“Fireball”-Triggered Vacuum Breakdown of RF Cavities

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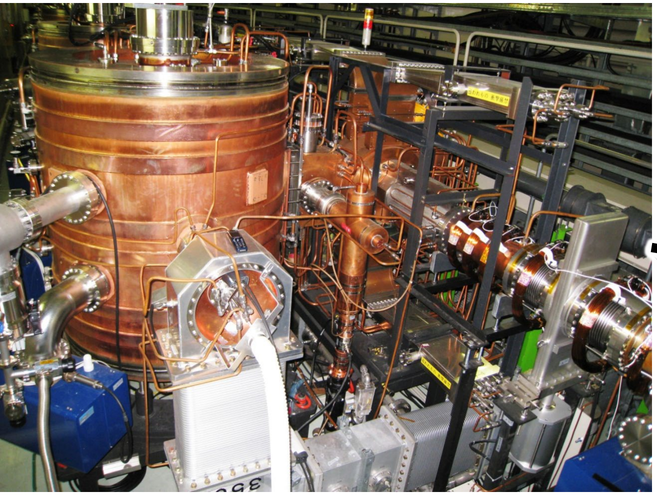
Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators @ CERN

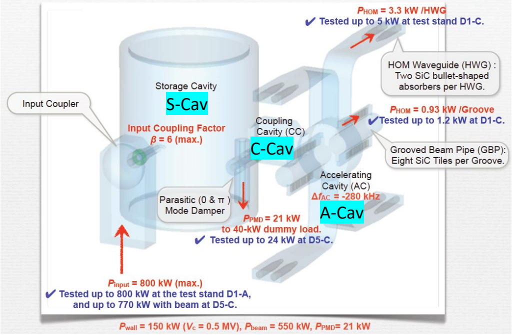
2023-06-13

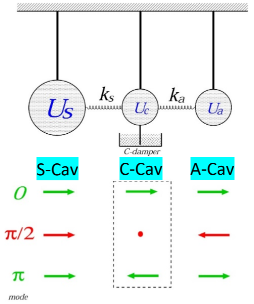
Normal-Conducting Accelerating Cavities for the SuperKEKB Rings

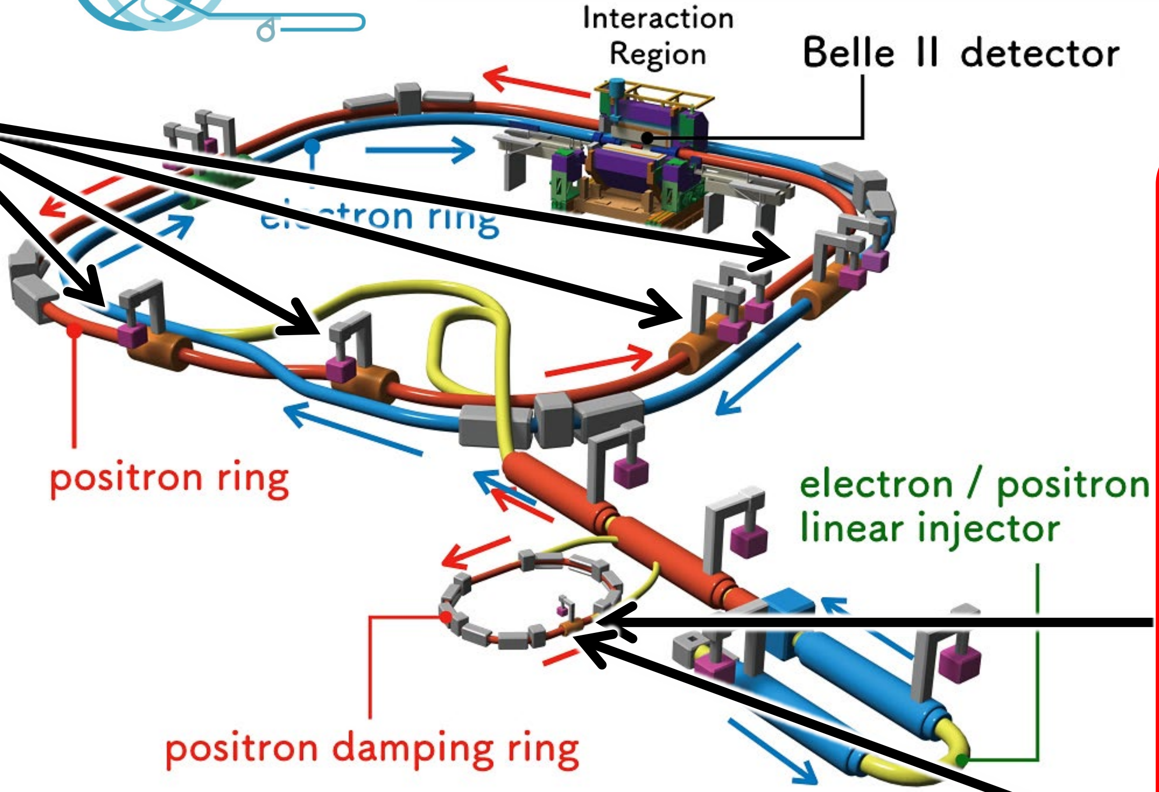
- Frequency: 509 MHz (Continuous wave (CW))
- Standing Wave
- Wall-loss power: P_c = ~60 kW (only A-cav)
- Cavity voltage: V_c = ~0.5 MV/cav

30 ARES cavities

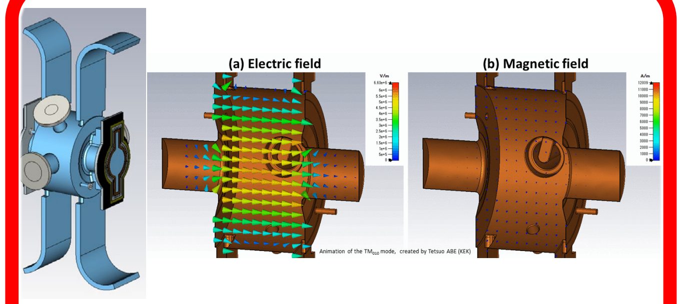




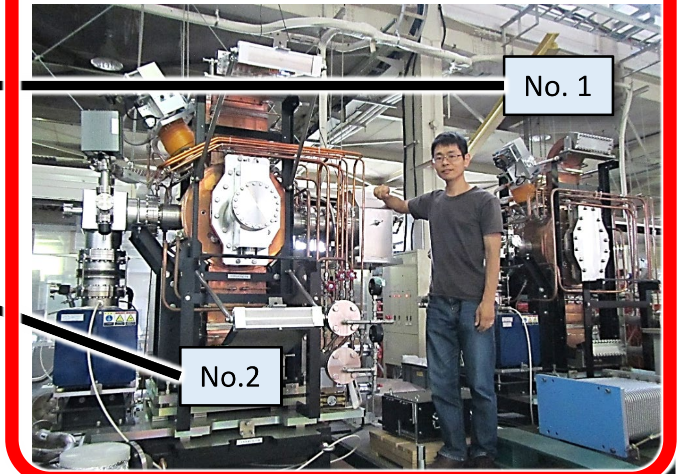




RF cavities used in this BD study



RF cavities for the e⁺ DR

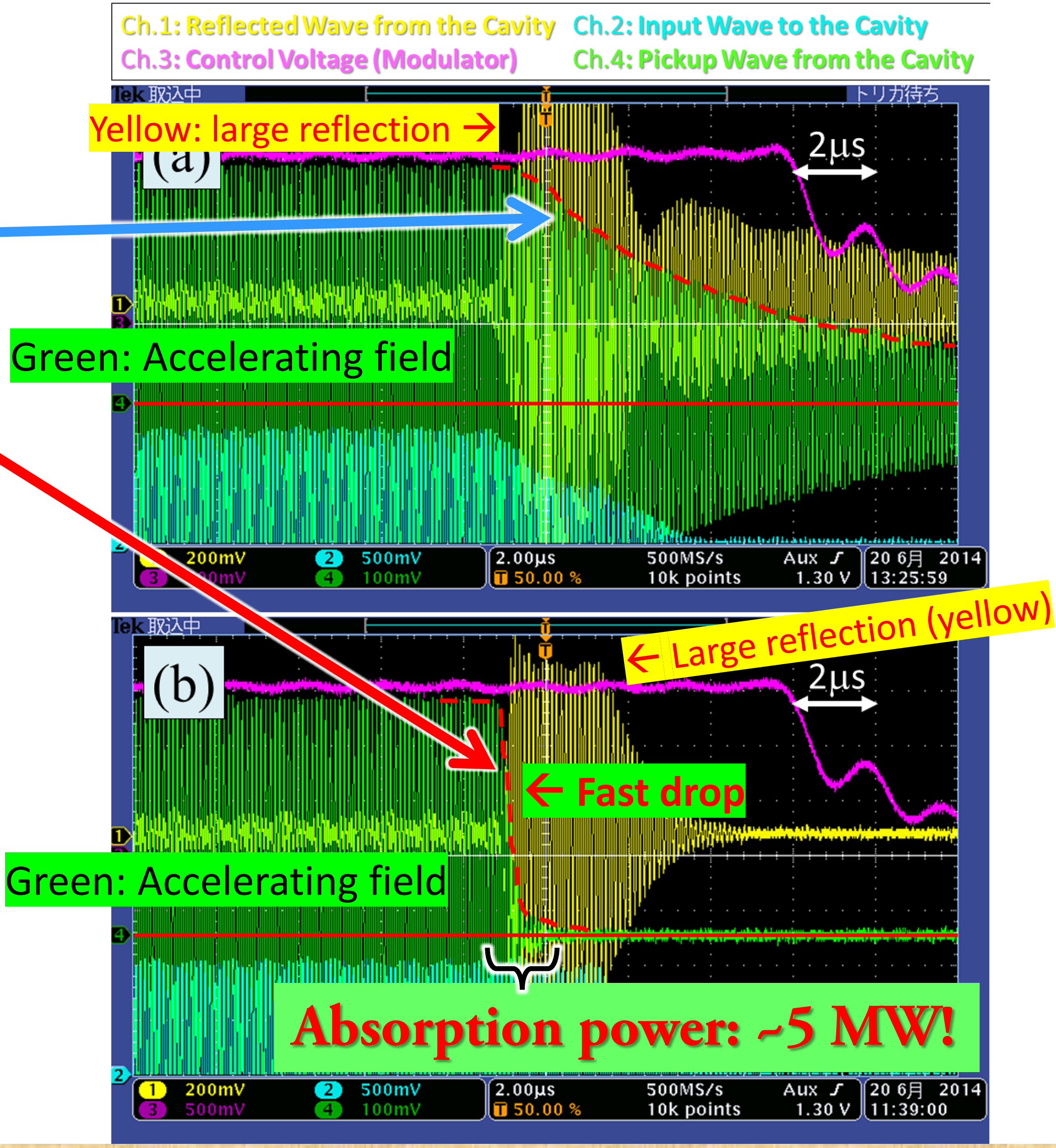


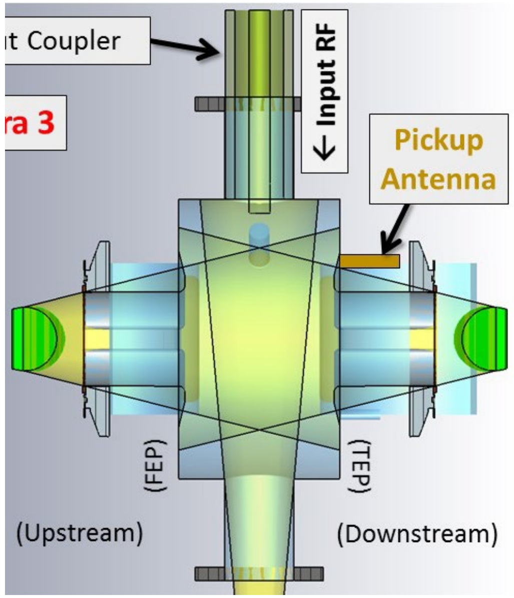
What's experimental definition of RF-cavity vacuum breakdown (BD)

BD Signal A: Fast drop of the accelerating field

Decay time:

- ➢ Normal RF-switch OFF → Decay time: 8 μs
- ➢ Breakdown candidate → Decay time: ~500 ns





Pickup antenna

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.

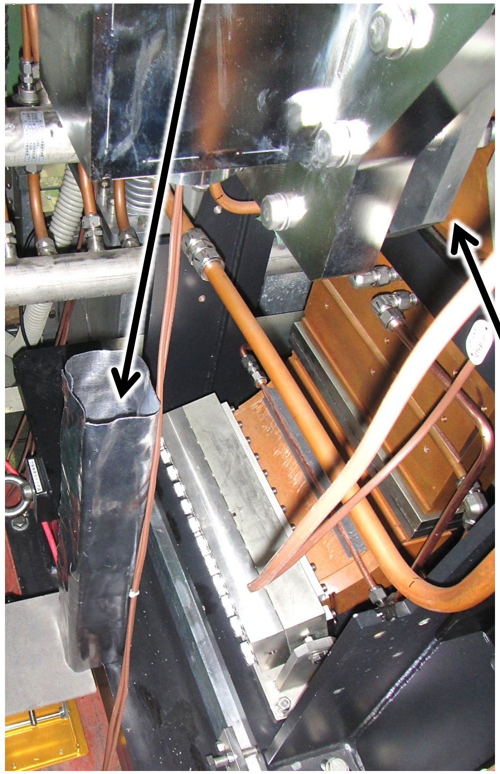
Q_L=13000@509MHz ⇒ Filling time: 8 μs

BD Signal B: Current flash

(During the high-power test of the RF cavity for the DR)

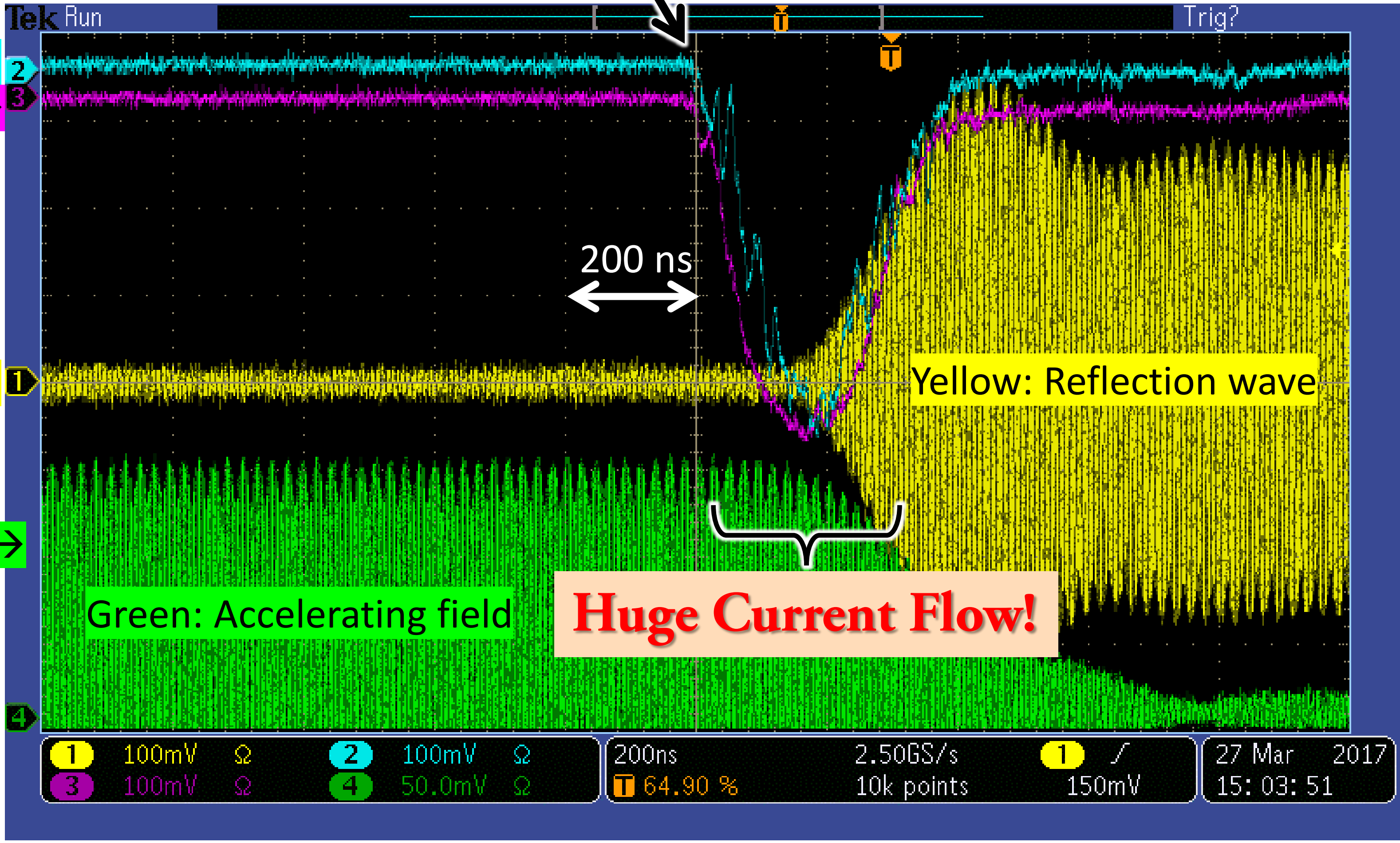
X-ray detector
(plastic scintillator + PMT)

