Updated Results of Breakdown Study for 509-MHz Continuous-Wave Accelerating Cavities based on Direct In-situ Observation

Tetsuo ABE

<tetsuo.abe@kek.jp>

High Energy Accelerator Research Organization (KEK), Japan

MeVArc2018 @ Puerto Rico

2018-05-22

Purposes of This Study

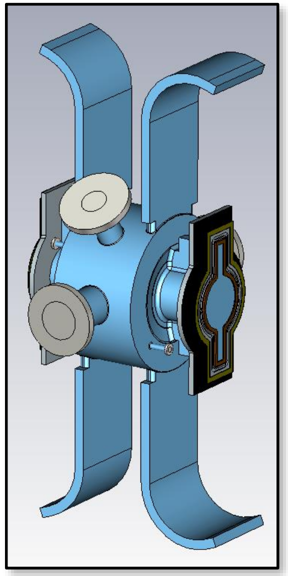
1. To elucidate the breakdown-trigger mechanism of normal-conducting accelerating structures

→ Application to accelerating-structure developments with better performance

→ Application to performance-recovery measures for deteriorated accelerating structures

Review of the Previous Results Shown in MeVArc2015

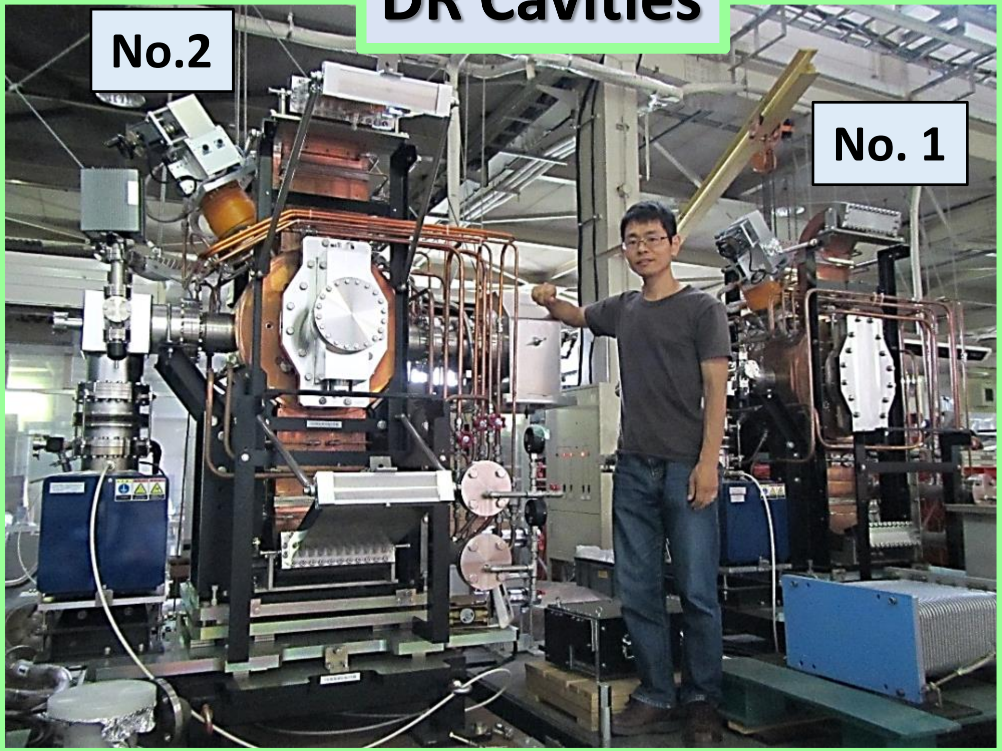
Normal-Conducting Accelerating Cavities for SuperKEKB Positron Damping Ring (DR)



← The inside (blue region) is **ultrahigh vacuum** during operation.

0. Cavity No.0 (prototype) developed in FY2011
   - ➢ Surface protection of the endplates: acid cleaning followed by chromating
1. **Cavity No.1** fabricated in FY2012
   - ➢ Surface protection of the endplates: Electropolishing (EP)
2. **Cavity No.2** fabricated in FY2013
   - ➢ Surface protection of the endplates: Electropolishing (EP)

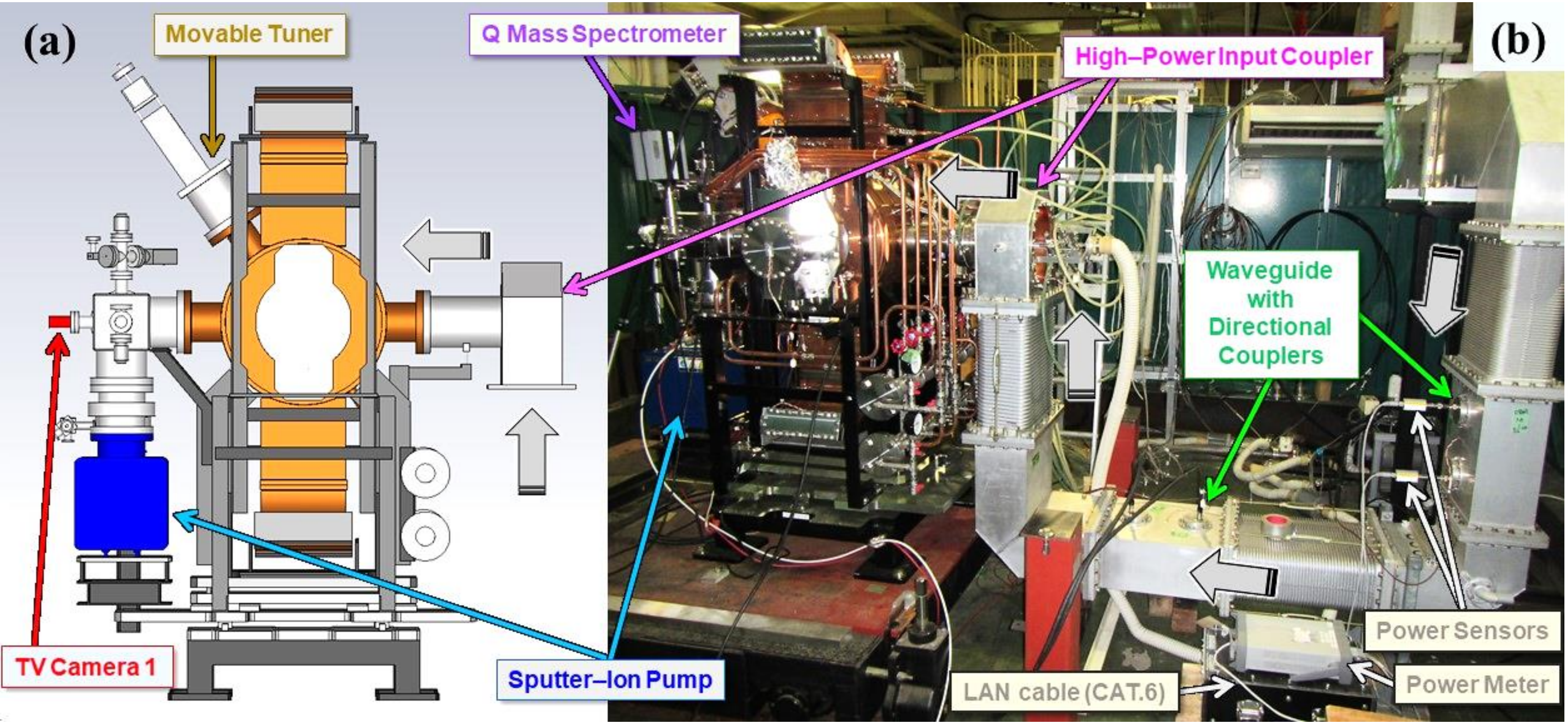
DR Cavities



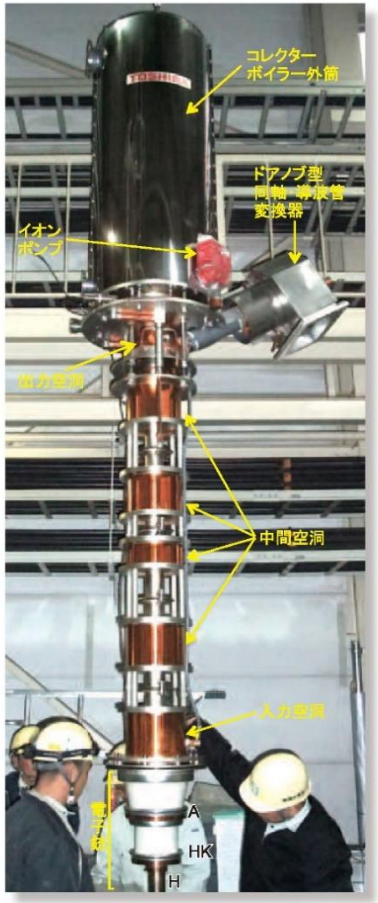
- Accel. mode: 509 MHz Continuous Wave (CW) TM_{010}
- Made of Oxygen Free Copper (Class1)
- Q_0 = ~30000 (97%IACS)
- $R_{sh}/Q_0 = 150\ \Omega$
- Max. V_c = 0.95 MV (→ E_{acc} = 3.7 MV/m ← Cav. gap: 256 mm)
- Wall-loss power: 110 to 140 kW for V_c = 0.7 to 0.8 MV

For more details, T. Abe, "Completion of the First Production Version of the Accelerating Cavity for the SuperKEKB Positron Damping Ring", KEK Accl. Lab. Topics 2013/10/7 (web article): http://www2.kek.jp/accl/eng/topics/topics131007.html

Setup of the High-Power Test of DR Cavities



Toshiba
CW Klystron
E3732
(1MW, 508.9 MHz)



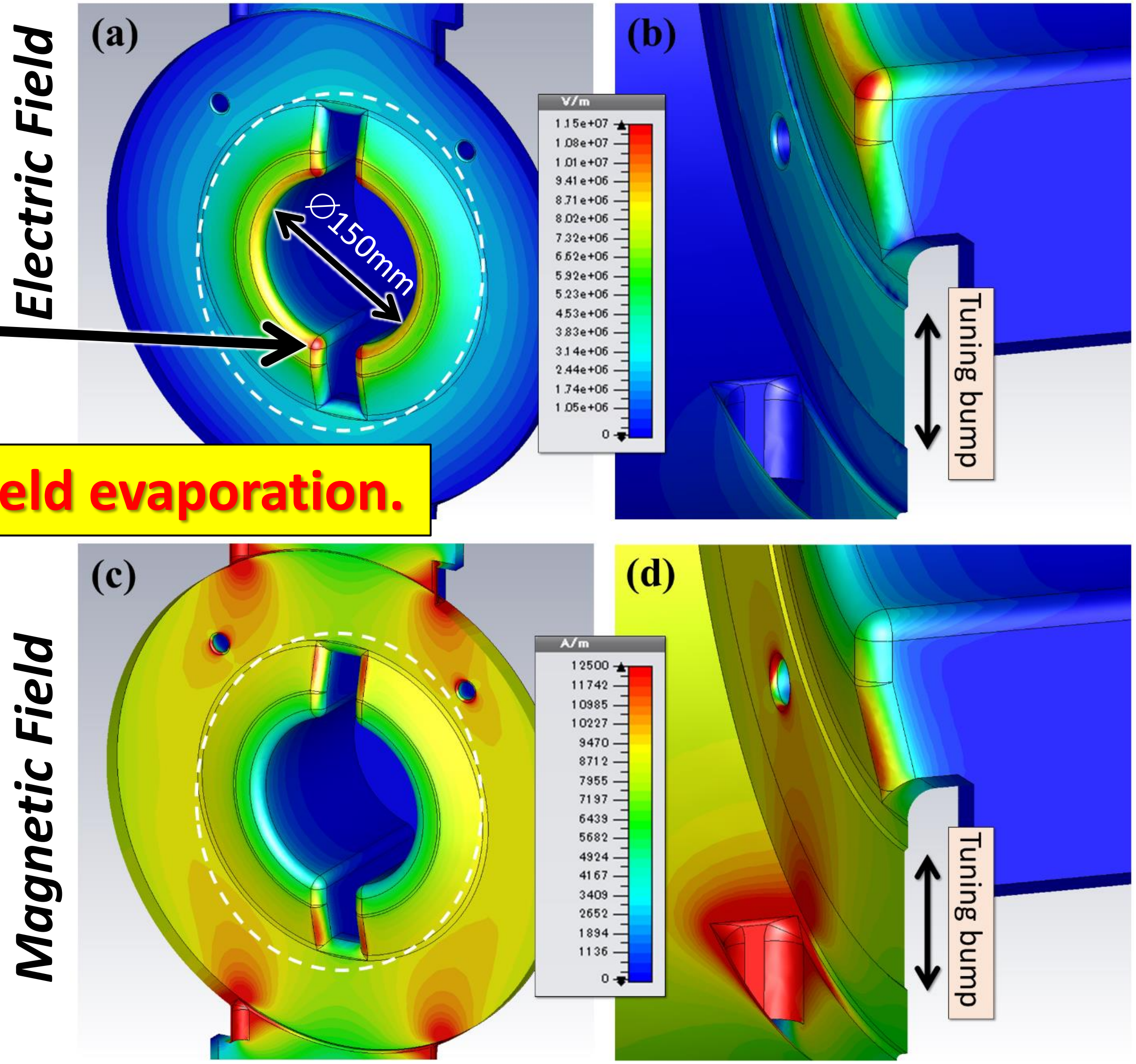
(No beam injected into the cavity during the high-power test)

Surface Field of the Accelerating Mode

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

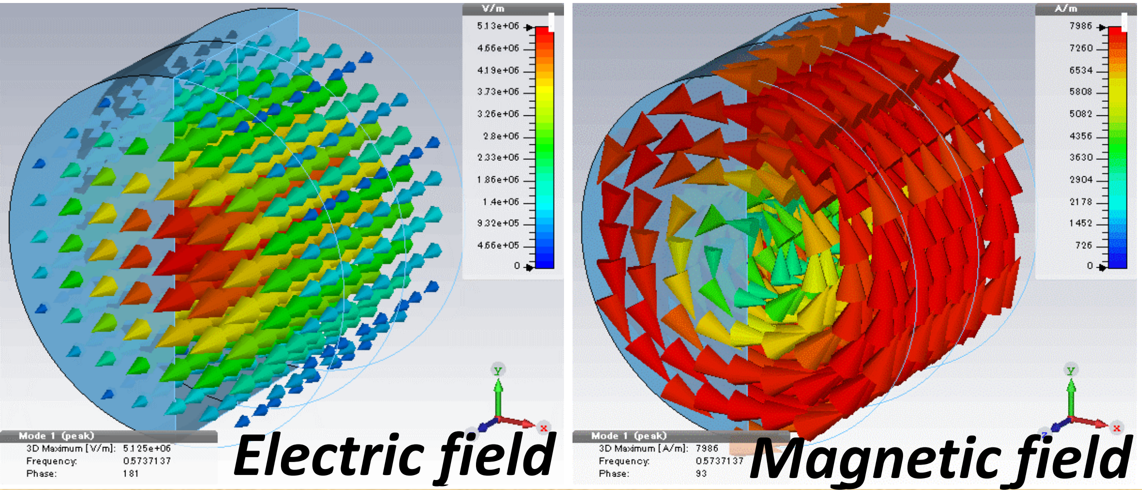
The dashed white lines indicate visible regions by the TV cameras.

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

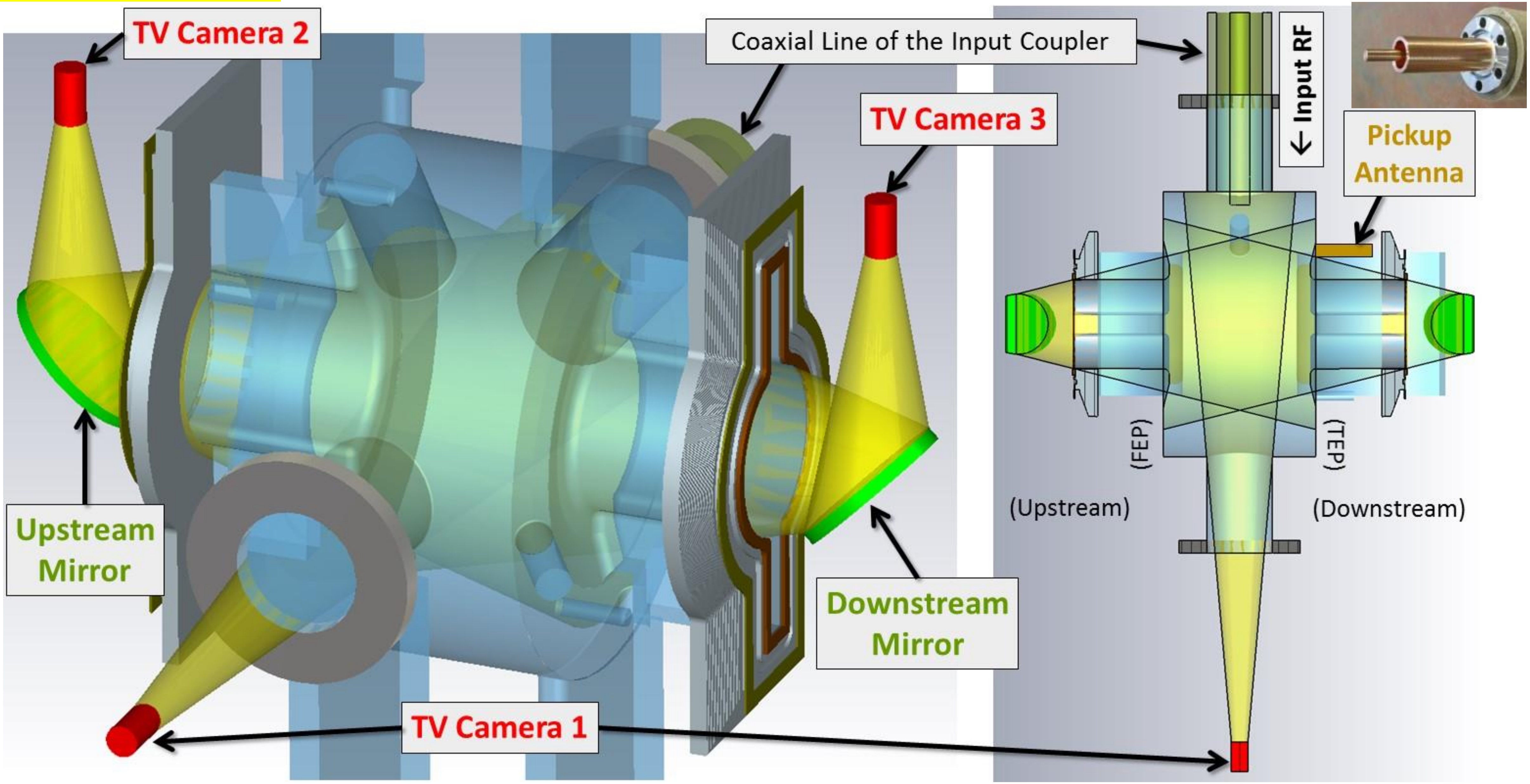


This max. field is much lower than that for field evaporation.

Accelerating mode: TM_{010}, 509 MHz

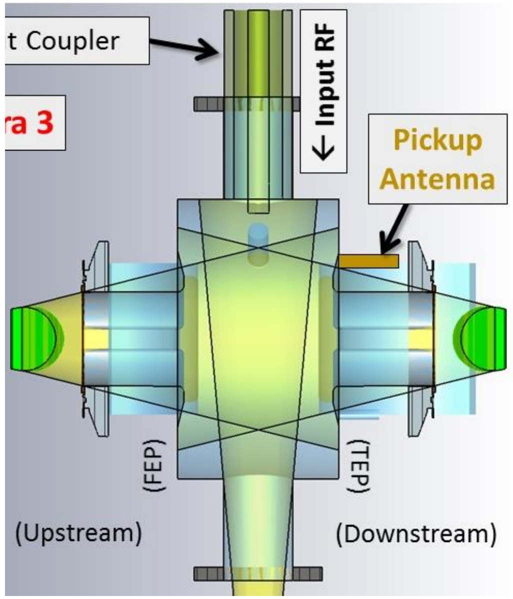


3 TV cameras for **Multi-directional and wide-field** observation



Breakdown Detection by using pickup signals

1. Candidates selected by reflected-wave interlock.
2. Check the decay time of the pickup signal of the accelerating mode :
   - ~8 μs ➔ Not breakdown
   - << 8 μs ➔ Breakdown



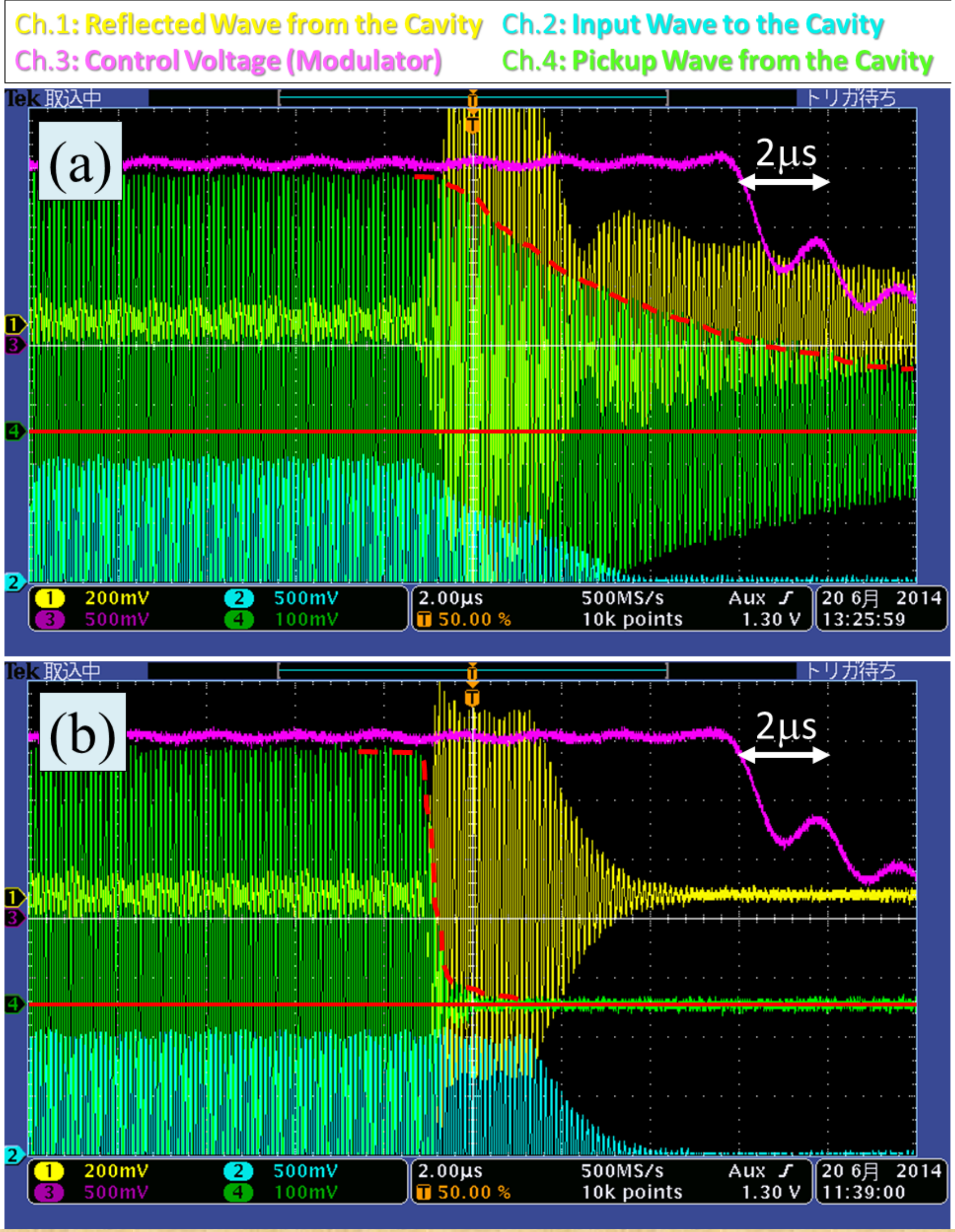
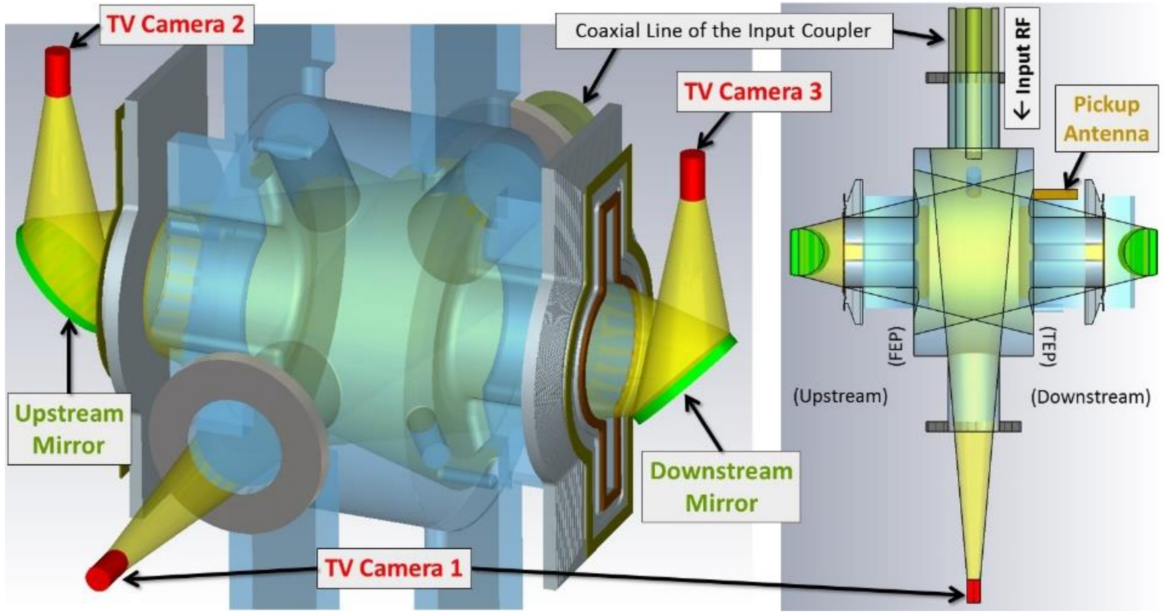


FIG. 6: Waveforms of the oscilloscope displayed for a time span of 20 μs (= 2 μs/div) when the interlock system was activated. The red dashed curves indicate the envelope of the 508.9-MHz pickup signal from DR Cavity No. 2, and the red solid lines indicate its zero level. (a) The RF switch was turned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

Q_L=13000@509MHz ⇒ Filling time: 8μs

We observed "*Bright Spots*".

Upstream Endplate at V_c = 0.90 MV



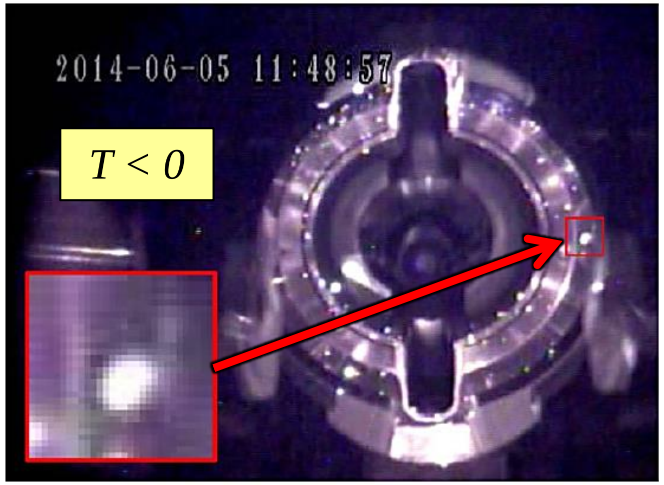
- ✓ Image recorded by TV camera 3
- ✓ During operation with V_c = 0.90 MV
  - ➢ E_{acc} = 3.5 MV/m (← Gap: 256 mm)
  - ➢ E_{surf} = 4〜13 MV/m
- ✓ Non-breakdown status

During the high-power operation, such bright spots:

- ➢ **Maintained their intensity for hours or longer, and**
- ➢ **Had no significant effects on the high-power operation as long as they remained stable.**

Example of Breakdown Events (1)

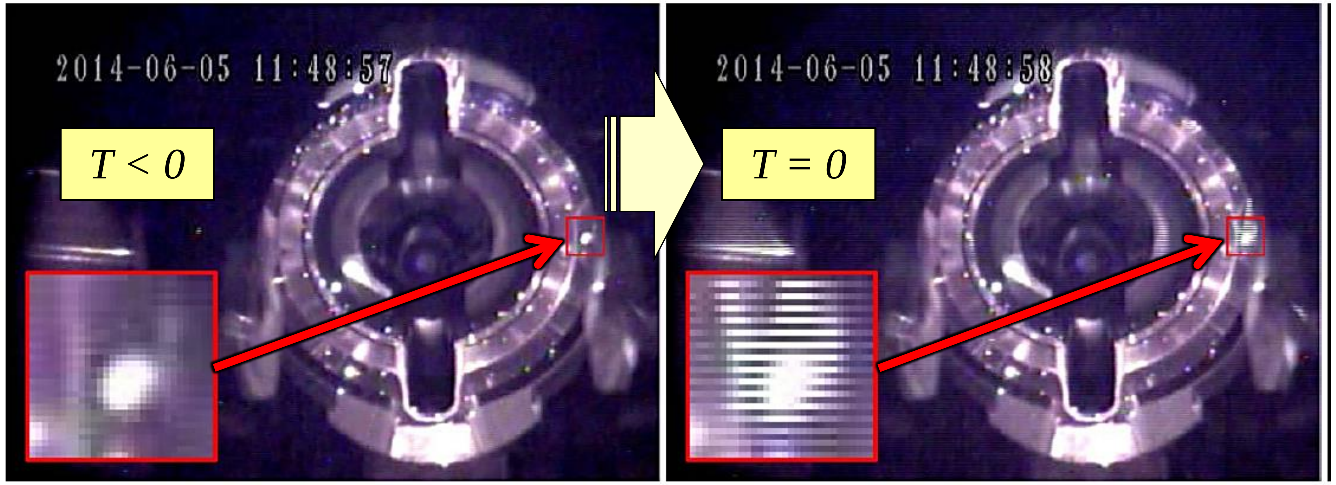
A stable bright spot
at V_c = 0.95 MV (E_{acc} = 3.7 MV/m)



(a) 1 frame (1/30 s) before this cavity breakdown.

Example of Breakdown Events (1)

A stable bright spot at V_c = 0.95 MV (E_{acc} = 3.7 MV/m) exploded at the moment of breakdown,

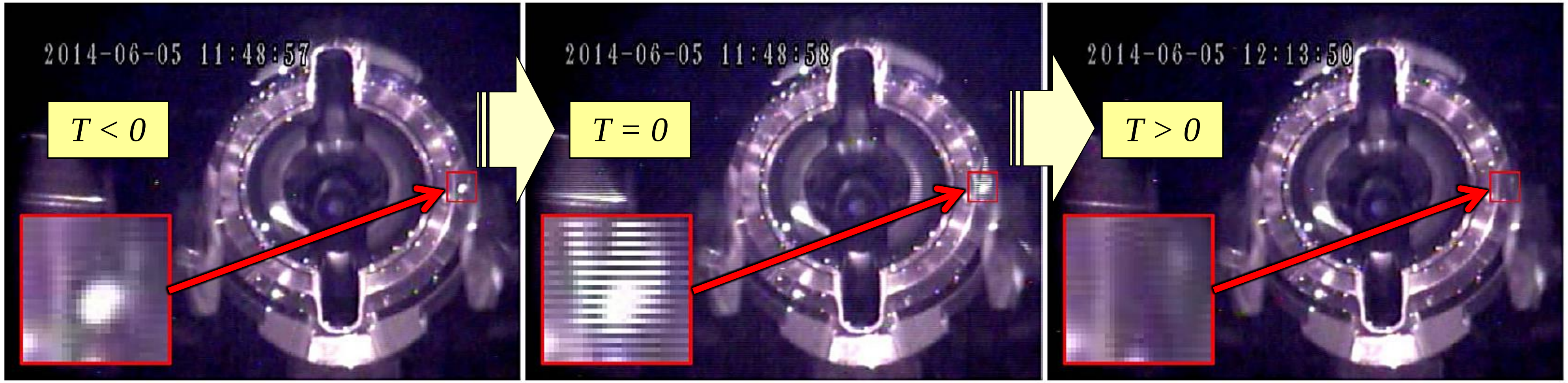


(a) 1 frame (1/30 s) before this cavity breakdown.

(b) At the moment of this cavity breakdown.

Example of Breakdown Events (1) **Supernova!**

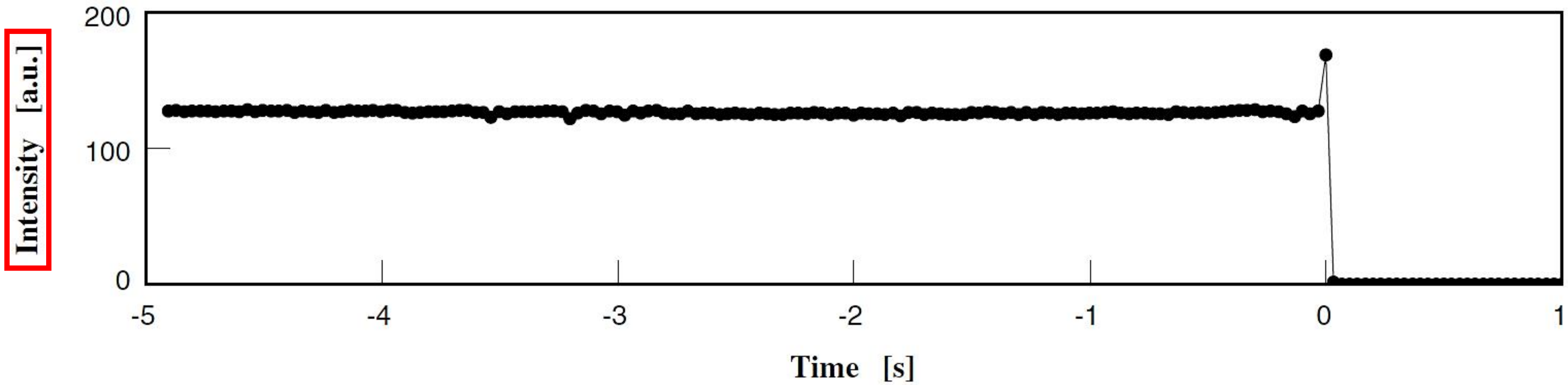
A stable bright spot at V_c = 0.95 MV (E_{acc} = 3.7 MV/m) exploded at the moment of breakdown, then, disappeared!



(a) 1 frame (1/30 s) before this cavity breakdown.

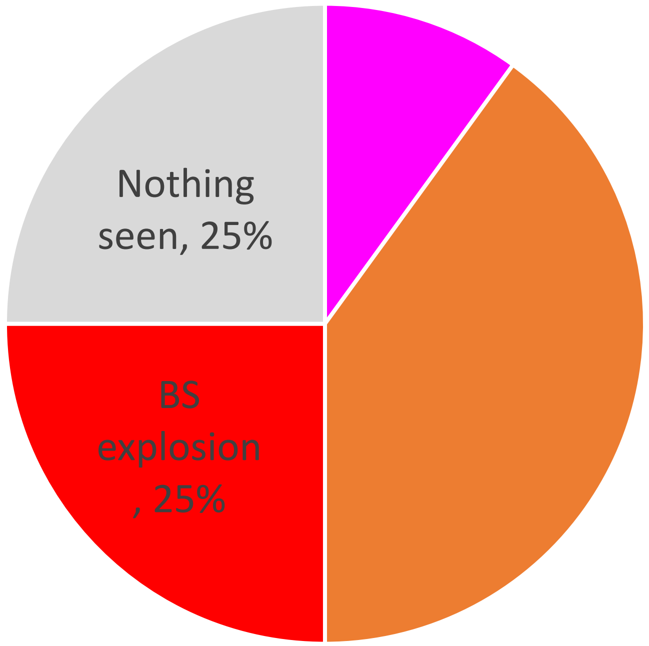
(b) At the moment of this cavity breakdown.

(c) Shortly after recovering from this cavity breakdown at V_c = 0.95 MV.



Statistics on all the 205 breakdown events detected

- 25% accompanied by a bright-spot (BS) explosion

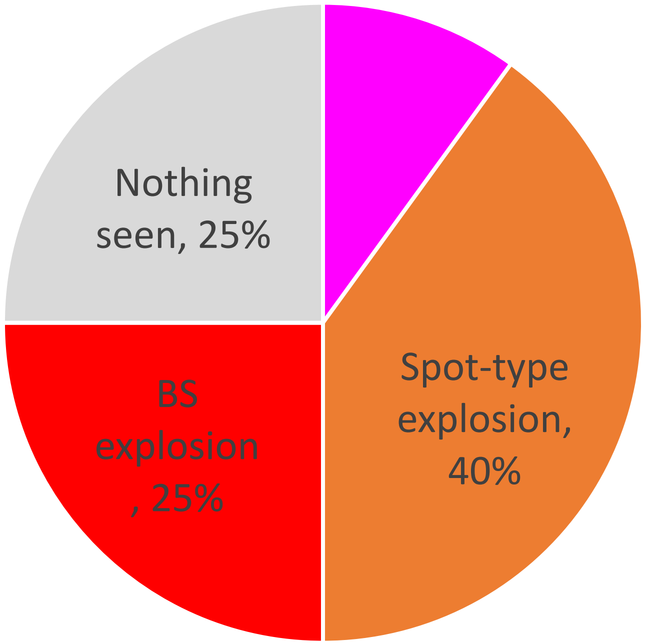


For more details:

- ✓ T. Abe, "Visual Imaging of Radio-Frequency Cavity Breakdown ", KEK Accl. Lab. Topics 2016/10/5 (web article): http://www2.kek.jp/accl/eng/topics/topics161005.html
- ✓ 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*", Physical Review Accelerators and Beams **19**, 102001 (2016).

Statistics on all the 205 breakdown events detected

- 25% accompanied by a bright-spot (BS) explosion
- 40% accompanied by a spot-type explosion not originating from a stable bright spot

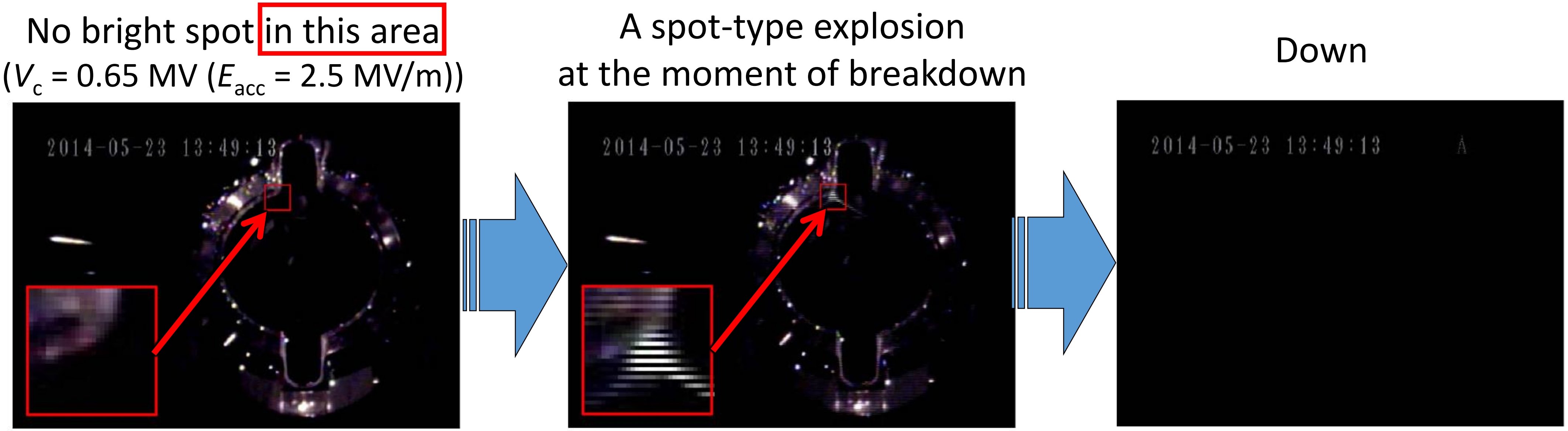


For more details:

- ✓ T. Abe, "Visual Imaging of Radio-Frequency Cavity Breakdown ", KEK Accl. Lab. Topics 2016/10/5 (web article): http://www2.kek.jp/accl/eng/topics/topics161005.html
- ✓ 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*", Physical Review Accelerators and Beams **19**, 102001 (2016).

Example of Breakdown Events (2)

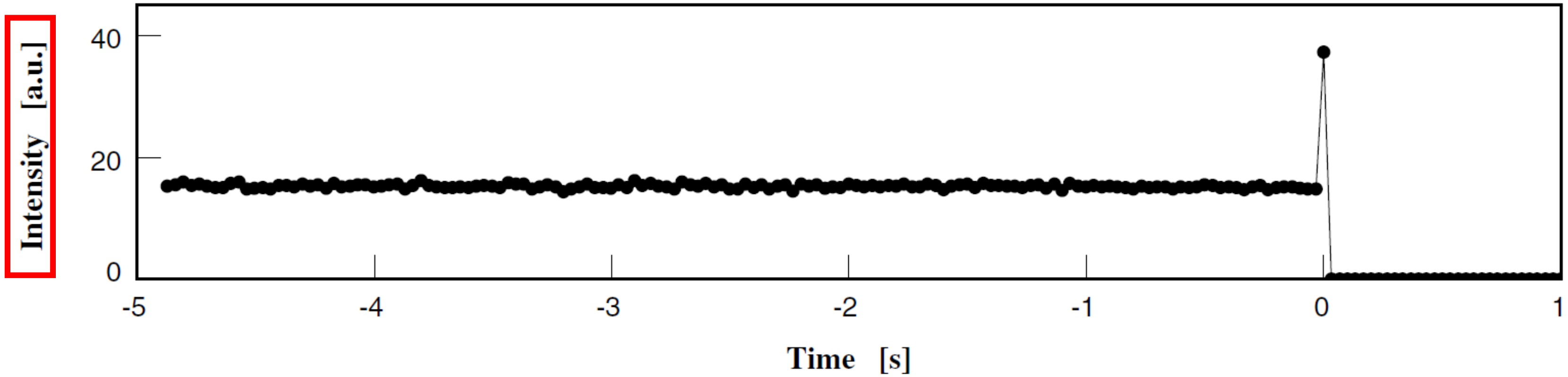
Spot-type explosion not originating from a stable bright spot



(a) 1 frame (1/30 s) before this cavity breakdown.

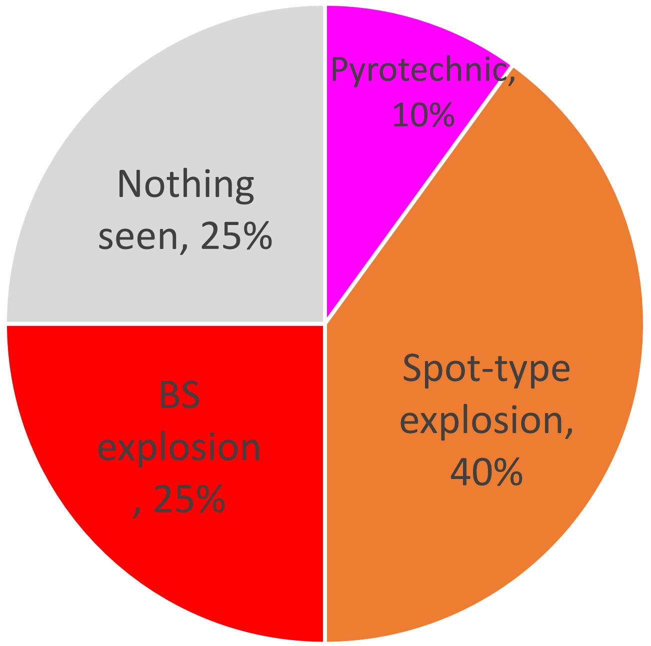
(b) At the moment of this cavity breakdown.

(c) 1 frame (1/30 s) after this cavity breakdown.



Statistics on all the 205 breakdown events detected

- 25% accompanied by a bright-spot (BS) explosion
- 40% accompanied by a spot-type explosion not originating from a stable bright spot
- 10% "Pyrotechnic" breakdowns
  - Observed only in the initial stage of RF conditioning



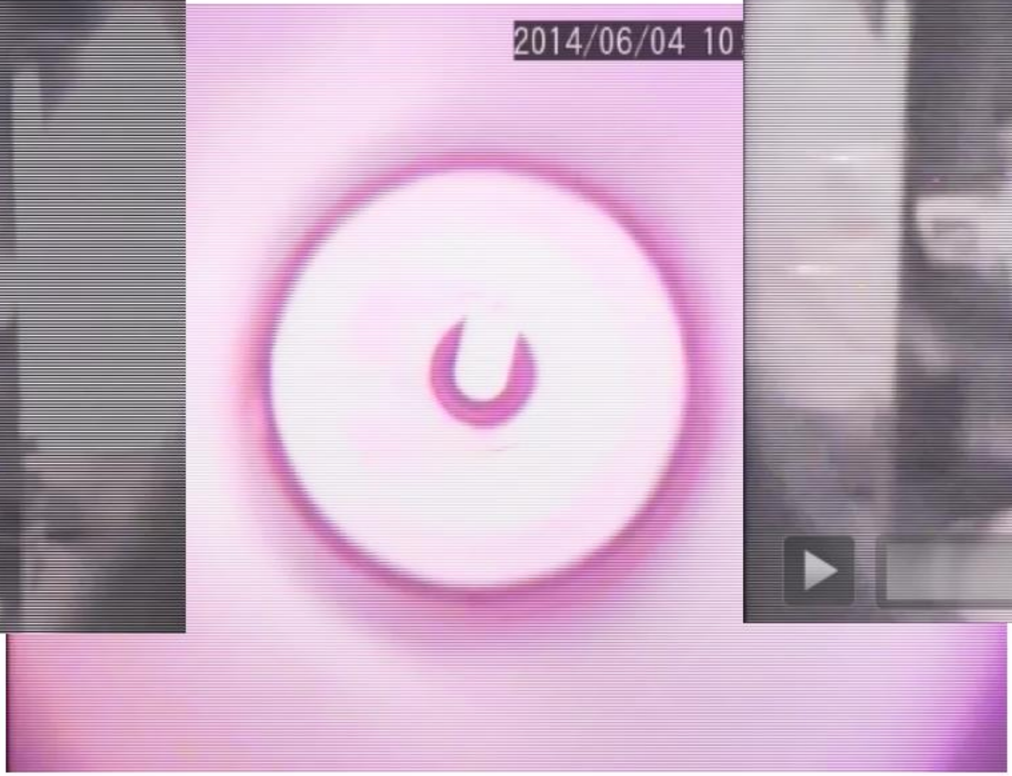
For more details:
- ✓ T. Abe, "Visual Imaging of Radio-Frequency Cavity Breakdown ", KEK Accl. Lab. Topics 2016/10/5 (web article): http://www2.kek.jp/accl/eng/topics/topics161005.html
- ✓ T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino, "*Breakdown Study Based on Direct In-Situ Observation of Inner Surfaces of an RF Accelerating Cavity during a High-Gradient Test*", Physical Review Accelerators and Beams **19**, 102001 (2016).

