FireBall-Triggered Vacuum BreakDown (FB BD) in Particle Accelerators

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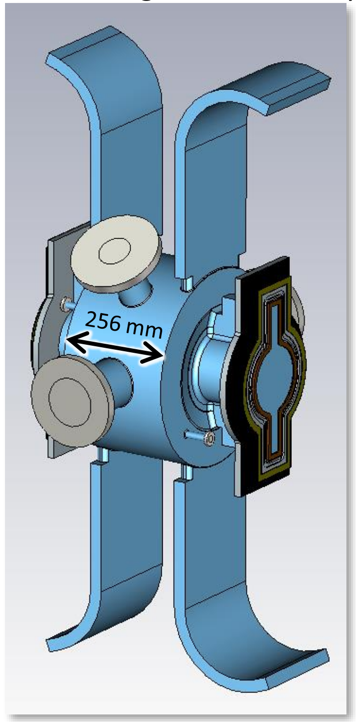
FB BD discovered in High-Power Tests of 509 MHz (CW) RF Cavities

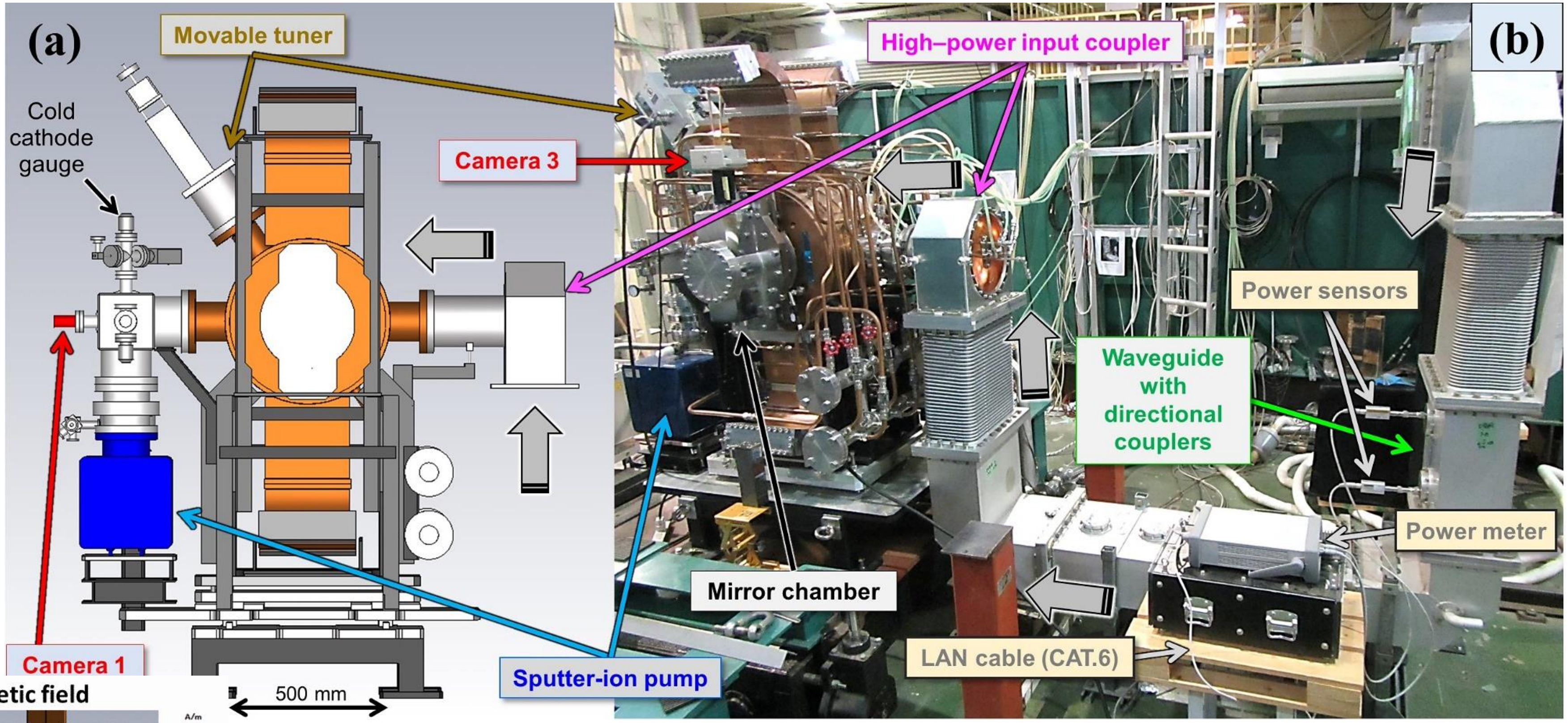
(FireBall BreakDown)

@ KEK / MR-D1-AT

Max. RF power input to the cavity: ~200 kW (CW)

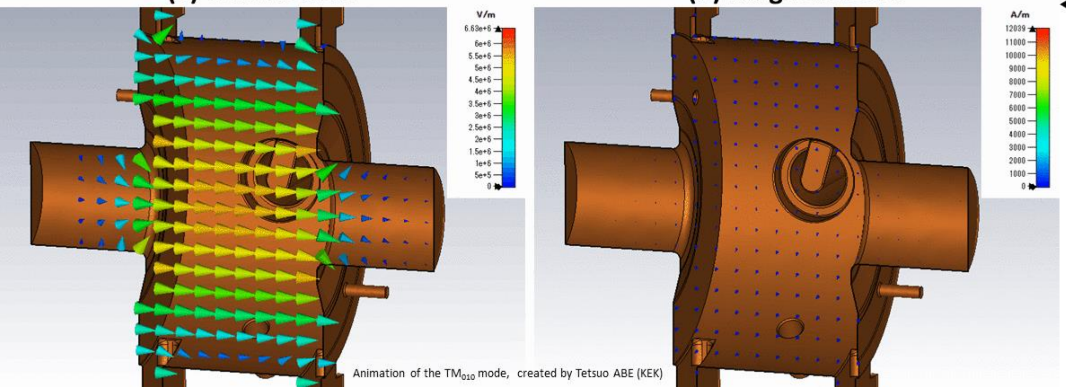
Vacuum region in the cavity





↓ Excited electromagnetic field↓

(a) Electric field (b) Magnetic field



- Accel. mode: 509 MHz Continuous Wave (CW) TM_{010}
- Made of Oxygen Free Copper (Class1)
- Q_0 = ~30000
- $R_{sh}/Q_0 = 150\ \Omega$
- Spec. V_c = 0.8 MV (→ E_{acc} = 3.1 MV/m)
- Wall-loss power: ~150 kW @V_c = 0.80 MV
- Vacuum pressure: ~1e-5 Pa

For more details,
https://www2.kek.jp/accl/legacy/eng/topics/topics131007.html

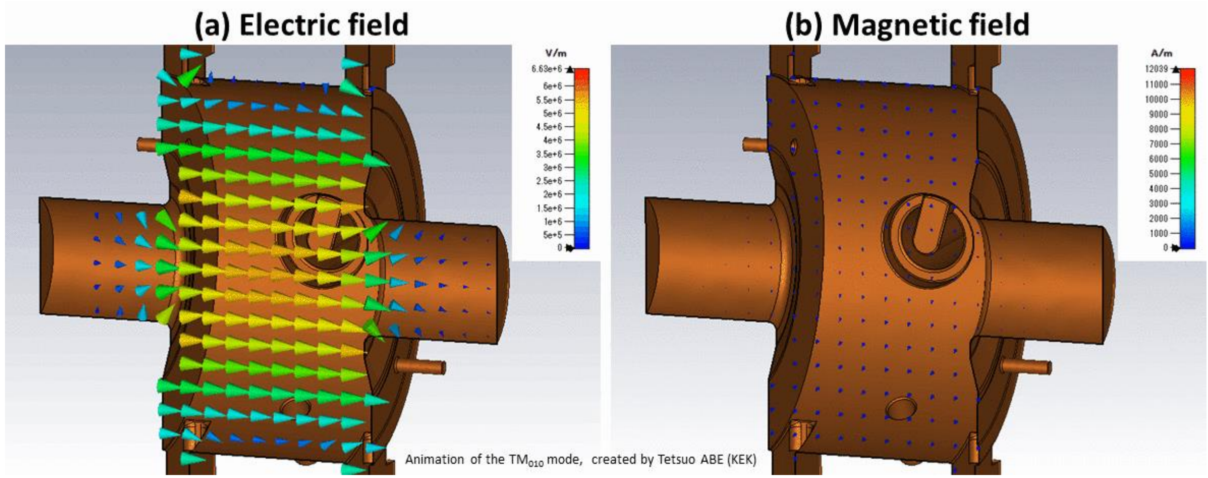
Surface field at V_c = 0.9 MV (Input RF power: ~200 kW)

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

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

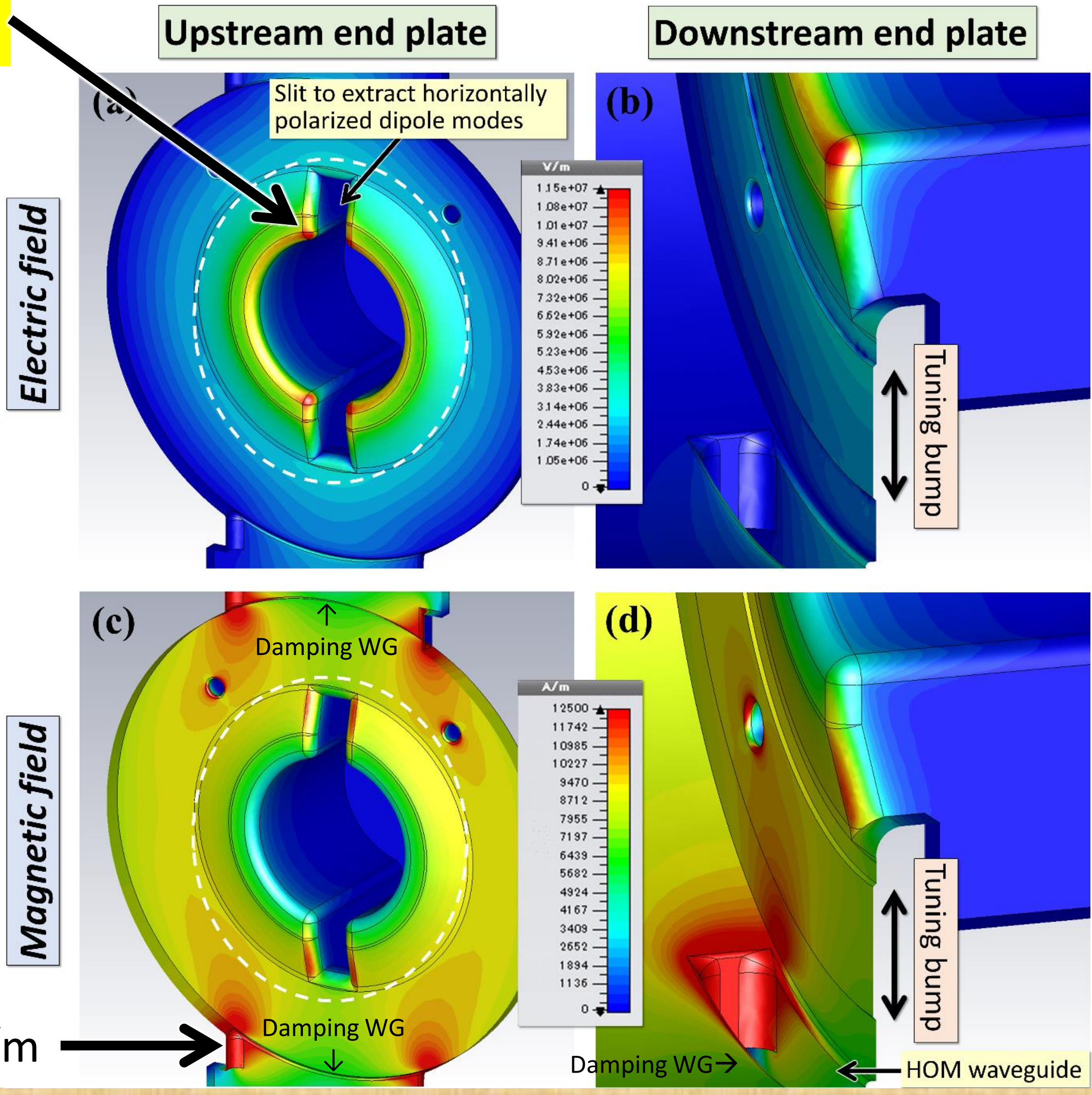
- **Field evaporation (> ~GV/m)**
- **X-band HG accel. structures (~200 MV/m)**
- **DC HV experiments (~100 MV/m)**

➔ But breakdowns occur in UHF NC CW cavities.



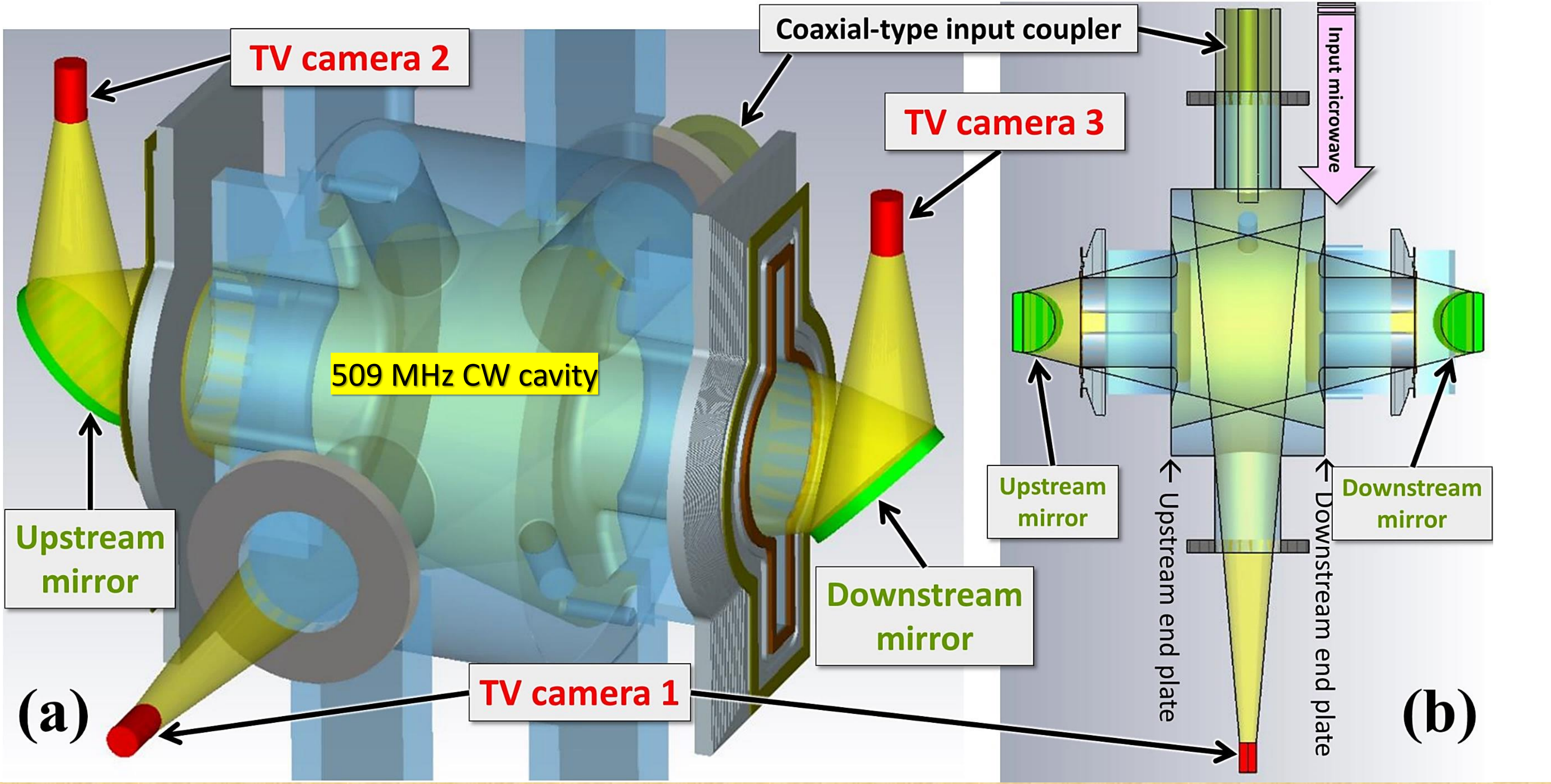
↑ Upstream end plate

↑ Downstream end plate



H_{max} = 34 kA/m

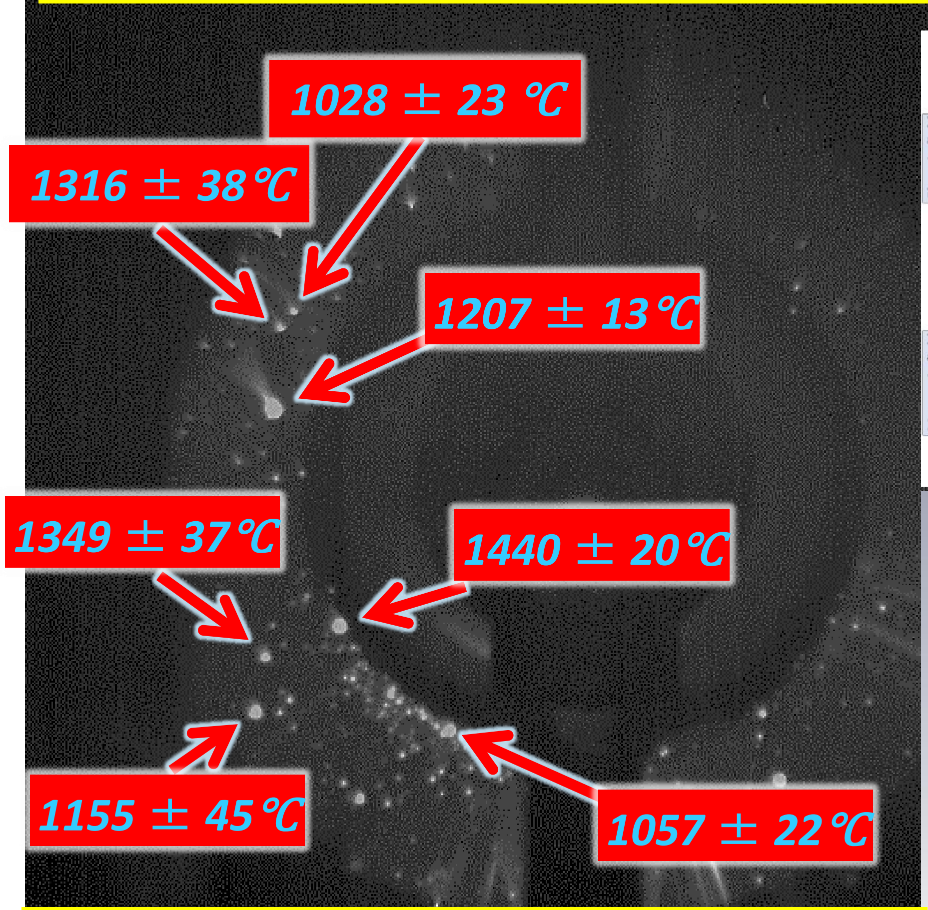
Multi-directional and wide-field observation with Three Cameras



Observation1: “Adherent” fireballs

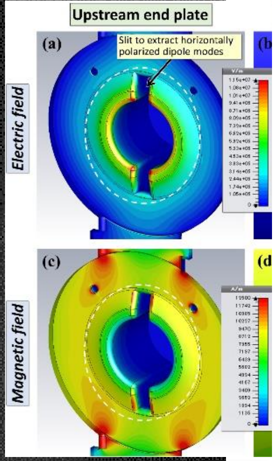
During high-power operation with V_c = 0.95 MV (E_{acc} = 3.7 MV/m)

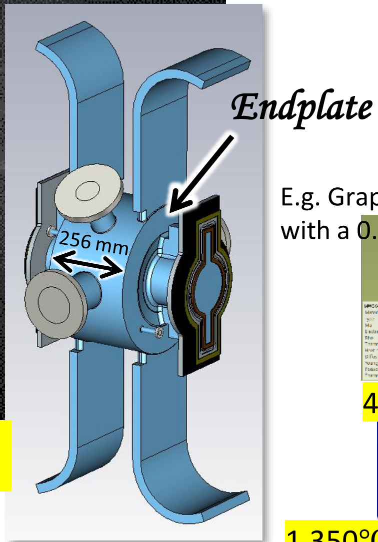
Bright spots observed on the endplate are high-temperature (> 1,000℃) micro-particles (< 0.1 mm)



Emitting significant lights for a long time (> day)

Observation of the emission spectra using a spectrum camera
→ After various corrections, the temperatures were estimated.





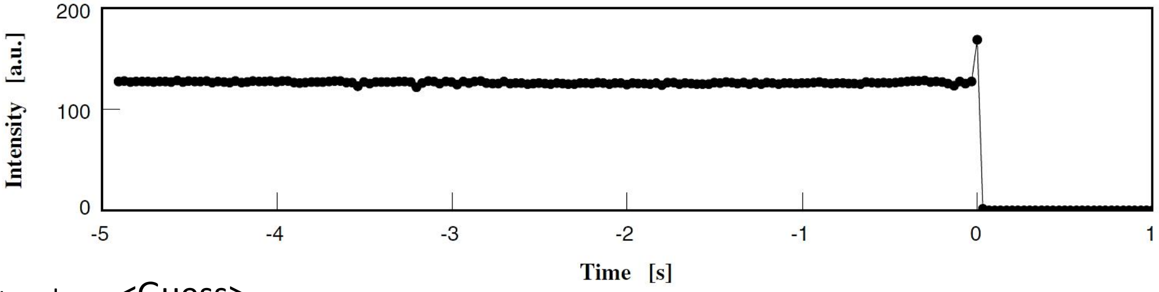
509 MHz cavity

One of the bright spots | suddenly exploded at the moment of breakdown. | Then, disappeared in the following high-power operation.

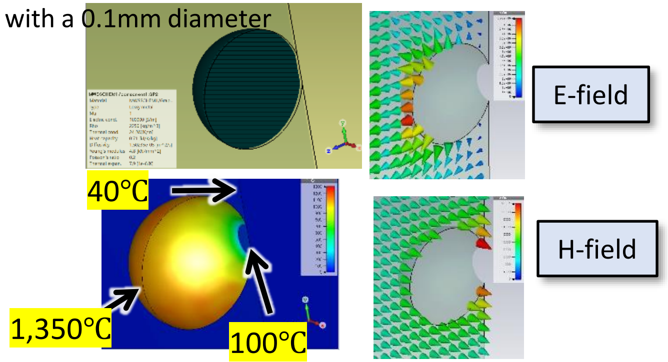
(a) 1 frame (1/30 s) before this cavity breakdown.