Field emitted e^-
→ Impact on the metal surface
→ X-ray radiation



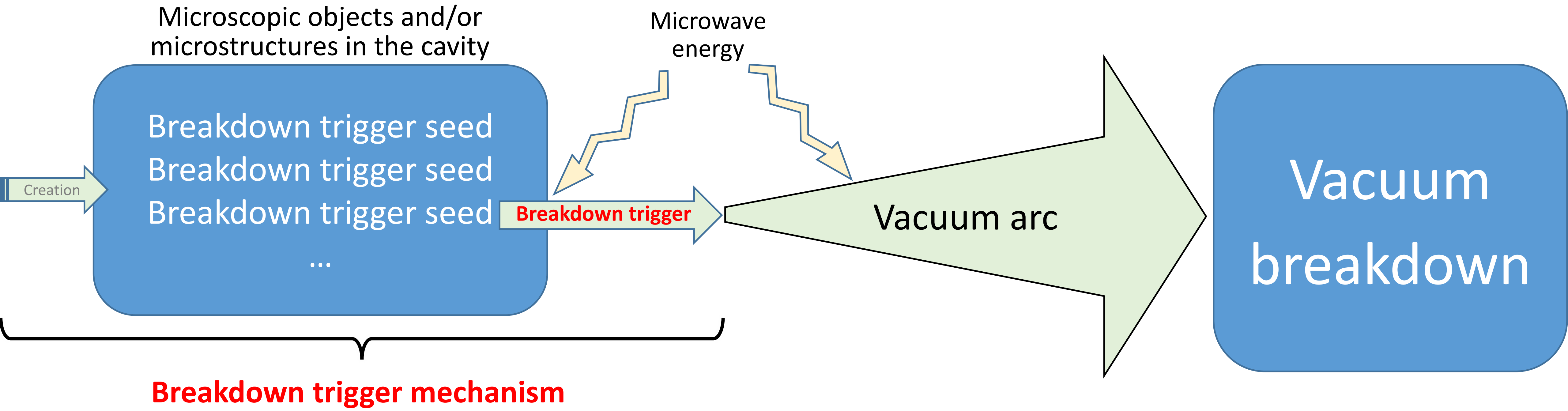
RF cavity
for the e+ DR

Ch.2 : X-ray (UP) →
Ch.3 : X-ray (DN) →
Ch.1 : Cav. Refl. →
Ch.4 : Cav. Pickup →

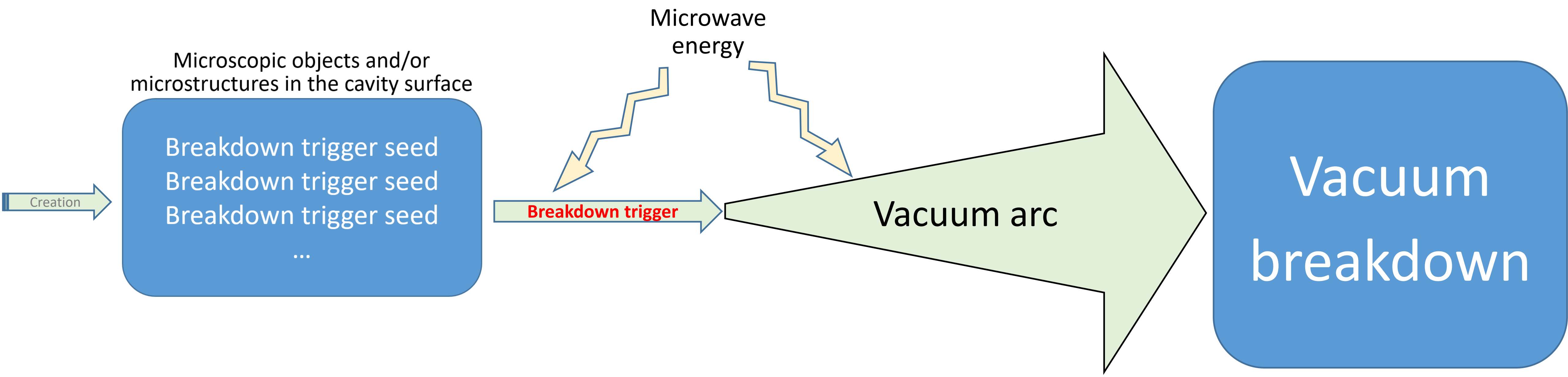


What triggers BD

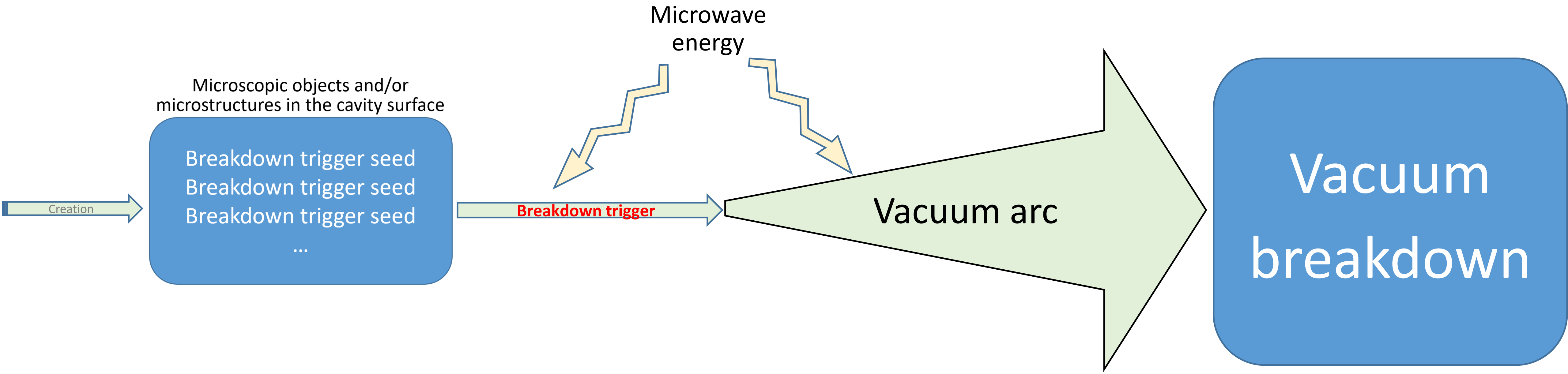
Physics leading to BD



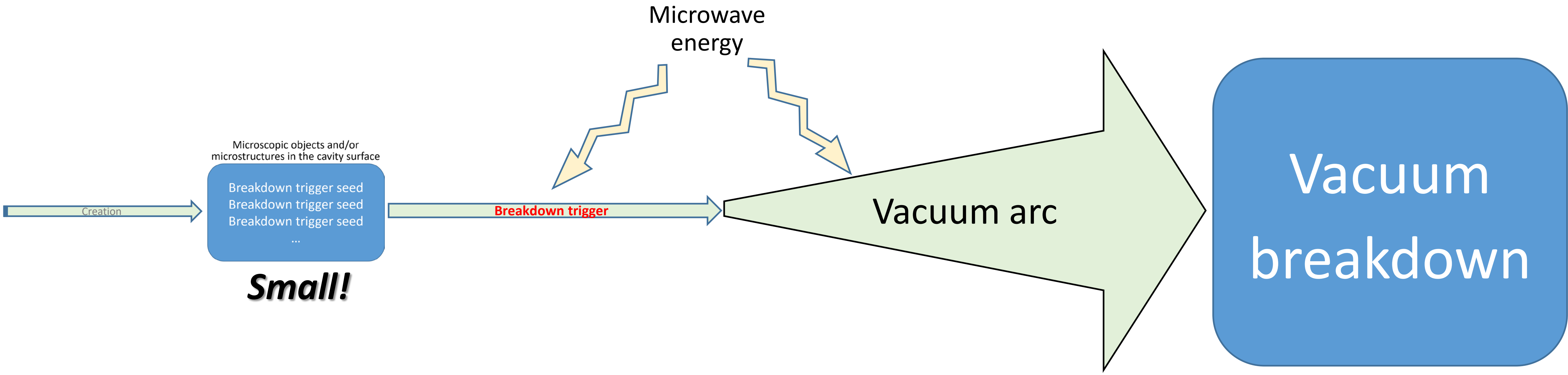
Physics leading to BD



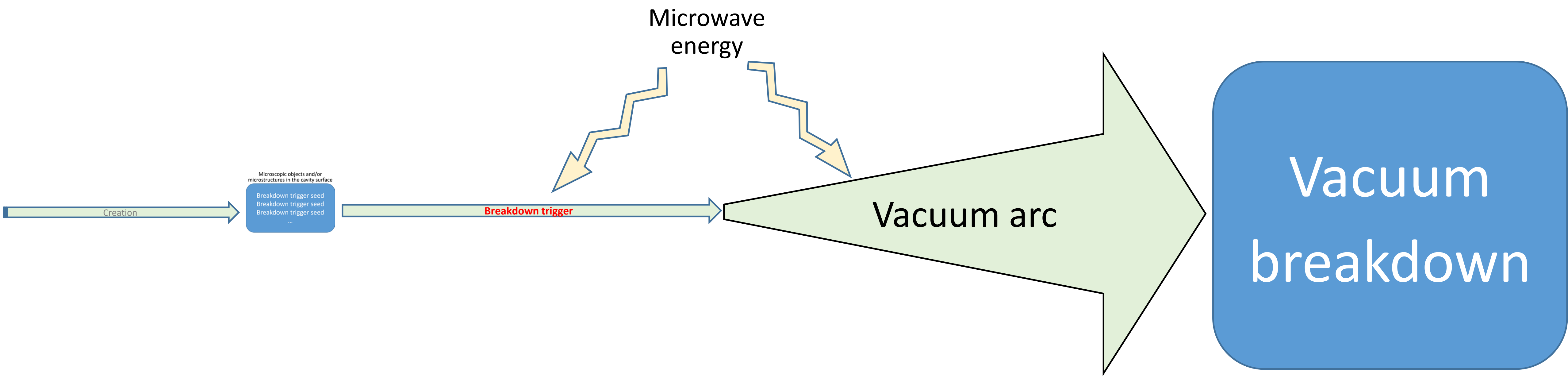
Physics leading to BD



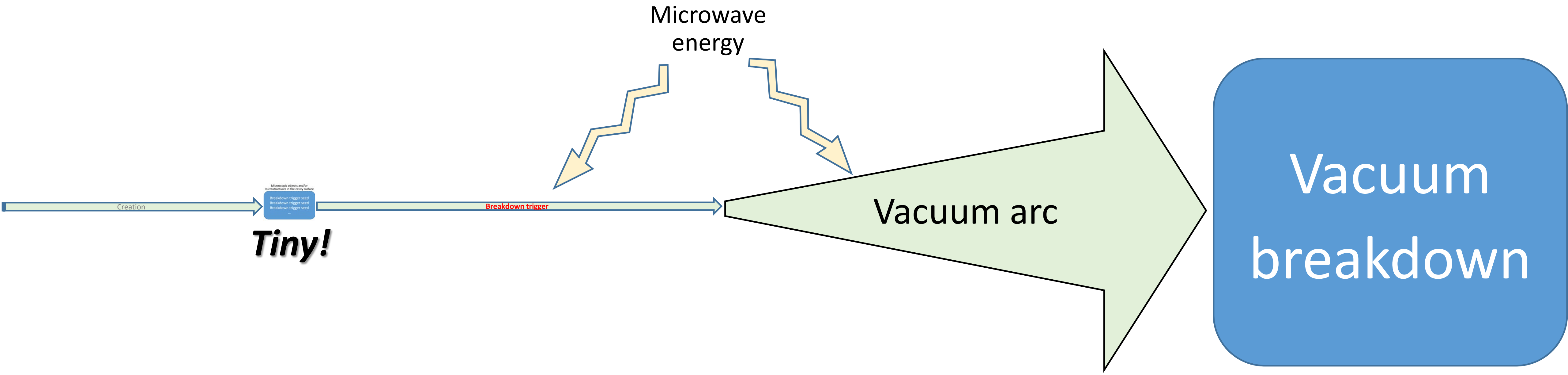
Physics leading to BD



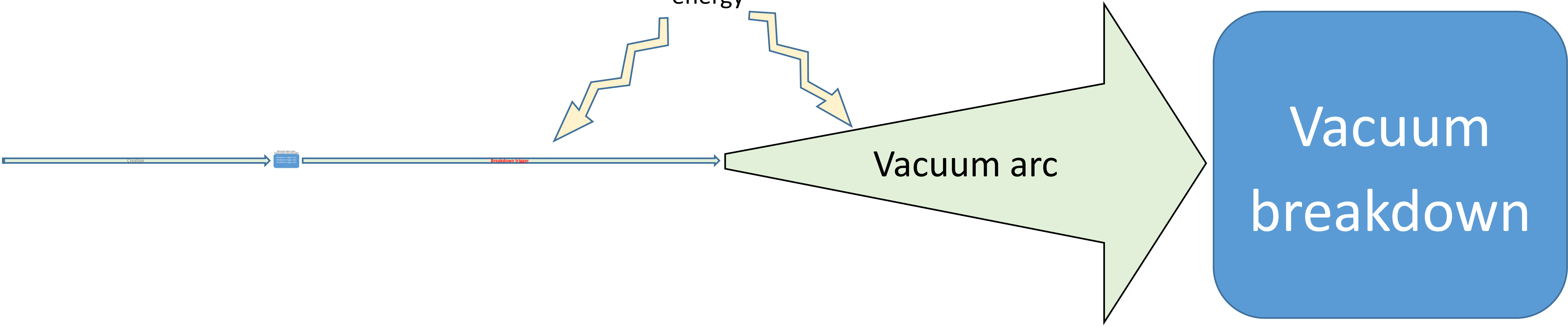
Physics leading to BD



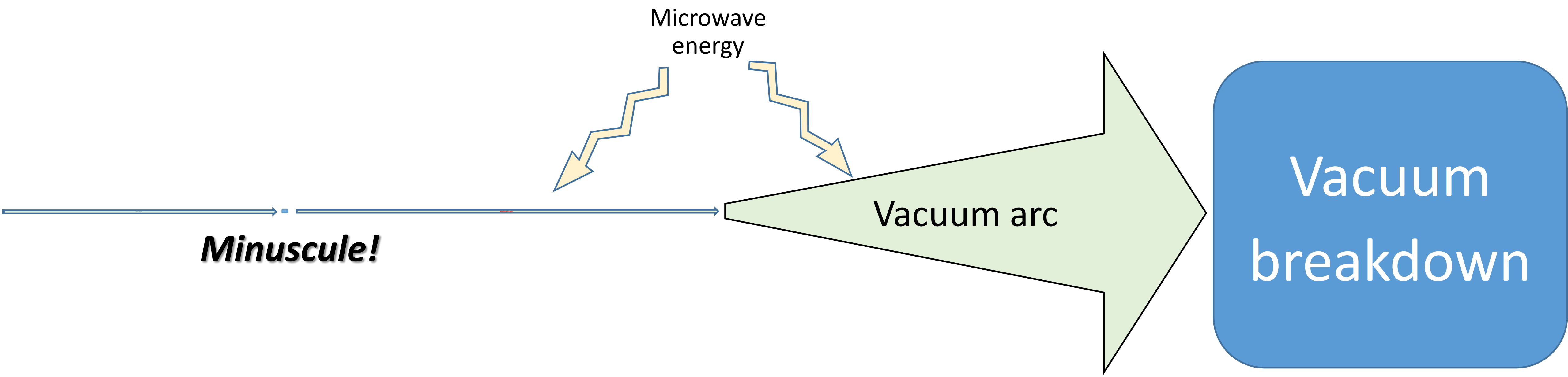
Physics leading to BD



Physics leading to BD



Physics leading to BD



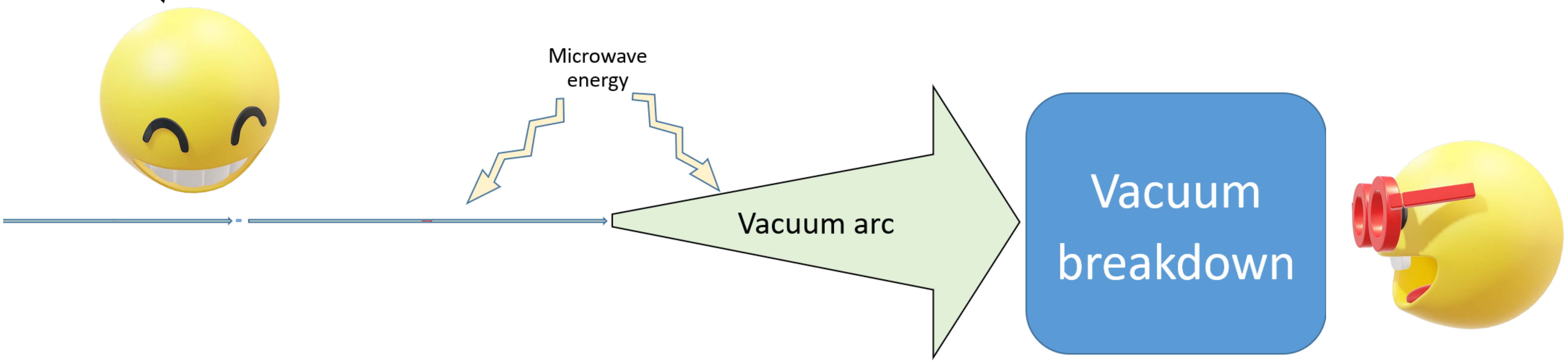
The information on the breakdown trigger seed can be mostly
- destroyed by
- hidden in
the much larger phenomenon of a vacuum arc.

Method of This Study

***Direct visual observation* of the inside of the cavity**

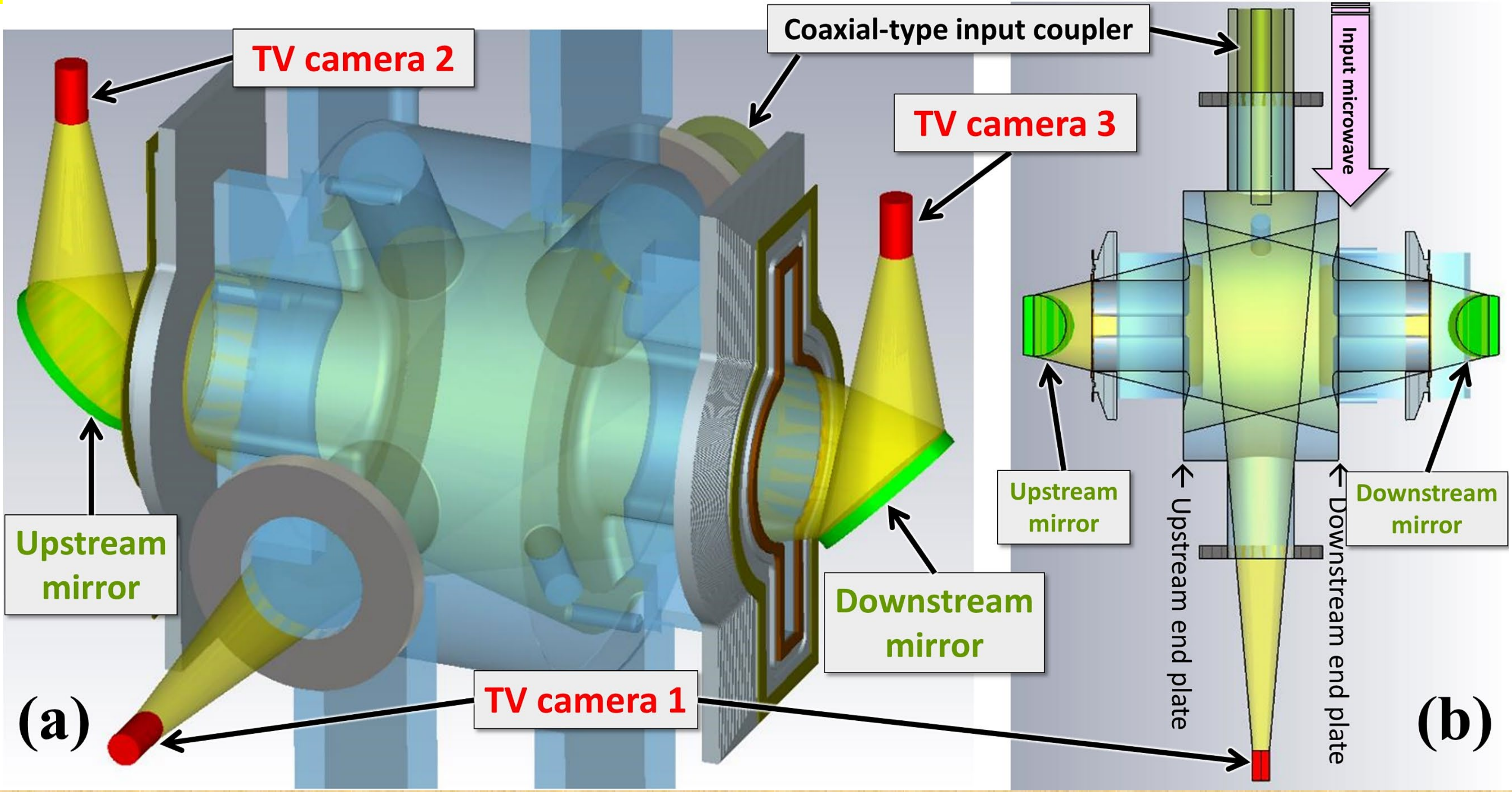
with (TV) cameras

at the moment of (and shortly before) every breakdown

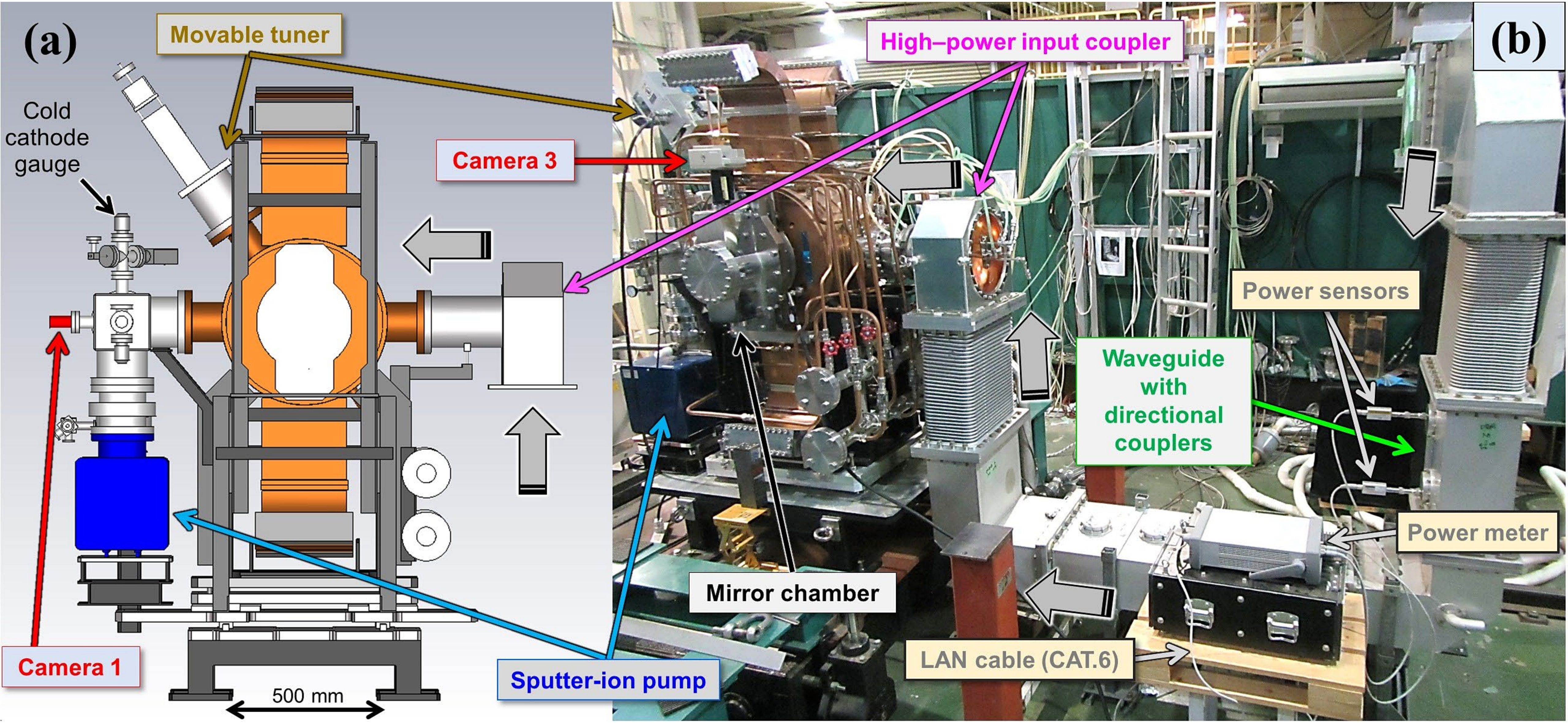


Direct Observation of RF BDs

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

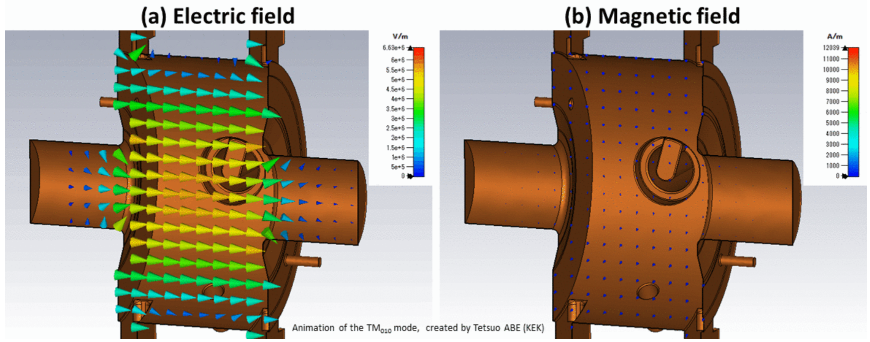


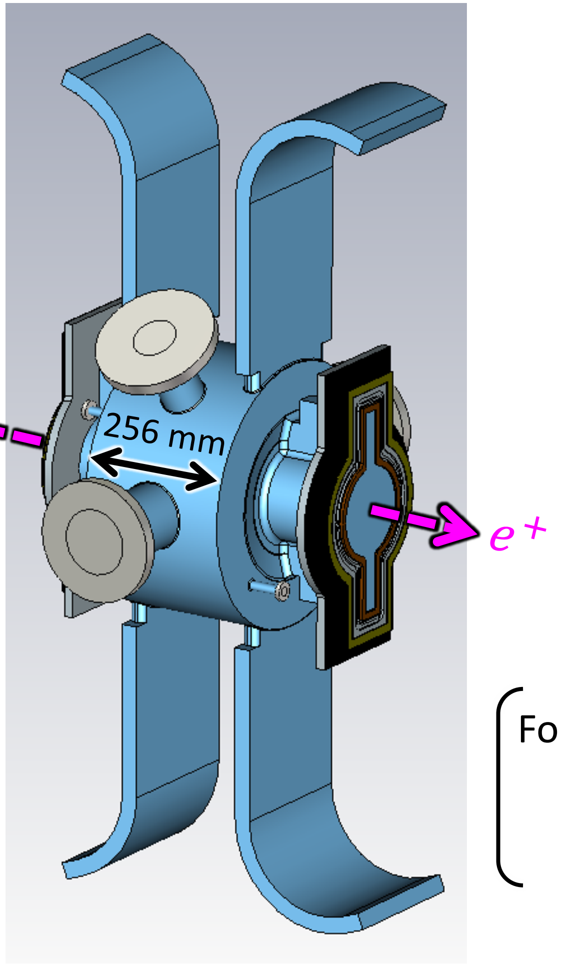
Setup of the Experiment



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

Accelerating Structure used in This Study:
normal-conducting standing-wave single-cell cavity operated with continuous 509-MHz input wave developed for SuperKEKB Positron Damping Ring (DR)





- Accel. mode: 509 MHz Continuous Wave (CW) TM_{010}
- Made of Oxygen Free Copper (Class1)
- Q_0 = ~30000
- R_{sh}/Q_0 = 150 Ω
- Spec. V_c = 0.8 MV (→ E_{acc} = 3.1 MV/m)
- Wall-loss power: ~150 kW @V_c = 0.80 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)

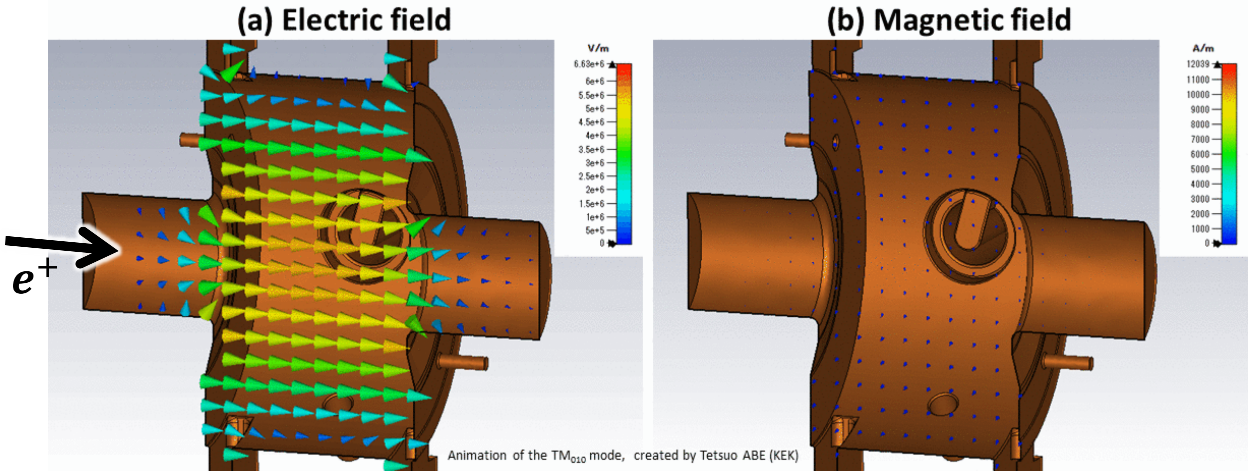
Surface field at $V_c = 0.9$ MV

$E_{max}^{(surf)} = 13$ MV/m

This max. surface E-field is much lower than that in

- **Field evaporation (> ~GV/m)**
- **X-band HG accel. structures (~200 MV/m)**
- **DC HV experiments (~100 MV/m)**