An Example of Pyrotechnic Breakdown Events

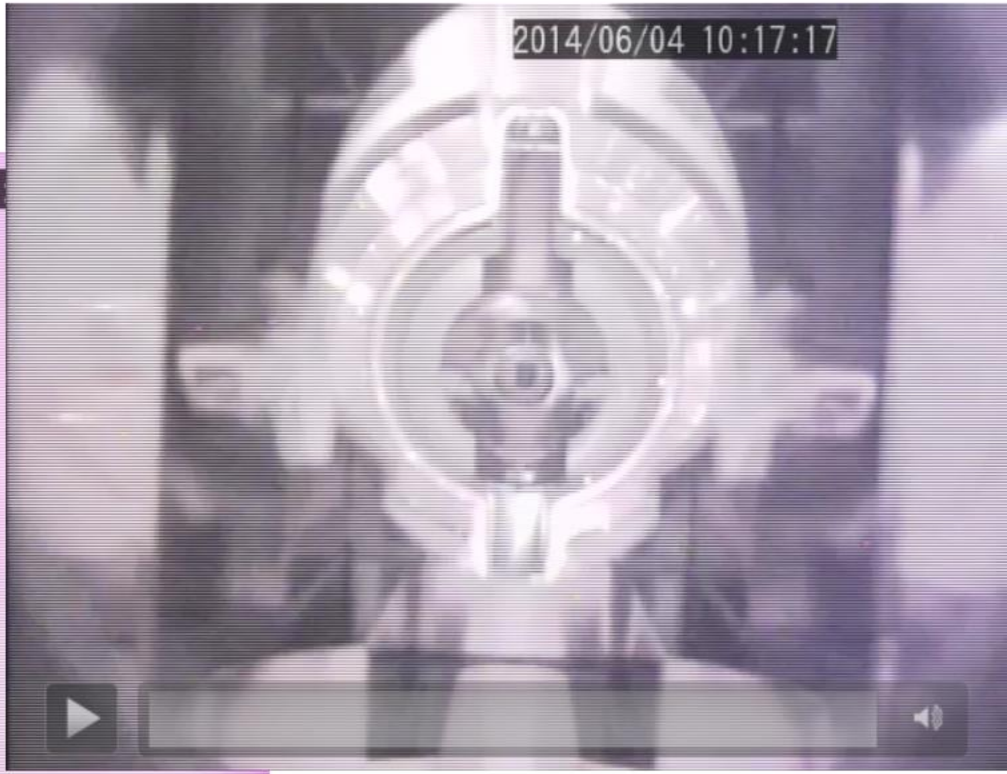
V_c=0.89 MV (E_{acc} = 3.5 MV/m)

Big Flash!

Upstream Endplate



Coaxial Line of the Input Coupler



Downstream Endplate

Questions?

1. What are the bright spots?
    - Spectrum?
    - Temperature?
    - Why exploded?

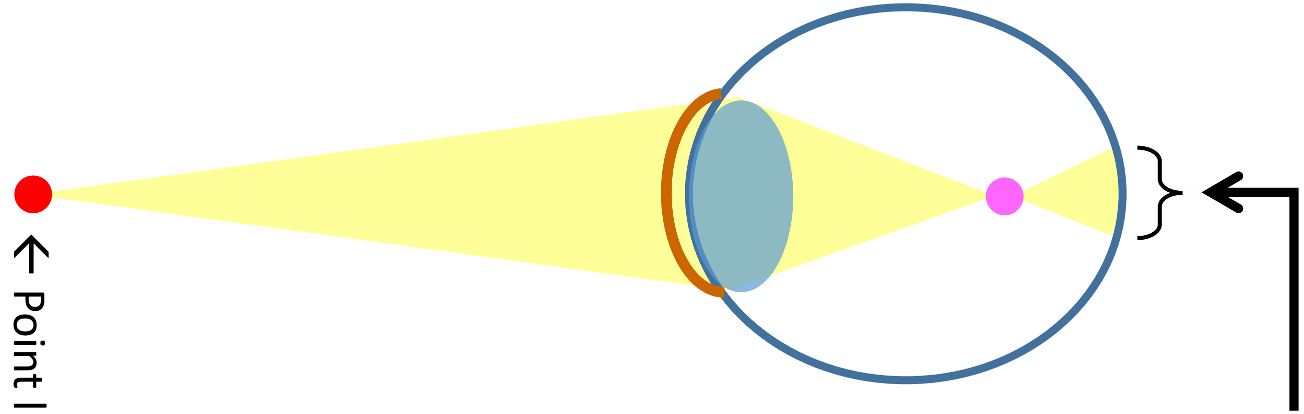
2. What is the physical process of the spot-type explosion?
    - Generation → Growth → Explosion of a bright spot in a moment?

New!

Measurement of the Spectrum of Bright Spots

Defocus Effect

If the **focus point** is off the sensor,

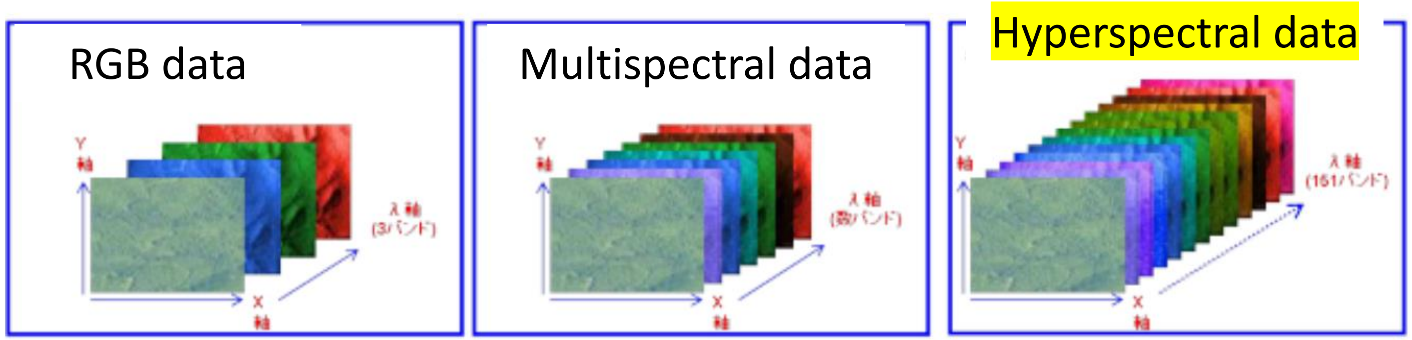


➔ The image is defocused and dispersed.

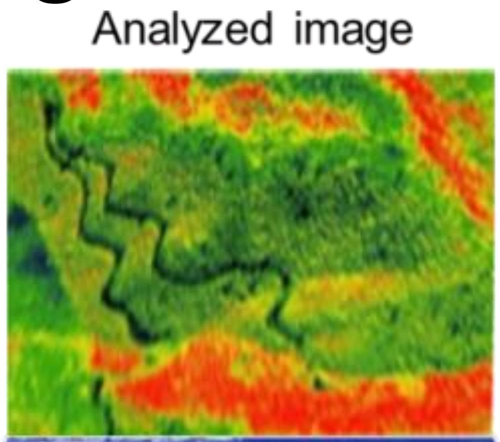
It is difficult to make a perfect focus.

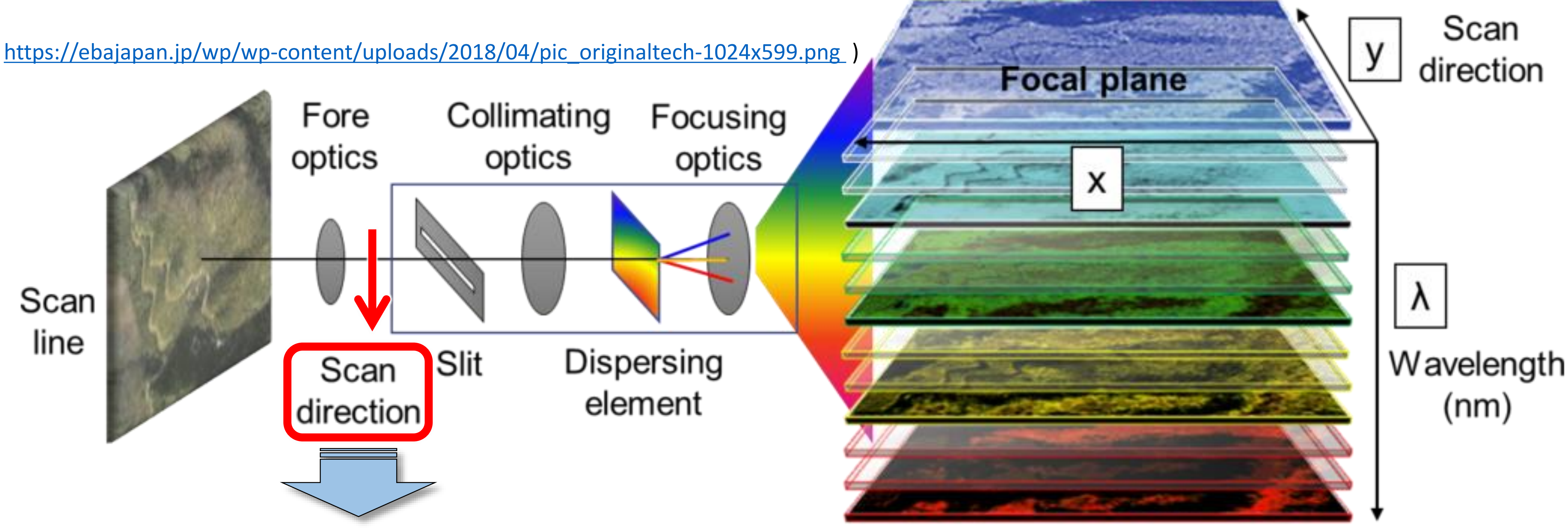
We need **2D spectroscopy**!

Hyperspectral Imaging



(Image from https://ebajapan.jp/wp/wp-content/uploads/2018/04/pic_originaltech-1024x599.png)





Hyperspectral data cube

2D spectroscopy.

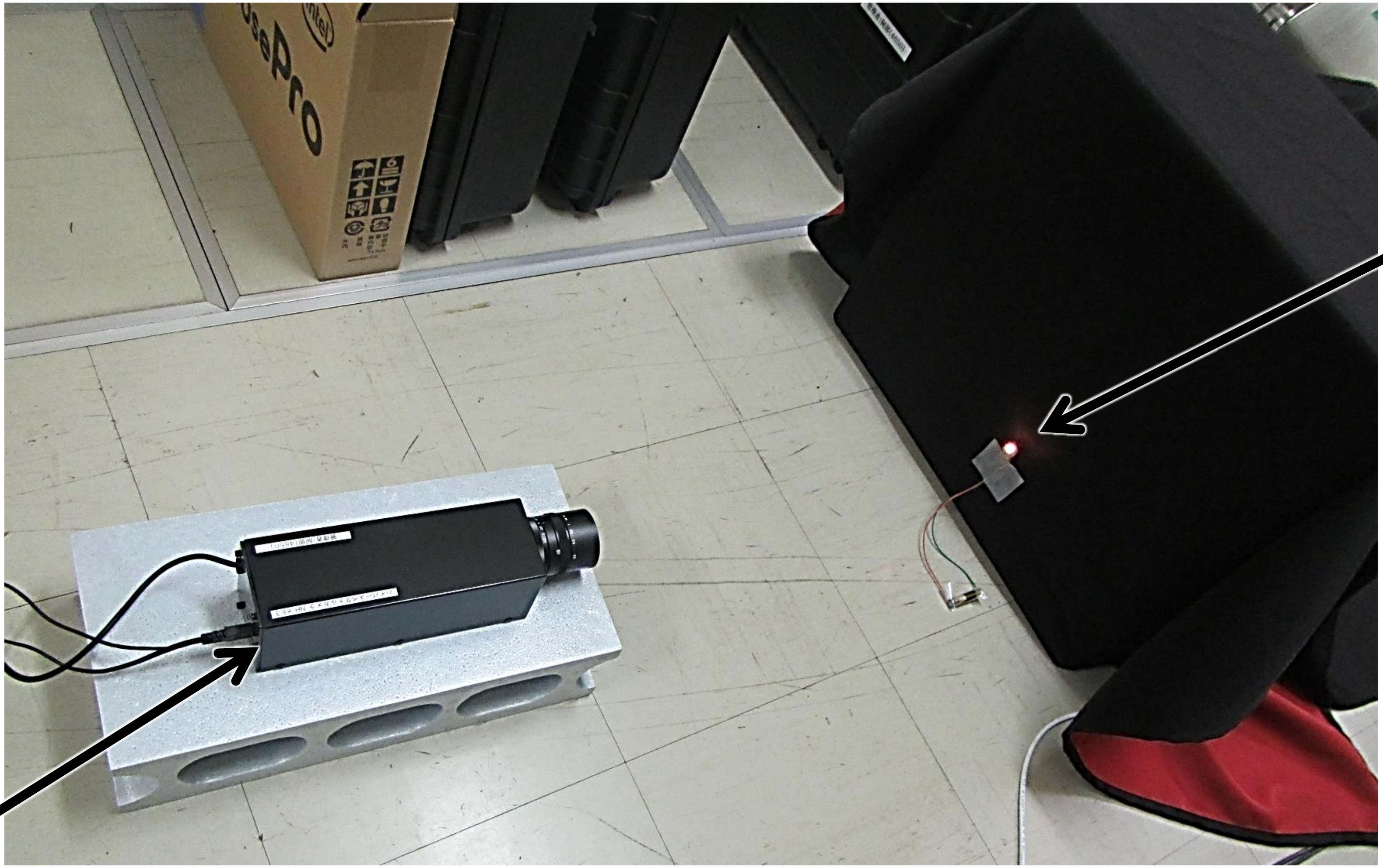
Hyperspectral camera used in this measurement

Model: NH-KE3
made by EBA JAPAN CO.,LTD.
https://ebajapan.jp/spectraltechnology/

Item	Spec.
Detector	CMOS
Number of pixels	360,000
Max. frame rate	100 fps
ADC bits	10
Range of wavelength	400 to 1000 nm
Enclosure size	H76.0mm x W72.4mm x L213mm
Net weight	1030g

Check of the defocus effect

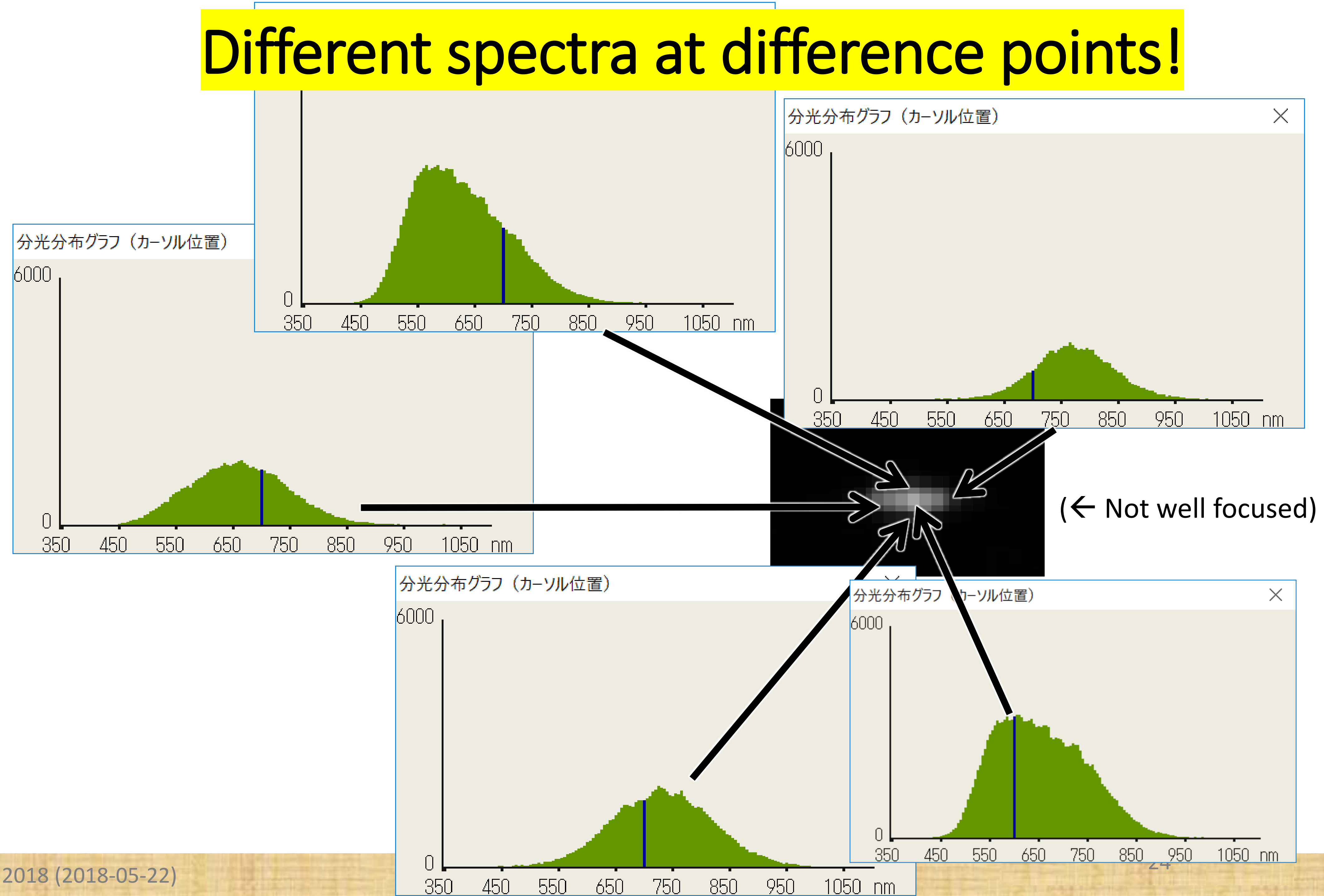
Measurement Setup



Miniature bulb

Hyperspectral camera

Different spectra at difference points!

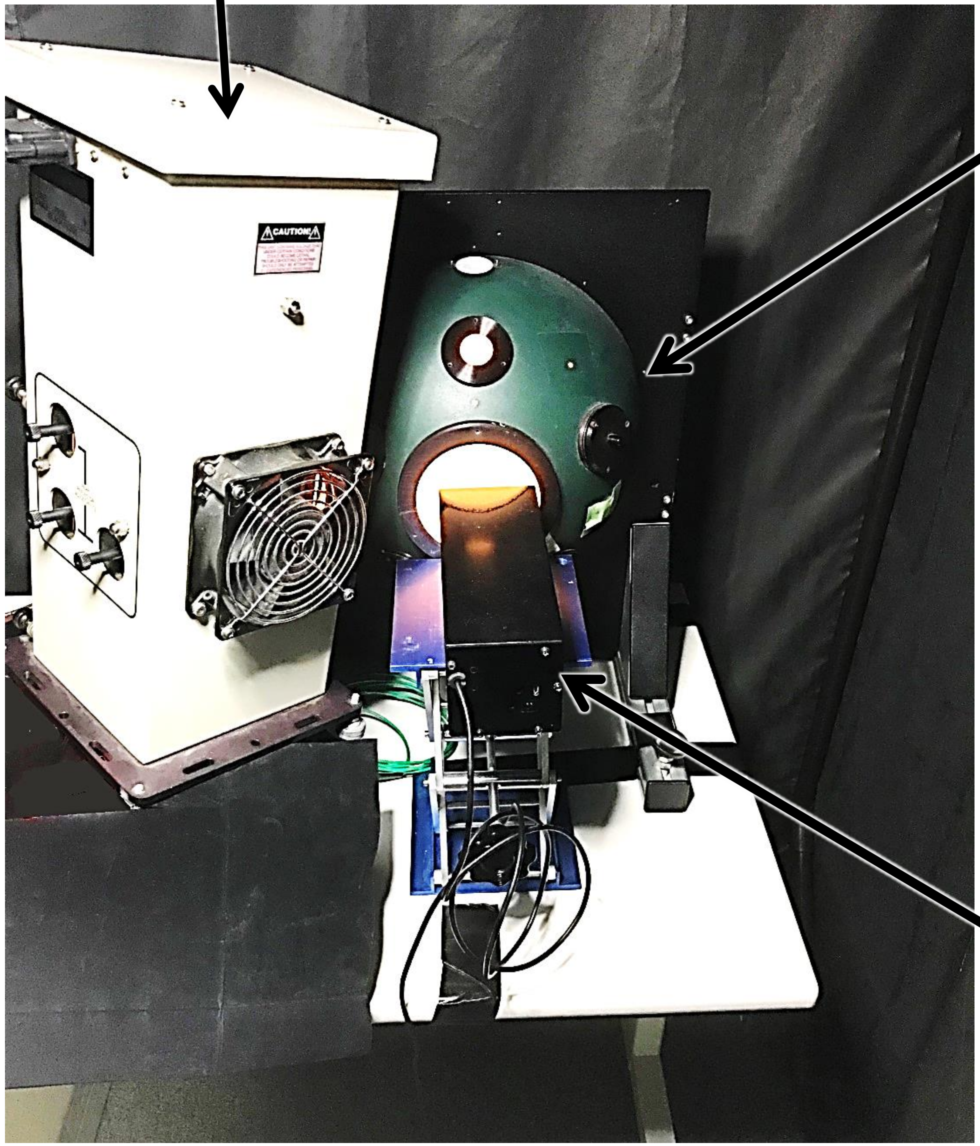


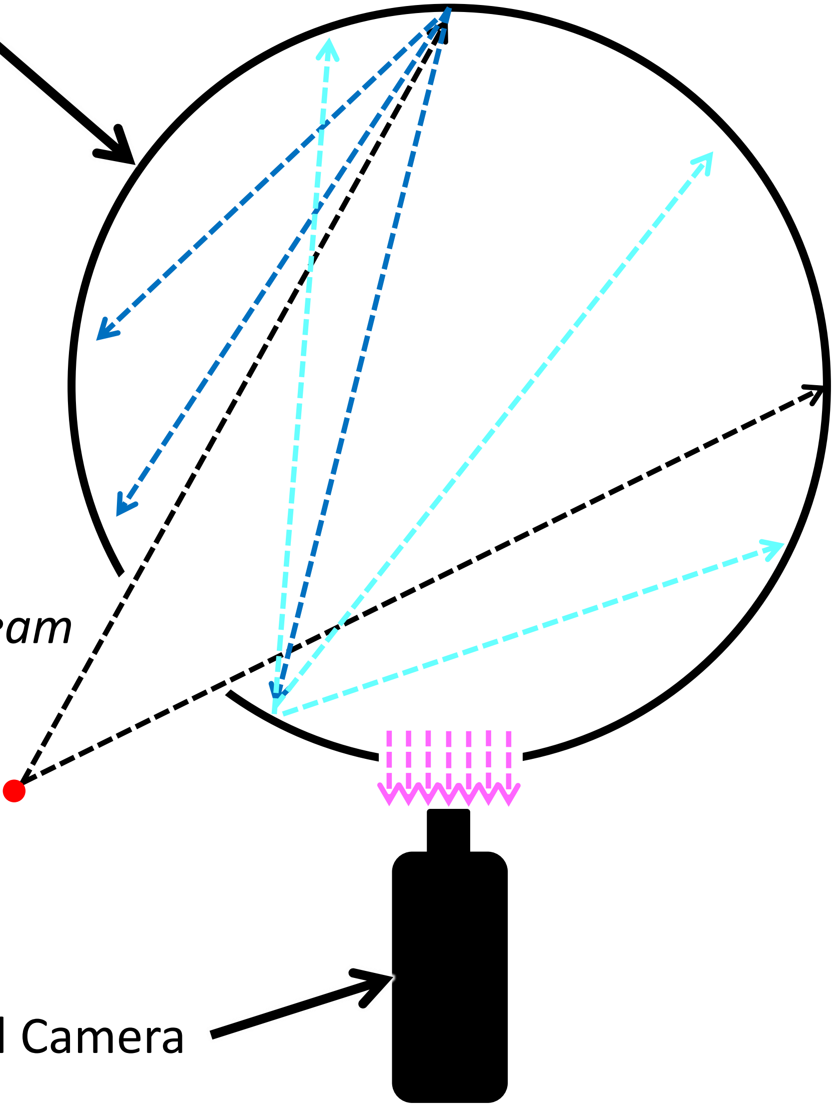
Calibration of Pixel Sensitivity of the CMOS Sensor

Using an Integrating Sphere

Halogen lamp

(Photo by courtesy of EBA JAPAN CO.,LTD.)



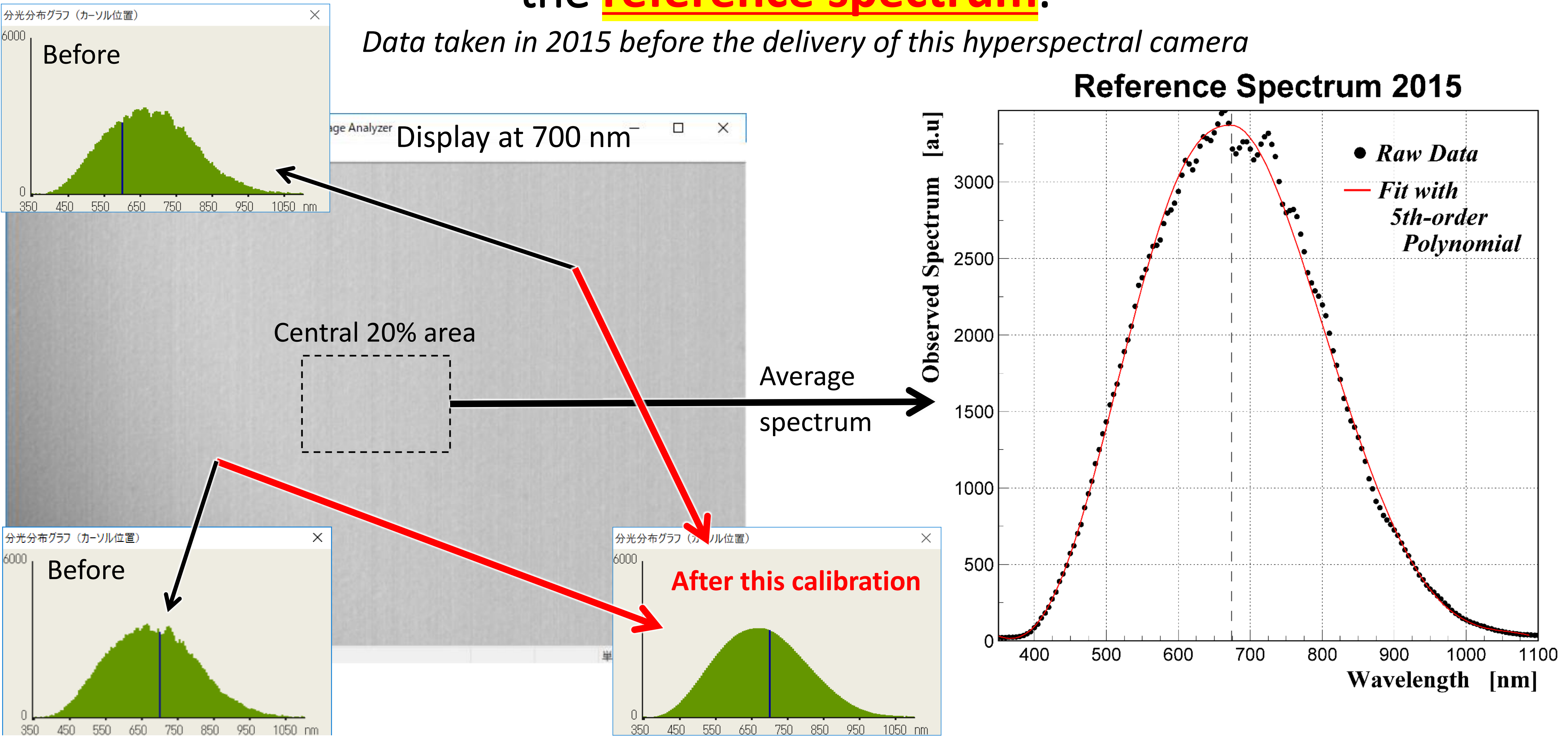


Hyperspectral Camera

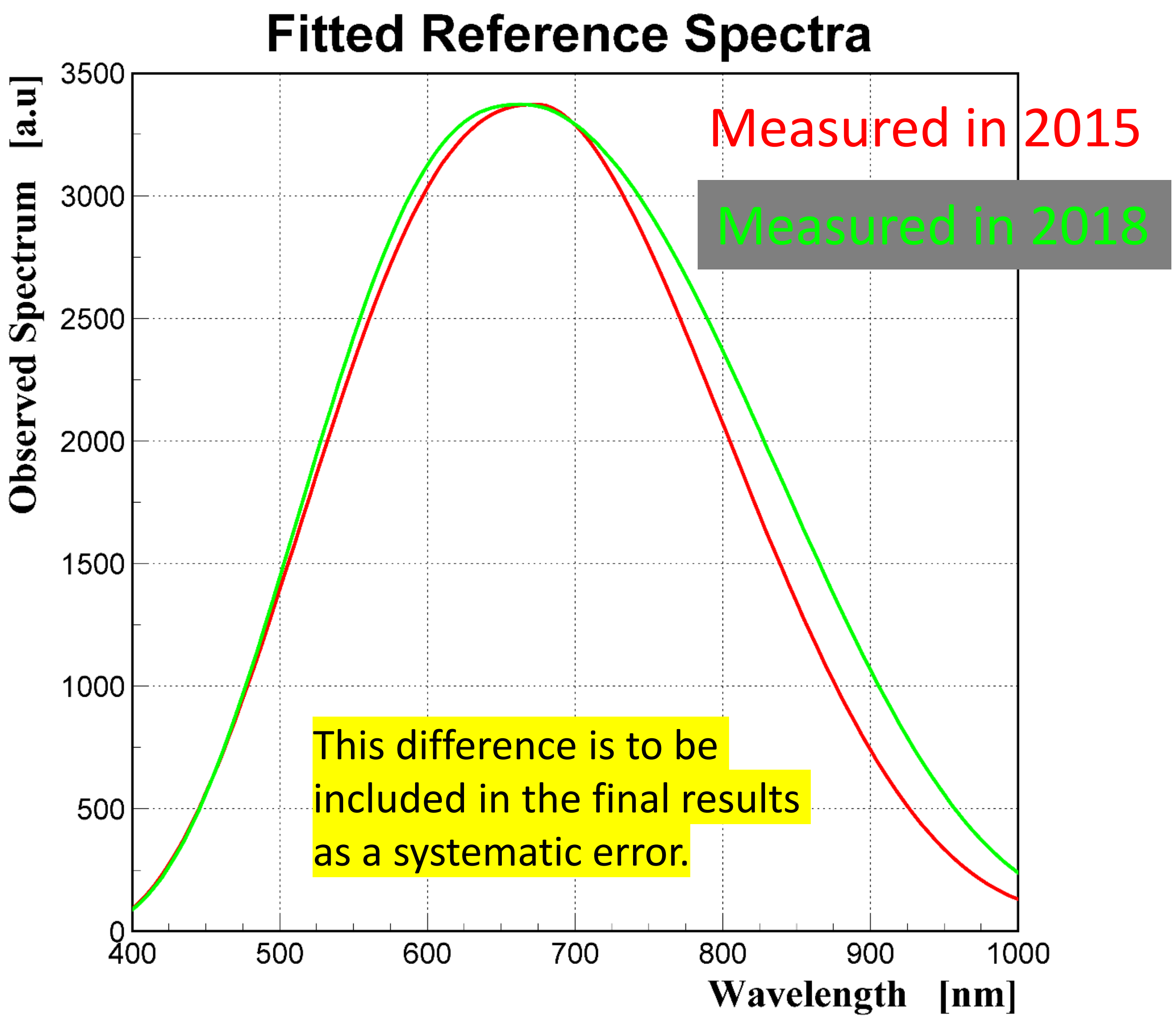
*The "detector" receives **uniform Light**.*

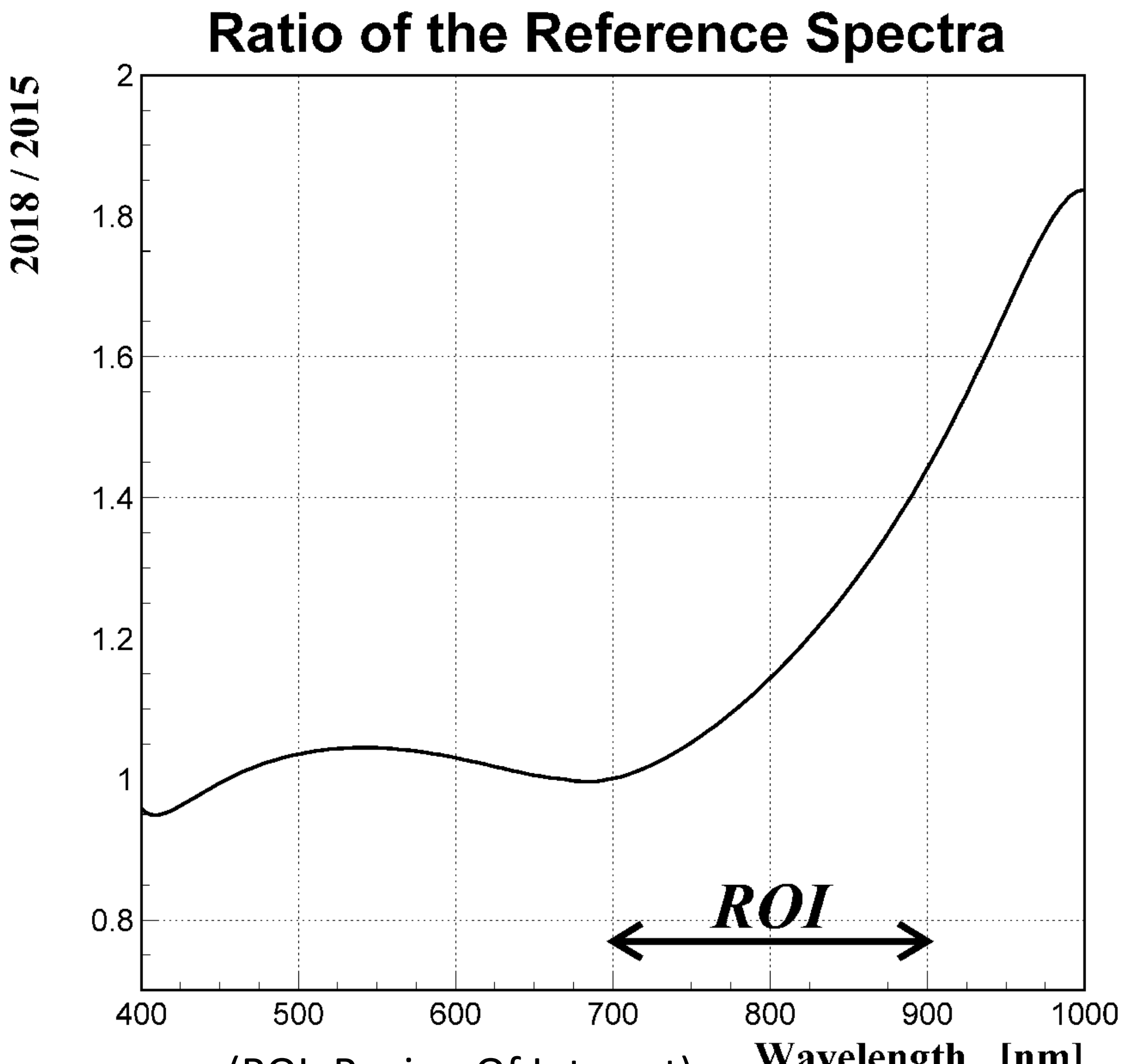
Calibrated so that any spectrum measured at each pixel should show the **reference spectrum**.

Data taken in 2015 before the delivery of this hyperspectral camera



Reference spectra are different before and after the relevant measurements in this study.

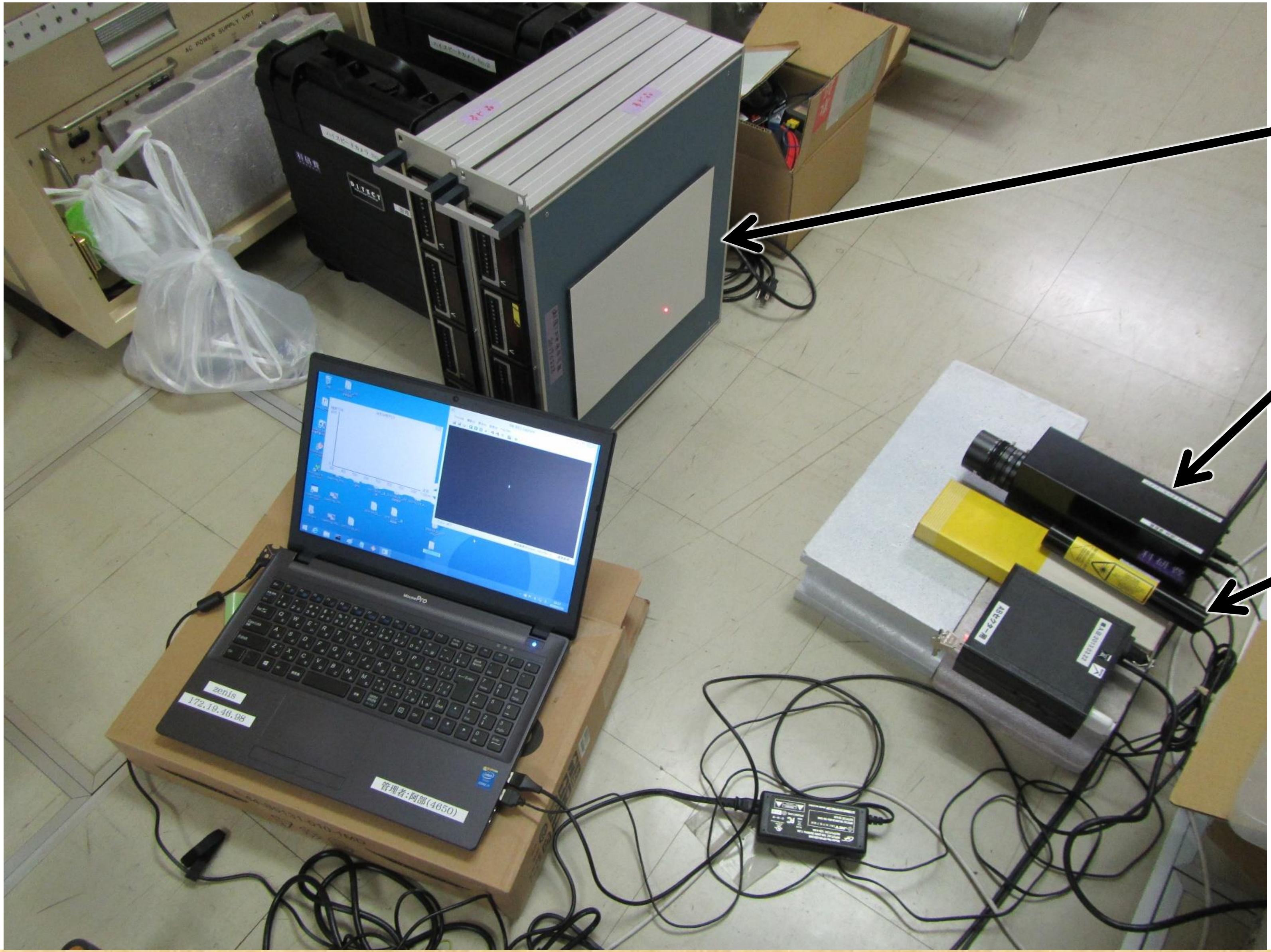




(ROI: Region Of Interest)

Wavelength Calibration

Using a He-Ne Red Laser (632.8 nm)

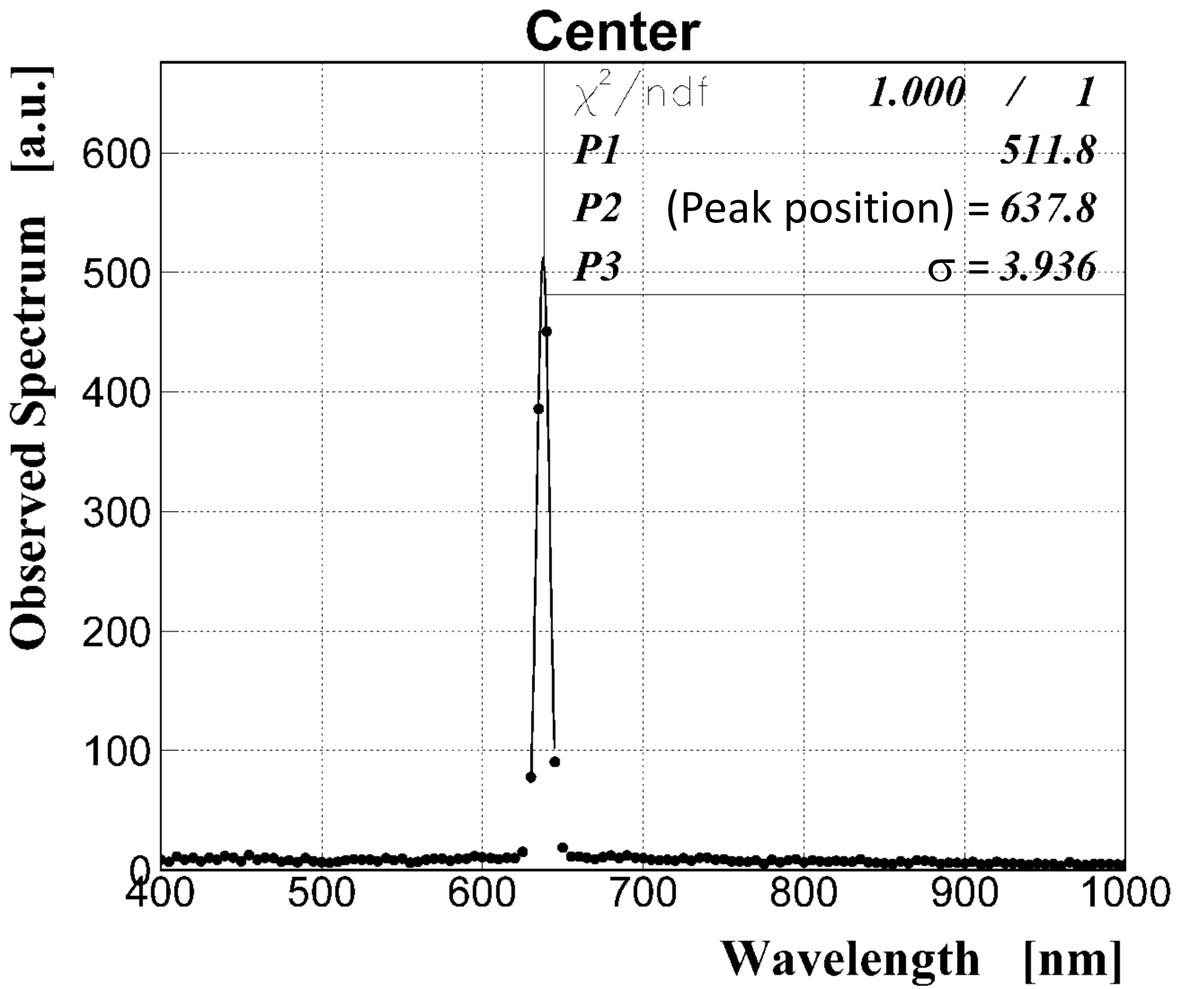


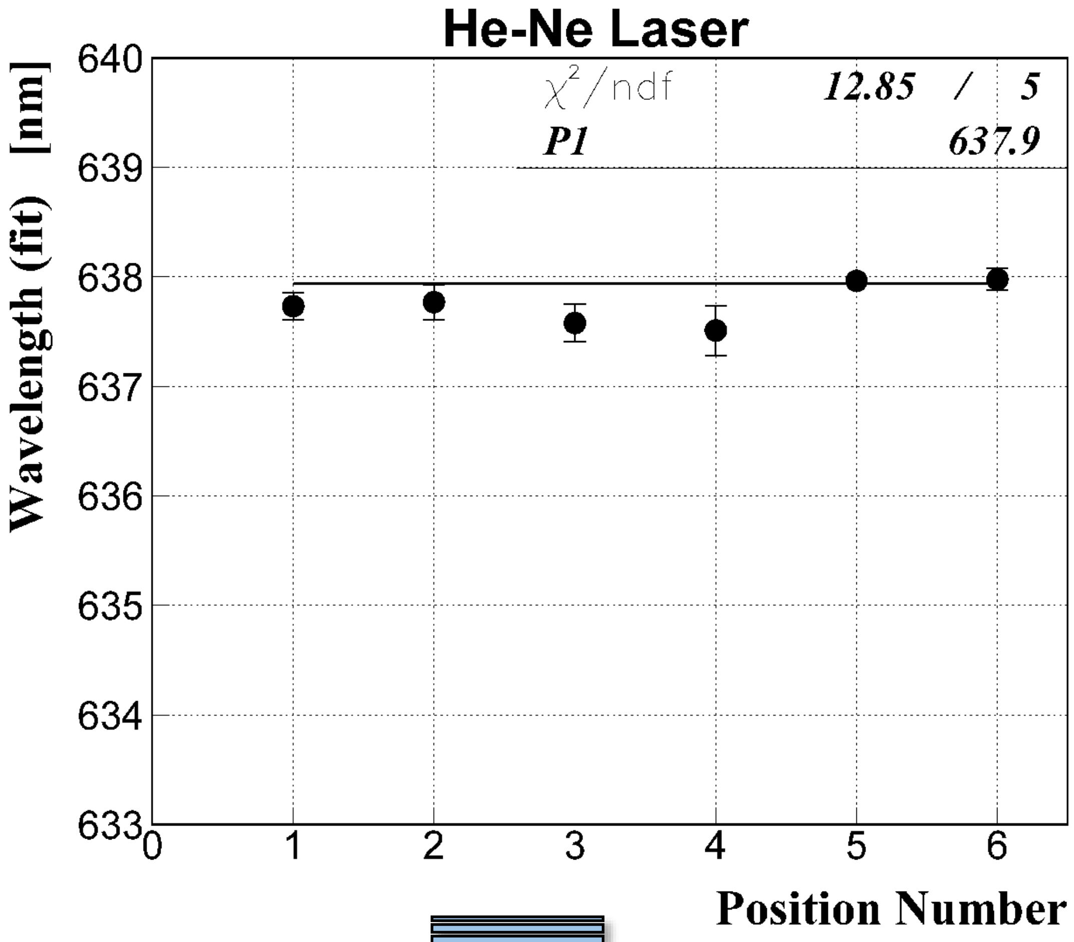
White board

Hyperspectral camera

He-Ne Red Laser

Using a He-Ne Laser (632.8 nm)



