RF Accelerating Cavity for SuperKEKB Damping Ring and its Breakdown Study

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on behalf of SuperKEKB-RF / ARES Cavity group

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

This presentation is based on the following papers:
- T. Abe, et al., Paper ID: THLR06, in Proceedings of the 9th Annual Meeting of Particle Accelerator Society of Japan, Aug. 2012
- T. Abe, et al., Paper ID: SAP057, in Proceedings of the 10th Annual Meeting of Particle Accelerator Society of Japan, Aug. 2013
- T. Abe, et al., Paper ID: SAP050, in Proceedings of the 11th Annual Meeting of Particle Accelerator Society of Japan, Aug. 2014

Updated version to be submitted to PRST-AB

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2015-06-19

New Positron Damping Ring (DR)

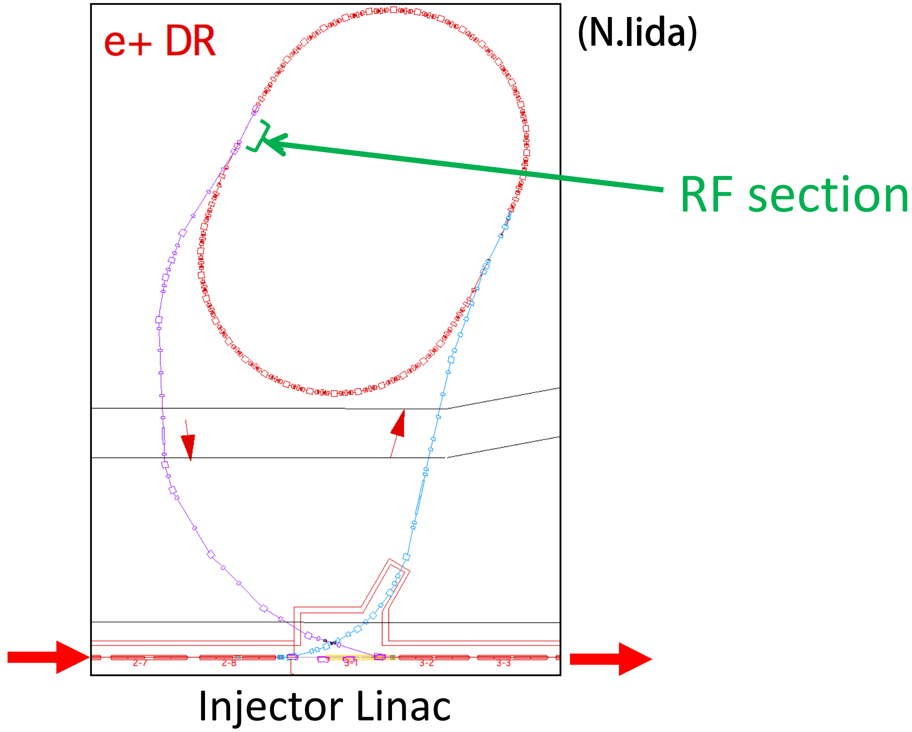
for low-emittance beam injection to SuperKEKB / LER(e^+)

Parameters of the Damping Ring

Parameter	Value	Unit	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



- ✓Construction of the tunnel and facility finished
- ✓Installation of magnets and vacuum chambers this year
- ✓Installation of RF cavities next year

DR Facility on the Ground

Building facade

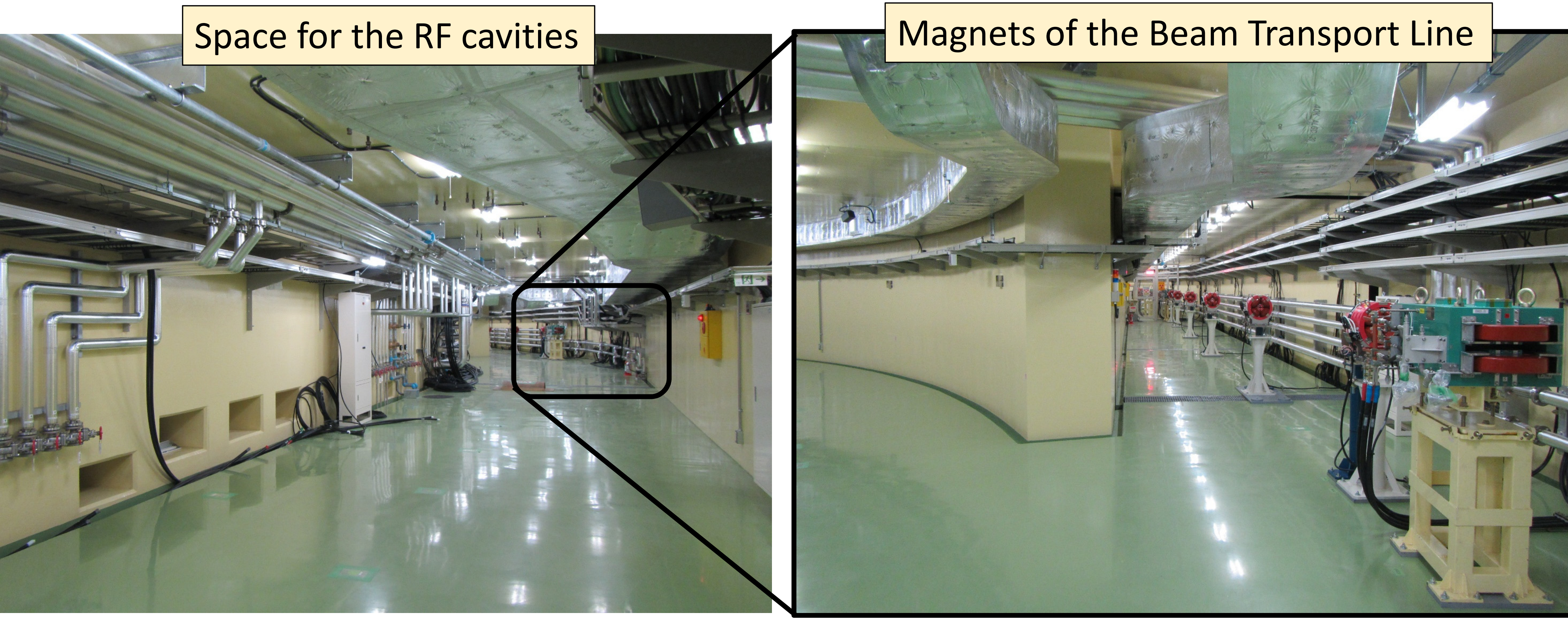
(Photos taken on 2015-06-12)

Space for the 1MW CW klystron

Inside the building

Local control room

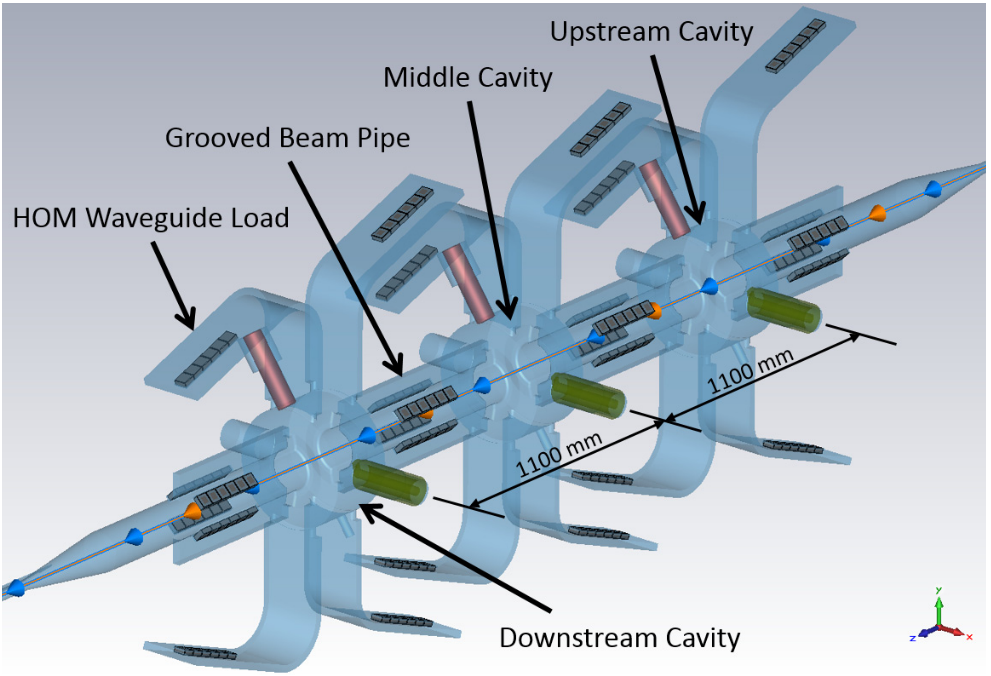
In the DR Tunnel

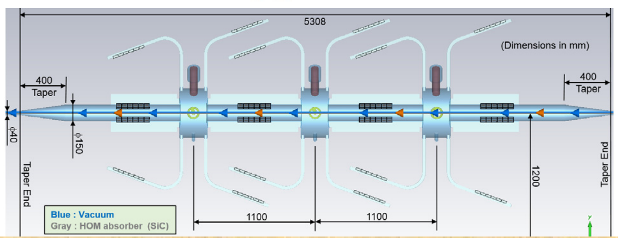


(Photos taken on 2015-06-12)

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.



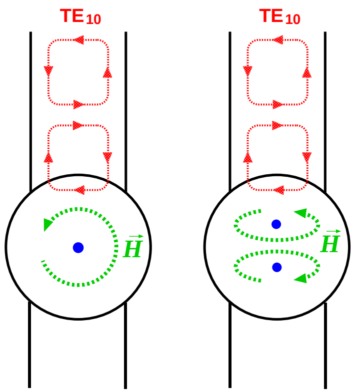


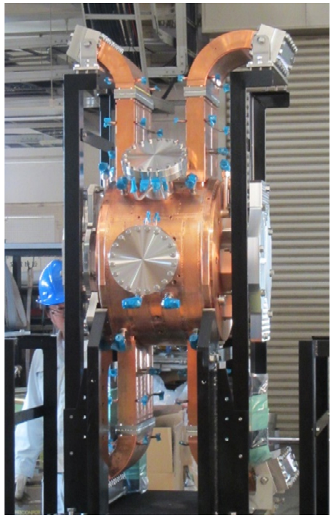
- RF operation frequency: 508.9MHz
  - Same as that of the MRs
- Based on the HOM-damped structure of the successful ARES cavity system
- Three cavities at max. to be installed in a space originally designed for one cavity (~3m in the beam direction)
  - Total V_c = 2.4MV at max.
- Apart from the CC 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.

Two Types of HOM Damped Structures

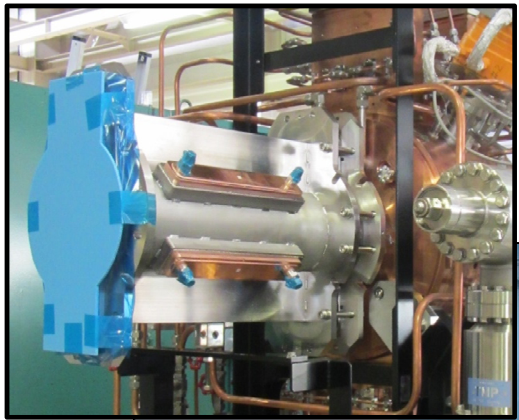
Proven by the long-term successful operation at KEKB

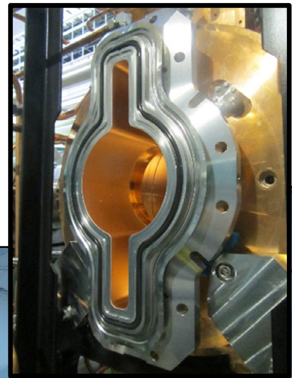
HOM waveguides for damping:
✓Monopole HOMs
✓Vertically-polarized dipole modes



