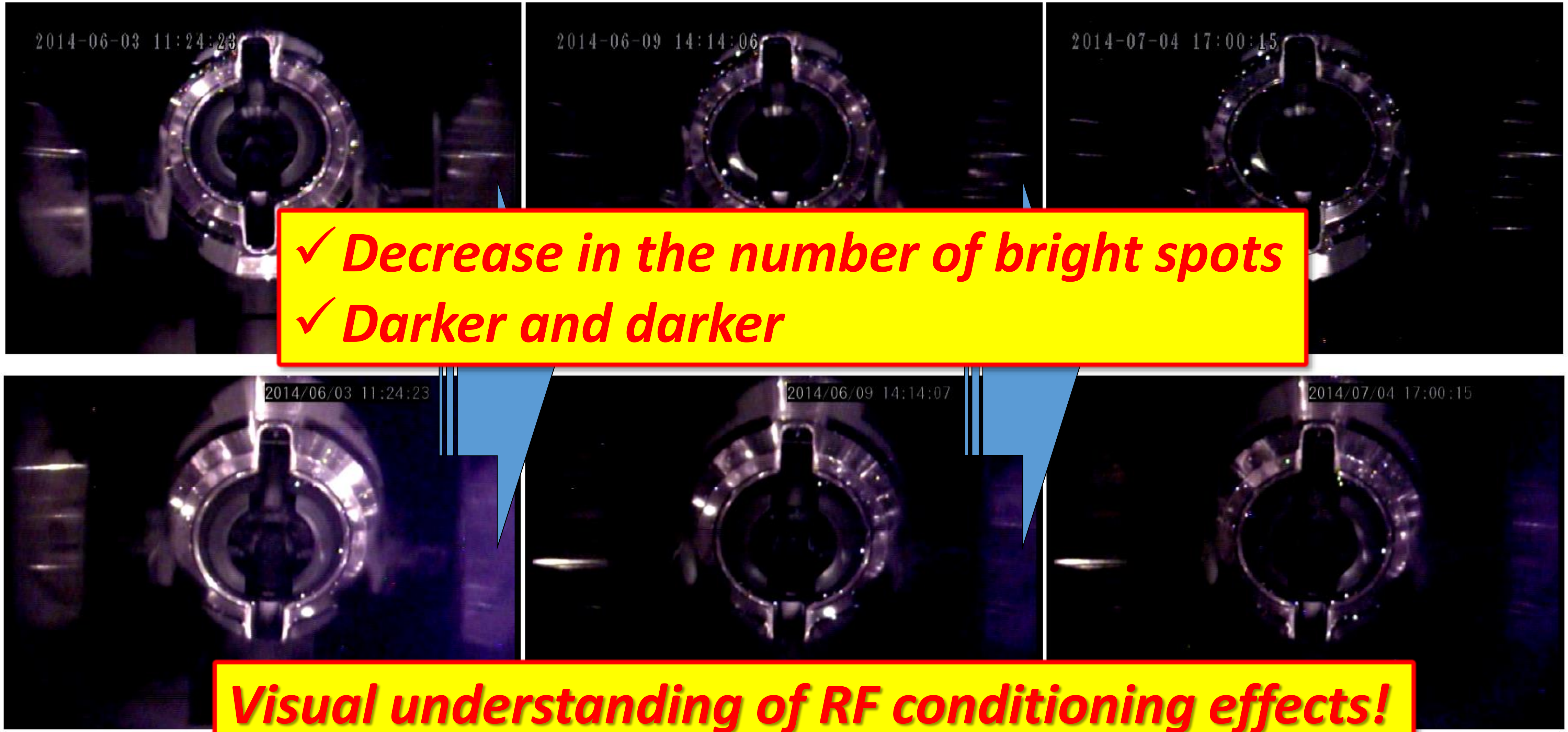


Bright Spots @ V_c = 0.90 MV (E_{acc} = 3.5 MV/m)

During RF Conditioning → At the beginning of the stability test → At the end of the stability test

Upstream Endplate

Downstream Endplate



✓ ***Decrease in the number of bright spots***

✓ ***Darker and darker***

Visual understanding of RF conditioning effects!

Counting Cavity Breakdown Events for each Category

Period	Sudden BS[a] appearance
RF conditioning	6
	[3.3%] (4.2%)
Stability test (total)	0
Stability test ($V_c = 0.90$ MV)	0

[a] BS indicates bright spot.

TABLE VI: Number of cavity breakdown events with sudden appearance of a bright spot just prior to the cavity breakdown. Numbers enclosed in square brackets (parentheses) are percentages of the total numbers of cavity breakdown events (with any observed abnormalities).