(b) At the moment of this cavity breakdown.

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



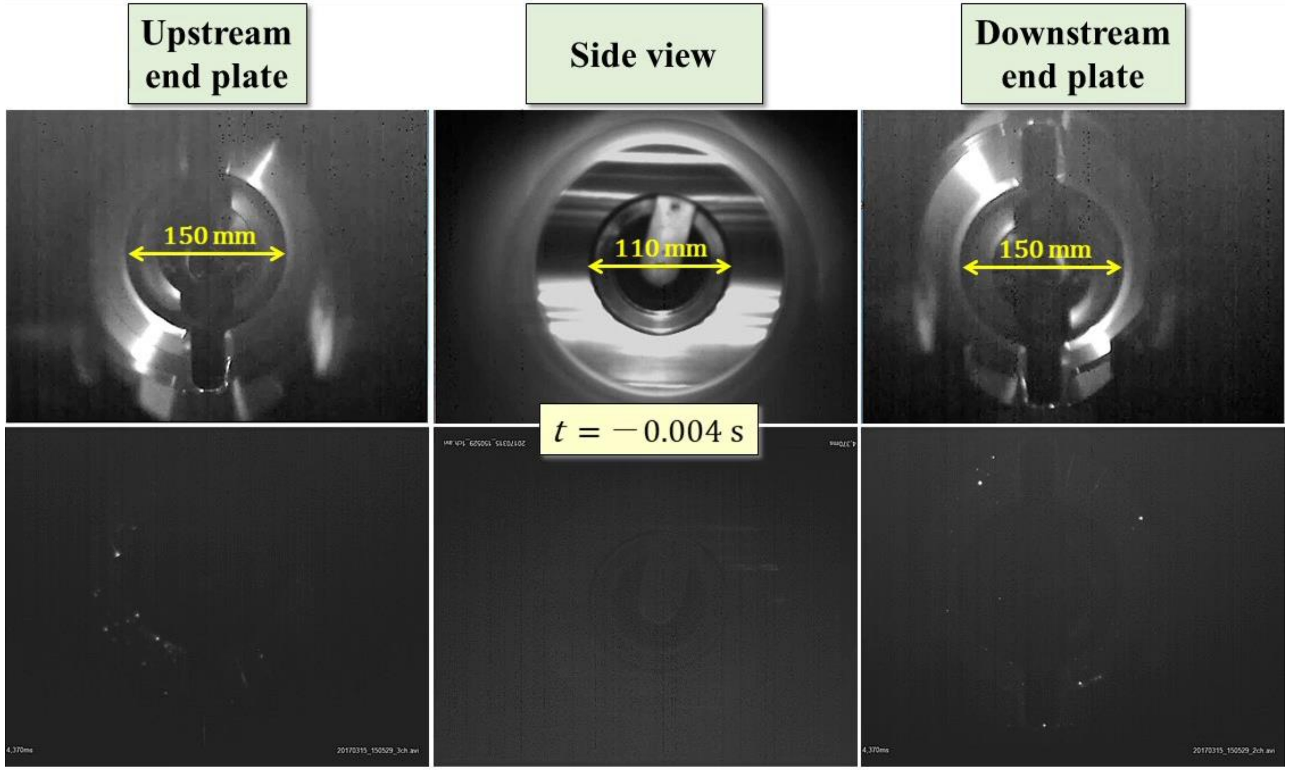
E.g. Graphite sphere with a 0.1mm diameter <Guess>



A stable fireball adhering to a copper surface can explode, leading RF-cavity breakdown

Observation2: "Flying" fireballs

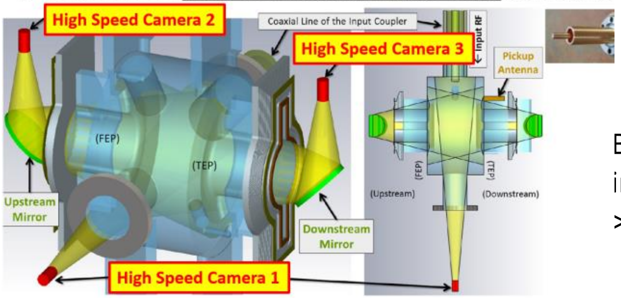
Three high-speed cameras used for multi-directional observation during HP operation of 509MHz (CW) NC cavity at V_c = 0.88 MV



509 MHz cavity with a cavity gap voltage: 0.88 MV (= accelerating gradient: 3.4 MV/m)

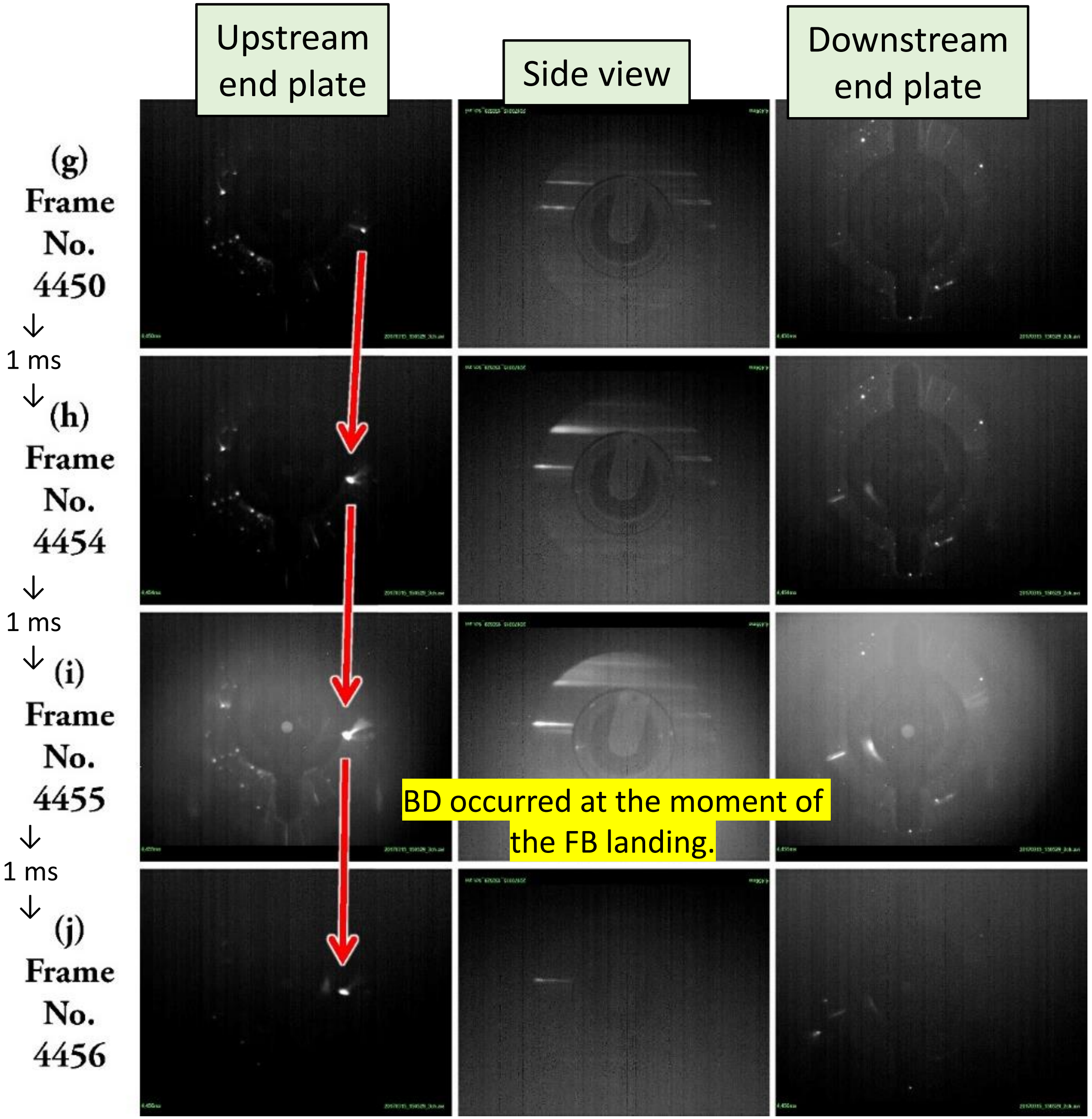
Recorded by Tetsuo ABE (KEK)

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



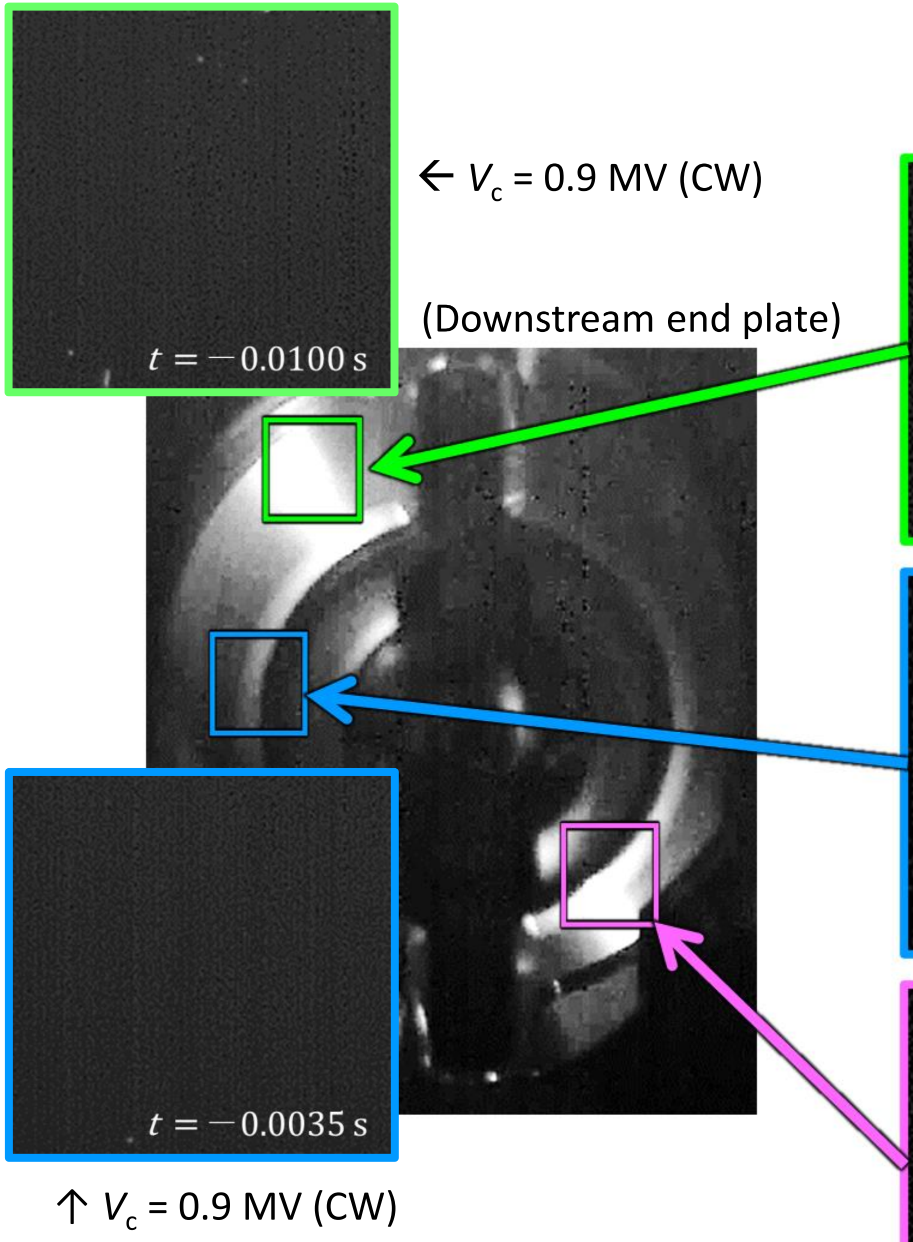
This video → https://youtu.be/VZe8dVLqWH0

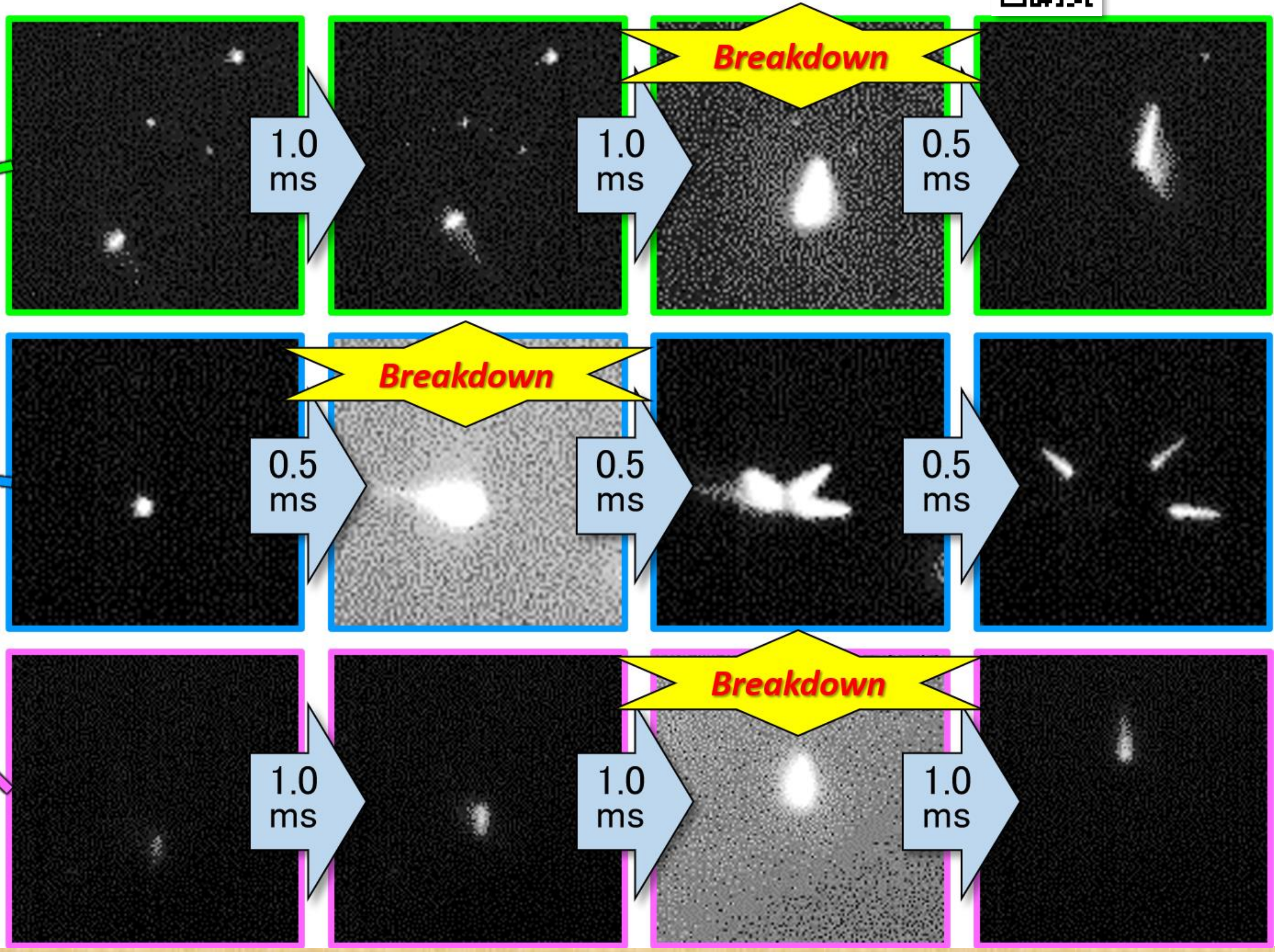
Because the high speed cameras are not sensitive to infrared, the flying bright spot should be a fireball with > 1,000℃ if the size is small (≲ 0.1mm).



Other flying fireballs

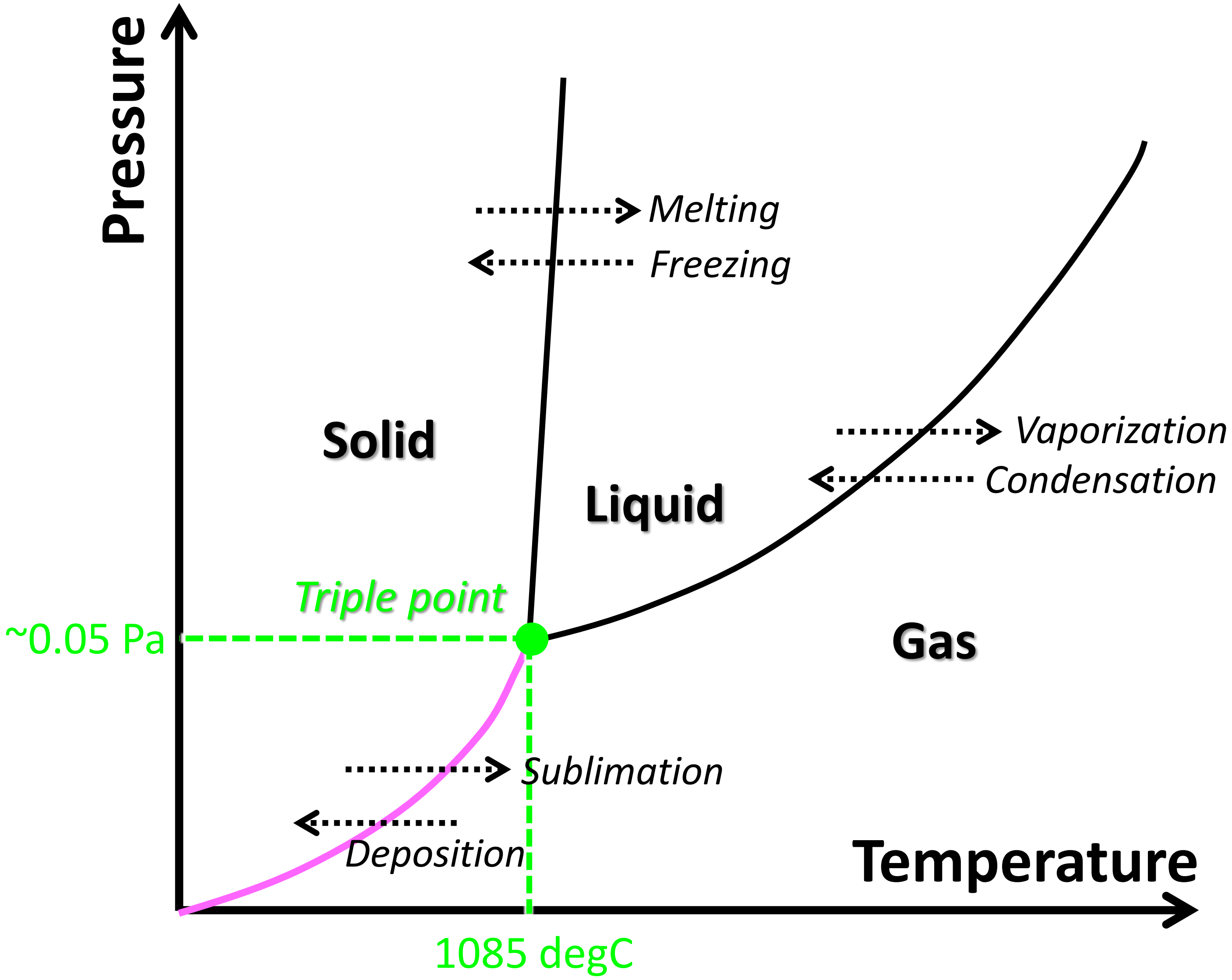
https://youtu.be/MqFYk4EVr7w



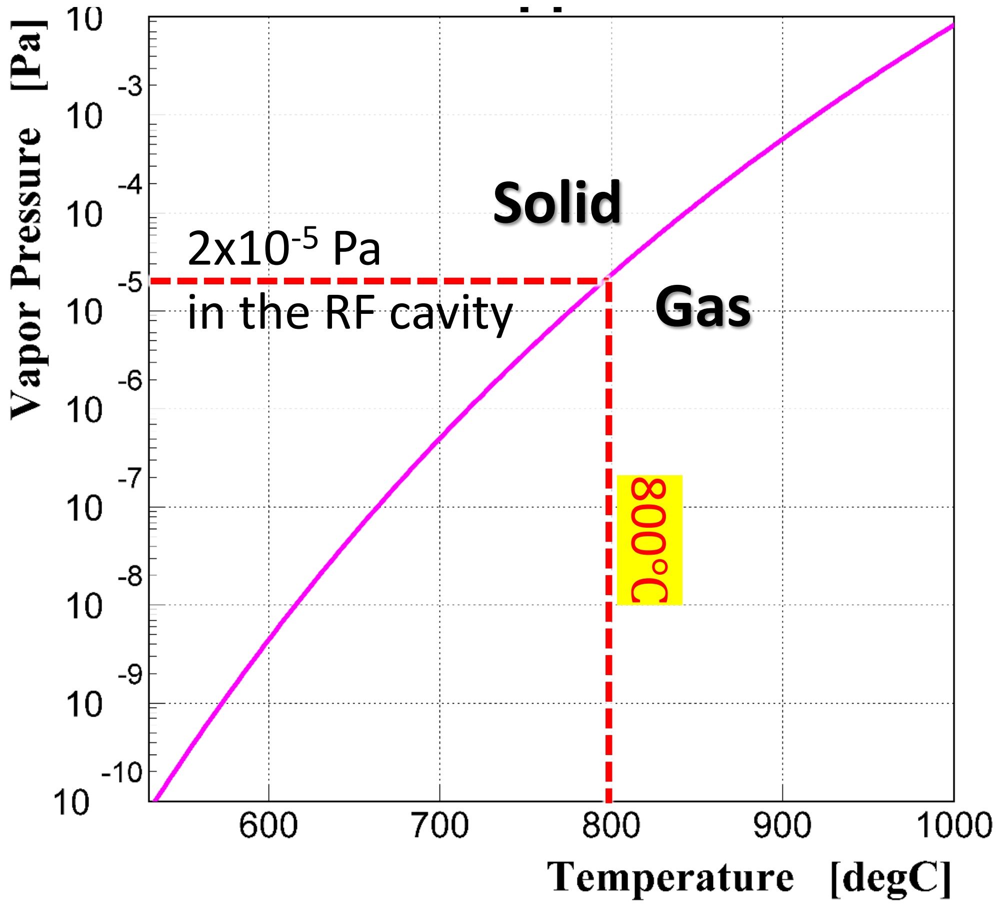


What is the fireball made of?