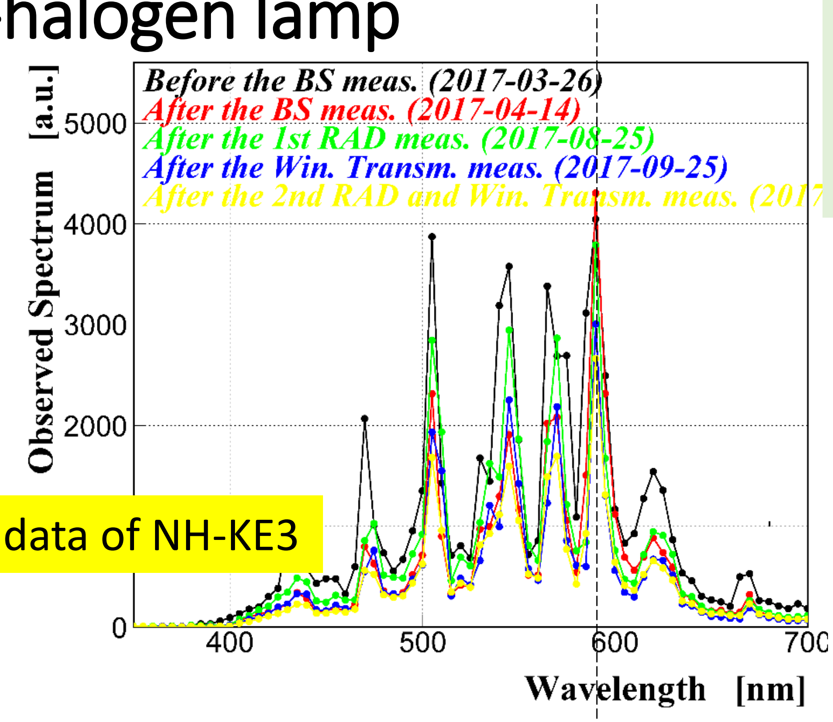


Correction by "-5.1 nm"

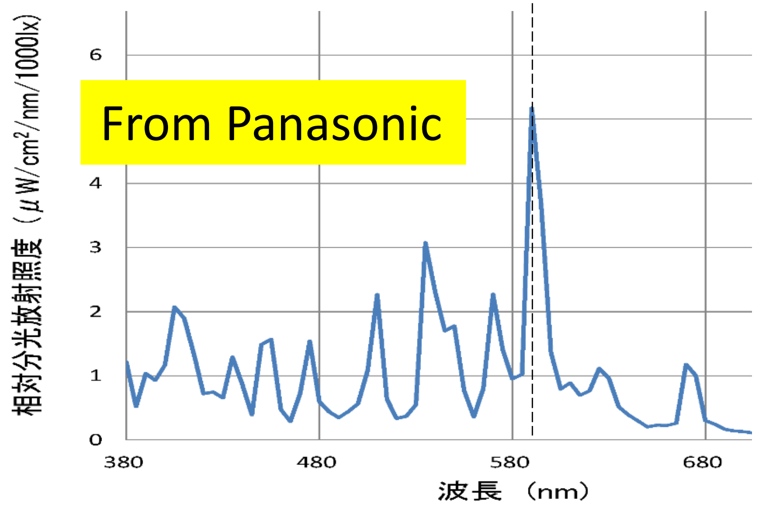
Check of the wavelength calibration using a multi-halogen lamp

- Made of Panasonic
- Model: MF400LBUSCN
- Included elements
  - ① Sodium (Na)
  - ② Thallium (Tl)
  - ③ Indium (In)
  - ④ Scandium (Sc)
  - ⑤ Lithium (Li)

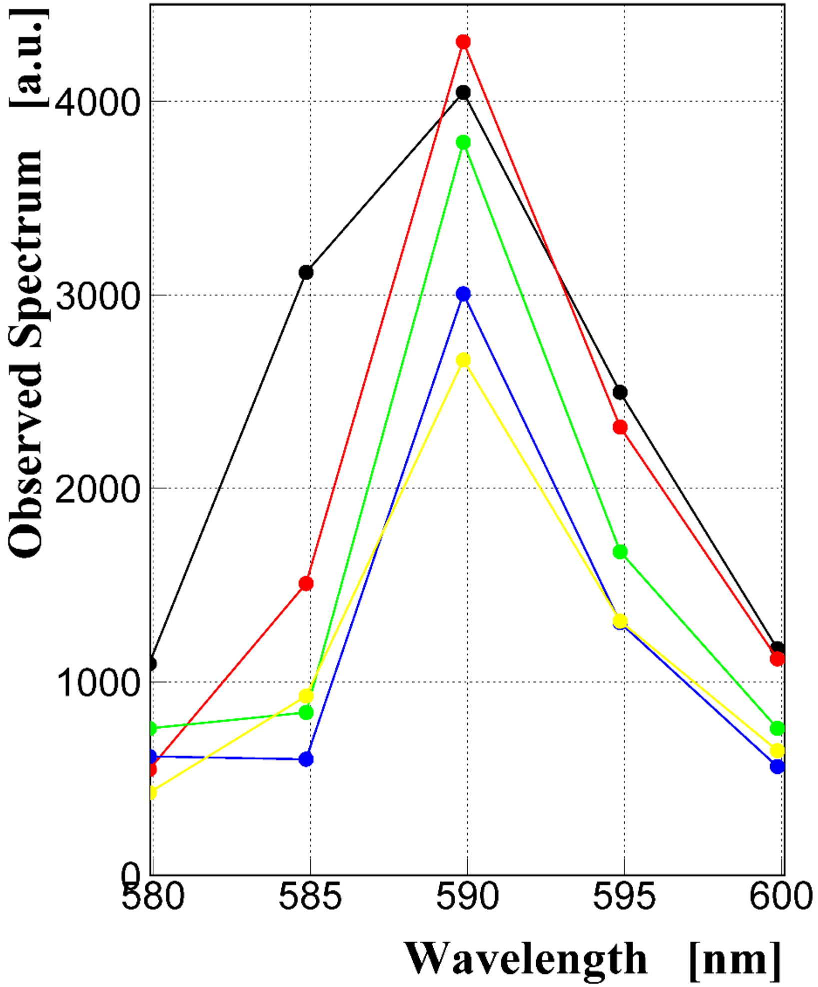
Raw data of NH-KE3



From Panasonic

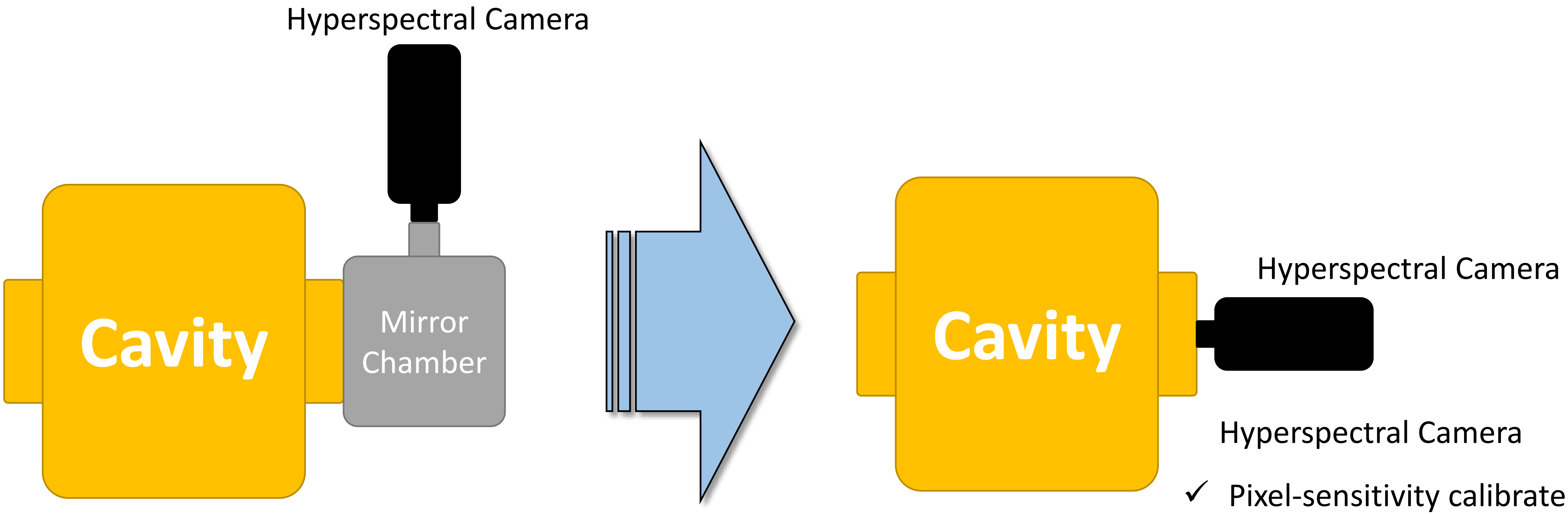


We confirmed that the peak of the Na D-lines (589.0 nm, 589.6 nm) did not change before and after any measurements.



Measurement of Wavelength Dependence of Transmissivity of the Mirror Chamber

Correction for the Mirror-Chamber Transmissivity



- ✓ Pixel-sensitivity calibrated
- ✓ Wavelength calibrated

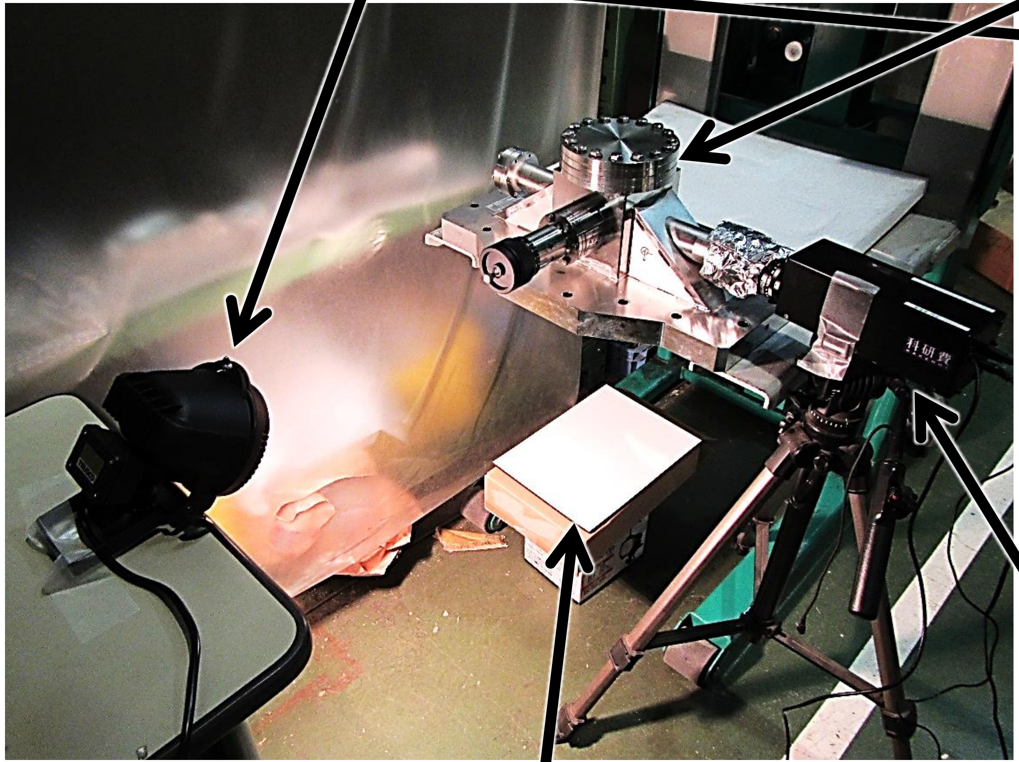
Observed Spectrum

Transmissivity of the Mirror Chamber

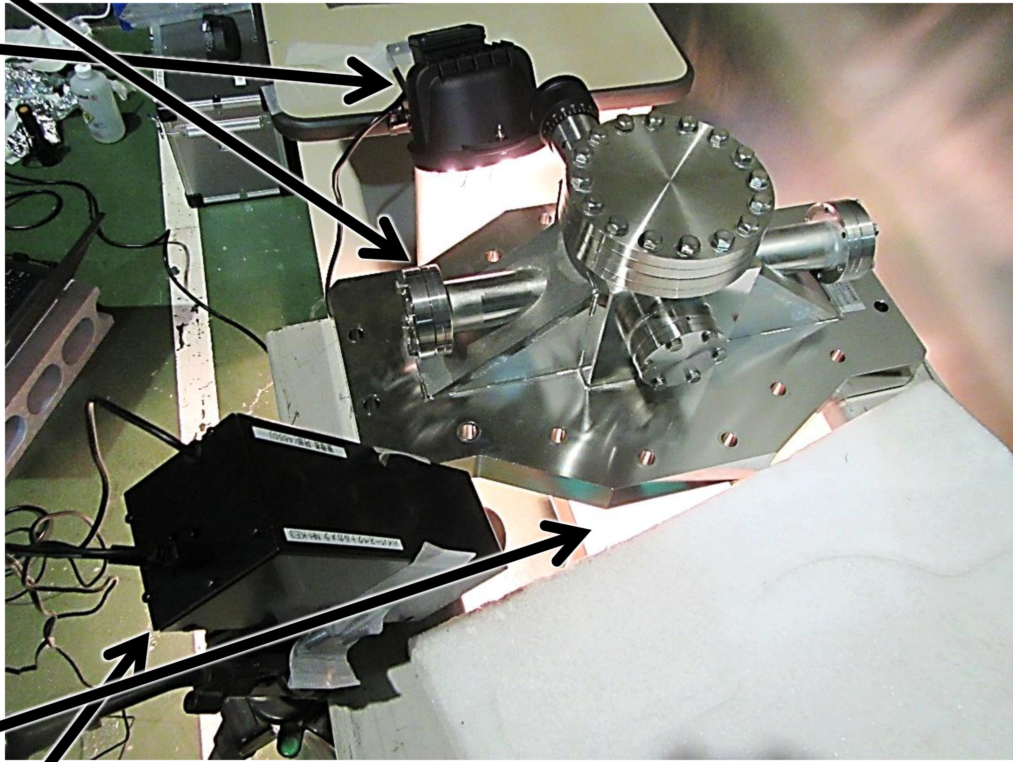
Xenon Lamp

Mirror Chamber

=



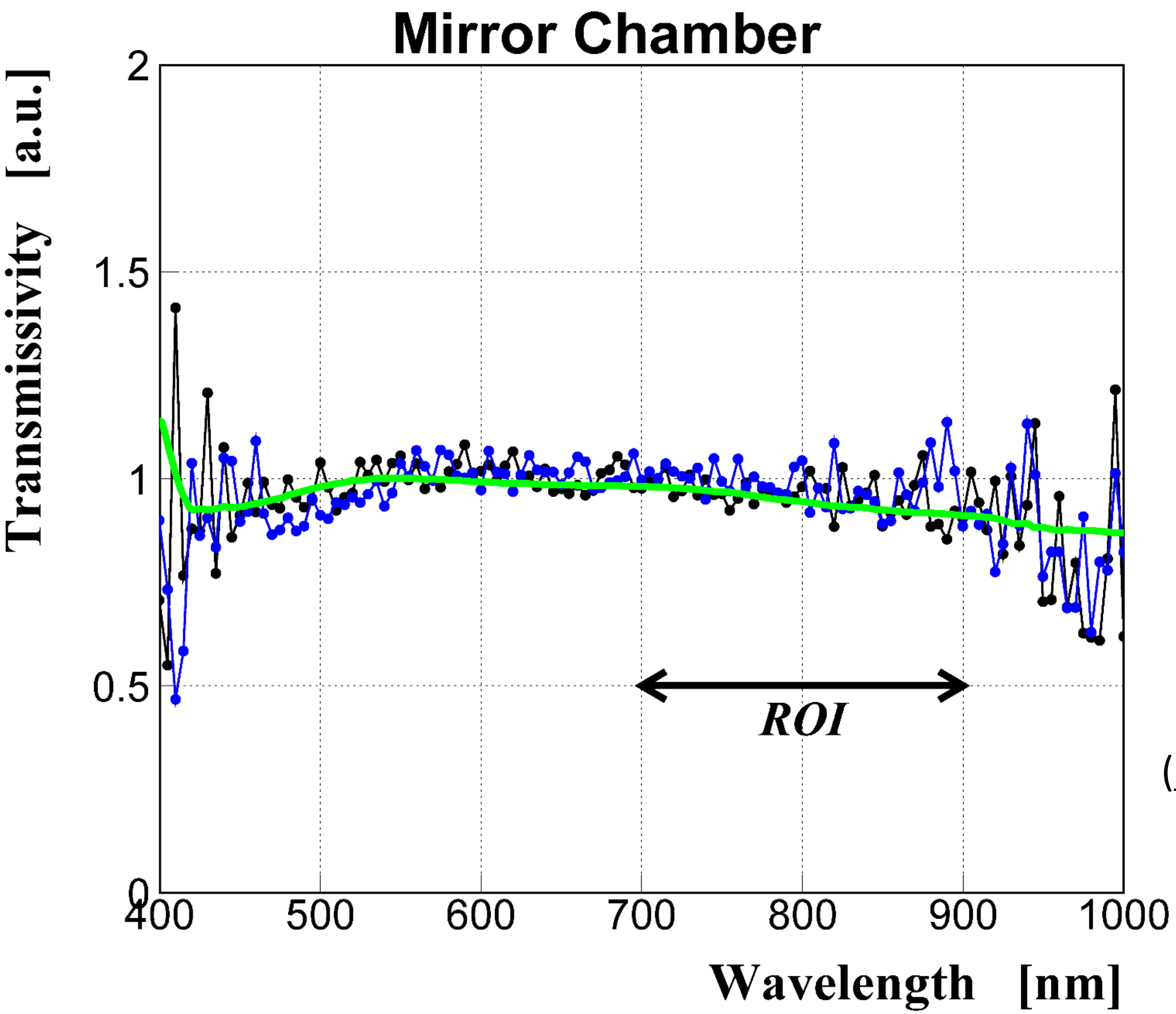
/

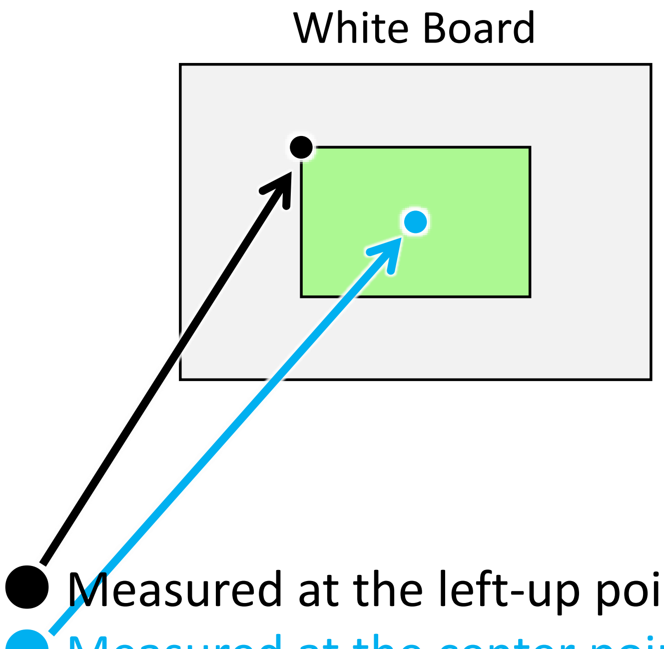


Hyperspectral Camera

White Board

Measurement of the Transmissivity of the Mirror Chamber





Measured at the left-up point

Measured at the center point

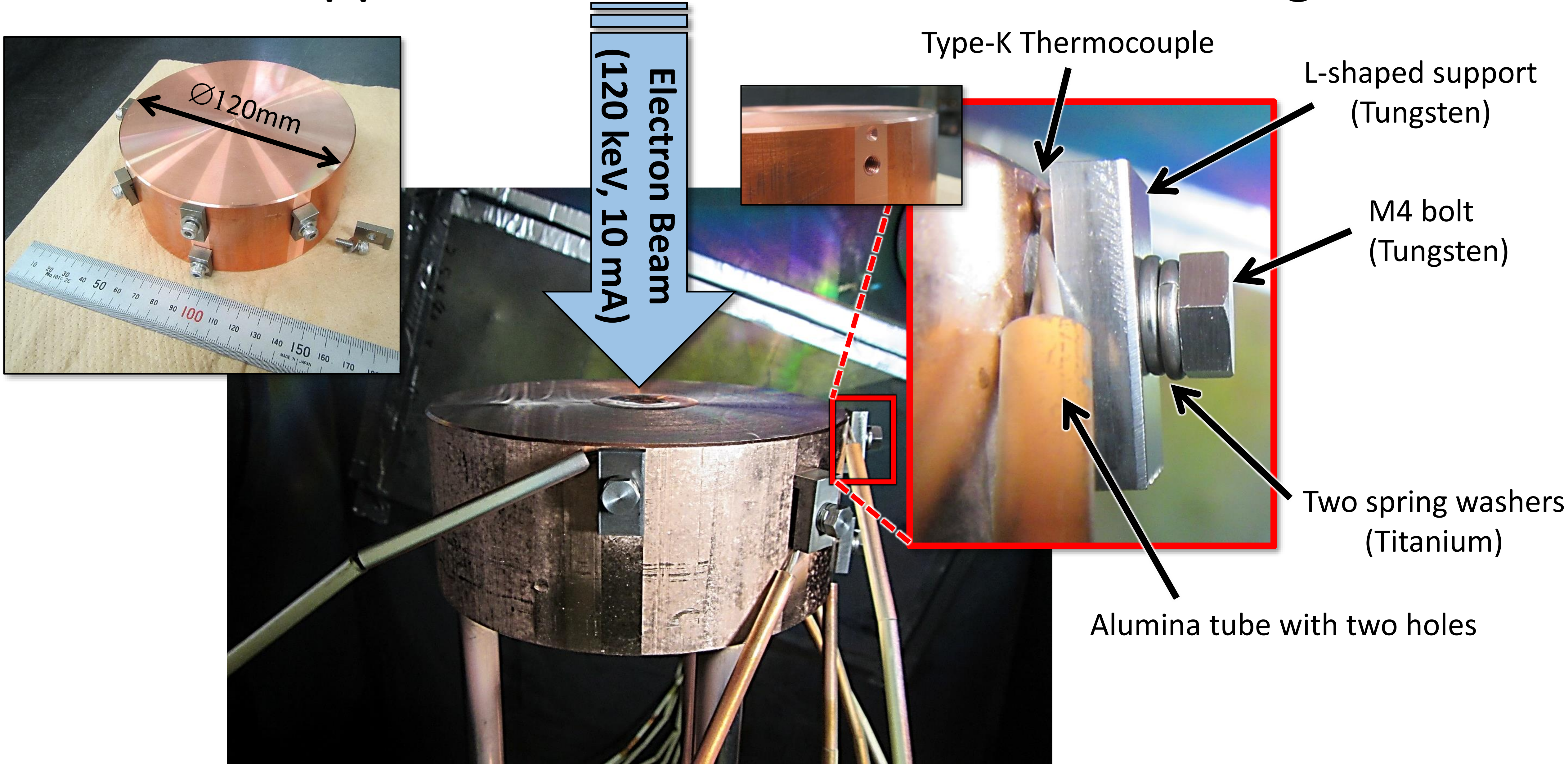
Average for the central green region

(ROI: Region Of Interest)

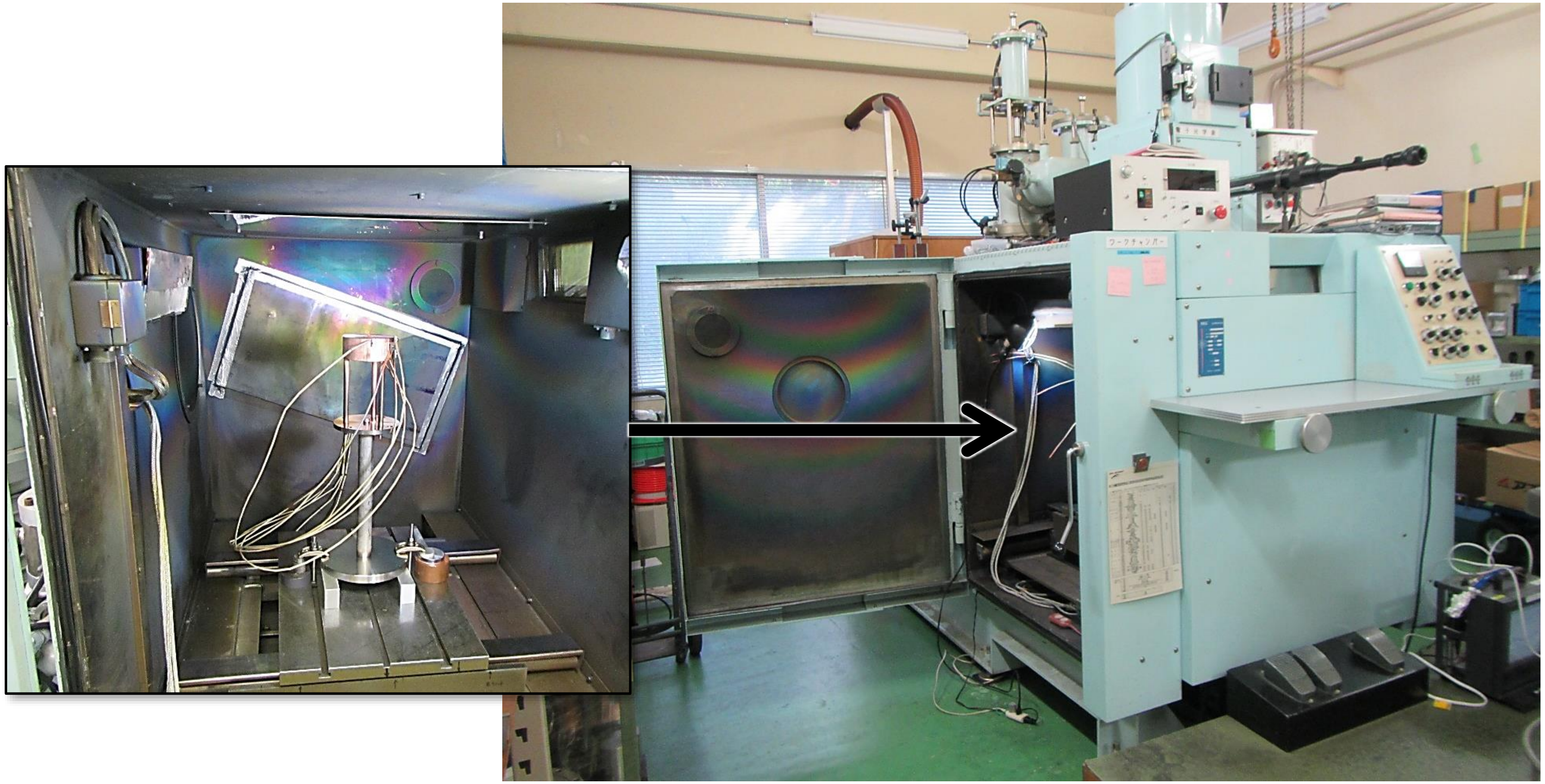
Only the wavelength dependence is used in this study; the absolute value has no meaning.

Measurement of Thermal-Radiation Spectra

Copper Block to be irradiated for heating



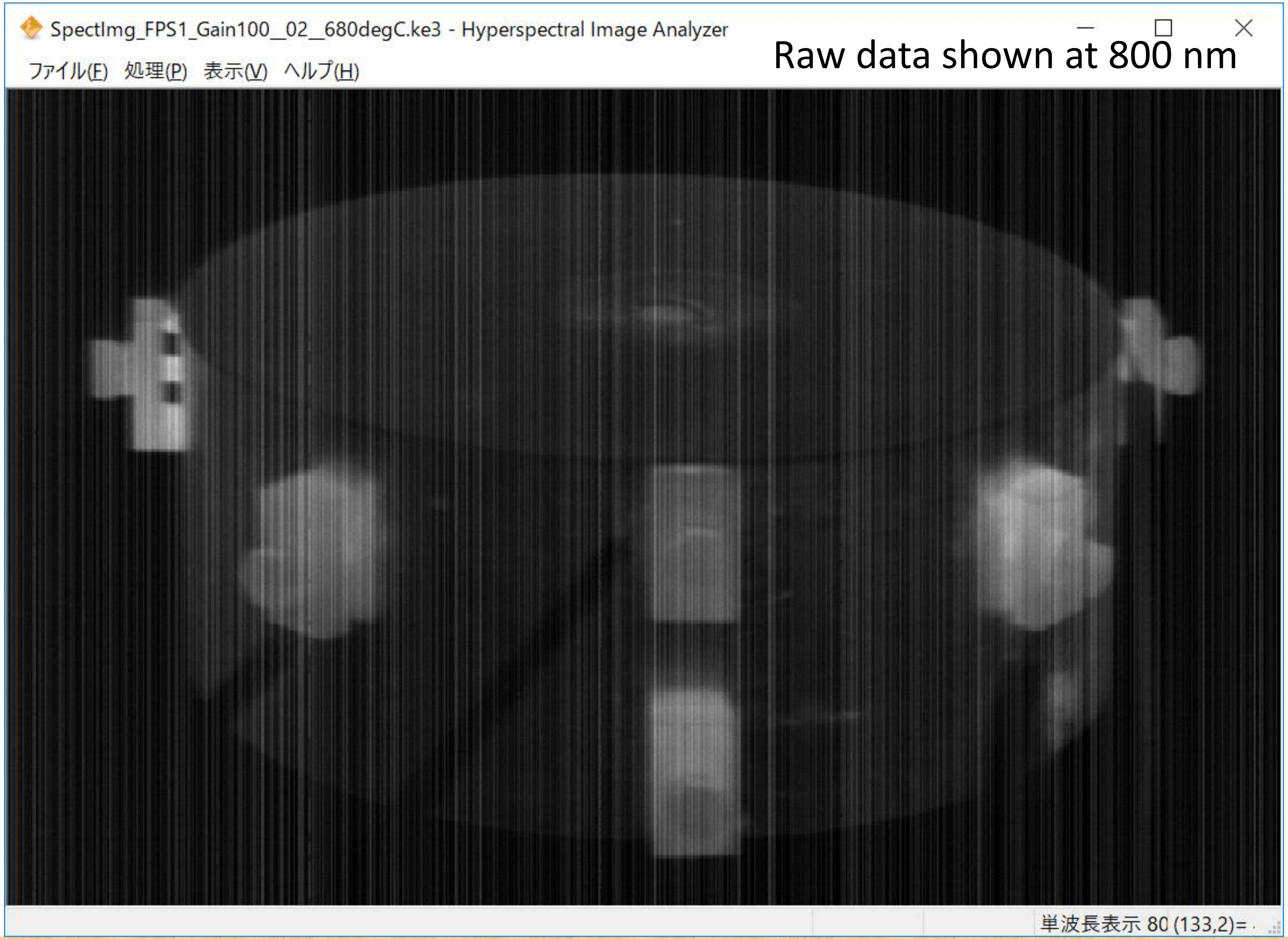
Electron-Beam-Welding machine at KEK Mechanical Engineering Center was used.



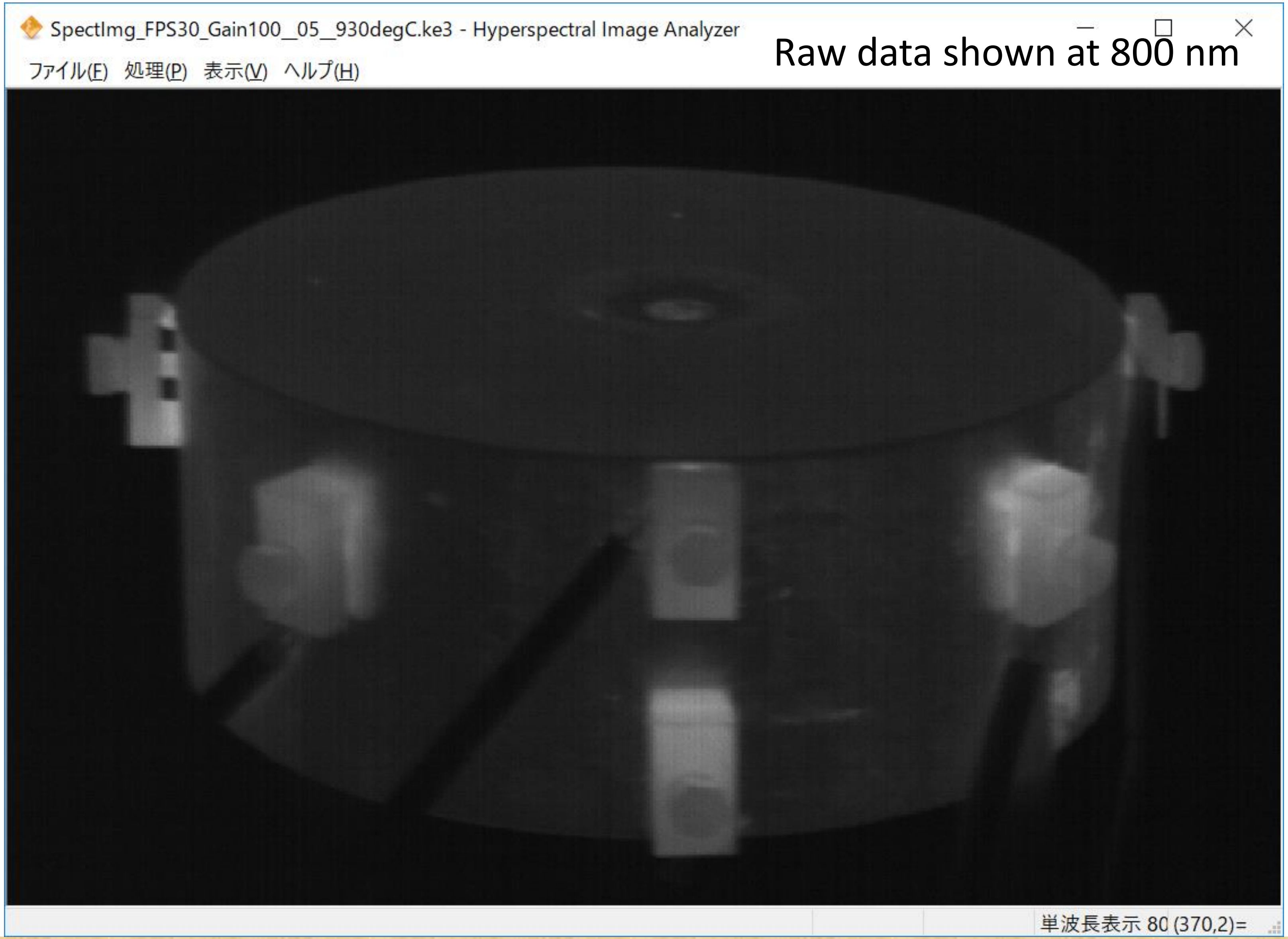
~580 degC

Raw data shown at 800 nm

~680 degC

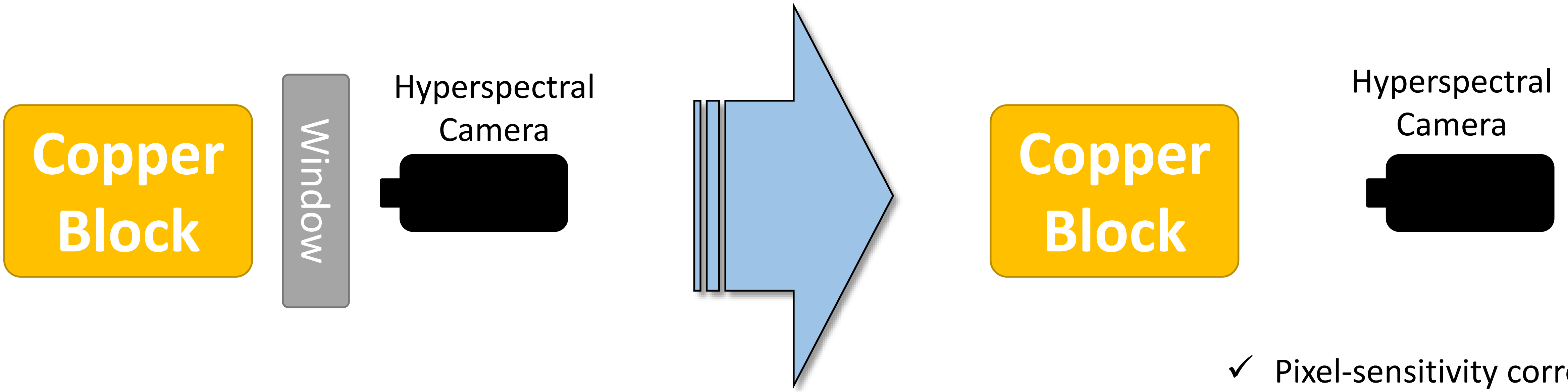

SpectImg_FPS1_Gain100__02__680degC.ke3 - Hyperspectral Image Analyzer
ファイル(F) 処理(P) 表示(V) ヘルプ(H)
Raw data shown at 800 nm
単波長表示 80 (133,2)=

~930 degC



Raw data shown at 800 nm

Correction on the Window Transmissivity of the EBW machine



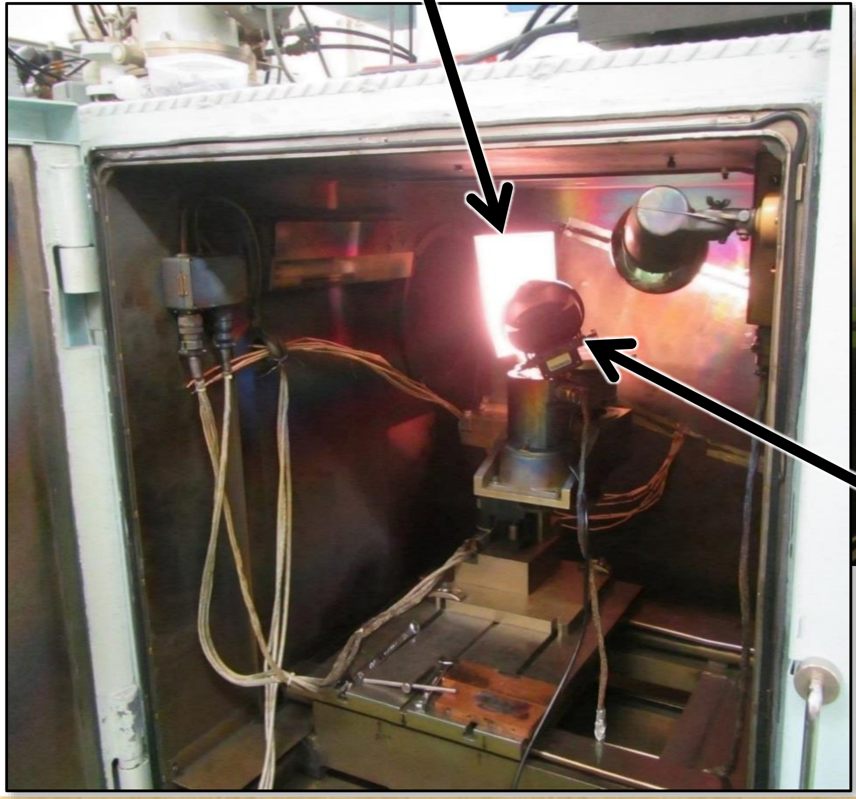
- ✓ Pixel-sensitivity corrected
- ✓ Wavelength calibrated

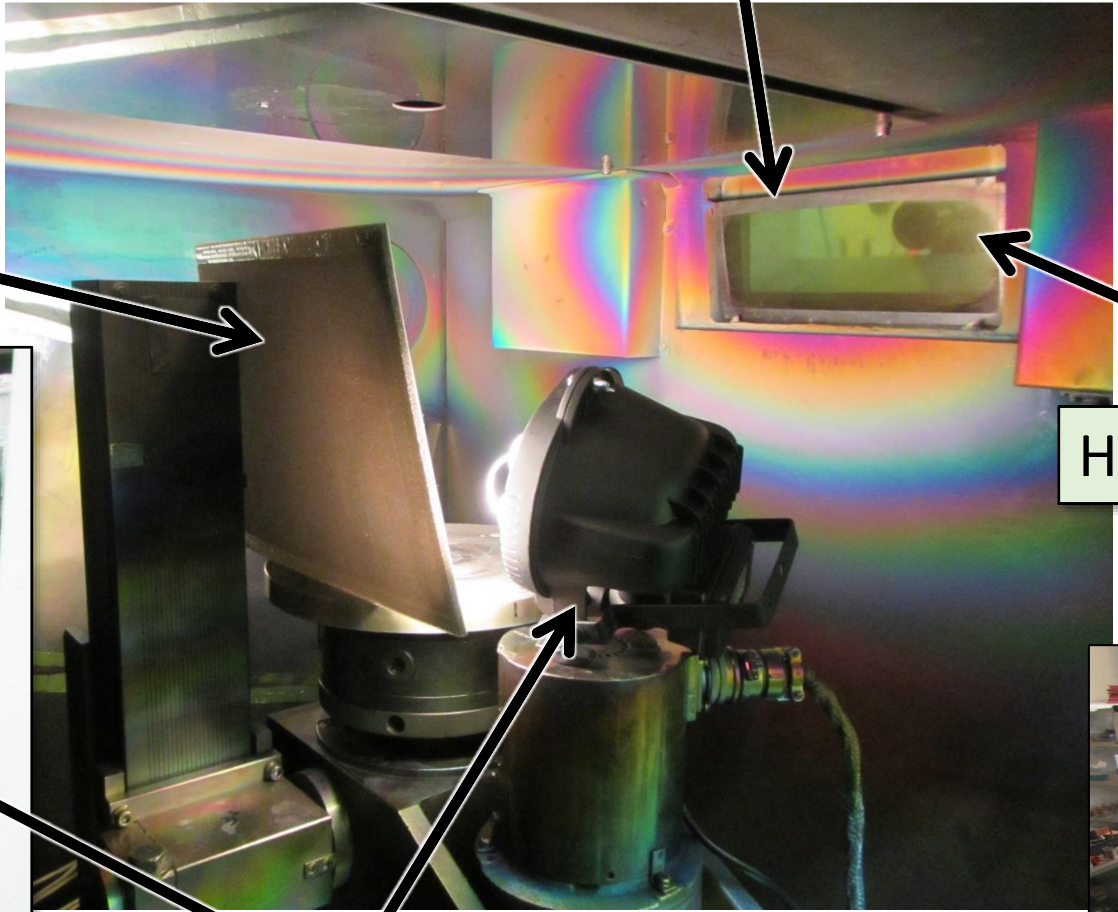
Observed Spectrum

Measurement of the Transmissivity of the EBW-Machine Window

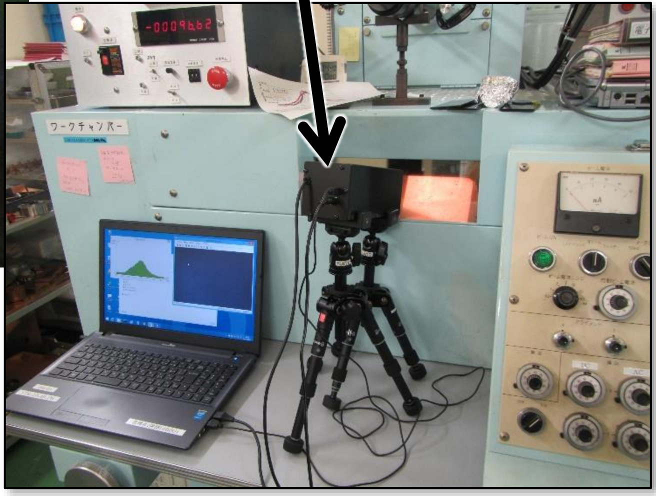
Window (= Lead glass + TEMPAX)

