Fireball Hypothesis and Acoustic Observation for Elucidation of the Mechanism of Sudden Beam Losses at the SuperKEKB Main Ring

Tetsuo ABE
<tetsuo.abe@kek.jp>

KEK / ACCL

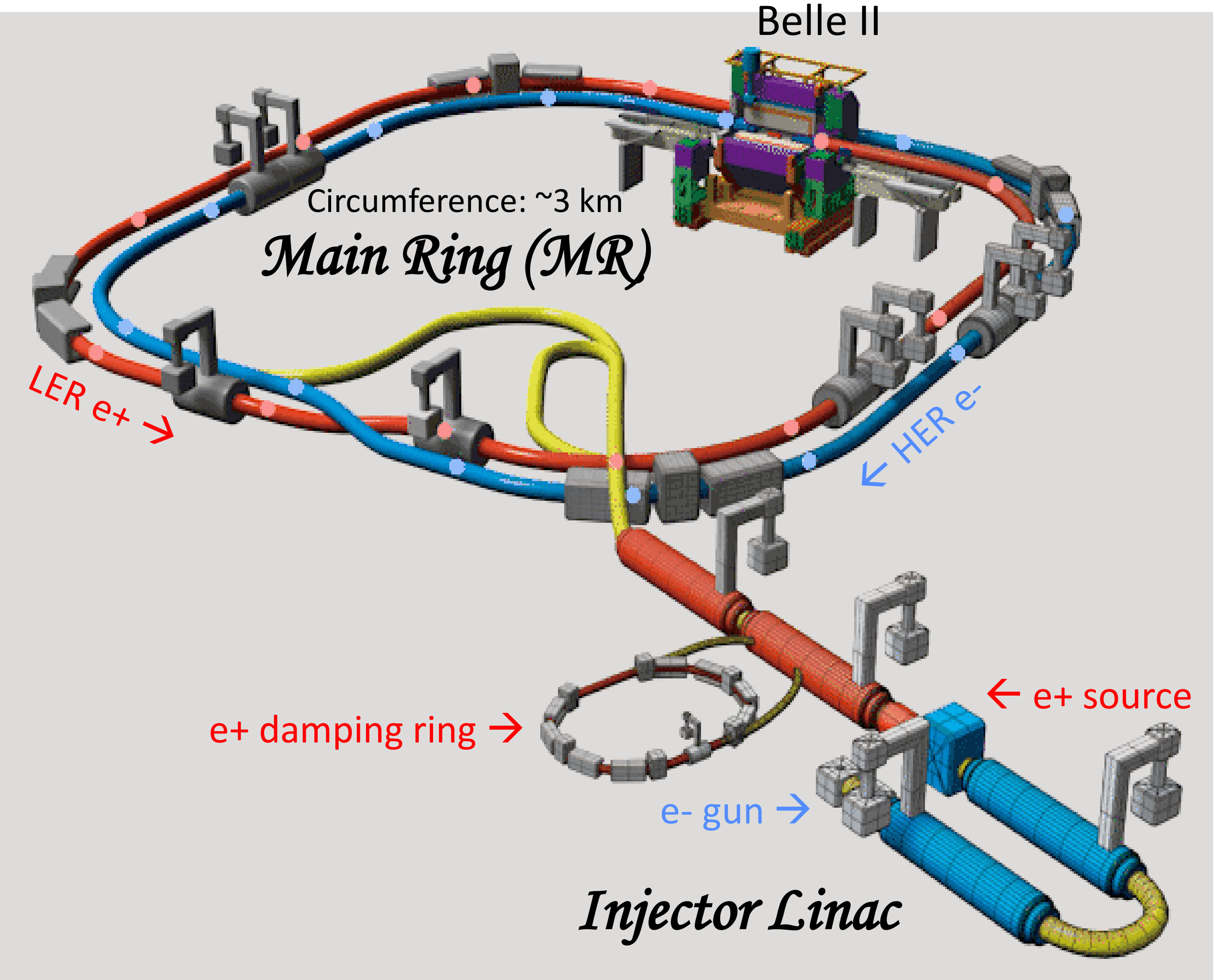
B2GM

2024-01-29

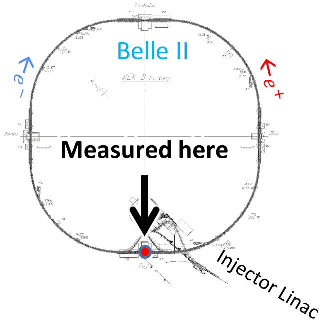
SuperKEKB Accelerator

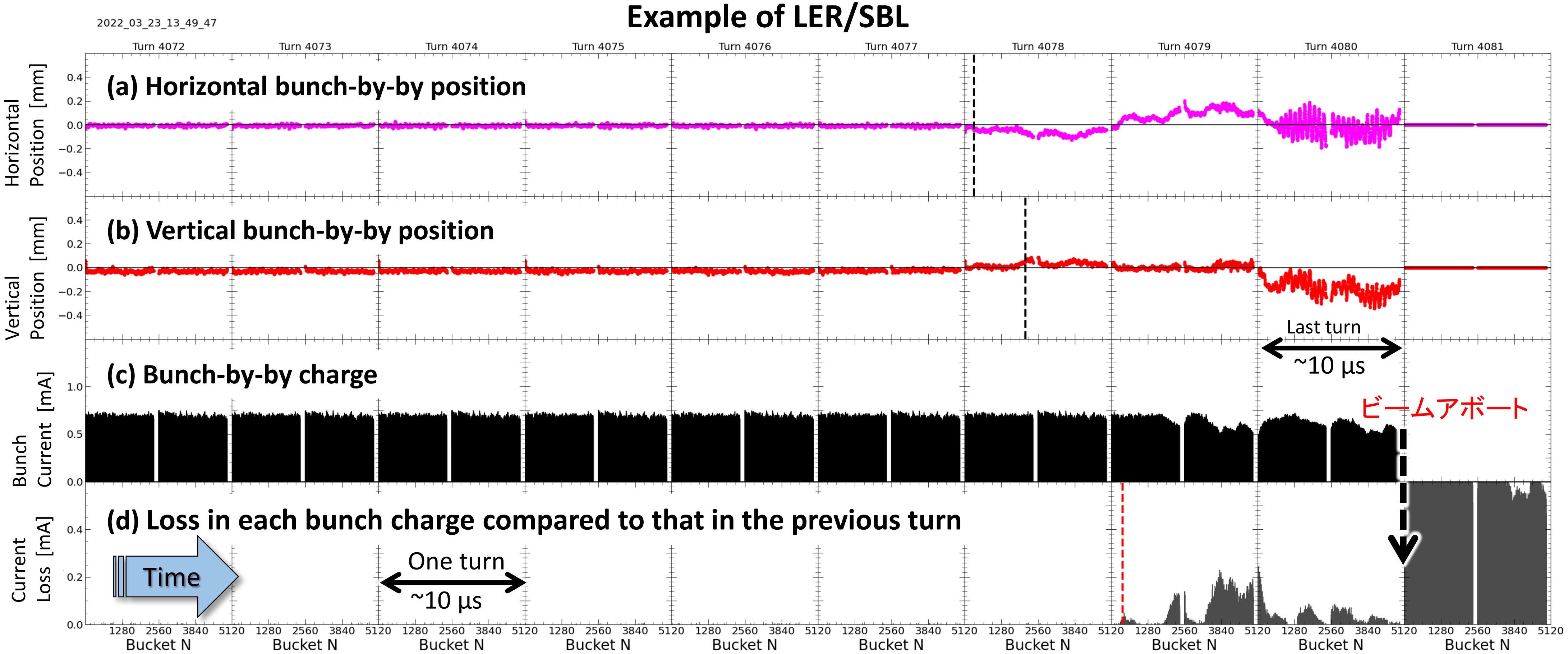
~ Asymmetric-energy e^+e^- double-ring collider ~

- Upgraded from KEKB B-factory (KEKB)
- Stored-beam energies
  - **H**igh **E**nergy **R**ing (**HER**) : 7.0 GeV (e^-)