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℃.
- ✓ Adherent fireballs can emit significant light for > day.

➔ The fireball material is not copper!

Candidates of the Fireball Materials

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

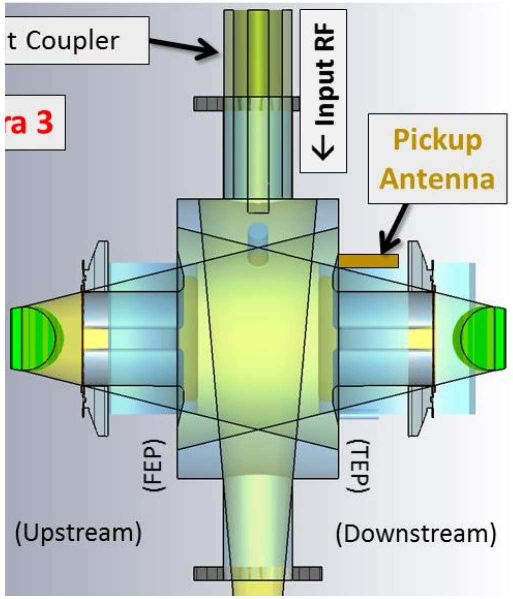
Element	Sublimation point [℃] @ 2 x 10^{-5} Pa	Remarks
W	2258.6	Materials of the SuperKEKB collimator heads
Ta	2123.4	
C (Graphite)	1769.9	Heater materials of vacuum furnaces for RF-cavity fabrication
Mo	1705.7	
Zr	1565.7	Material of NEG pump strips (e.g. St707)
Ti	1162.6	Material of the KEKB collimator heads
Au	894.7	
Cu	795.3	Material of normal-conducting RF cavities
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

Physics in Fireball Breakdown

Breakdown observable A: Fast drop of the accelerating field

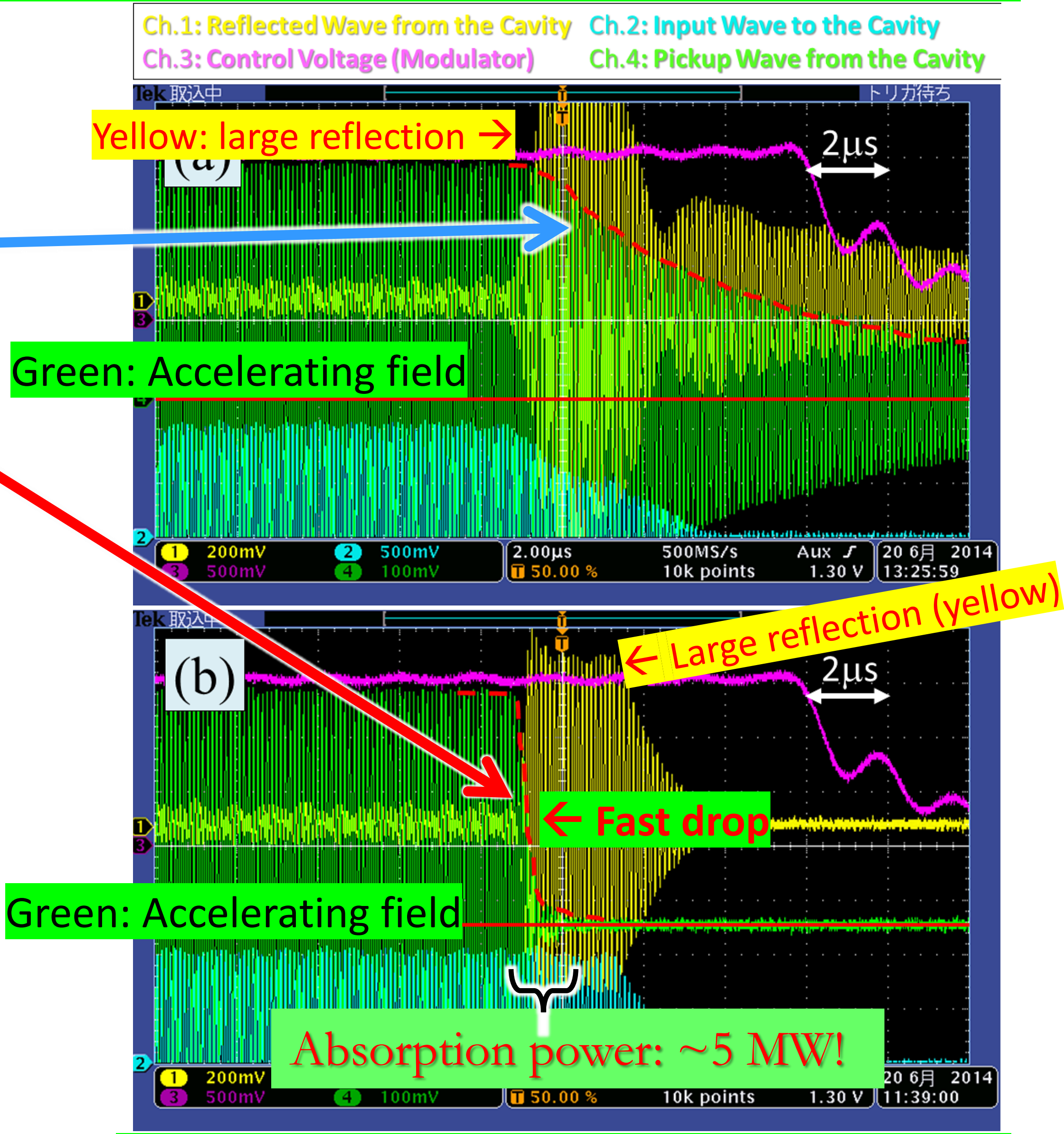
Decay time:
- Normal RF-switch OFF → Decay time: 8 μs
- Fireball breakdown → Decay time: < ~500 ns



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 ⇒ Fill time: 8 μs



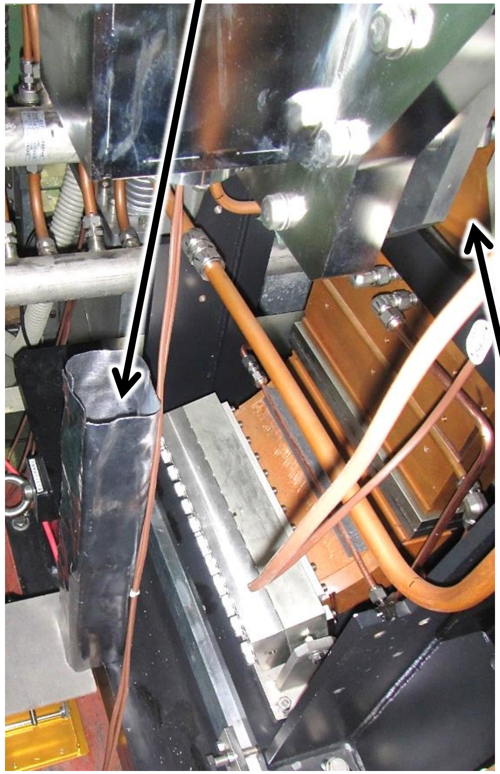
If this power is absorbed in < 0.1 mm²
→ > ~GW/cm²

Breakdown Observable B: Current flash

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

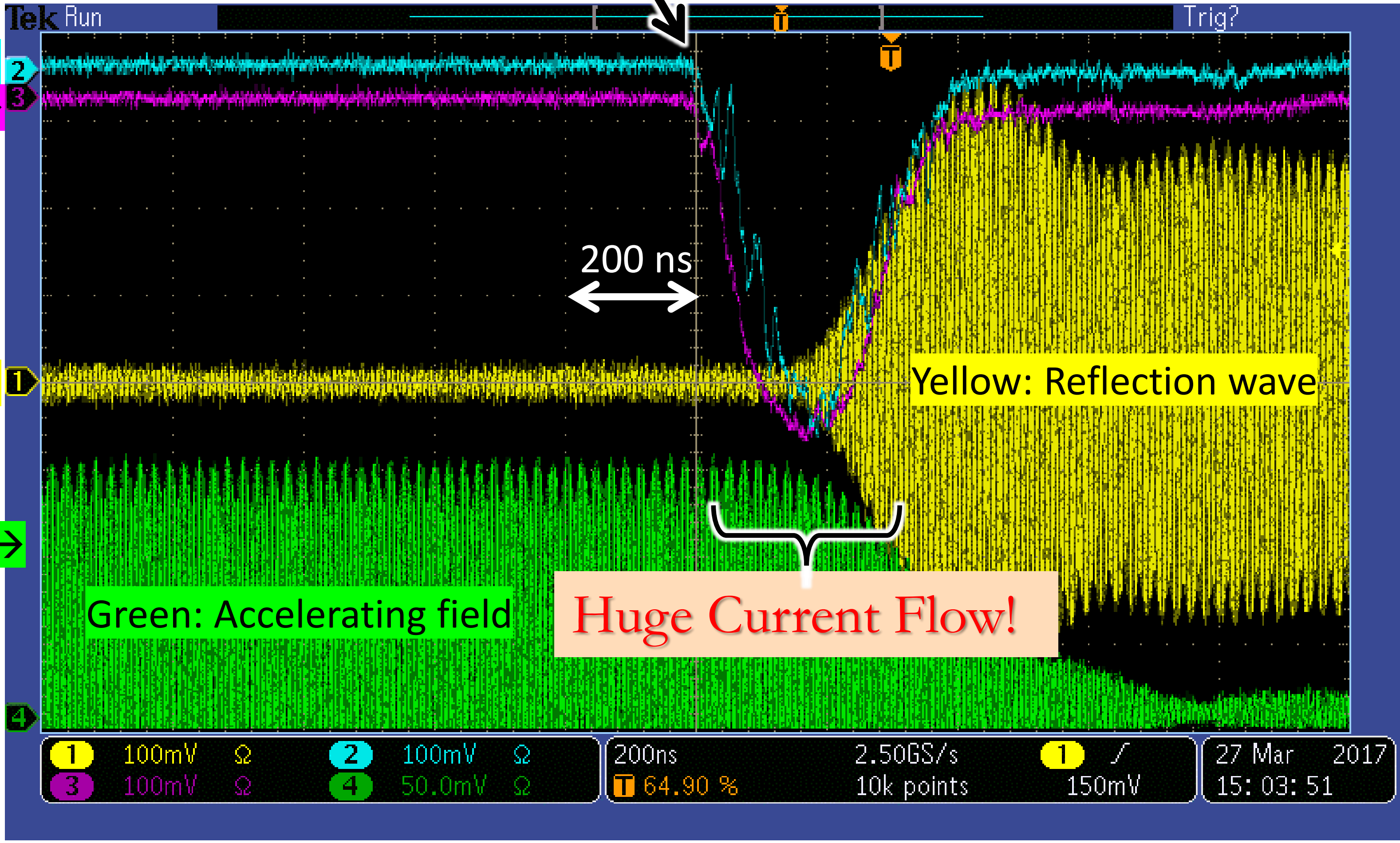
Field emitted e^-
→ Impact on the metal surface
→ X-ray radiation

X-ray detector
(plastic scintillator + PMT)



RF cavity
for the e+ DR

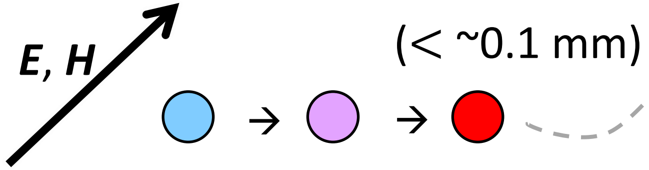
Ch.2 : X-ray (UP) →
Ch.3 : X-ray (DN) →
Ch.1 : Cav. Refl. →
Ch.4 : Cav. Pickup →

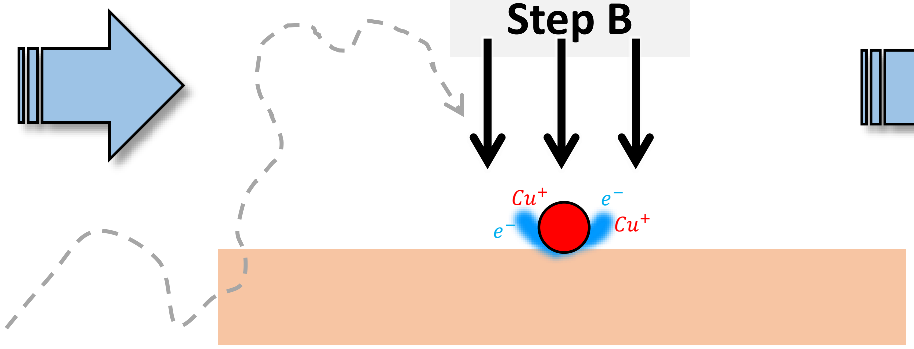


Physical process of FB BD revealed by the observations

Step A

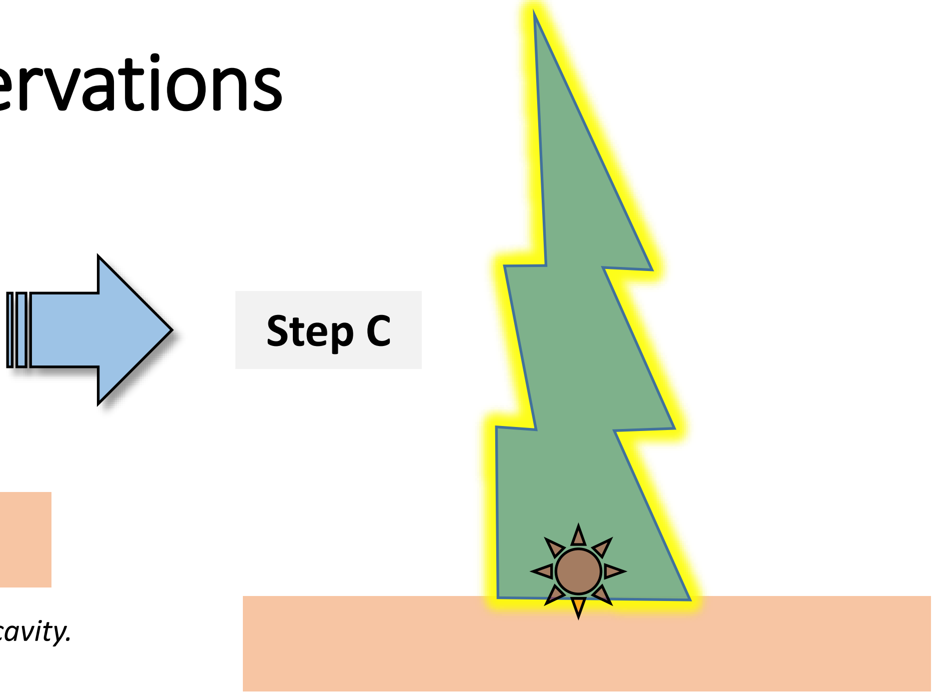
A microparticle is heated by the RF field into a fireball.





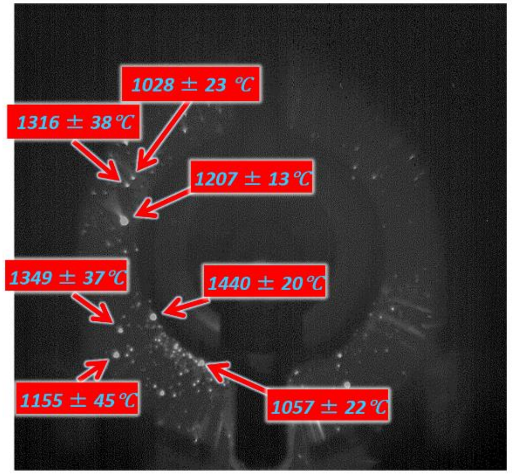
Step B

Plasma is generated with eating the RF field in the cavity.

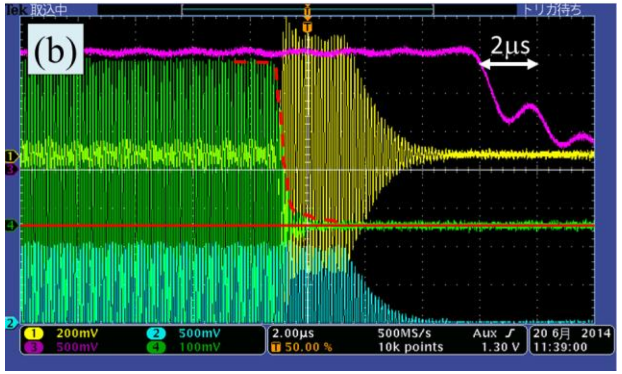


Step C

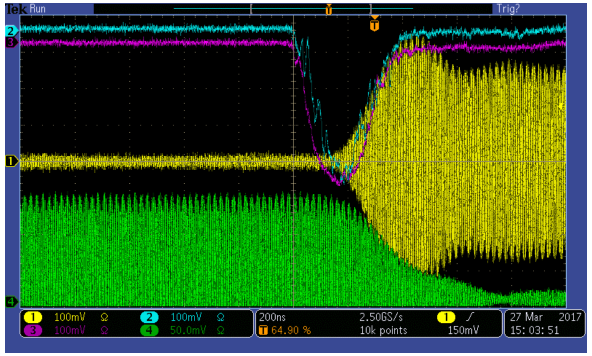
<u>Huge current</u> flow leads to vacuum breakdown.



Temperature measurements



Very high power density of ~GW/cm²

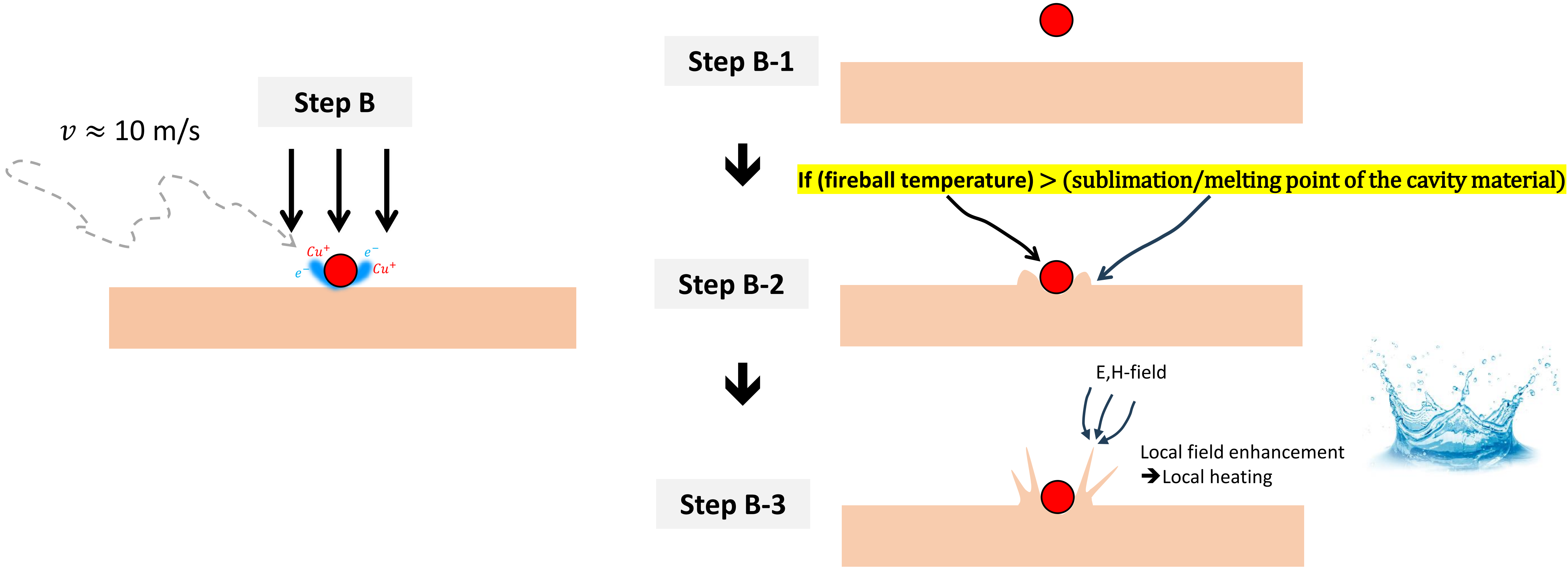


Huge X-ray detected

(Plasma generation and its exponential growth are needed for vacuum breakdown.)