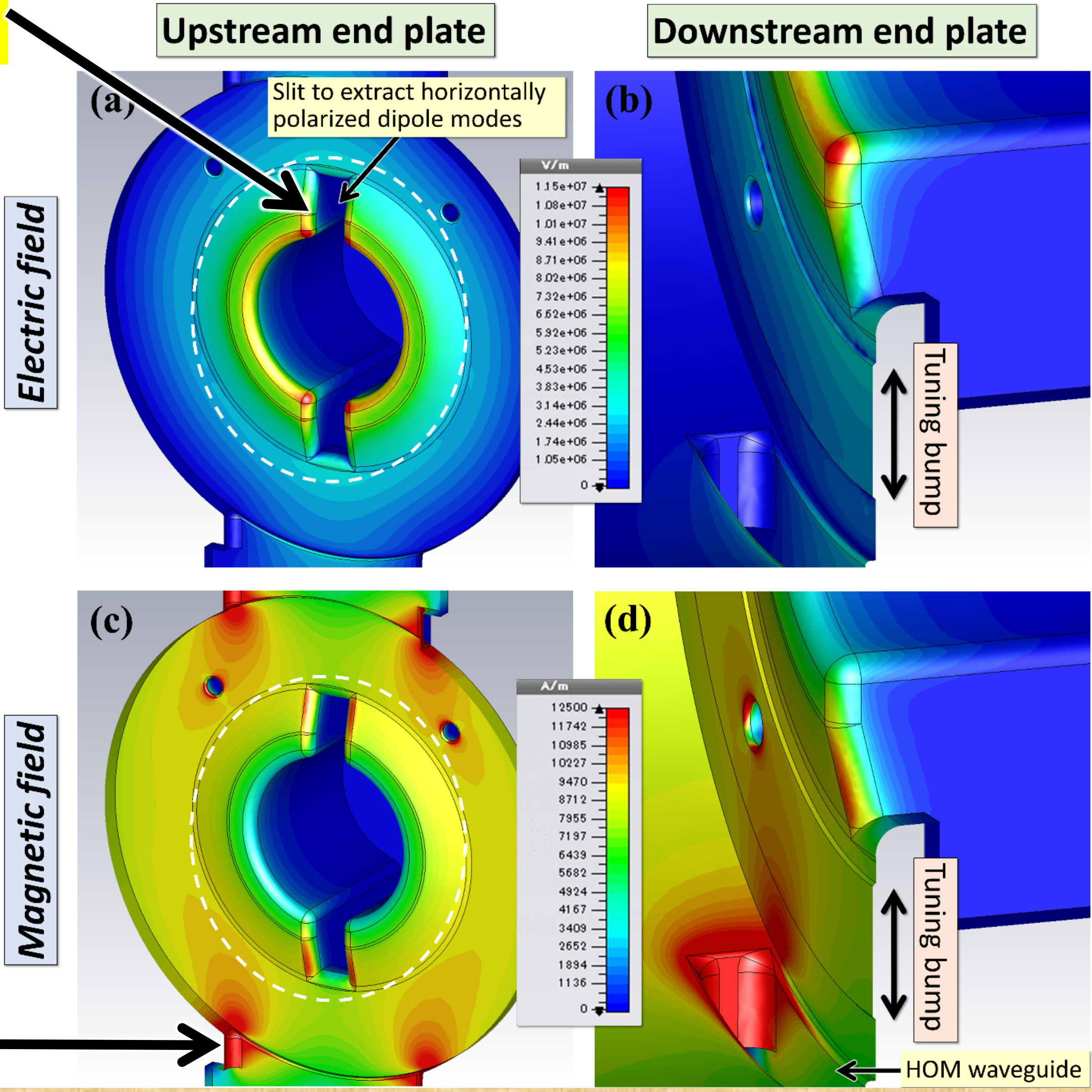
➔ There seems to be a special BD mechanism.



↑ Upstream end plate

↑ Downstream end plate

$H_{max} = 34$ kA/m



Details on the RF cavity used in this experiment

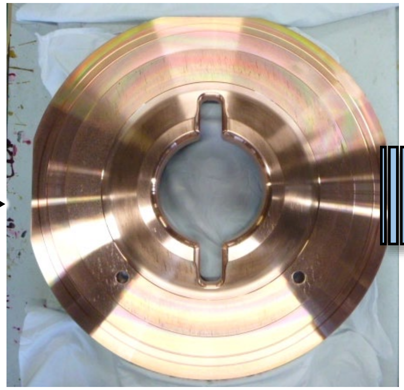
■ Normal fabrication method

- Precision machining of OFC (class1)
- Chemical etching for the barrel
- Electropolishing (EP) for the endplates
  - ➢ The inner surface is very smooth.
- Brazed in a vacuum furnace
- Fabricated by an accelerator manufacturer

■ Good high-power performance

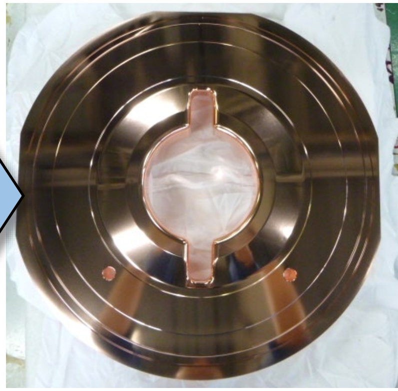
- The breakdown rates are the same as those of other UHF CW cavities
- The vacuum pressure level is normal during high-power operation.

< Before EP >



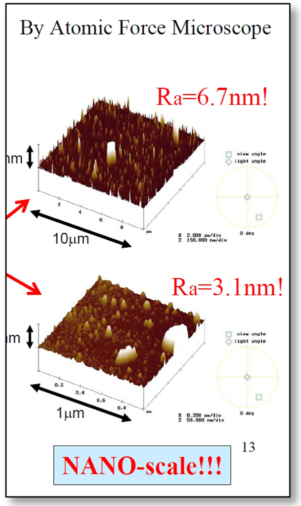
R_a = ~1.5 μm
R_y = ~8 μm

< After EP >



R_a < ~0.2 μm
R_y < ~1 μm

PAC'05, TPPT007→



The results obtained in this study have generality.

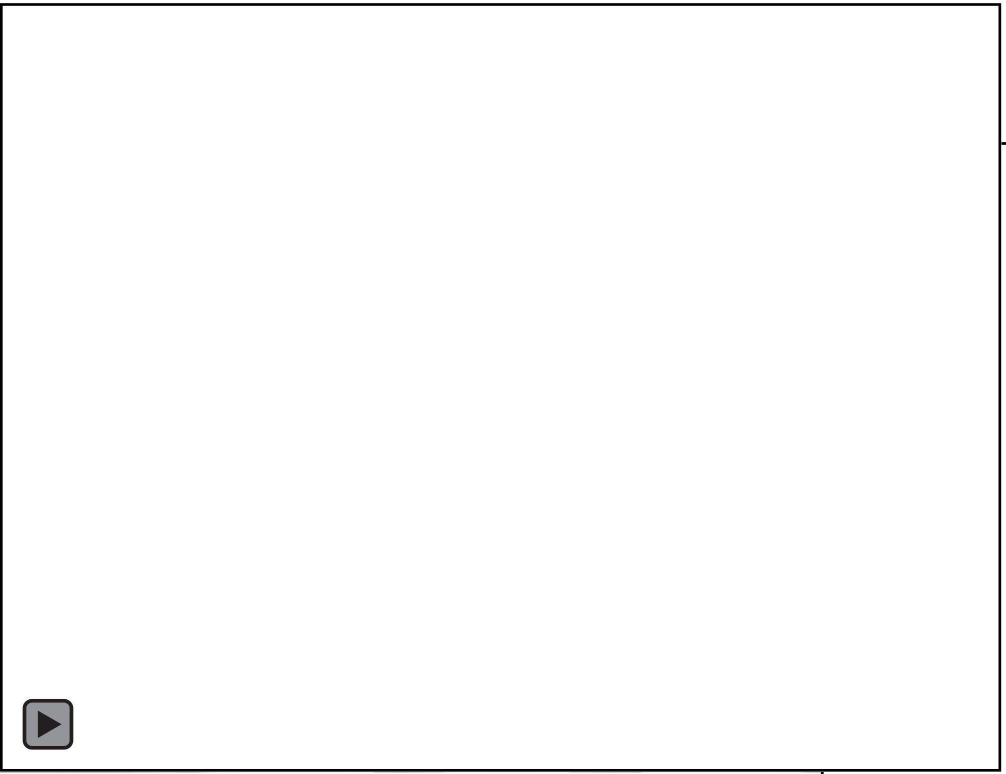
What we observed with three TV cameras (NTSC) from 205 breakdown events

(30 frames/s)

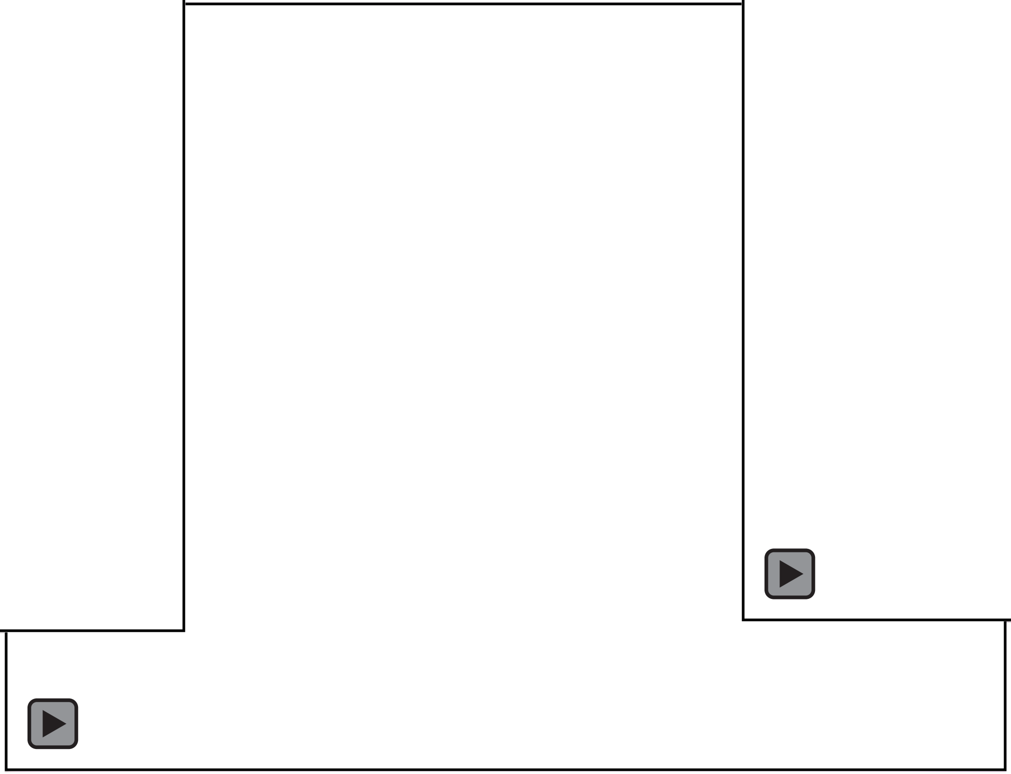
Example (1/3)

Big Flash!

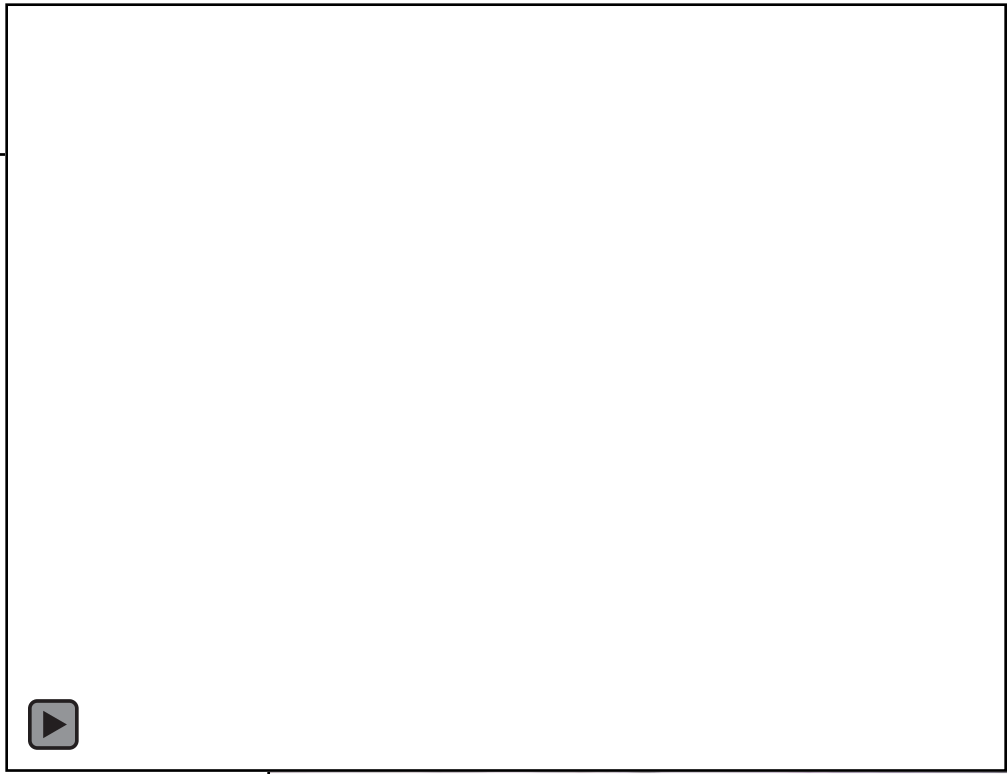
V_c = 0.89 MV (E_{acc} = 3.5 MV/m)



Upstream Endplate



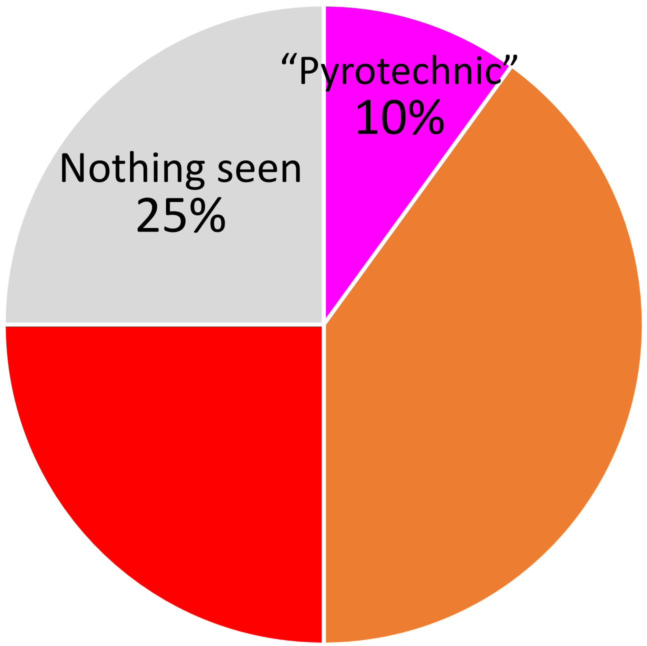
Side View



Downstream Endplate

Statistics on all the 205 breakdown events

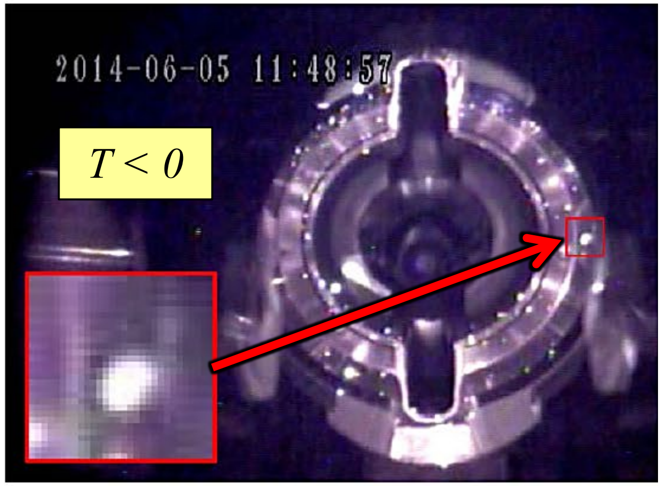
- 10% “Pyrotechnic” breakdowns
  - Observed only in the initial stage of RF conditioning



Example (2/3)

Stable bright spots on the end plate

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

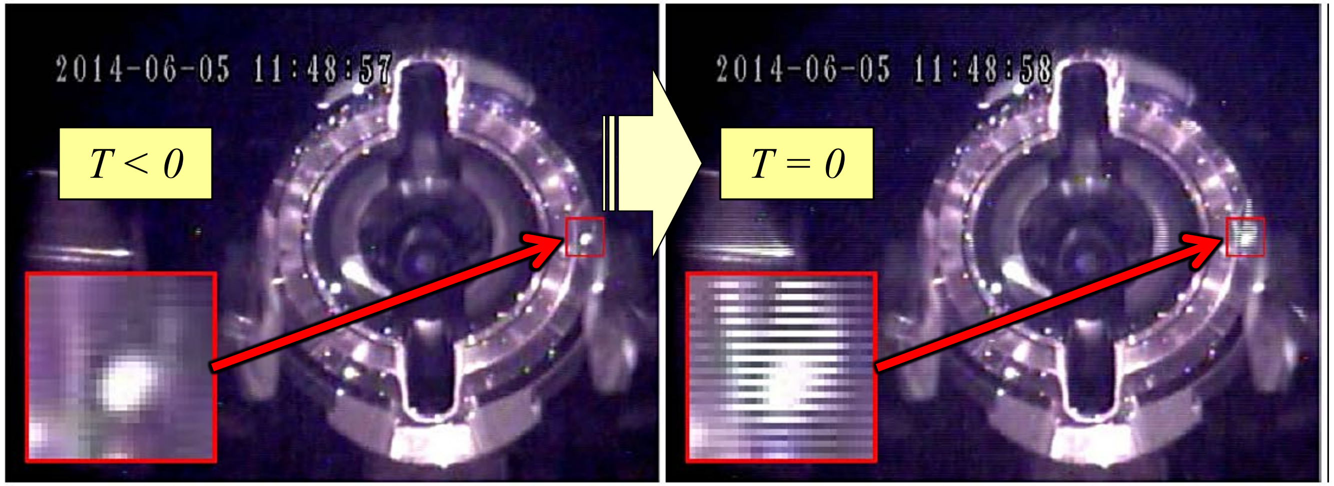


(a) 1 frame (1/30 s) before this cavity breakdown.

Example (2/3)

One of the 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.

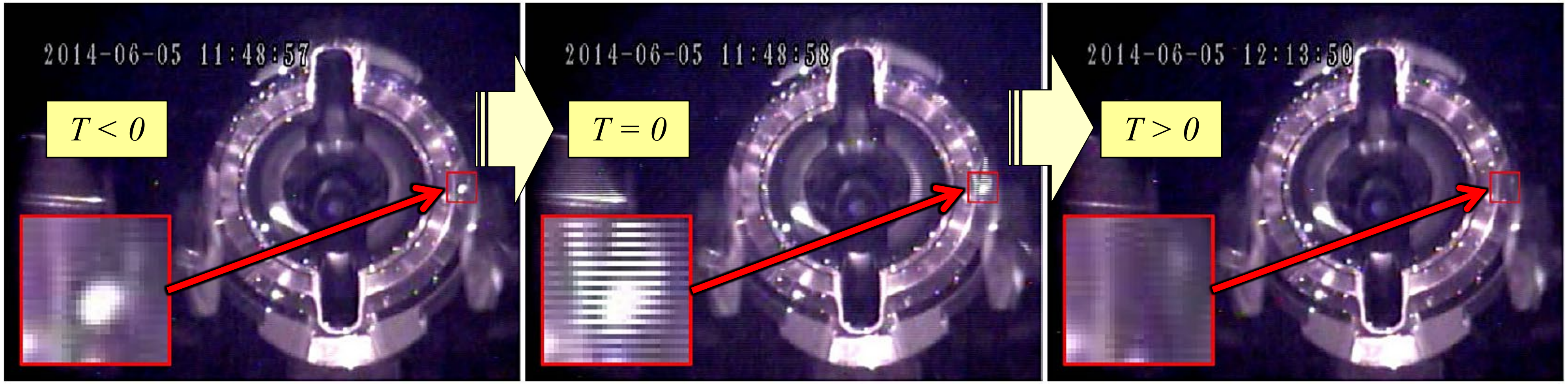
Example (2/3)

Mini-Supernova!

One of the stable bright spots at V_c = 0.95 MV (E_{acc} = 3.7 MV/m)

exploded at the moment of breakdown,

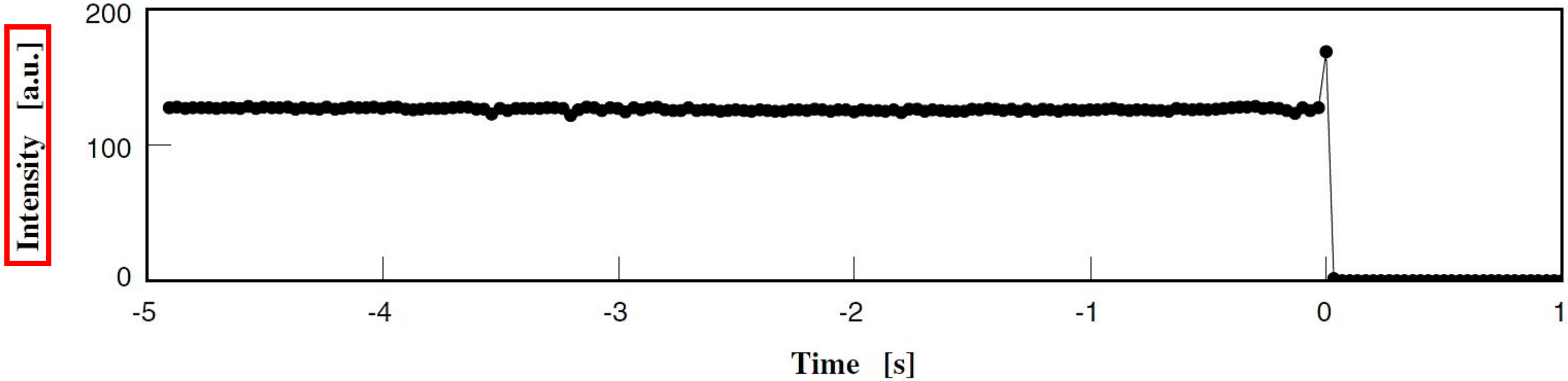
then, disappeared!