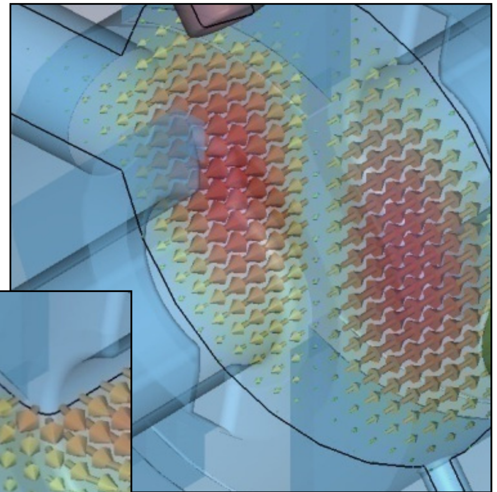


Grooved Beam Pipe (GBP) for damping:
✓Horizontally-polarized dipole modes

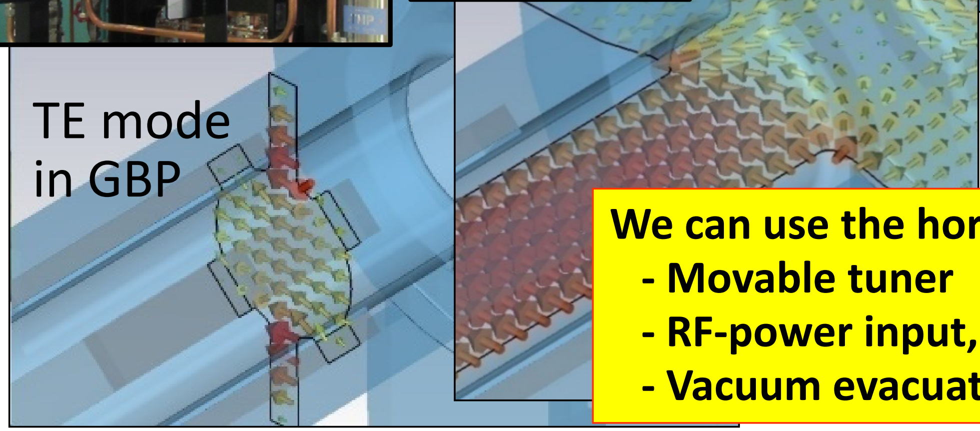




TM$_{110}$ in Cavity



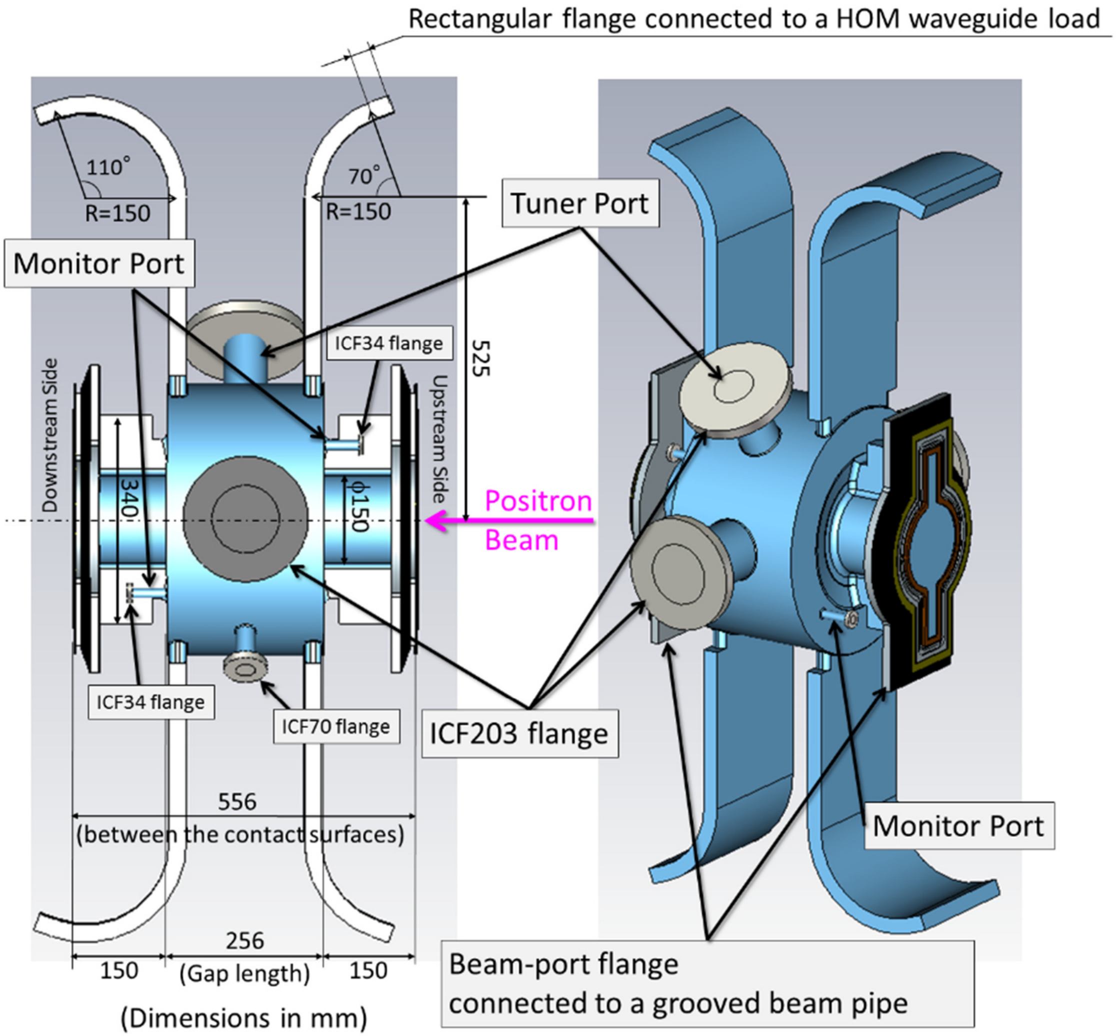
TE mode in GBP



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)



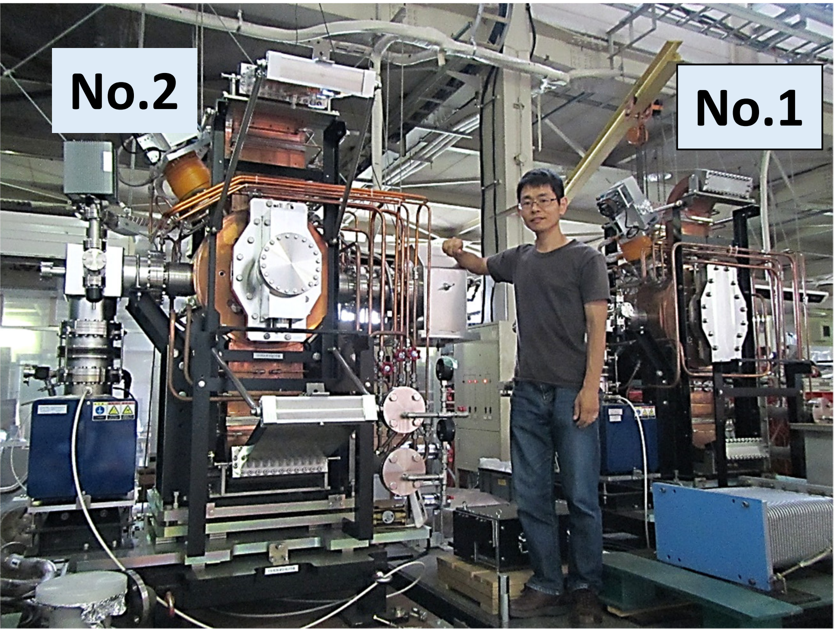
UHF CW Single-Cell NC Cavity

RF operation frequency	508.9 MHz
R_{sh}/Q_0	$150\,\Omega$
Q_0	≈ 30000 (97 %IACS)
Gradient required in operation	$V_c = 0.7$ MV ($E_{acc} = 2.7$ MV/m)
Gradient in specification	$V_c = 0.8$ MV ($E_{acc} = 3.1$ MV/m)
Wall-loss power at $V_c = 0.7$ MV	≈ 110 kW
Wall-loss power at $V_c = 0.8$ MV	≈ 140 kW

- Made of OFC (class1)
- Gap length: 256 mm
- $E_{surf}/E_{acc} = 3.8$ (max) →

$E_{surf} < \sim 13$ MV/m

DR Cavities



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: electro-polishing
2. **Cavity No.2** fabricated in JFY2013
   - Surface protection of the endplates: electro-polishing

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 Electro-Polished (EP).

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

Before EP

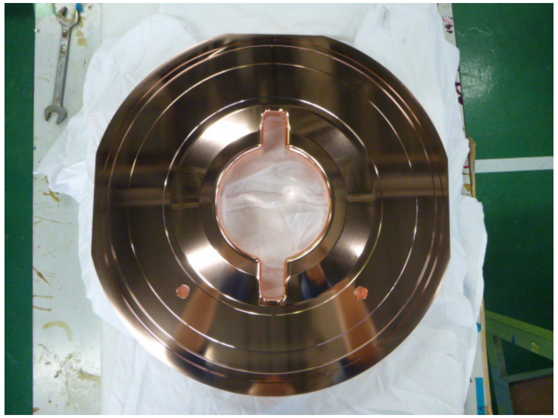
R_a=1.5μm, R_y=8μm

After EP

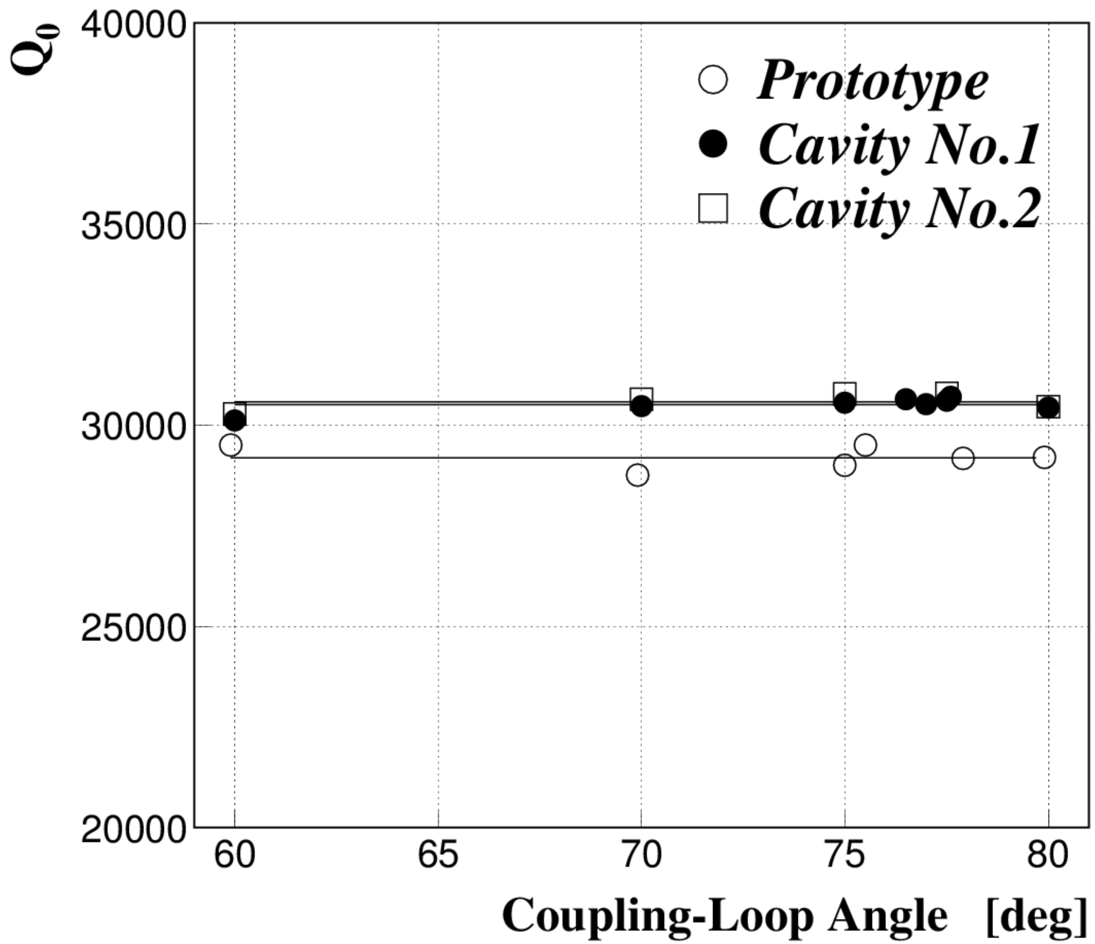
R_a=0.2μm, R_y=1μm (< δ = 3μm)

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

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

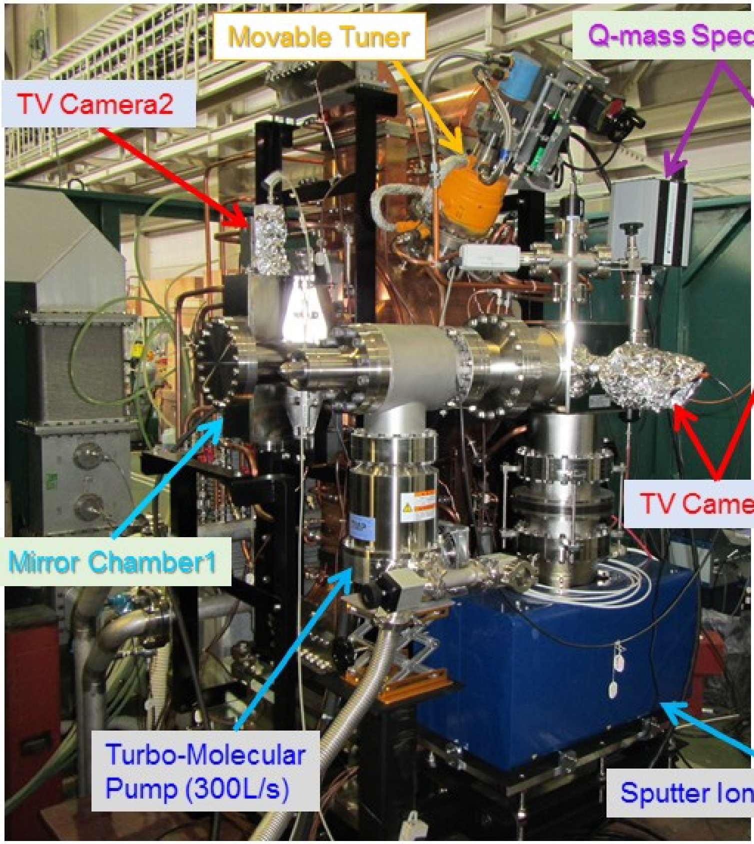
(Note: No EP applied to the barrel)