Essential Condition for FB BD

Coexistence of different materials
with largely different sublimation/melting points in the same place



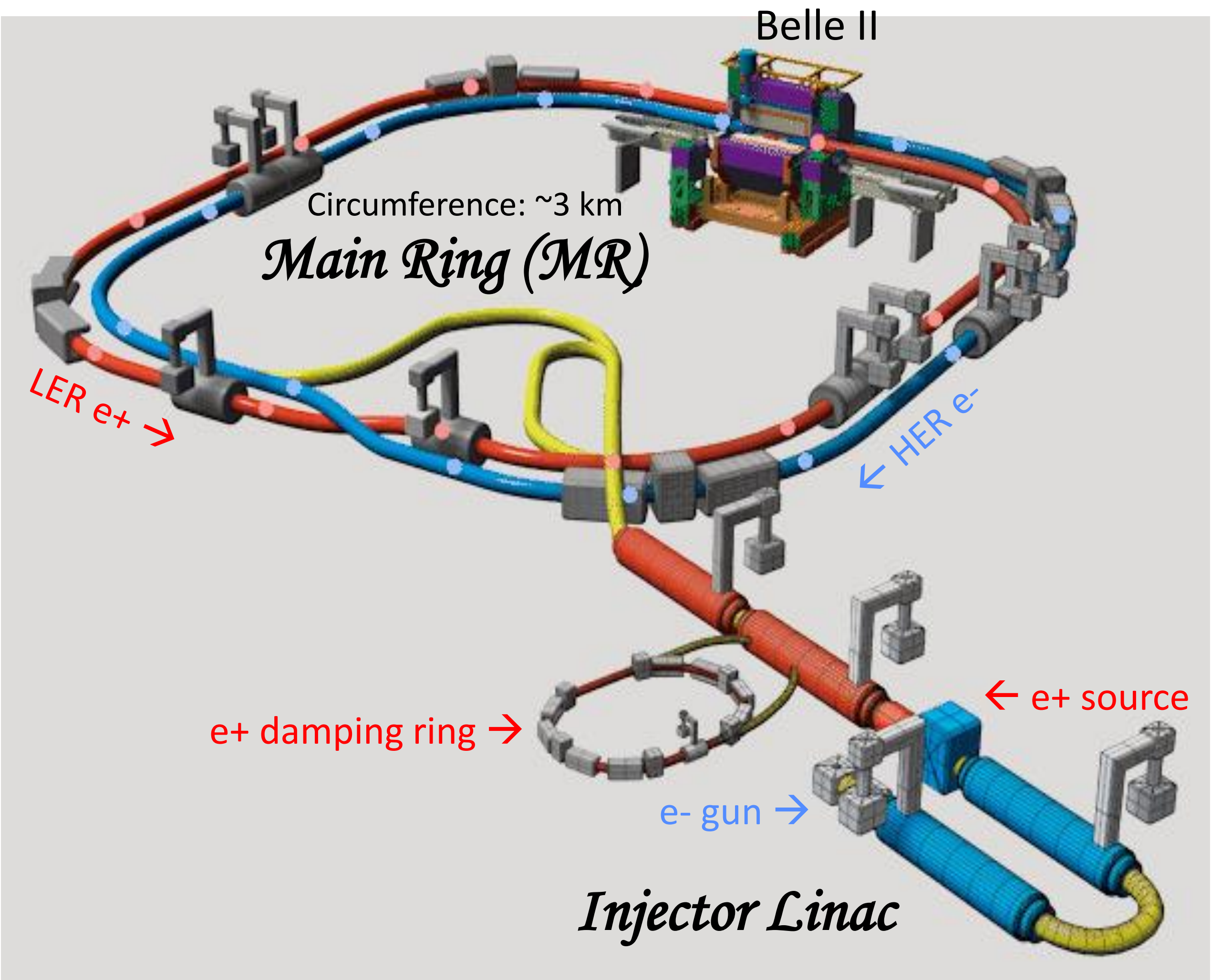
(Just my speculation; detailed investigations needed)

Unexpected relationship with the beam operation of SuperKEKB accelerator

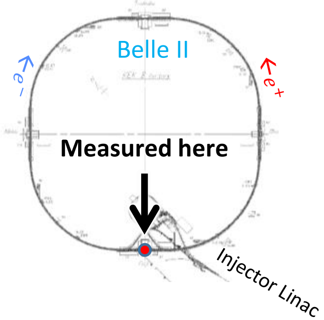
SuperKEKB Accelerator

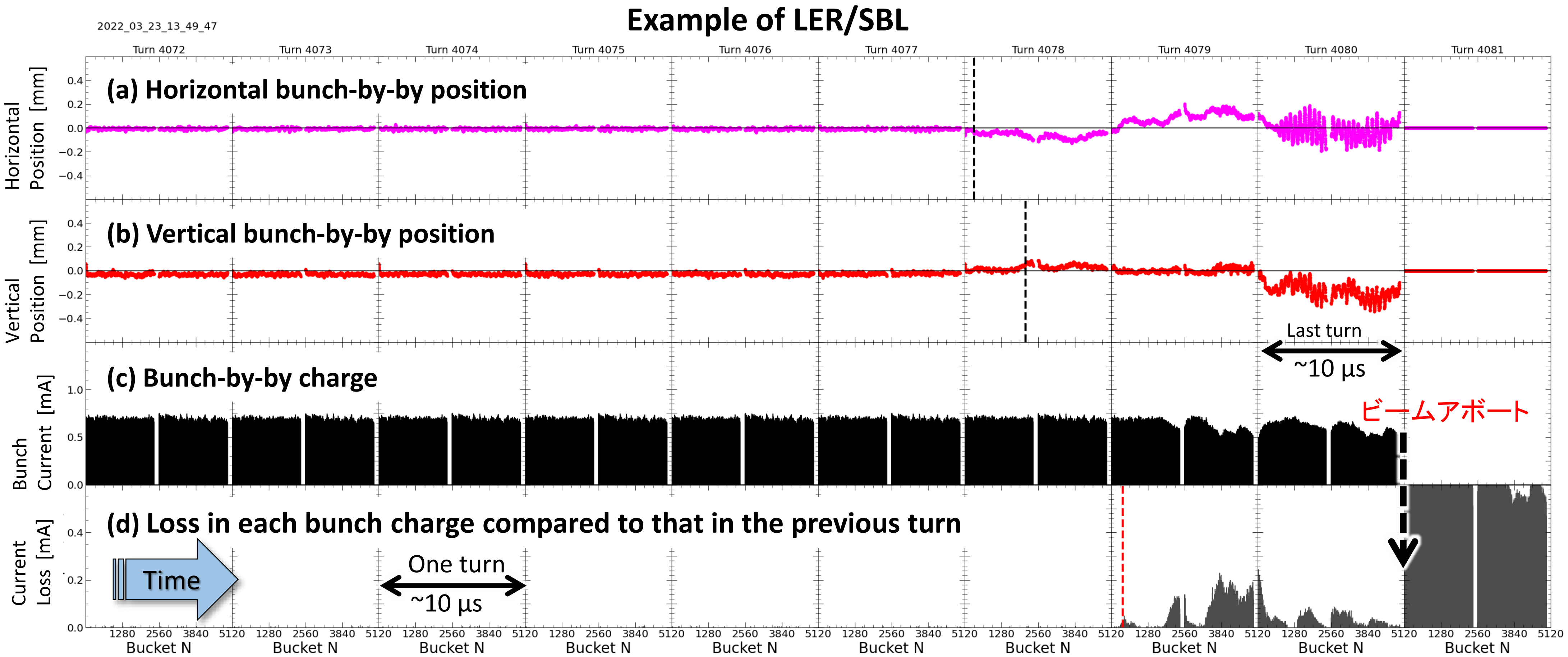
～Asymmetric-energy e^+e^- double-ring collider ～

- Upgraded from KEKB B-factory (KEKB)
- Stored-beam energies
  - High Energy Ring (HER) : 7.0 GeV (e^-)
  - Low Energy Ring (LER) : 4.0 GeV (e^+)
- $E_{\mathrm{cms}} \approx M_{\Upsilon(4S)}$
- Stored-beam currents (design)
  - HER : 2.6 A
  - LER : 3.6 A
- Positron damping ring newly constructed
- Final target luminosity: $6.0{\times}10^{35}\ \mathrm{cm}^{-2}{\cdot}\mathrm{s}^{-1}$
  - Higher beam currents than those at KEKB
  - Squeezing β_y^* with the nano-beam collision scheme
- Goal: 50-fold more integrated luminosity than recorded in KEKB
- **To increase the luminosity in the future, we need to increase the stored beam currents in addition to squeezing $\boldsymbol{\beta_y^*}$**



What's Sudden Beam Loss (SBL)?





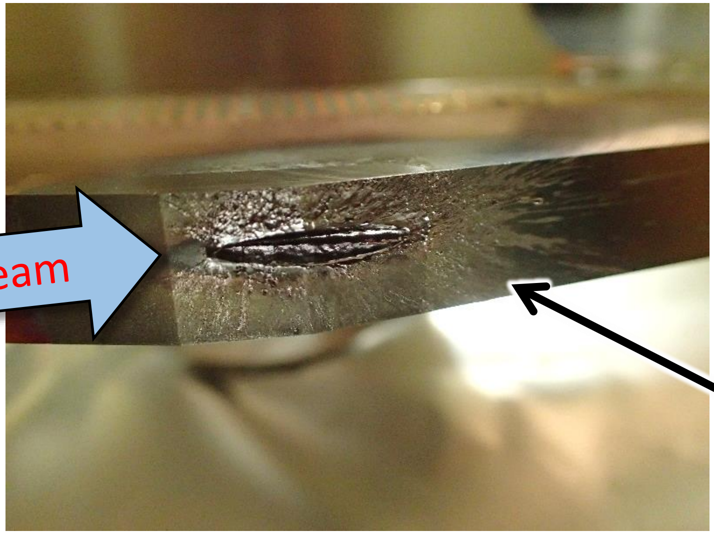
Characteristics

A) Beam bunches are suddenly kicked in the transverse direction, leading to significant beam losses.
B) Fast phenomena of the order of ~10µs
C) No change in the size or energy of the beam bunches
D) Observed not only in LER (e^+) but also in HER (e^-) (The bunch-charge loss patterns different between the two)
E) Not observed before SuperKEKB / Phase 2
F) Largely depends on the bunch current (not total current)

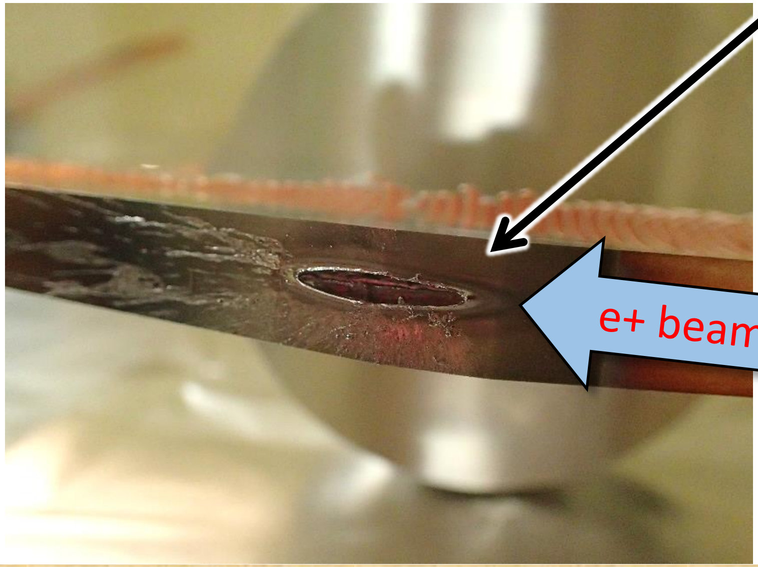
Example of serious hardware damages due to SBL

LER / vertical beam collimator “D02V1” just upstream of the IR

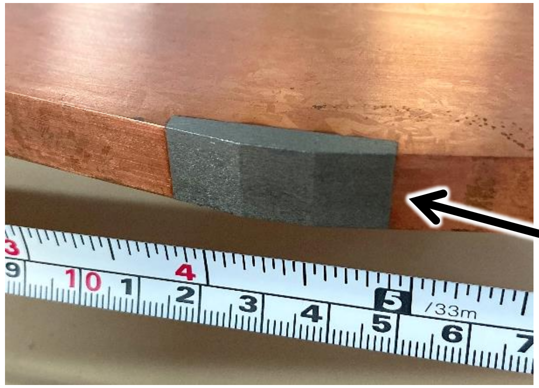
TOP side



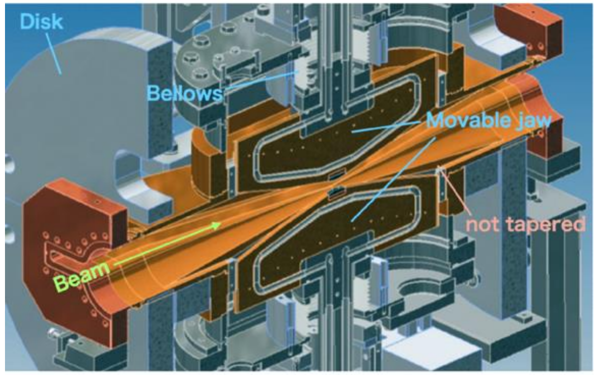
Bottom side



Damaged heads (Ta)

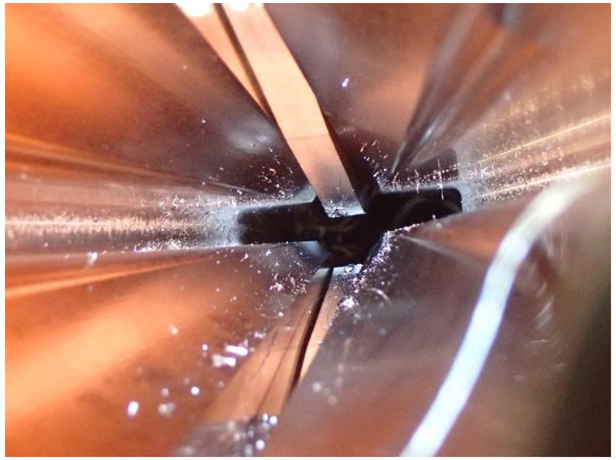


Cf. An undamaged head (W)



Phys. Rev. Accel. Beams 23, 053501 (2020)

A lot of rubble of the Ta heads strewn



(Photos courtesy of Shinji TERUI)

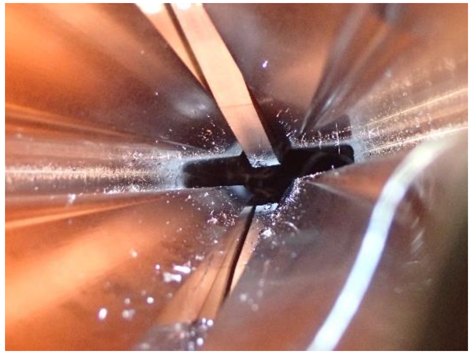
- ✓ **The impedance ↑**
- ✓ **More difficult to suppress beam backgrounds at Belle II**

Essential Condition for FB BD

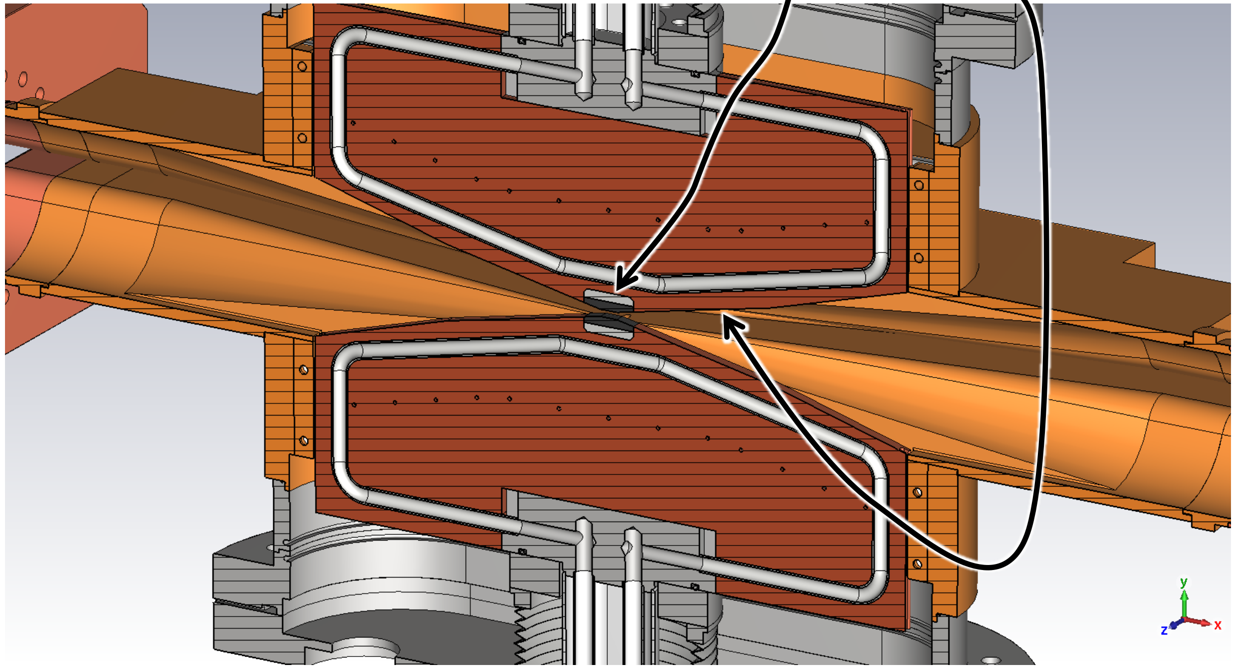
Coexistence of different materials with largely different sublimation/melting points in the same place

- In the case of the beam collimators at SuperKEKB
  - Heads made of W, Ta with a high sublimation point
  - Chambers made of Cu with a low sublimation point

A lot of FB candidates from the damaged collimator heads



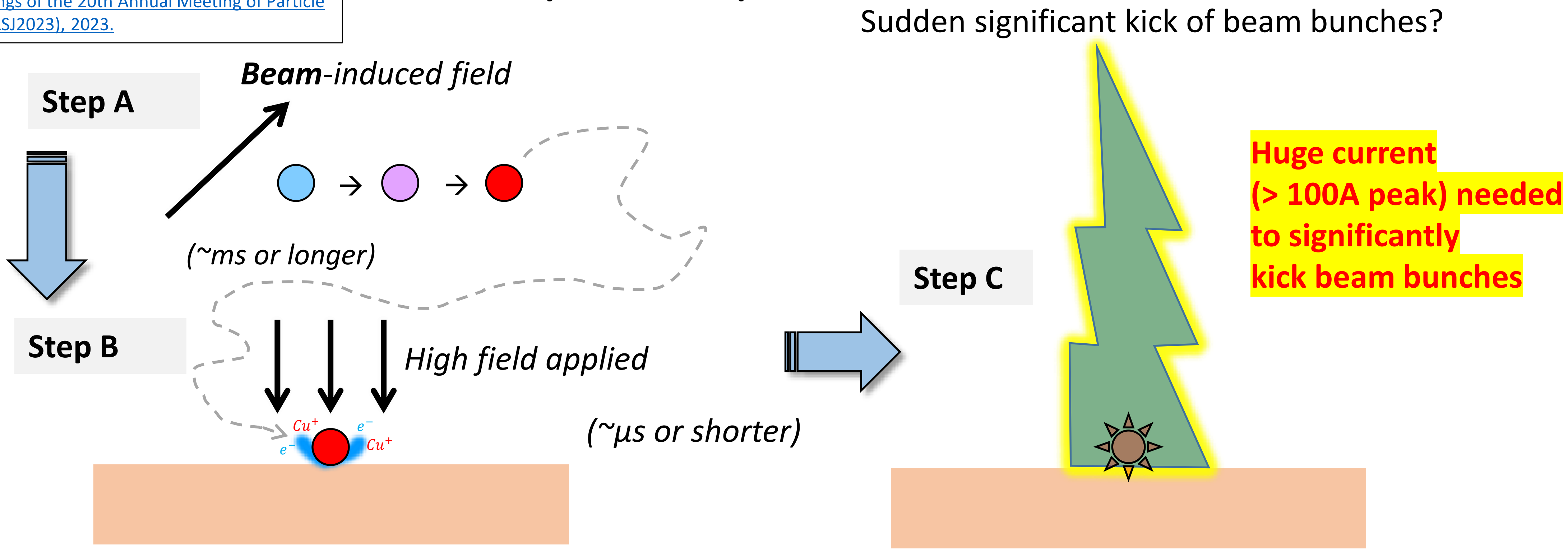
Phenomena similar to FB BD can occur around beam collimators.



SuperKEKB beam collimator

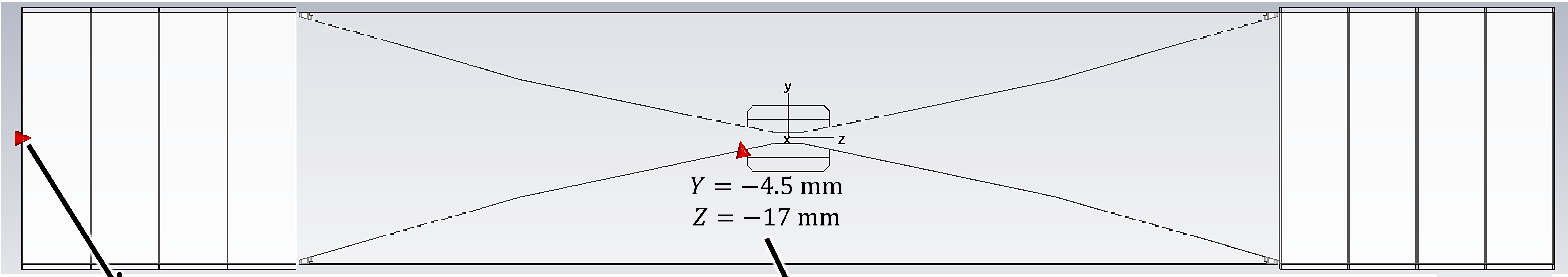
A fireball could cause a sudden beam instability in an accelerator with very small apertures.

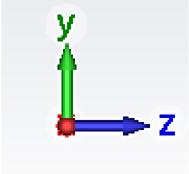
T. Abe, "Fireball Hypothesis for the Trigger of Sudden Beam Losses at SuperKEKB", TUP01 in Proceedings of the 20th Annual Meeting of Particle Accelerator Society of Japan (PASJ2023), 2023.