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

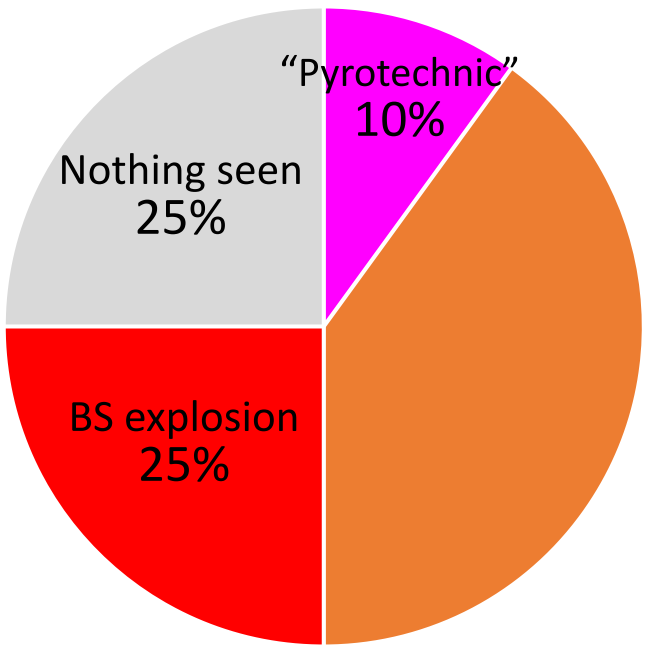
(b) At the moment of this cavity breakdown.

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



Statistics on all the 205 breakdown events

- 10% “Pyrotechnic” breakdowns
  - Observed only in the initial stage of RF conditioning
- 25% accompanied by a bright-spot (BS) explosion



(BS: Bright Spot)

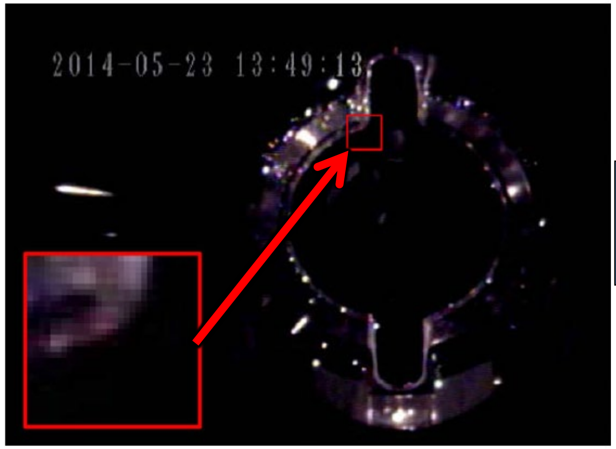
Example (3/3)

Spot-type explosion not originating from a stable bright spot

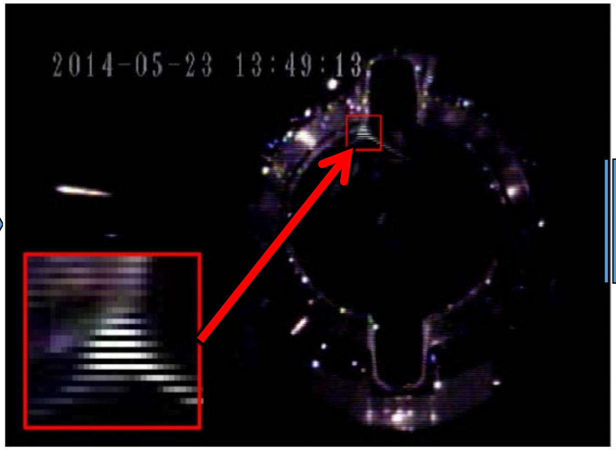
No bright spot in this area
(V_c = 0.65 MV (E_{acc} = 2.5 MV/m))

A spot-type explosion
at the moment of breakdown

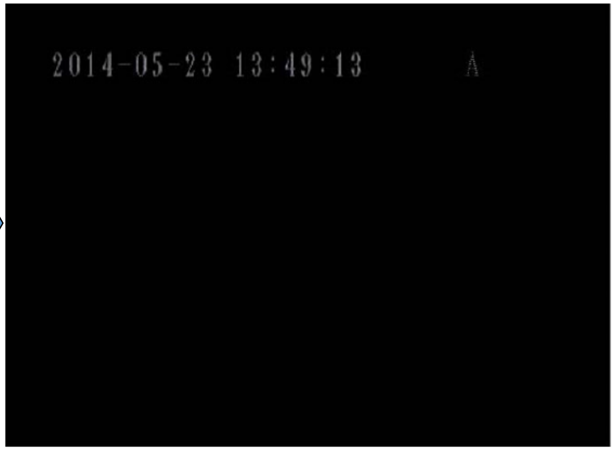
Down



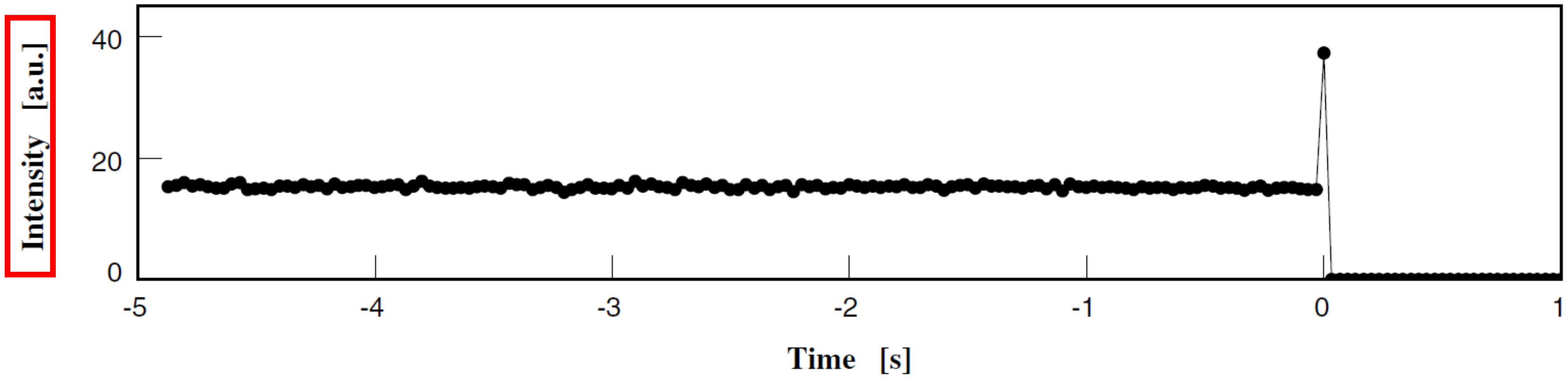
(a) 1 frame (1/30 s) before this cavity breakdown.



(b) At the moment of this cavity breakdown.

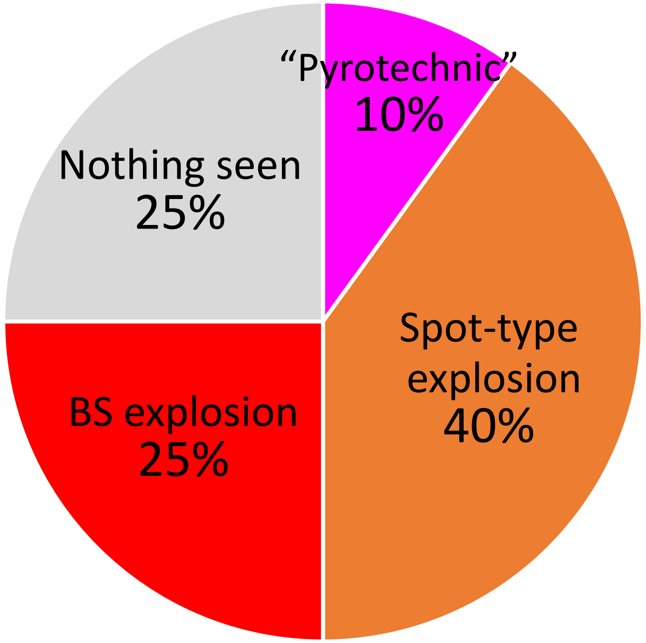


(c) 1 frame (1/30 s) after this cavity breakdown.



Statistics on all the 205 breakdown events

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



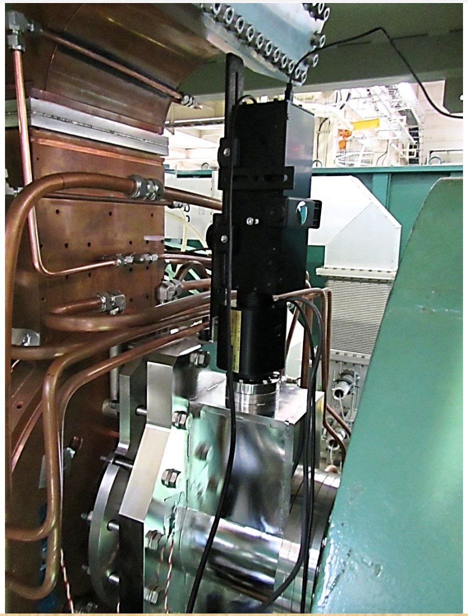
(BS: Bright Spot)

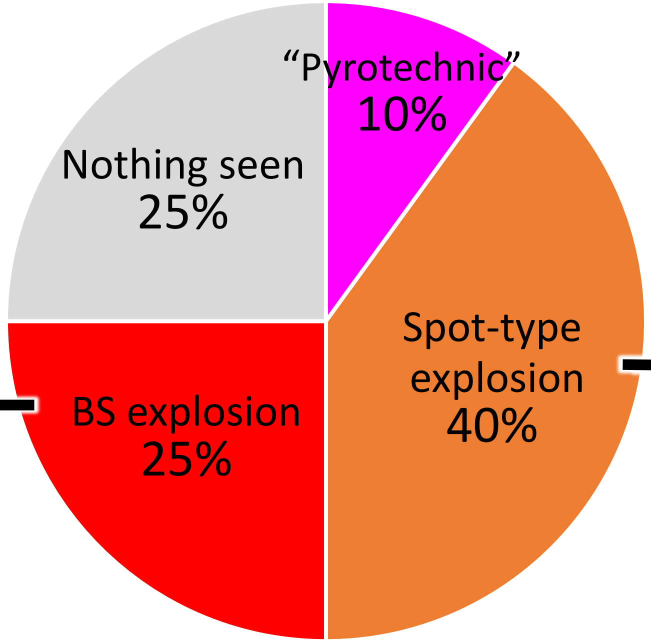
No observed breakdown events were accompanied by two or more explosions.
➔ Such an explosion must be a breakdown trigger!

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, *et al.*, "*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).

Further investigations

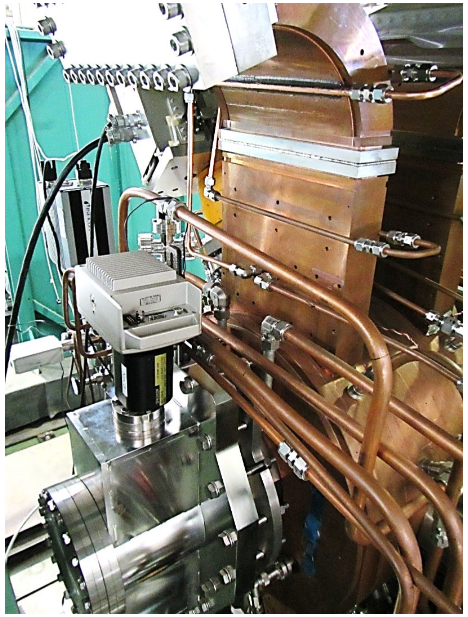
Measurement of the emission spectra and temperatures of the stable bright spots using a **hyperspectral camera**





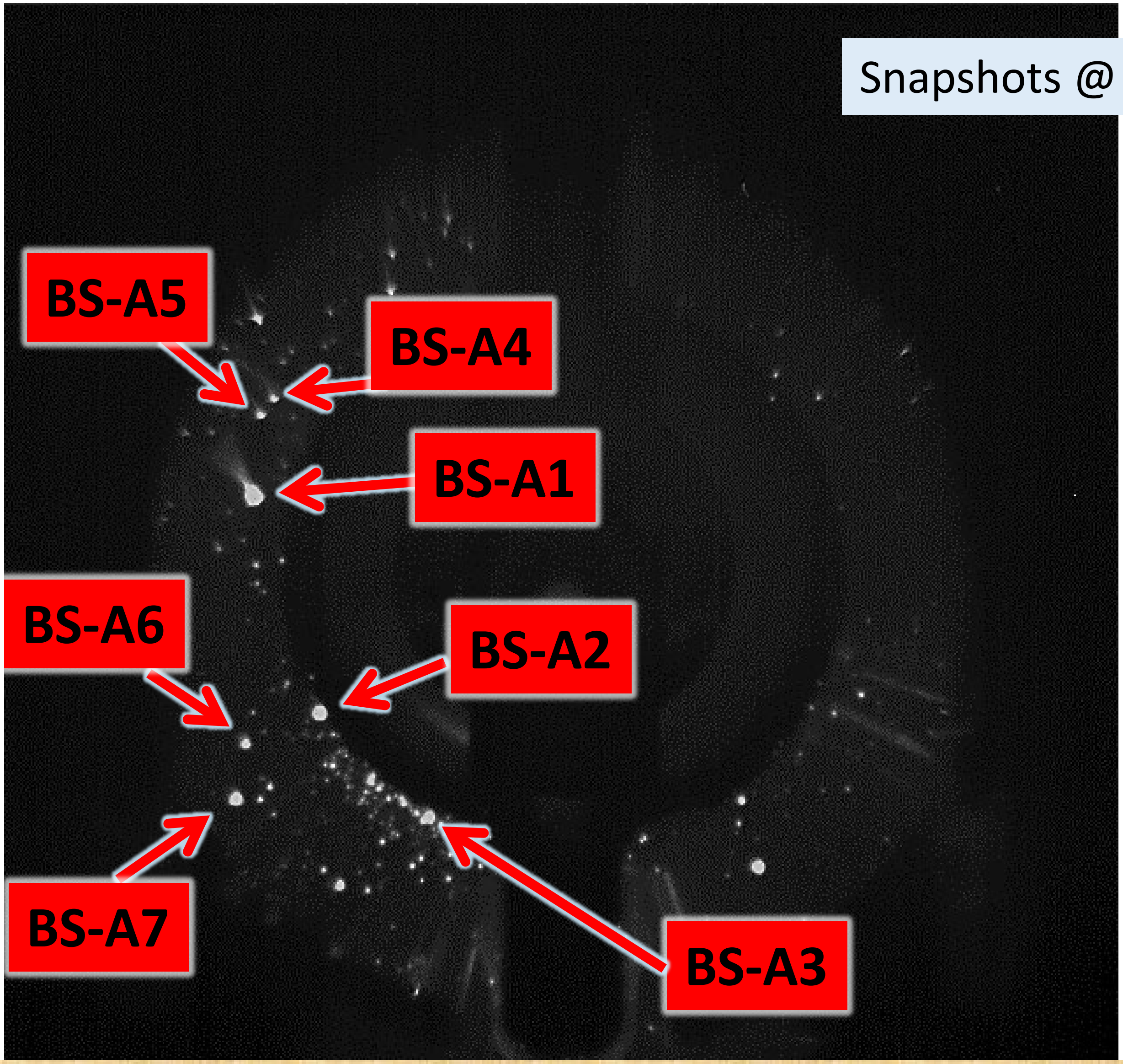
(BS: Bright Spot)

Video recording using **high-speed cameras**



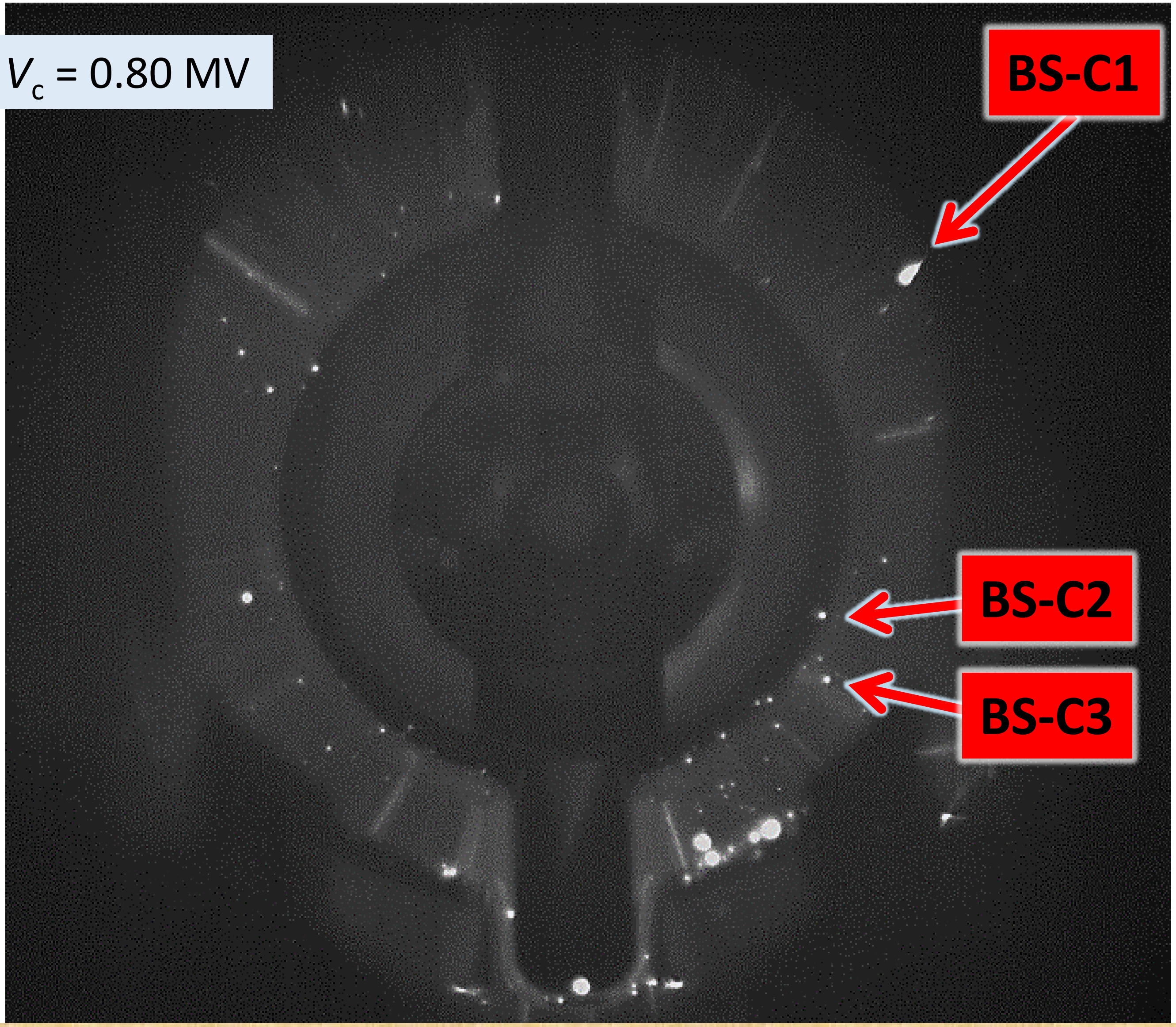
We observed emission spectra for 10 stable bright spots (BSs).

Upstream Endplate

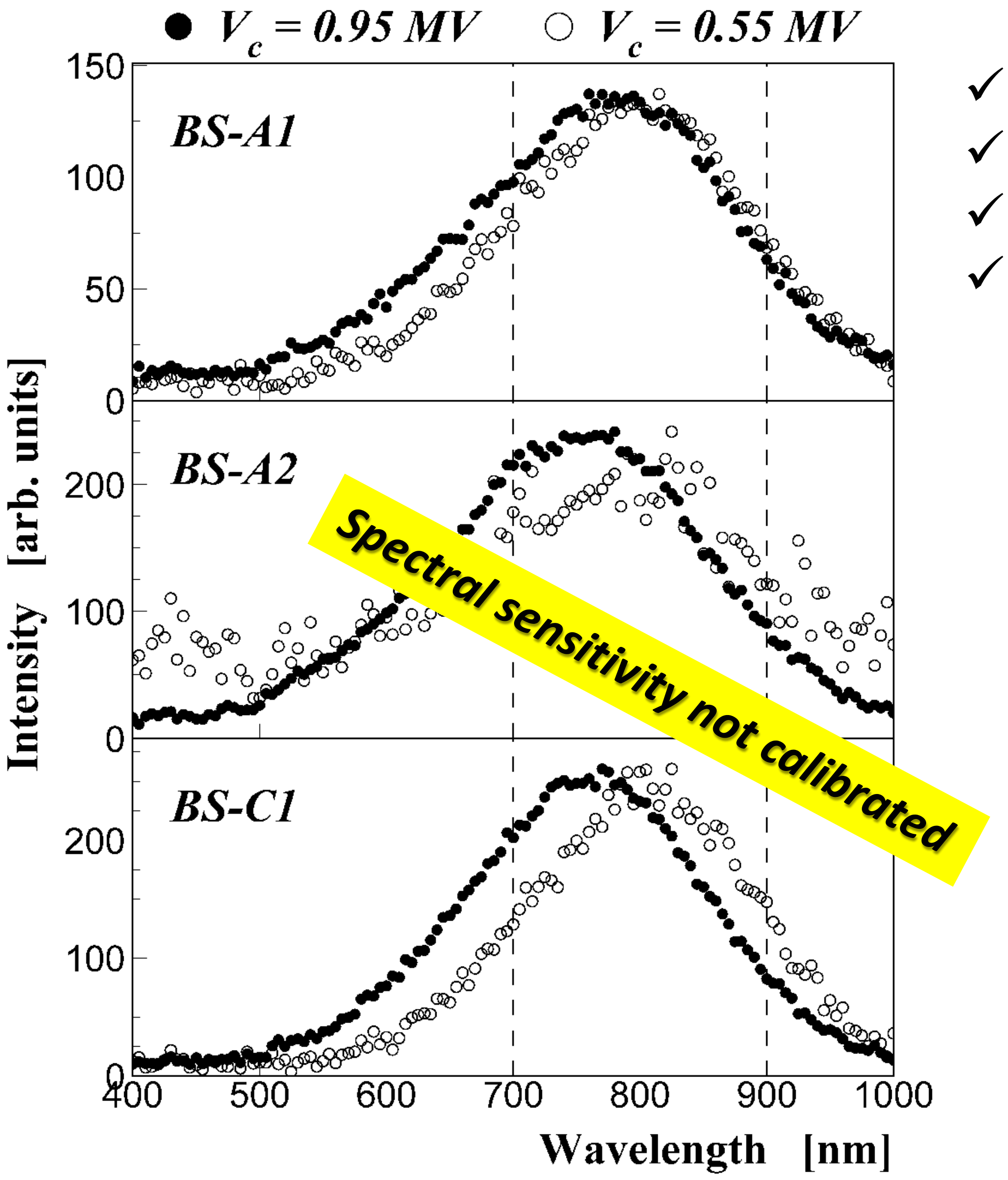


Snapshots @ V_c = 0.80 MV

Downstream Endplate



Observed Spectra



- ✓ Pixel-sensitivity calibration
- ✓ Wavelength calibration
- ✓ Corrections for the mirror and view-port windows
- ✓ Background subtraction