  - **L**ow **E**nergy **R**ing (**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: 6.0×10^{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)?





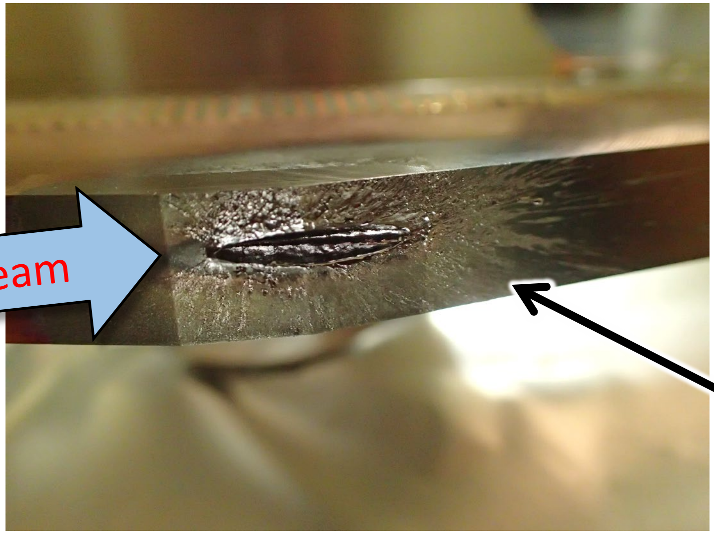
Characteristics

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)

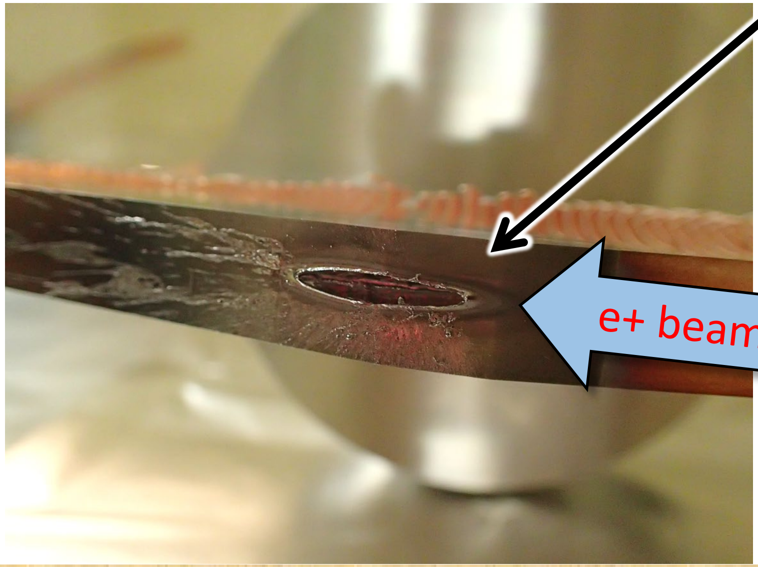
Example of serious hardware damages due to SBL

LER / vertical beam collimator "D02V1" just upstream of the IR

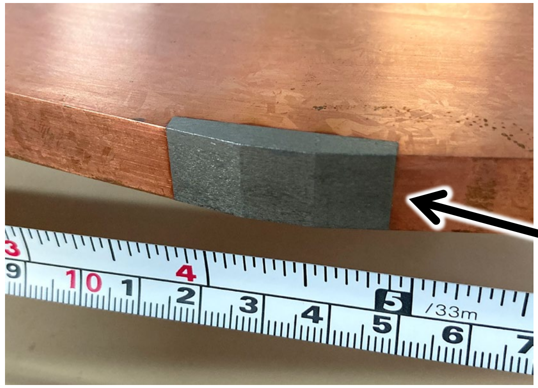
TOP side



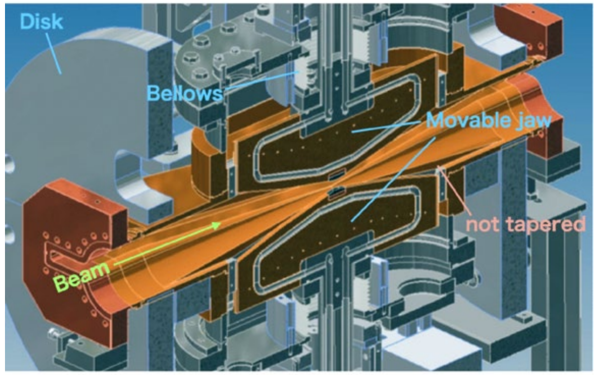
Bottom side



Damaged heads (Ta)