Aperture: $\pm$1mm at min. at SuperKEKB

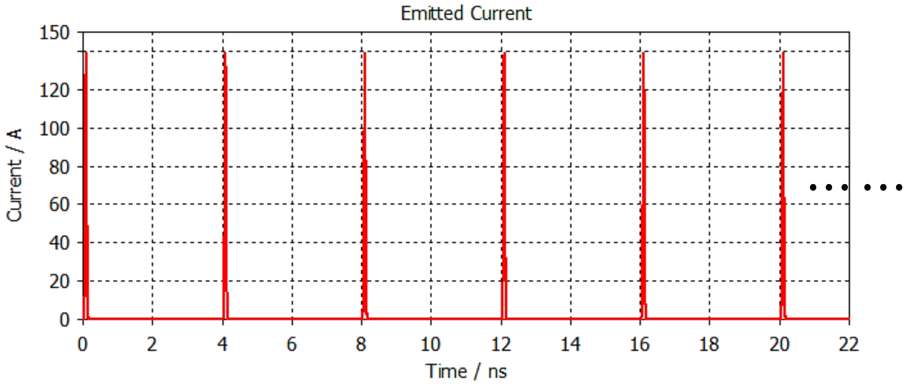
CST PIC Simulation / Particle Sources





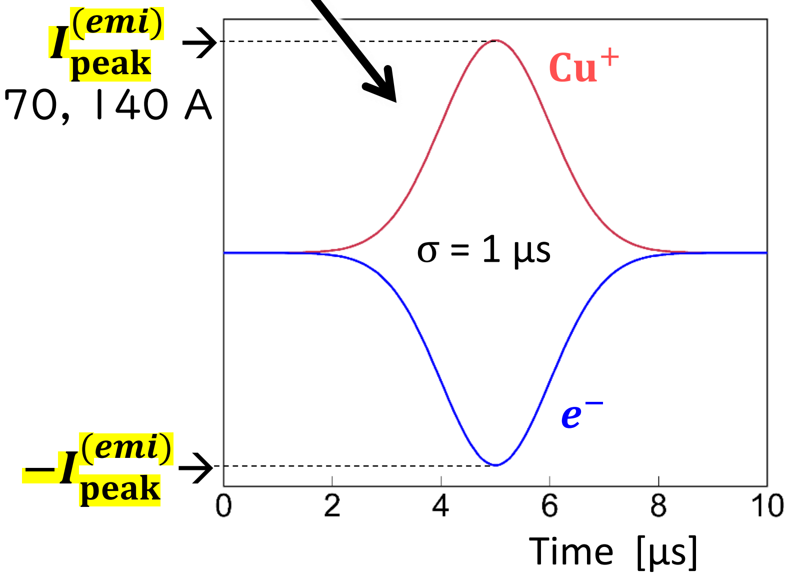
e^{+} bunches

- 4 GeV
- 7 nC/bunch
- 6 mm length in z with no transverse size
- 4ns spacing



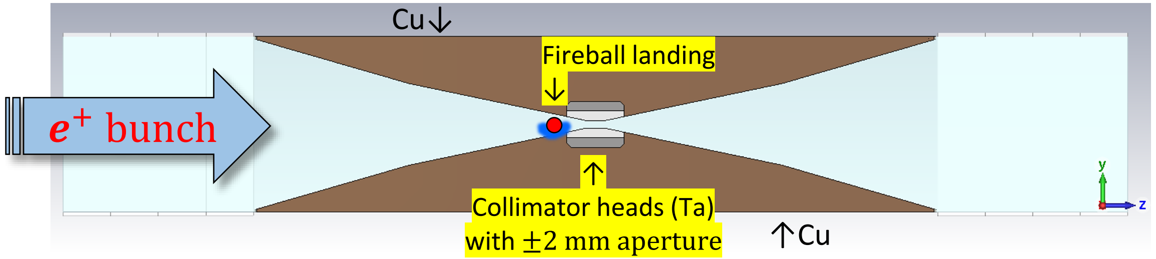
Simulating plasma generation

$= 35, 70, 140$ A
など



Initial velocities of emitted particles are determined from the initial temperature ($T_{\mathrm{ini}}^{(emi)}$) of the plasma according to Maxwellian distribution

Results of the CST PIC Simulation

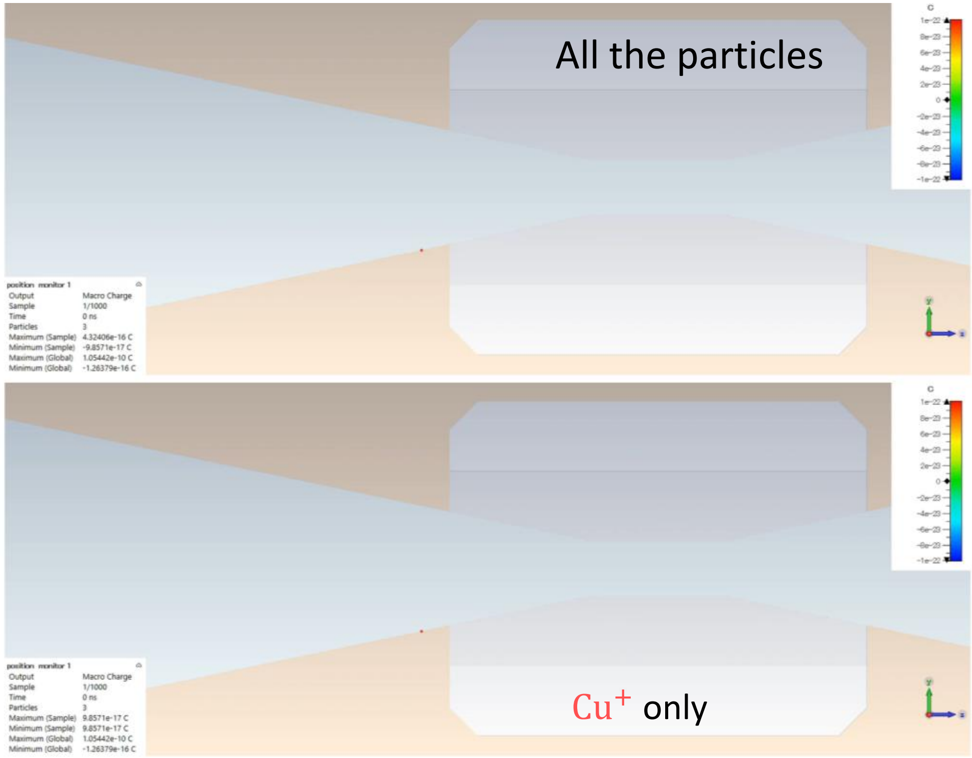


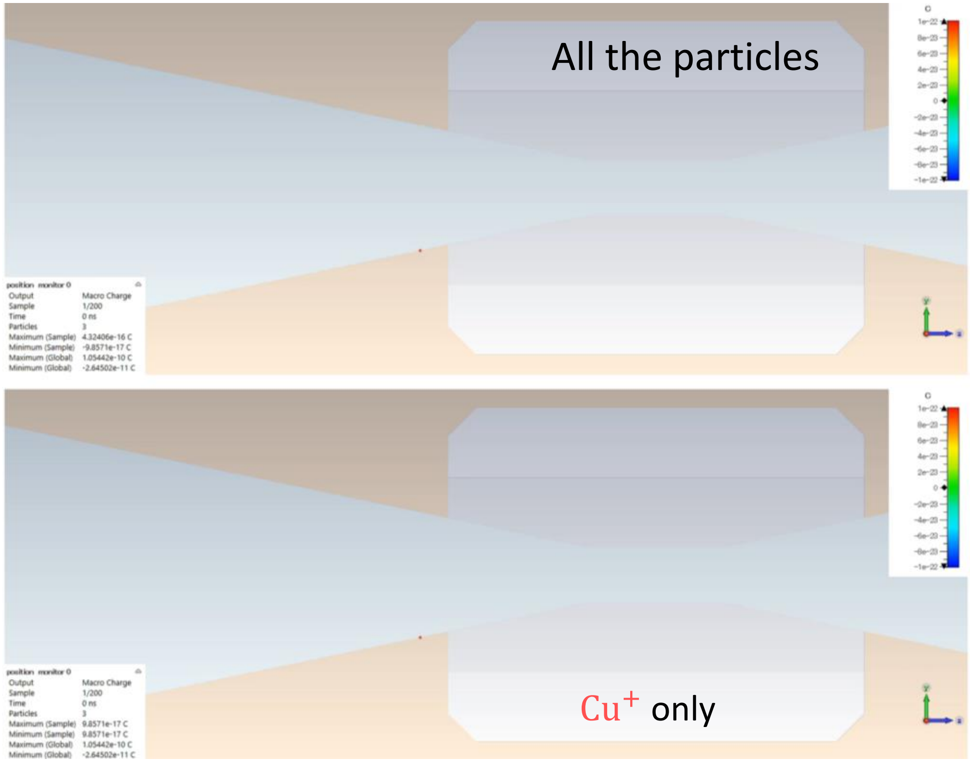
Full simulation of the dynamics of the LER e^+
and emitted e^- , Cu^+
and interactions among them

$+$ positive charge
$-$ negative charge

(Short time range)

t = 0–50 ns





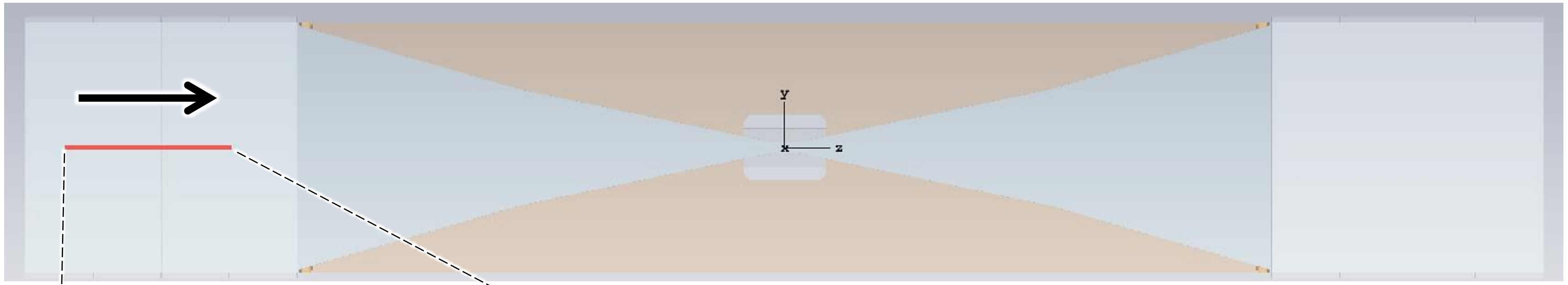
(long time range)

t = 0–10 μs

https://youtu.be/Ow0IX8bEB9g

https://youtu.be/5pHMwFmjSyo

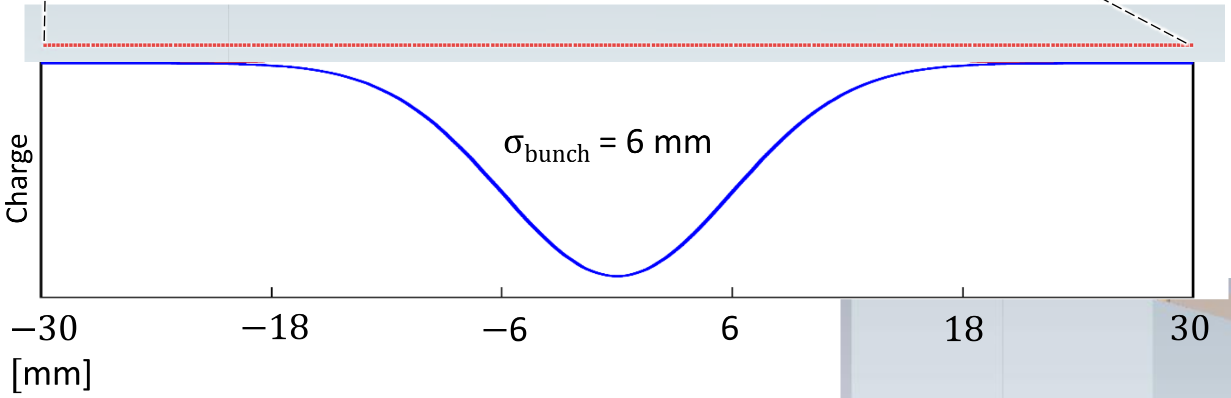
Calculation formula of the transverse kick



Initial state

$$p_y^{(i)} = 0$$

(i: macro-particle, $1, 2, \cdots, \mathbf{265}$)



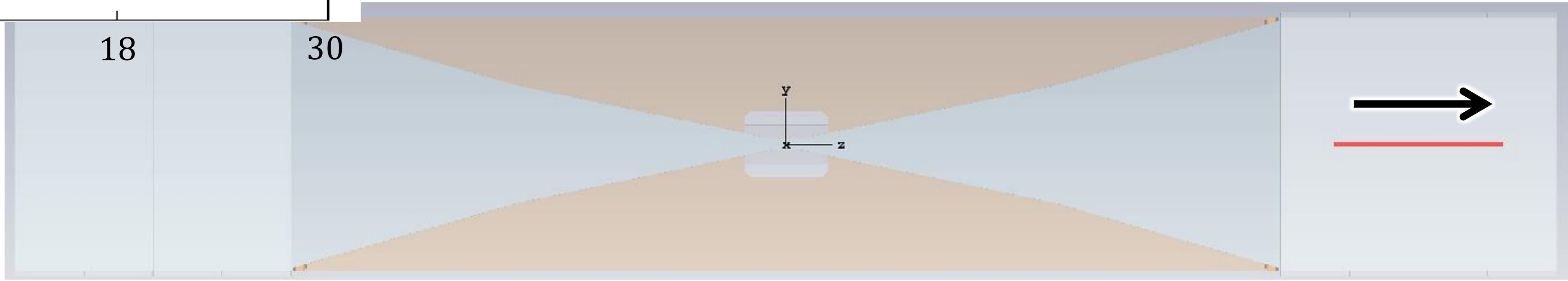
Final state

$$\boxed{k_y = P_y / P_z}$$

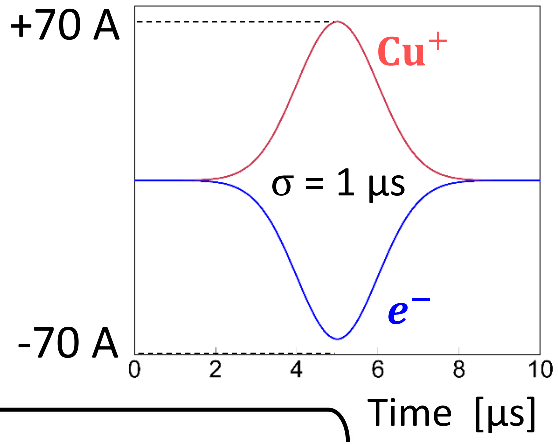
$$P_y = \frac{1}{Q_b} \sum_{i=1}^{N_{\text{mp}}} p_y^{(i)} q^{(i)}$$

$$\Delta P_y = \sqrt{\frac{1}{Q_b} \sum_{i=1}^{N_{\text{mp}}} \left(p_y^{(i)} - P_y\right)^2 q^{(i)}}$$

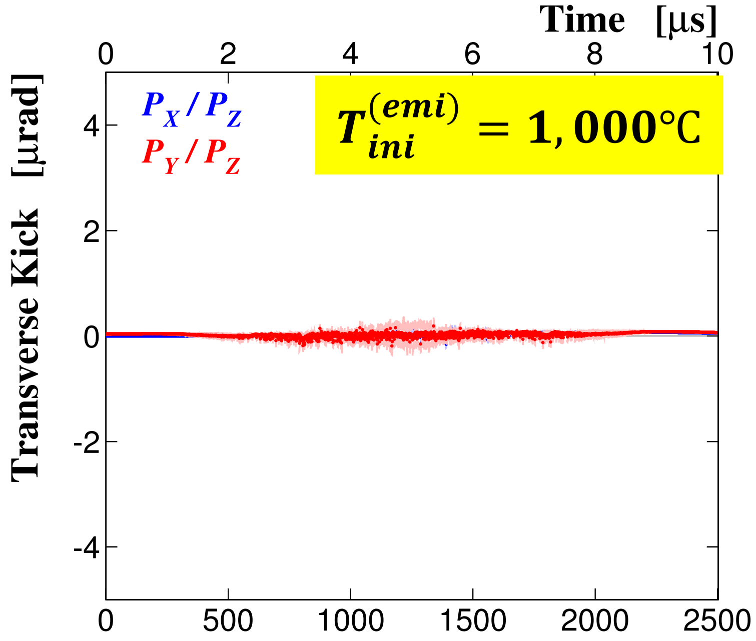
$p_y^{(i)}$: Y-momentum of particles in the i-th macro-particle
$q^{(i)}$: Charge of the i-th macro-particle
Q_b: Bunch charge

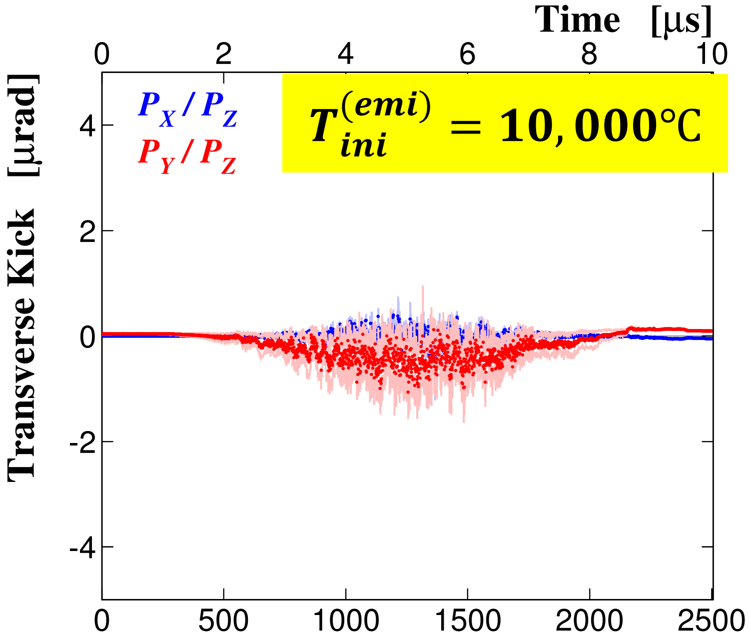


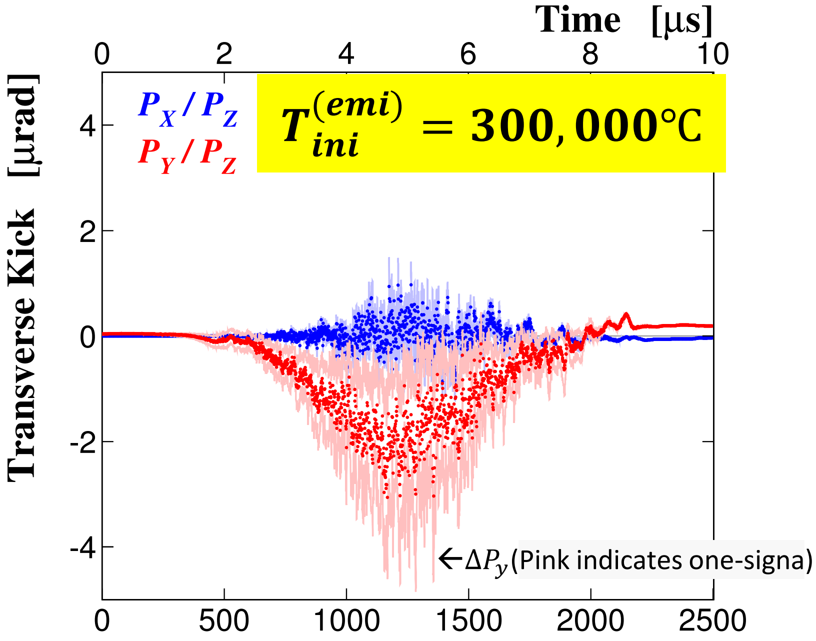
Transverse kick angles for $I_{peak}^{(emi)} = 70\ A$



$I_{peak}^{(emi)} = 70\ A$





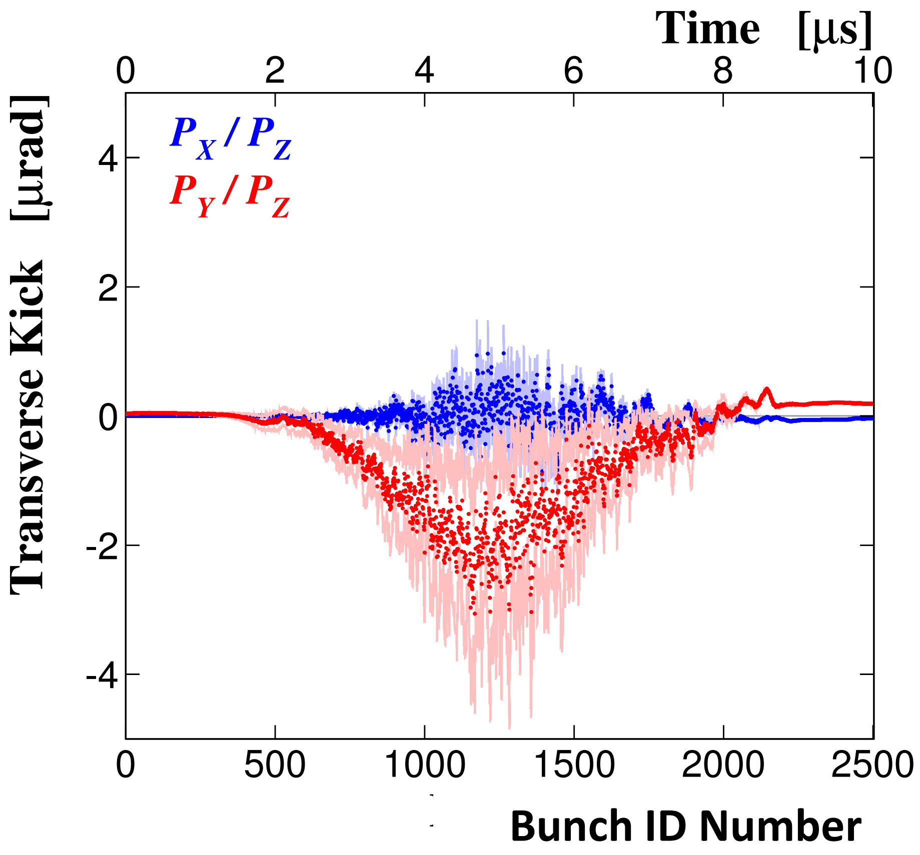


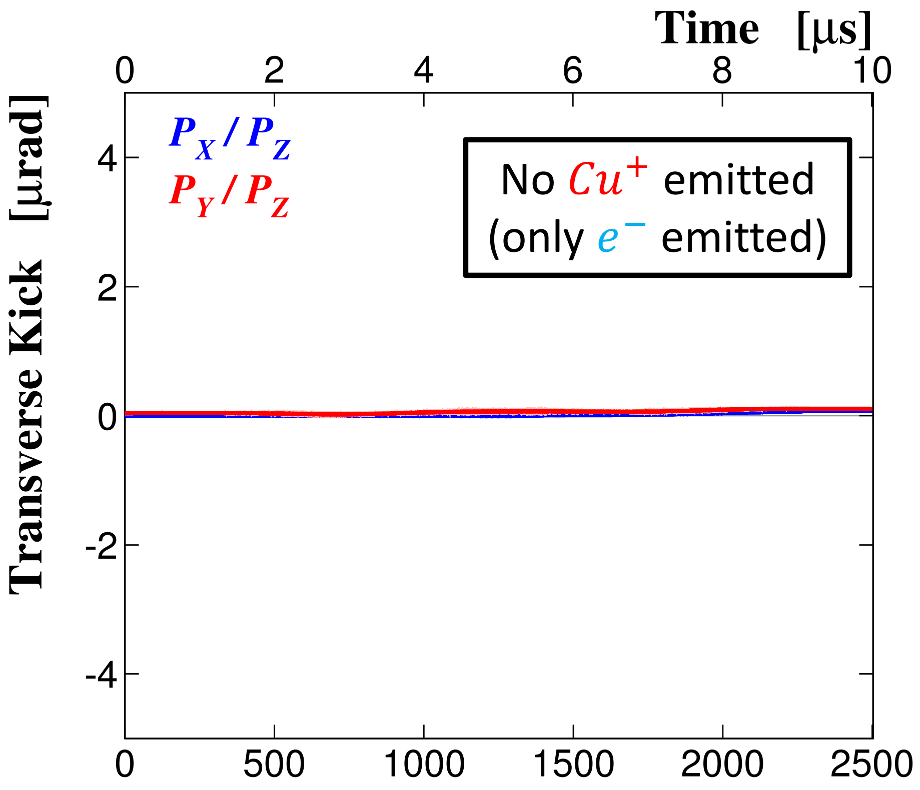
LER e^+ attracted by e^- emited from the FB landing point

(Kick angle does not increase with any further increase in initial temperature.)