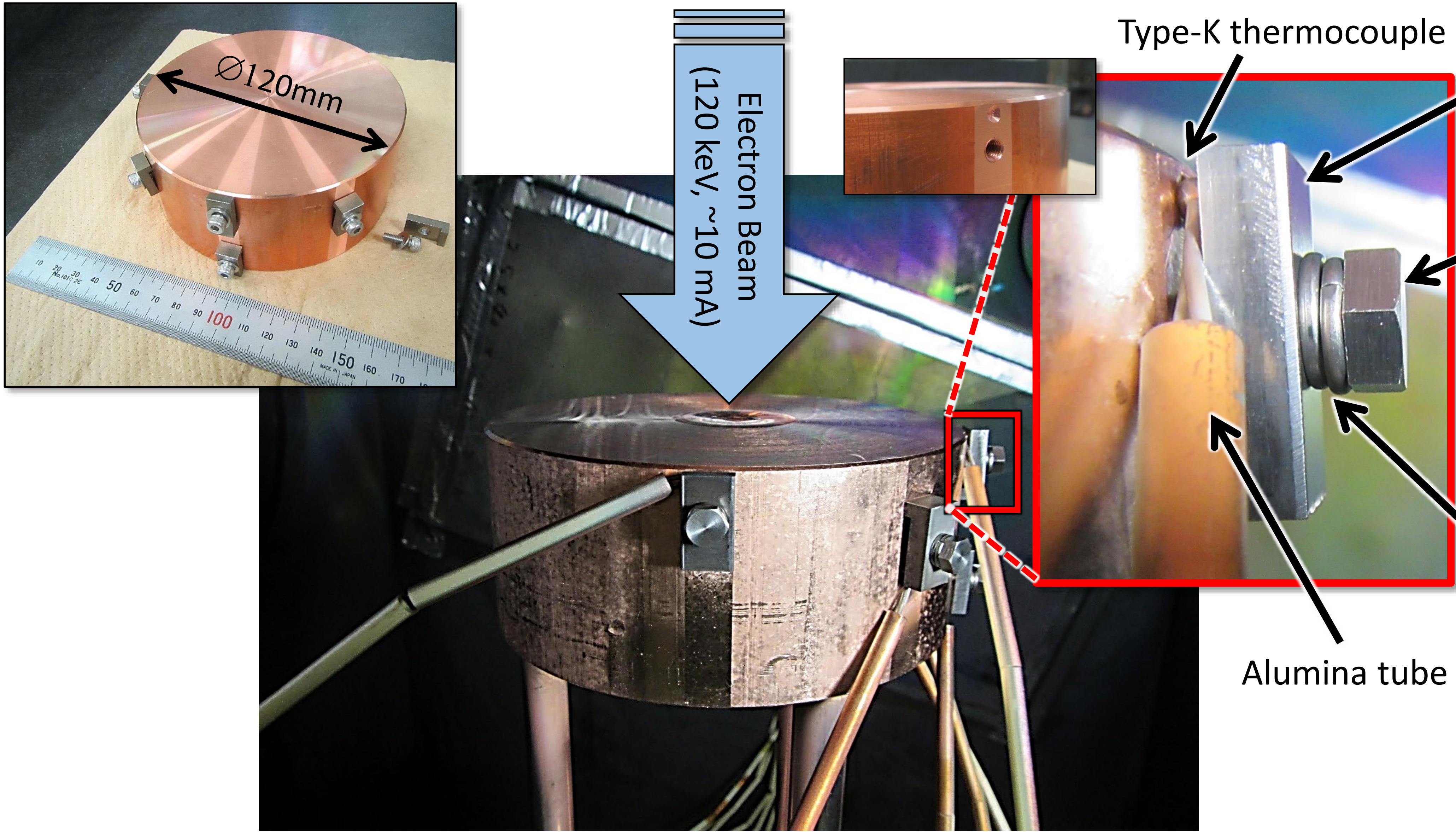
} applied

① No line or band spectrum in the visible light or near-infrared regions

② The spectra move toward lower wavelengths at higher cavity voltages

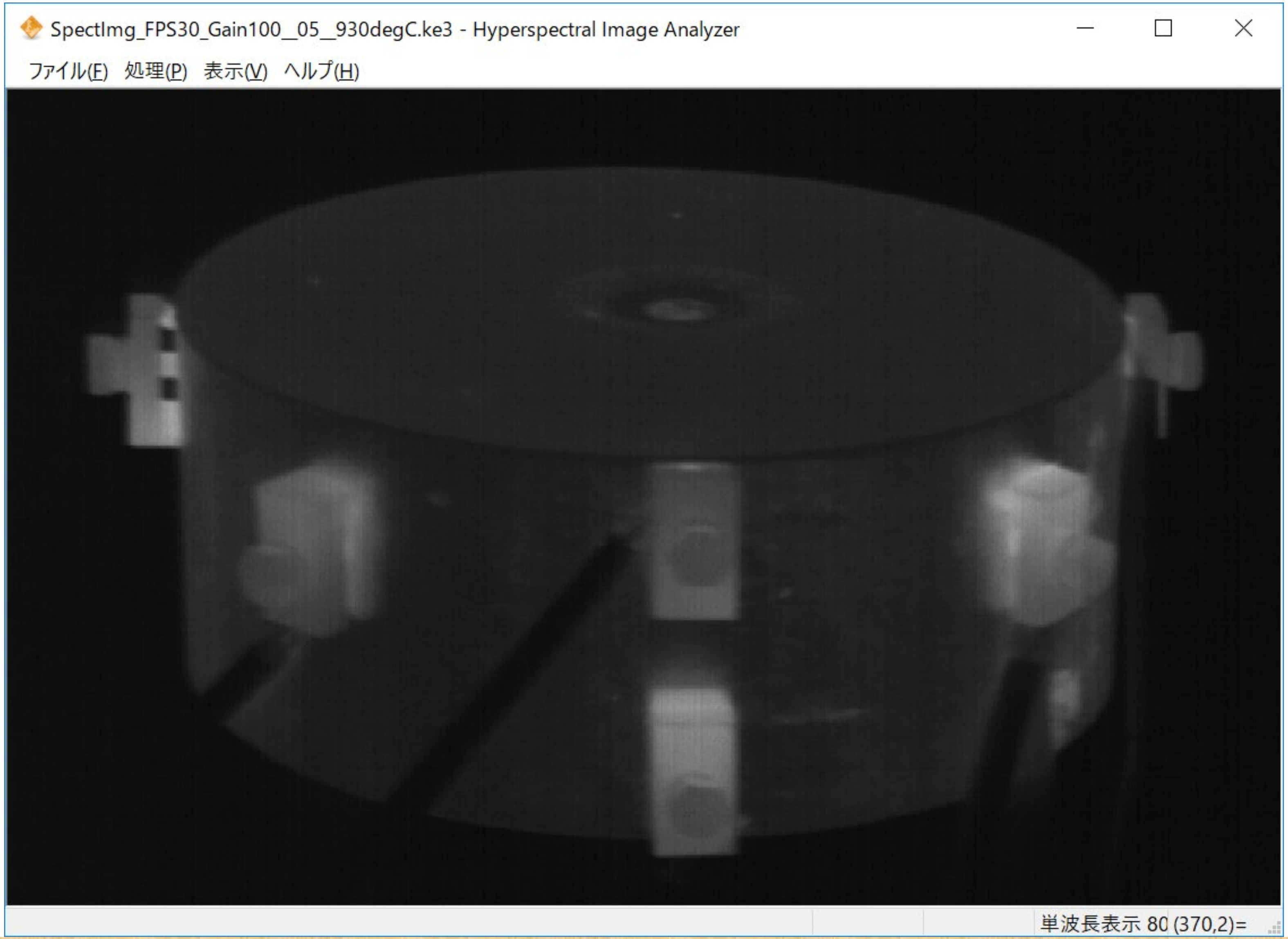
Thermal radiation!

Experimental setup to take a spectrum and temperature simultaneously to calibrate the spectral sensitivity of the hyperspectral camera



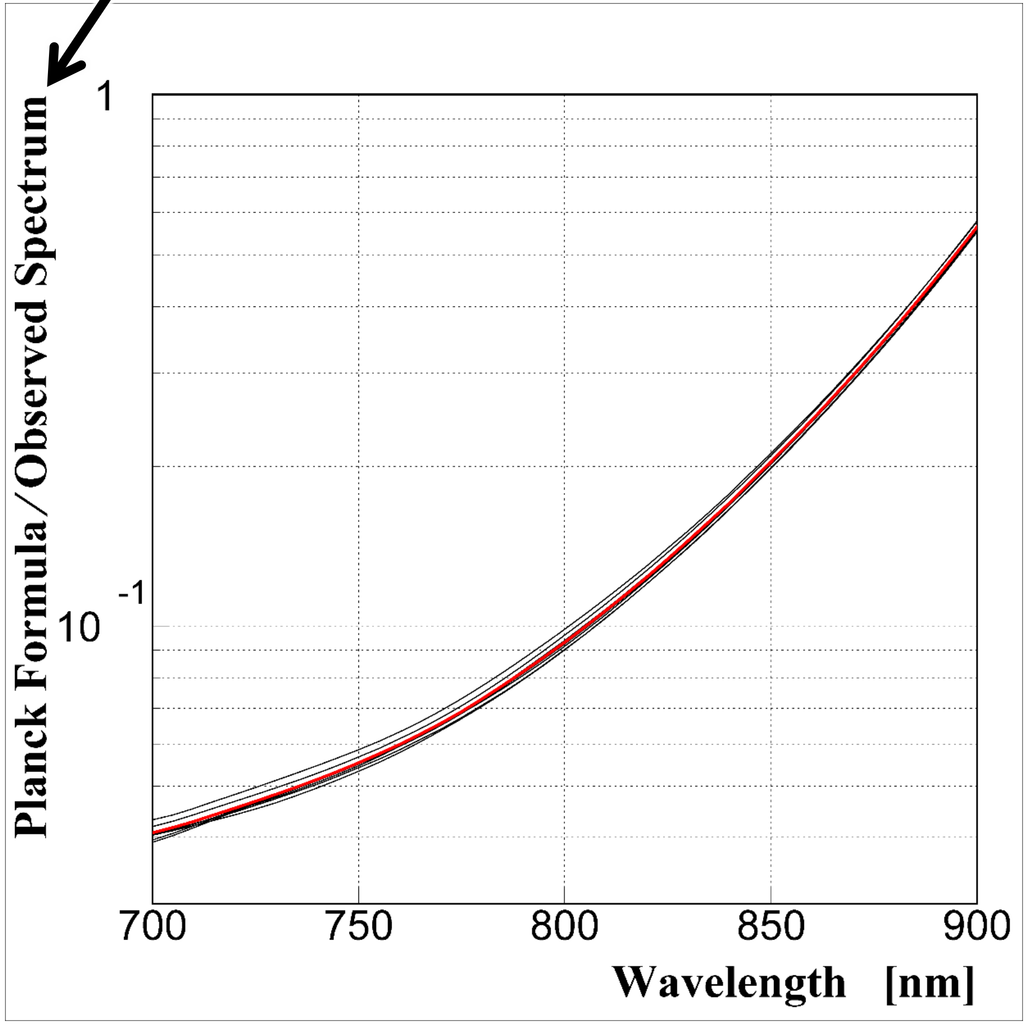
The thermocouple temperature: 930 degC

Raw data shown at 800 nm

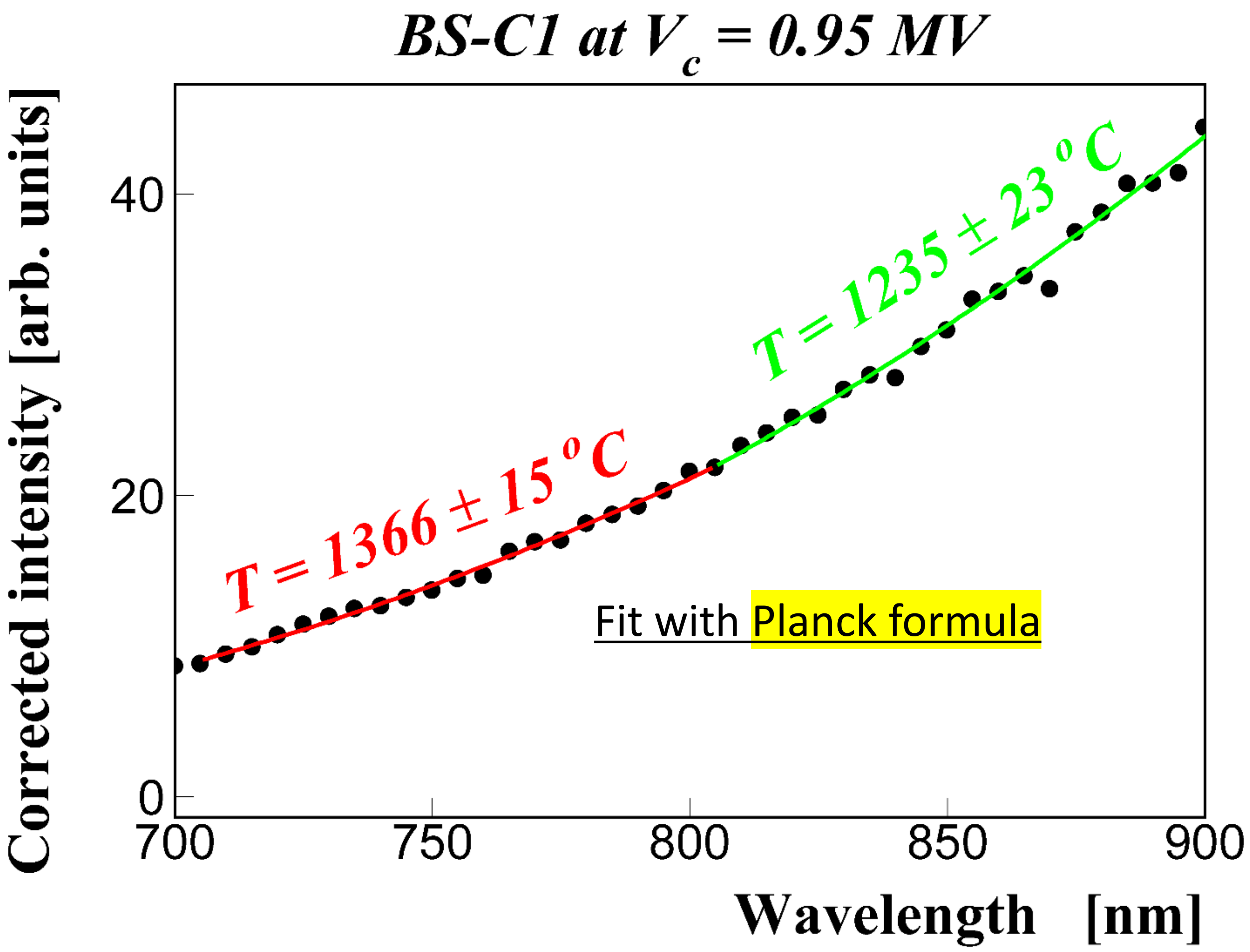


How to derive the temperature from the spectrum

for the high-temperature thermocouple

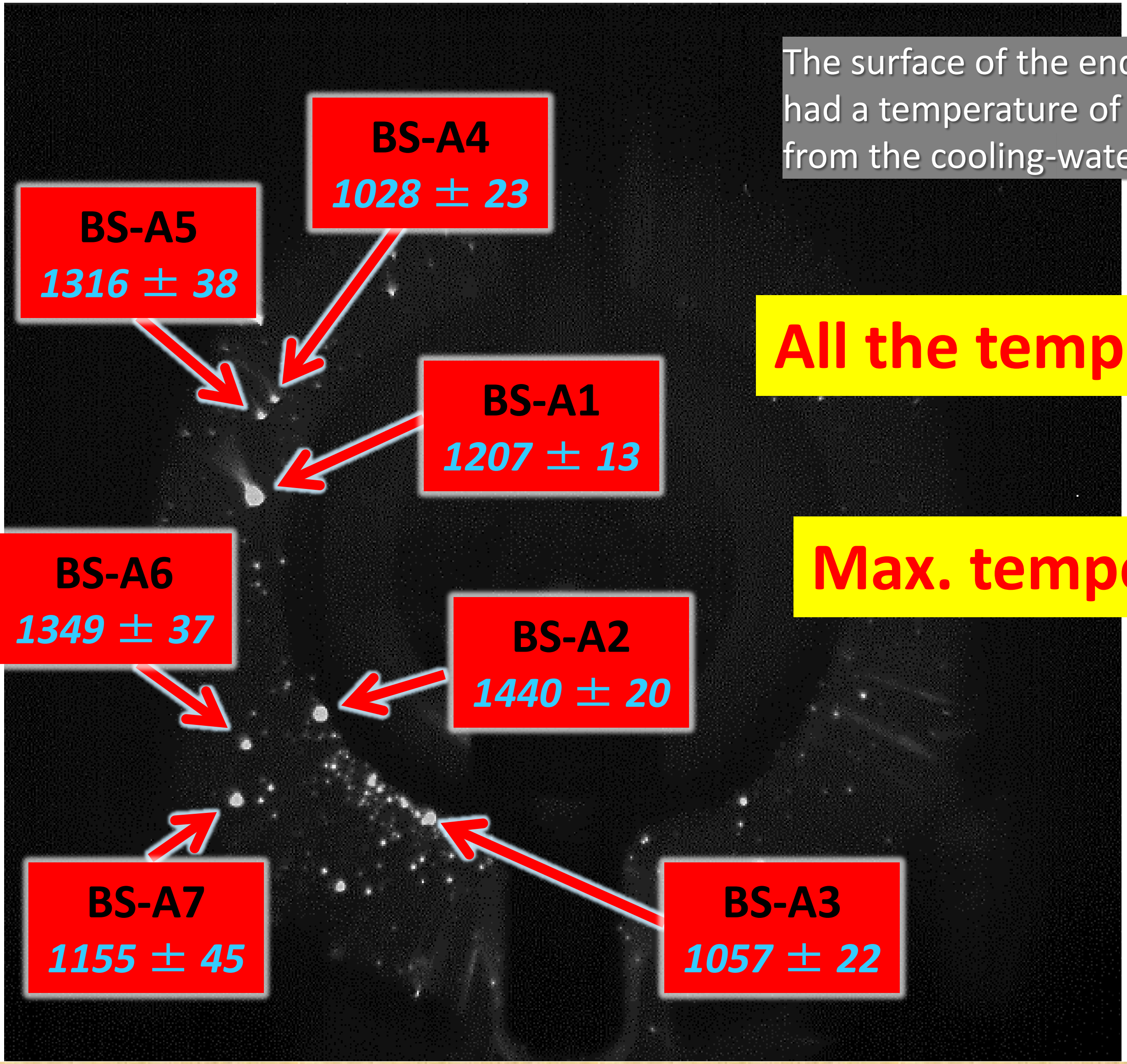


$$\text{Planck Formula} \propto \frac{1}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

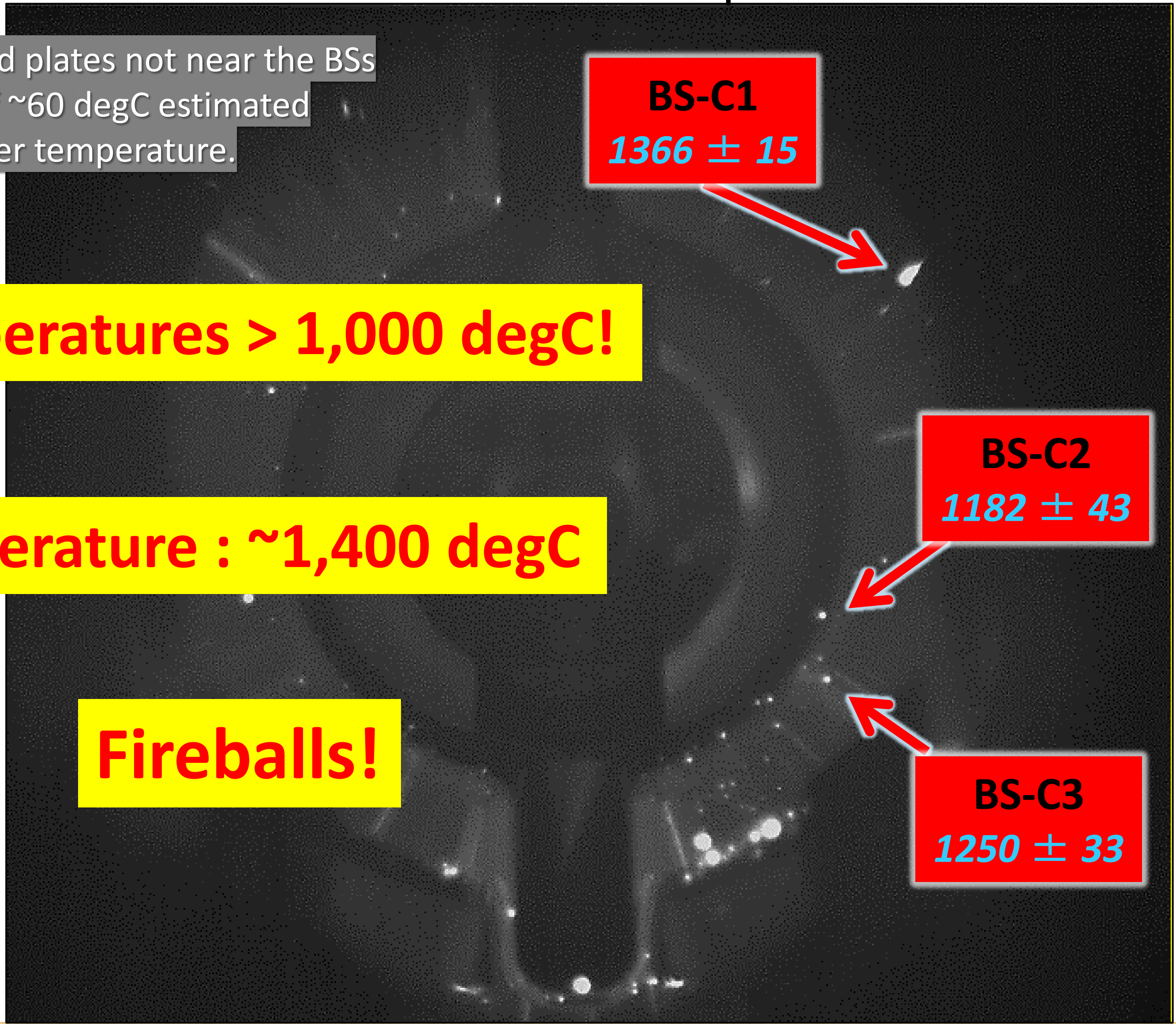


Measured temperatures in degC @ V_c = 0.95 MV

Upstream Endplate



Downstream Endplate

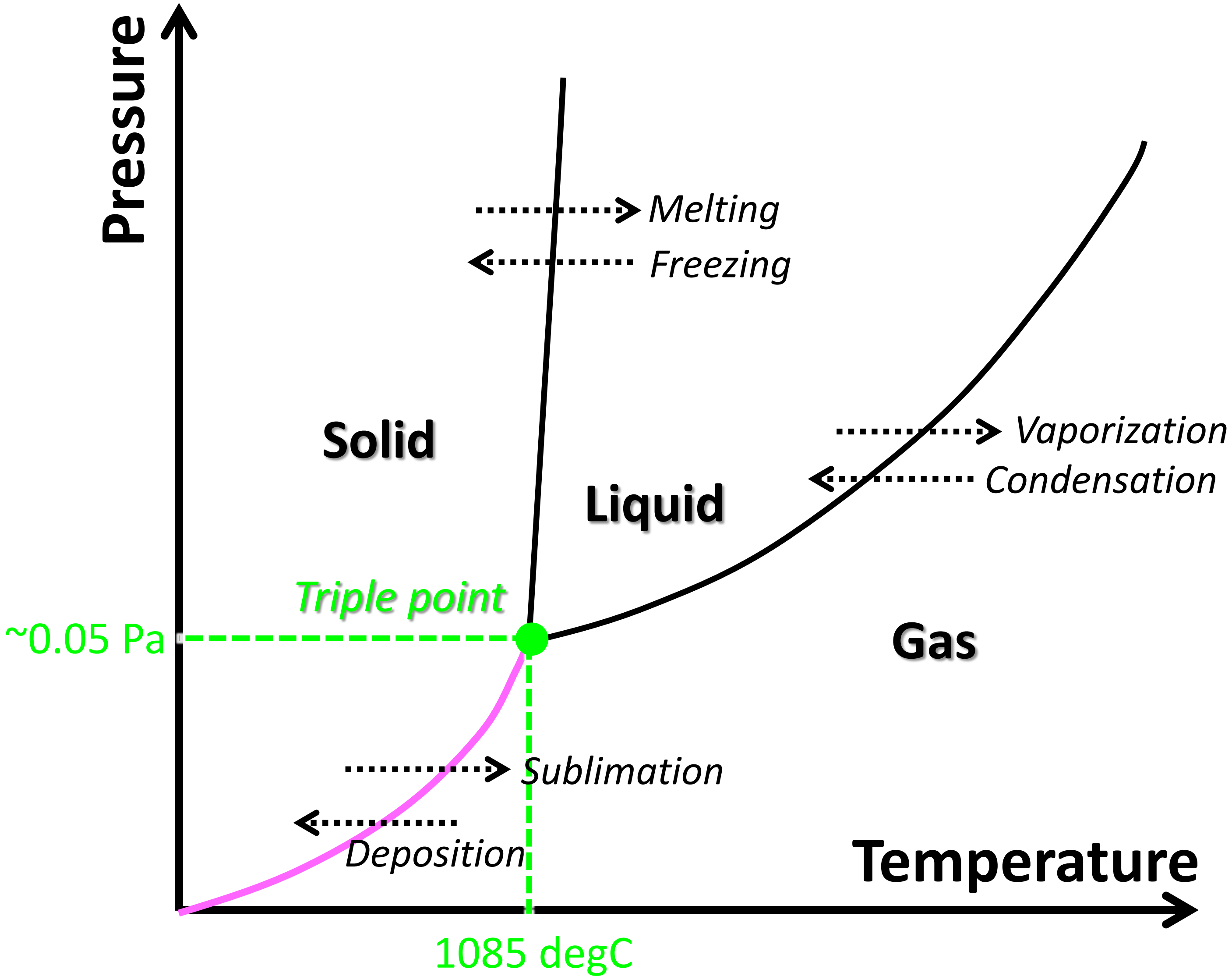


The surface of the end plates not near the BSs had a temperature of ~60 degC estimated from the cooling-water temperature.