White Board

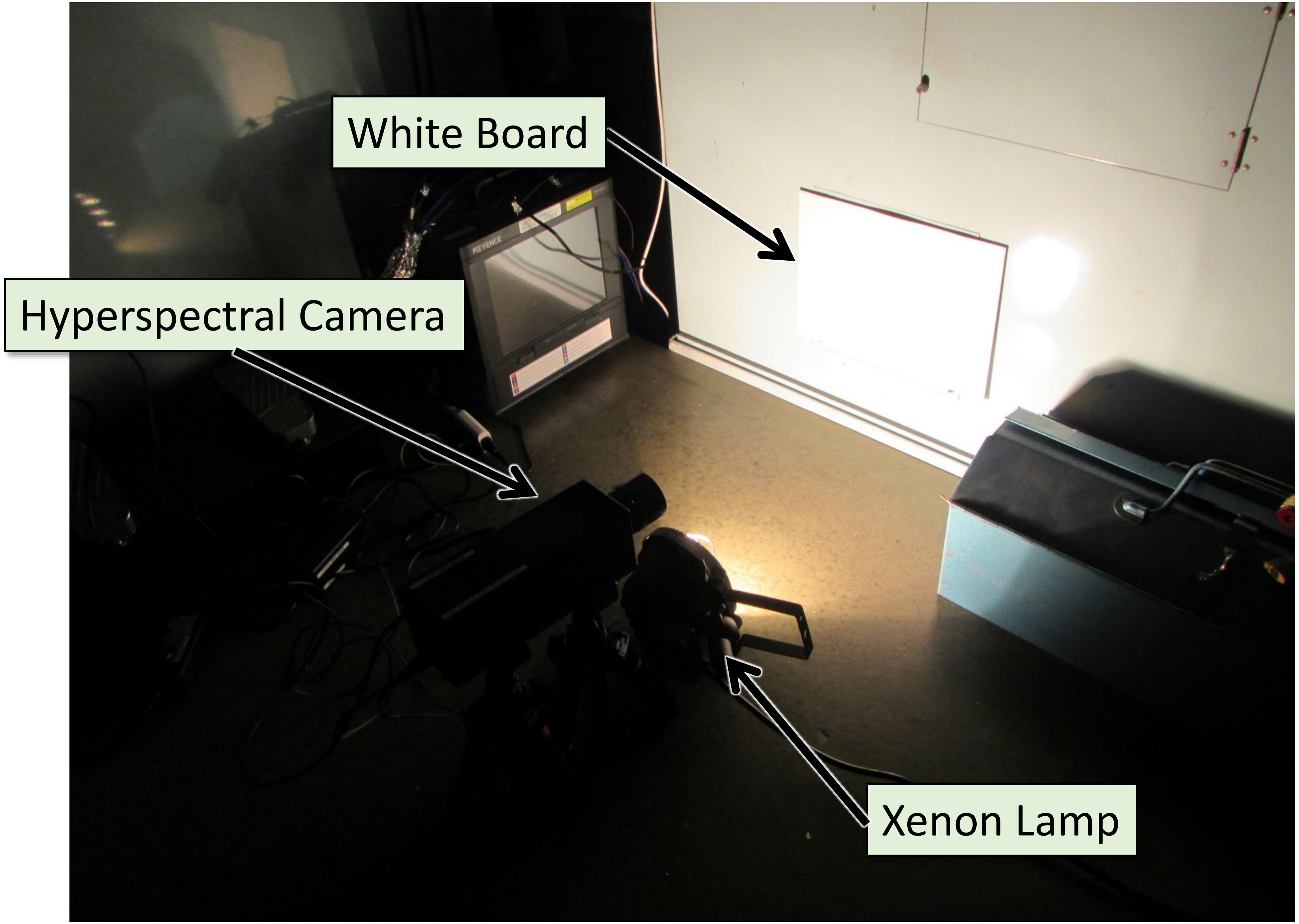




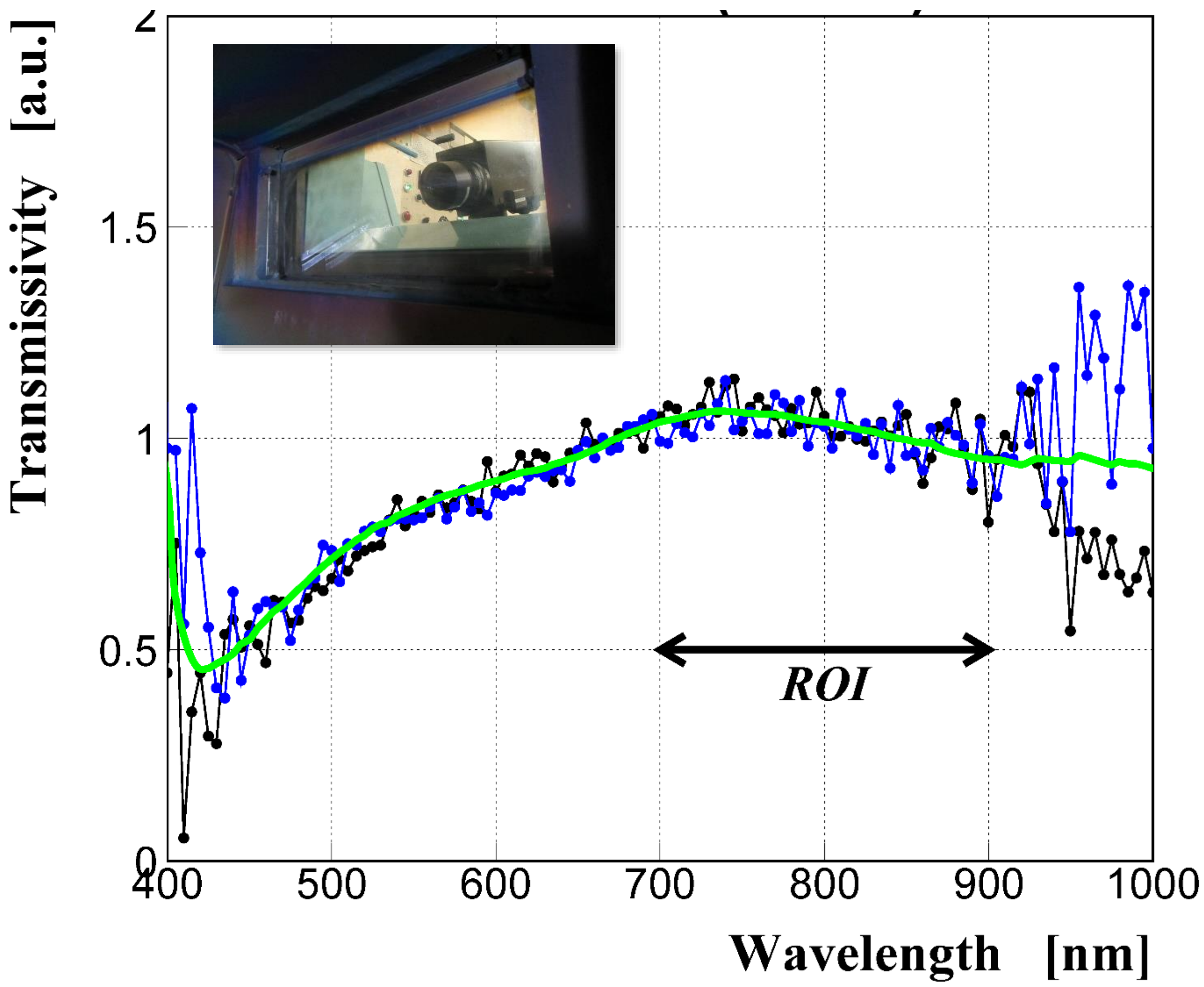
Hyperspectral Camera

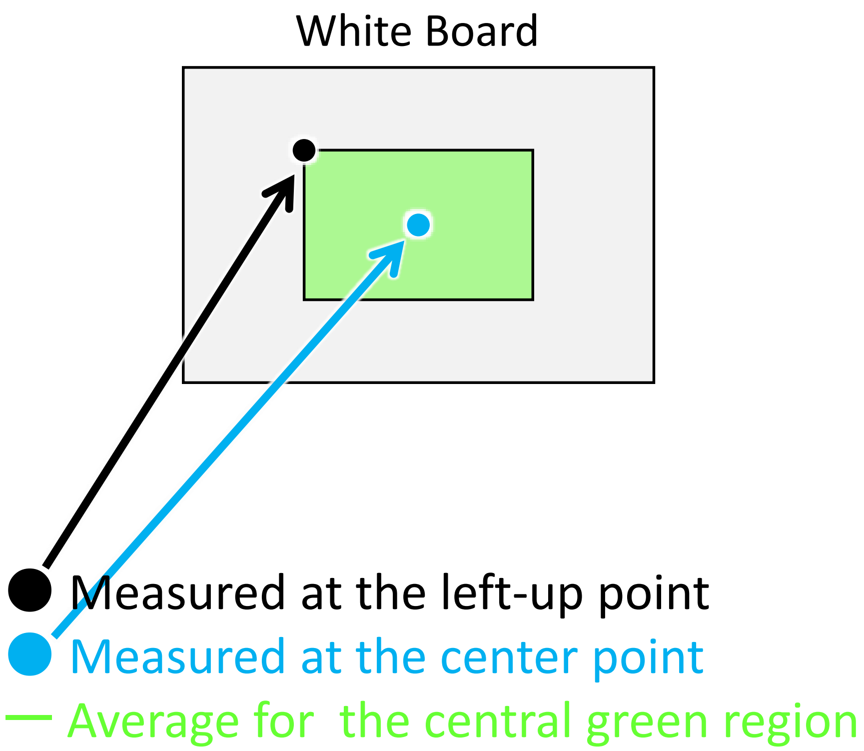


Xenon Lamp


White Board
Hyperspectral Camera
Xenon Lamp
KEYENCE

Measurement of the Transmissivity of the EBW-Machine Window





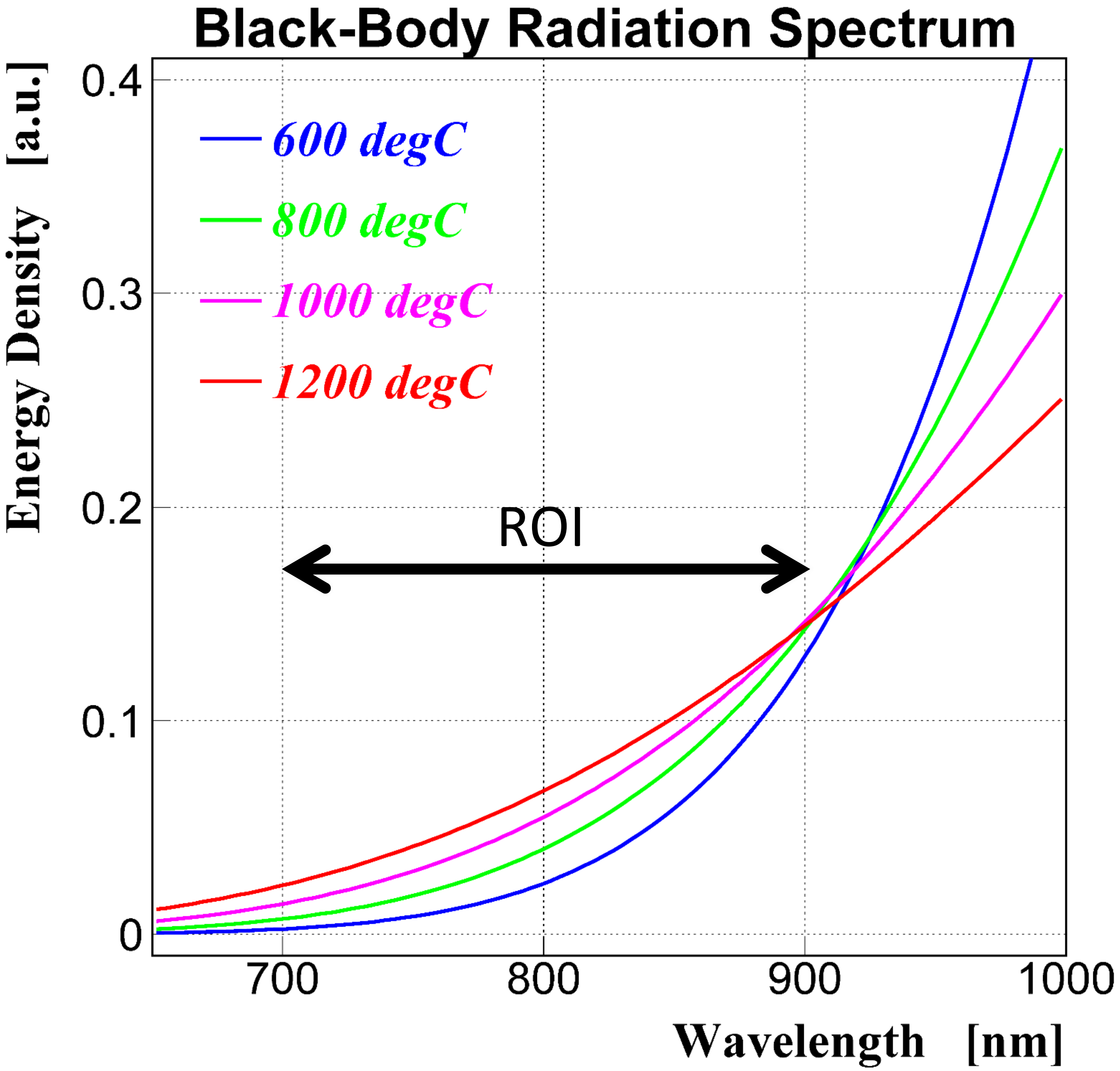
(ROI: Region Of Interest)

Only the wavelength dependence is used in this study; the absolute value has no meaning.

Correction factor to convert observed spectra to physical spectra

using the thermal-radiation measurement results

and Planck Formula: (Black-body radiation spectrum) $\propto \frac{1}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$

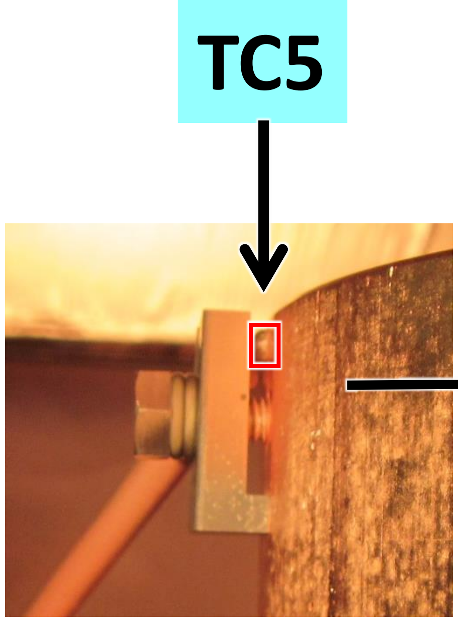


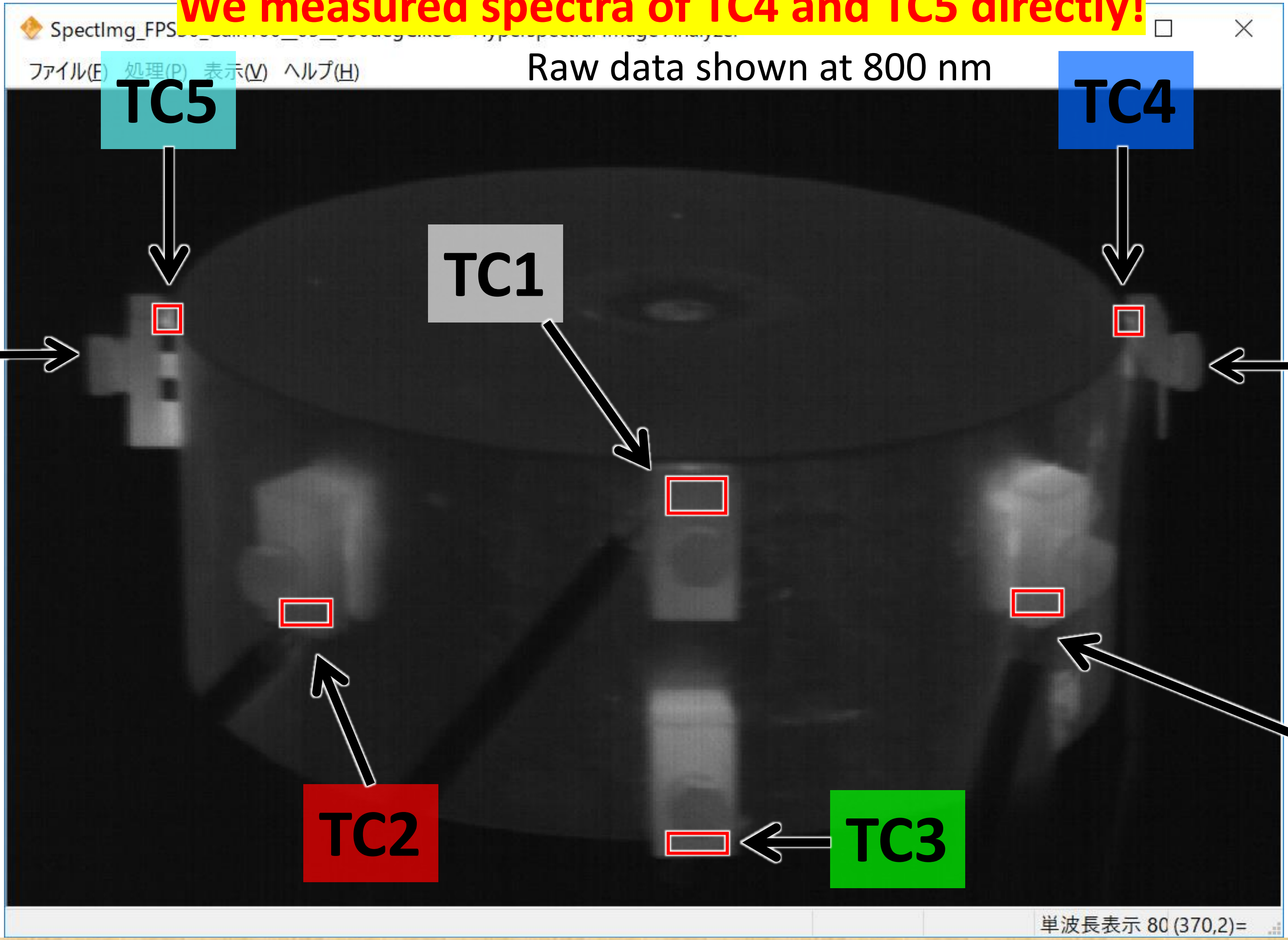
(ROI: Region Of Interest)

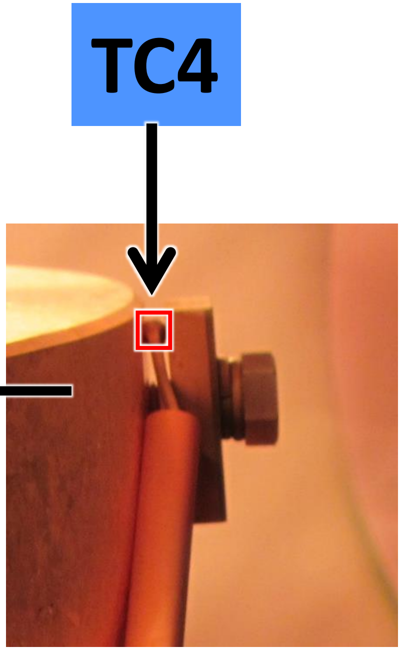
(TC : ThermoCouple)

Thermocouples and Meas. Region

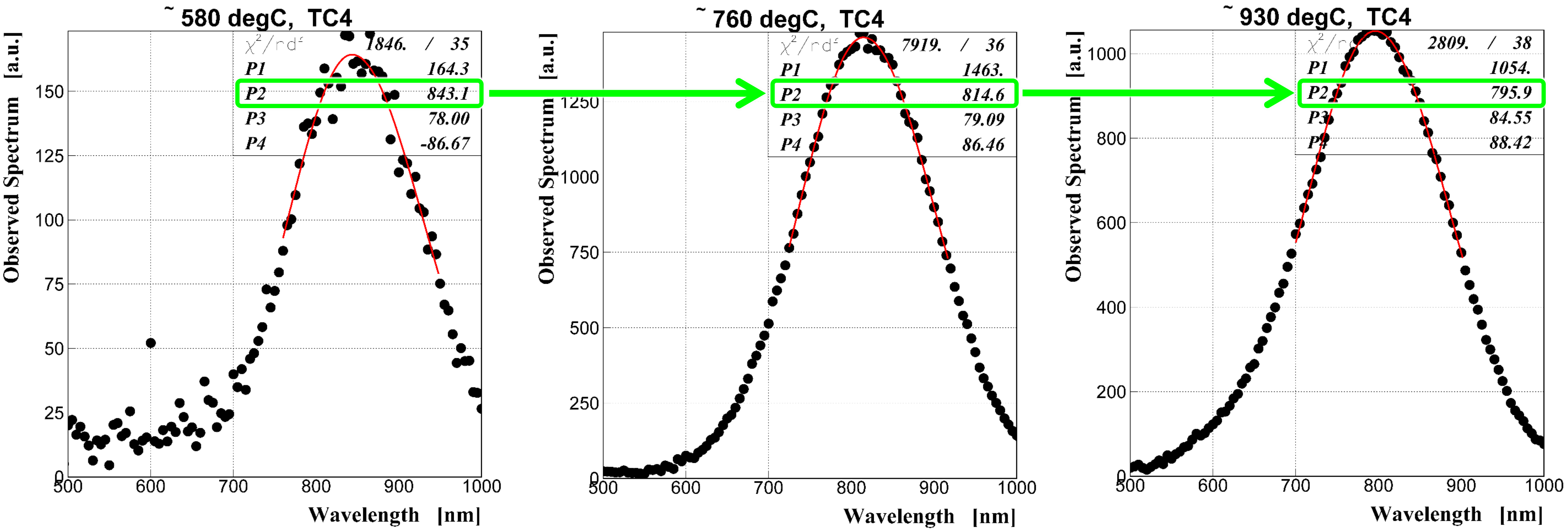
We measured spectra of TC4 and TC5 directly!





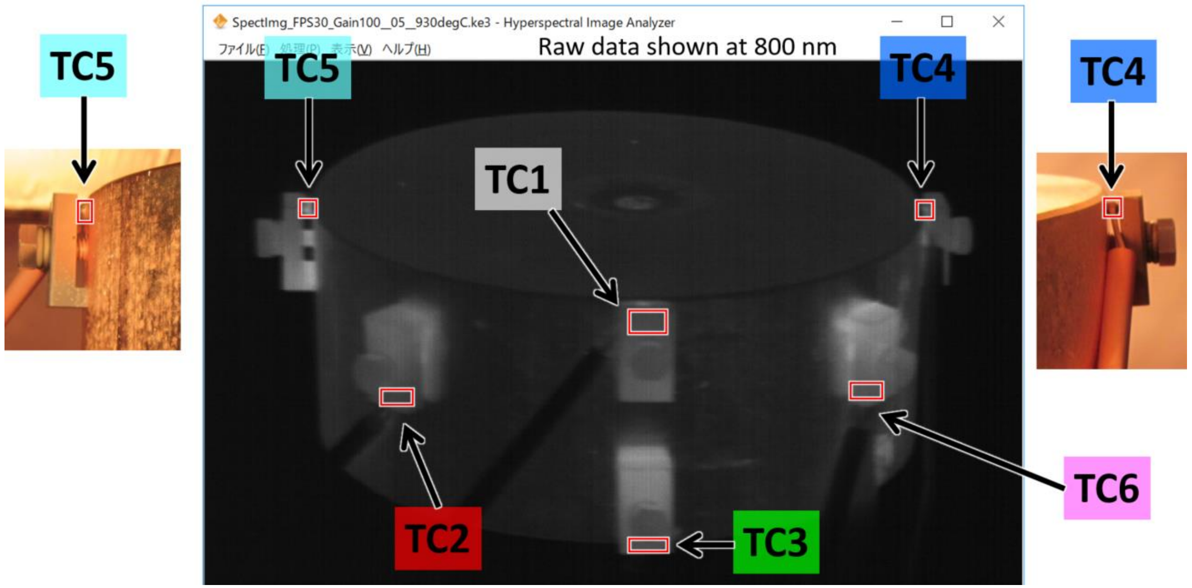


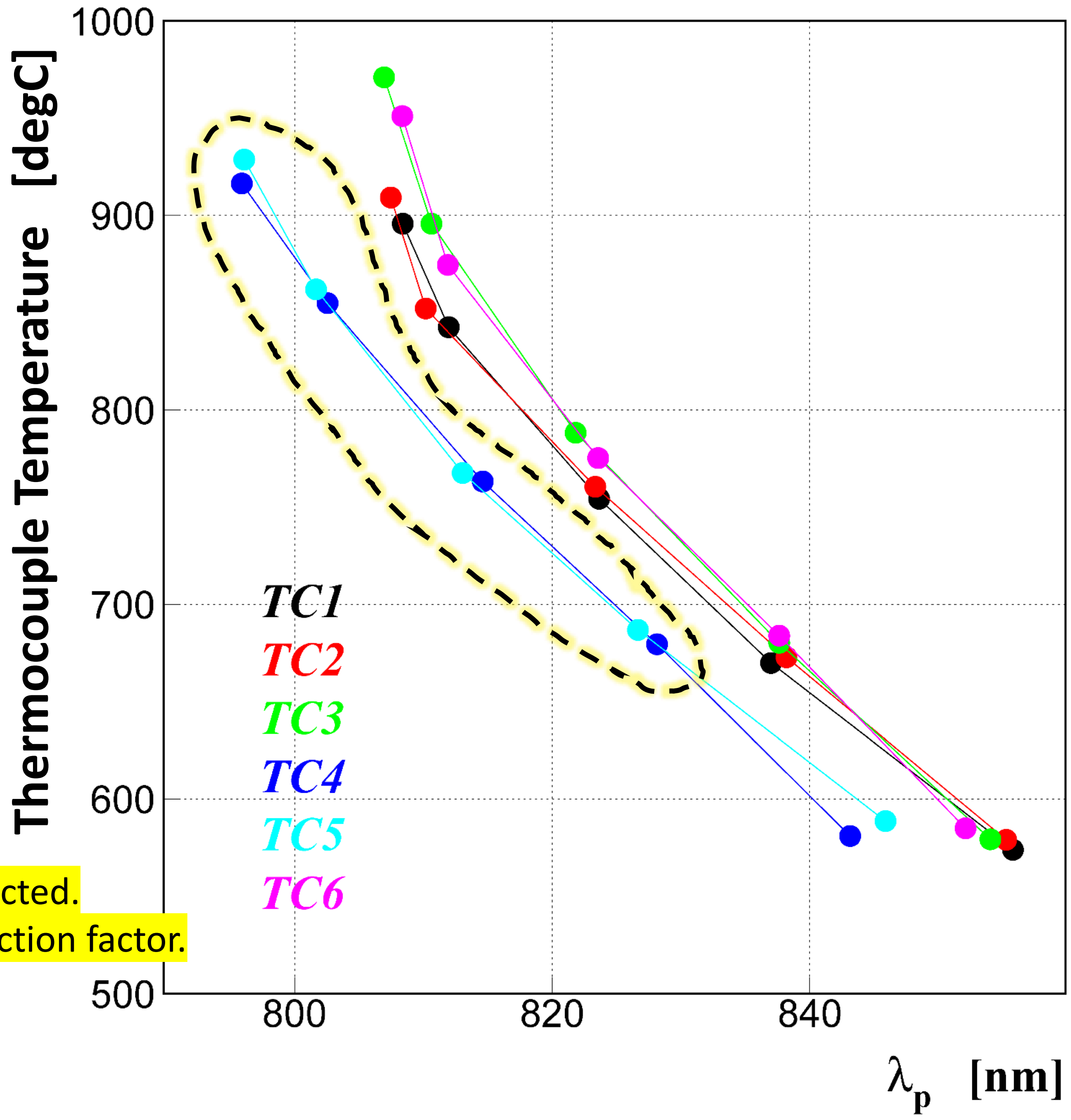
Peak position (λ_p) by fitting the observed spectrum with an asymmetric gaussian



After subtracting background spectrum with

- ✓ No beam irradiation
- ✓ Temperature of the copper block < 100 degC
- ✓ Cathode voltage ON (120 kV)



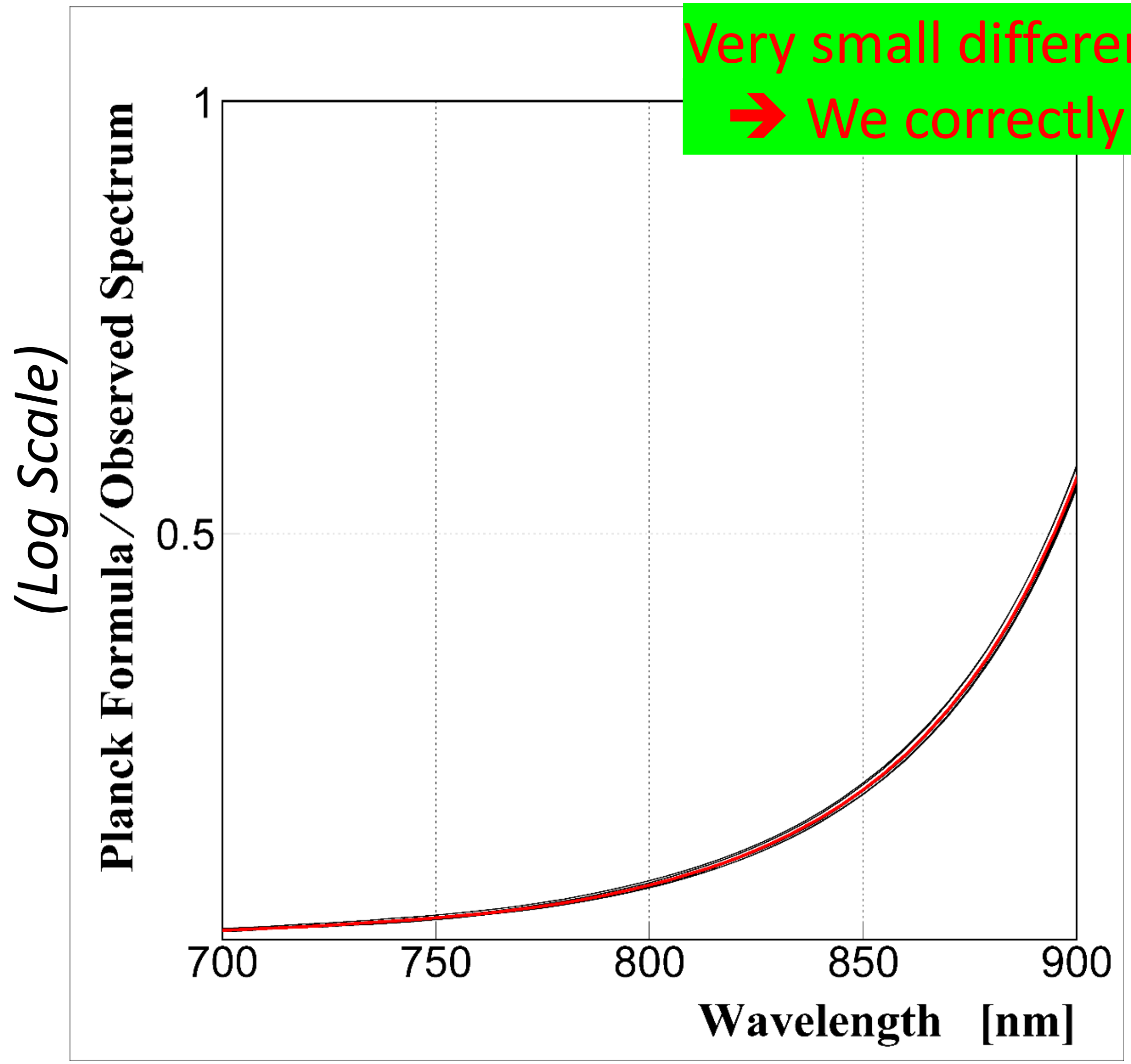


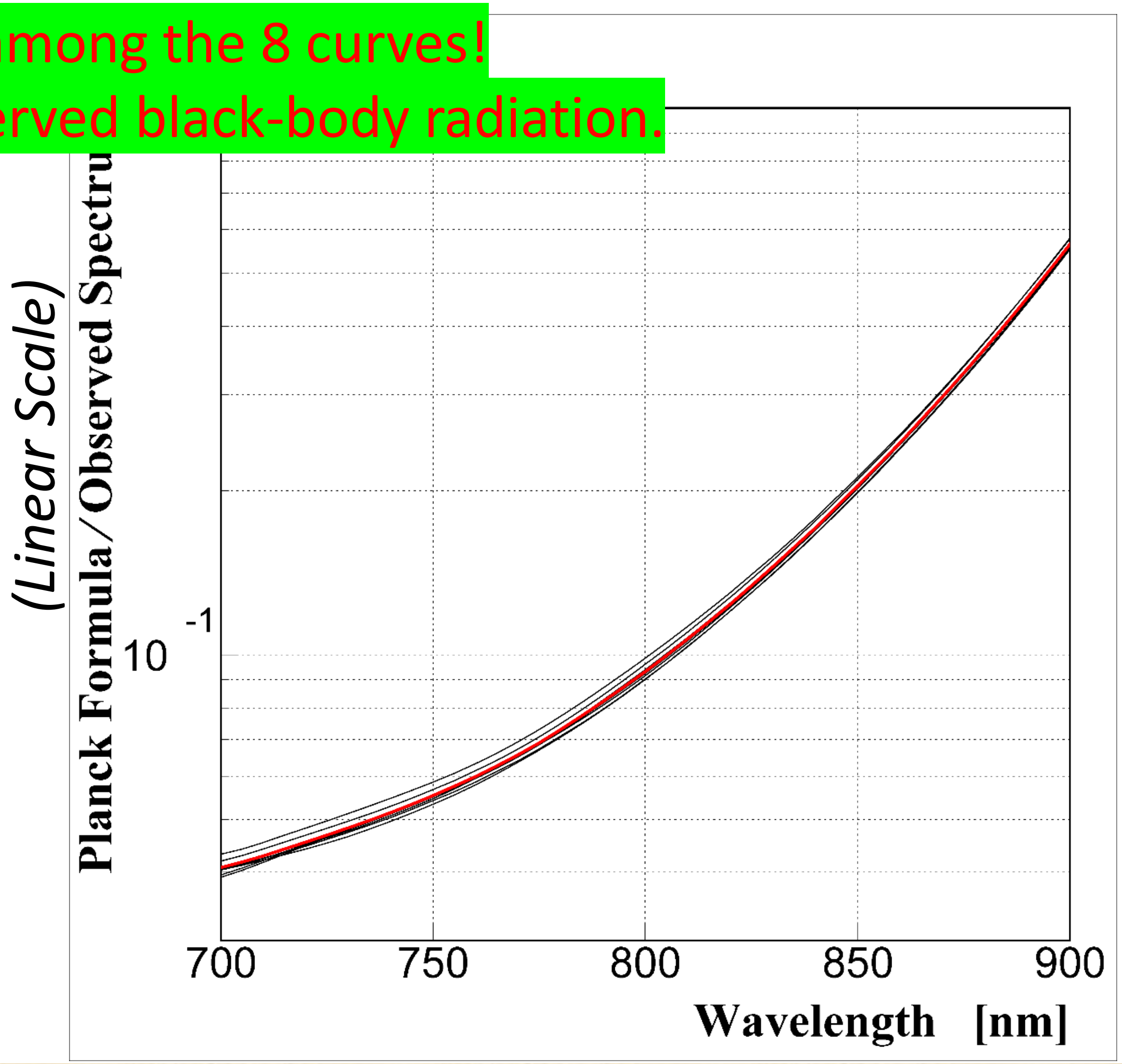
- ✓ The spectra for TC4,5 are different from the others, as expected.
- ✓ Only the data for TC4,5 will be used in calculating the correction factor.

(Correction factor) = (Planck Formula) / (Observed Spectrum)

— *Average to be used in the following analyses*

Very small difference among the 8 curves!
➔ We correctly observed black-body radiation.





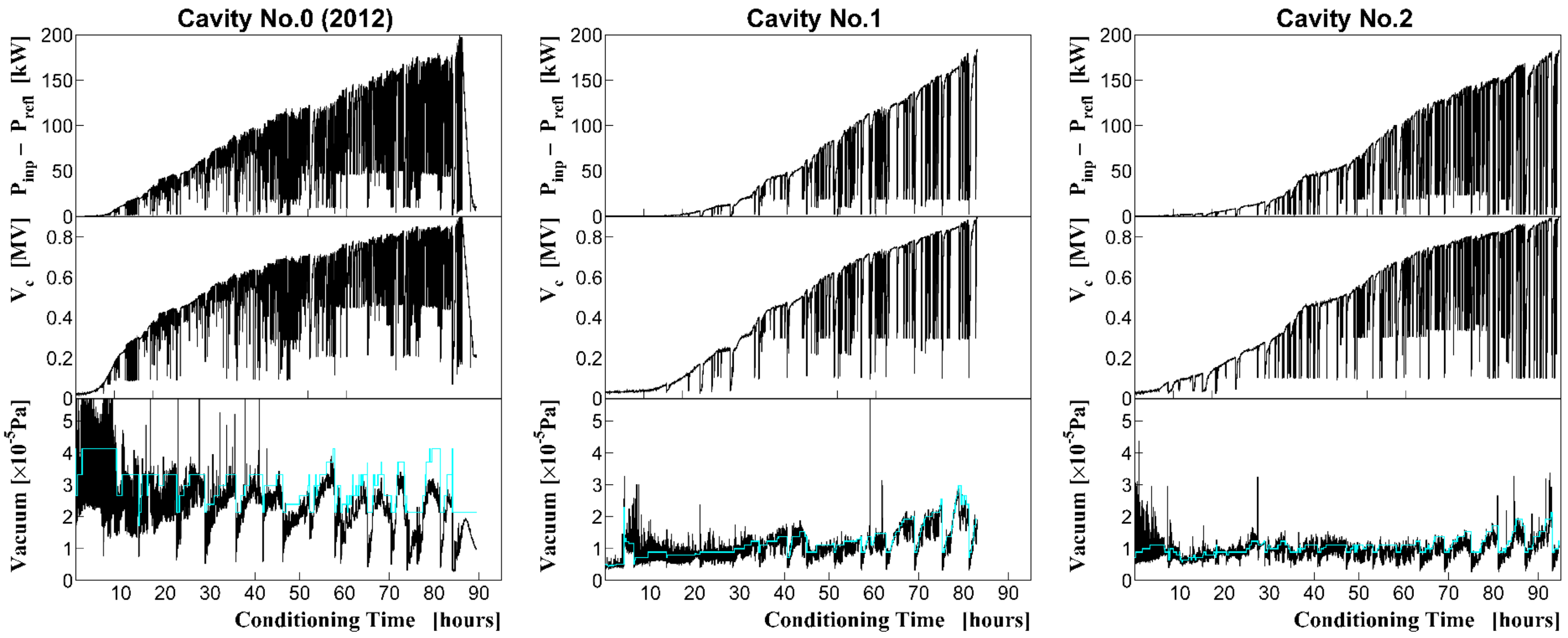
Observation of Bright Spots during High-Power Operation of DR Cavity No.0

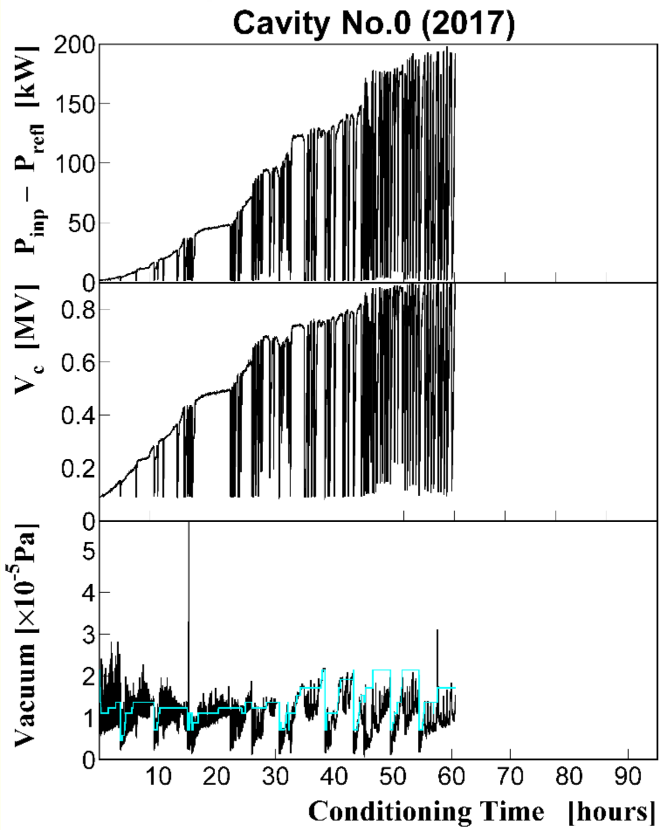
This high-power test was performed by SuperKEKB-RF / ARES Cavity group
(T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi, and K. Yoshino).

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

March, 2017

Conditioning Histories up to V_c = 0.90 MV/cavity





DR Cavity No.0 showed good performance comparable with No. 1, 2.

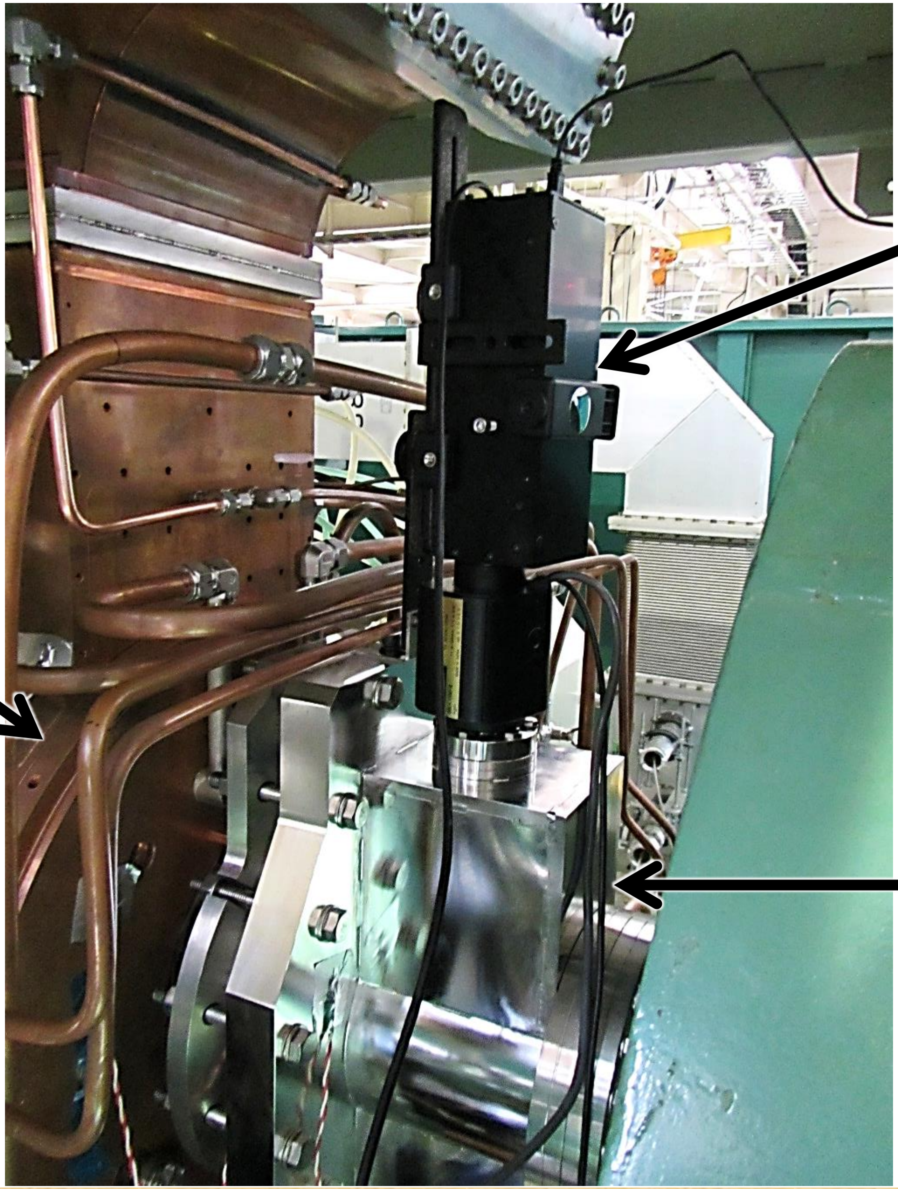
controlled automatic aging.

(1) Reached V_c = 0.90 MV (radiation limit) smoothly.
(2) Maintained V_c = 0.90 MV for six hours..