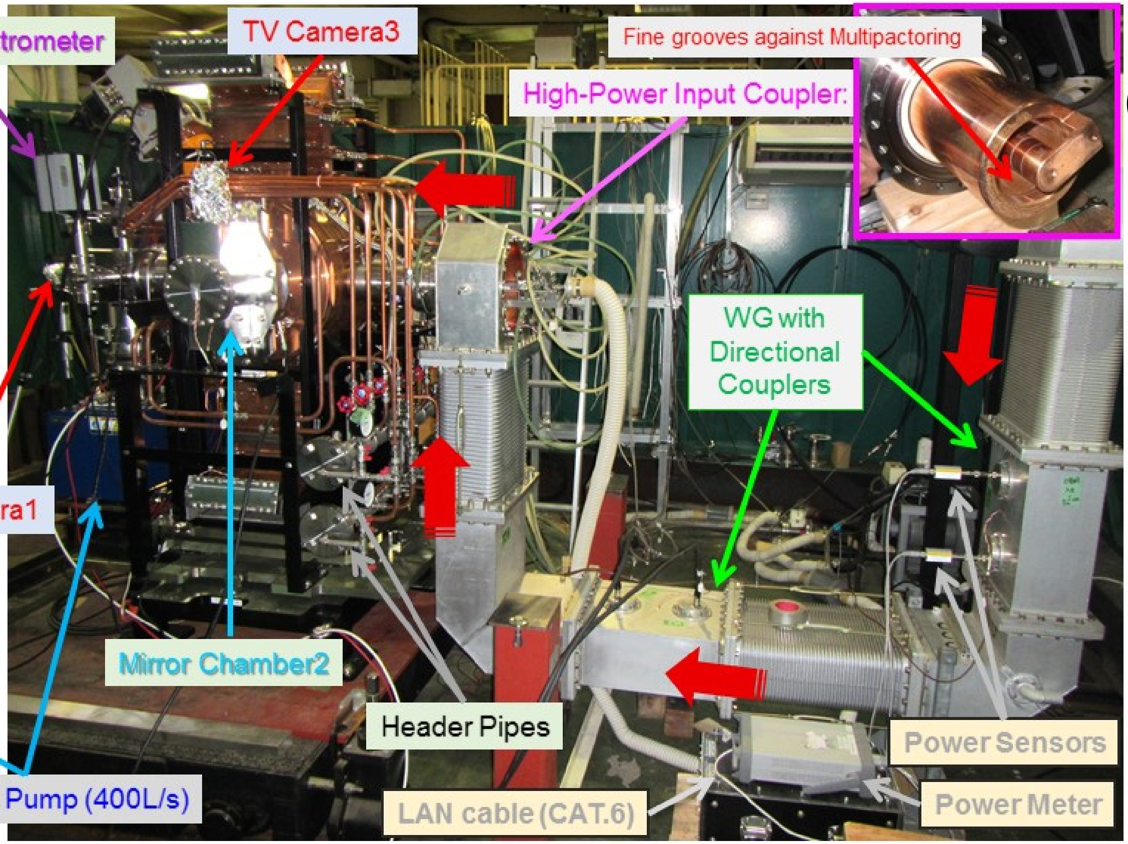
Breakdown Study based on Direct In-Situ Observation of Inner Surfaces of the DR Cavity No.2

which has the following 3 characteristics:

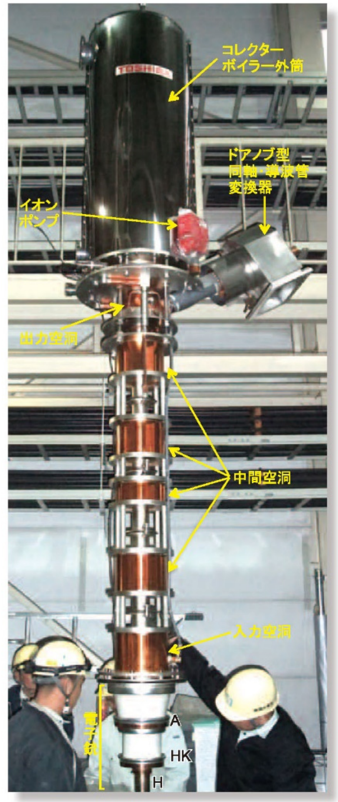
1. **Exhaustive** observation
   - To capture all of cavity breakdowns
2. **Multi-directional** and **wide-field** observation
   - To witness the origin of the cavity breakdown
3. **Quantitative** data analyses
   - What is majority and significant?

Setup of High-Gradient (HG) Test

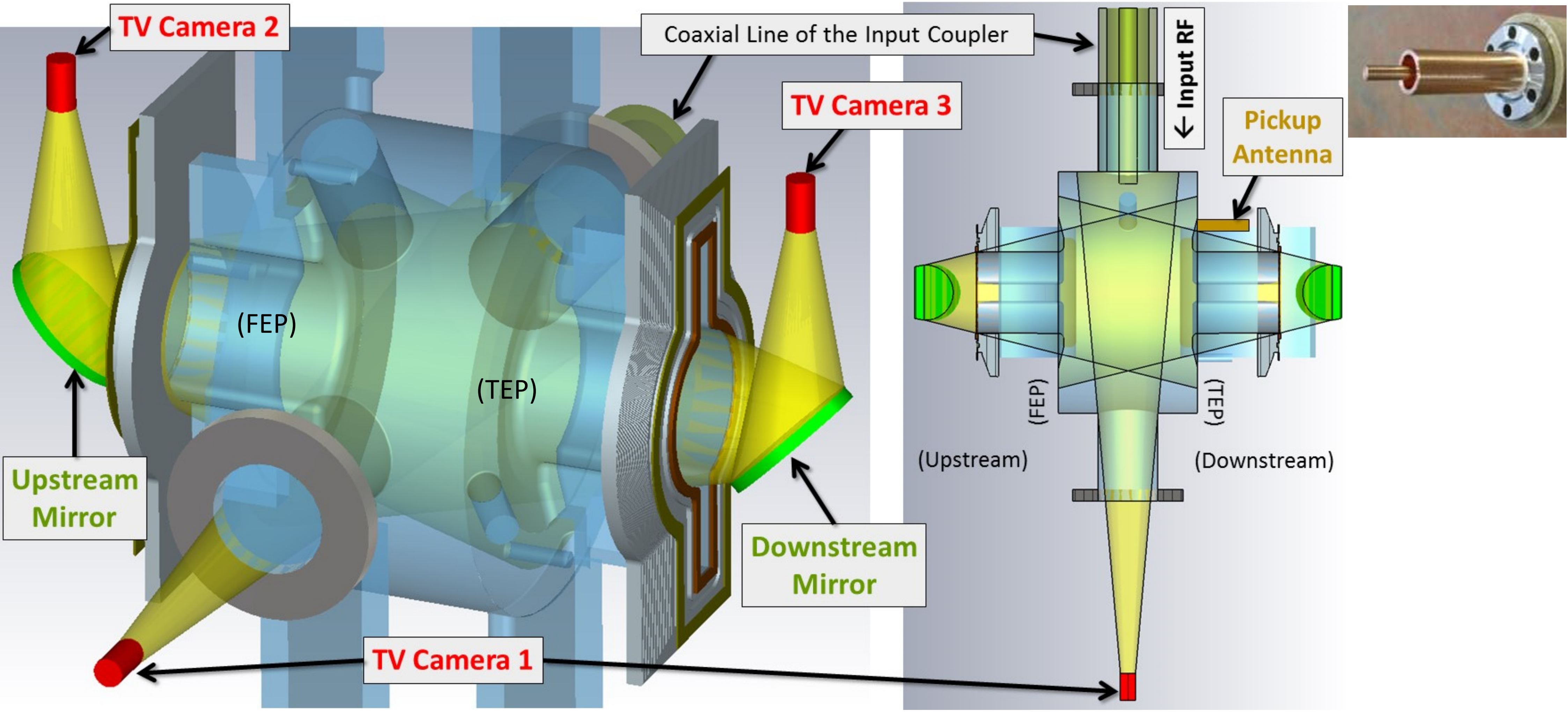




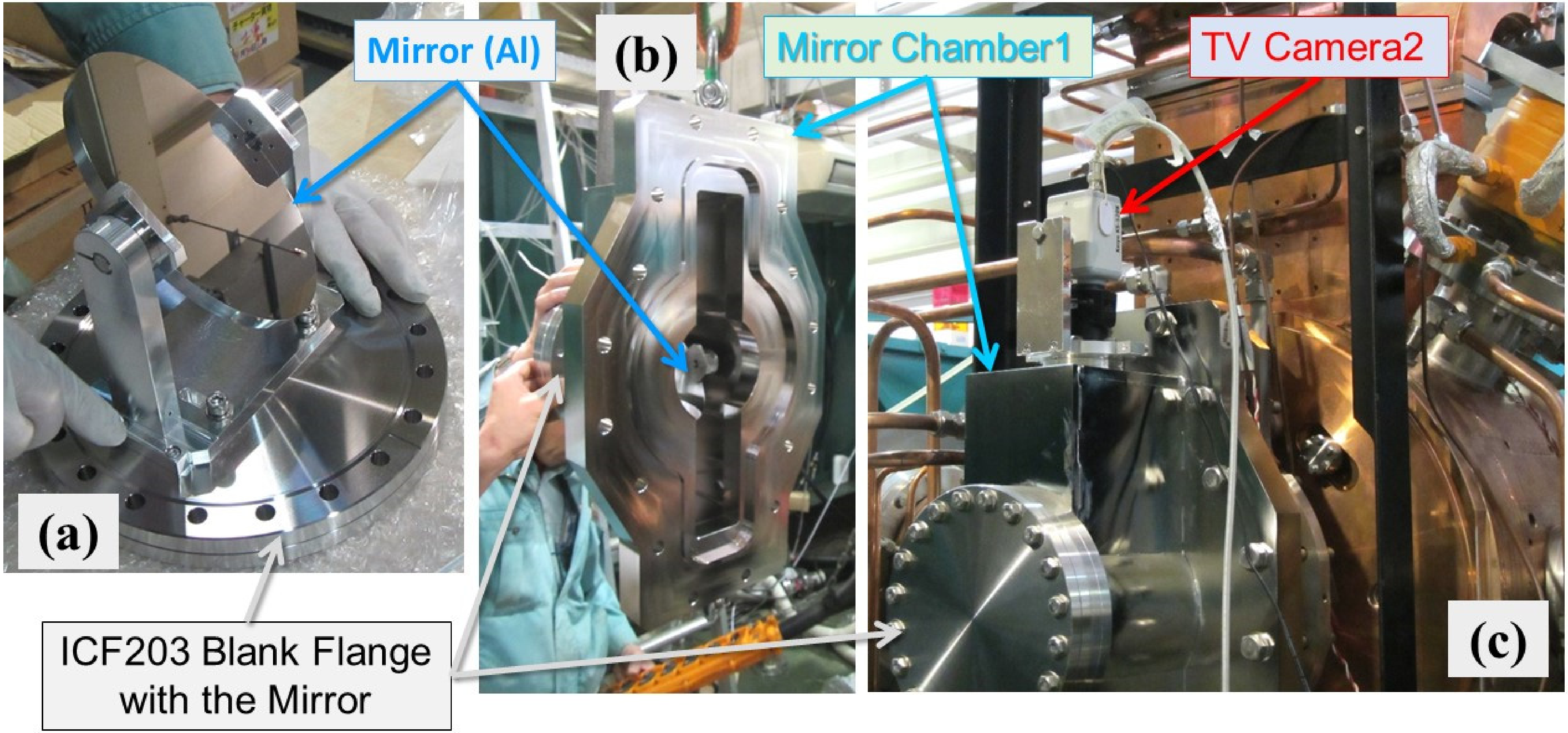
Toshiba
CW Klystron
E3732
(1MW, 508.9 MHz)