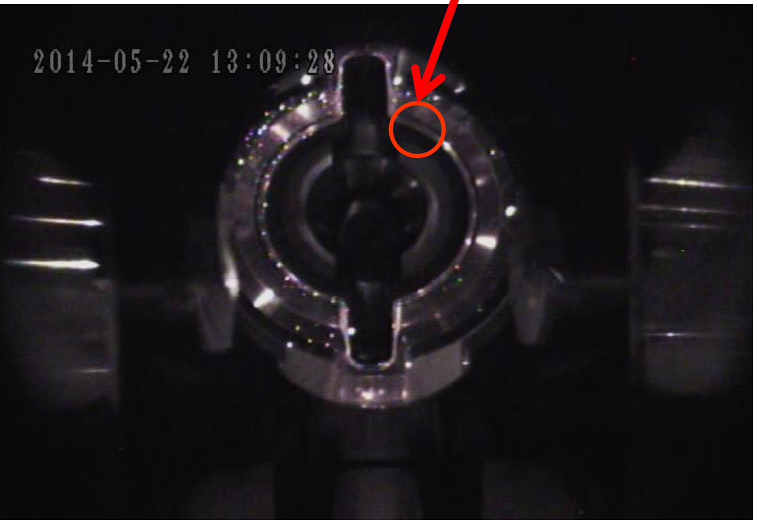
In 3% or more of the cavity-breakdown events,
we observed sudden appearance of bright spots
in a time range of the last 2 seconds before the explosions at the breakdowns.

Example of Cavity-Breakdown Events (5)

Spot-type explosion w/o a bright spot which had kept its intensity

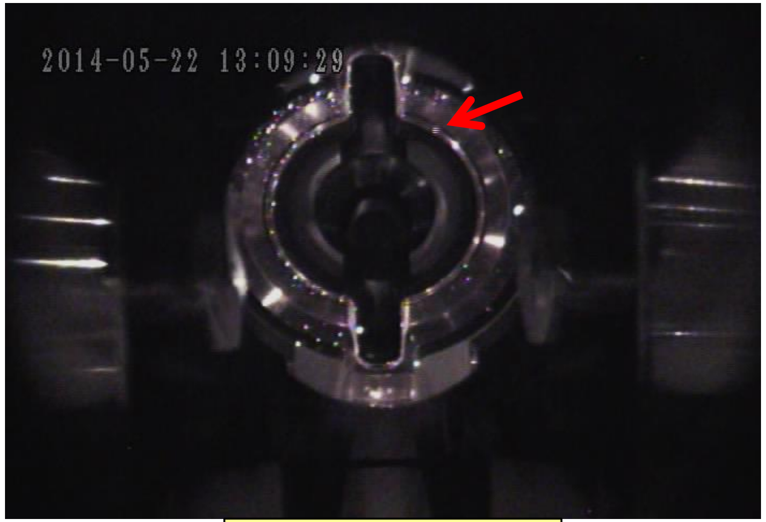
V_c = 0.56 MV (E_{acc} = 2.2 MV/m)

No bright spot here



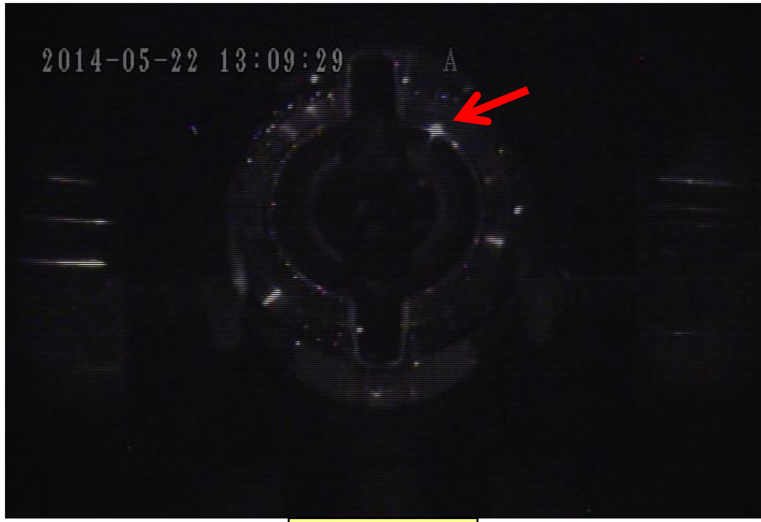
T < −0.03 s

A new bright spot appeared!



T = −0.03 s

Cavity Breakdown!