Measurement Setup

Hyperspectral Camera

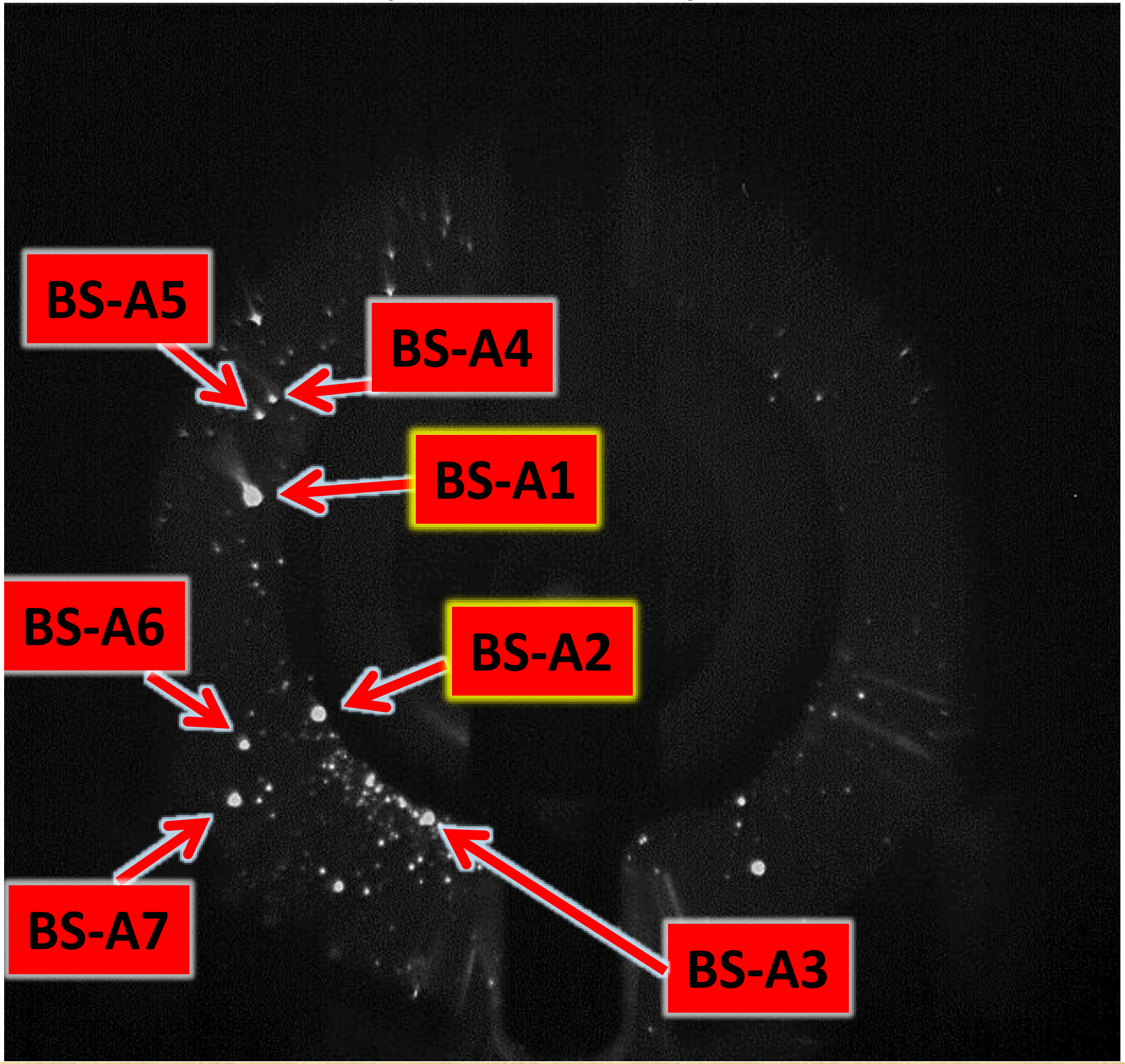
DR Cavity No.0



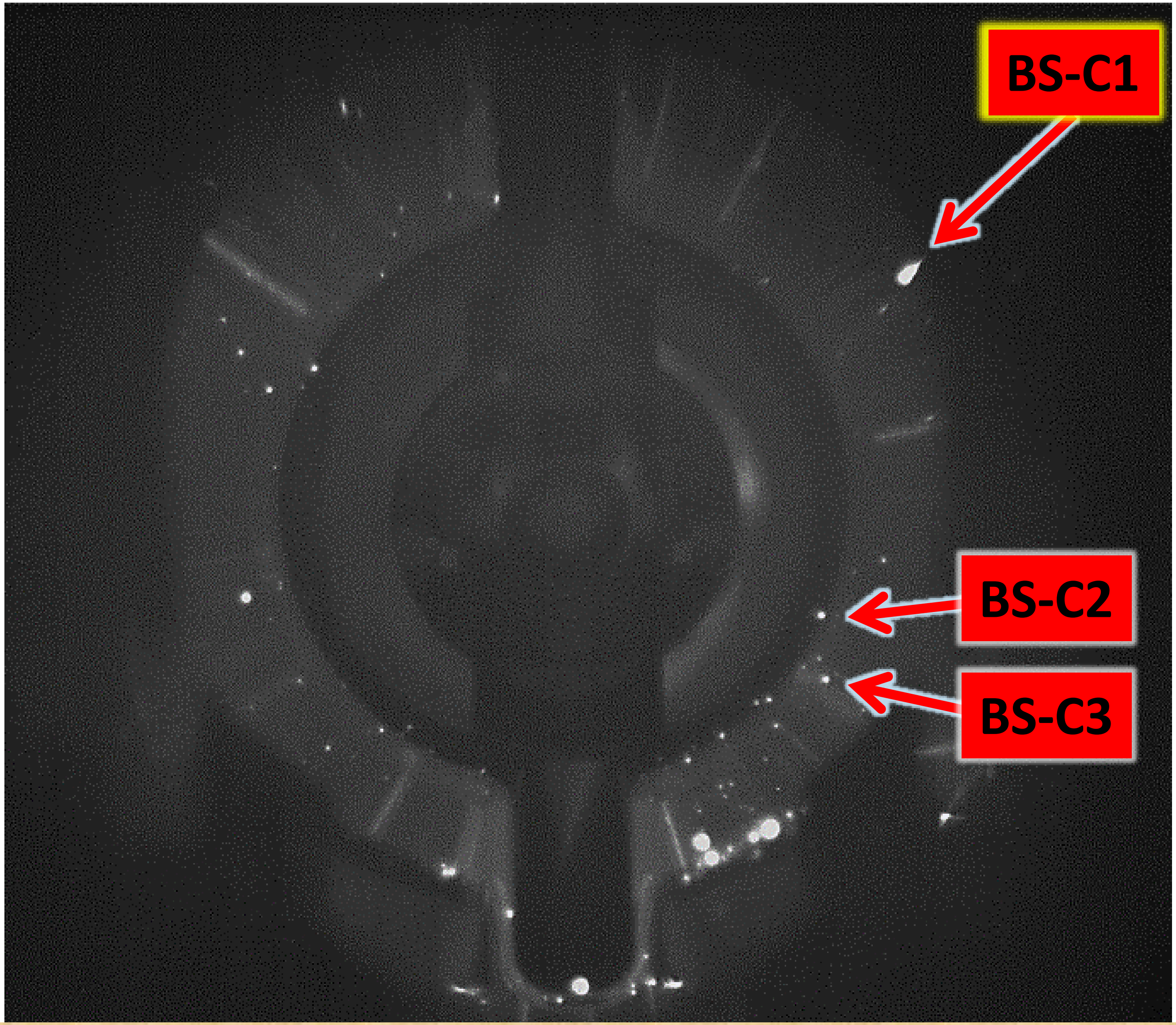
Mirror Chamber

Bright Spots (BSs) during High-Power Operation

Upstream Endplate

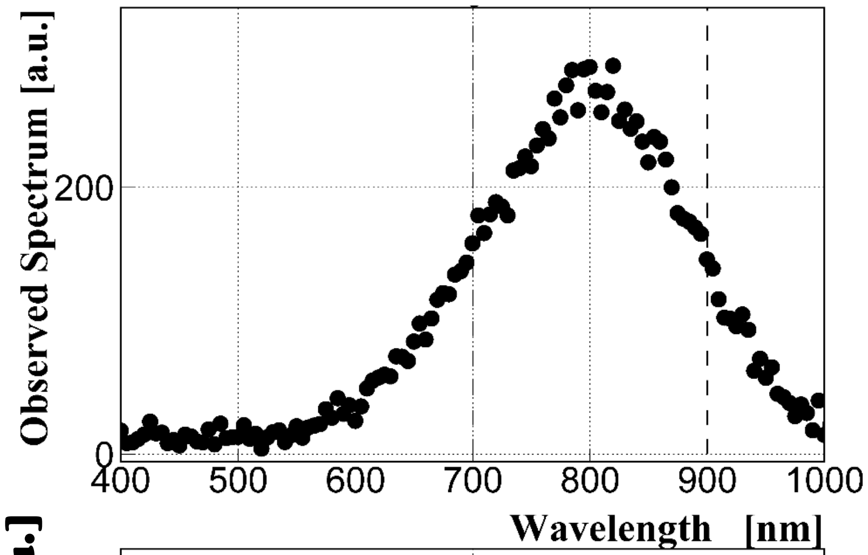


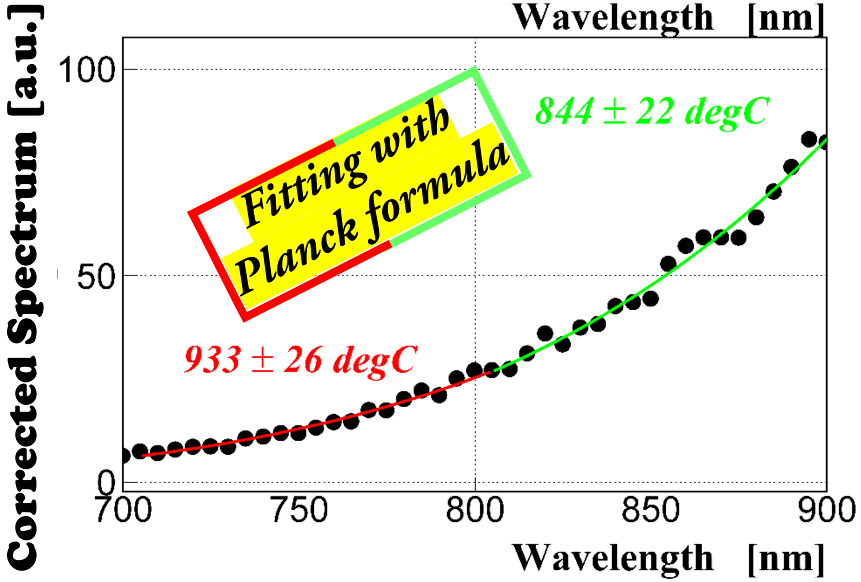
Downstream Endplate



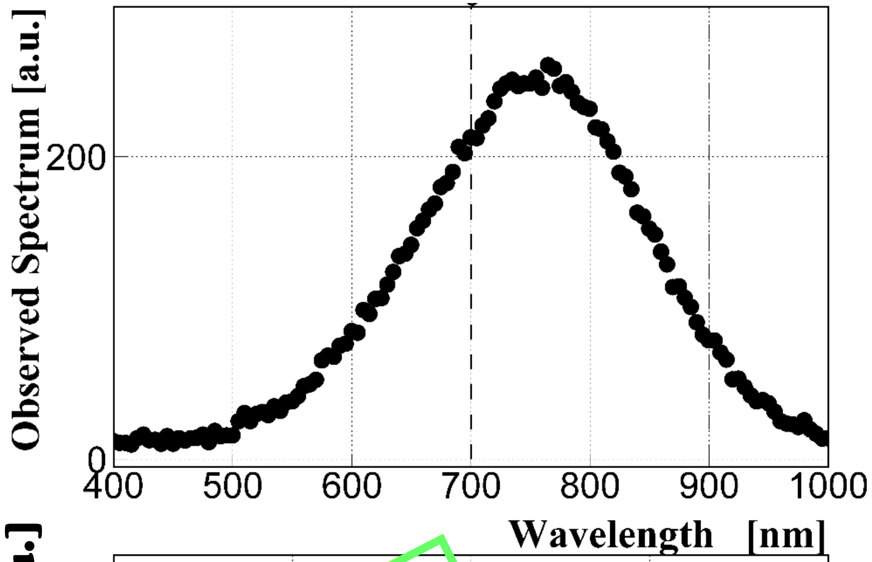
Spectra and Temperatures of BS-C1

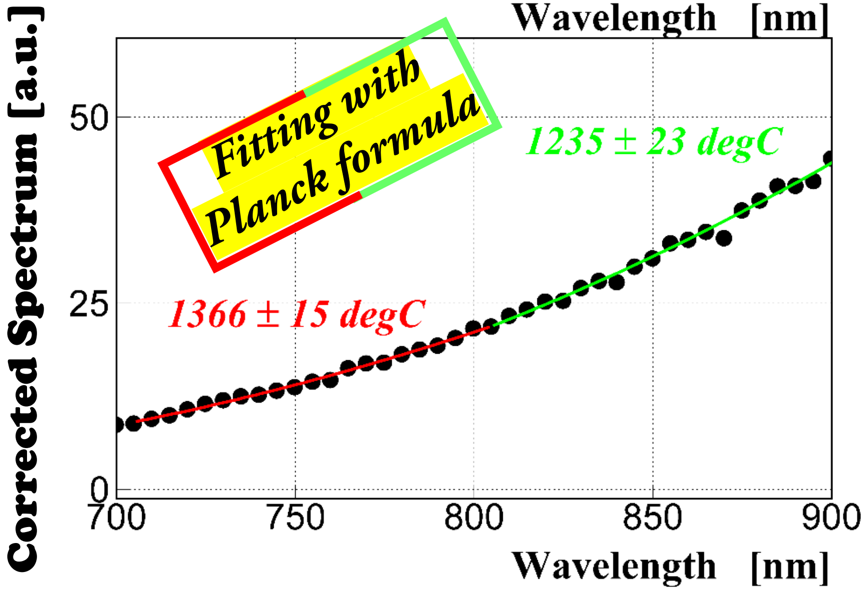
At V_c = 0.55 MV



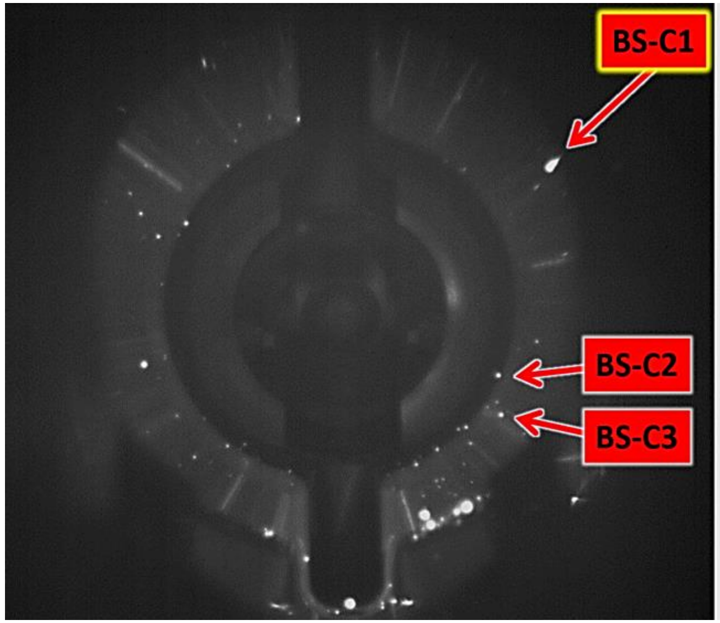


At V_c = 0.95 MV





Downstream Endplate

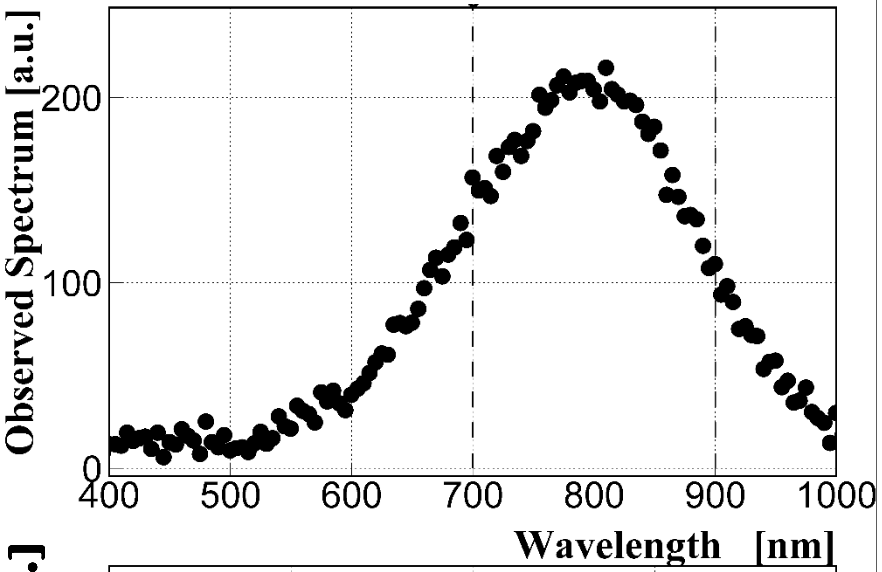


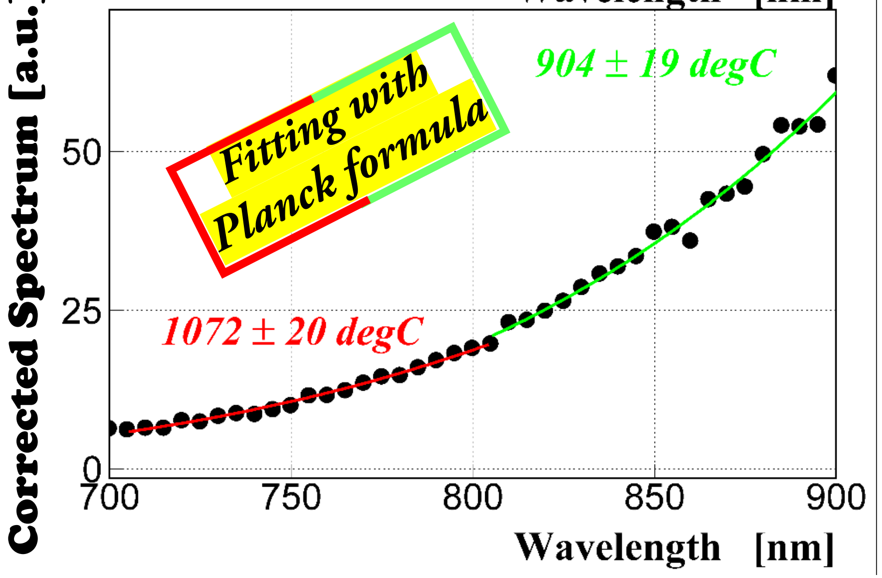
Error bars on temperature are determined for χ^2/ndf = 1.

- ✓ Significant increase in the temperature with higher cavity voltage (x1.7)
- ✓ No significant difference between the temperatures in 700 - 800 nm and 800 - 900 nm

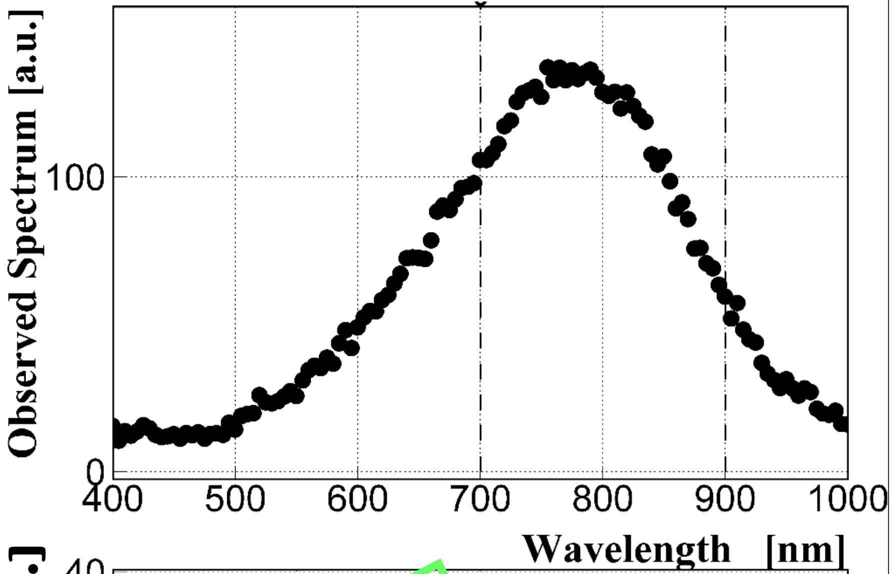
Spectra and Temperatures of BS-A1

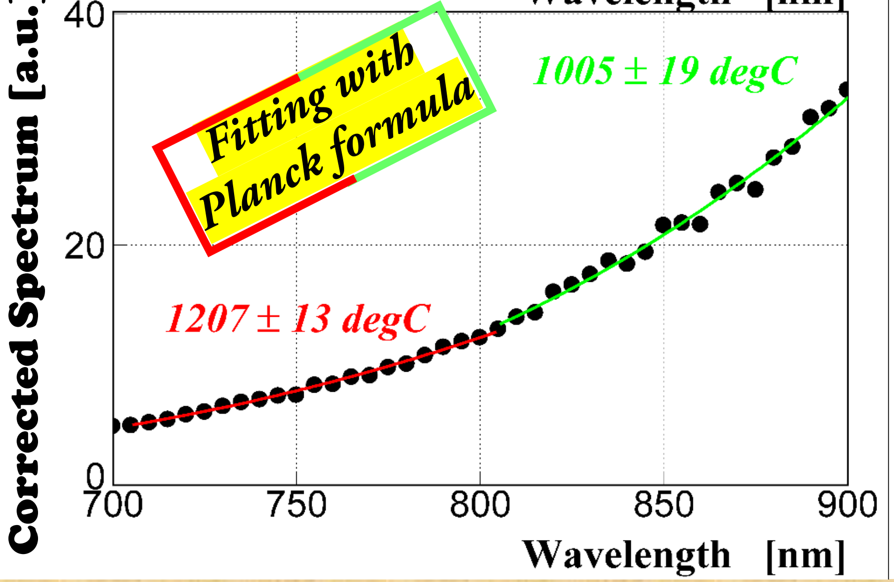
At V_c = 0.55 MV



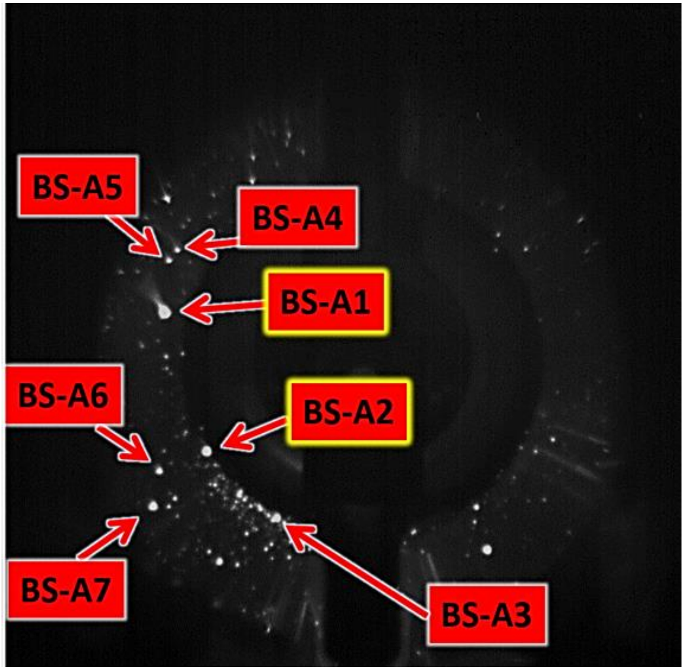


At V_c = 0.95 MV





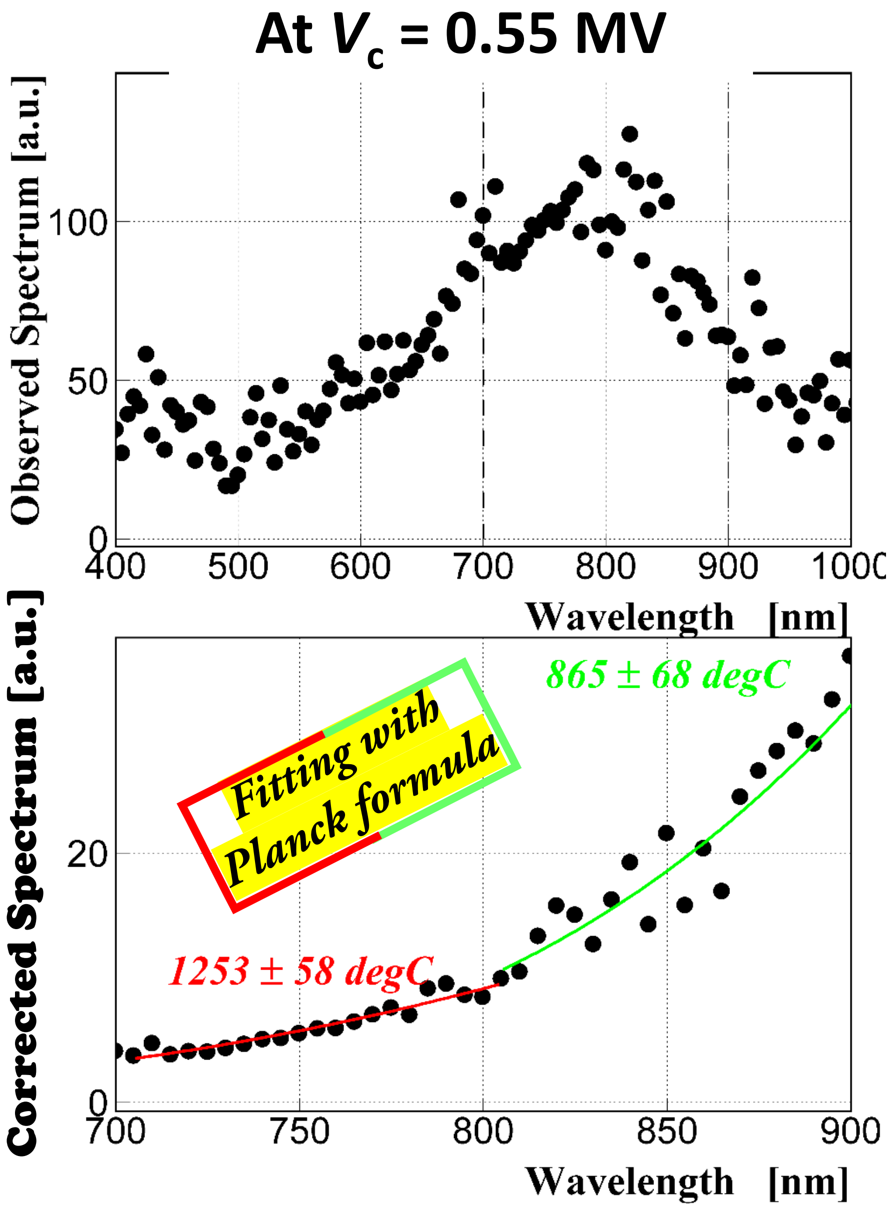
Upstream Endplate

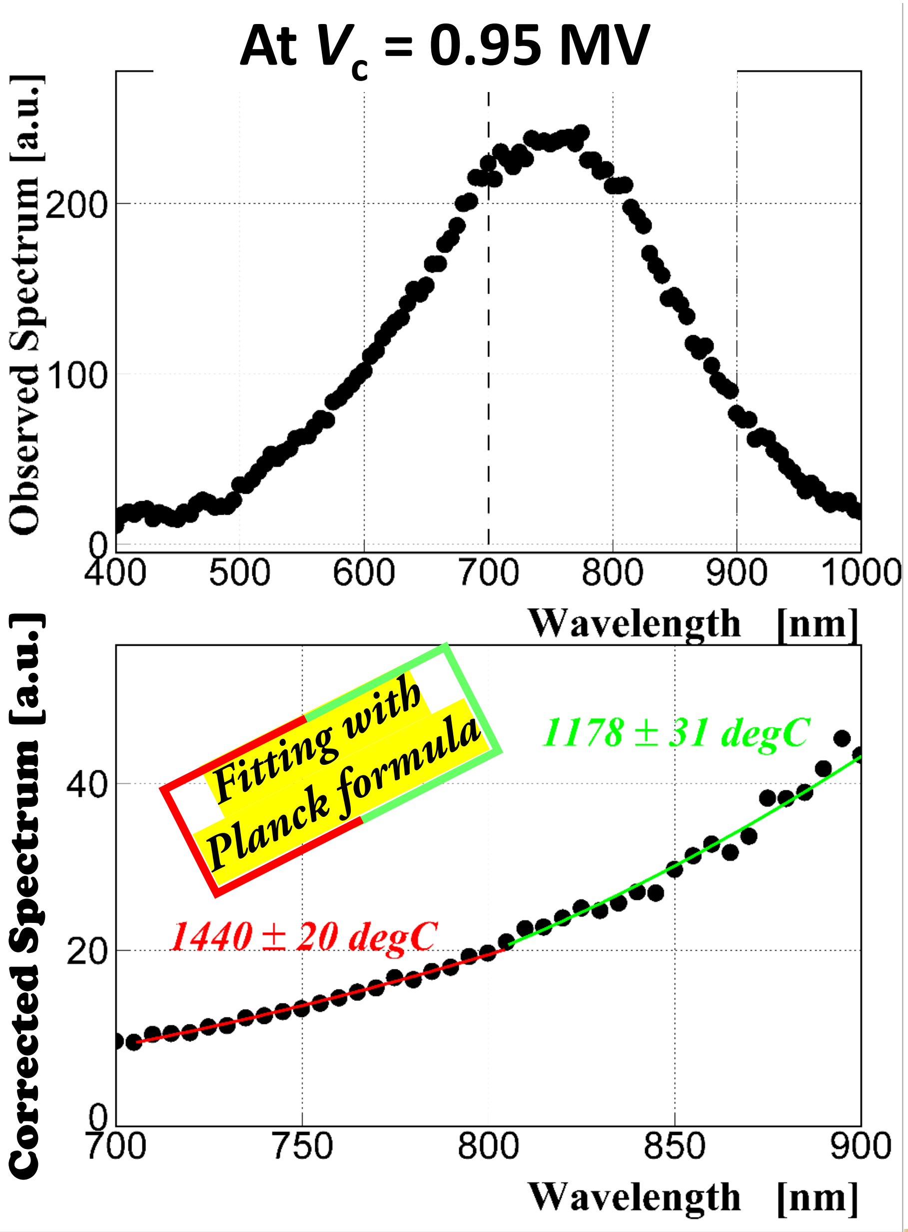


(Error bars on temperature are determined for χ^2/ndf = 1.)

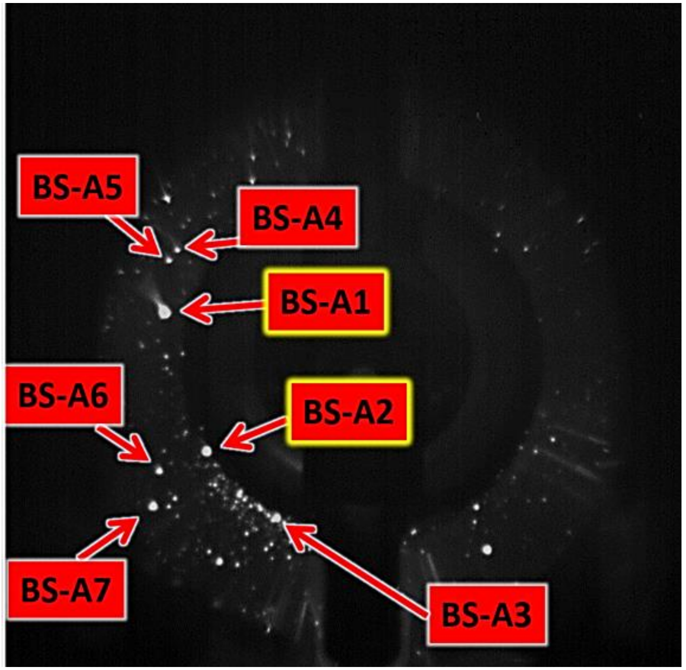
- ✓ Temperature increase also seen with higher cavity voltage, but about half of that for BS-C1
- ✓ Small difference between the temperatures in 700 - 800 nm and 800 - 900 nm

Spectra and Temperatures of BS-A2





Upstream Endplate



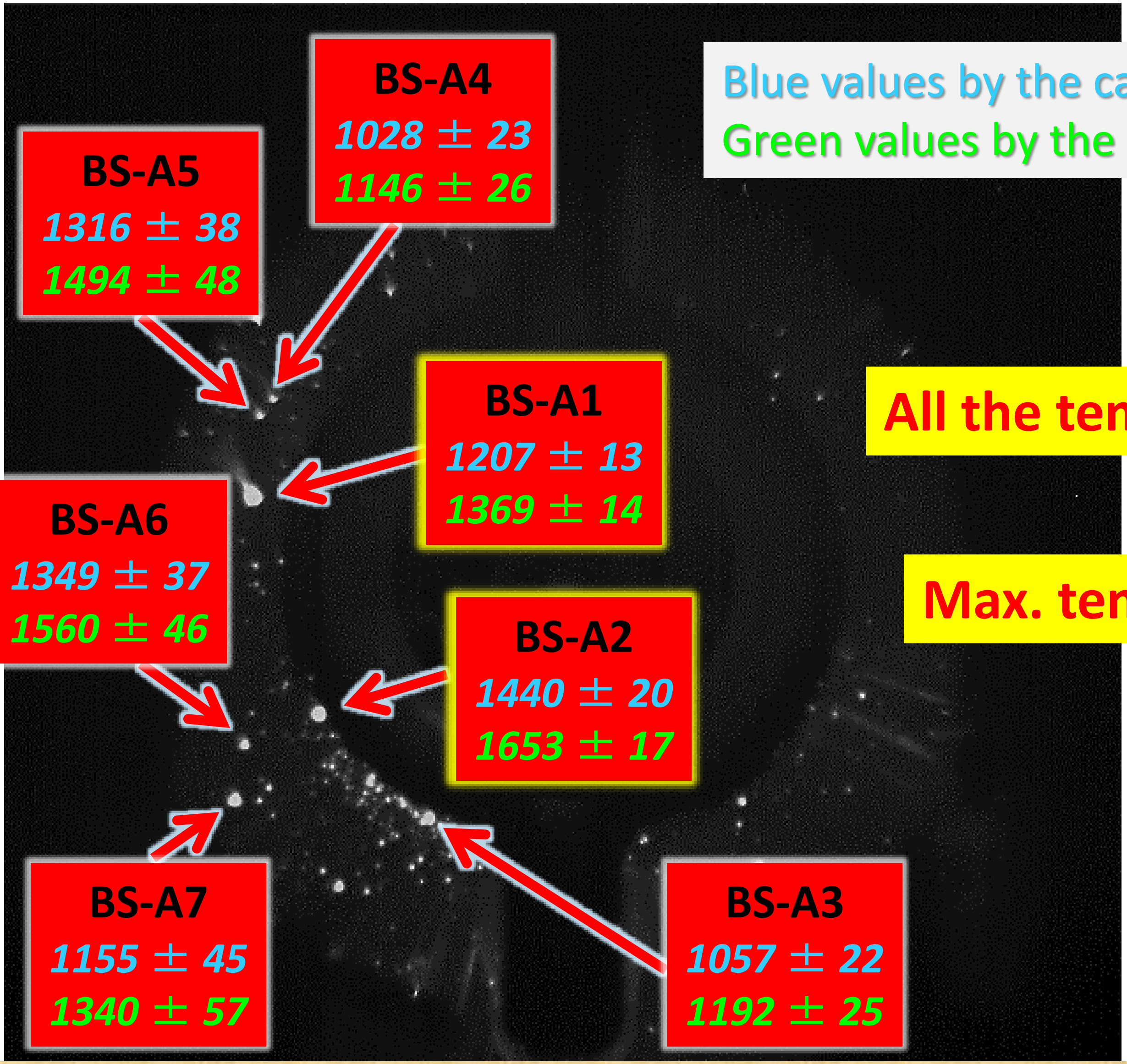
Error bars on temperature are determined for χ^2/ndf = 1.

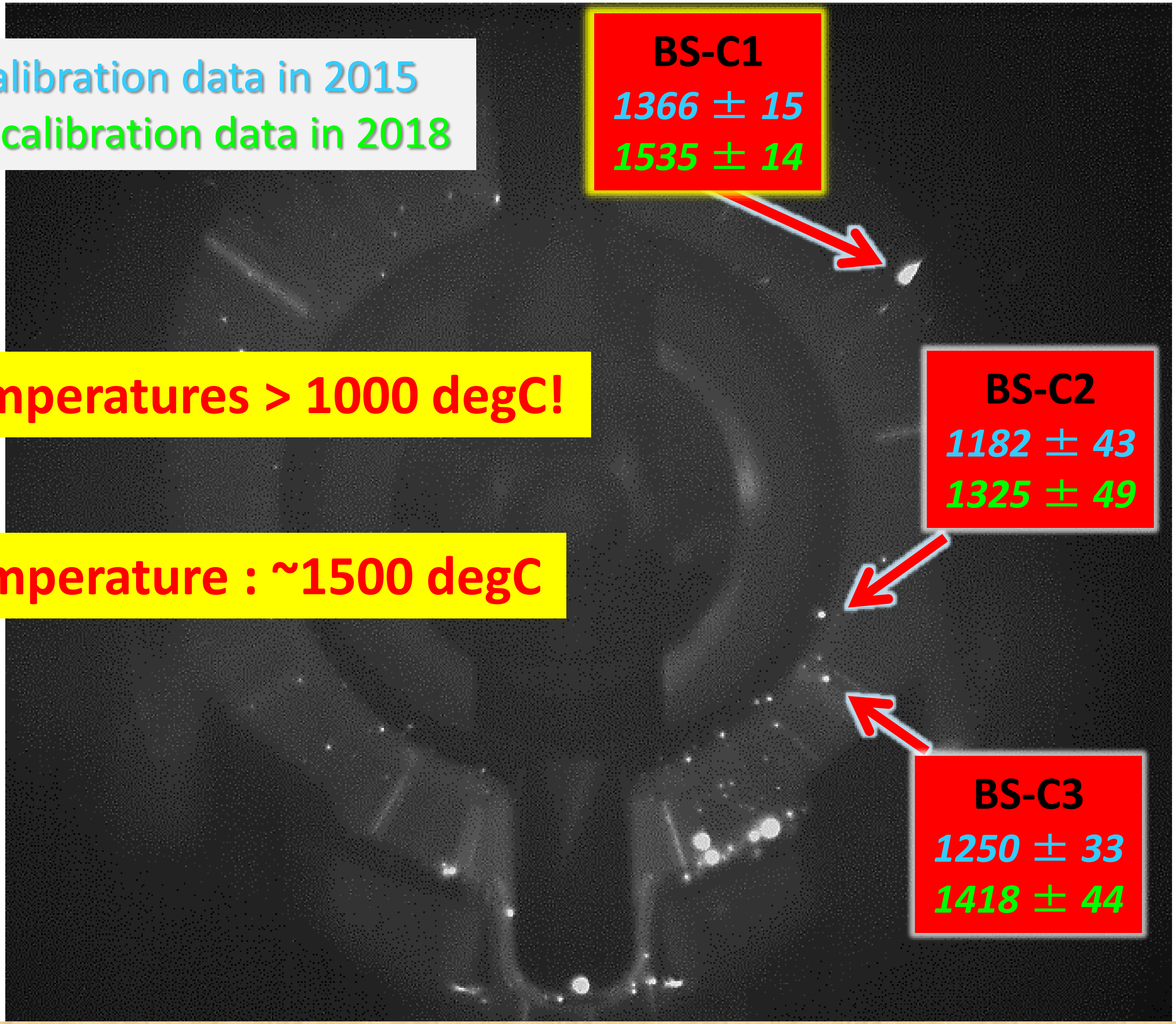
- ✓ Temperature increase also seen with higher cavity voltage
- ✓ Small difference between the temperatures in 700 - 800 nm and 800 - 900 nm

Measured Temperatures [degC] at V_c = 0.95 MV for 700 – 800 nm

Upstream Endplate

Downstream Endplate





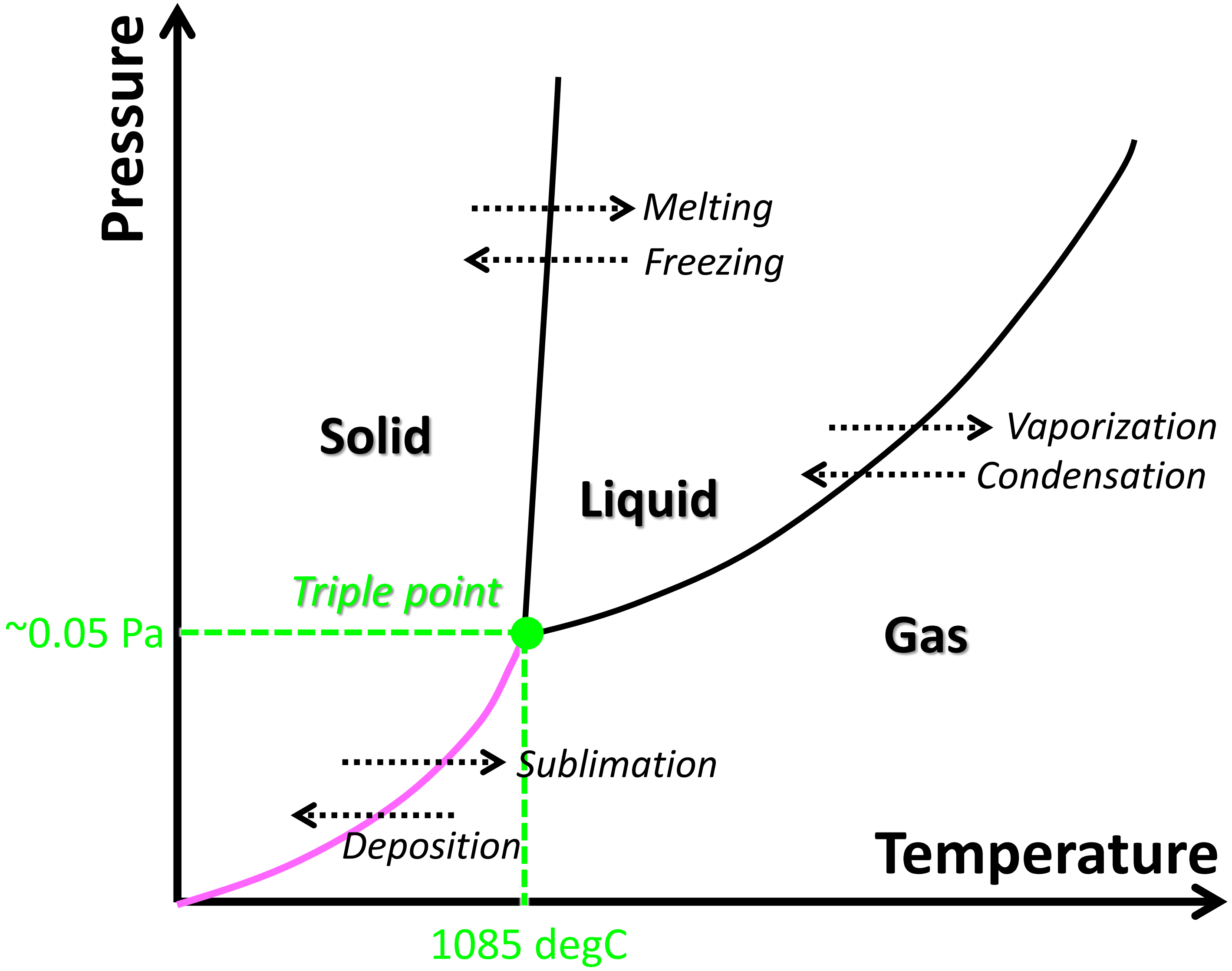
Blue values by the calibration data in 2015

Green values by the calibration data in 2018

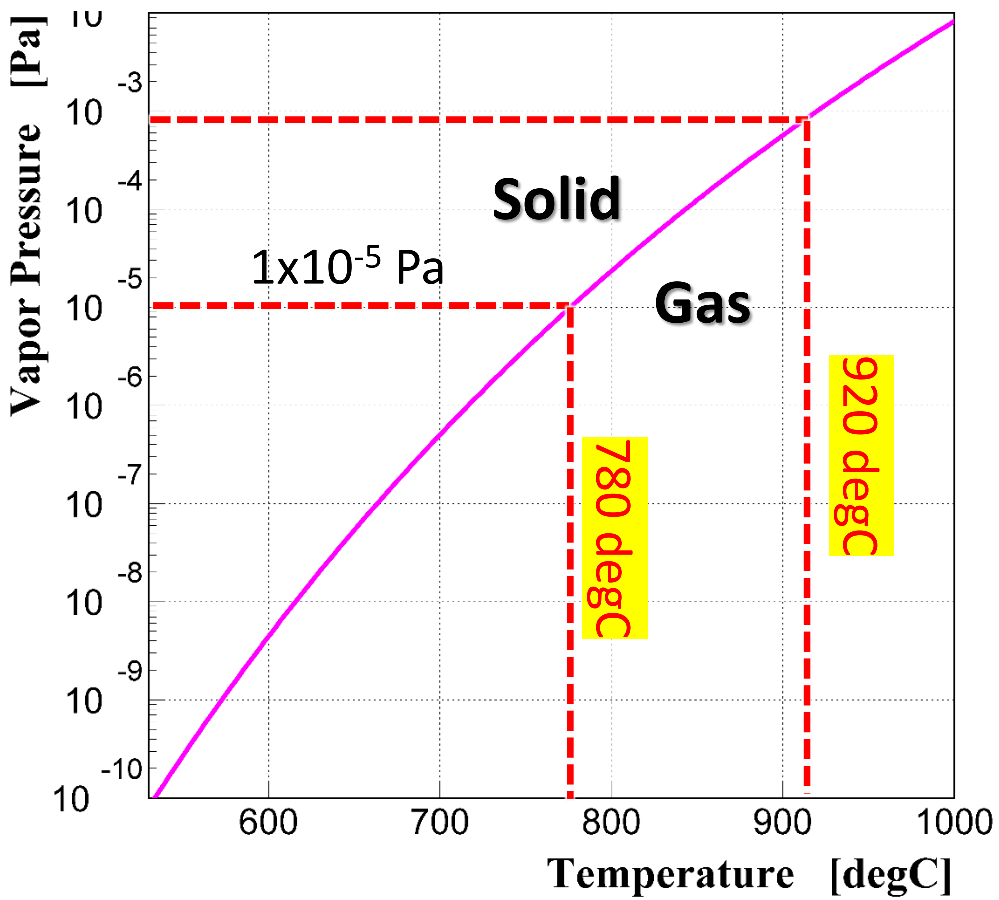
All the temperatures > 1000 degC!

Max. temperature : ~1500 degC

Phase Diagram of Copper



(Data from https://www.iap.tuwien.ac.at/www/surface/vapor_pressure)



Temperatures of copper surfaces exposed to ultrahigh vacuum cannot be higher than 1000 degC.

The bright spots are not copper!

List of Elements with High Sublimation Points

At 1×10^{-5} Pa

• Graphite	1740.1 degC
• Ce	1084.4 degC
• Hf	1610.4 degC
• Ir	1675.4 degC
• La	1099.9 degC
• Lu	1056.7 degC
• Mo	1671.2 degC
• Nb	1831.1 degC
• Os	2003.4 degC
• Pt	1385.6 degC
• Re	2066.9 degC
• Rh	1361.1 degC
• Ru	1598.0 degC
• Si	1055.3 degC
• Ta	2082.4 degC
• Th	1584.8 degC
• Ti	1137.3 degC
• V	1234.1 degC
• W	2215.5 degC
• Y	1036.9 degC
• Zr	1533.3 degC

List of Elements with High Sublimation Points

Hypothesis

At 1x10^{-5} Pa

\> 1400 degC

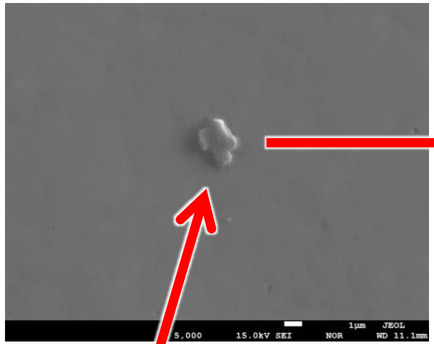
- **Graphite 1740.1 degC**
- Ce 1084.4 degC
- Hf 1610.4 degC
- Ir 1675.4 degC
- La 1099.9 degC
- Lu 1056.7 degC
- Mo 1671.2 degC
- Nb 1831.1 degC
- Os 2003.4 degC
- Pt 1385.6 degC
- Re 2066.9 degC
- Rh 1361.1 degC
- Ru 1598.0 degC
- Si 1055.3 degC
- Ta 2082.4 degC
- Th 1584.8 degC
- Ti 1137.3 degC
- V 1234.1 degC
- W 2215.5 degC
- Y 1036.9 degC
- Zr 1533.3 degC

Bright spots are high-temperature carbonic particles!?