Comparison between w/ and w/o Cu^+

$$I_{peak}^{(emi)} = 70\ A$$
$$T_{ini}^{(emi)} = 300,000℃$$



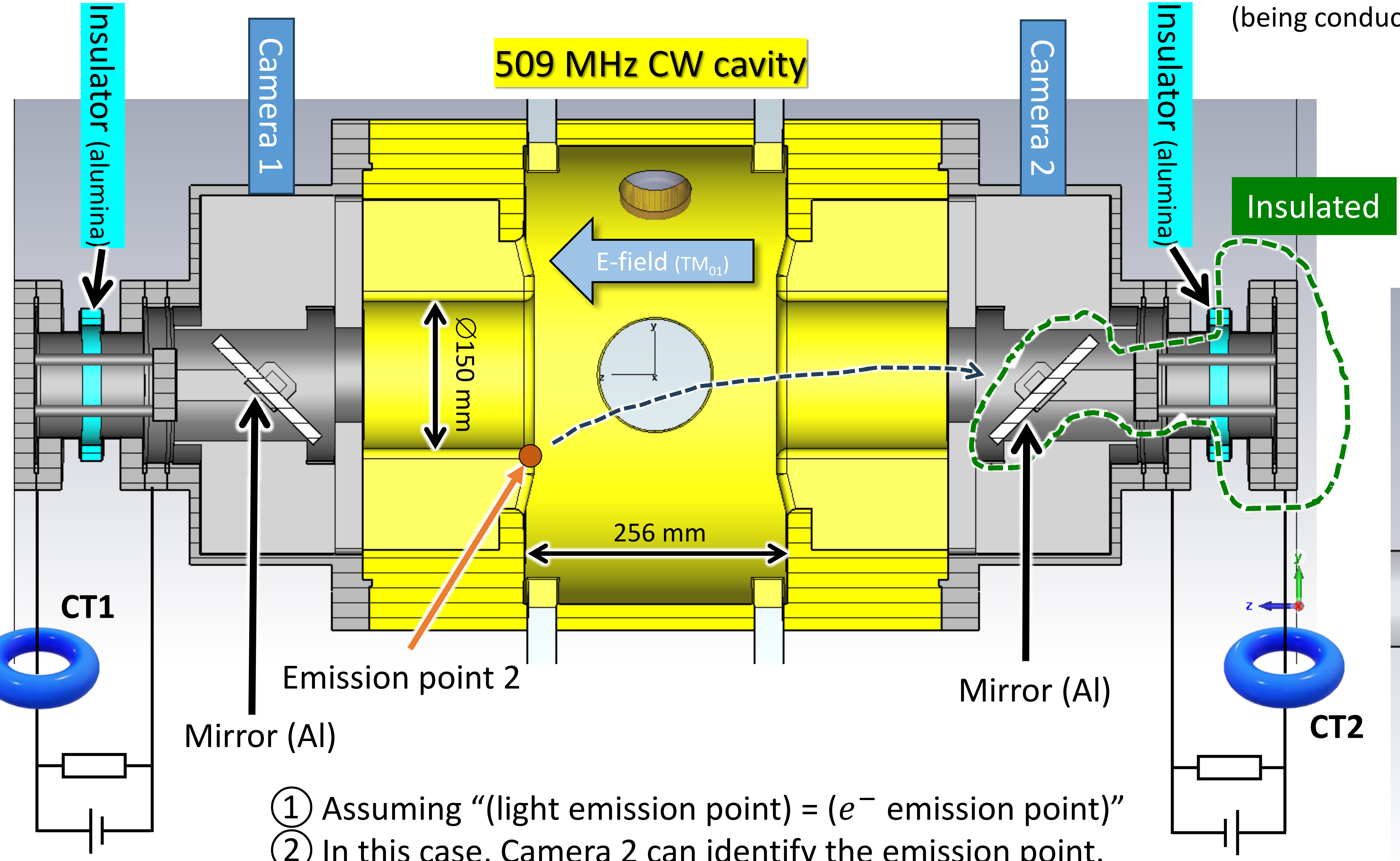


$\mathbf{Cu^+}$ pushes up the space charge limit of emitted $\boldsymbol{e^-}$

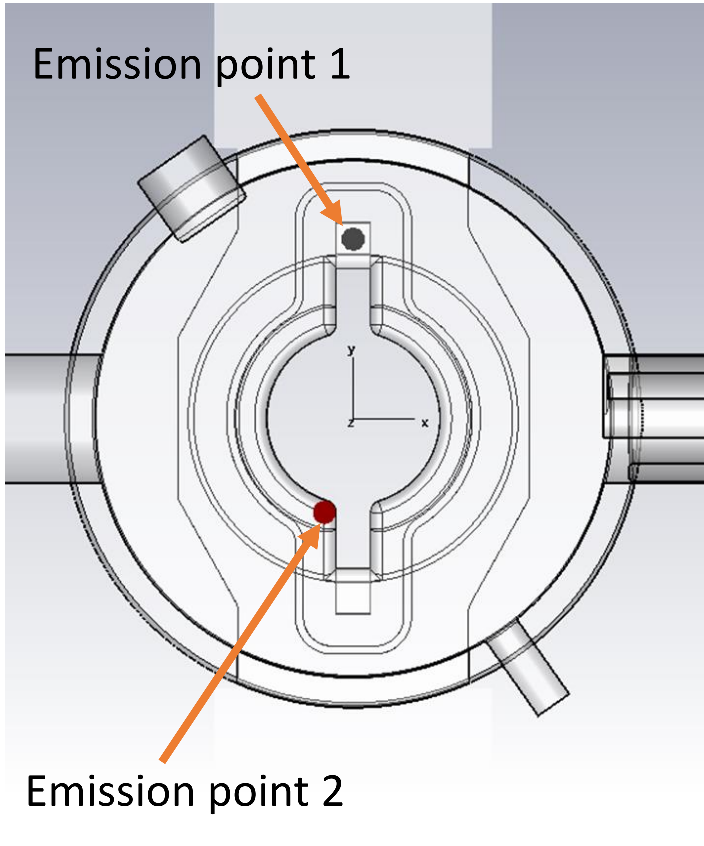
Relevant Experiment and Observation

Measurement of total breakdown current

(being conducted by Takaaki YAMAGUCHI (KEK))



Suggests huge currents (peak)
(> 100A!?)
See Takaaki YAMAGUCHI's poster presentation!

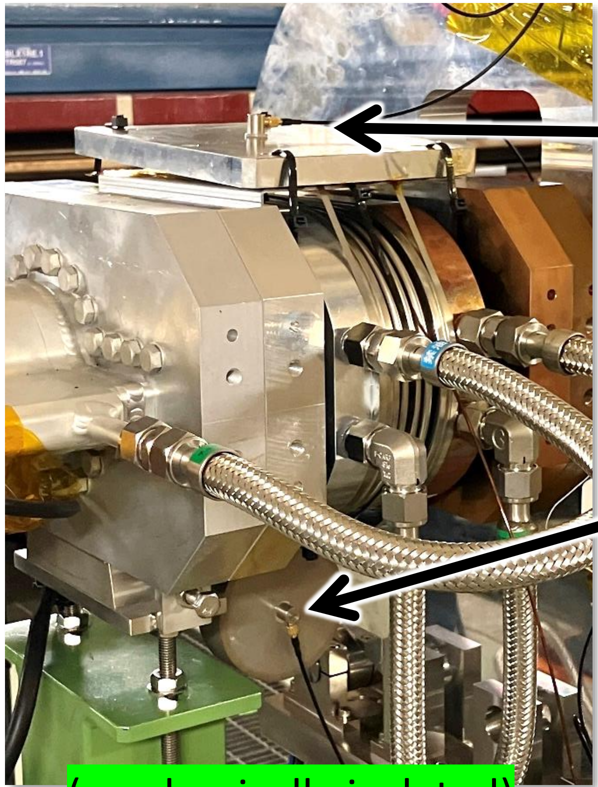


① Assuming "(light emission point) = (e^- emission point)"
② In this case, Camera 2 can identify the emission point.
③ Percentage of e^- reaching the mirror to be estimated with PIC sim.

Acoustic observation to verify the fireball hypothesis for SBL at SuperKEKB beam collimators

Iori OKADA (Nara Women's University) attached all the sensors in collaboration with K. Uno and T. Abe.

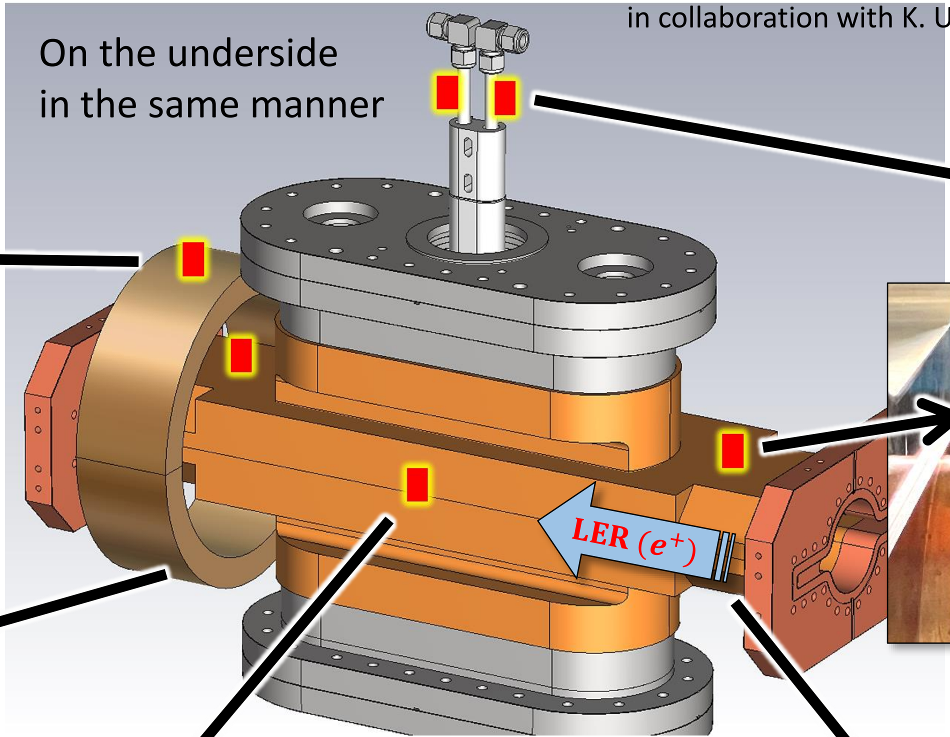
Acoustic loss monitor

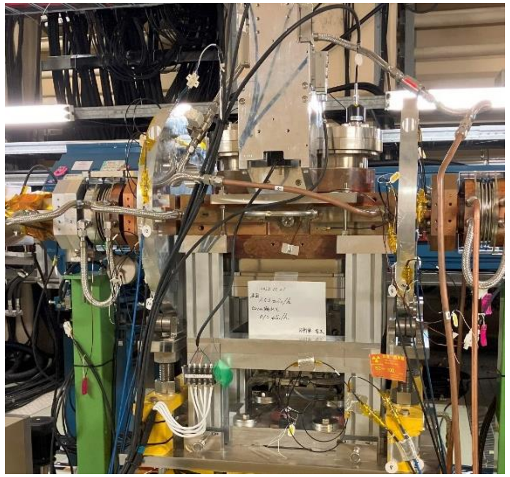


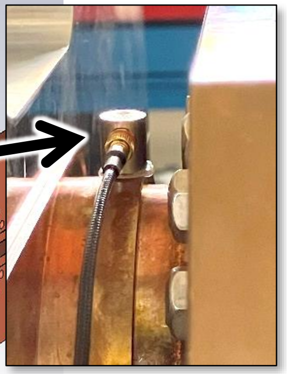
(mechanically isolated)

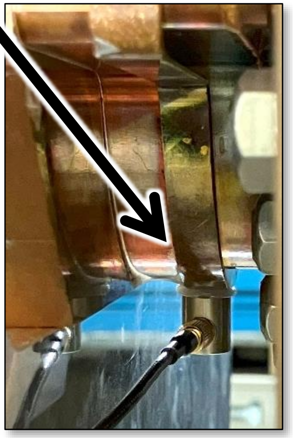
Can hear particle showers

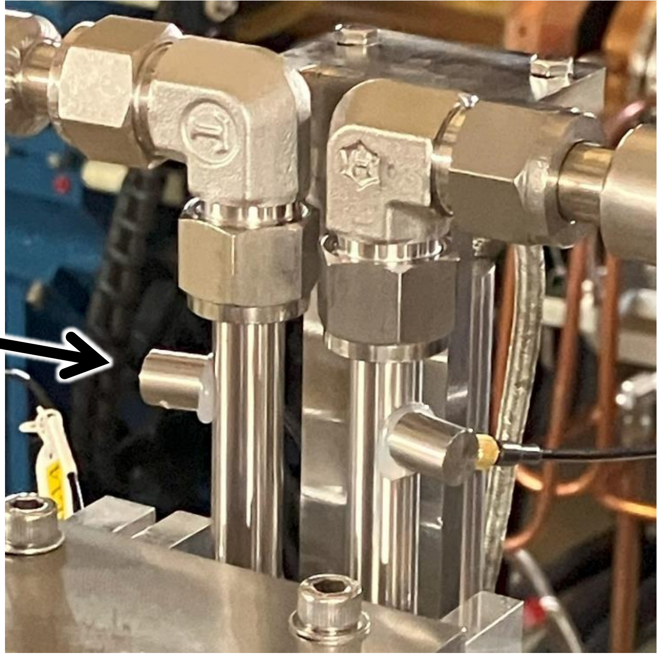
On the underside in the same manner



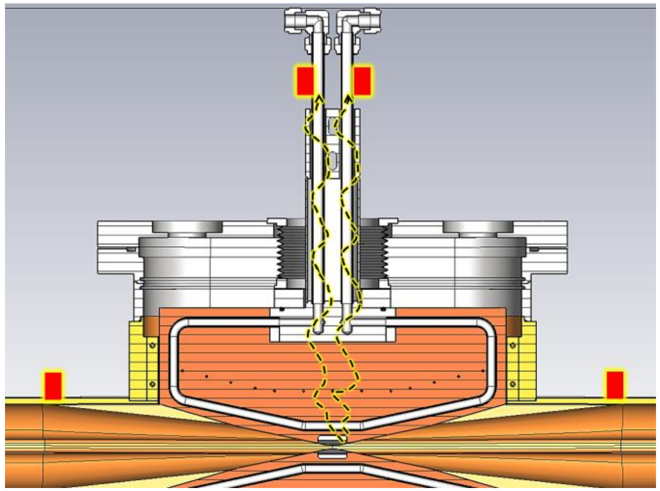






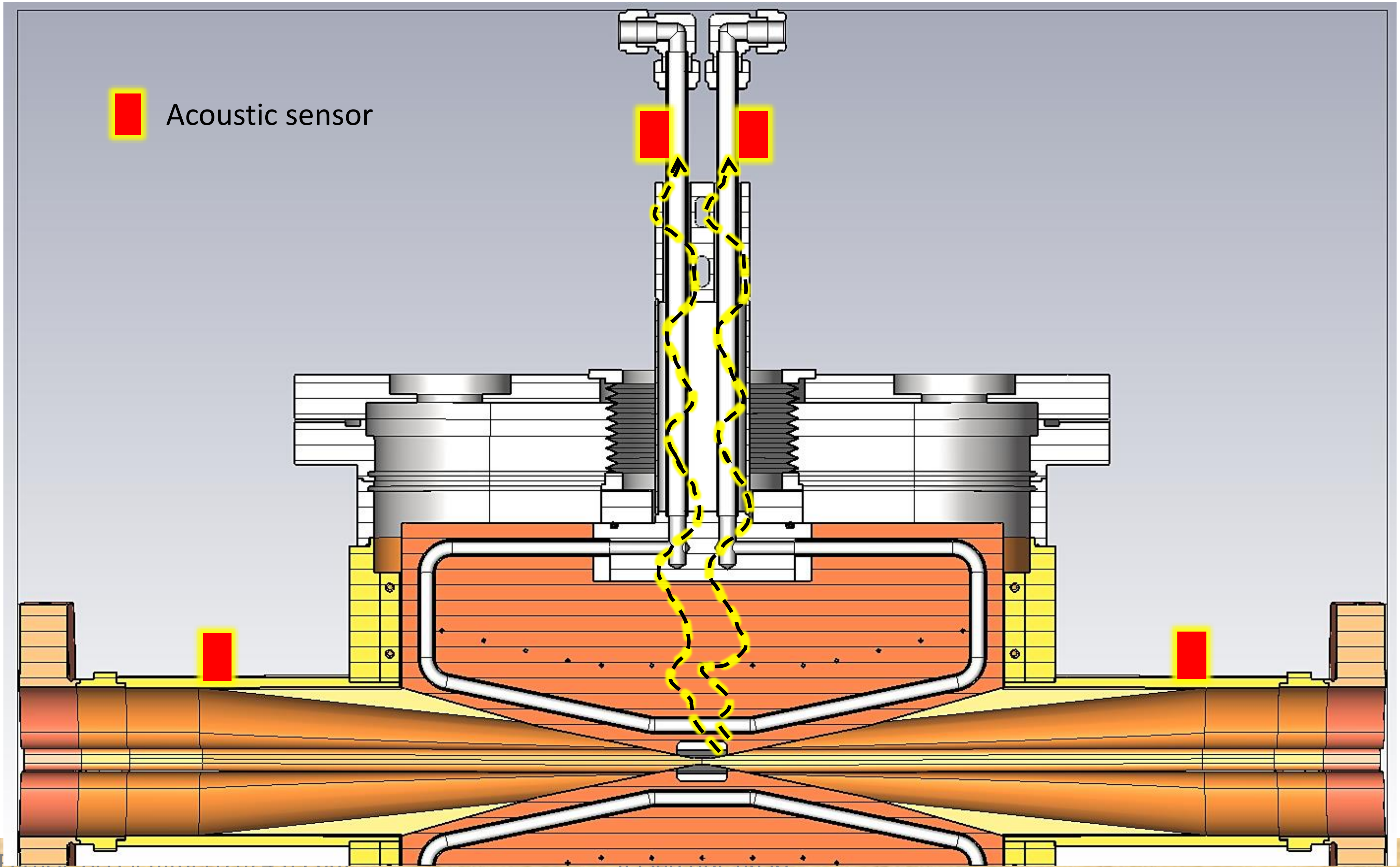


Can hear AE around the head.



In the same manner for D05V1 collimator (NCL)

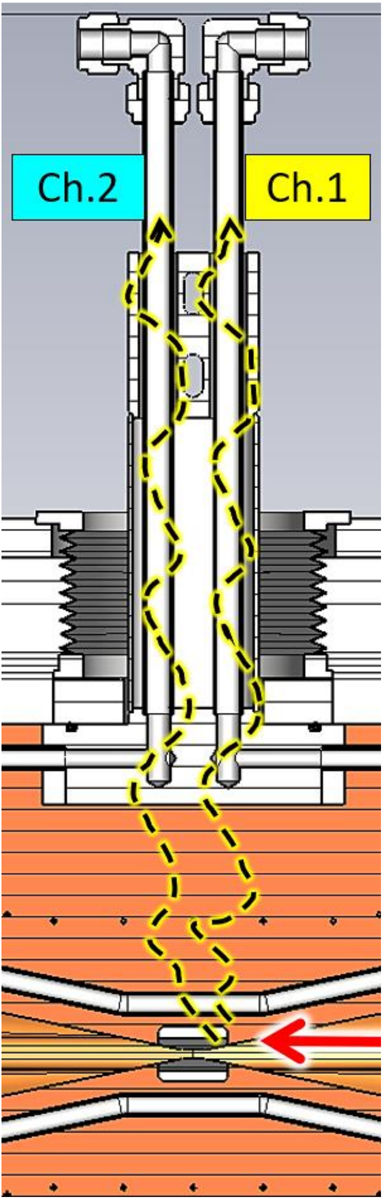
We can hear acoustic waves from the collimator head.