T = 0

1 frame before

Explosion!

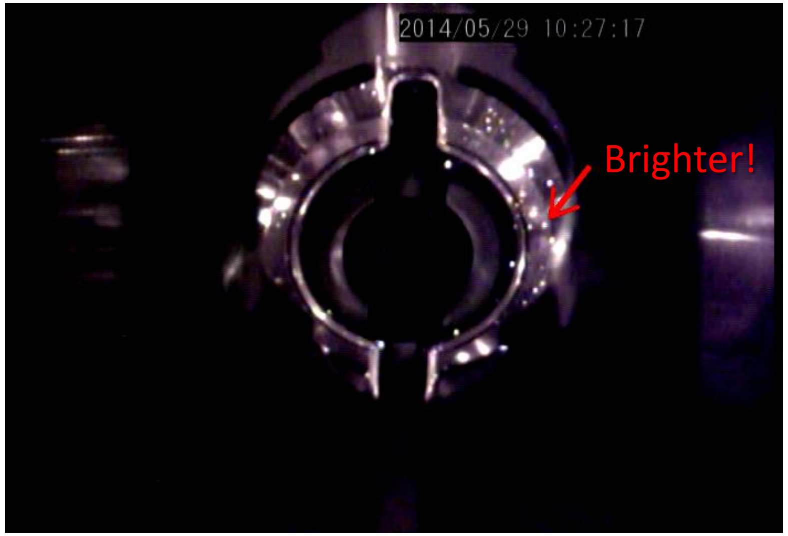
Example of Cavity-Breakdown Events (6)

V_c = 0.80 MV (E_{acc}=3.1 MV/m)

4 frames before

3 frames (0.1 s) before

2 frames before



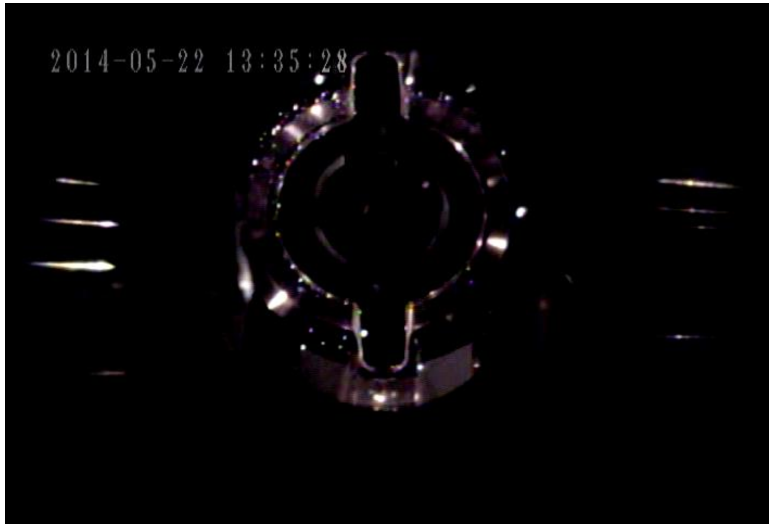
1 frame before

Cavity Breakdown!

1 frame after → It disappeared.

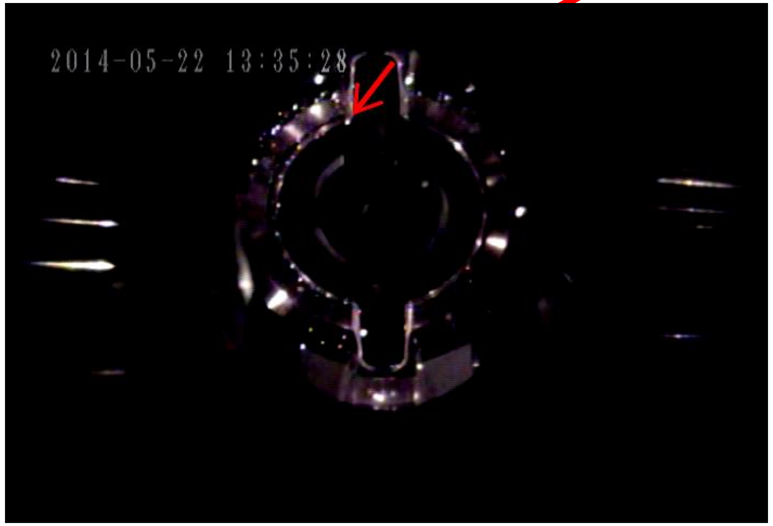
Example of Cavity-Breakdown Events (7)

46 frames before



45 frames (1.5 s) before

A small bright spot appeared!