Graphite burns at > 500 degC.
➔ No burning since no oxygen in vacuum

An Example of Carbonic Microparticles on Copper Surface

Size of this microparticle： 1 μm

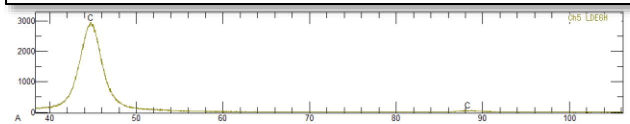


Surface inspection by EPMA (Electron Probe Micro Analyzer) after ultrasonic cleaning in isopropyl alcohol.

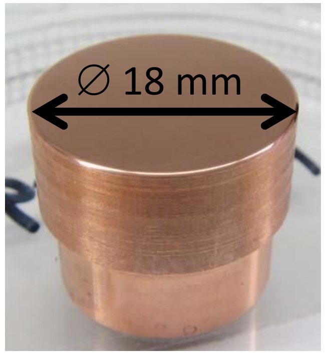
ZAF Metal

Element	Mass(%)	Atom(%)	K(%)
C	20.875	55.1060	8.987
O	3.011	5.9655	1.594
Mg	0.208	0.2711	0.100
Al	0.309	0.3630	0.189
Si	0.565	0.6383	0.436
S	0.241	0.2389	0.238
Ca	0.355	0.2809	0.421
Cu	74.437	37.1363	81.750
Total	100.000	100.0000	93.714

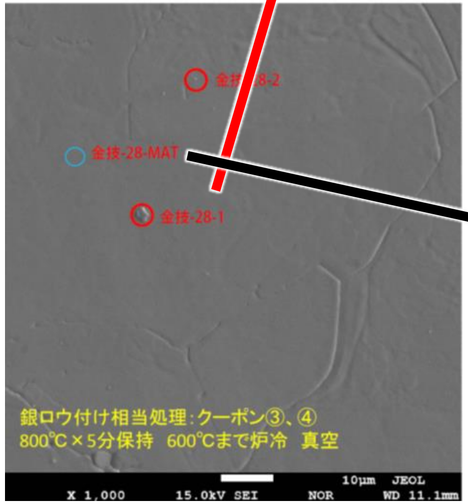
Norm.F = 0.844



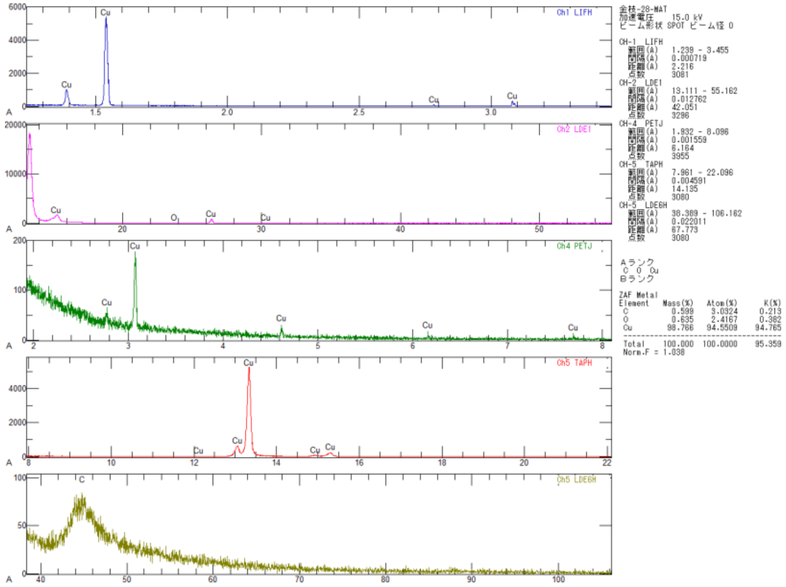
Copper Coupon



- ✓ Material： Oxygen Free Copper (Class1)
- ✓ The top surface has Ra=0.03μm.



Base

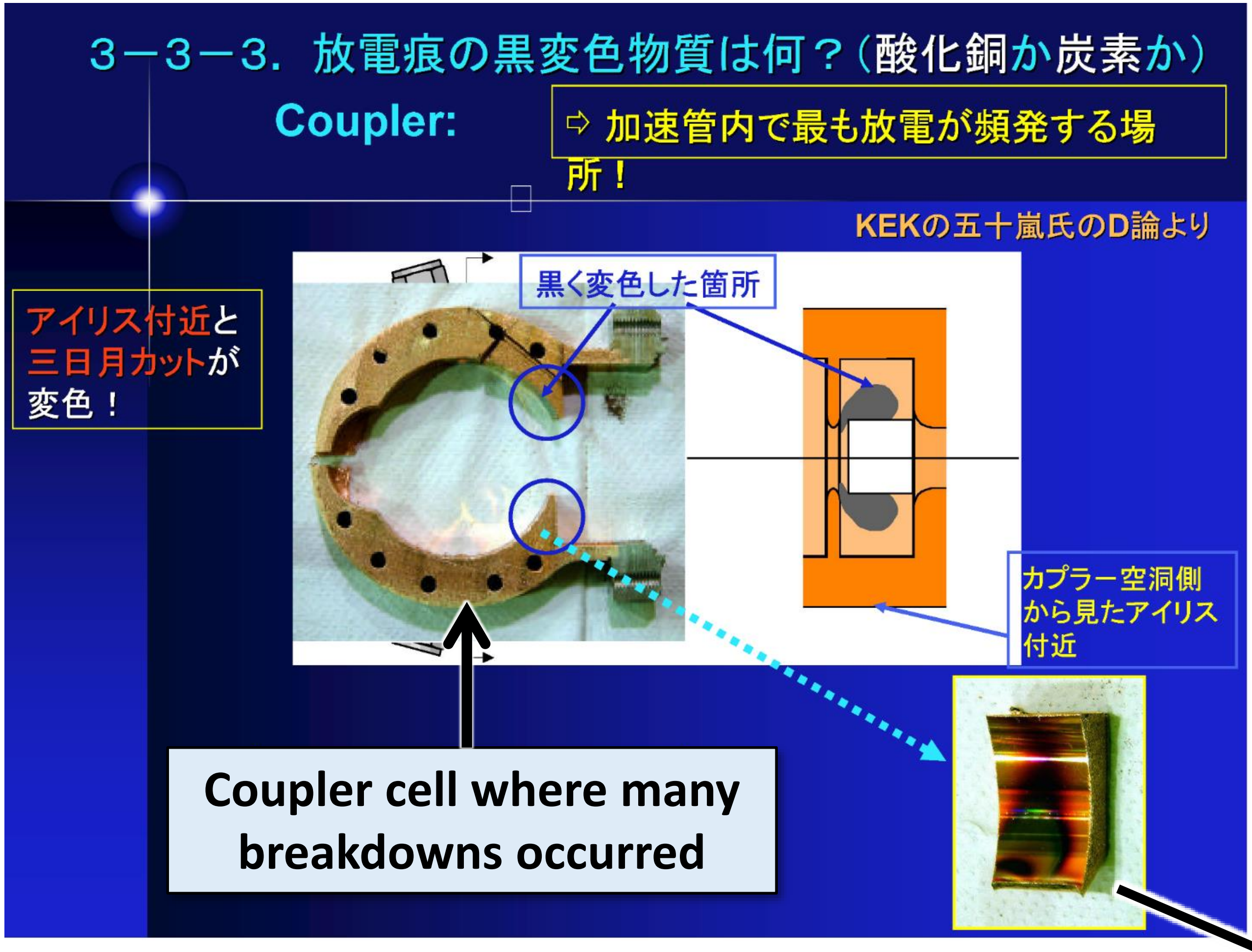


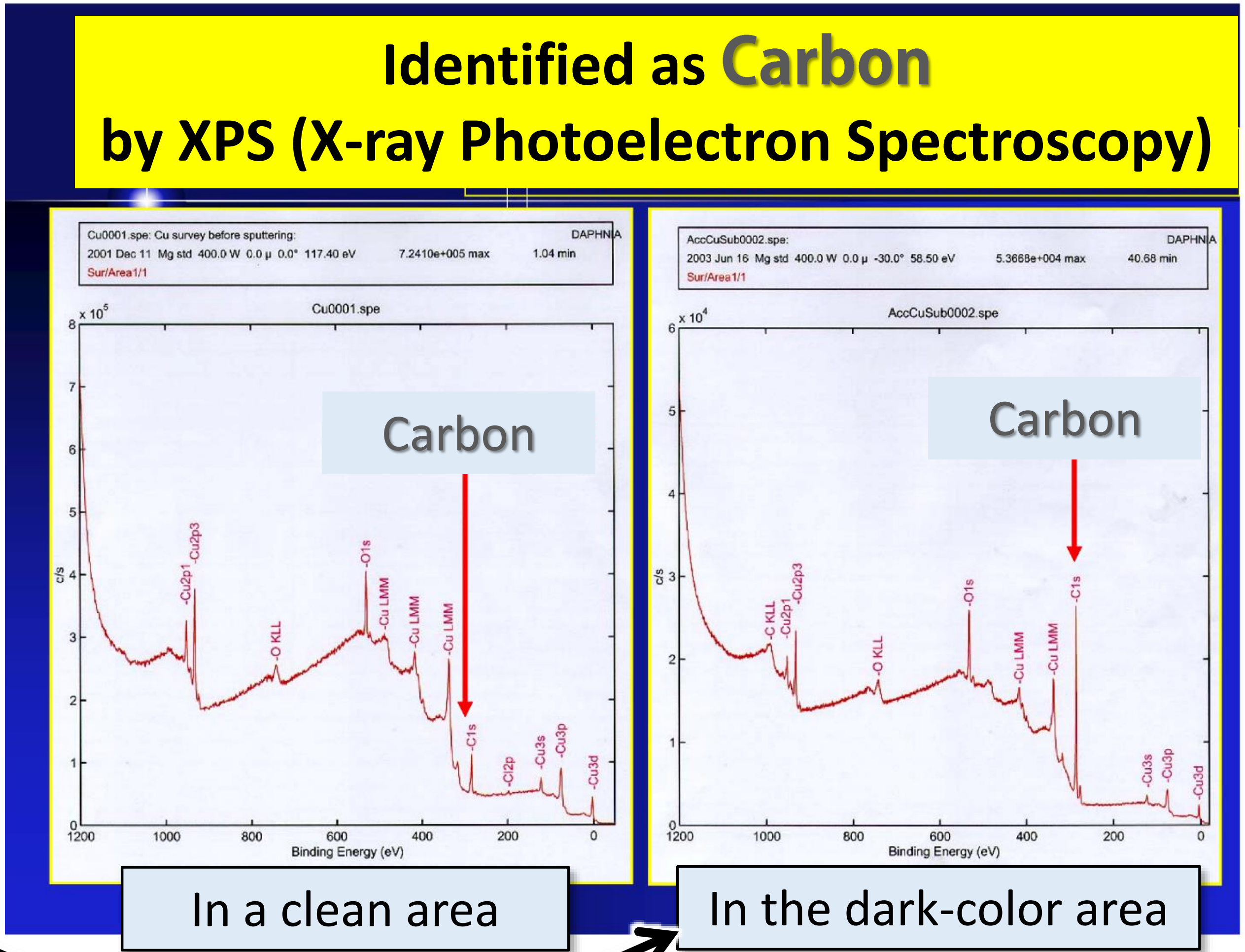
Inspection conducted by T. Higo (KEK)

Although carbon cannot be melt in copper, It can adhere to copper surface.

Another Example: Inspection of a coupler cell of S-band structure

Slides shown in Mechanical Engineering Workshop 2004 at KEK by Hiromitsu TOMIZAWA (JASRI/SPring-8)





Carbon can deposit in accelerating structures, and adhere to copper surfaces.

Answers for the Questions

Conclusions

1. What are the bright spots?
   - Spectrum?
     - Thermal radiation
   - Temperature?
     - > 1000 degC (← the 10 bright spots)
     - Max. ~1500 degC
   - Why exploded?

→ **The bright spots are NOT copper.**

Answers for the Questions

Conclusions

Hypothesis

1. What are the bright spots?
   - Spectrum?
     - Thermal radiation
   - Temperature?
     - > 1000 degC (← the 10 bright spots)
     - Max. ~1500 degC

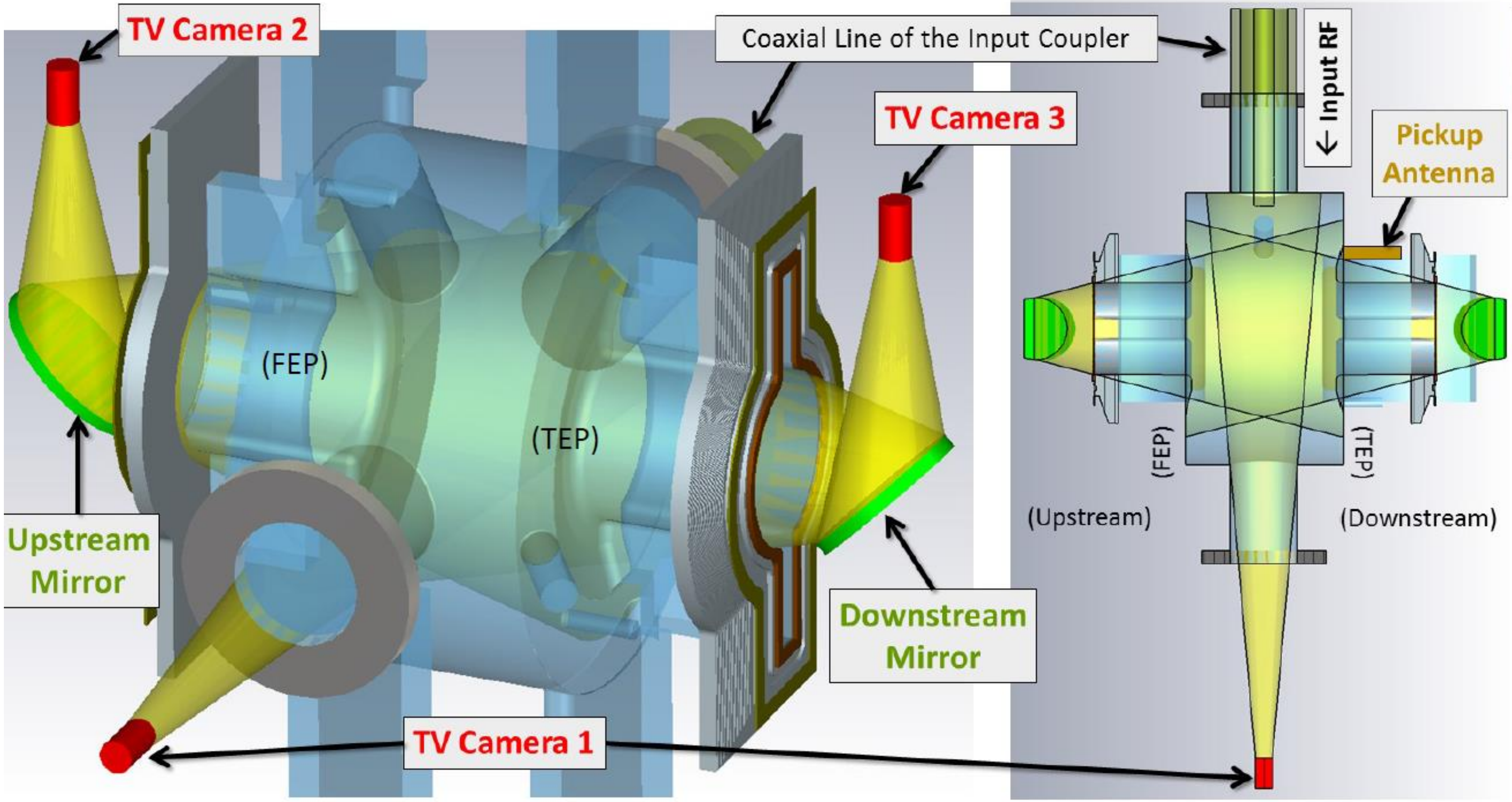
     → **The bright spots are NOT copper.**
   - Why exploded?
     - Burning of carbonic particles in a moment with oxygen provided from oxides in the copper surface?

New!

Observation of Flying Objects at Breakdowns

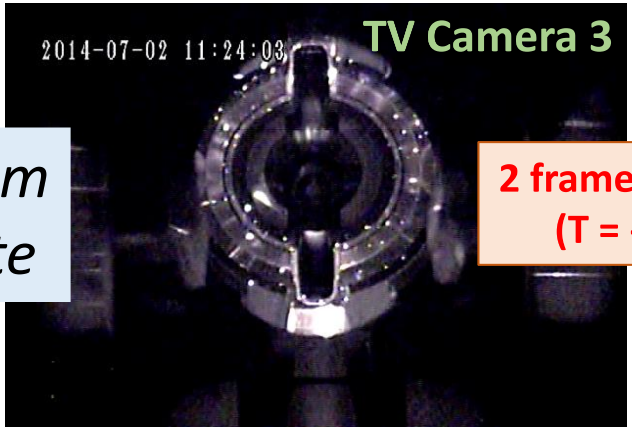
Using the "low-speed" (30 fps) cameras for DR Cavity No.2

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

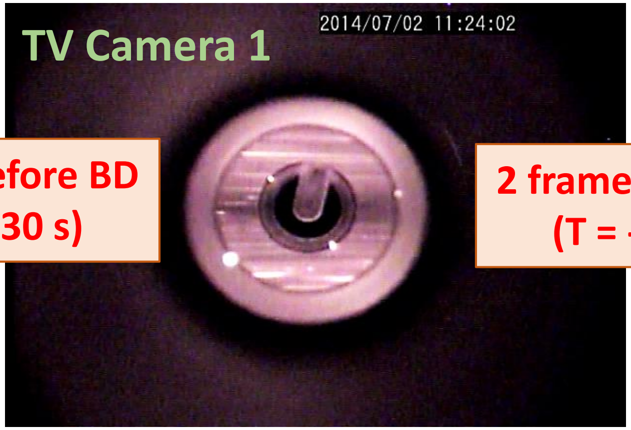


Out of the 205 breakdown events,
we found one event with
“Flying object → Impact on the copper surface → Breakdown”.

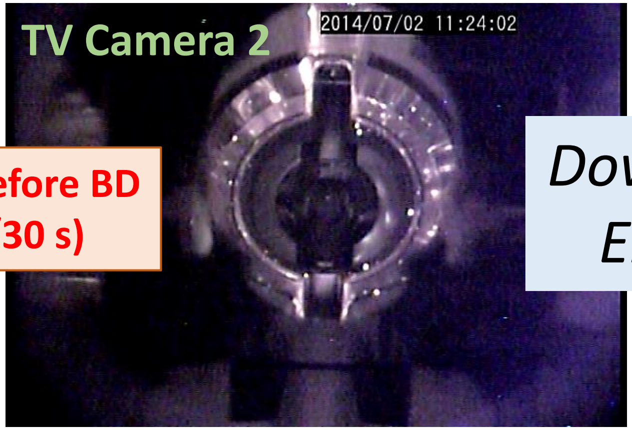
Upstream Endplate



2 frame before BD
(T = -2/30 s)

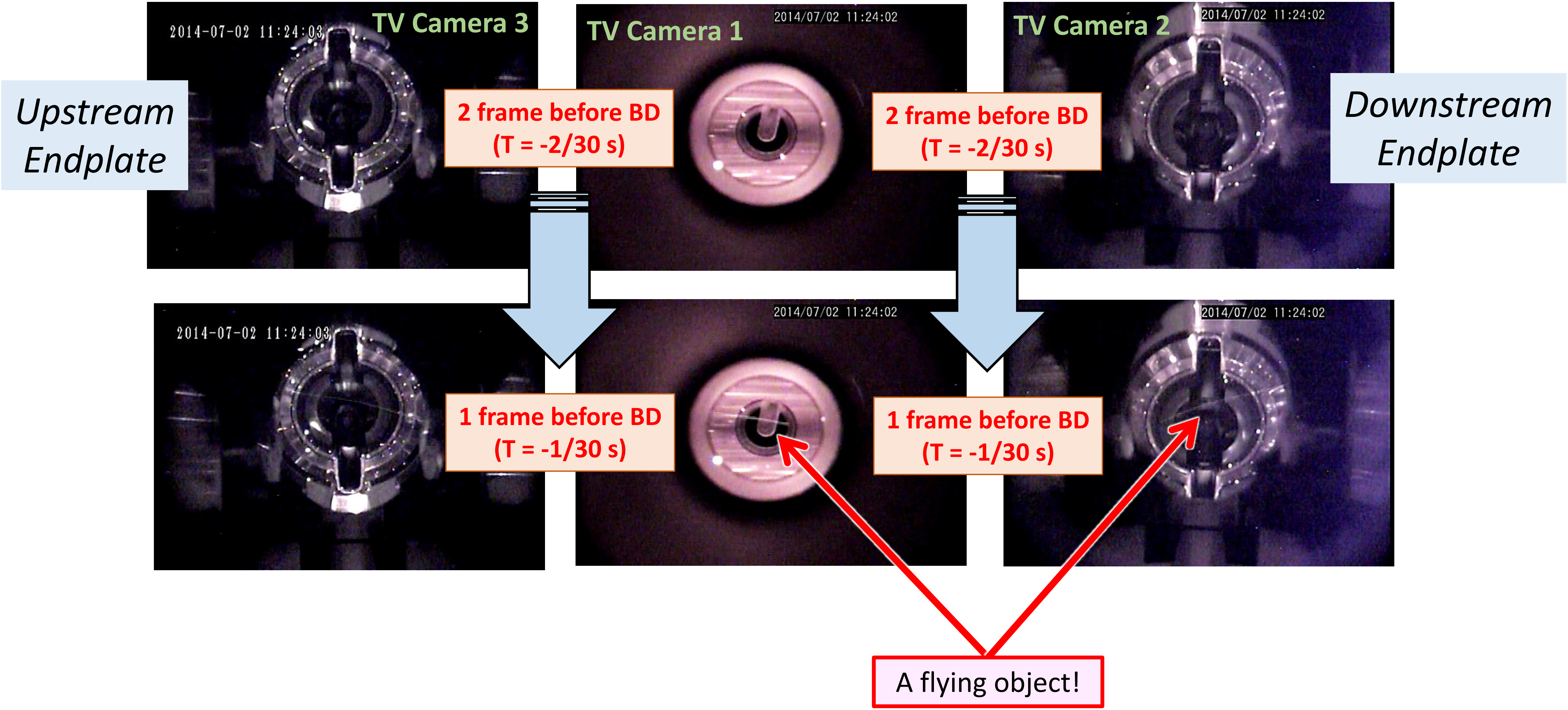


2 frame before BD
(T = -2/30 s)

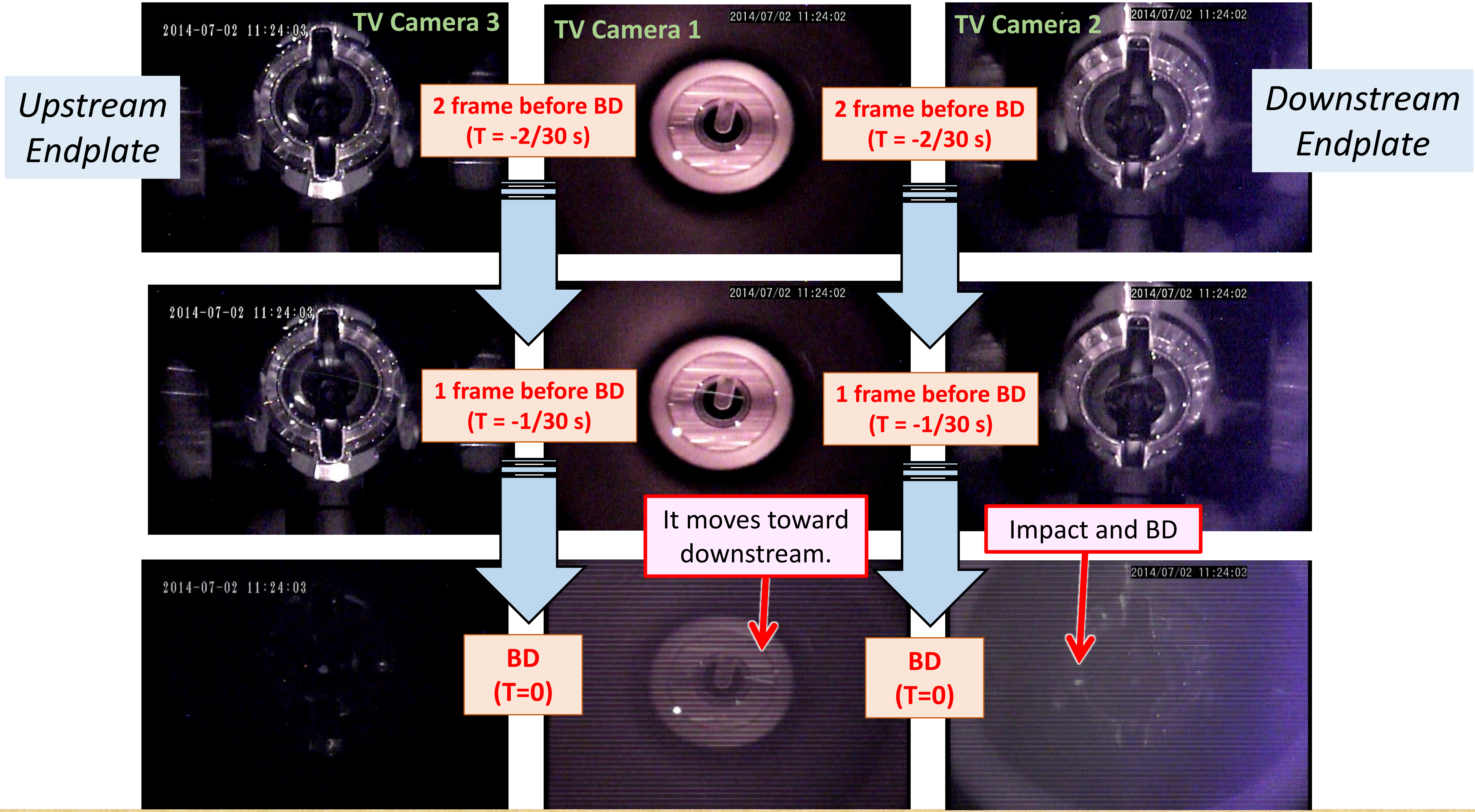


Downstream Endplate

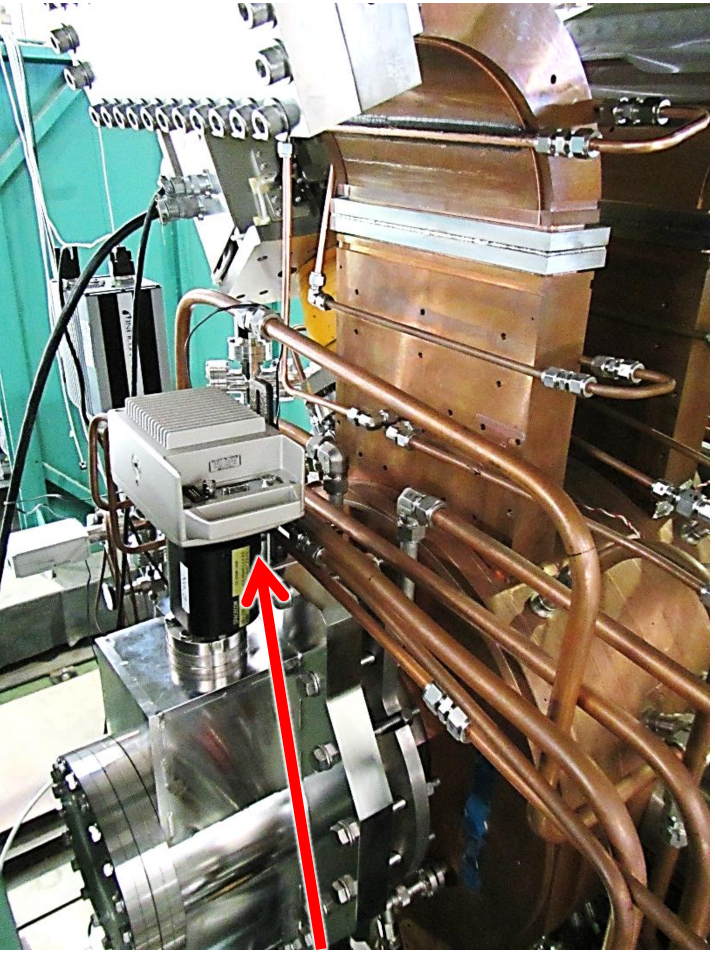
Still nothing special

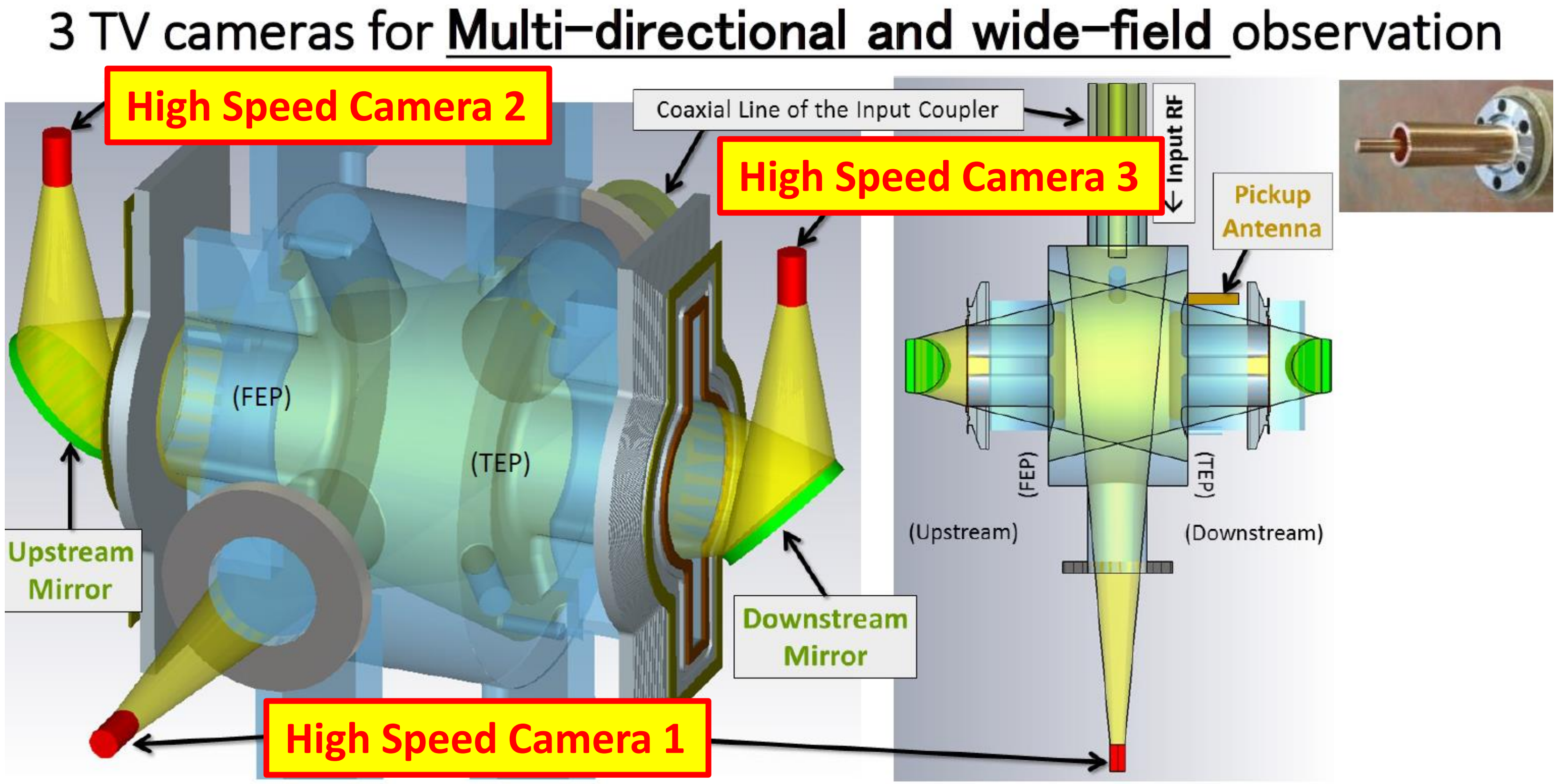


Upstream Endplate
TV Camera 3
2014-07-02 11:24:03
TV Camera 1
2014/07/02 11:24:02
TV Camera 2
2014/07/02 11:24:02
Downstream Endplate
2 frame before BD
(T = -2/30 s)
2 frame before BD
(T = -2/30 s)
2014-07-02 11:24:03
2014/07/02 11:24:02
2014/07/02 11:24:02
1 frame before BD
(T = -1/30 s)
1 frame before BD
(T = -1/30 s)
A flying object!


TV Camera 3
TV Camera 1
TV Camera 2
Upstream Endplate
Downstream Endplate
2014-07-02 11:24:03
2014/07/02 11:24:02
2 frame before BD (T = -2/30 s)
2 frame before BD (T = -2/30 s)
1 frame before BD (T = -1/30 s)
1 frame before BD (T = -1/30 s)
BD (T=0)
BD (T=0)
It moves toward downstream.
Impact and BD

Using 3 high-speed cameras for DR Cavity No.0





Model: "HAS-D3M"

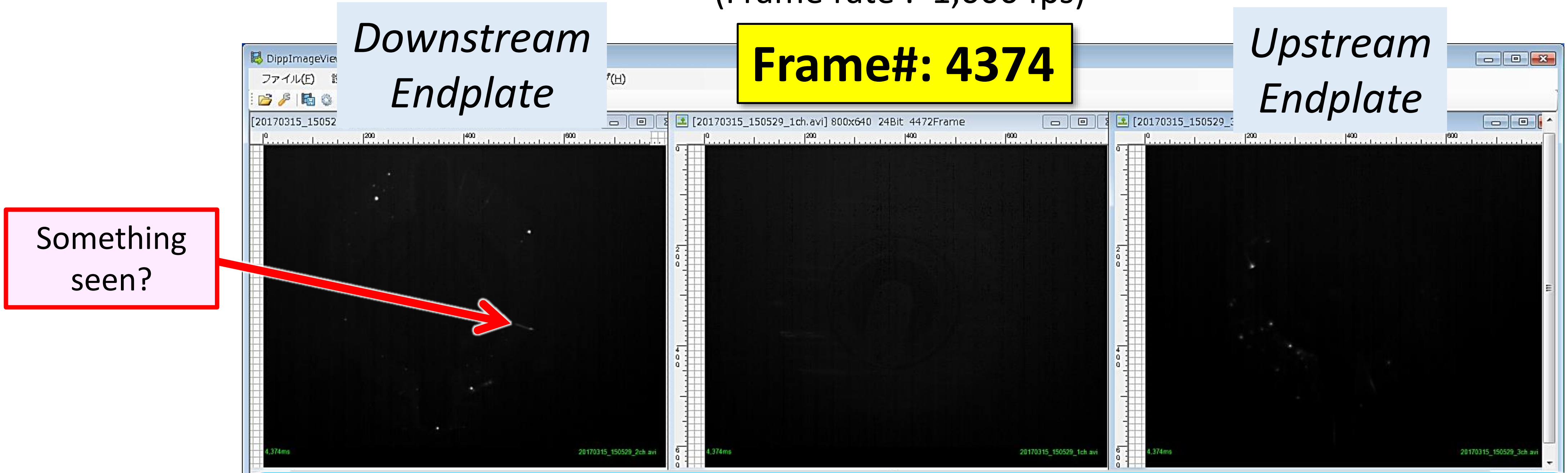
- ✓ Made by DITECT Co. Ltd. (http://www.ditect.co.jp/en/index.html)
- ✓ Frame rate: 100 to 100,000 fps (1,000 and 2,000 fps used in this observation)
- ✓ Frame-by-frame synchronization among the 3 cameras available

With this setup, we found 4 such kind of events out of 40 breakdown events!

(Preliminary)

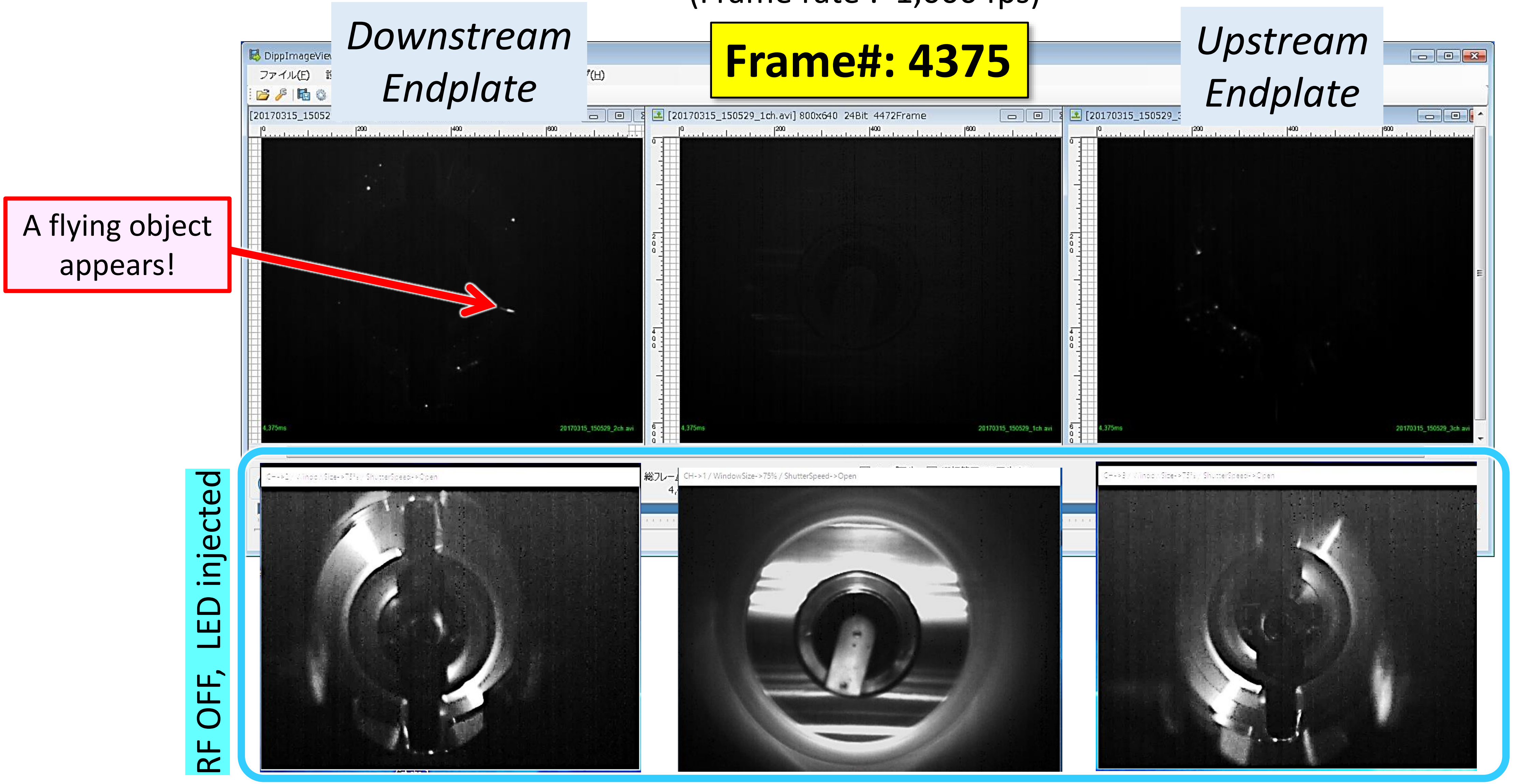
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



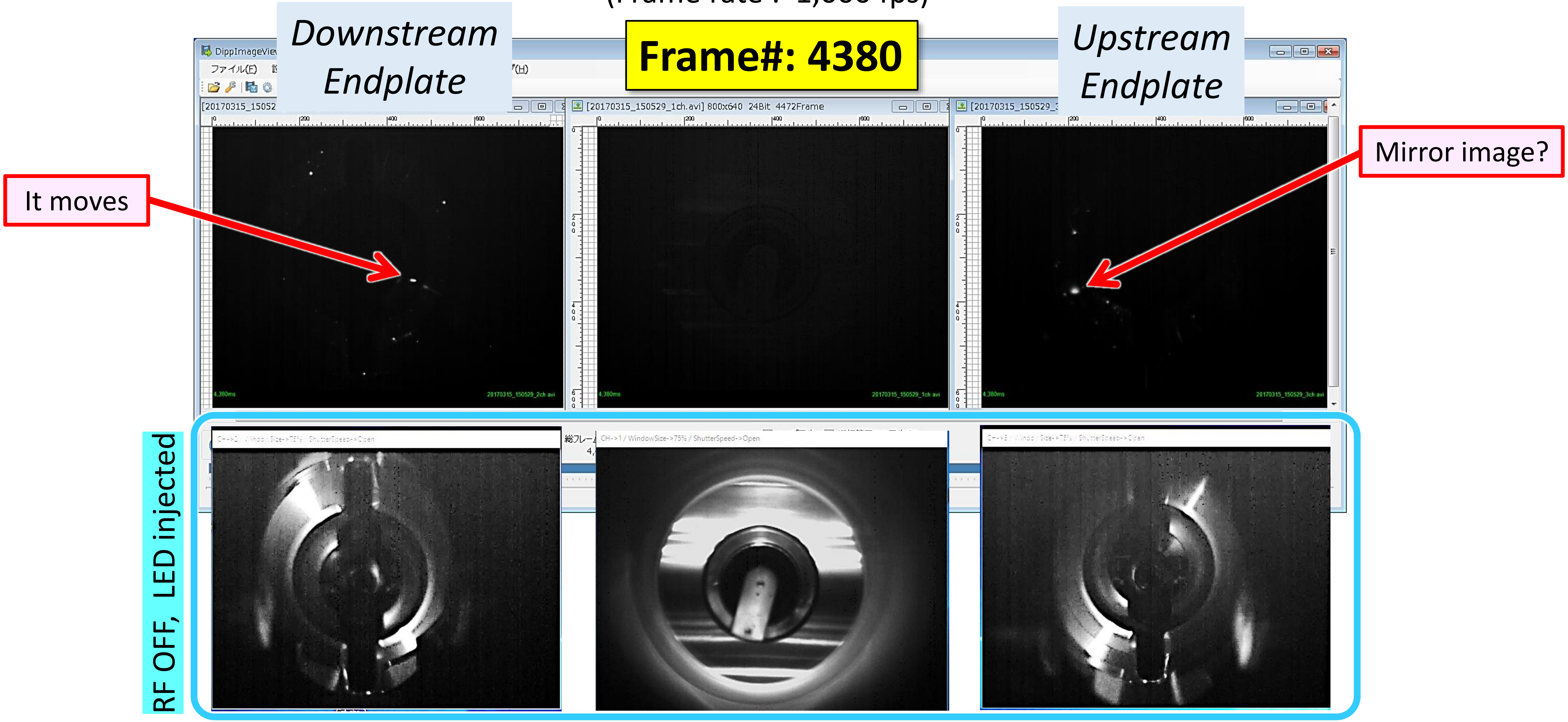
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



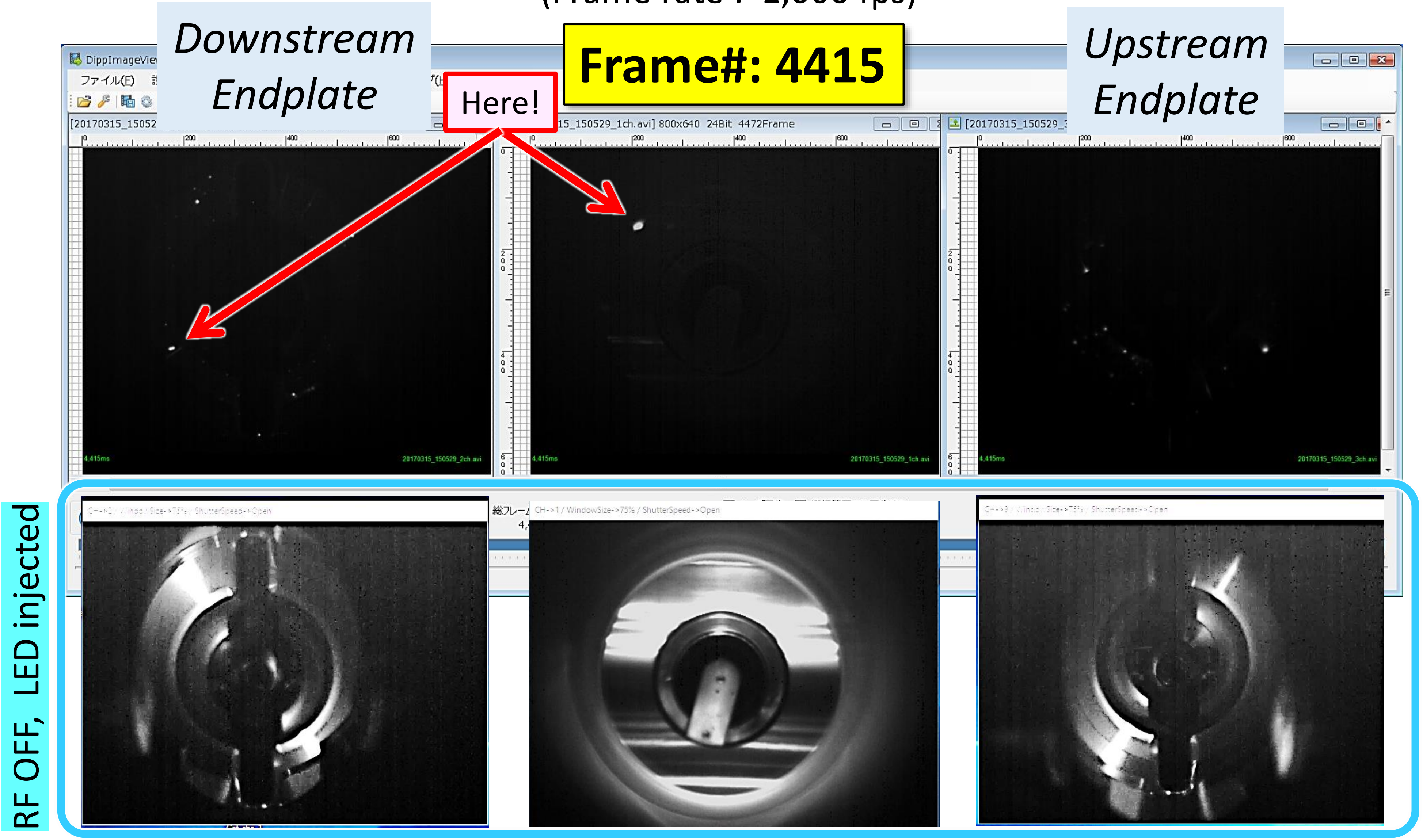
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