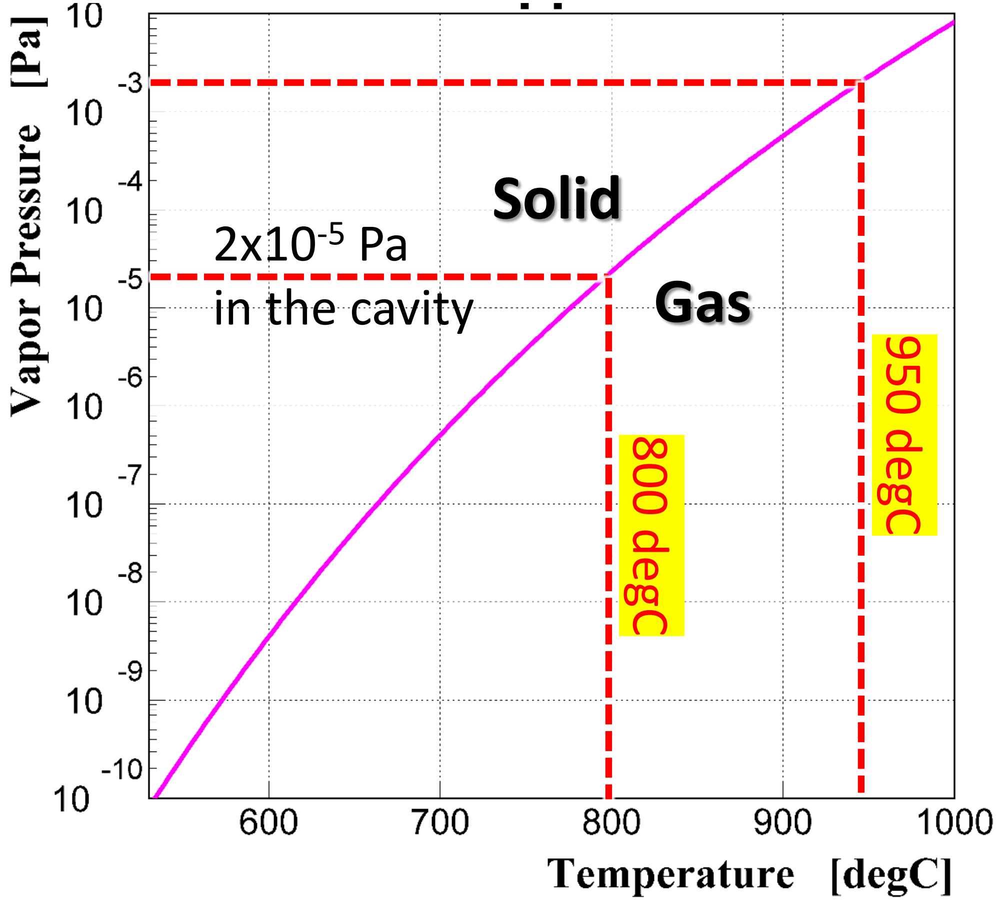
All the temperatures > 1,000 degC!

Max. temperature : ~1,400 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 1,000 degC.**
- ✓ **Bright spots can emit significant lights for > days.**

The BS emitters are not copper!

Candidates of the Fireball Materials

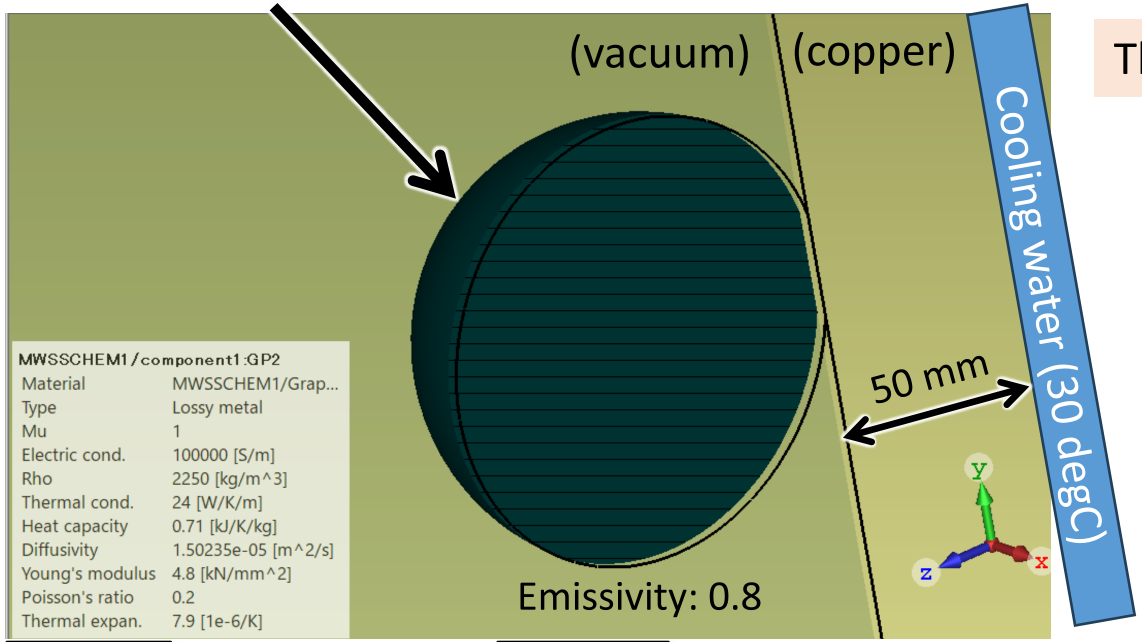
Should have a Sublimation point > 1,000℃ in ultrahigh vacuum.

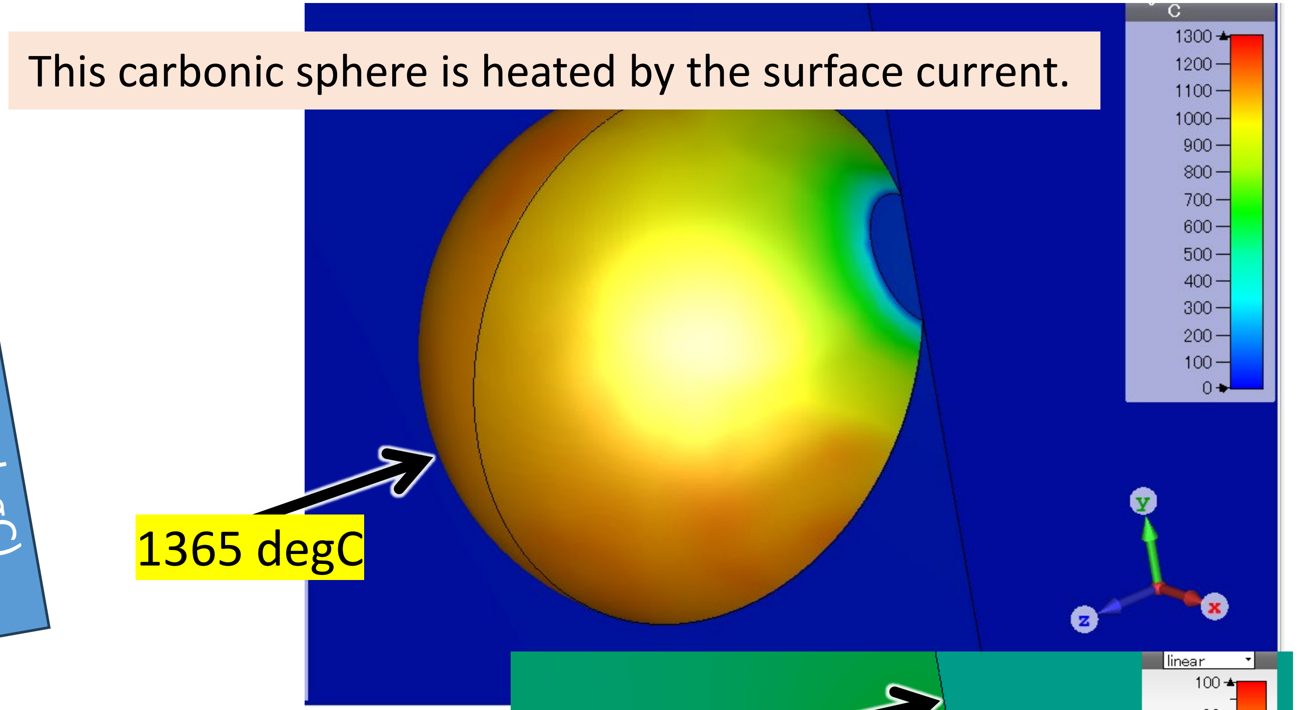
Element	Sublimation point [℃] @ 2 x 10^{-5} Pa	Remarks
W	2258.6	Materials of the SuperKEKB collimator heads
Ta	2123.4	
C (Graphite)	1769.9	Heater materials of vacuum furnaces for RF-cavity fabrication
Mo	1705.7	
Zr	1565.7	Material of NEG pump strips (e.g. St707)
Ti	1162.6	Material of the KEKB collimator heads
Au	894.7	
Cu	795.3	
Al	765.0	No chance of leading to fireball breakdown in RF cavities made of Cu
Be	764.2	
Ag	635.3	
In	541.0	

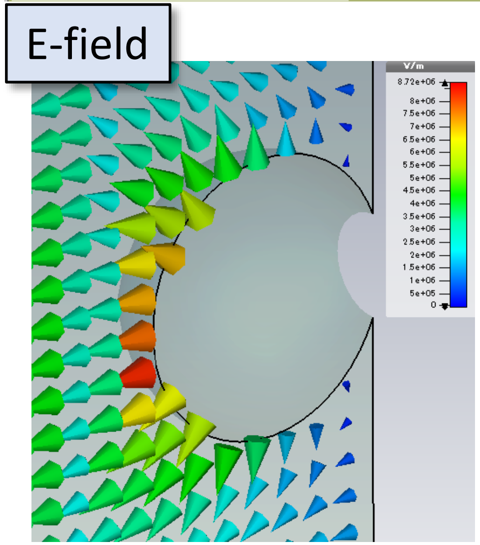
Data from https://www.iap.tuwien.ac.at/www/surface/vapor_pressure

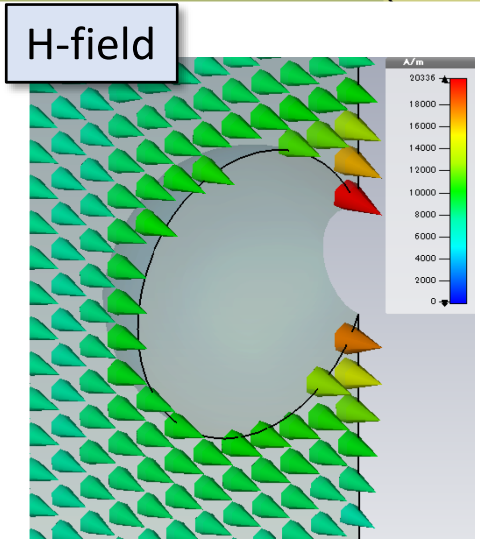
Simple Simulation using CST MPHYSICS STUDIO

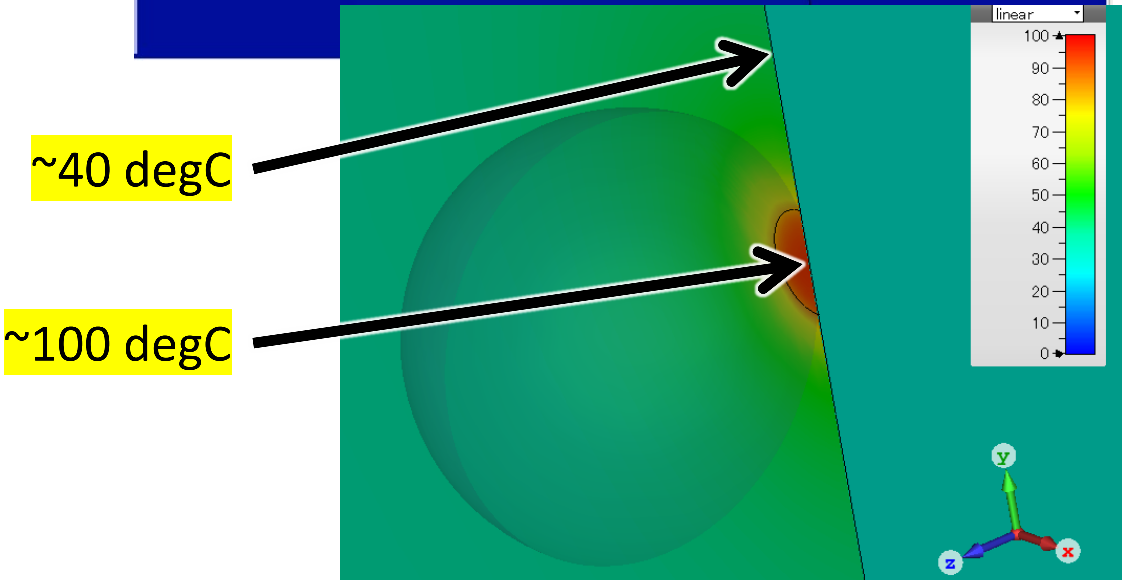
Simplified model of **graphite**



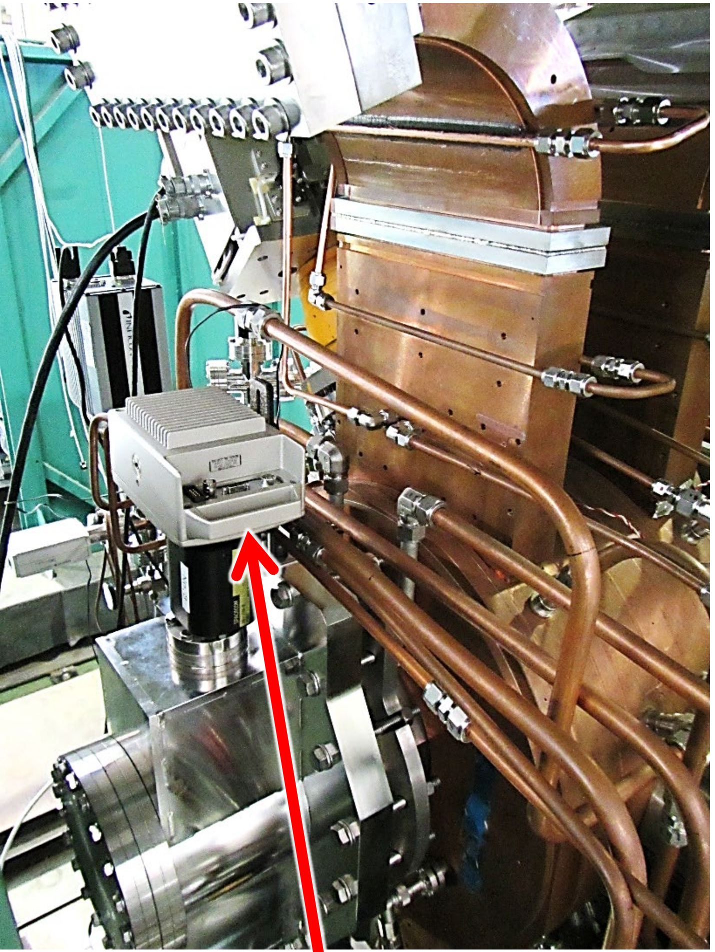


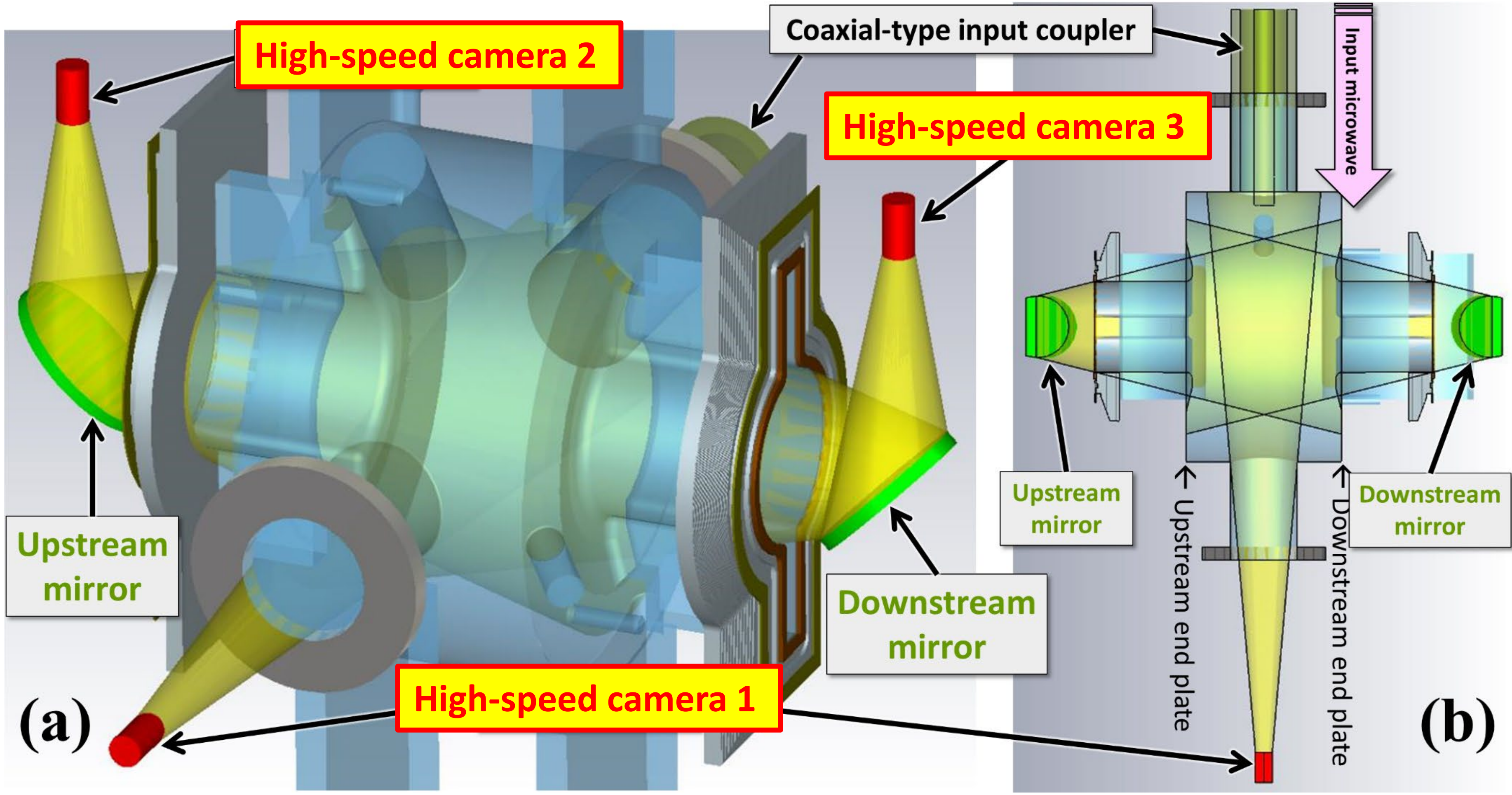






Three High-Speed Cameras





Model: "HAS-D3M"

- ✓ Made by DITECT Co., Ltd. (https://www.ditect.co.jp/en/)
- ✓ Max. 100,000 fps (1,000 or 2,000 fps used in this study)
- ✓ Three cameras can be synchronized frame by frame.

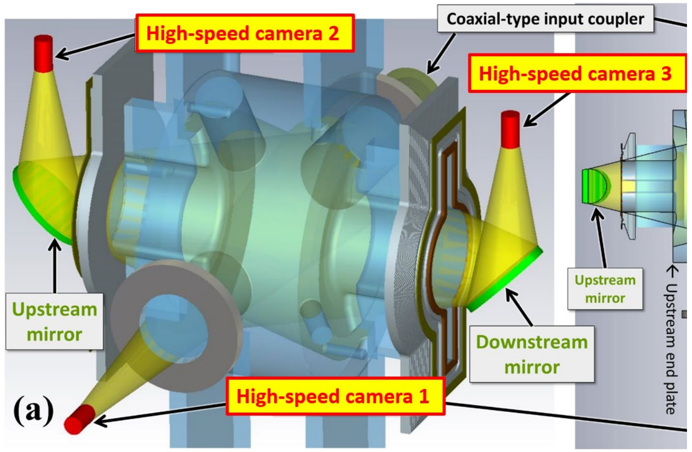
We detected 40 BD events with this setup.

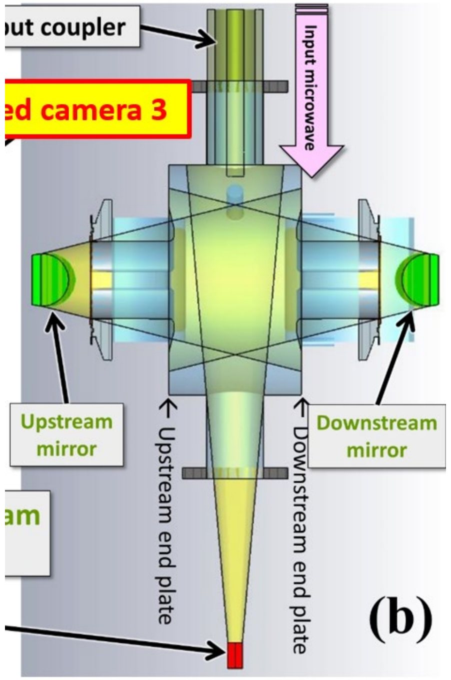
In 4 BD events out of the 40 BD events,
we observed a flying bright object!