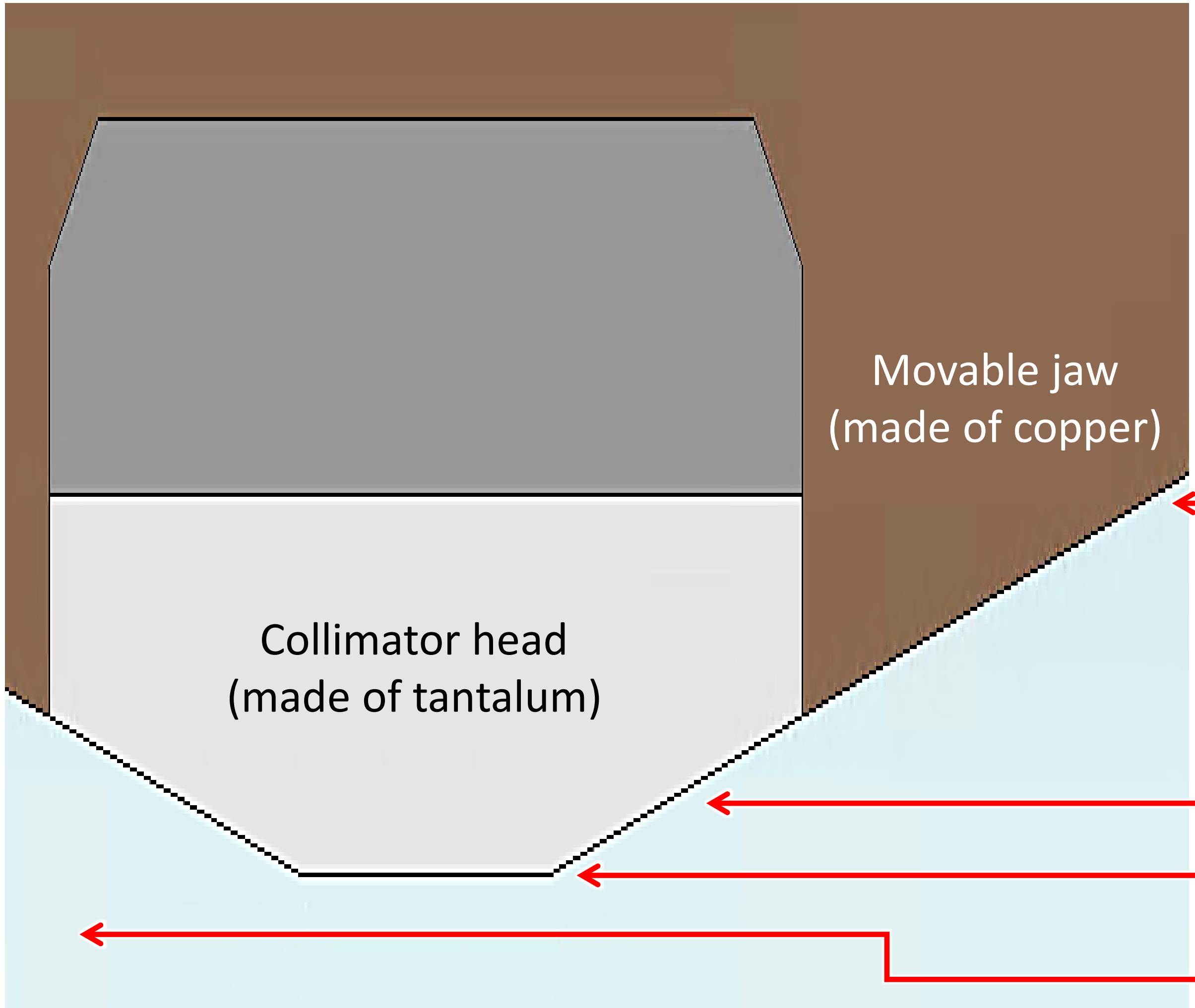


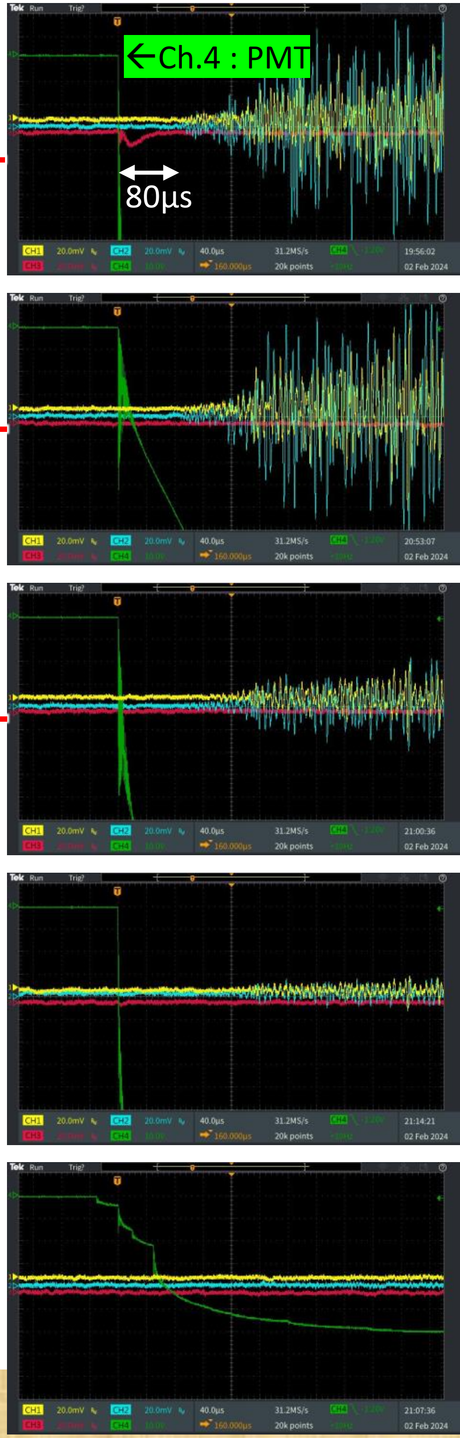
Machine study with single-bunch shots (4GeV, 0.5nC)

T. Abe, S. Ogasawara, H. Koiso, H. Ikeda, S. Terui, T. Ishibashi, N. Iida, Y. Ohnishi (SuperKEKB)
I. Okada, K. Uno, T. Koga, K. Miyabayashi (Belle II)

(The beam impact points indicated by the red arrows below are rough guesses.)







➔The bunch was Stored.

➔ *Precise timing reconstruction for acoustic wave generation*

Summary

- Fireballs, > 1,000degC electrically-charged micro-particles, have been observed in UHF CW cavities.
  - Adhering to 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 of RF breakdowns in UHF CW cavities.
  - Except for early stage of high-power RF conditioning
- Fireball hypothesis is proposed to explain the possible trigger of the sudden beam losses at SuperKEKB accelerator.
  - The cause might be the same mechanism as that of the fireball-triggered breakdown in RF cavities.
  - Relevant simulation, experiment, and observation on-going

Thank you for your attention

For more details on:

■ The fireball hypothesis

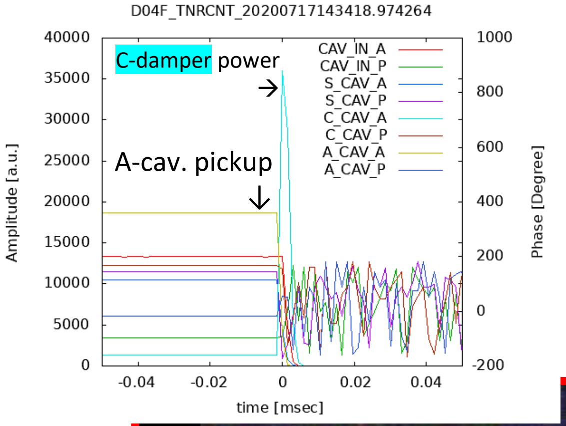
- T. Abe, "*Fireball Hypothesis for the Trigger of Sudden Beam Losses at SuperKEKB*", in Proceedings of the 20th Annual Meeting of Particle Accelerator Society of Japan, PASJ2023-TUP01 (2023).

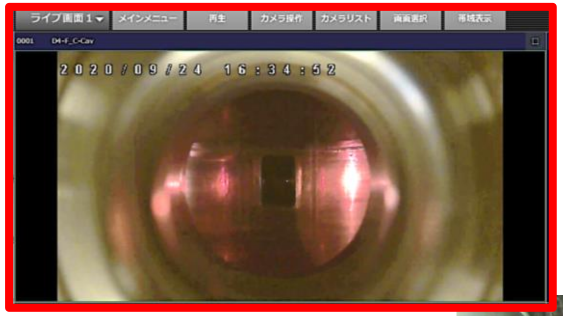
■ Fireball breakdown of RF cavities

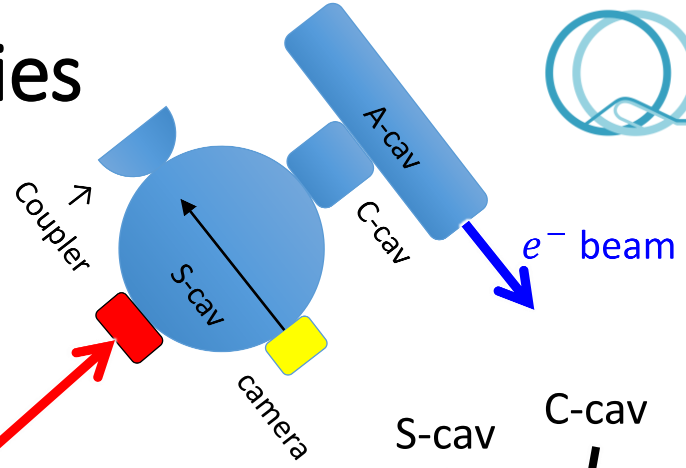
- **KEK Accl. Lab. Topics (web article)**
  - ➢ "*Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities*"
    - – https://www2.kek.jp/accl/eng/topics/topics190122.html
- **Presentations at Workshops**
  - ➢ T. Abe, "*Direct Observation of Breakdown Phenomena in Normal-Conducting 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.

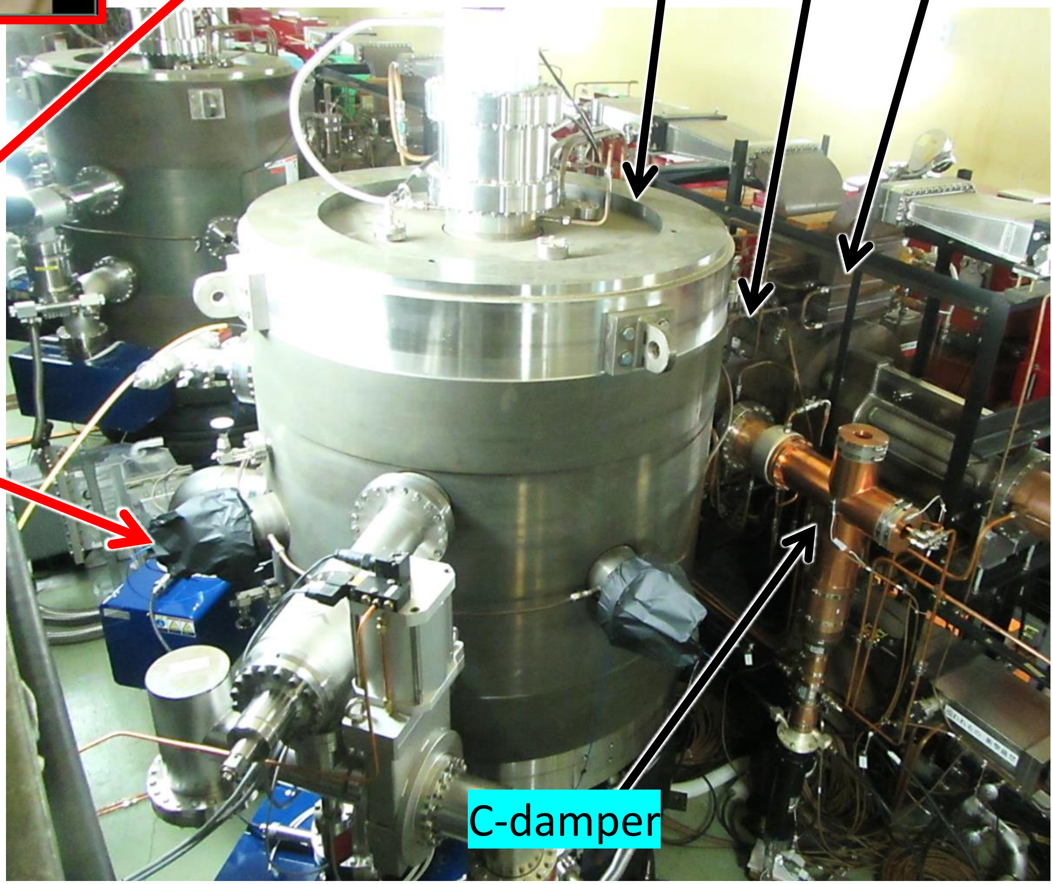
Backup slides

Example of Fireballs observed in the ARES Cavities



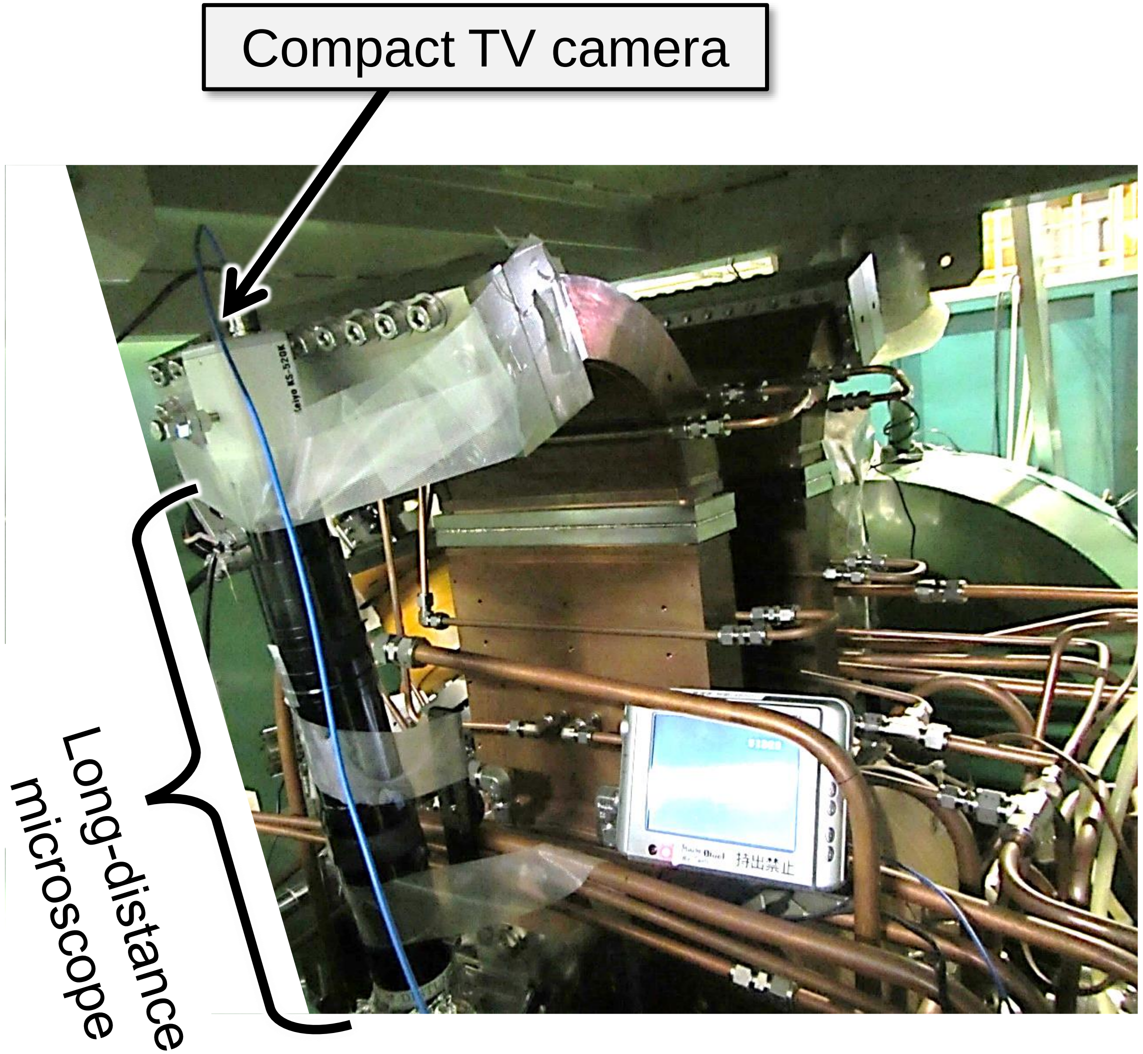






Video file: https://youtu.be/qtIB6kLf2j4

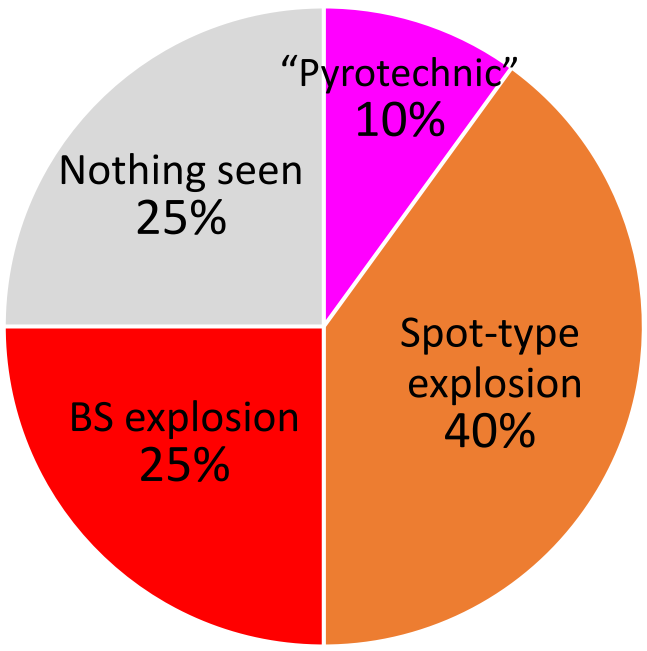
Observation of the FB size



$\lesssim$ ~0.1mm

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).

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.

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

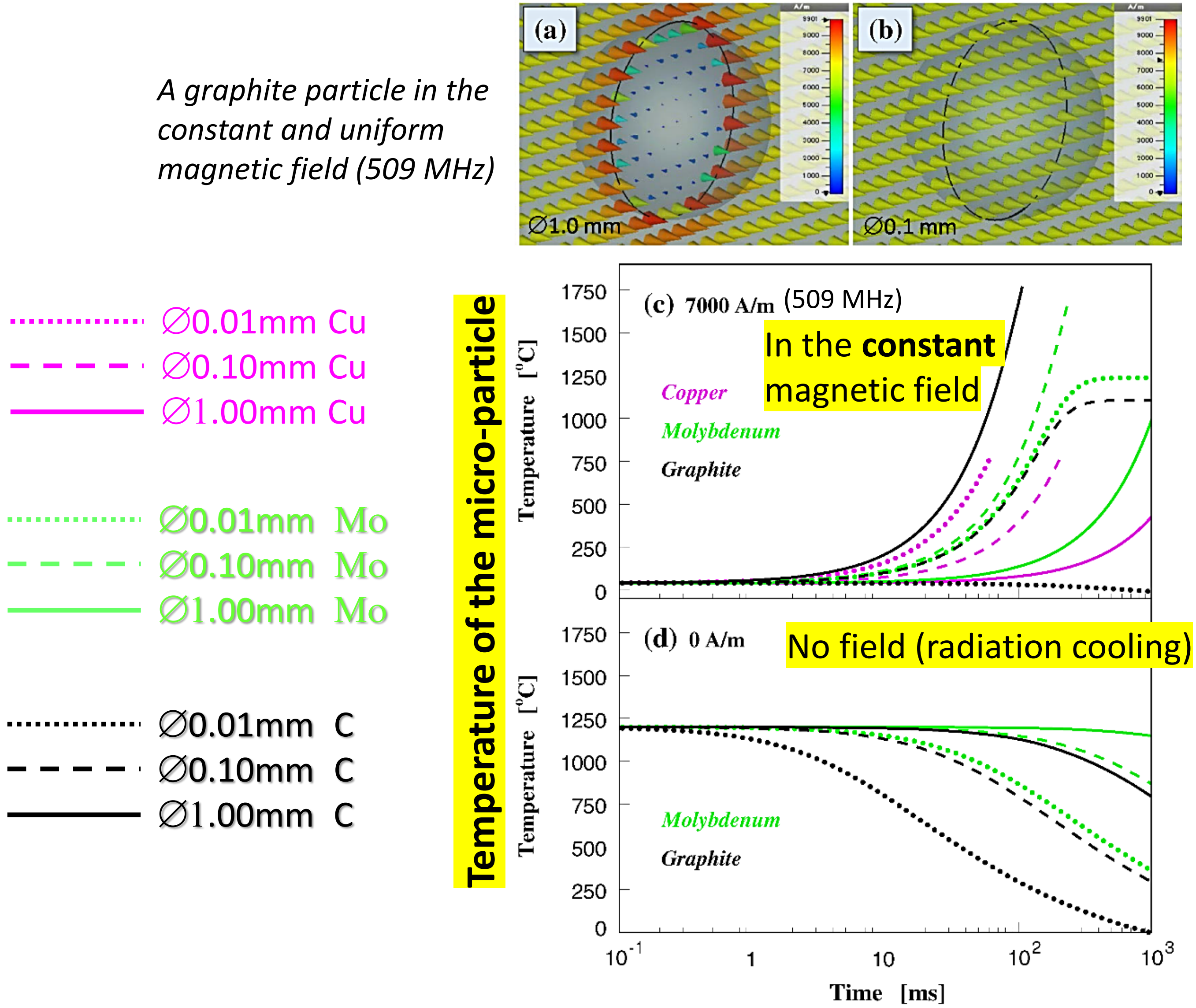
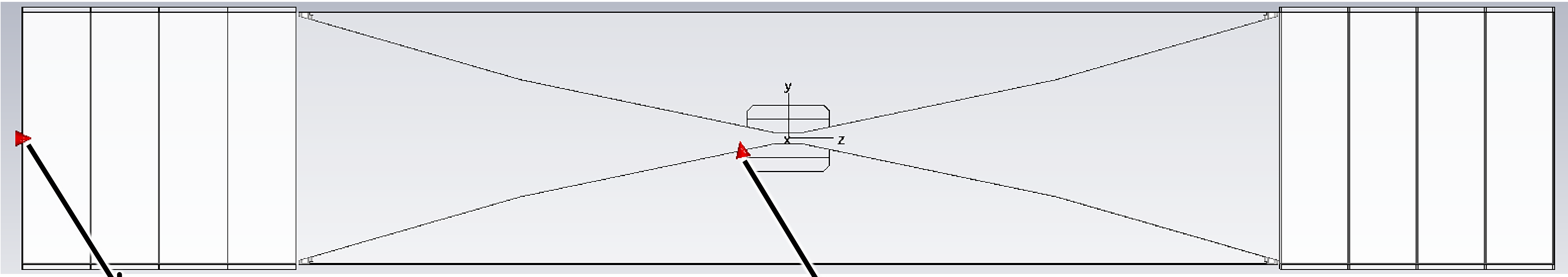


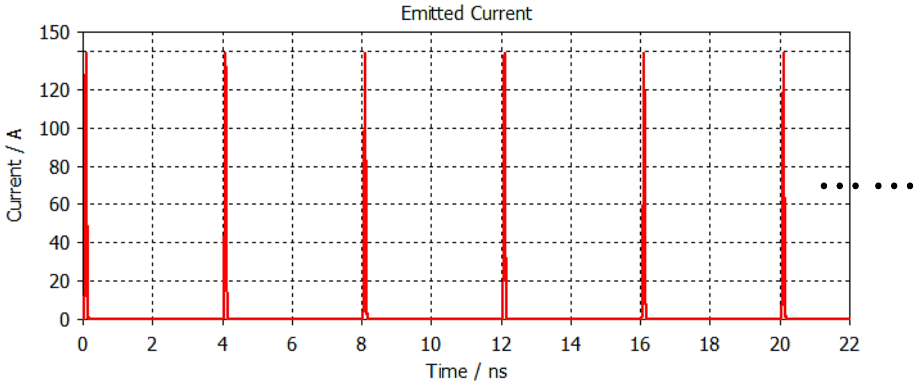
FIG. 22. Simulations of temperatures of spherical microparticles made of graphite (black lines), molybdenum (green lines), and copper (magenta lines) with diameters of 1.0 mm (solid lines), 0.1 mm (dashed lines), and 0.01 mm (dotted lines) located in a vacuum. Radiation cooling was calculated according 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.