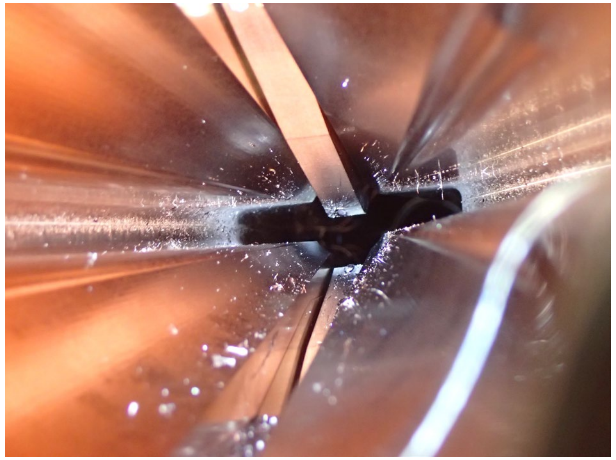


Cf. An undamaged head (W)



[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**

Investigation of the cause of SBL

- **Machine performance failure?**
  - All of the relevant components are carefully monitored, and no suspicious one found

- **Vacuum arc at RF contacts in vacuum components?**
  - In this case
    - Any beam-phase change (= energy loss) should be observed in ~ms time scale.
  - SBL occurred in ~10μs time scale, and no beam-phase change observed

- **Dust-beam interaction?**
  - In this case,
    - Vacuum pressure bursts and ~ms-time-scale beam loss should be observed.
  - SBL occurred in ~10μs time scale mostly with no pressure burst

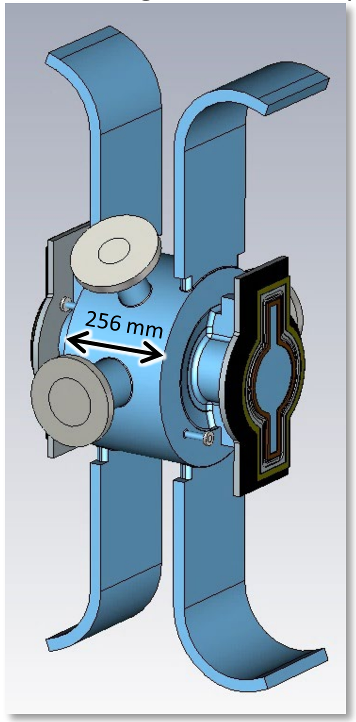
- **Electron cloud?**
  - In this case, SBL should occur only in LER (e+), but SBL also occurred in HER (e-).
  - Relevant simulation studies are on-going, and no clear relationship with SBL found so far