Slow motion video (slowed 200 times) of one of the strange breakdown events

During high-power operation with V_c = 0.88 MV

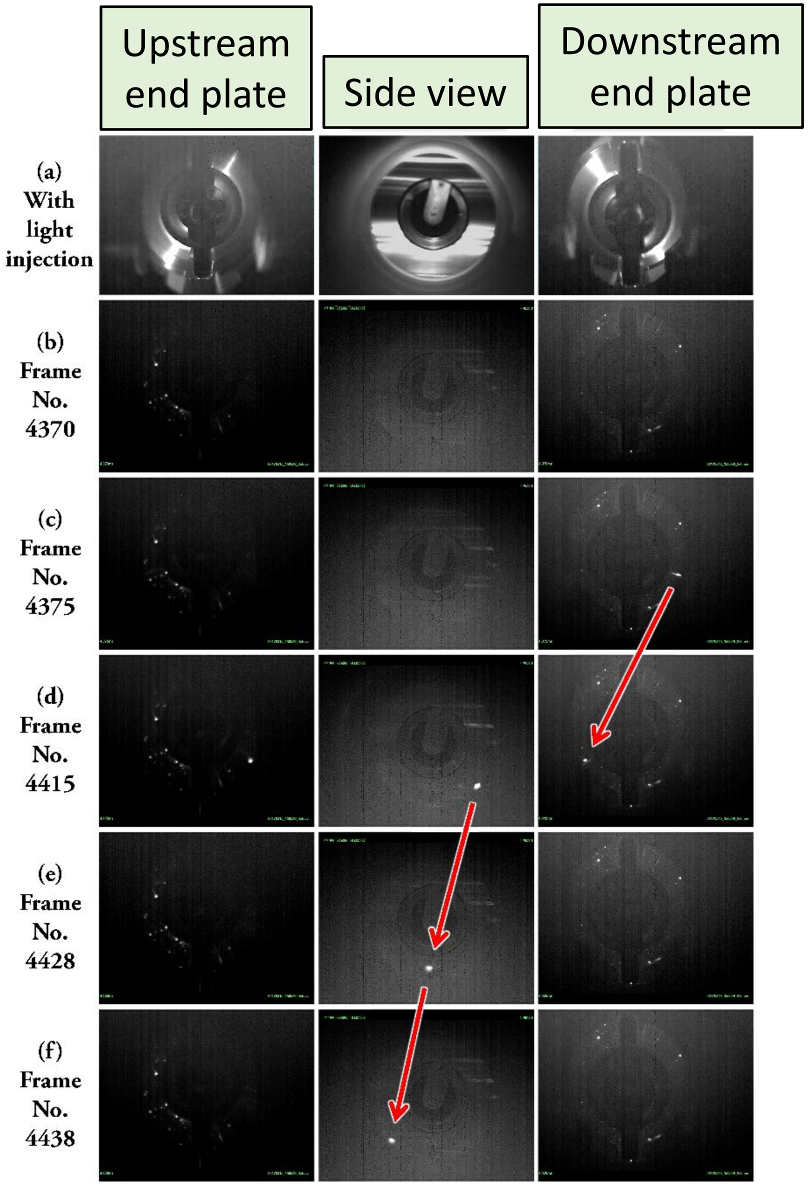
(No beam injected into the RF cavity during this high-power test)

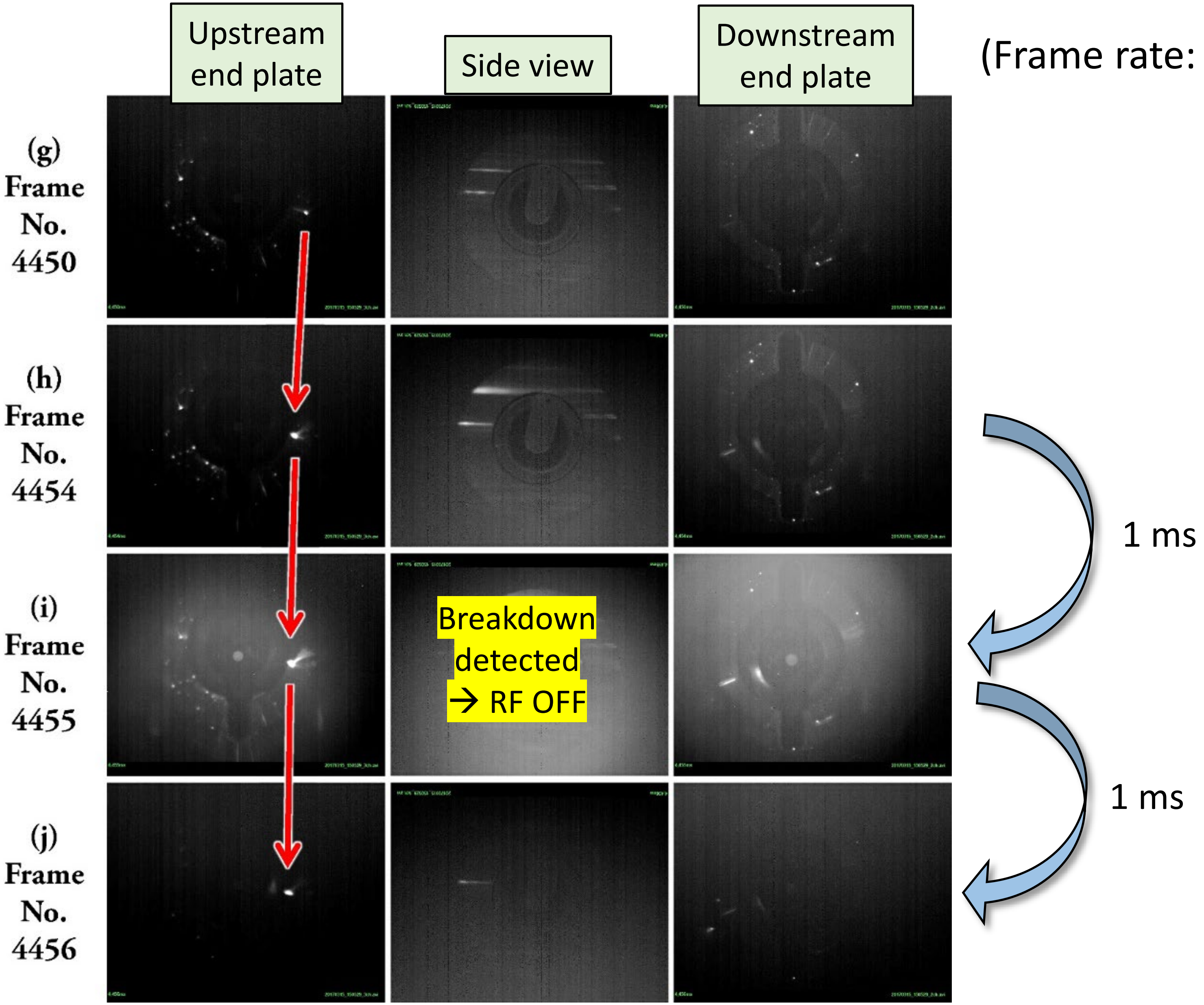




This video → https://youtu.be/VZe8dVLqWH0

Downstream → Upstream → Impact → Breakdown

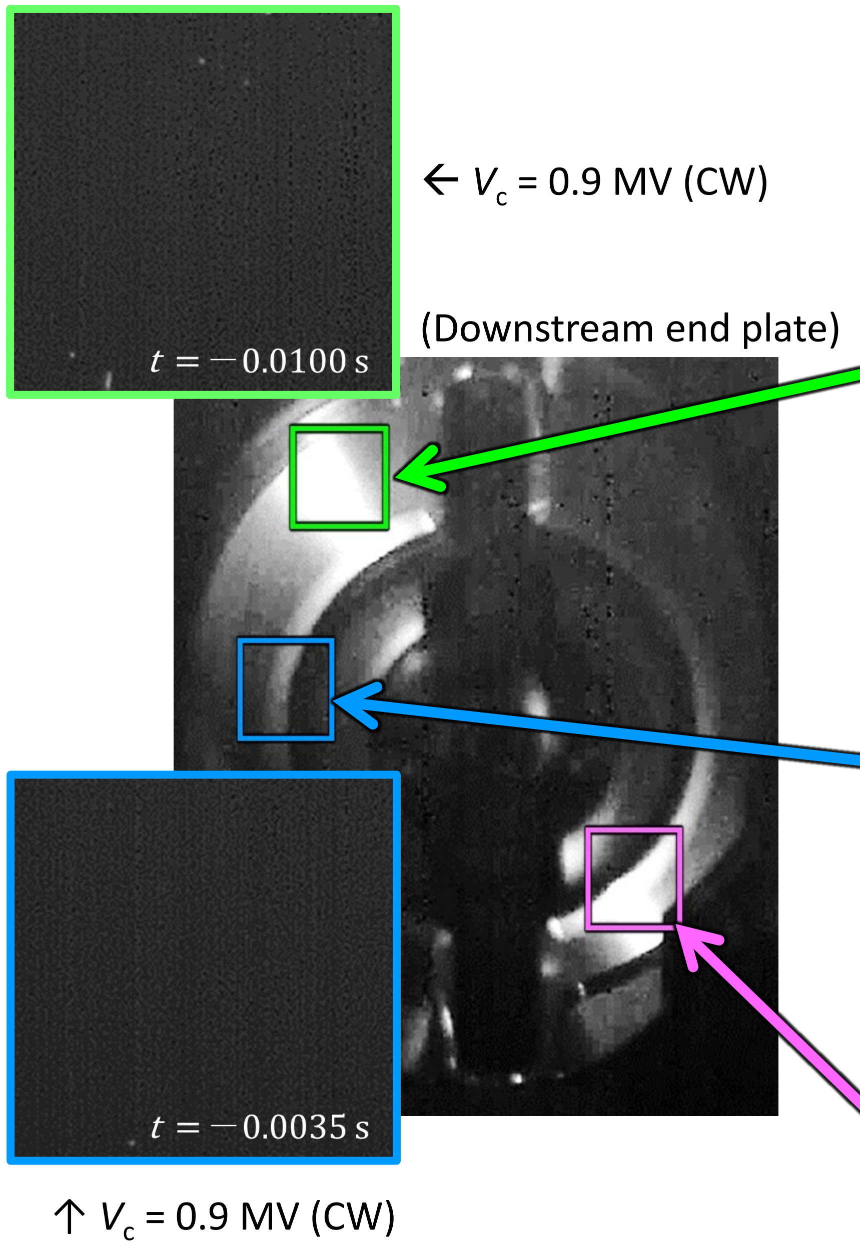


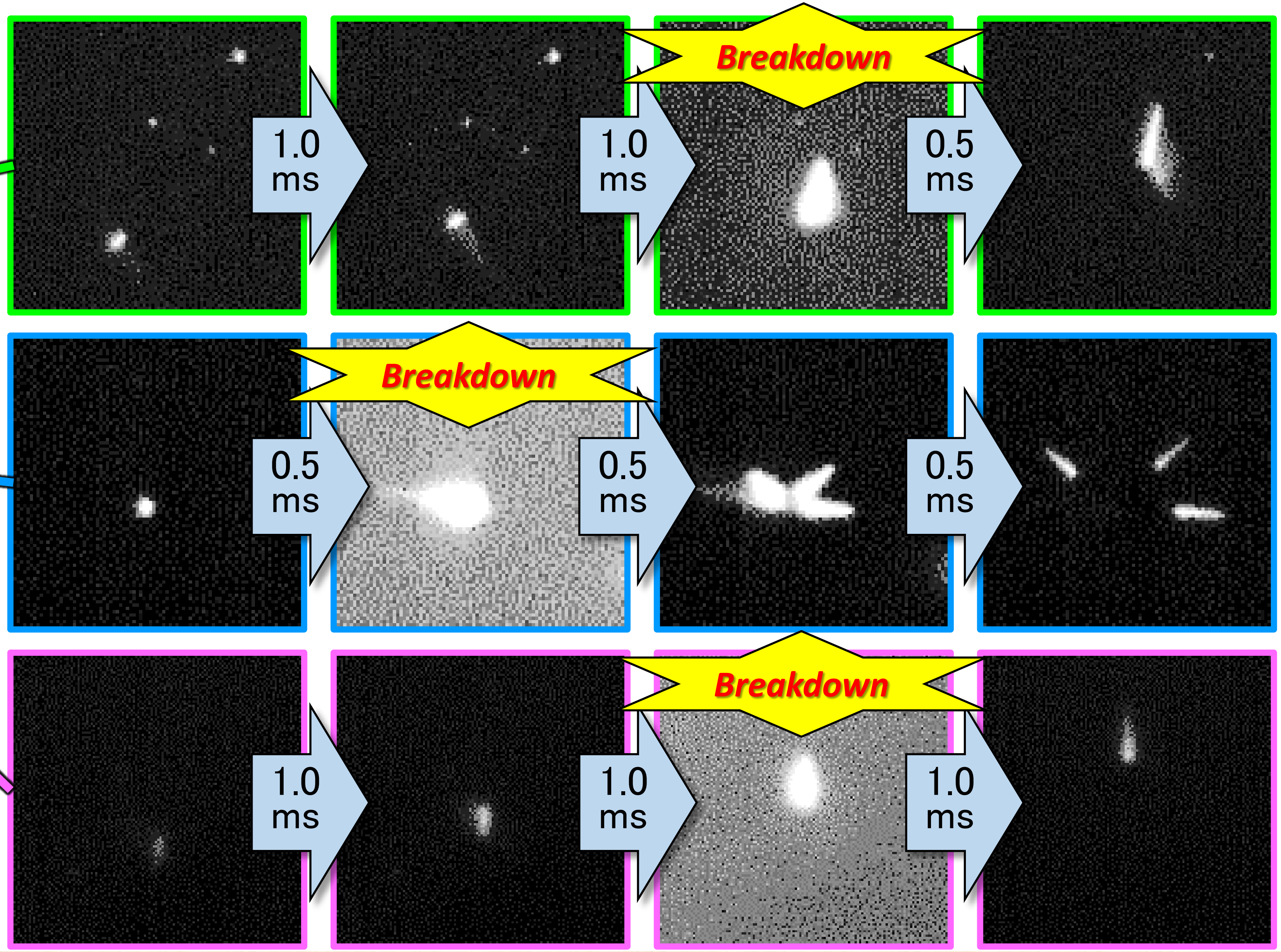


(Frame rate: 1,000 fps)

Other 3 events

(during the high-power test)





From the observation using the high-speed cameras

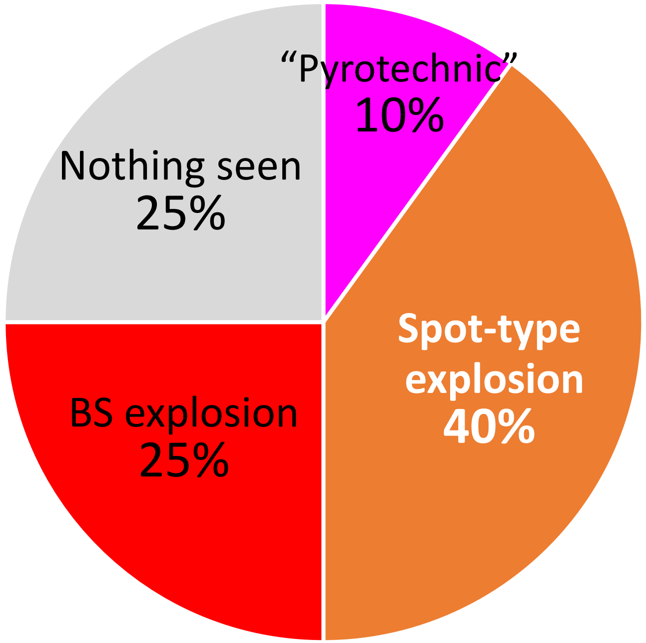
- More flying bright objects (→ breakdowns) observed using the high-speed cameras than using the low-spec cameras

  Breakdowns with spot-type explosion should be caused by flying bright objects.

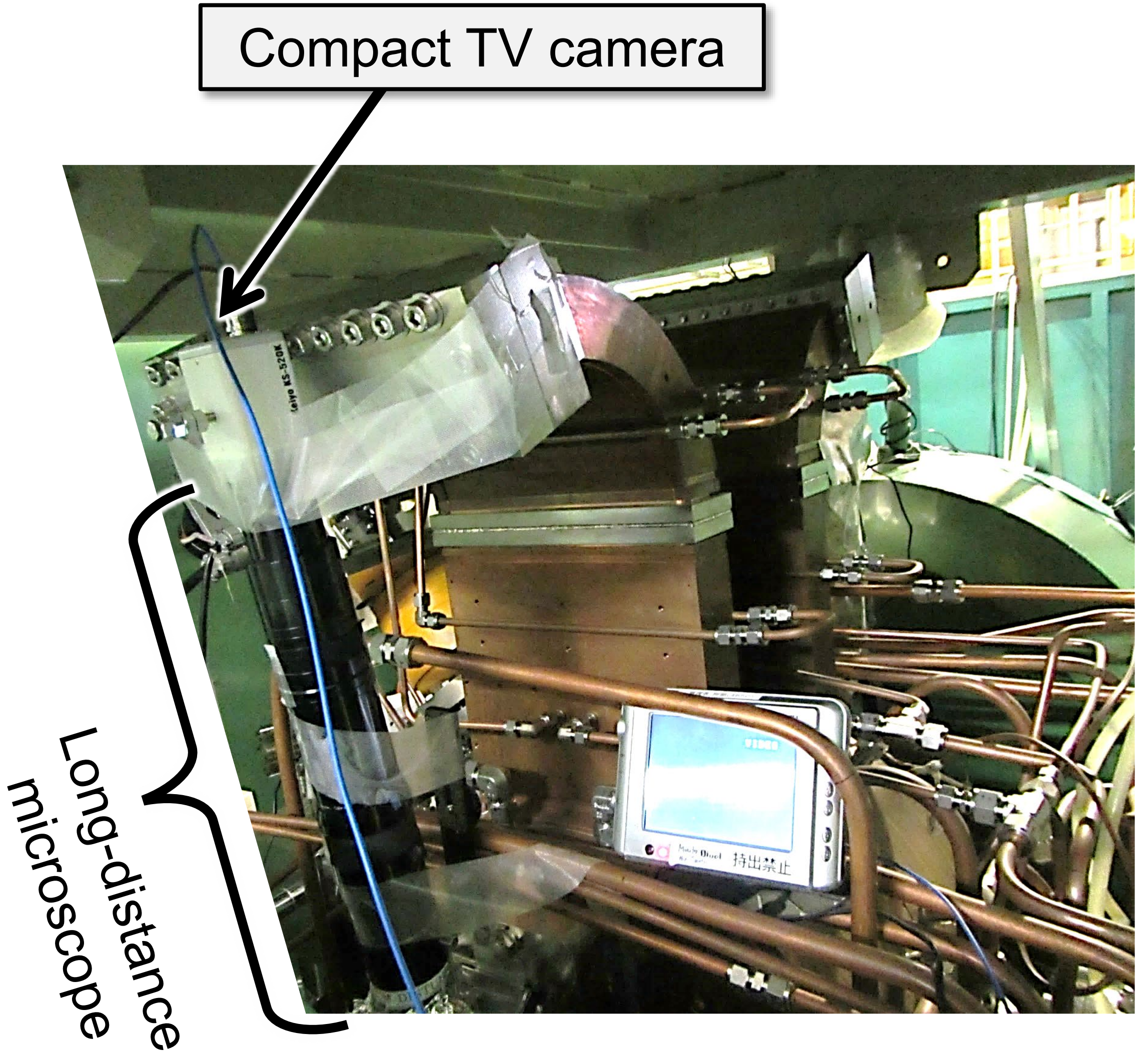
- The high-speed cameras are not sensitive to infrared.

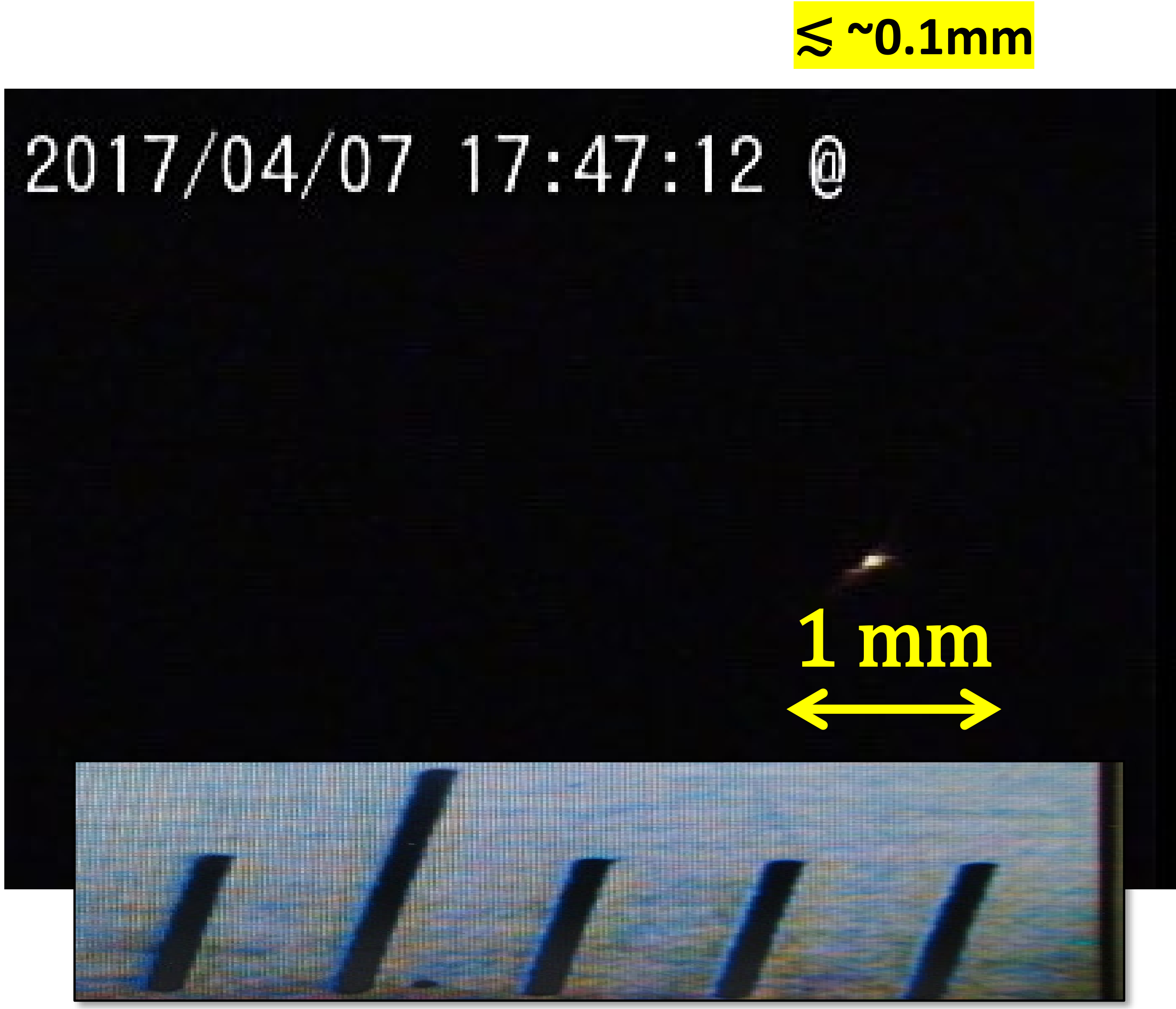
  → (Temperature of the emitters) > 1,000 degC if the object size is $\lesssim$ 0.1 mm