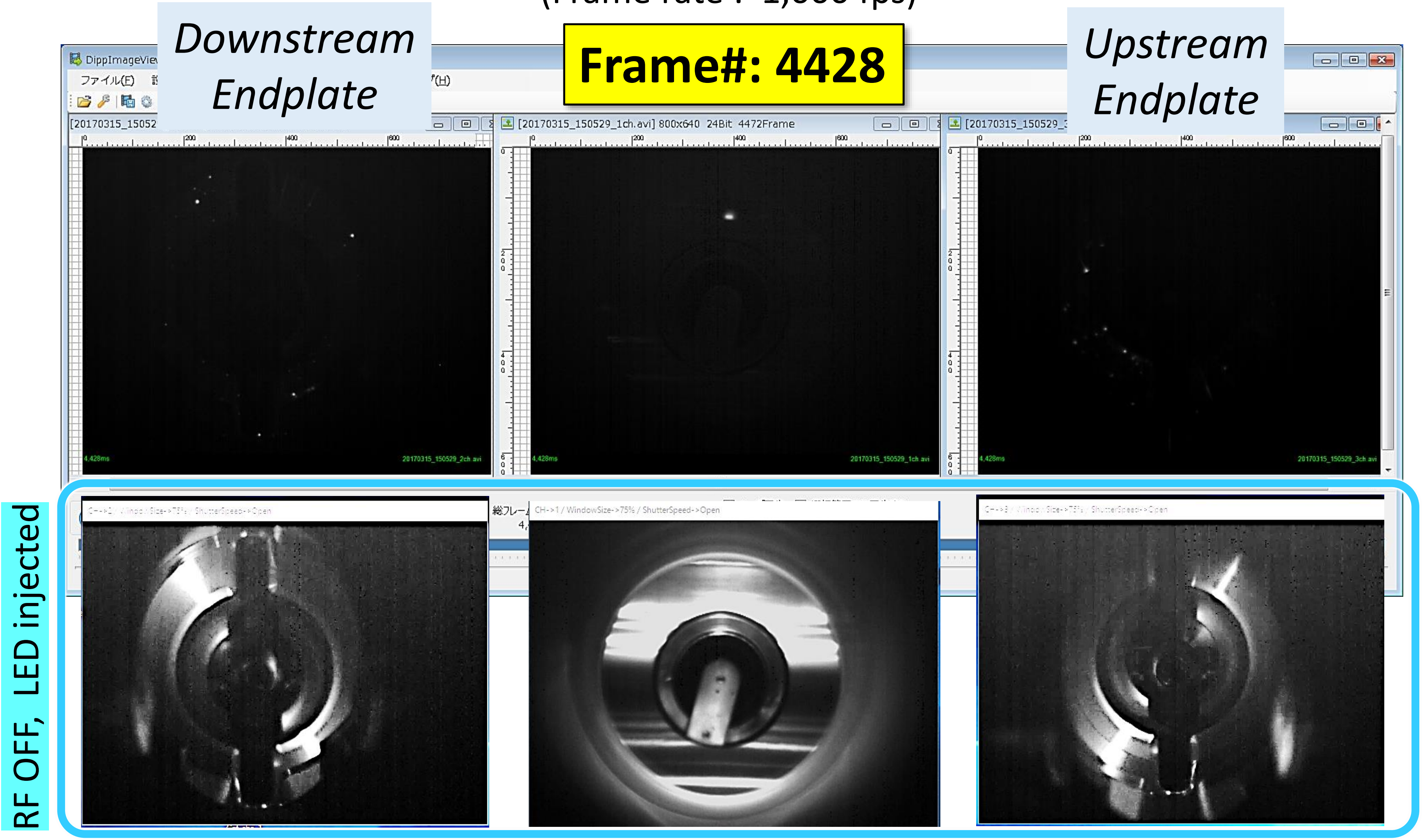
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



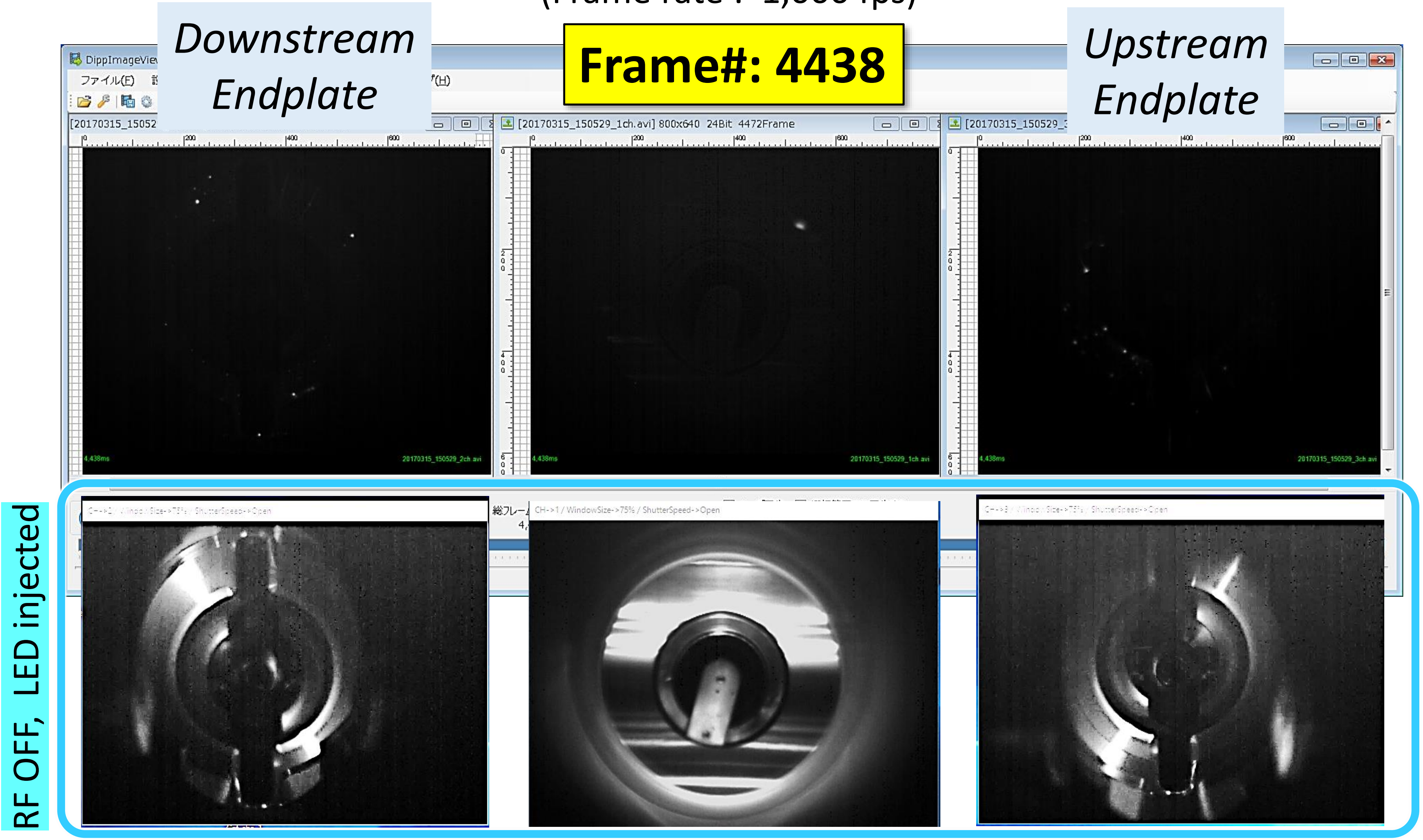
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



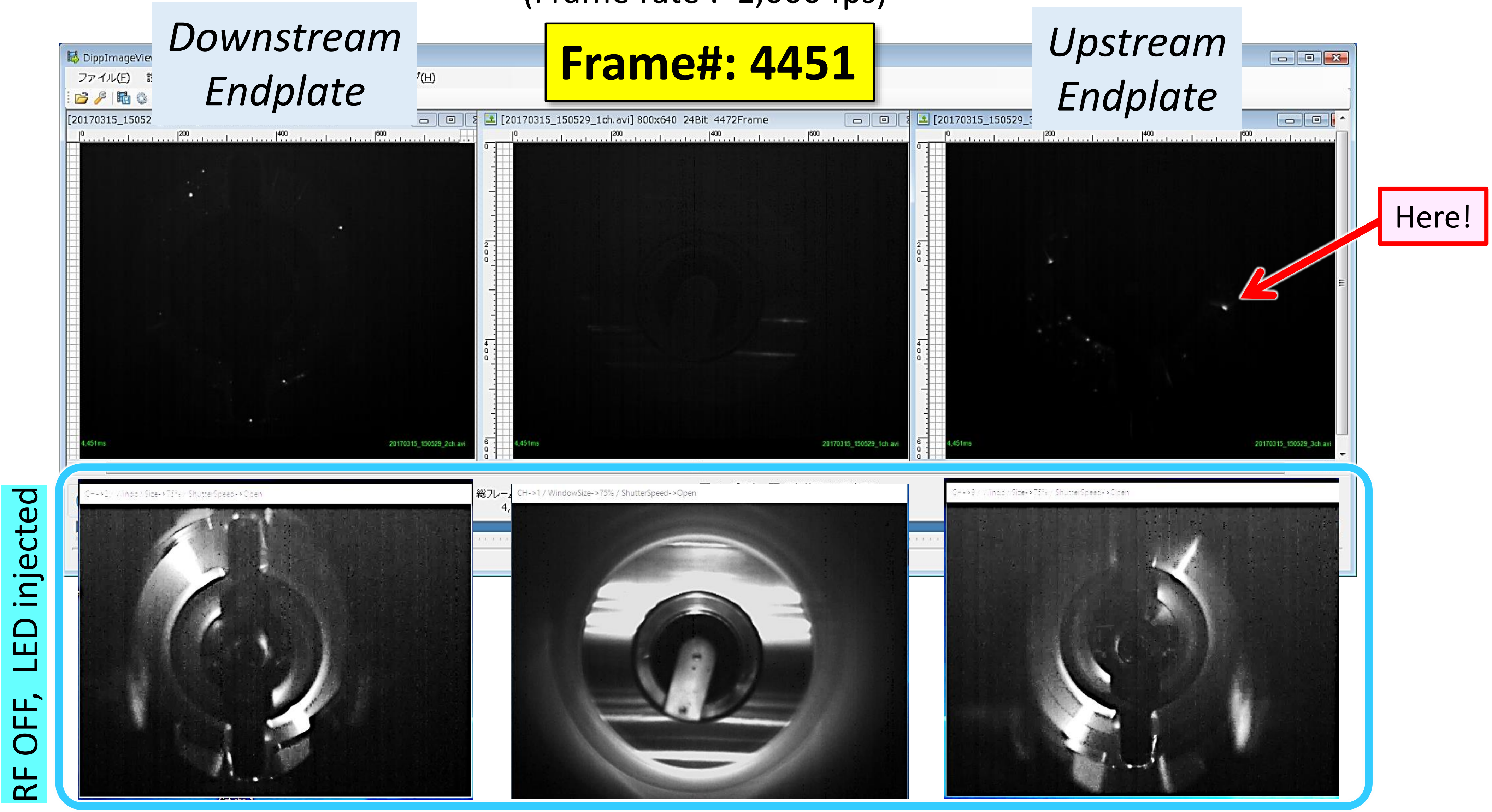
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



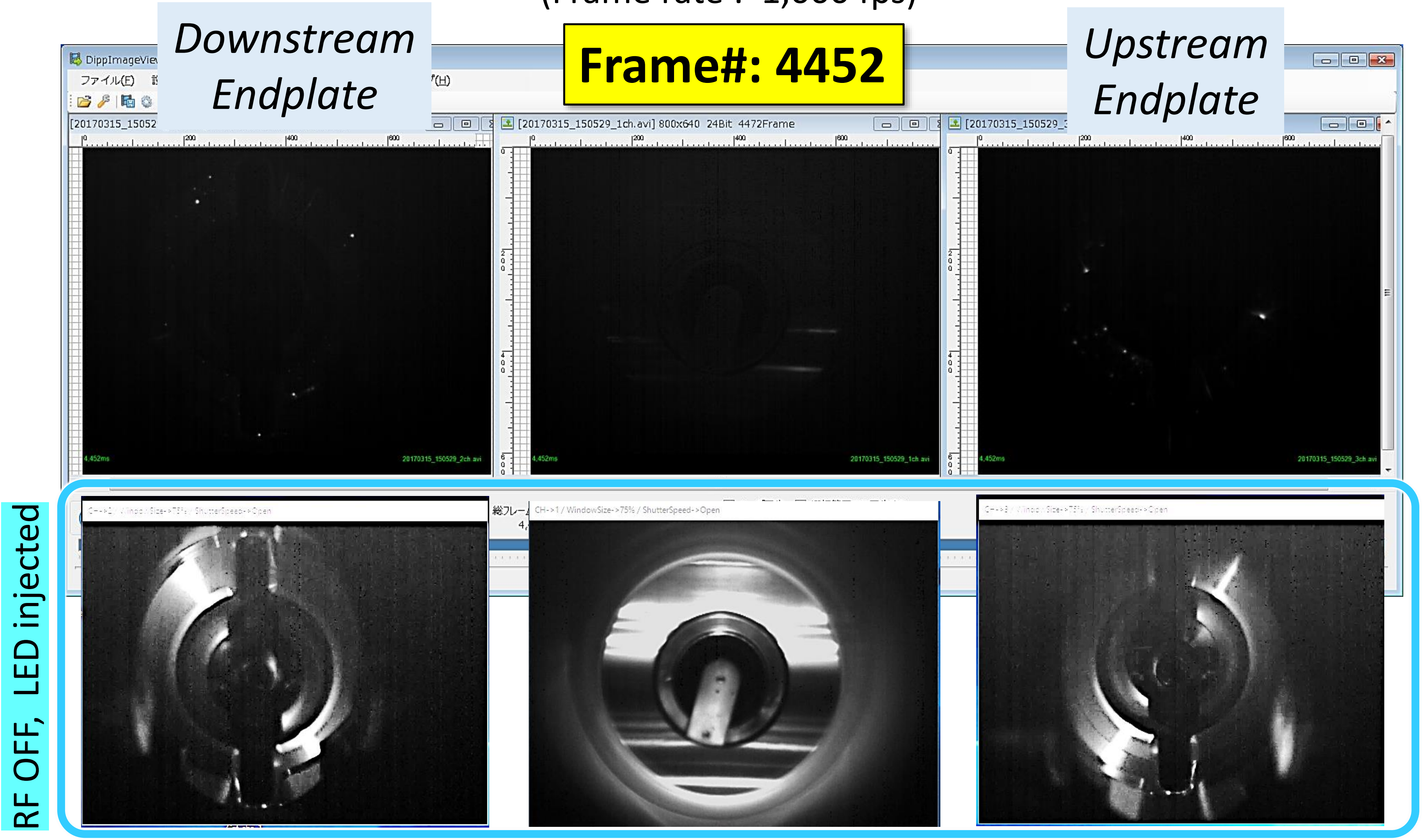
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



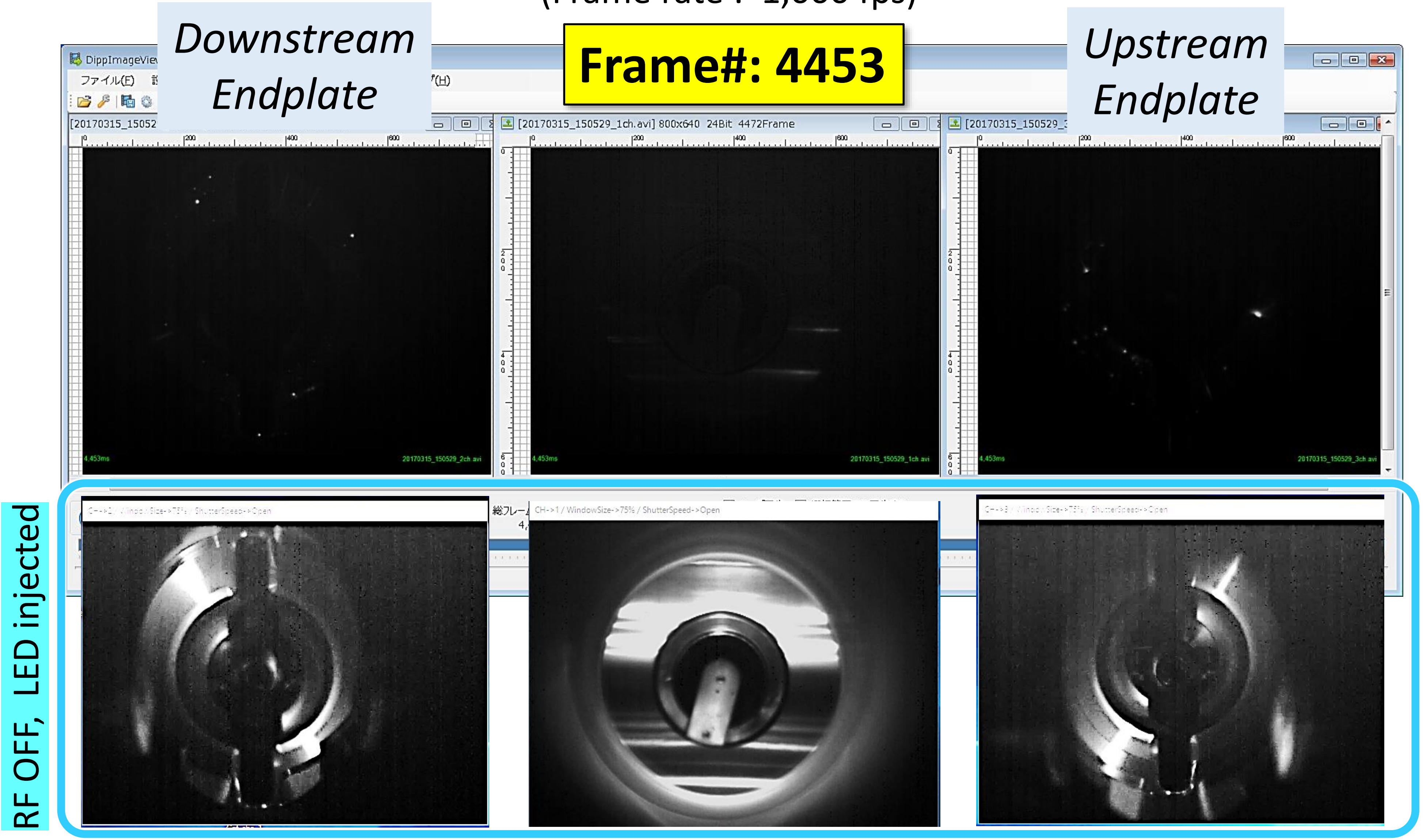
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



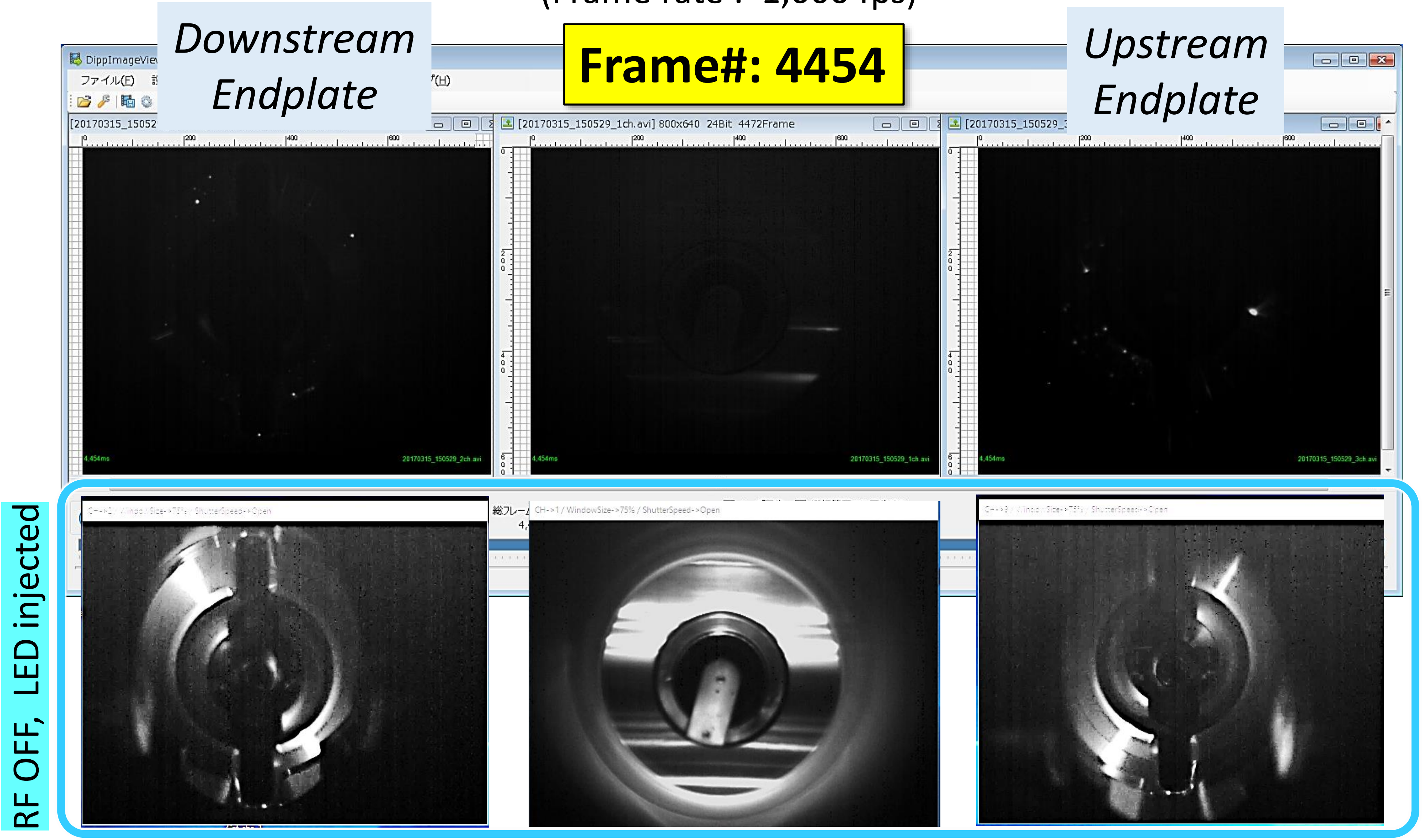
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



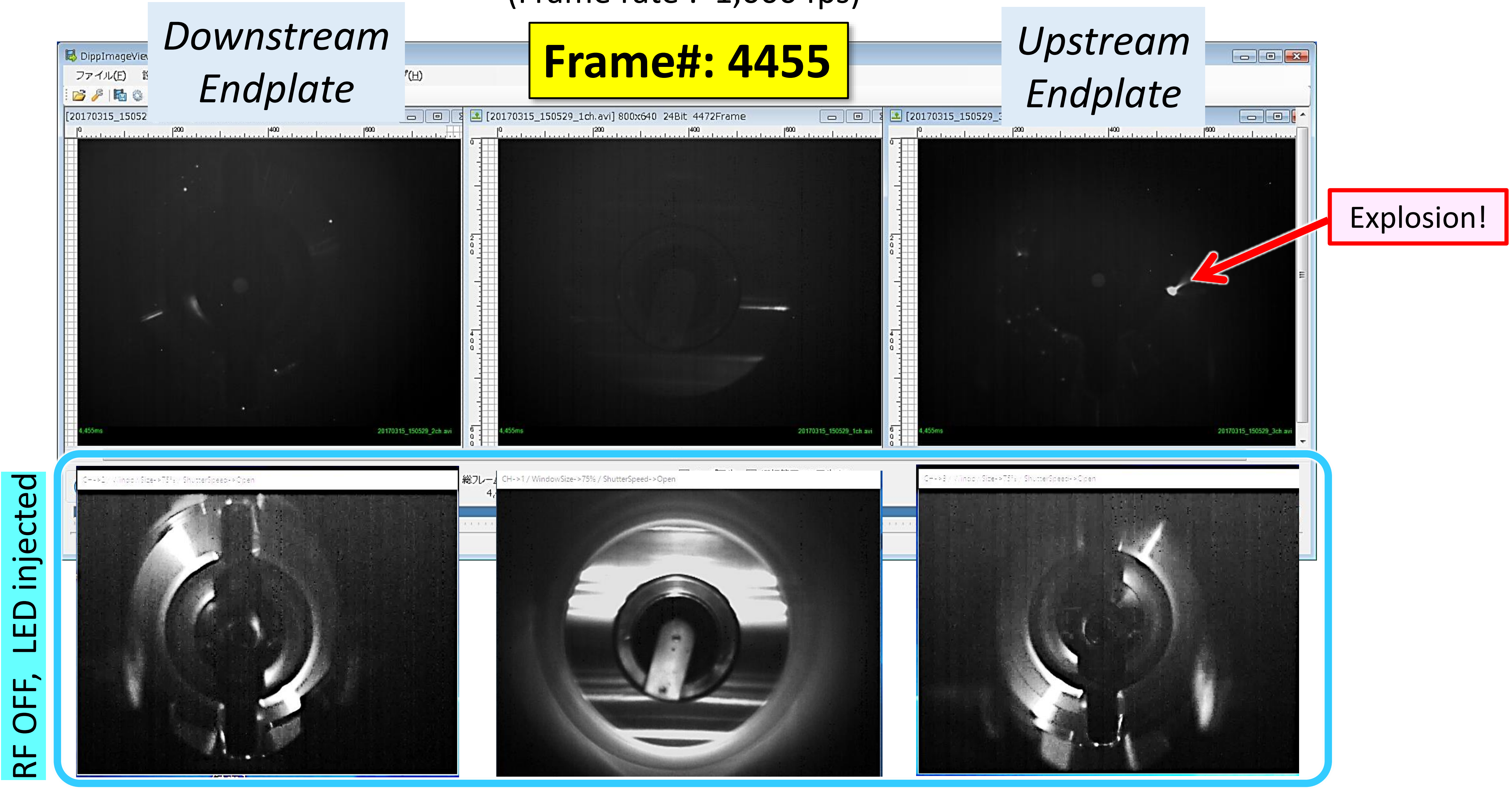
Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)

Downstream Endplate

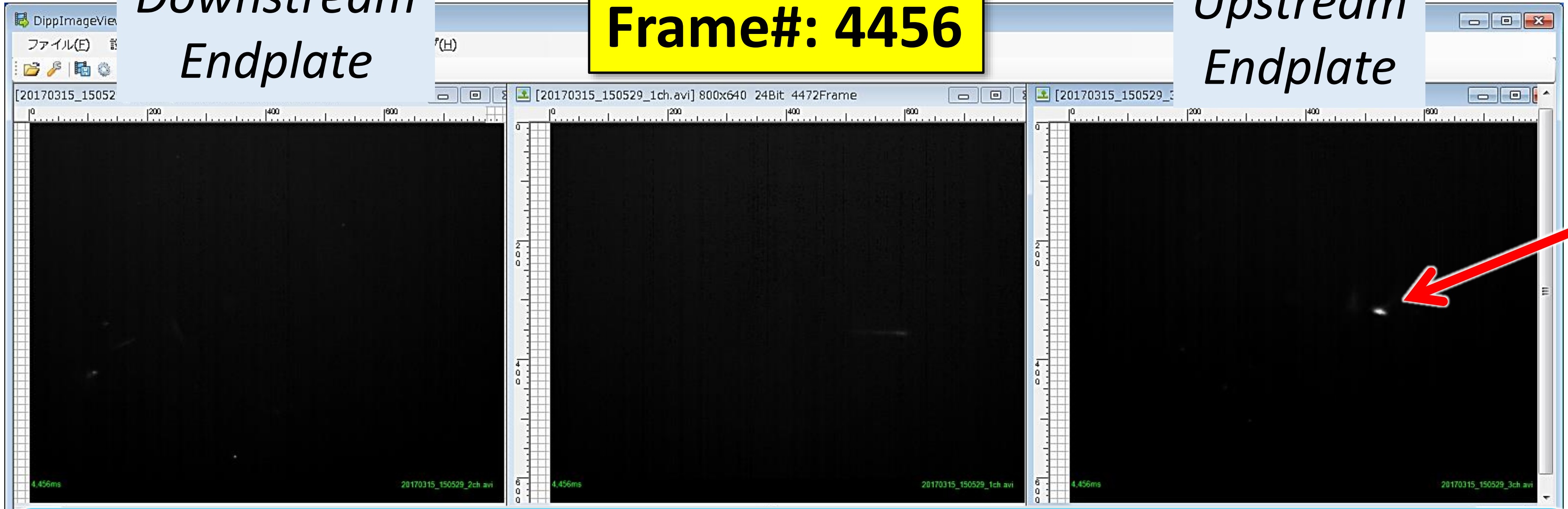
Frame#: 4456

Upstream Endplate

Other bright spots disappeared.

↓

BD occurred in the previous frame.

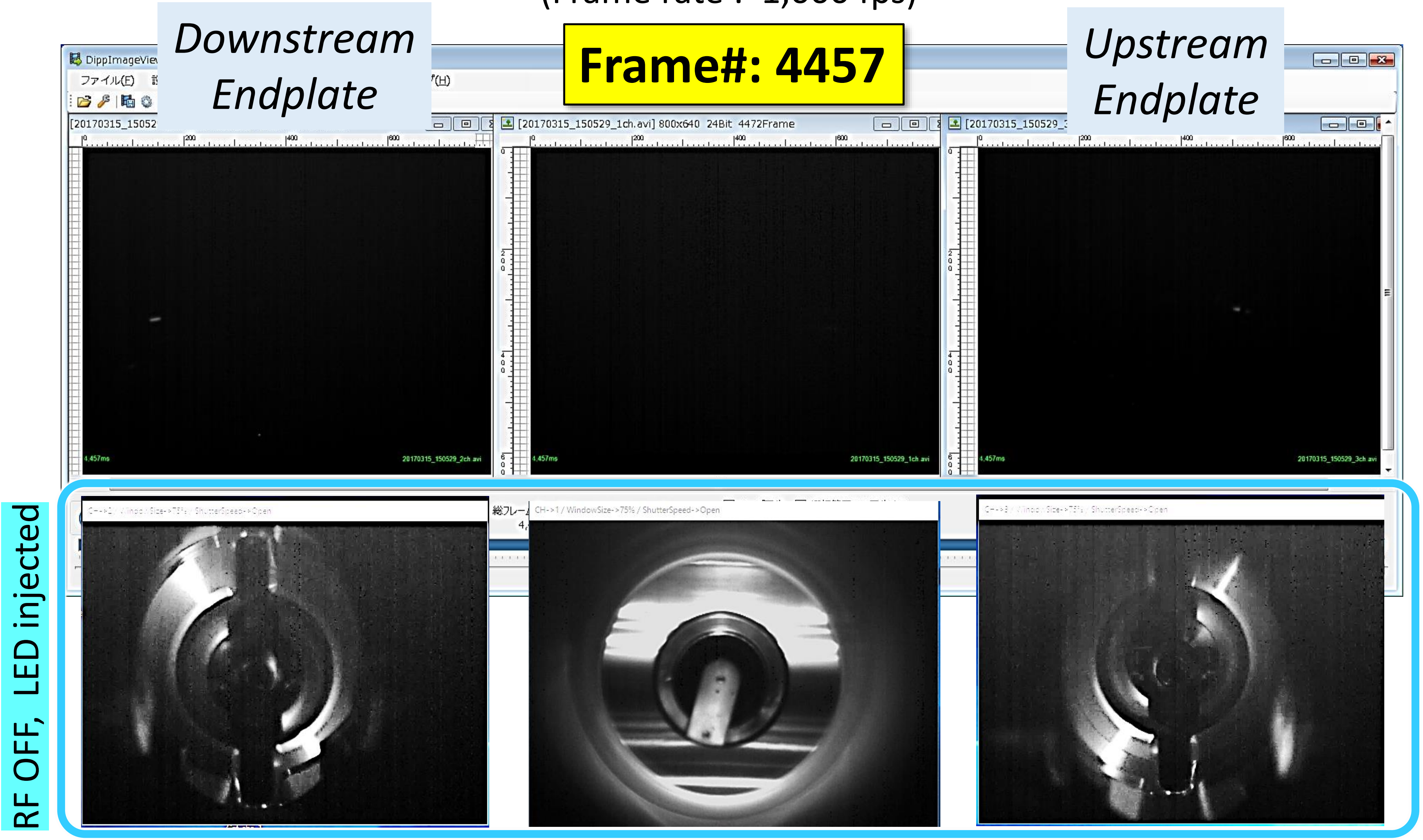


Still visible after BD

RF OFF, LED injected

Event 1/4: Downstream → Upstream, then impact and BD

(Frame rate : 1,000 fps)



Event 2/4: A flying object impacted on the downstream endplate!

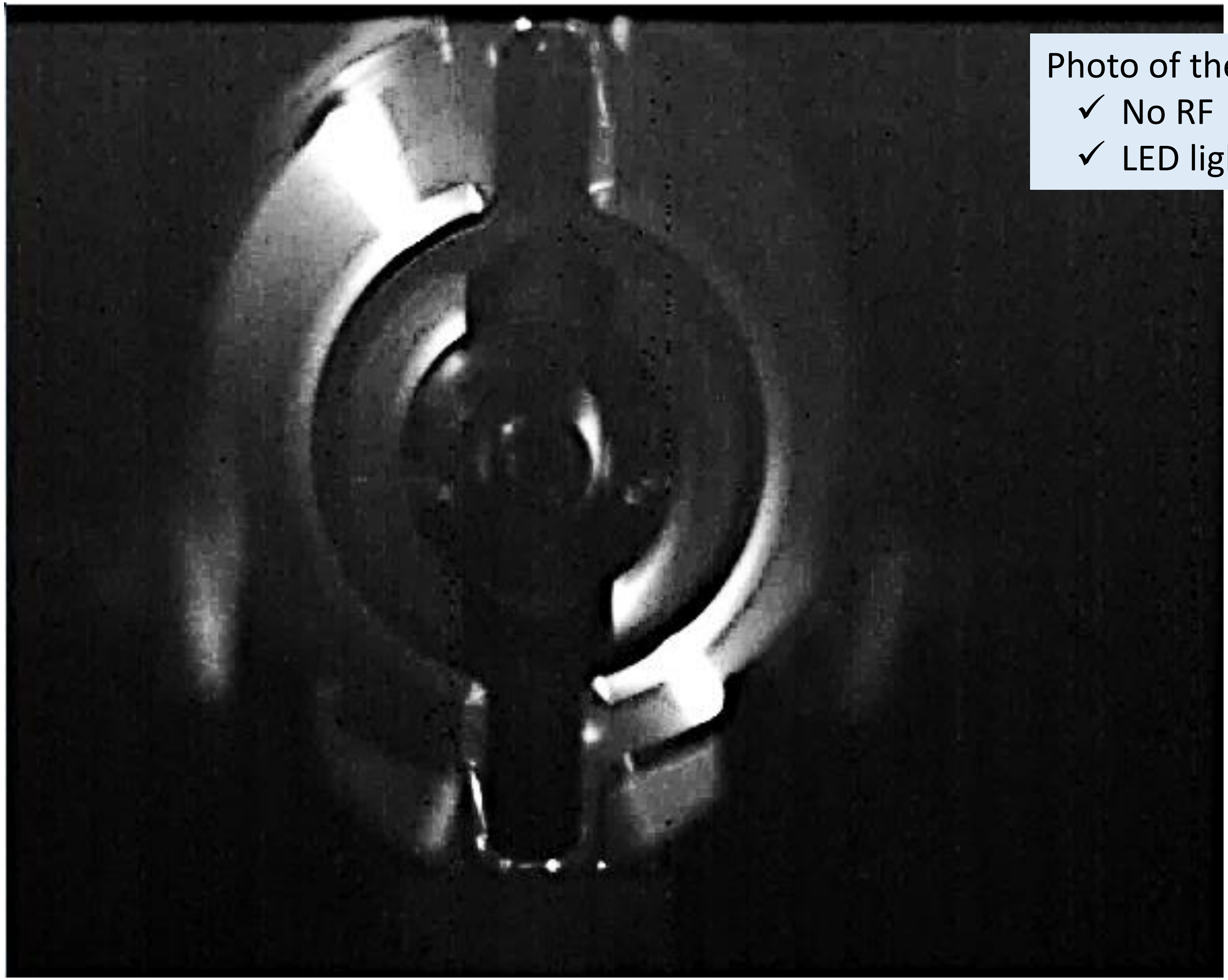


Photo of the downstream endplate
- ✓ No RF
- ✓ LED light injected

Event 2/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 1,000 fps

Event 2/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 1,000 fps

Event 2/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 1,000 fps

Event 2/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 1,000 fps

Event 2/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 1,000 fps

Event 3/4: A flying object impacted on the downstream endplate!

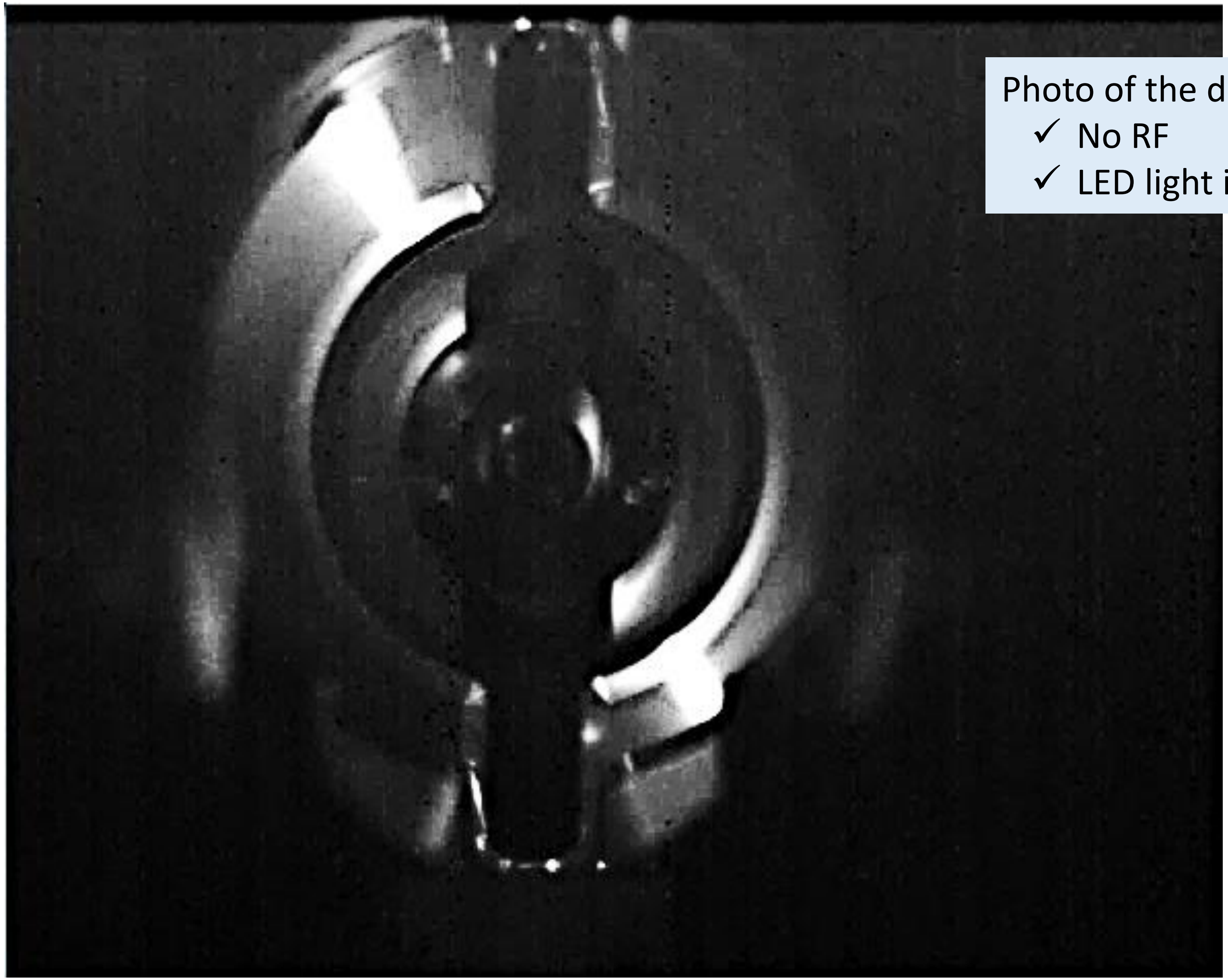
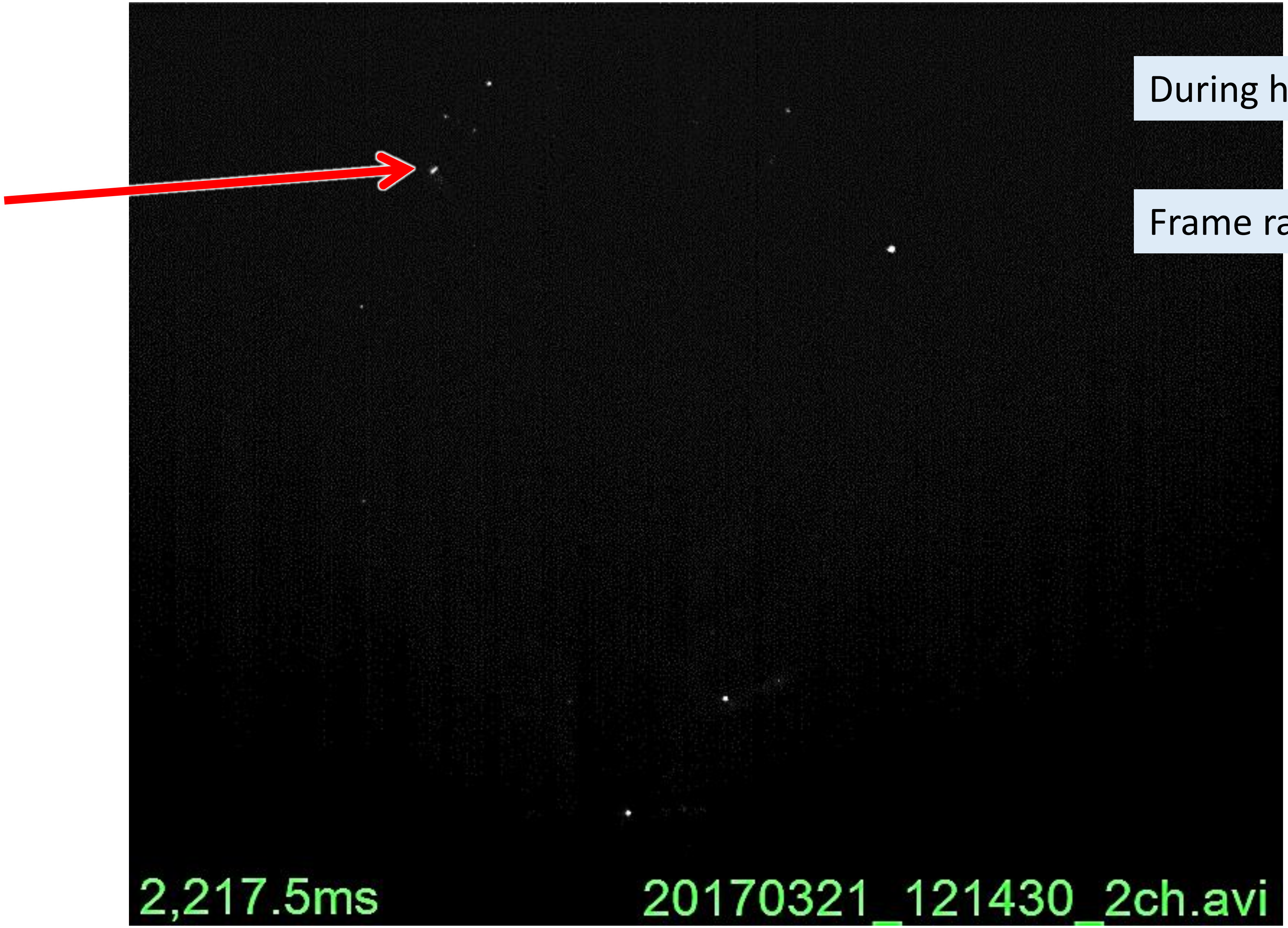


Photo of the downstream endplate
- ✓ No RF
- ✓ LED light injected

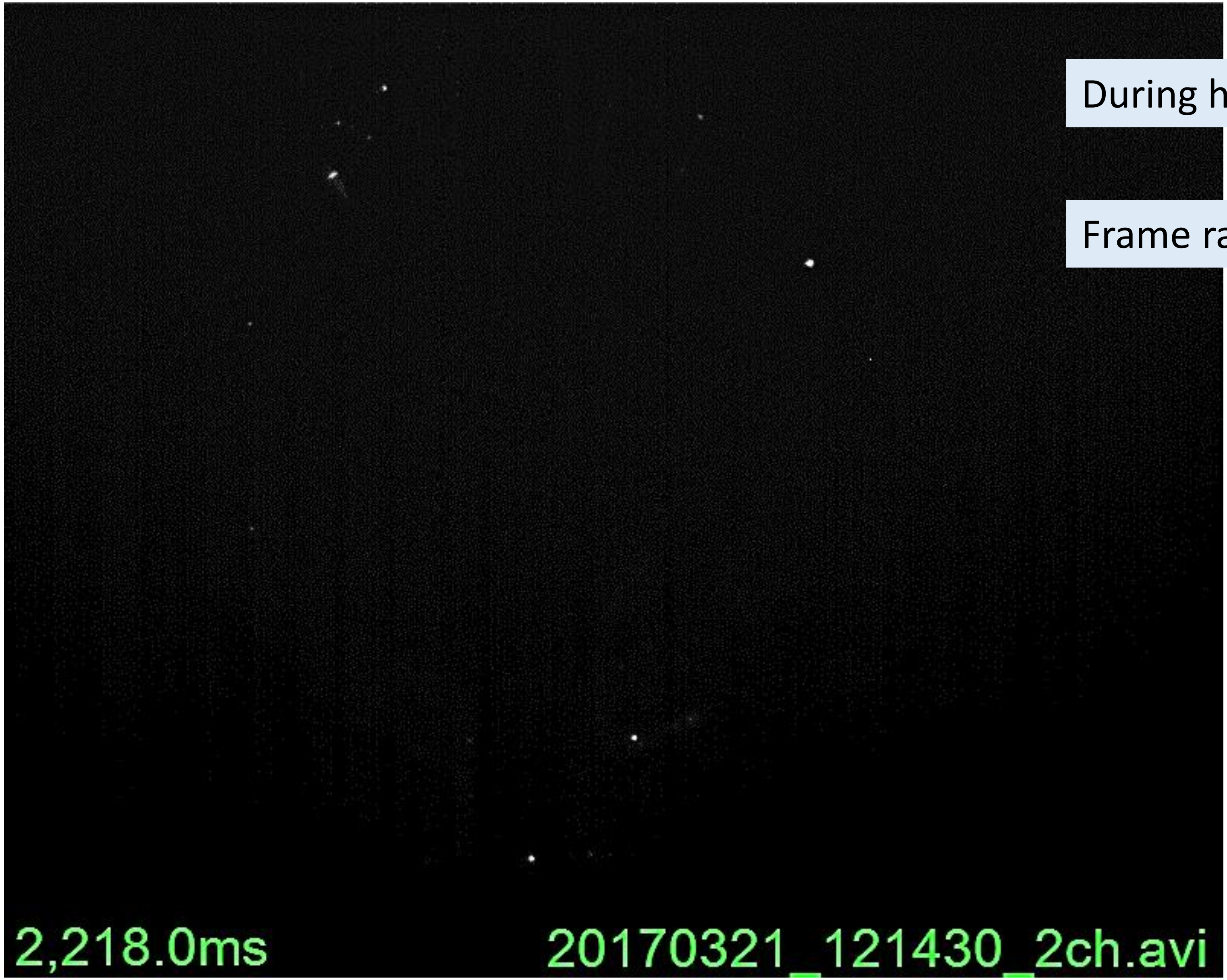
Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