- **"Fireball"?**

FireBall-Triggered Vacuum BreakDown (FB BD) in RF Cavities

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

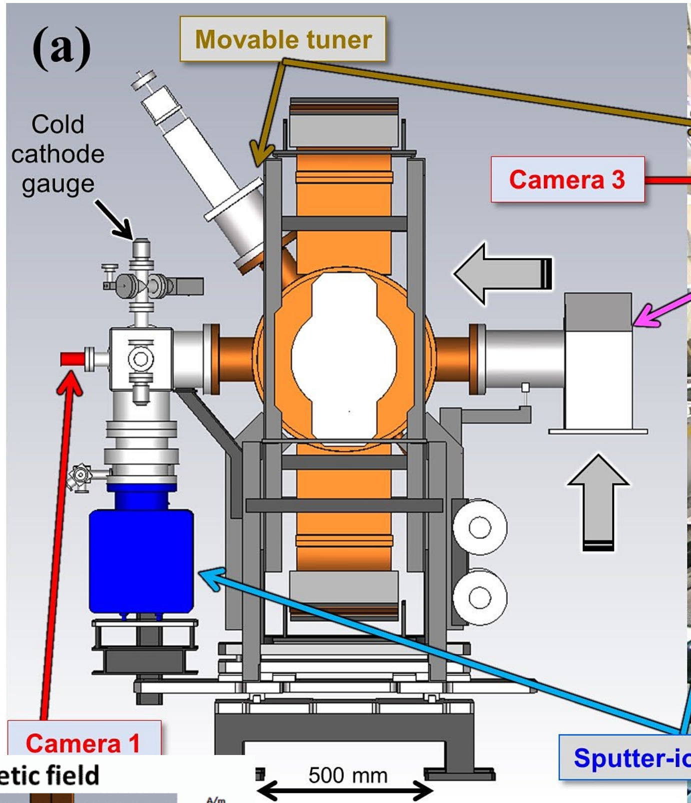
Vacuum region in the cavity

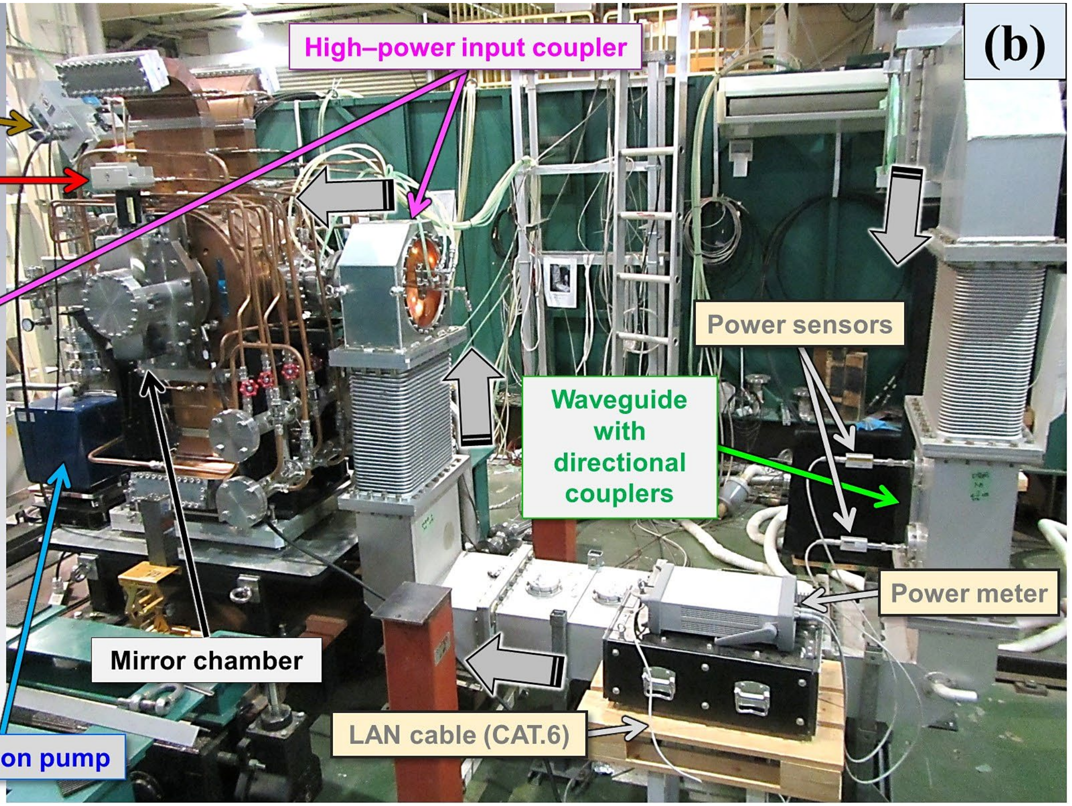


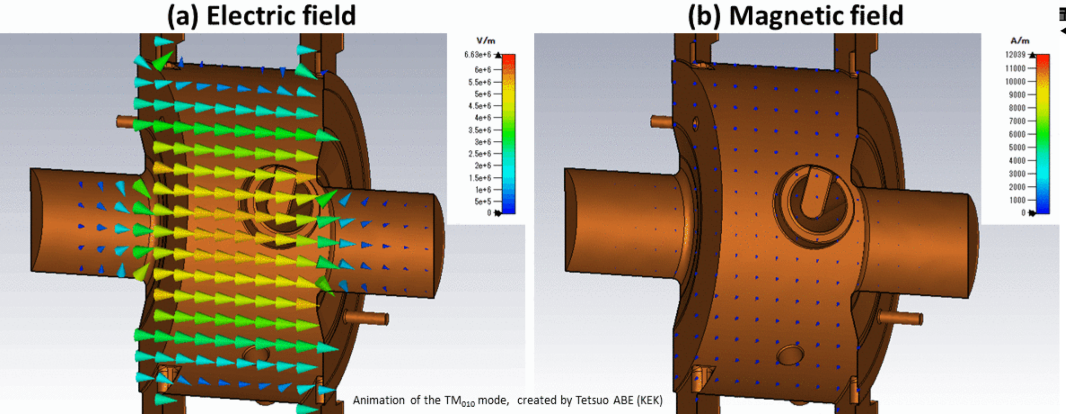
↓ Excited electromagnetic field↓

@ KEK / MR-D1-AT

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







- 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

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

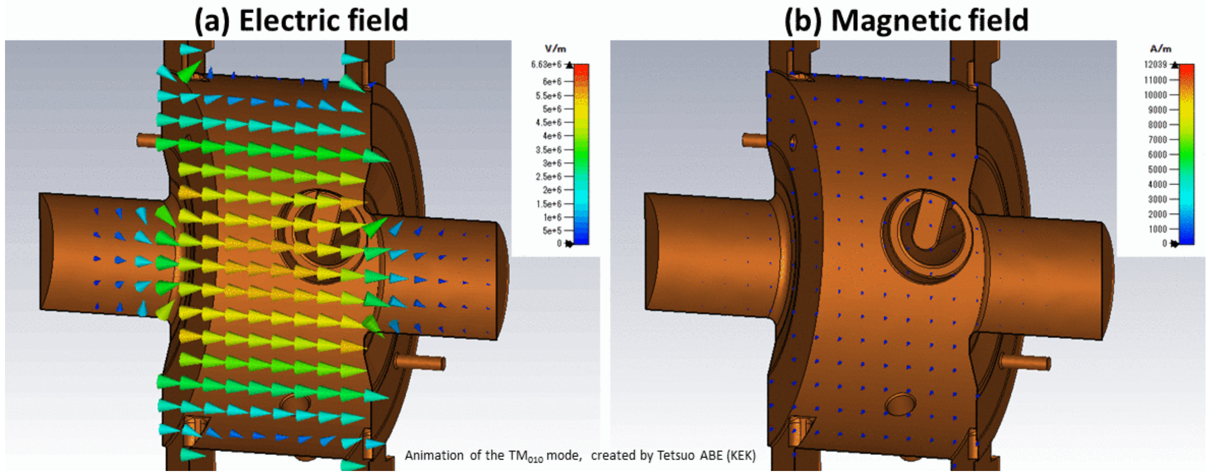
Surface field at V_c = 0.9 MV (Input RF power: ~200 kW)