  → **Flying "fireballs"**

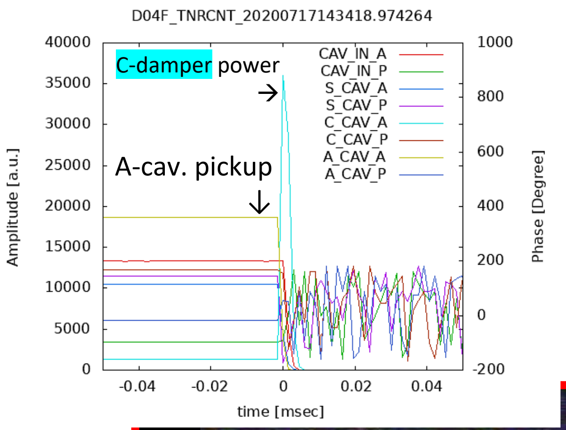


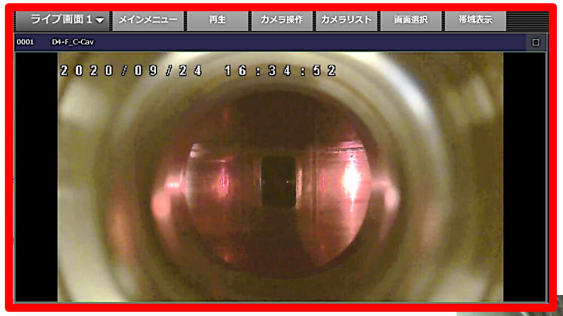
Observation of the size of the bright-spot emitters

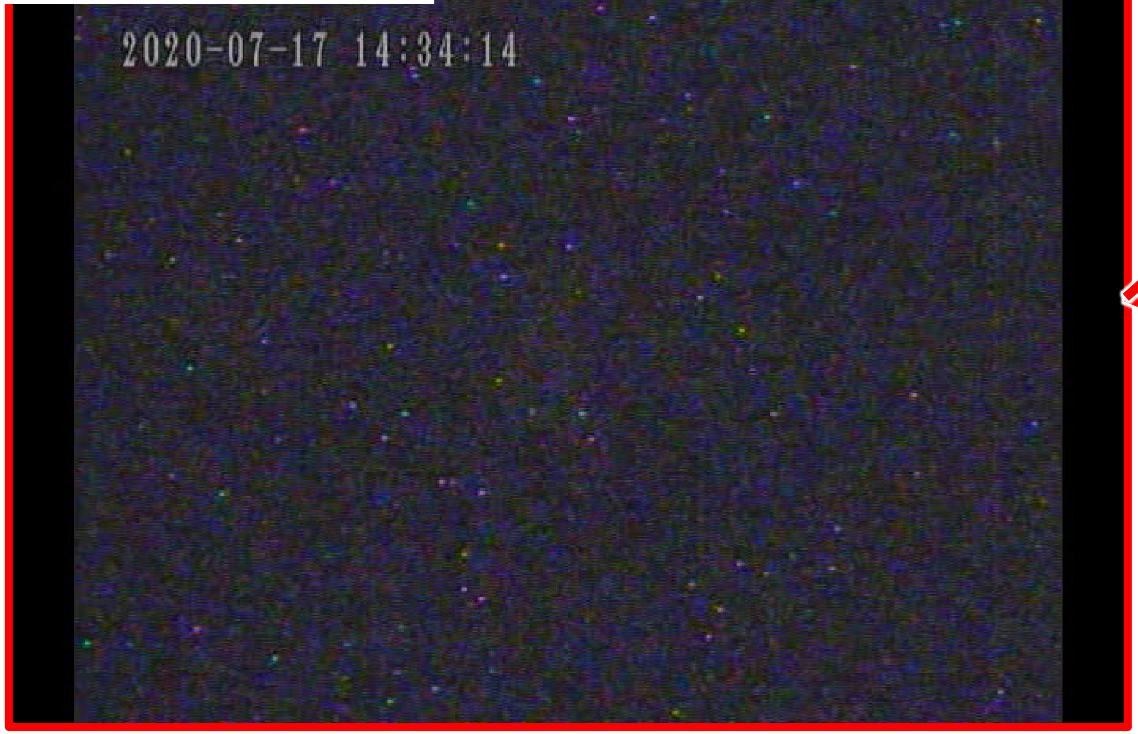


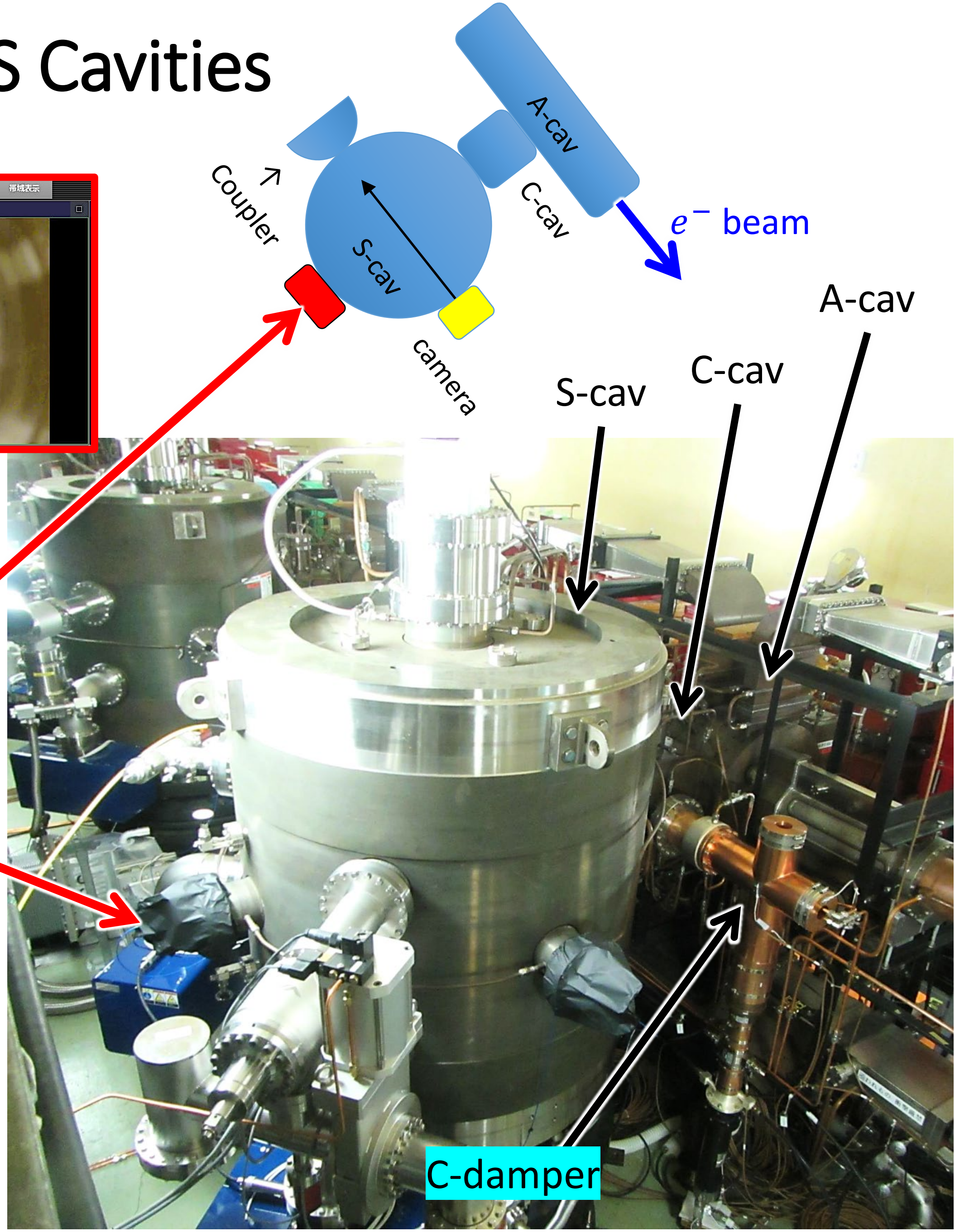


Example of Fireballs observed in the ARES Cavities









Video file: https://youtu.be/qtIB6kLf2j4

Fireball Hypothesis for Sudden Beam Losses (SBLs) at SuperKEKB

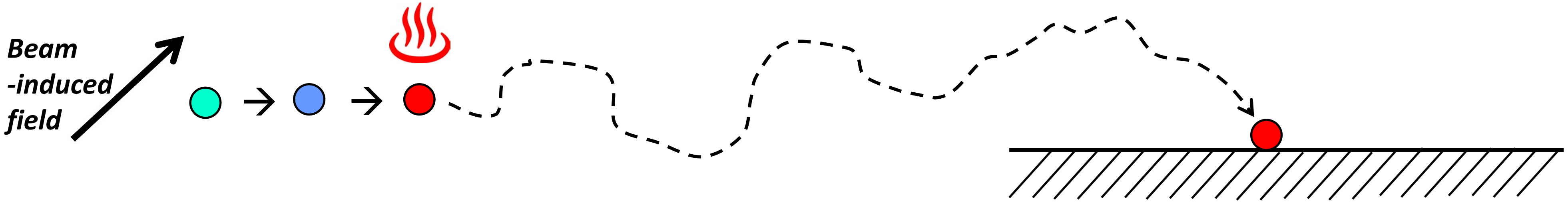
Physical process of the fireball hypothesis, leading to SBLs

(Sudden Beam Losses)

① A micro-particle with a high sublimation point is heated by the beam-induced field.

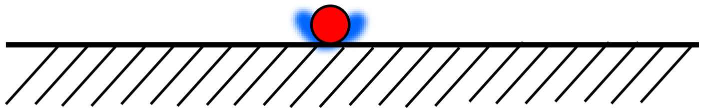
➔ **Fireball**

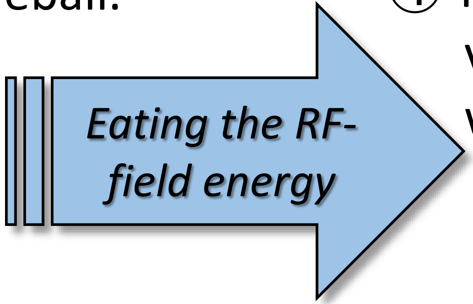
② The fireball touches some metal surface with a low sublimation point (e.g. copper).



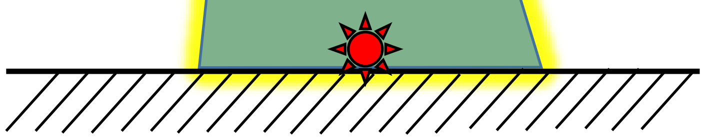
Order of ~ms or longer

③ Plasma is generated around the fireball.





④ The plasma grows up, leading to a macroscopic vacuum arc, and possibly significant interactions with the beam particles.



Order of ~μs or shorter

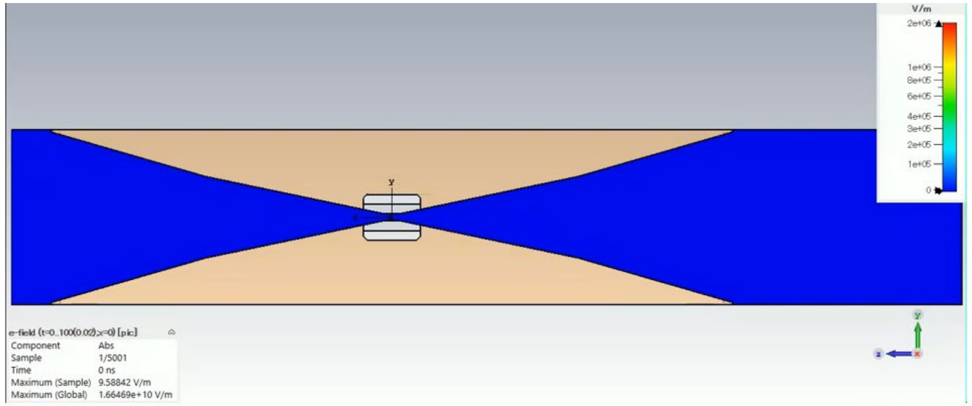
Essential Situation for the fireball breakdown

- Coexistence of different materials
  with largely different sublimation points in the same place.

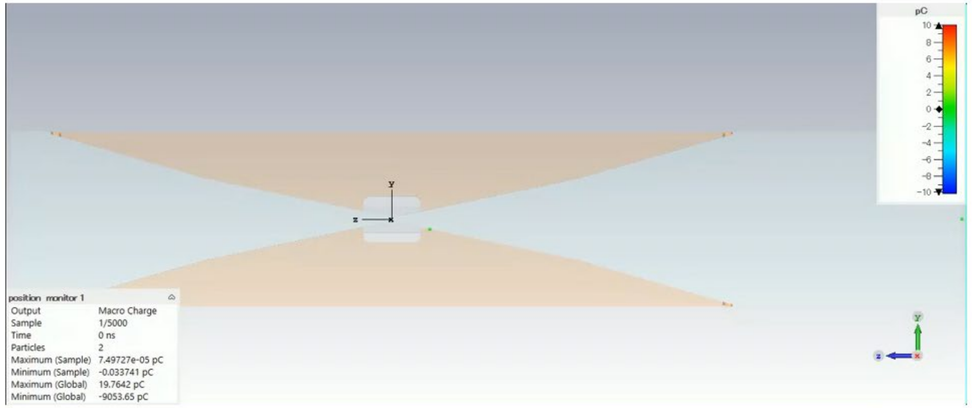
- In the case of the SuperKEKB collimators
  - Heads made of W or Ta with a high sublimation point
  - Vacuum chamber made of Cu with a low sublimation point

Simulation using CST / PIC solver for the SuperKEKB collimator

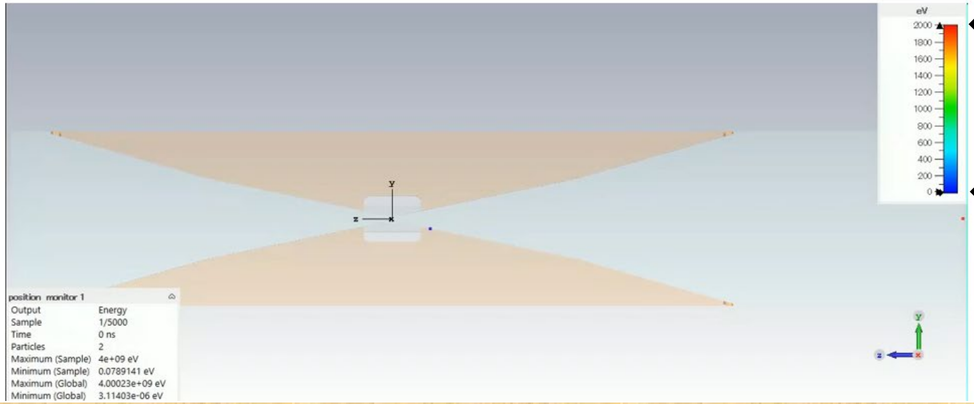
E-field
Red : strong
Blue : weak



E-charge density
Red: ＋
Blue: －

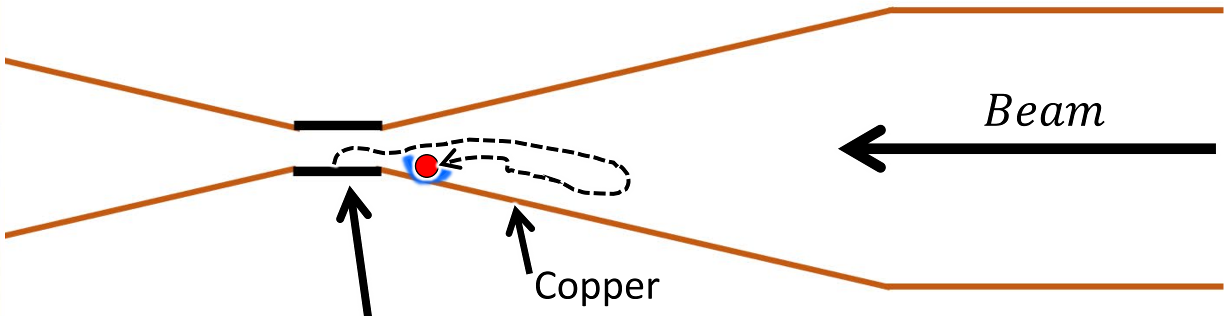


Energy
Red : high
Blue : low



← 2keV
← 0

Start after fireball landing and plasma generation



e.g. Damaged collimator head made of tungsten

Scattered tungsten micro-particles

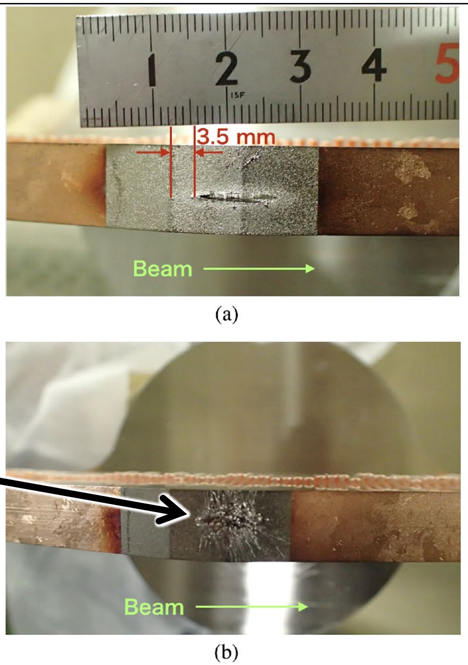


FIG. 16. Photograph of a damaged jaw in (a) a top side and (b) a bottom side of the D06V2 collimator. The traveling direction of the beam is from left to right in this photograph.

Extracted from
T. ISHIBASHI *et al.*, Phys. Rev. Accel. Beams 23, 053501 (2020)

Summary

- Fireballs, > 1,000degC electrically-charged micro-particles, have been observed in UHF CW cavities at KEK.
  - From the era of TRISTAN
  - Adhering on copper surfaces or flying
  - So far, we can operate the RF cavities with fireballs.
    - The breakdown rates are low enough for beam operation so far.
- Fireballs have been found to be a dominant trigger seed in RF cavity breakdowns for UHF CW cavities
  - Except for early stage of high-power RF conditioning.
- T. ABE proposed the fireball hypothesis to explain the trigger of the sudden beam losses at SuperKEKB.
  - Simulation and experimental studies are on-going.

For more details on the fireball breakdown

KEK Accl. Lab. Topics (Web article)

- *“Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities”*
  - https://www2.kek.jp/accl/eng/topics/topics190122.html

Presentations at Workshops

- T. Abe, "*Direct Observation of Breakdown Phenomena in Normal-Conducting Accelerating Structures: 509-MHz Continuous-Wave Cavity and 11.4-GHz Pulsed-Wave Cavity*", presented at the 12th International Workshop on Breakdown Science and High Gradient Technology (HG2019), Chamonix, France, June 2019.
- T. Abe, "*Updated Results of Breakdown Study for 509-MHz Continuous-Wave Accelerating Cavities based on Direct In-situ Observation*", presented at the 7th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2018), Puerto Rico, May 20-24, 2018.

Original paper

- T. Abe, *et al.*, "*Direct Observation of Breakdown Trigger Seeds in a Normal-Conducting RF Accelerating Cavity*", Physical Review Accelerators and Beams **21**, 122002, 2018.

Thank you for your attention!

Backup information

ABE, KAGEYAMA, SAKAI, TAKEUCHI, and YOSHINO PHYS. REV. ACCEL. BEAMS **21,** 122002 (2018)

A graphite particle in the constant and uniform magnetic field (509 MHz)

∅0.01mm Cu
∅0.10mm Cu
∅1.00mm Cu

∅0.01mm Mo
∅0.10mm Mo
∅1.00mm Mo

∅0.01mm C
∅0.10mm C
∅1.00mm C

Temperature of the micro-particle

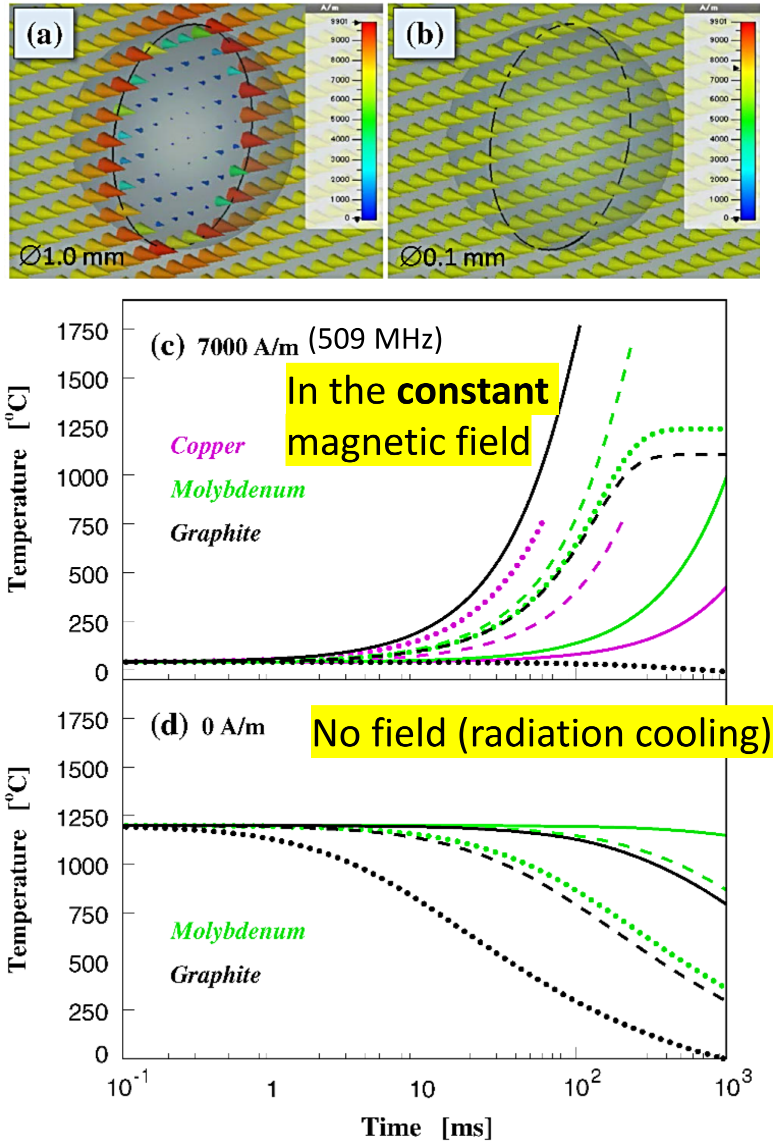


FIG. 22. Simulations of temperatures of spherical microparticles made of graphite (black lines), molybdenum (green lines), and copper (magenta lines) with diameters of 1.0 mm (solid lines), 0.1 mm (dashed lines), and 0.01 mm (dotted lines) located in a vacuum. Radiation cooling was calculated according to the Stefan–Boltzmann law with an emissivity of 0.8 for graphite and 0.1 for copper and molybdenum. Heat capacities of 0.71, 0.39, and 0.28 kJ/K/kg were used for graphite, copper, and molybdenum, respectively. (a) and (b) Application of a 508.9-MHz magnetic field of 7000 A/m to graphite microparticles with diameters of 1.0 and 0.1 mm, respectively, assuming an electric conductivity of 1.0×10^5 S/m for graphite. (c) Temperature variation of the microparticles from an initial temperature of 40 °C with heat generation by a magnetic field of 7000 A/m. (d) Temperature variation of the microparticles from an initial temperature of 1200 °C without heat generation.