…

→ It disappeared.

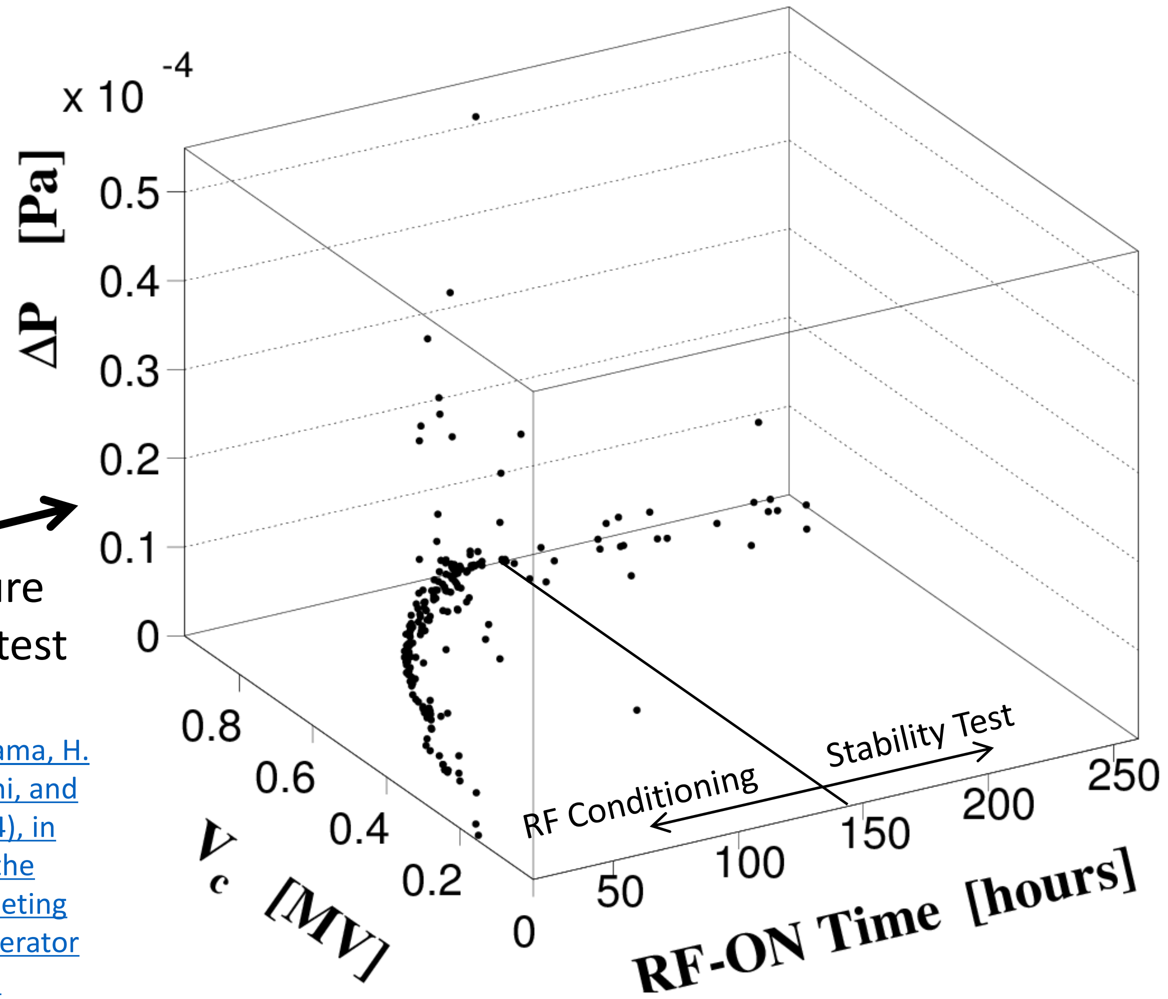
V_c = 0.55 MV (E_{acc} = 2.1 MV/m)

…

1 frame before

Cavity Breakdown!