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

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

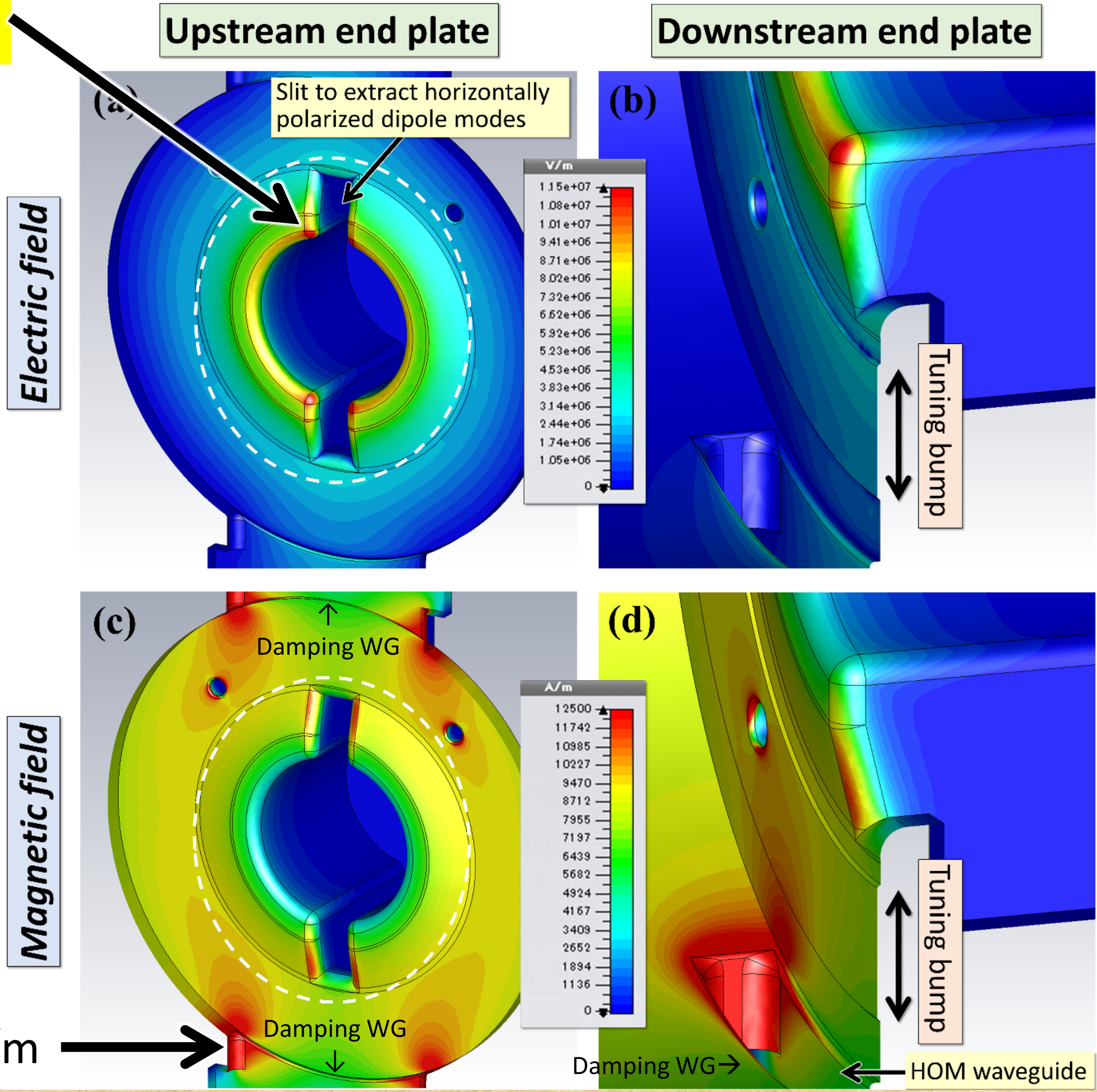
- Field evaporation (> ~GV/m)
- X-band HG accel. structures (~200 MV/m)
- DC HV experiments (~100 MV/m)

➔ But breakdowns occur in UHF NC CW cavities.