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



Mirror Chamber



TV Camera

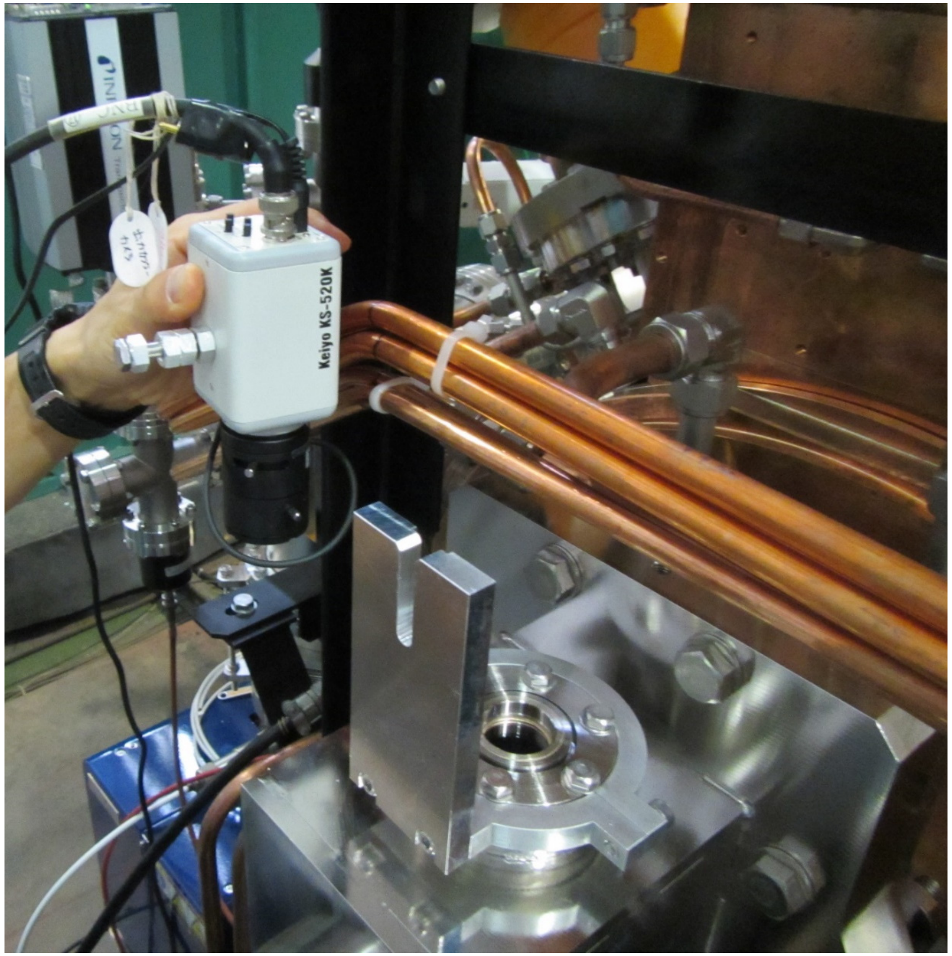
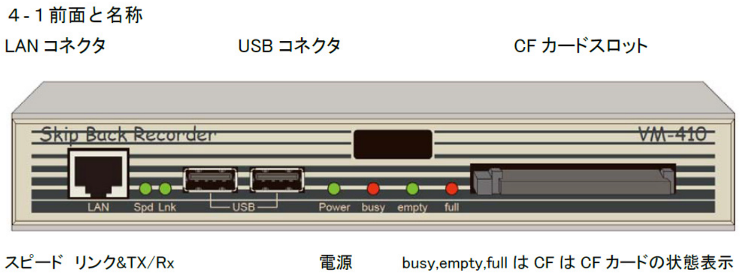
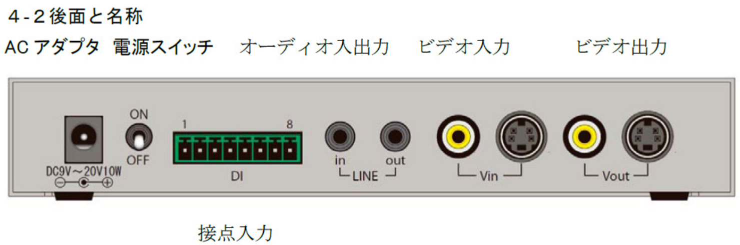


Image Sensor	1/3-inchi CCD
Minimum illuminance of object	0.05 lux (color)
S/N	> 52 dB
Gross Sensor Resolution	$52x10^4$ pixels
Output format	NTSC
Frame rate	30 fps
Price	About 20,000 YEN

Skip Back Recorder





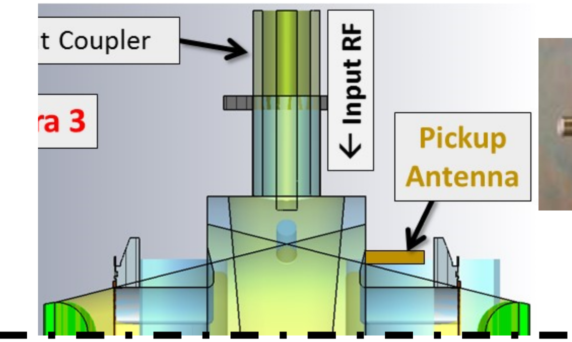
- ✓OS: Linux
- ✓**Input video: NTSC**
- ✓**<u>Trigger: RF switch “ON → OFF”</u>**

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. Interlock system works 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



ICF34 flange

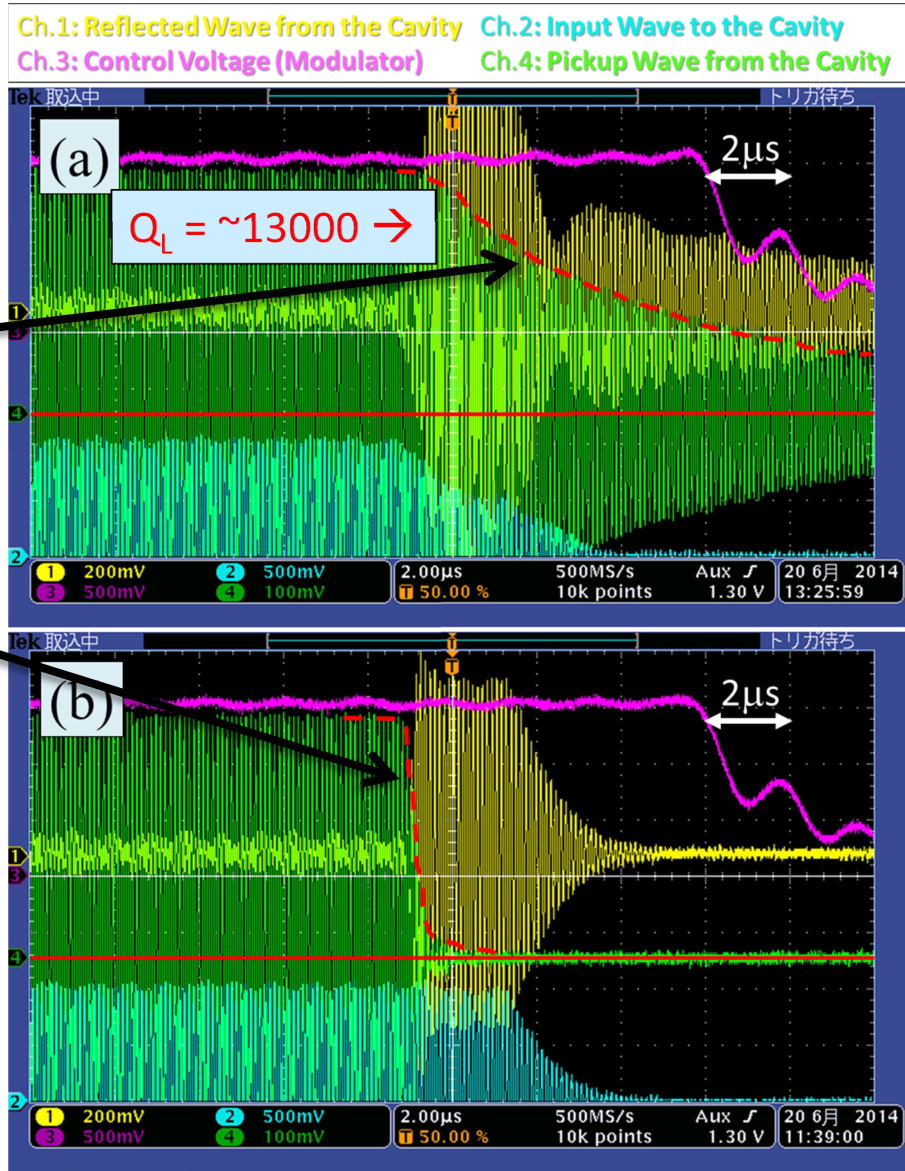
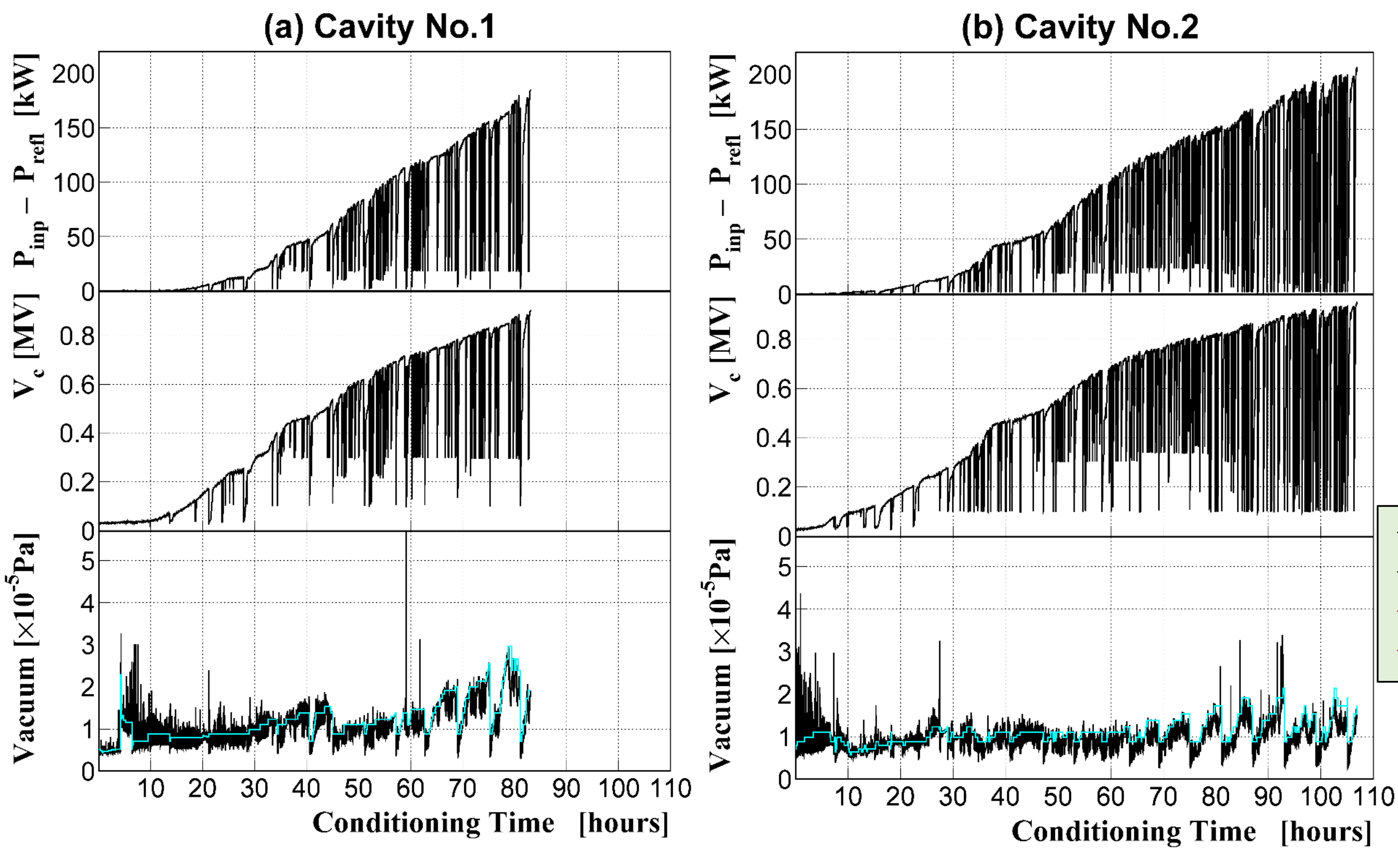


FIG. 6: Waveforms of the oscilloscope displayed with a time span of 20 μs (2 μs/div). The red dashed curves indicate the envelope of the 508.9 MHz pickup signal from DR Cavity No.2, and the red solid lines indicate its zero amplitude. (a) When the RF switch was turned off due to a reason related to the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

RF-Conditioning Histories

✓83 hours to reach 0.90MV/cav

✓ 95 hours to reach 0.90MV/cav
✓107 hours to reach 0.95MV/cav

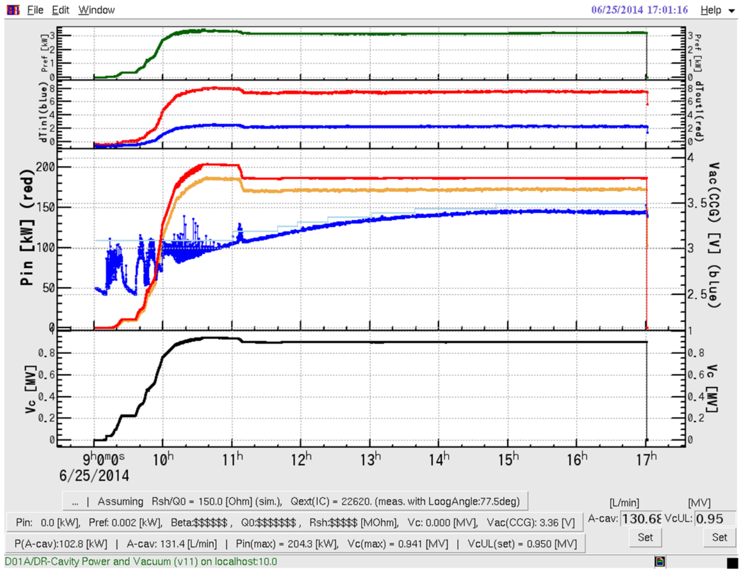


The light blue lines indicate the reference vacuum pressure specified by the computer controlled automatic aging.
If the vacuum pressure is higher than the reference, P_{in} is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{in} is slightly stepped up as 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: $P_{wall} = P_{in} - P_{refl} = \sim 0.99 \times P_{in}$
- ✓ **Cavity No.2 reached 0.95MV/cavity successfully.**
- ✓ **Comparable conditioning speeds btwn Cavity No. 1 and 2**