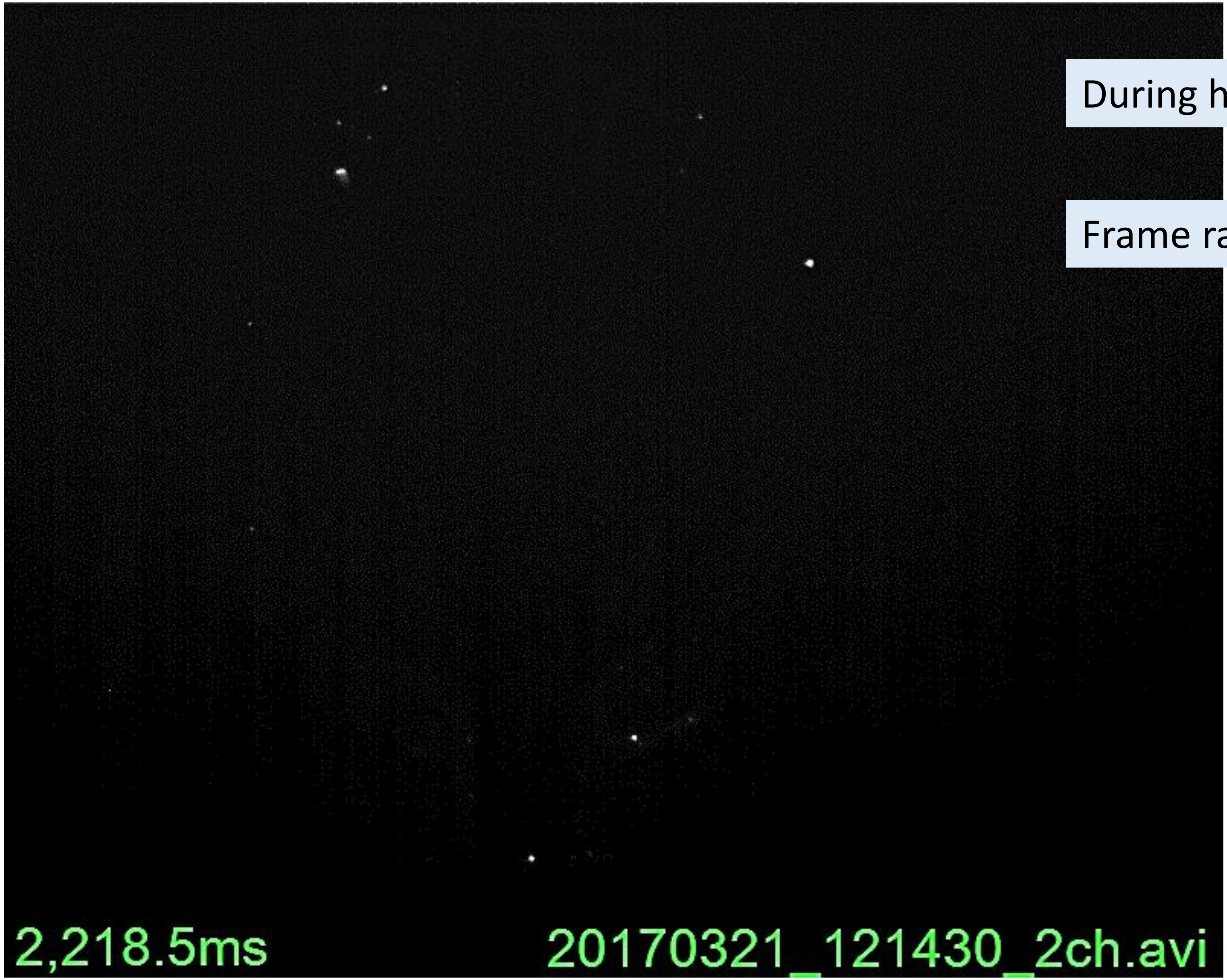
Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

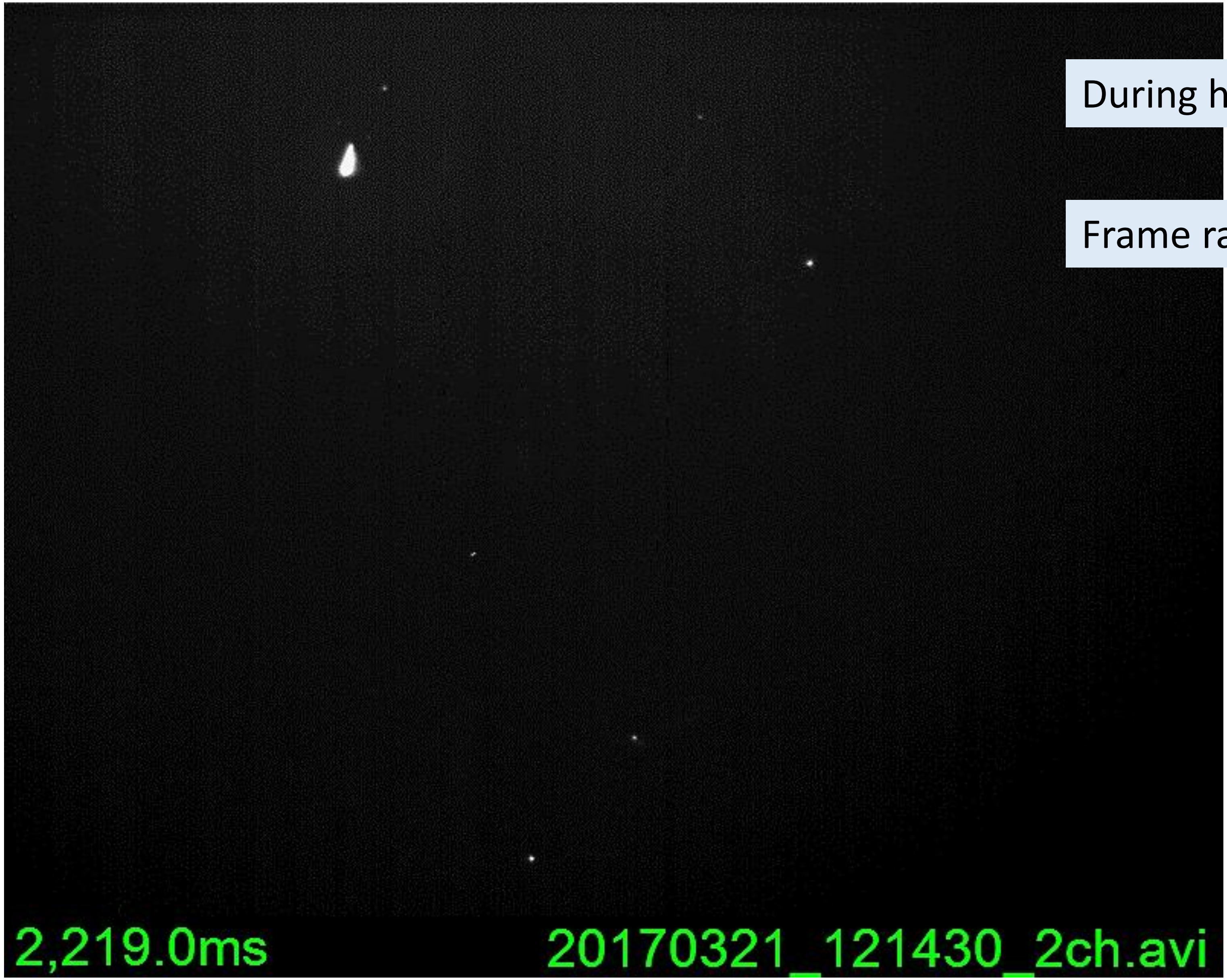
Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

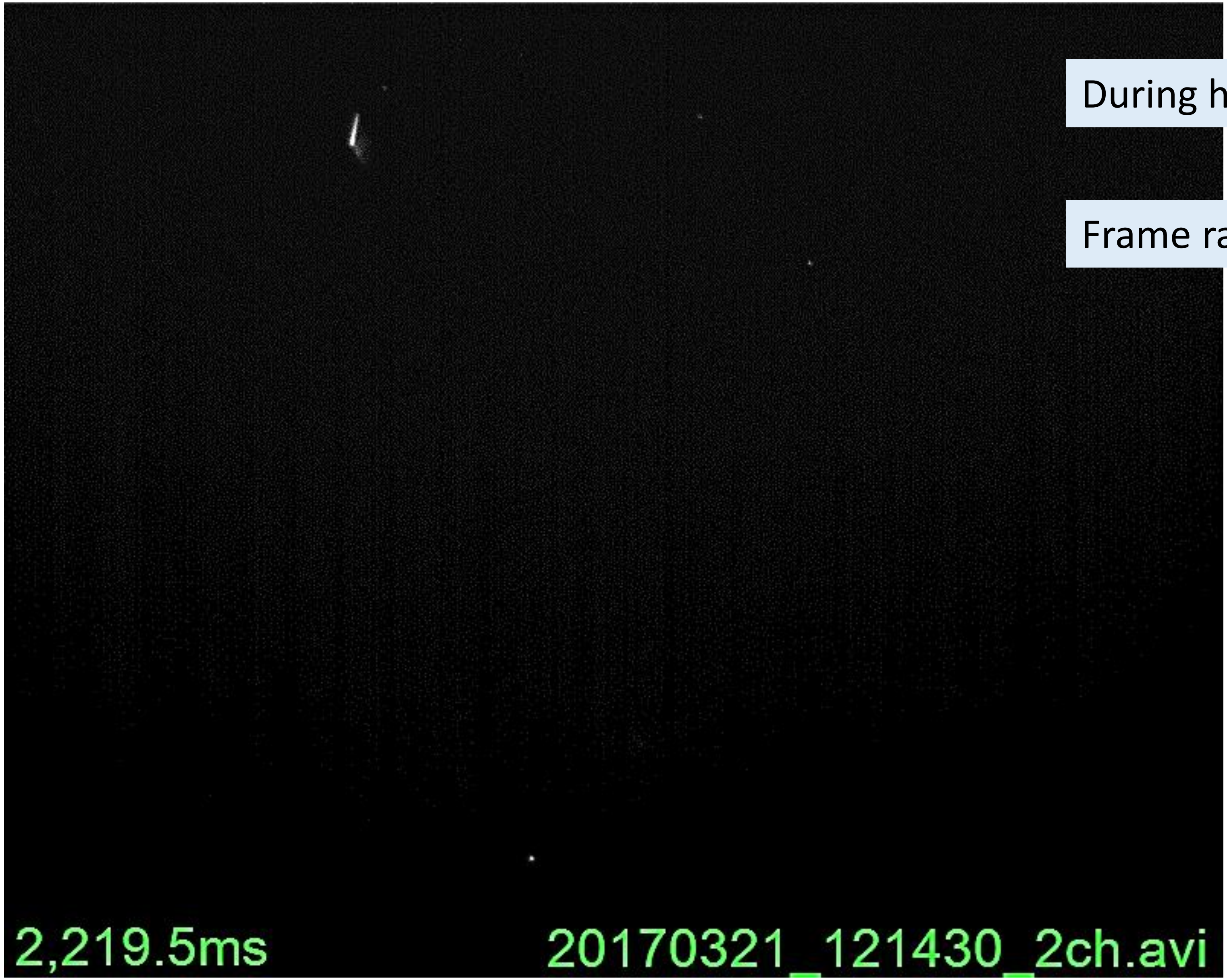
Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

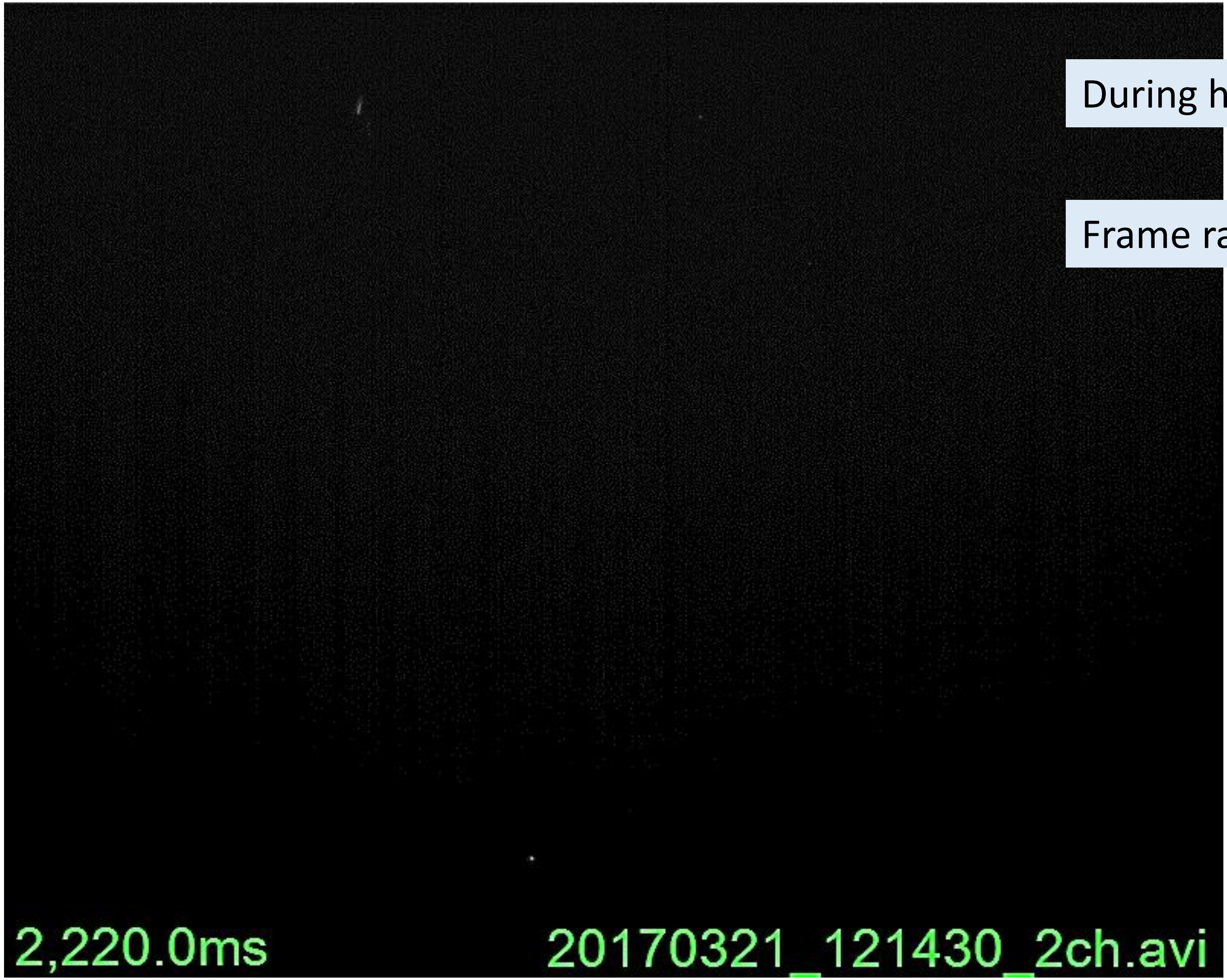
Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

Event 3/4: A flying object impacted on the downstream endplate!



During high-power operation

Frame rate : 2,000 fps

Event 4/4: A flying object impacted on the downstream endplate!

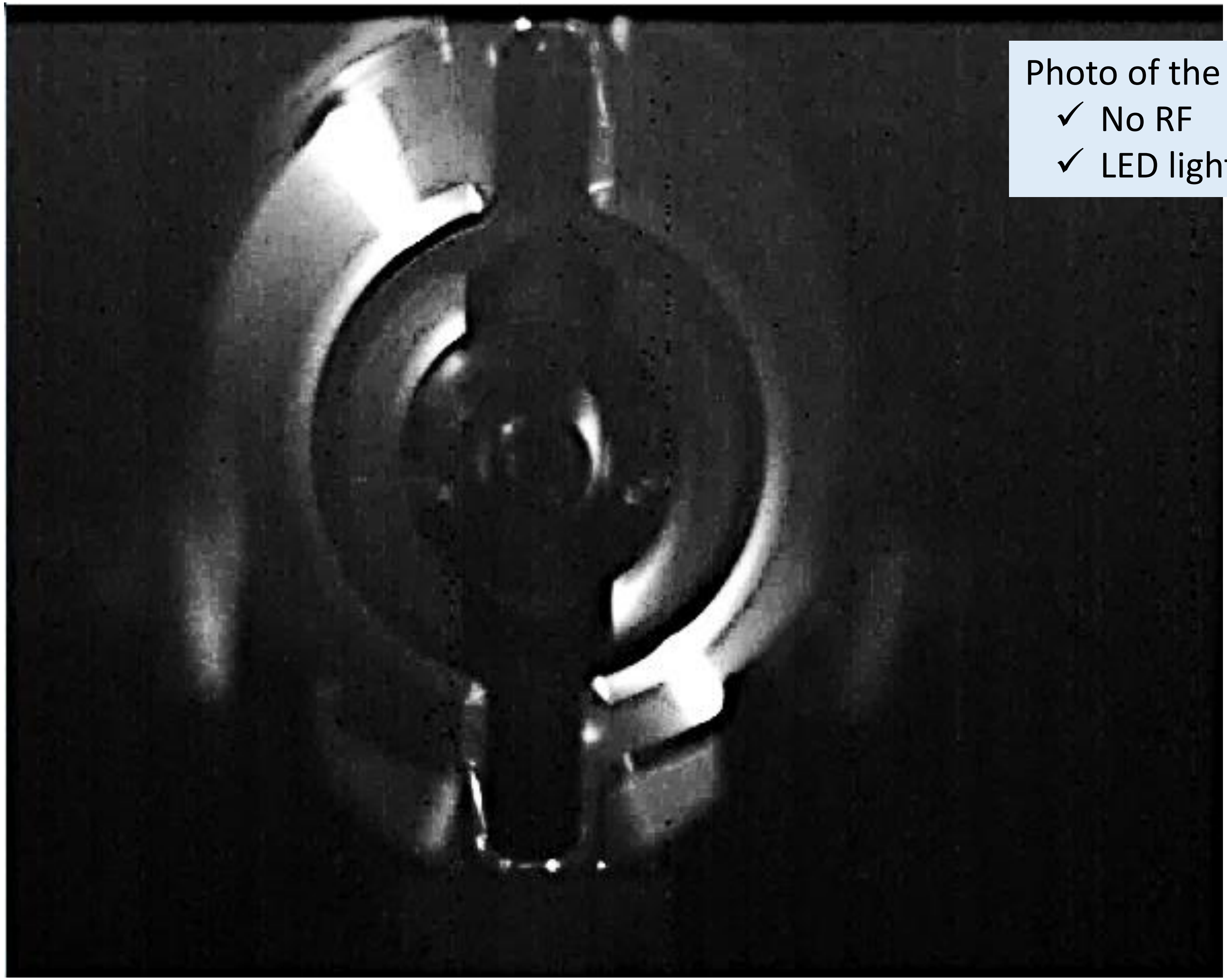


Photo of the downstream endplate
- ✓ No RF
- ✓ LED light injected

Event 4/4: A flying object impacted on the downstream endplate!

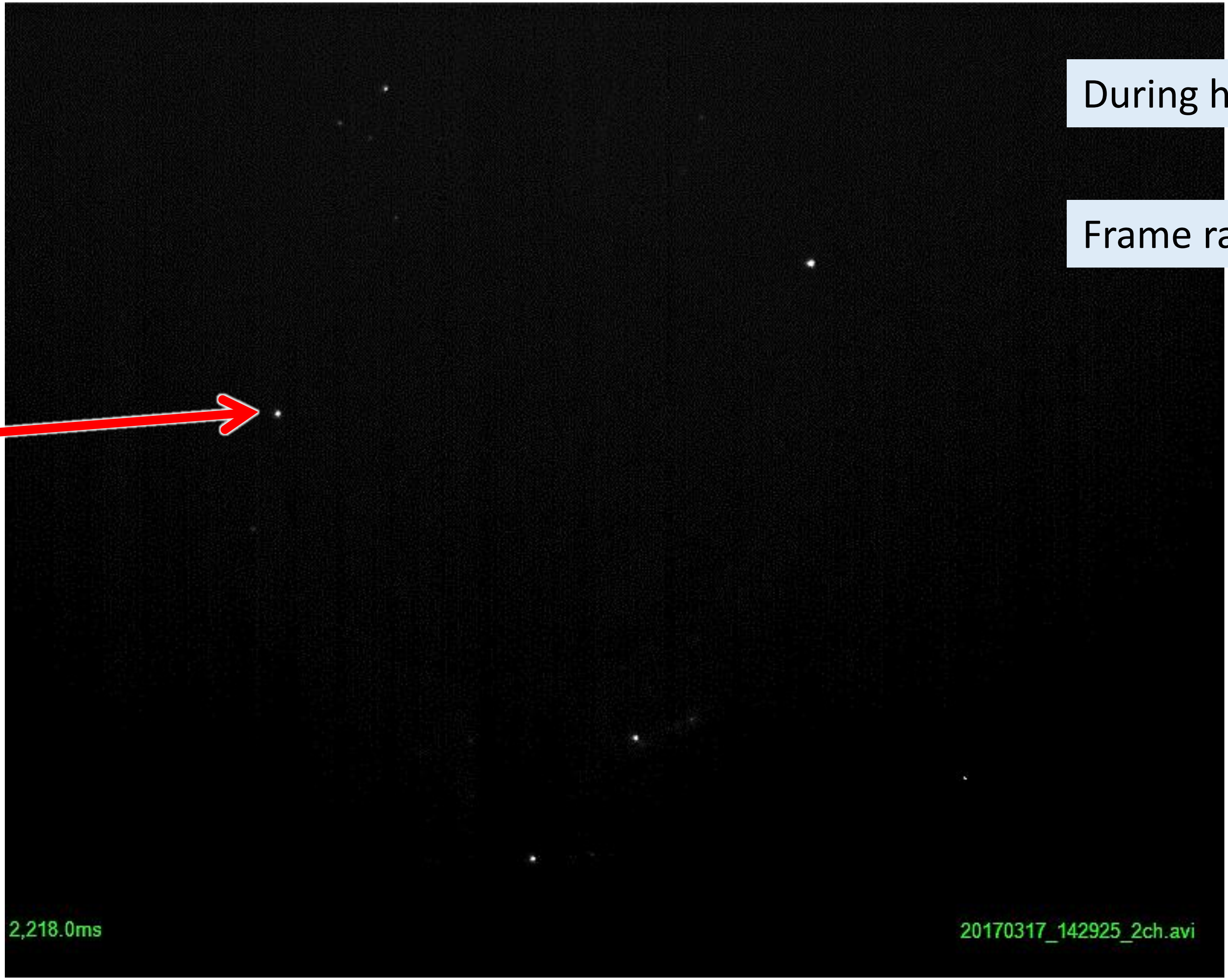
During high-power operation

Frame rate : 2,000 fps

Event 4/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 2,000 fps



Event 4/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 2,000 fps

Event 4/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 2,000 fps

Event 4/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 2,000 fps

Event 4/4: A flying object impacted on the downstream endplate!

During high-power operation

Frame rate : 2,000 fps

Answers for the Questions

Conclusions

Hypotheses

2. What is the physical process of the spot-type explosion?
   - Generation → Growth → Explosion of a bright spot in a moment?
     - If we use higher-speed cameras, we should observe more this kind of events; however, in this observation, no more events.
     - On the other hand, events with flying objects impacting on the copper surface triggering BD observed more
       - 1 event found out of 205 BD events using the low-speed cameras (30 fps)
       - 4 events found out of 40 BD events using the high-speed cameras (1,000 to 2,000 fps)

         (Dedicated computer programs are being prepared for detailed analyses.)
     - This "Flying Object" might be an answer.
       - If the temperature of the flying objects is not so high, we cannot see them as visible lights, and just observe them as spot-type explosion events.

New!

Vacuum Breakdown Model

A Thermochemical Vacuum Breakdown Model is Proposed.

Vacuum breakdowns are triggered by the following thermochemical reaction processes:

$$C(s) + O_2(g) = CO_2(g) + 394\ kJ$$
$$C(s) + \tfrac{1}{2}O_2(g) = CO(g) + 111\ kJ$$

(← thermochemical equations)

Steps

A Thermochemical Vacuum Breakdown Model is Proposed.

Vacuum breakdowns are triggered by the following thermochemical reaction processes:

$$C(s) + O_2(g) = CO_2(g) \quad + 394\ \text{kJ}$$
$$C(s) + \tfrac{1}{2}O_2(g) = CO(g) \quad + 111\ \text{kJ}$$

(← thermochemical equations)

Steps

1. Carbonic microparticles:
   - Enter from outside into the cavity, and/or
   - Created from hydrocarbons, etc., by using energies of RF fields, breakdowns, and/or field emissions.

A Thermochemical Vacuum Breakdown Model is Proposed.

Vacuum breakdowns are triggered by the following thermochemical reaction processes:

$$C(s) + O_2(g) = CO_2(g) \quad + 394\ \text{kJ}$$
$$C(s) + \tfrac{1}{2}O_2(g) = CO(g) \quad + 111\ \text{kJ}$$

(← thermochemical equations)

Steps

1. Carbonic microparticles:
   - Enter from outside into the cavity, and/or
   - Created from hydrocarbons, etc., by using energies of RF fields, breakdowns, and/or field emissions.
2. Such microparticles adhere to the copper surface of the cavity.

A Thermochemical Vacuum Breakdown Model is Proposed.

Vacuum breakdowns are triggered by the following thermochemical reaction processes:

$$C(s) + O_2(g) = CO_2(g) \ + 394 \text{ kJ}$$
$$C(s) + \tfrac{1}{2}O_2(g) = CO(g) \ + 111 \text{ kJ}$$

(← thermochemical equations)

Steps

1. Carbonic microparticles:
   - Enter from outside into the cavity, and/or
   - Created from hydrocarbons, etc., by using energies of RF fields, breakdowns, and/or field emissions.
2. Such microparticles adhere to the copper surface of the cavity.
3. A part of the microparticle is heated by surface currents and/or field emissions over the ignition temperature of carbon (~500 degC).
   - However, no burning since no oxygen in vacuum

A Thermochemical Vacuum Breakdown Model is Proposed.

Vacuum breakdowns are triggered by the following thermochemical reaction processes:

$C(s) + O_2(g) = CO_2(g)$ + **394 kJ**
$C(s) + \frac{1}{2}O_2(g) = CO(g)$ + **111 kJ**

(← thermochemical equations)

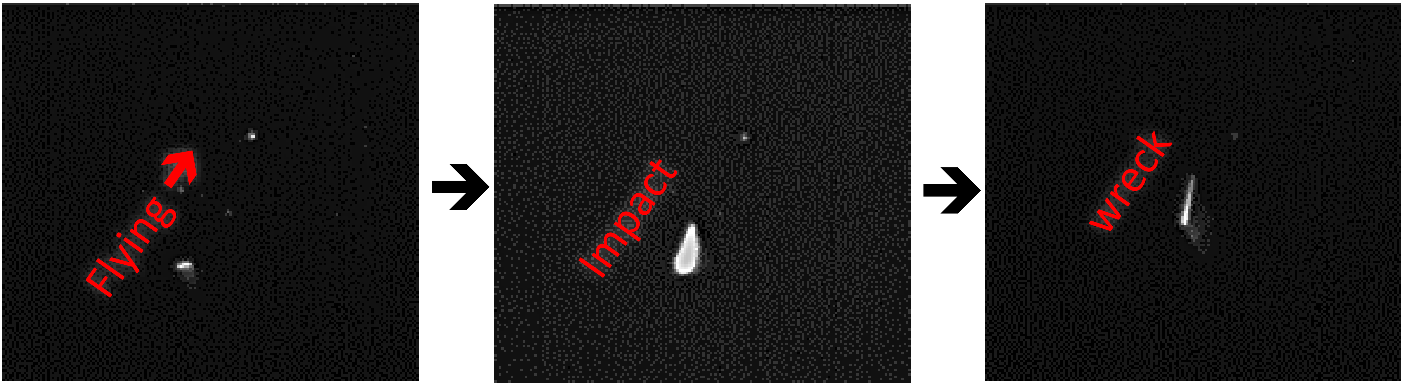
Steps

1. Carbonic microparticles:
   - Enter from outside into the cavity, and/or
   - Created from hydrocarbons, etc., by using energies of RF fields, breakdowns, and/or field emissions.
2. Such microparticles adhere to the copper surface of the cavity.
3. A part of the microparticle is heated by surface currents and/or field emissions over the ignition temperature of carbon (~500 degC)
   - However, no burning since no oxygen in vacuum
4. Enough oxygen is provided to the high-temperature part of the microparticle in a moment

   → Explosion → Ionization of C and/or Cu, etc., using the above energies → Vacuum breakdown

Speculations

Spot-type explosion not originating from a stable bright spot



A charged-up carbonic microparticle with > 500 degC was extracted by the RF field from the copper surface in one side.

➔ Accelerated by the RF field

➔ Impact on the copper surface in the other side

➔ Enough oxygen was provided from oxides, including H_2O, in the copper surface at the impact point in a moment.

➔ Explosion

➔ Vacuum breakdown

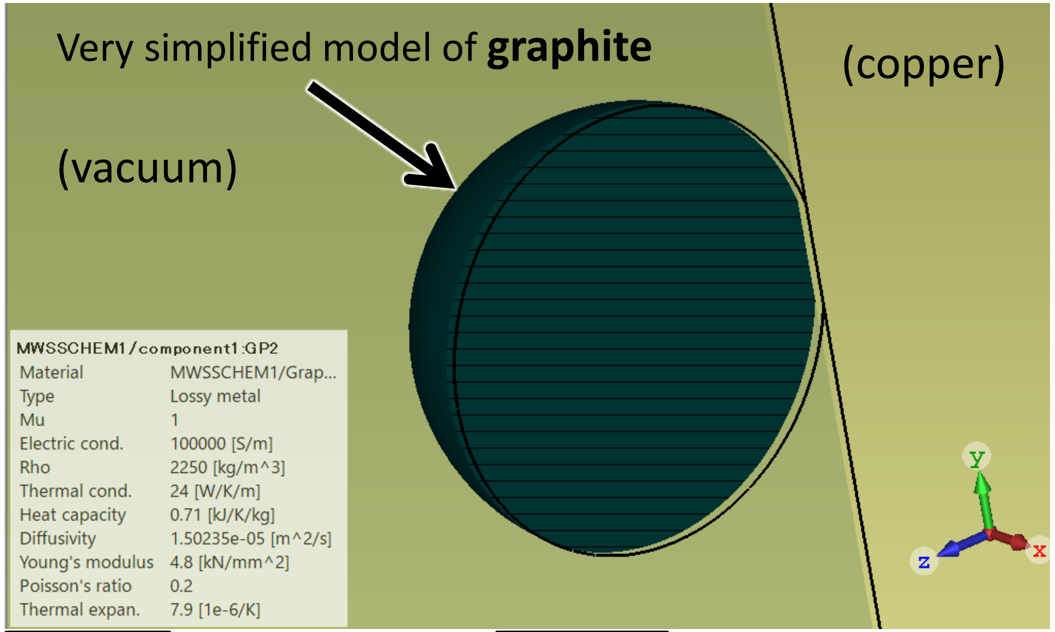
Spot-type explosion of a stable bright spot

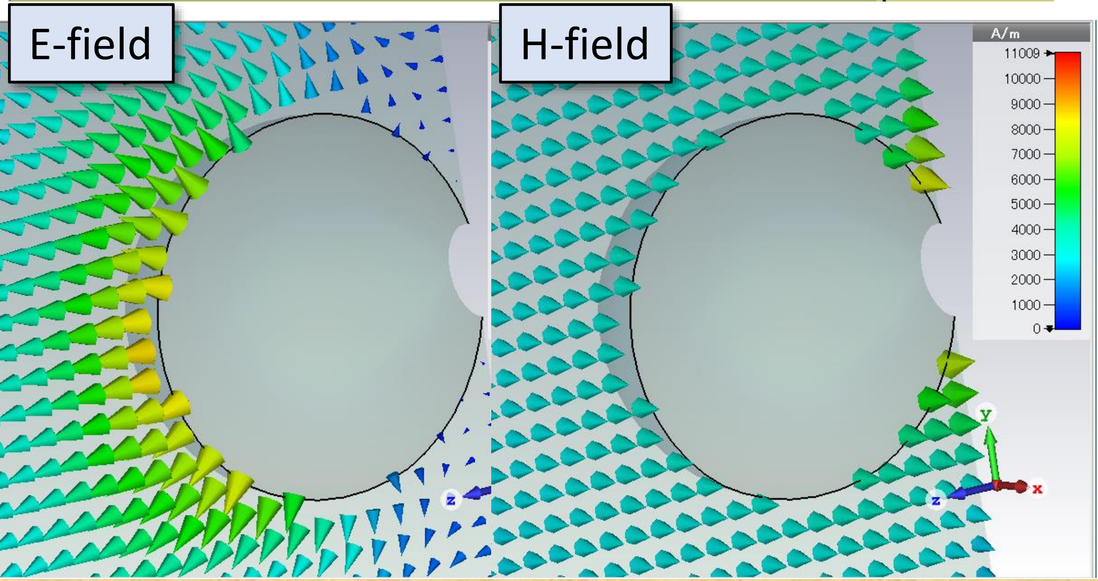
Enough oxygen was provided to the bright spot (= carbonic microparticle with > 500 degC) by a certain mechanism.

➔ Bright-spot explosion

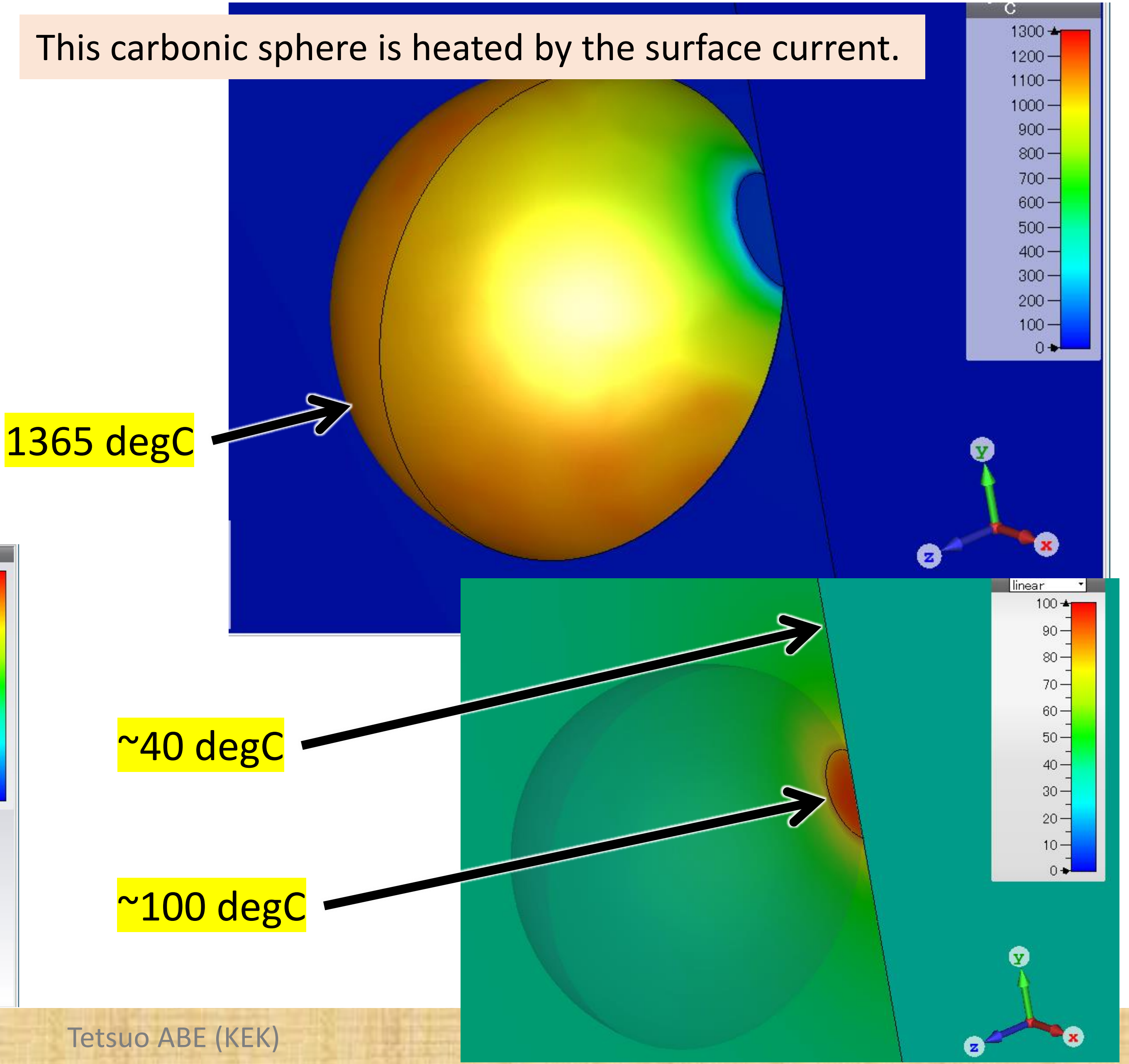
➔ Vacuum breakdown

Simple Simulation using CST MPHYSICS STUDIO





This carbonic sphere is heated by the surface current.



Consequences and Predictions by This Model

A) Observed temperatures of bright spots cannot exceed the sublimation point of carbon.
   - ~1740 degC at 1×10^{-5} Pa (for graphite)

B) Breakdowns can occur even with electric fields much lower than those for field evaporation.

C) Carbons of embers should be detected around breakdown spots more than in other areas by microelement analyses after high-power tests.

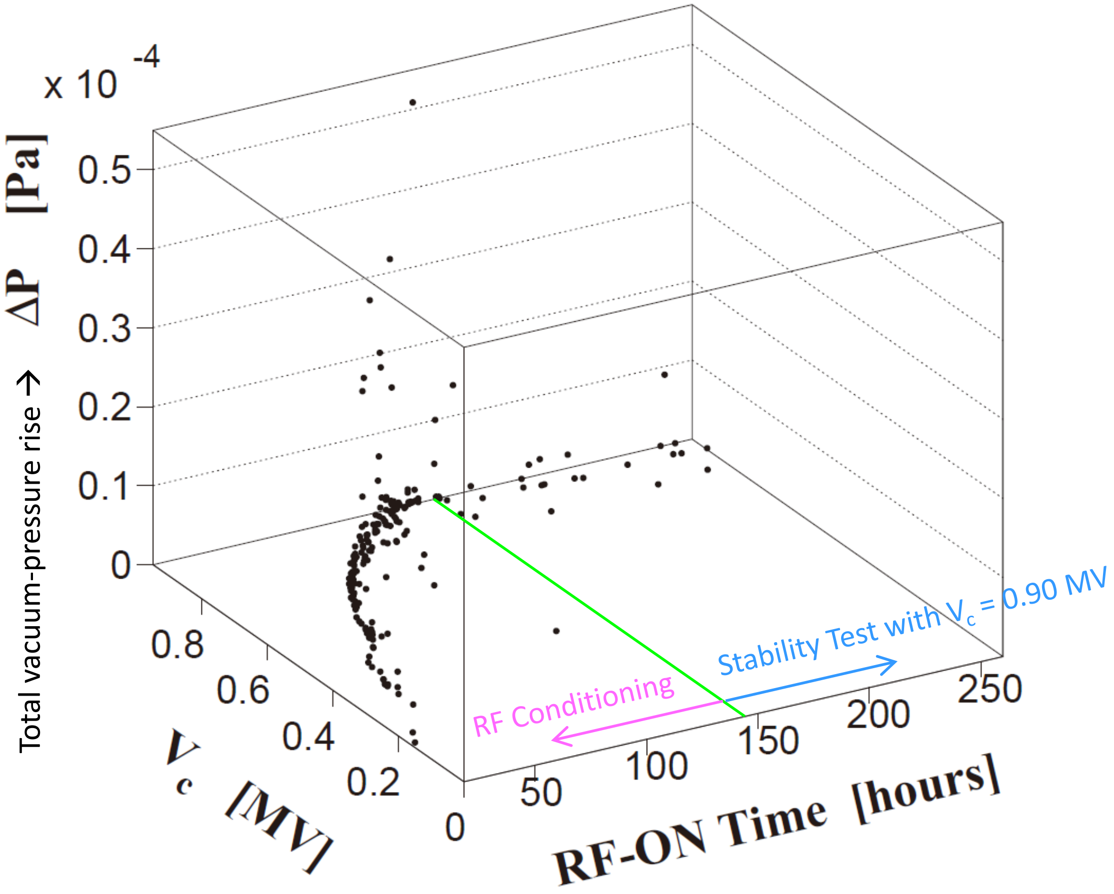
D) Copper surfaces are reduced by breakdowns.

E) Smaller (larger) amount of oxides, including H_2O, in the copper surface leads to lower (higher) breakdown rates.

F) Partial vacuum pressures of CO and CO_2 should increase at breakdowns.
   → See the next two pages.

Vacuum-Pressure Rises at Breakdowns of DR Cavity No. 2 (509 MHz, CW cavity)

Extracted from
[T. Abe, Y. Takeuchi, T. Kageyama, H. Sakai, and K. Yoshino, "Test Results on RF Accelerating Cavities for the Positron Damping Ring at SuperKEKB", in Proceedings of the 11th Annual Meeting of Particle Accelerator Society of Japan, 2014 (SAP050).]



(Vacuum pressure during this high-power test: ~1x10^{-5} Pa)

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

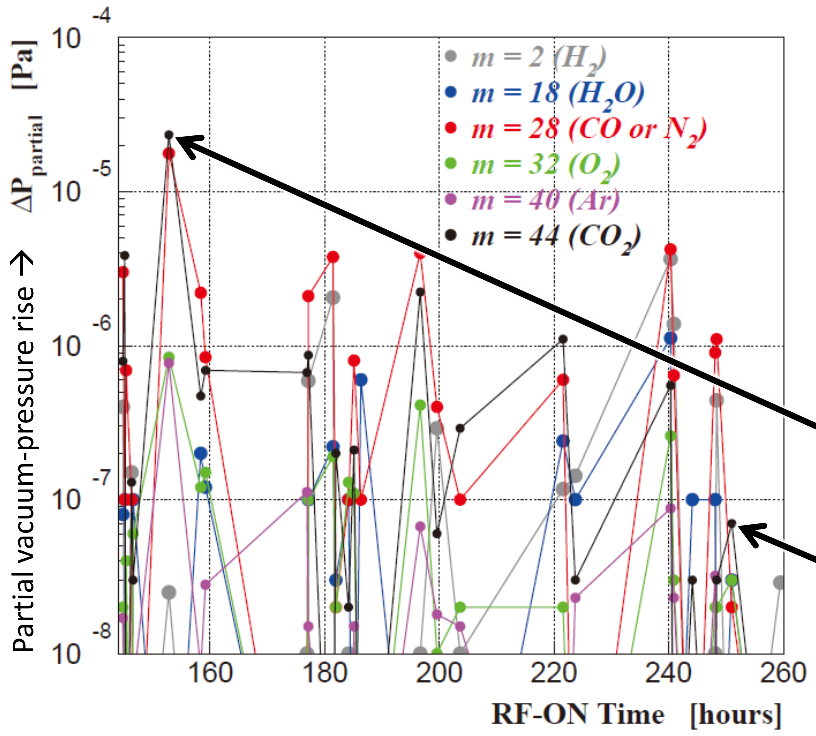


Figure 17: Partial vacuum-pressure rises ($\Delta P_{partial}$) at the cavity breakdowns, measured using the Q-mass spectrometer shown in Fig.5 every one second, for mass numbers of 2, 18, 28, 32, 40, and 44 as a function of the RF-ON time during the stability test.

Max. size of the carbonic particle (graphite) estimated from the pressure rise

< ~40 μm

< ~4 μm

CO and CO_2 are dominant components of emitted gases at breakdowns!

(H_2 visible only when increasing V_c)

Summary

- Using the hyperspectral camera, we measured temperatures of the 10 bright spots during high-power operation.
  - > 1,000 degC at V_c = 0.95 MV (E_{acc} = 3.7 MV/m)
  - The bright spots are not copper.
  - Primary candidate of the bright spots is a carbonic microparticle.

- Using the high-speed cameras, we observed flying objects triggered breakdown.
  - All of, or most of, the spot-type explosion events might be accompanied by a flying object triggering breakdown.

- Based on the observation results in this study, the thermochemical vacuum breakdown model has been proposed.
  - It is hypothesized that burning of a hot carbonic microparticle in a moment might trigger vacuum breakdown.

Thank you for your attention!

This work was supported by Grant-in-Aid for Scientific Research (JSPS KAKENHI) (Grant No. 15H03671).