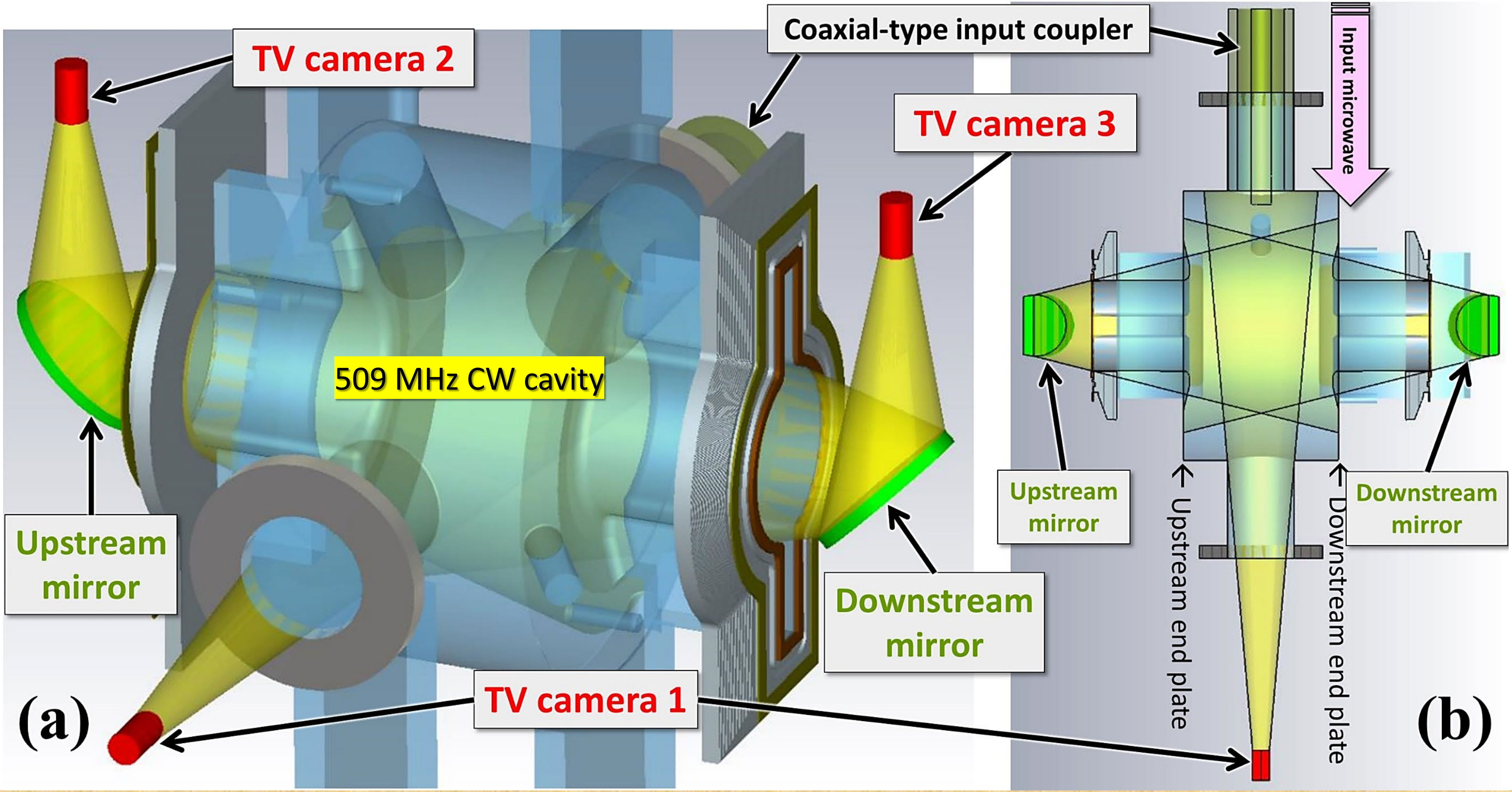


↑ Upstream end plate ↑ Downstream end plate

H_{max} = 34 kA/m



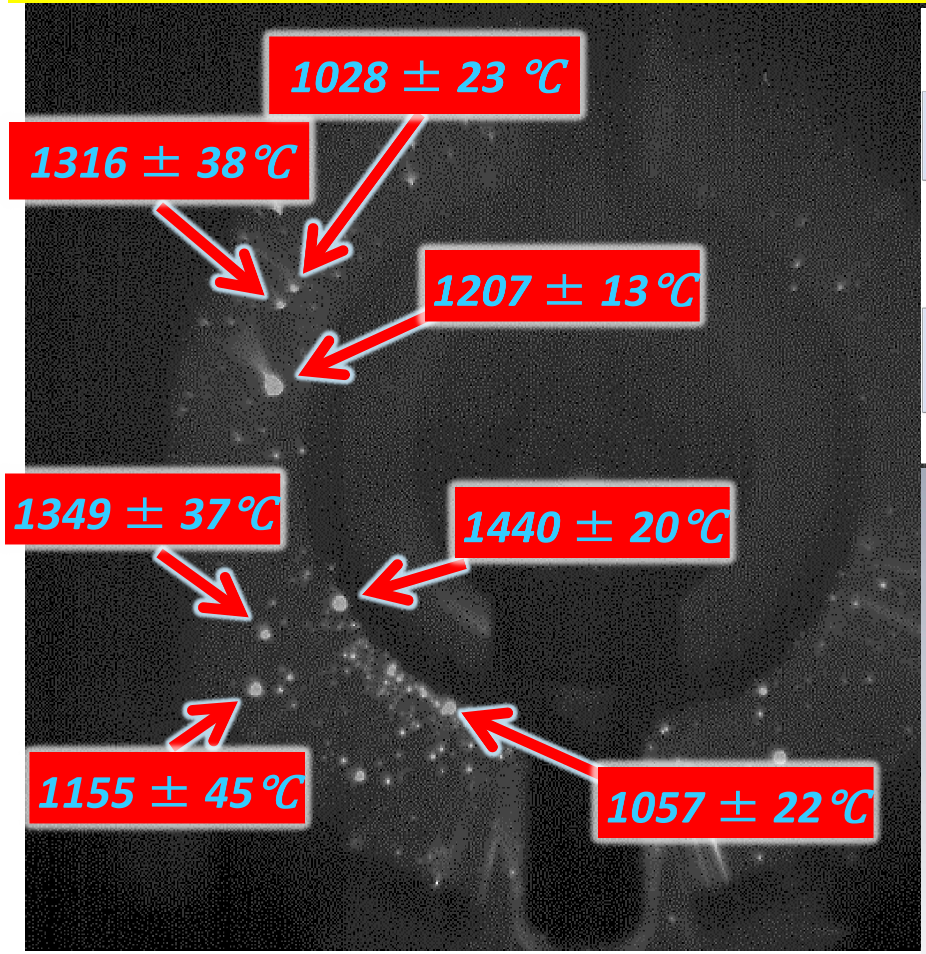
<u>Multi-directional and wide-field</u> observation with Three Cameras

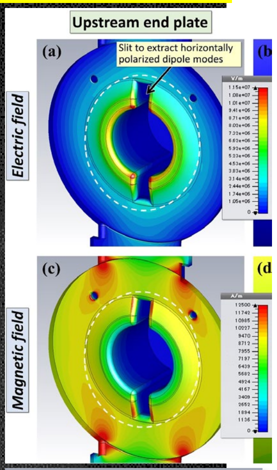


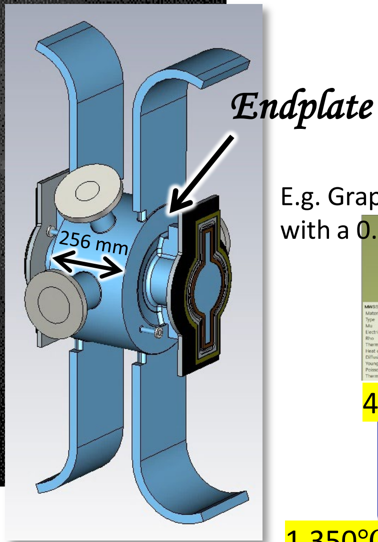
Observation1: "Adherent" fireballs

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)





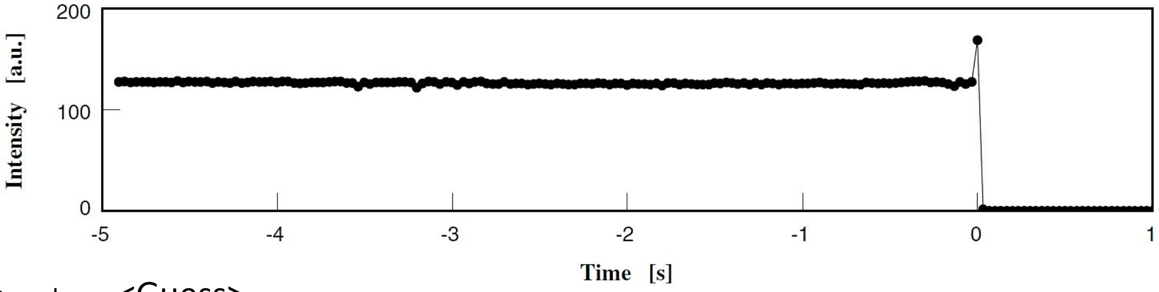


509 MHz cavity

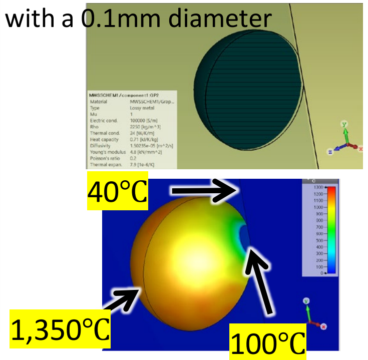
Observation of the emission spectra using a spectrum camera
→ After various corrections, the temperatures were estimated.