After the RF Conditioning completed, Stability Test with Keeping $\underline{V_c = 0.90\ \mathrm{MV/cav}}$

Example of the daily histories →



> $\underline{V_c = 0.70\ \mathrm{MV/cav}}$
(required for DR operation)

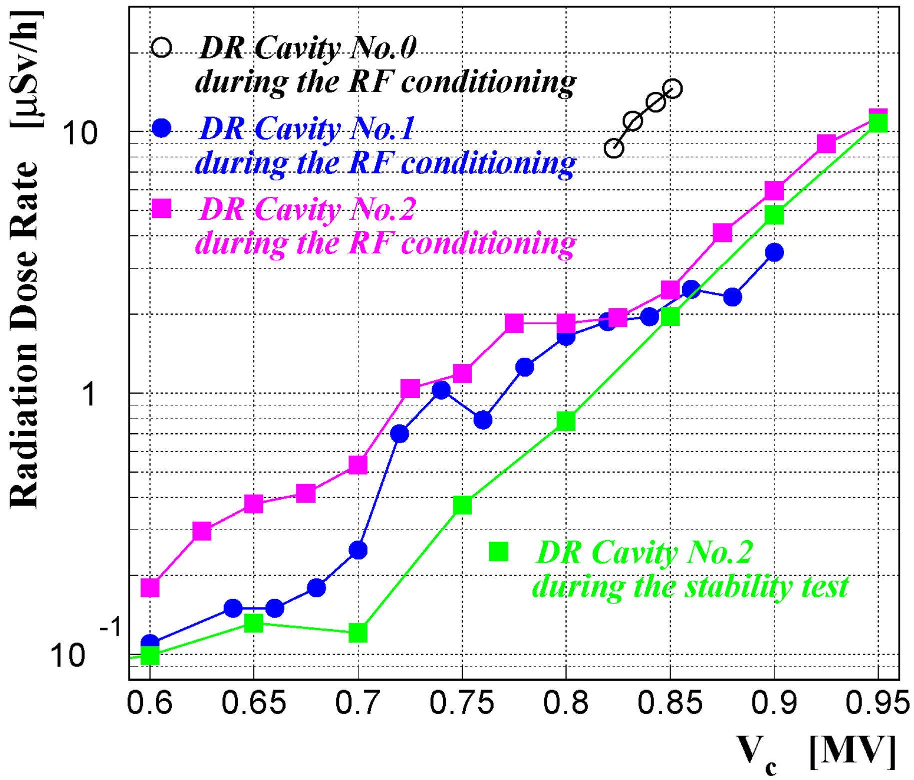
- Cavity No.1: 3 breakdowns for 14.5 hours in total = **$5.0^{+4.8}_{-2.7}$ /24hrs**
- Cavity No.2: 11 breakdowns for 80 hours in total = **$3.3^{+1.3}_{-1.0}$ /24hrs**

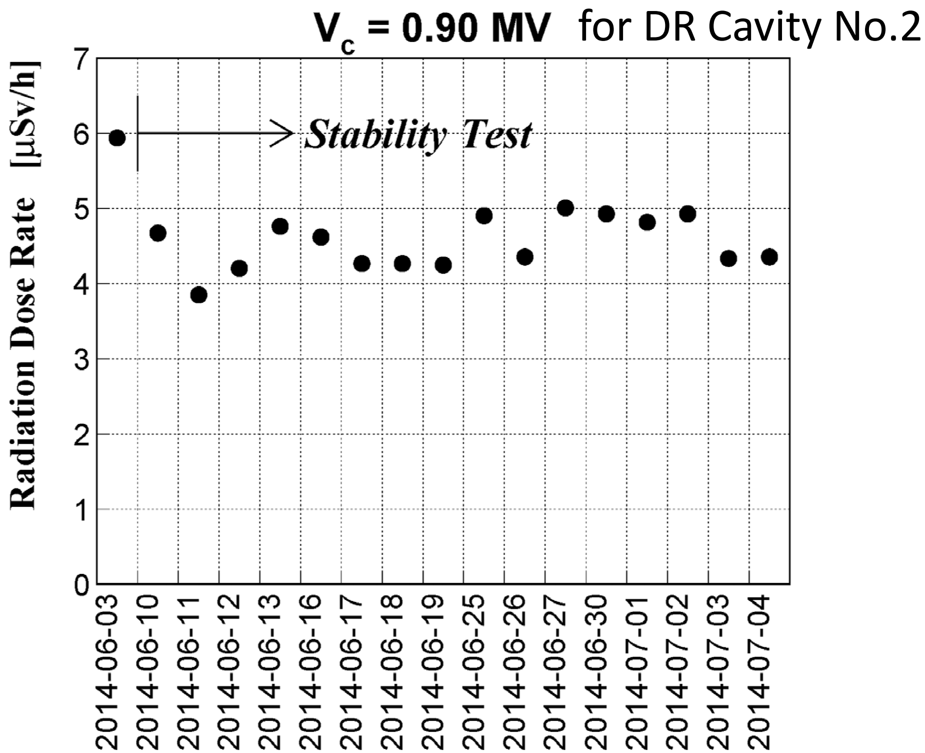
Same stability between DR Cavity No. 1 and 2 within the statistics

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

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

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

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

⇓

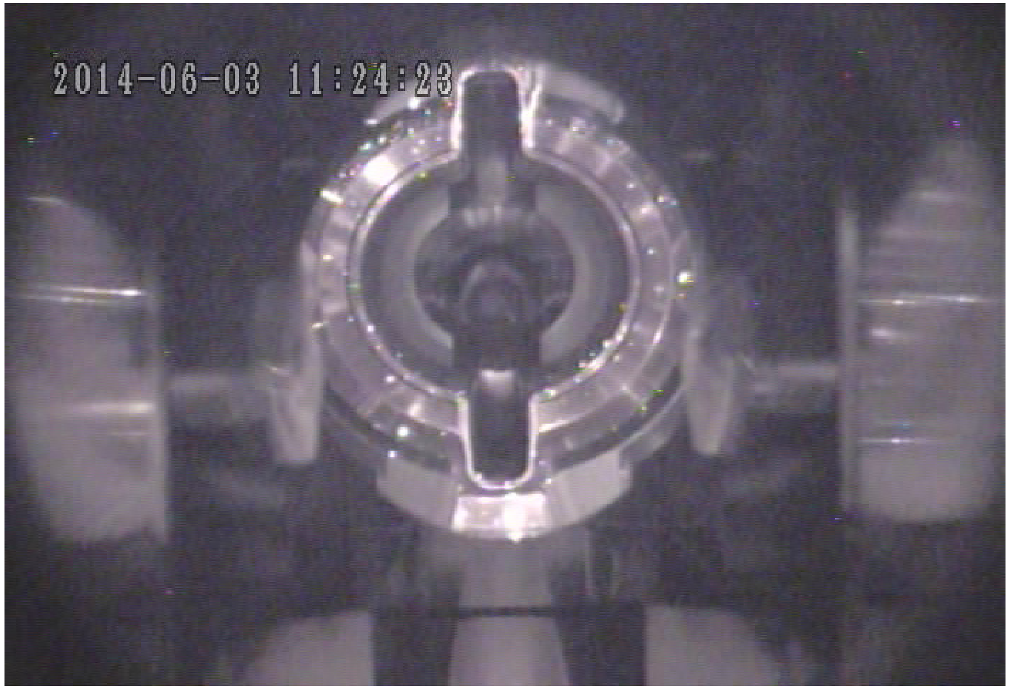
No cavity's particular problems or characteristics found

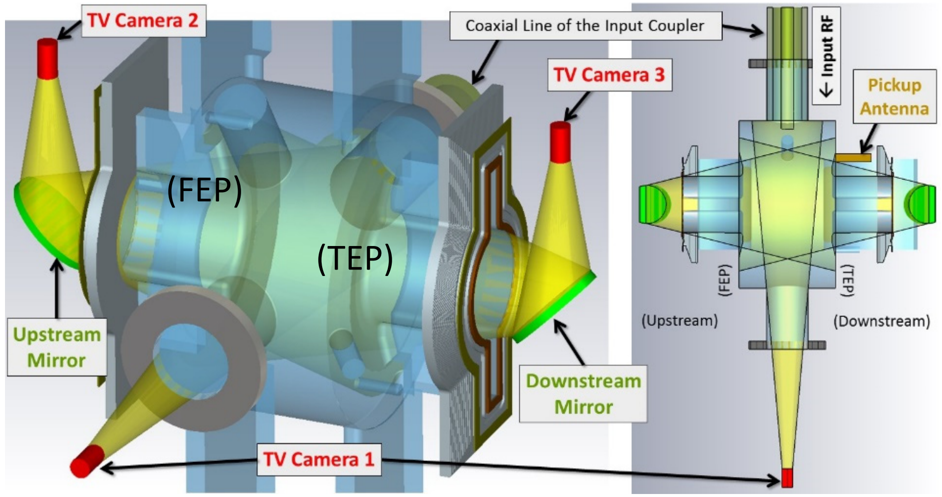
⇓

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

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

Example of the Recorded Videos





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

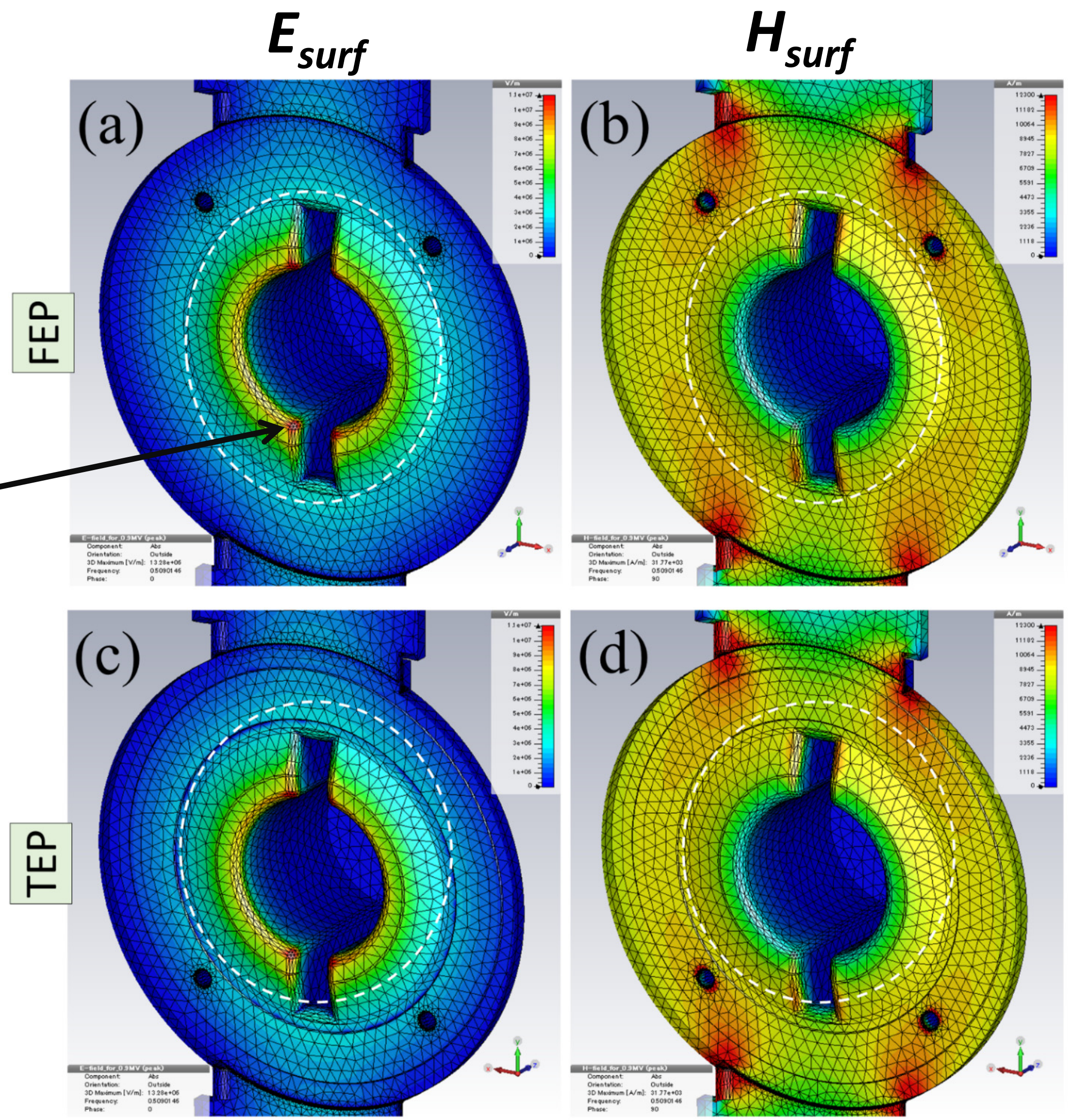
Clear bright spots observed on the endplates during the RF operation

- ➢ **Keeping their intensity**
- ➢ **Giving no significant effects on the RF operation as long as the intensity remaining stable**