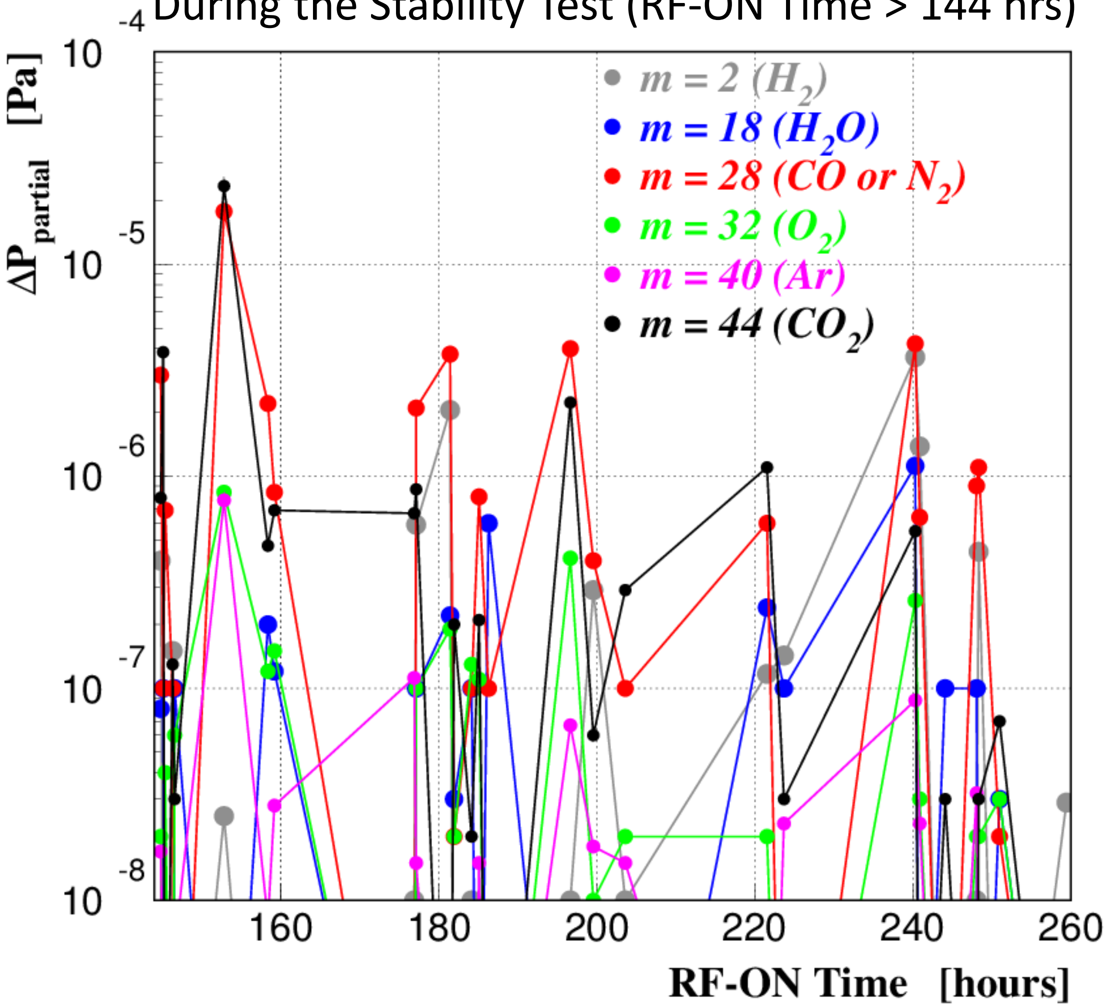
Vacuum Pressure Rise at the Moment of Cavity Breakdown



Vac. pressure during HG test

T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino (2014), in Proceedings of the 11th Annual Meeting of Particle Accelerator Society of Japan (Paper ID: SAP050).

During the Stability Test (RF-ON Time > 144 hrs)



Pressure rise much lower than the vacuum pressure in the cavity during the HG test

- ✓ Main components: CO, CO_2
- ✓ H_2 only when increasing Vc

Conclusions on this Breakdown Study

for DR Cavity No.2 (508.9 MHz, CW, single-cell)

- We observed **clear stable bright spots** on the endplates during the HG operation.
  - Most of the bright spots had maintained their intensity with no significant effects on the HG operation as long as they remained stable.
  - Even after RF conditioning (during the stability test at V_c = 0.90 MV)
- We have demonstrated that decrease in the number of bright spots after explosion is a **significant component of RF conditioning** of the cavity.
- We observed **sudden appearance of bright spots** immediately before breakdowns.
  - The time scale from the sudden appearance to the breakdown is ~1 sec or shorter.
  - Stimulates our interest in the microscopic dynamics of the generation, growth, and explosion of bright spots and their correlation with RF conditioning effects and cavity breakdown rates.
- **From the radiation-dose measurements**
  - The total field emission became the minimum level at the end of RF conditioning.
  - The stable bright spots which exploded were not dominant continuous field emitters before the explosions during the stability test.
- **More advanced study** is on-going, supported in part by MEXT KAKENHI Grant-in-Aid for Scientific Research (B).

Thank you for your attention!