CST PIC simulation / particle sources

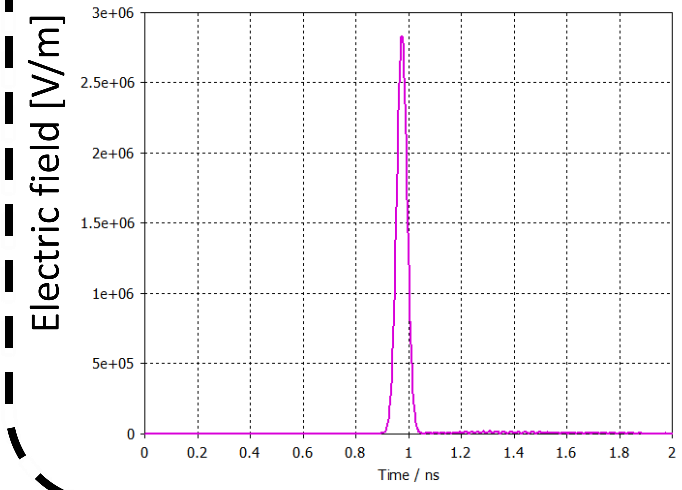


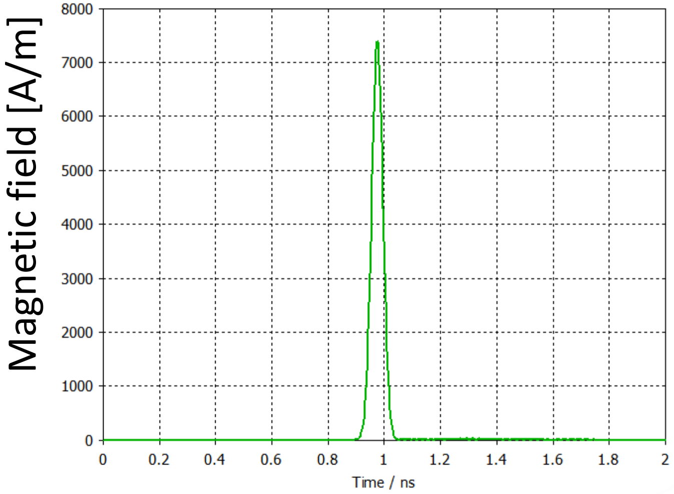
e^+ bunches

- 4 GeV
- 7 nC/bunch
- 6 mm length in z with no transverse size
- 4ns spacing

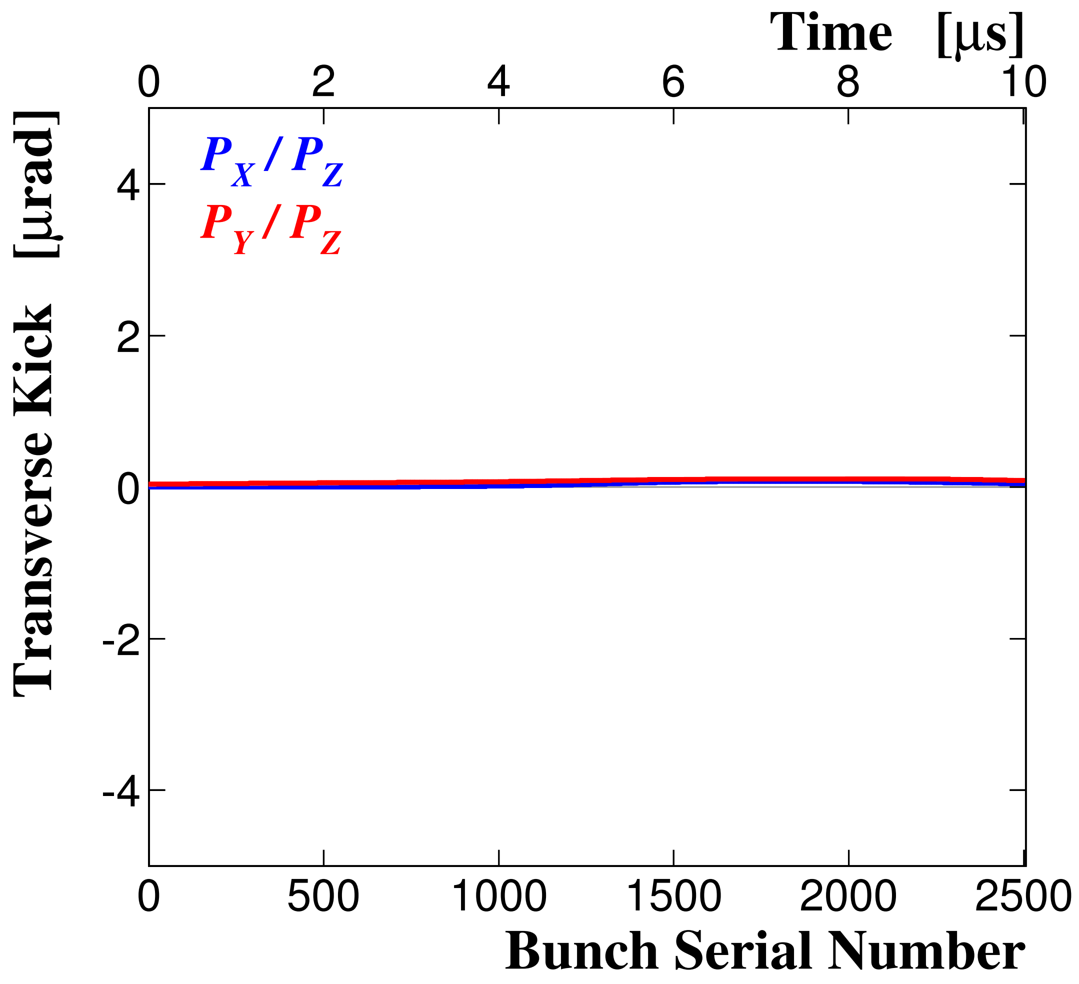


The peak field strength at the FB landing point is comparable with that in the RF cavity.





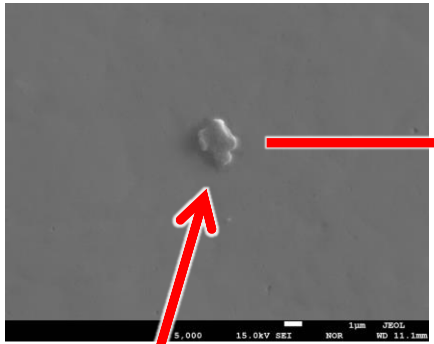
In the special case of no particle emission from the FB landing point (i.e., $I_{\text{peak}}^{(emi)} = 0$)



Numerical noise level in the PIC simulation: ≲ 0.1μrad

An Example of Carbonic Microparticles on Copper Surface

Size of this microparticle： 1 μm

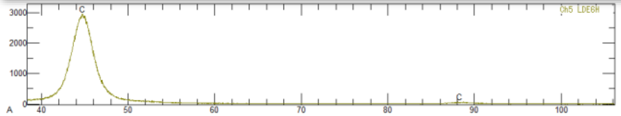


Surface inspection by EPMA (Electron Probe Micro Analyzer)
after ultrasonic cleaning in isopropyl alcohol.

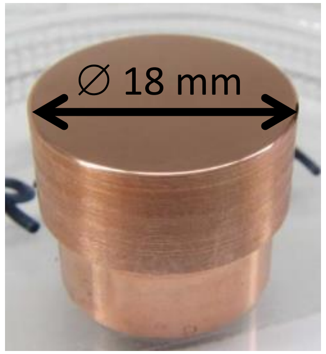
ZAF Metal

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

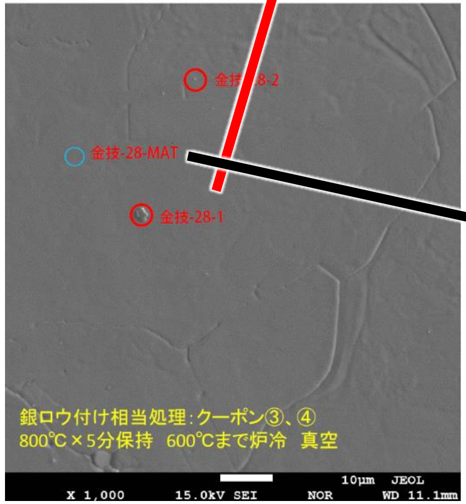
Norm.F = 0.844



Copper Coupon

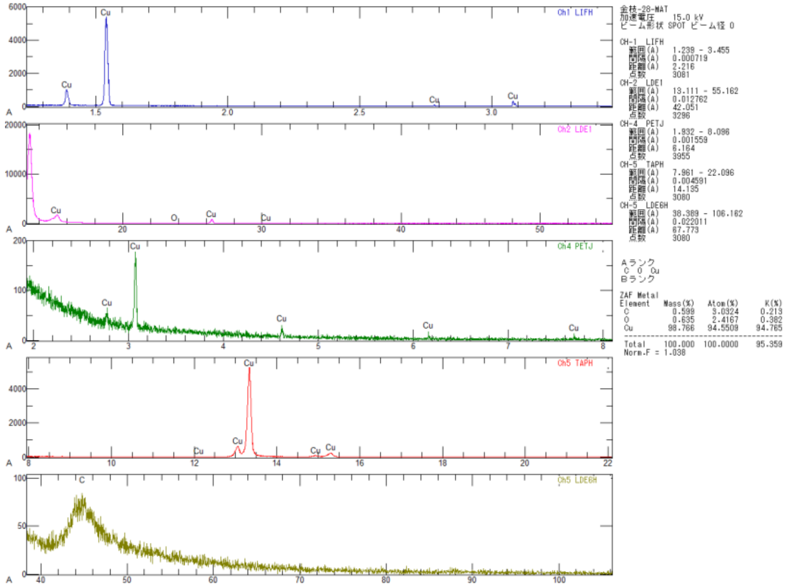


- ✓ Material： Oxygen Free Copper (Class1)
- ✓ The top surface has Ra=0.03μm.



Base

Inspection conducted by T. Higo (KEK)



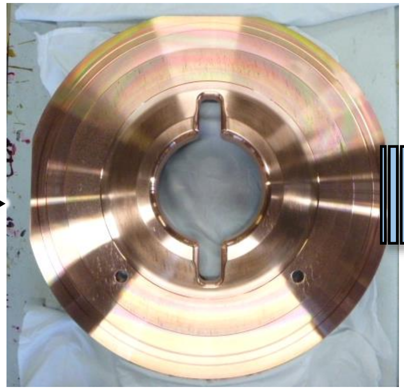
Although carbon cannot be melt in copper,
It can adhere to copper surface.

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 >

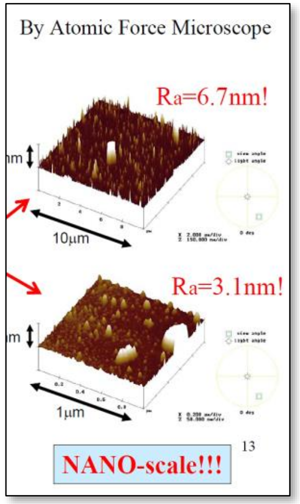


R_a = ~1.5 µm
R_y = ~8 µm

< After EP >

R_a < ~0.2 µm
R_y < ~1 µm

PAC'05, TPPT007→

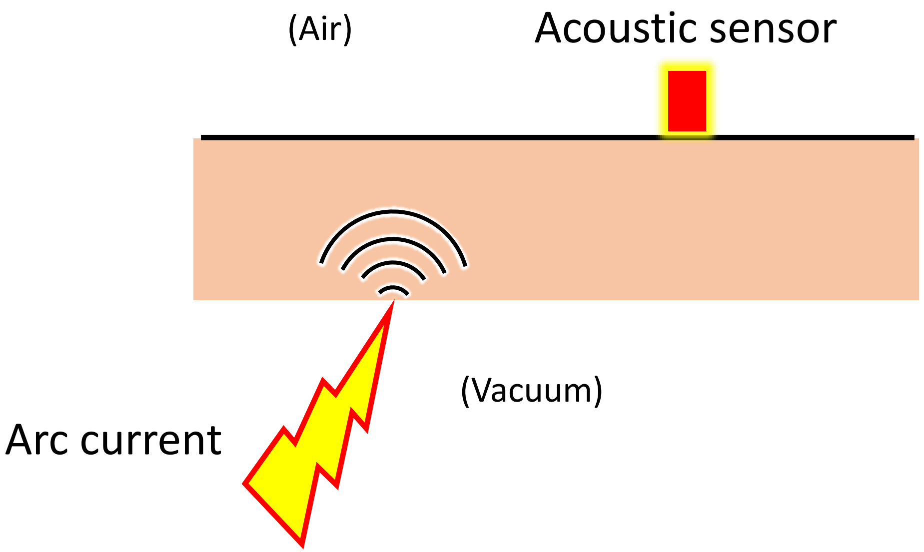


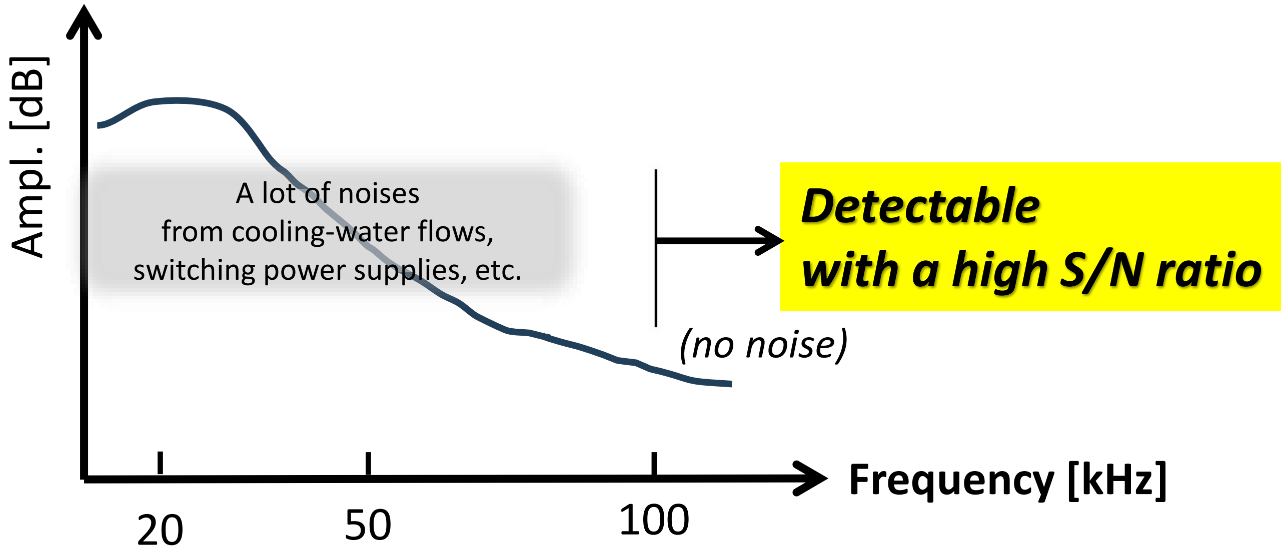
The results obtained in this study have generality.

Why Acoustic Observation?

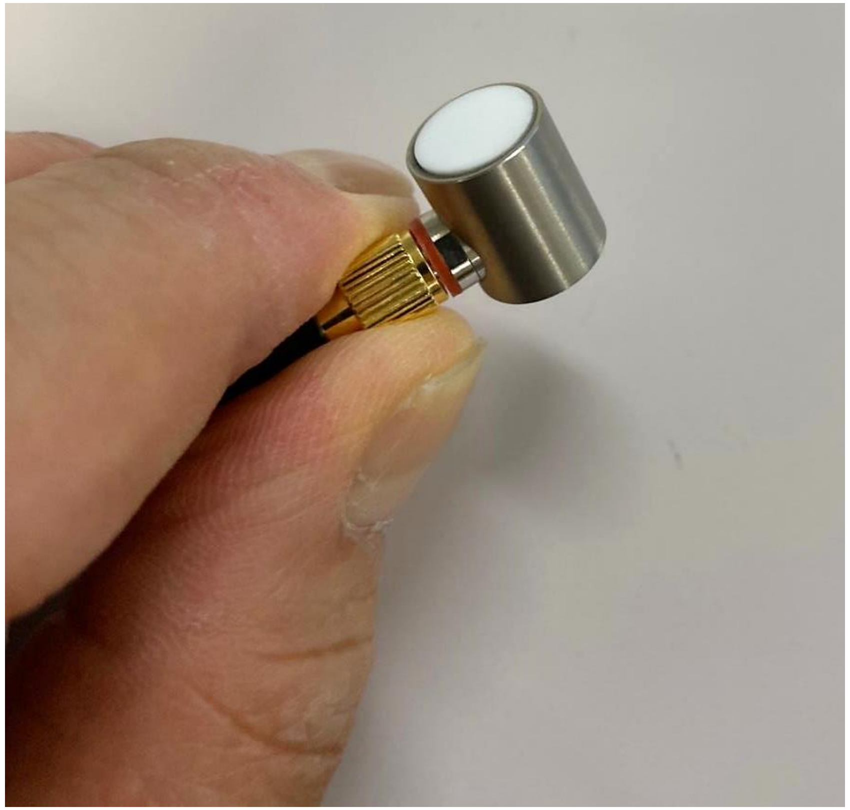
■ How to detect vacuum arcs through:

1. RF-field change → Impossible (no RF monitor port, low Q-value)
2. X-ray emission → Difficult to detect due to the stored beam
3. Light emission → Impossible due to strong synchrotron radiation
4. Acoustic emission: the only one to be detected
   - ➢ Acoustic emission is generated by thermal shock when an arc current impacts a metal surface.

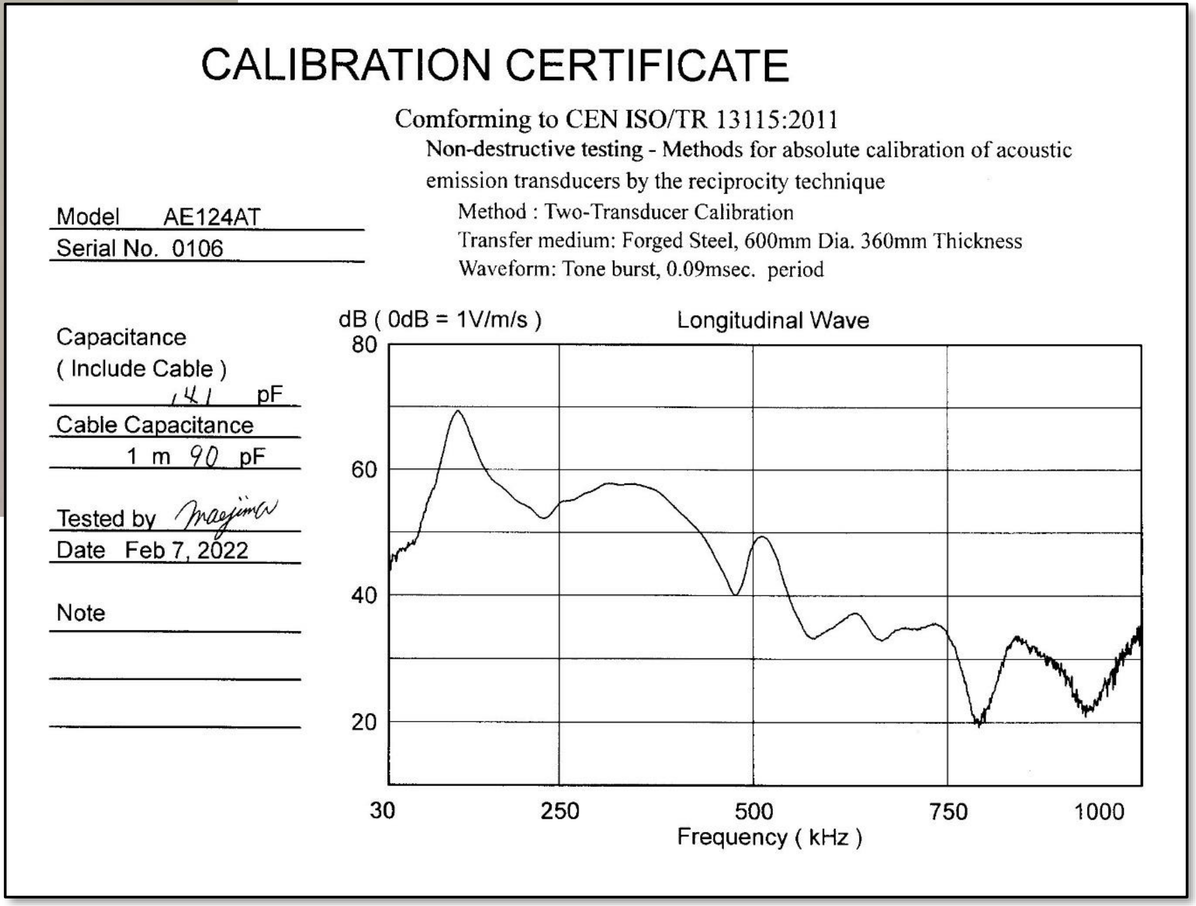




Acoustic sensor used in this observation: AE124AT



- ✓ Resonator type
- ✓ Sensitive only around 120 kHz



CALIBRATION CERTIFICATE

Comforming to CEN ISO/TR 13115:2011
Non-destructive testing - Methods for absolute calibration of acoustic emission transducers by the reciprocity technique
Method : Two-Transducer Calibration
Transfer medium: Forged Steel, 600mm Dia. 360mm Thickness
Waveform: Tone burst, 0.09msec. period

Model AE124AT
Serial No. 0106

Capacitance
(Include Cable)
141 pF
Cable Capacitance
1 m 90 pF

Tested by Maejima
Date Feb 7, 2022

Note

(Selection by Toshiyasu HIGO (KEK/e+e-Linac))

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