Surface field on the Endplates

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

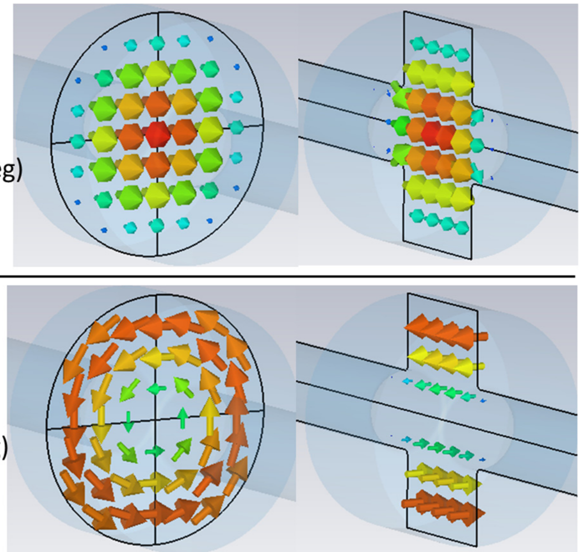
E-field_for_0.9MV (peak)	
Component:	Abs
Orientation:	Outside
3D Maximum [V/m]:	13.28e+06
Frequency:	0.5090146
Phase:	0



Accelerating mode: TM_{010}

E
(Phase: 90deg)

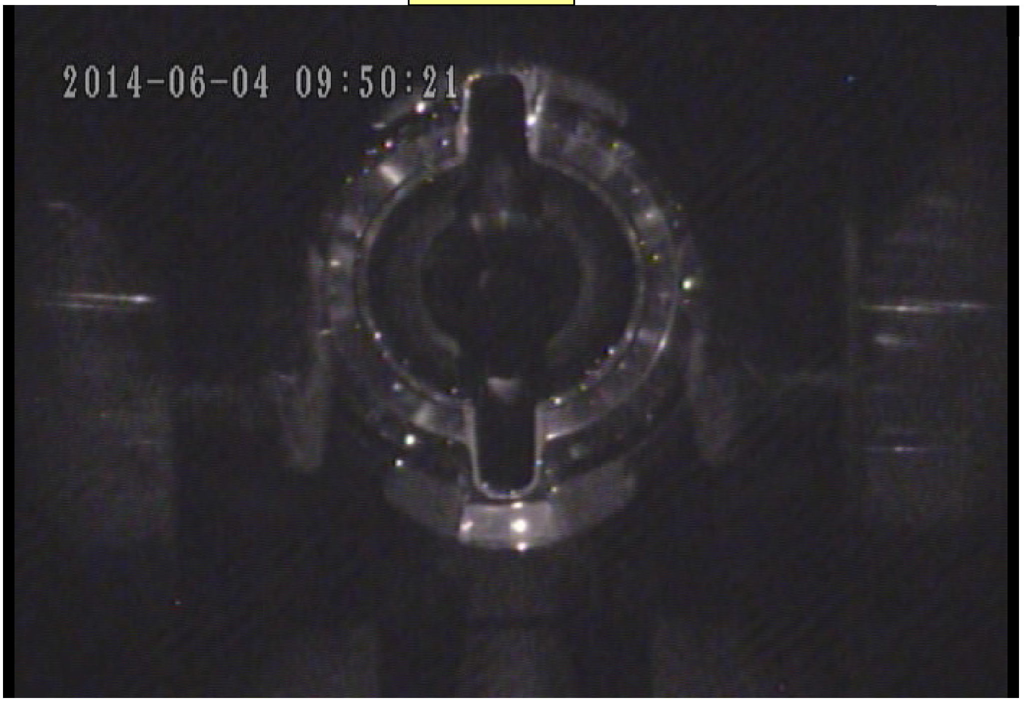
H
(Phase: 0deg)



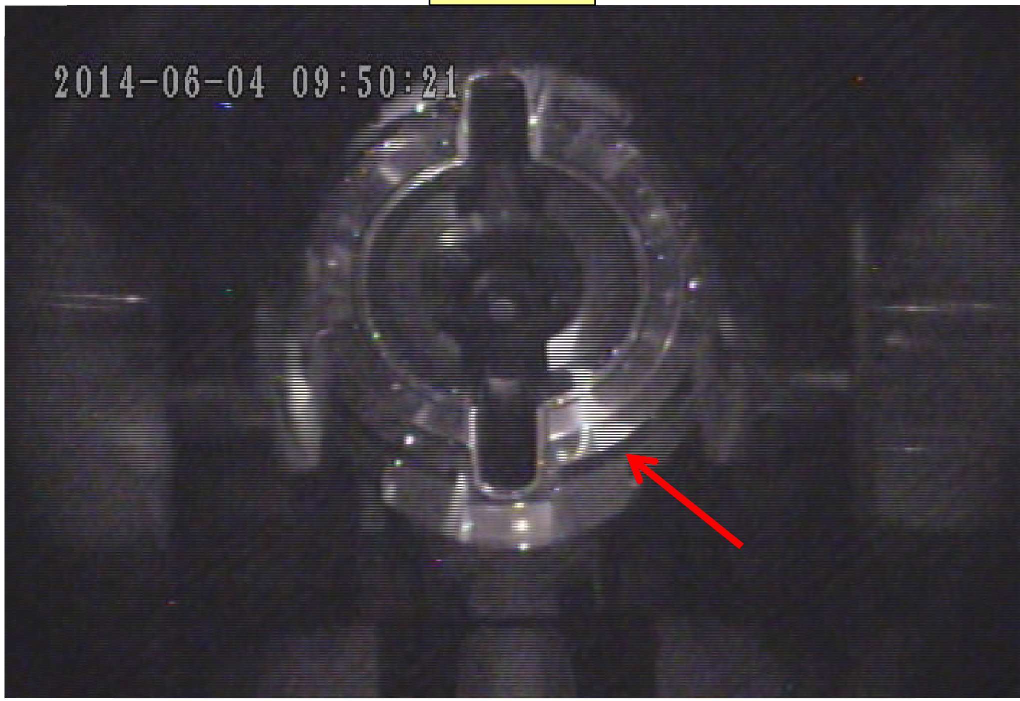
Example of Cavity-Breakdown Events (1)

Flash!

$T < 0$



$T = 0$

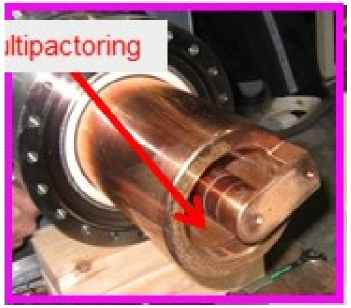


Cavity Breakdown!

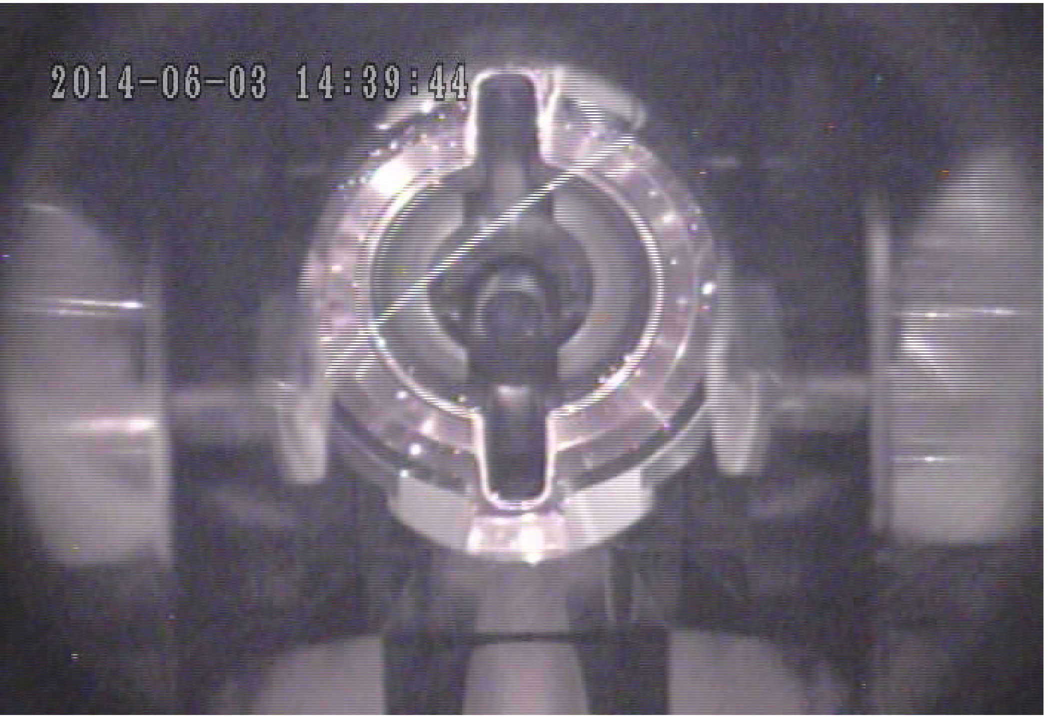
at V_c=0.76MV (E_{acc} = 3.0 MV/m)

Example of Cavity-Breakdown Events (2)

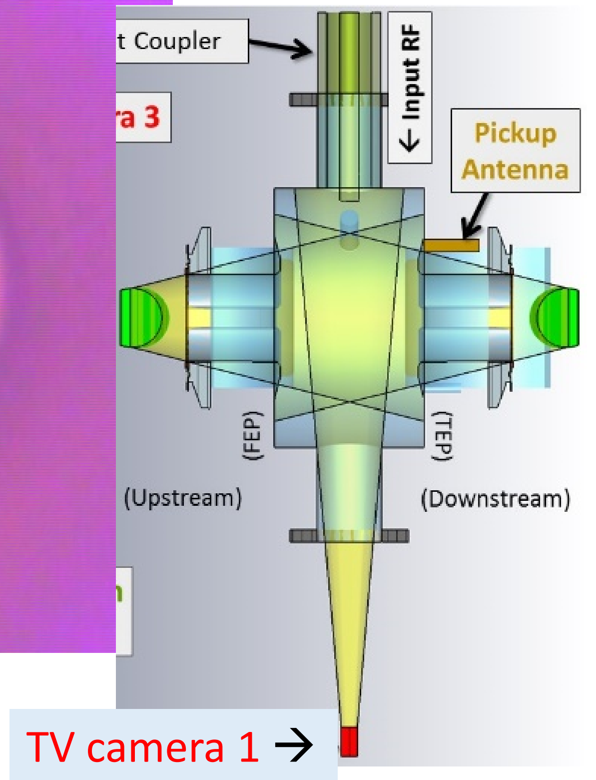
Lightning!



Captured by the TV camera 3



Captured by the TV camera 1



Cavity Breakdown at V_c = 0.90 MV (E_{acc} = 3.5 MV/m)

By the Statistical Analysis

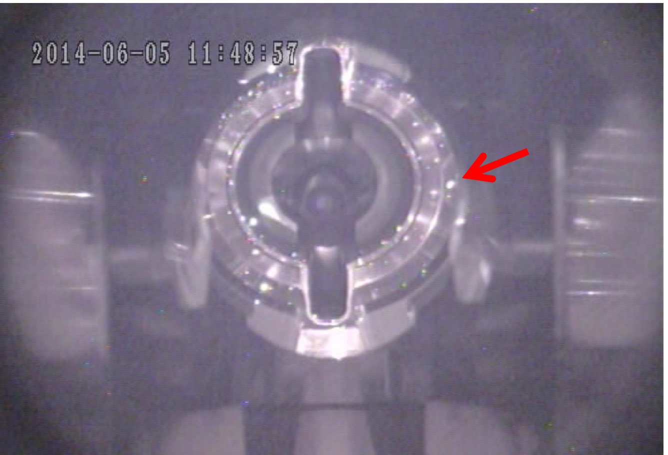
- We have found that such pyrotechnical phenomena are minority in the cavity-breakdown events using those TV cameras.

- What is majority?

Example of Cavity-Breakdown Events (3)

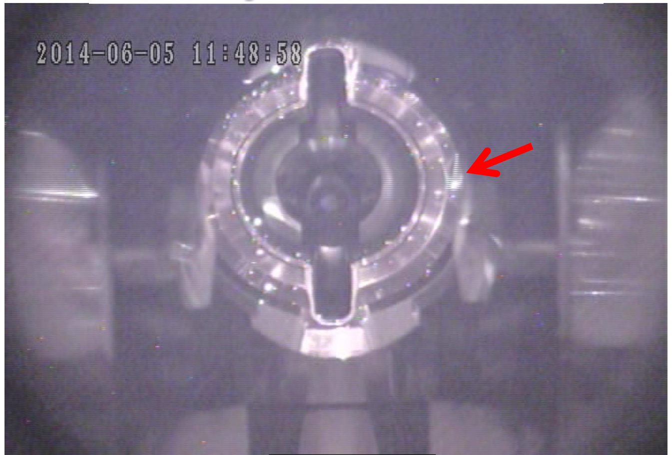
Spot-type explosion of a bright spot which had kept its intensity until the explosion, followed by disappearance

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



$T < 0$

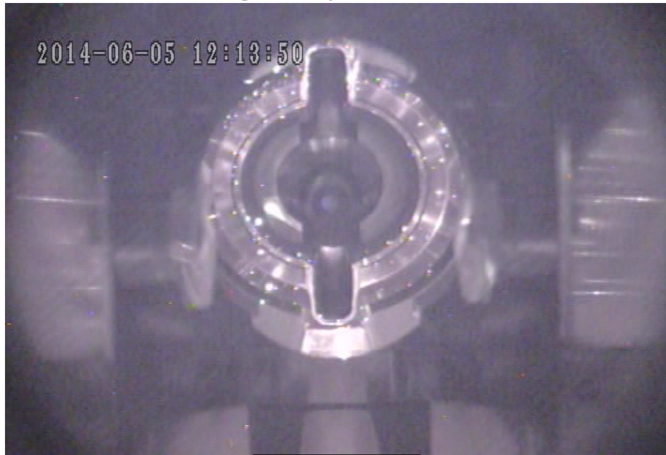
Cavity Breakdown!