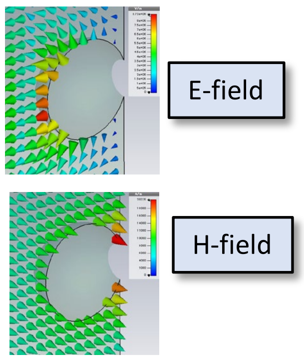
One of the bright spots | suddenly exploded at the moment of breakdown. | Then, disappeared in the following high-power operation.

(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>



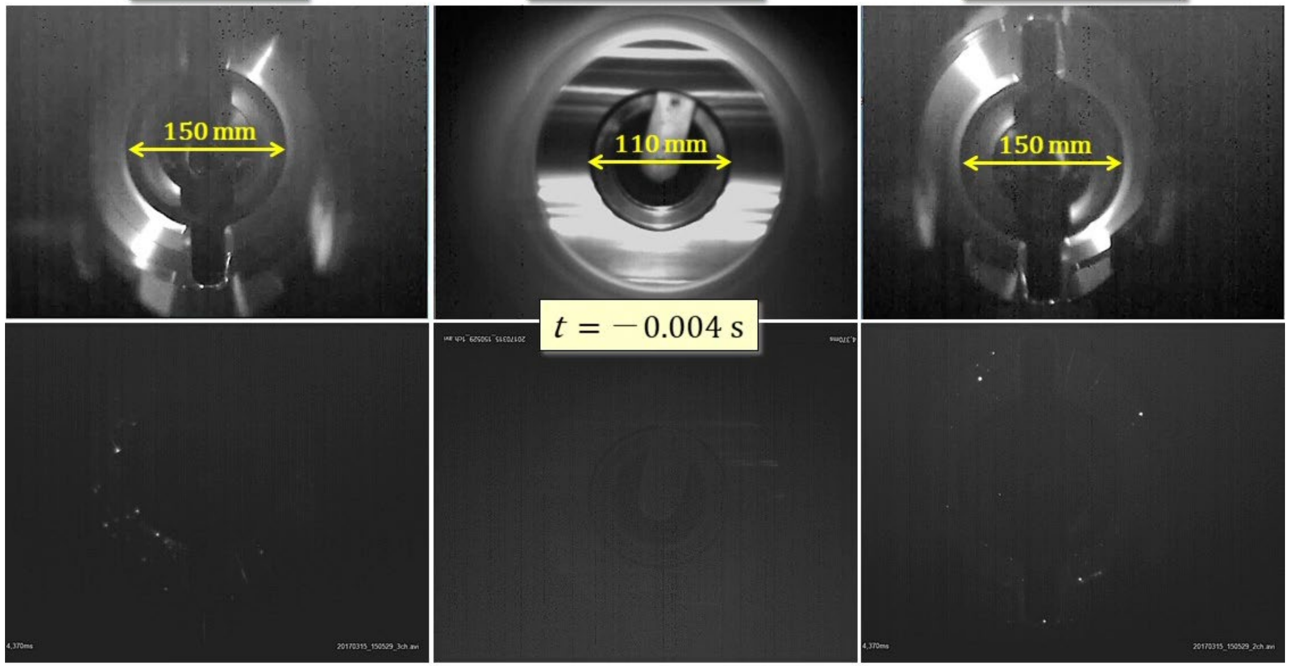


A fireball adhering to a copper surface exploded, then RF-cavity breakdown

Observation2: "Flying" fireballs

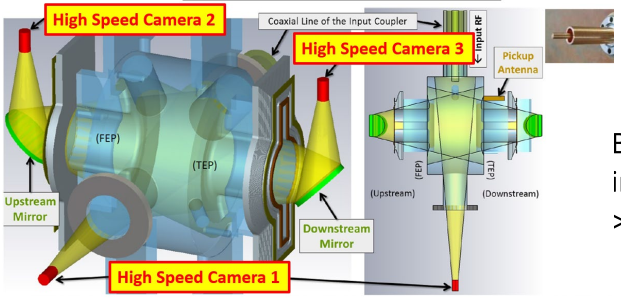
Three high-speed cameras used for multi-directional observation during HP operation of 509MHz (CW) NC cavity at V_c = 0.88 MV