$T = 0$

Mini-Supernova

No bright spot there!



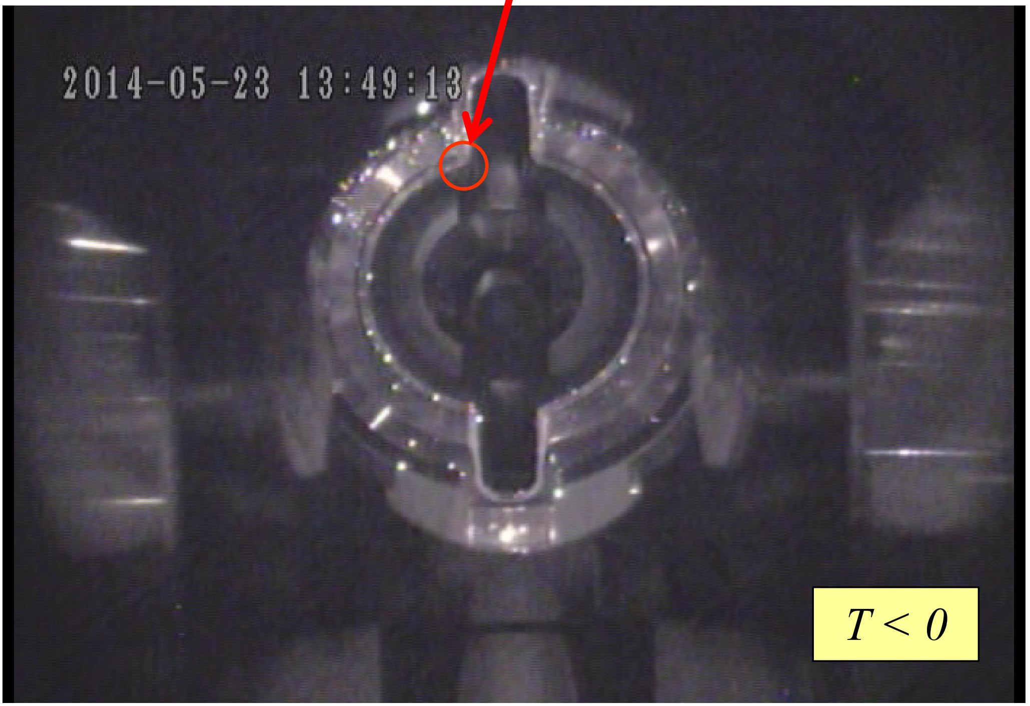
$T > 0$

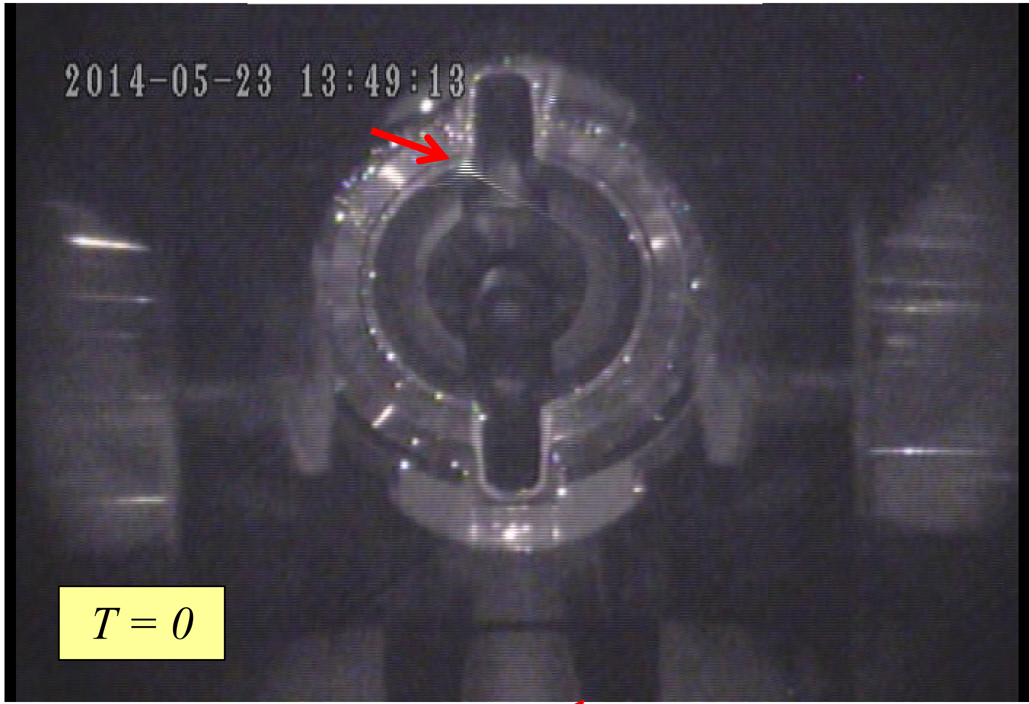
Example of Cavity-Breakdown Events (4)

Spot-type explosion without a 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

(BS: Bright Spot)

TABLE IV: Breakout of the cavity-breakdown events. The numbers enclosed in square brackets (parentheses) indicate proportions to the cavity-breakdown events (events with any abnormality observed).

Period	Spot-type explosion with a BS	Spot-type explosion without any BS	Non-spot-type flash	Non-spot-type lightning(s) only	Others
Conditioning	44 [24.4%] (30.8%)	72 [40.0%] (50.3%)	4 [2.2%] (2.8%)	14 [7.8%] (9.8%)	9 [5.0%] (6.3%)
Stability test (total	7 [28.0%] (35.0%)	9 [36.0%] (45.0%)	3 [12.0%] (15.0%)	1 [4.0%] (5.0%)	0
Stability test ($V_c = 0.90\,\mathrm{MV}$)	5 [45.5%] (55.6%)	2 [18.2%] (22.2%)	1 [9.1%] (11.1%)	1 [9.1%] (11.1%)	0

More than 50% 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).

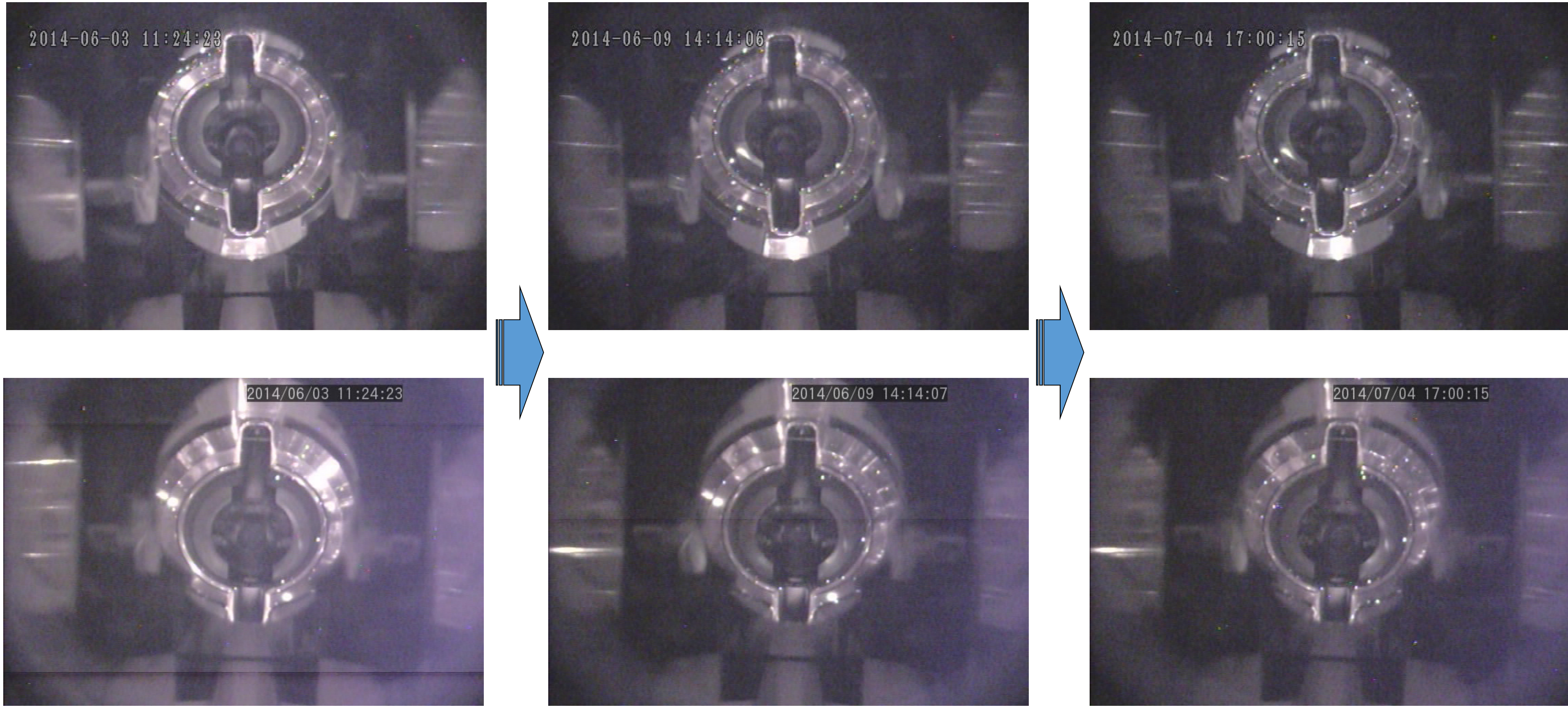
In 20% (or higher) of the cavity-breakdown events, the bright spots exploded, and then disappeared.

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

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

FEP

TEP

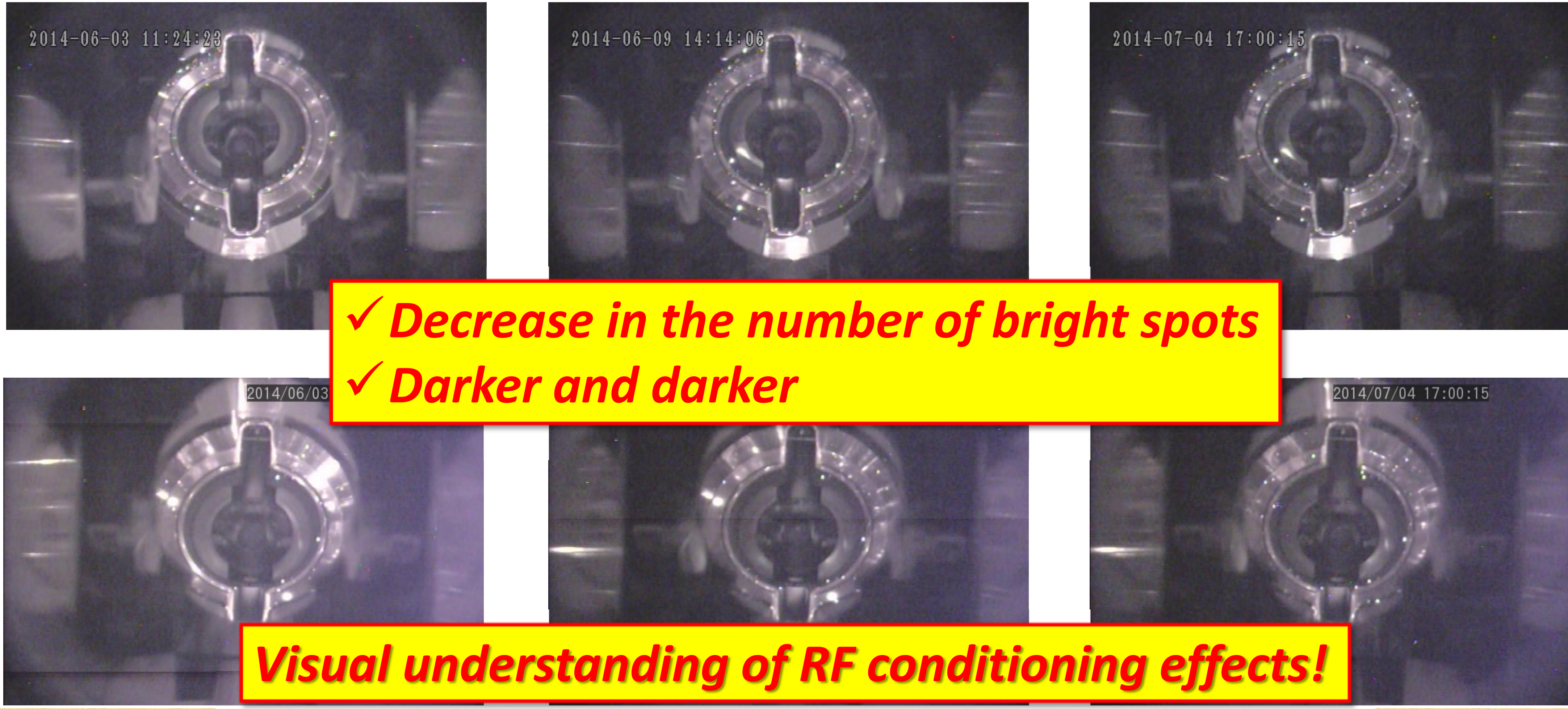


Bright Spots @ V_c = 0.90 MV (E_{acc} = 3.5 MV/m)

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

FEP

TEP



✓ ***Decrease in the number of bright spots***
✓ ***Darker and darker***

Visual understanding of RF conditioning effects!

Counting Cavity Breakdown Events for each Category

(BS: Bright Spot)

Period	Sudden BS appearance
Conditioning	6 [3.3%] (4.2%)
Stability test (total)	0
Stability test ($V_c = 0.90\,\mathrm{MV}$)	0

TABLE VI: Number of cavity-breakdown events with sudden BS appearance. The numbers enclosed in square brackets (parentheses) indicate proportions to the total number of the cavity-breakdown events (events with any abnormality observed).

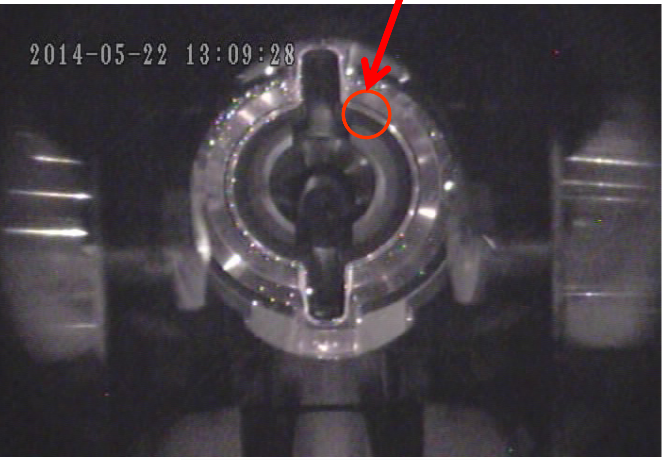
For 3% of the cavity-breakdown events,
we observed sudden appearance of bright spots
in a time range of the last 2 seconds before the explosions at the breakdowns.

Example of Cavity-Breakdown Events (5)

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

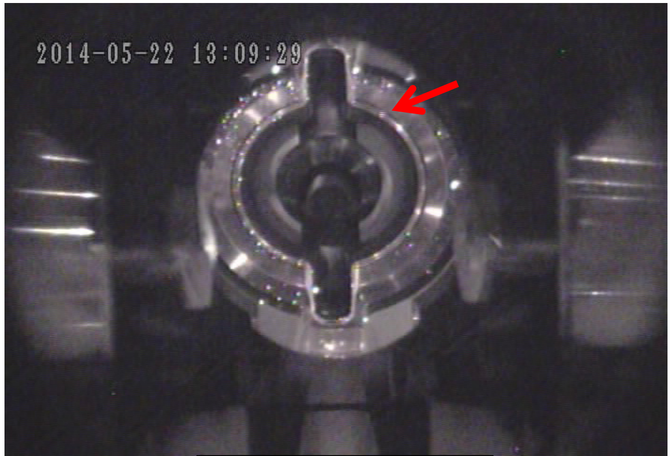
V_c = 0.56 MV (E_{acc} = 2.2 MV/m)

No bright spot here



$T < -0.03\ s$

A new bright spot appeared!



$T = -0.03\ s$

Cavity Breakdown!

$T = 0$

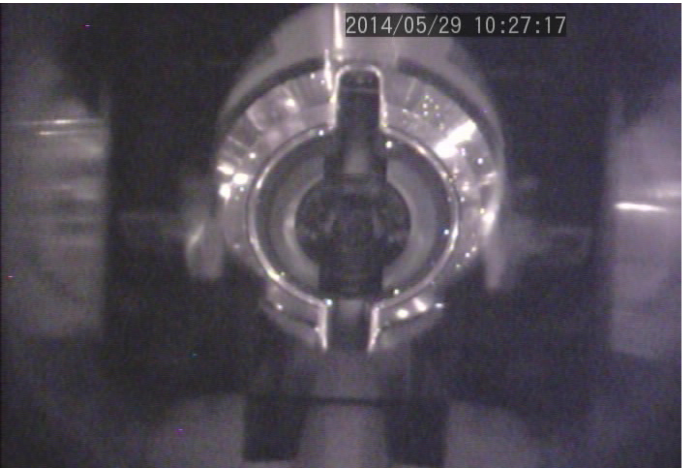
1 frame before

Explosion!

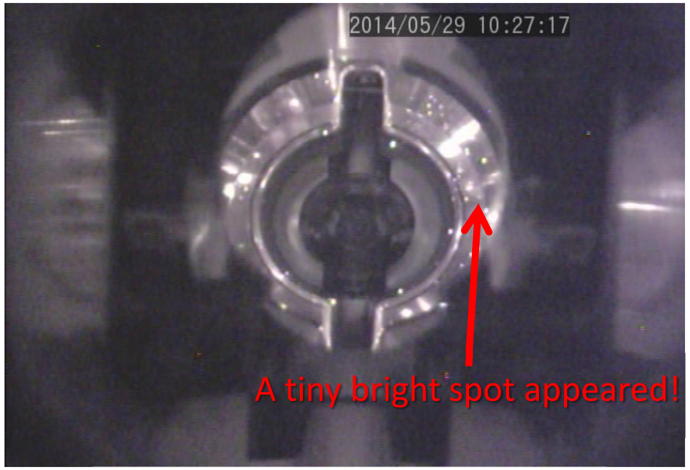
Example of Cavity-Breakdown Events (6)

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

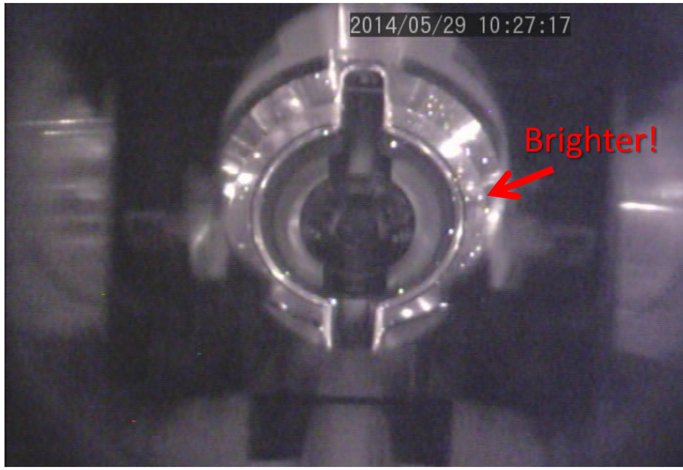
4 frames before



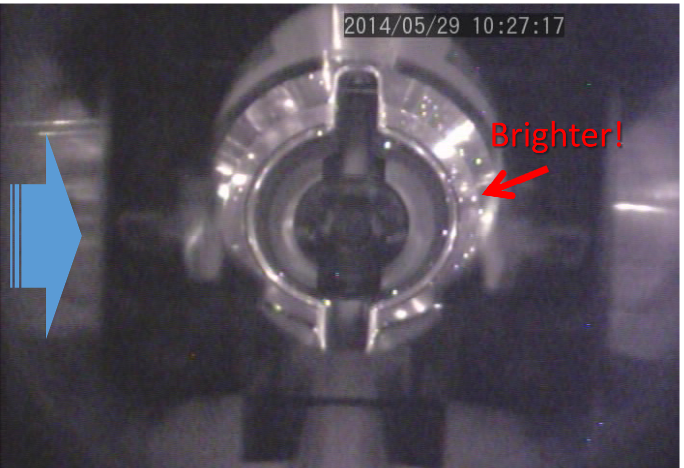
3 frames (0.1 s) before



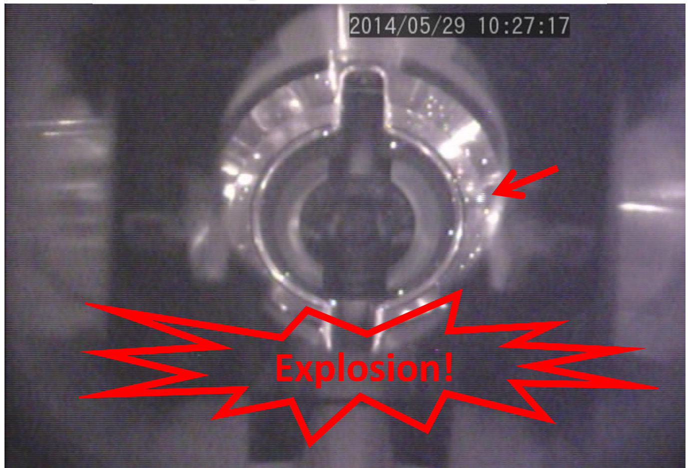
2 frames before



1 frame before



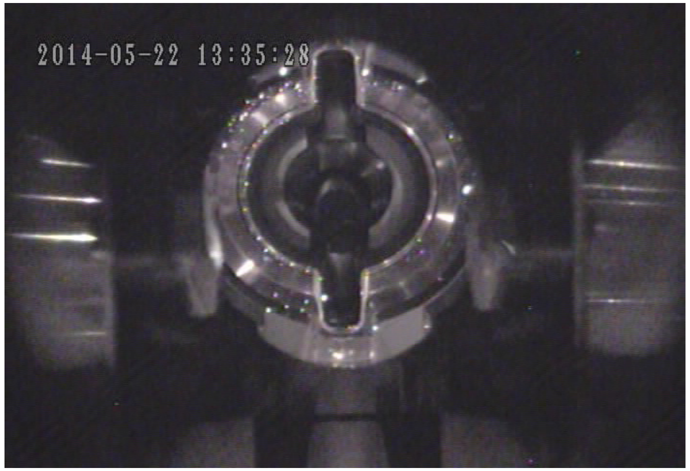
Cavity Breakdown!



1 frame after → It disappeared.

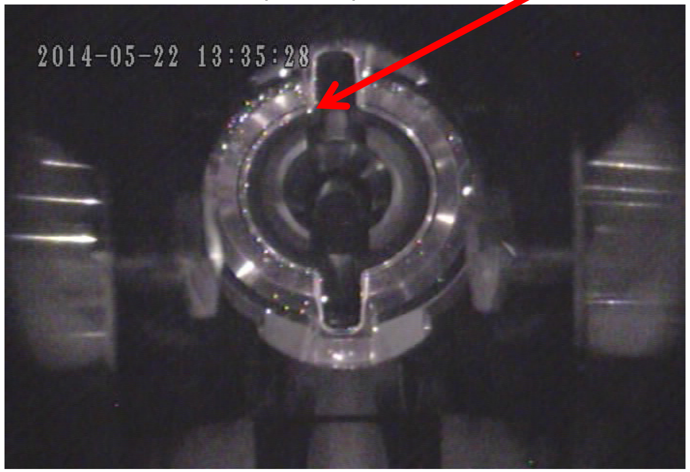
Example of Cavity-Breakdown Events (7)

46 frames before



45 frames (1.5 s) before

A small bright spot appeared!



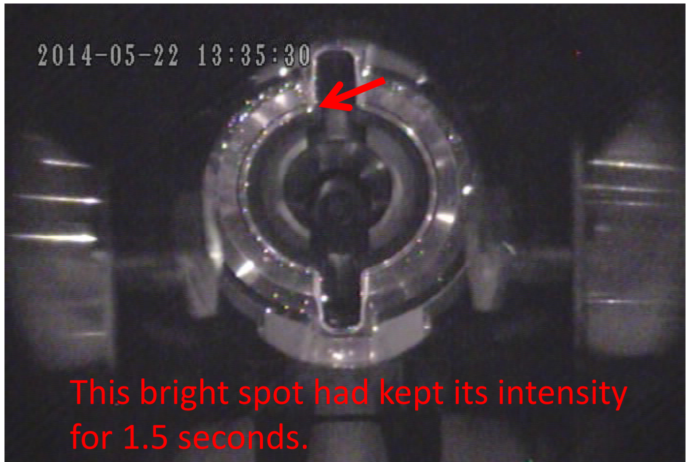
…

→ It disappeared.

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

…

1 frame before



Cavity Breakdown!

Conclusions on this Breakdown Study

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

- We observed **clear bright spots** on the endplates during the RF operation.
  - Most of the bright spots had kept their intensity with no significant effects on the RF operation as long as those remaining stable.
  - Even after the RF conditioning (during the stability test with keeping $V_c = 0.90$ MV)
- We have discovered 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** just before breakdowns.
  - The time scale from the sudden appearance to the breakdown is ~1 sec or shorter.
  - Stimulates our interest in microscopic dynamics of generation, growth, and explosion of bright spots and its correlation with conditioning effects and breakdown rates.
- **From the radiation-dose measurements**
  - The total field emission became the minimum level at the end of the RF conditioning (just before the stability test).
  - The 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!