Upstream end plate	Side view	Downstream end plate



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

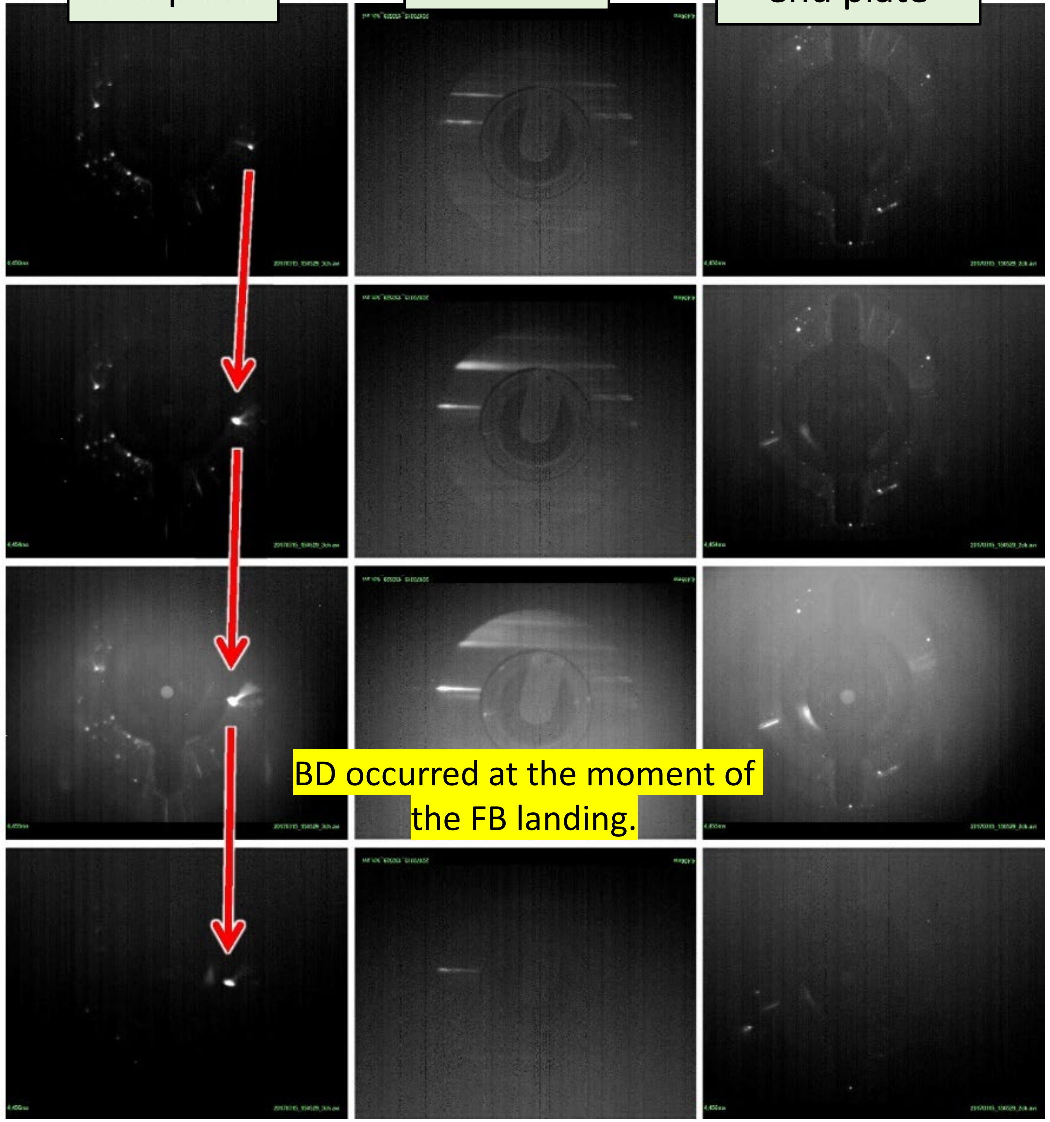


This video → https://youtu.be/VZe8dVLqWH0

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).

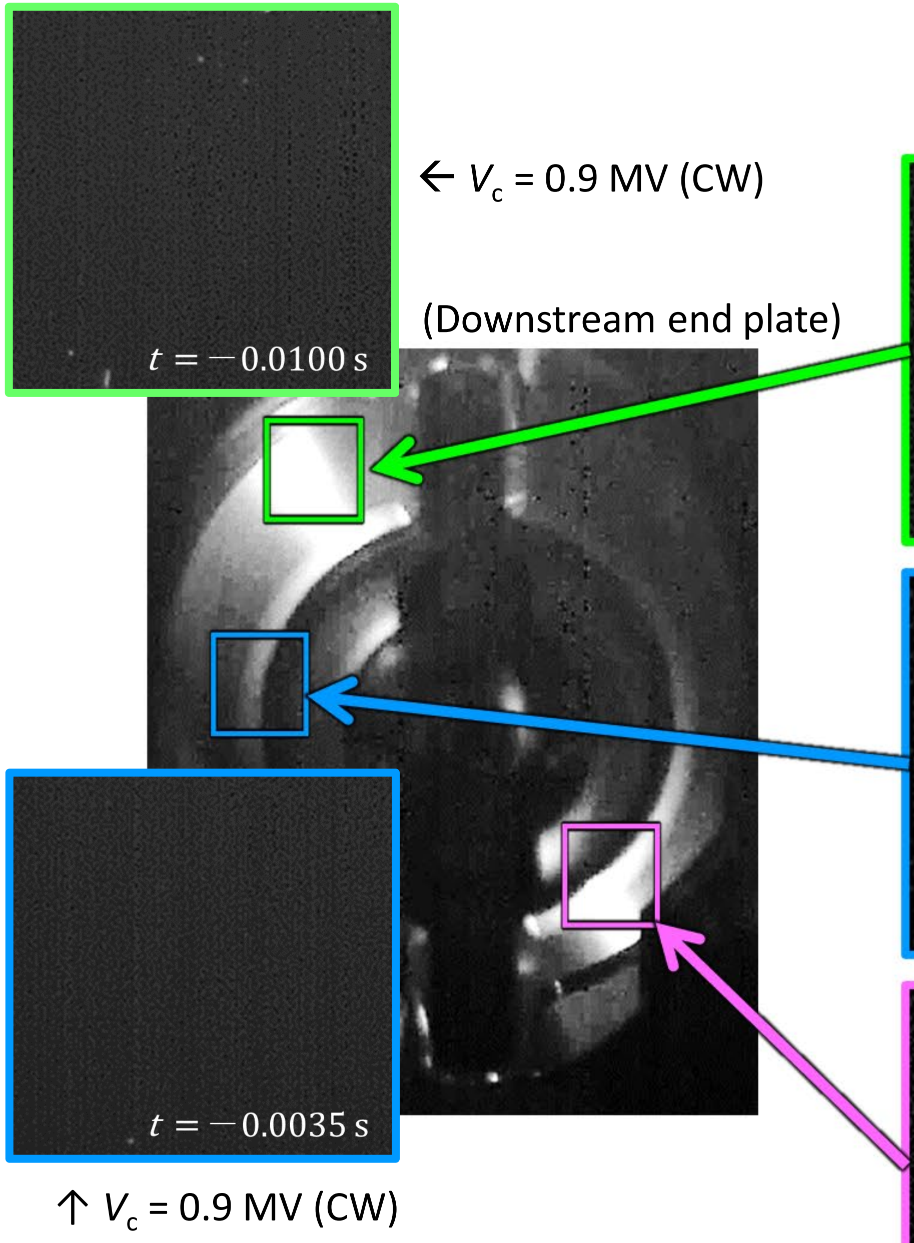
Upstream end plate	Side view	Downstream end plate

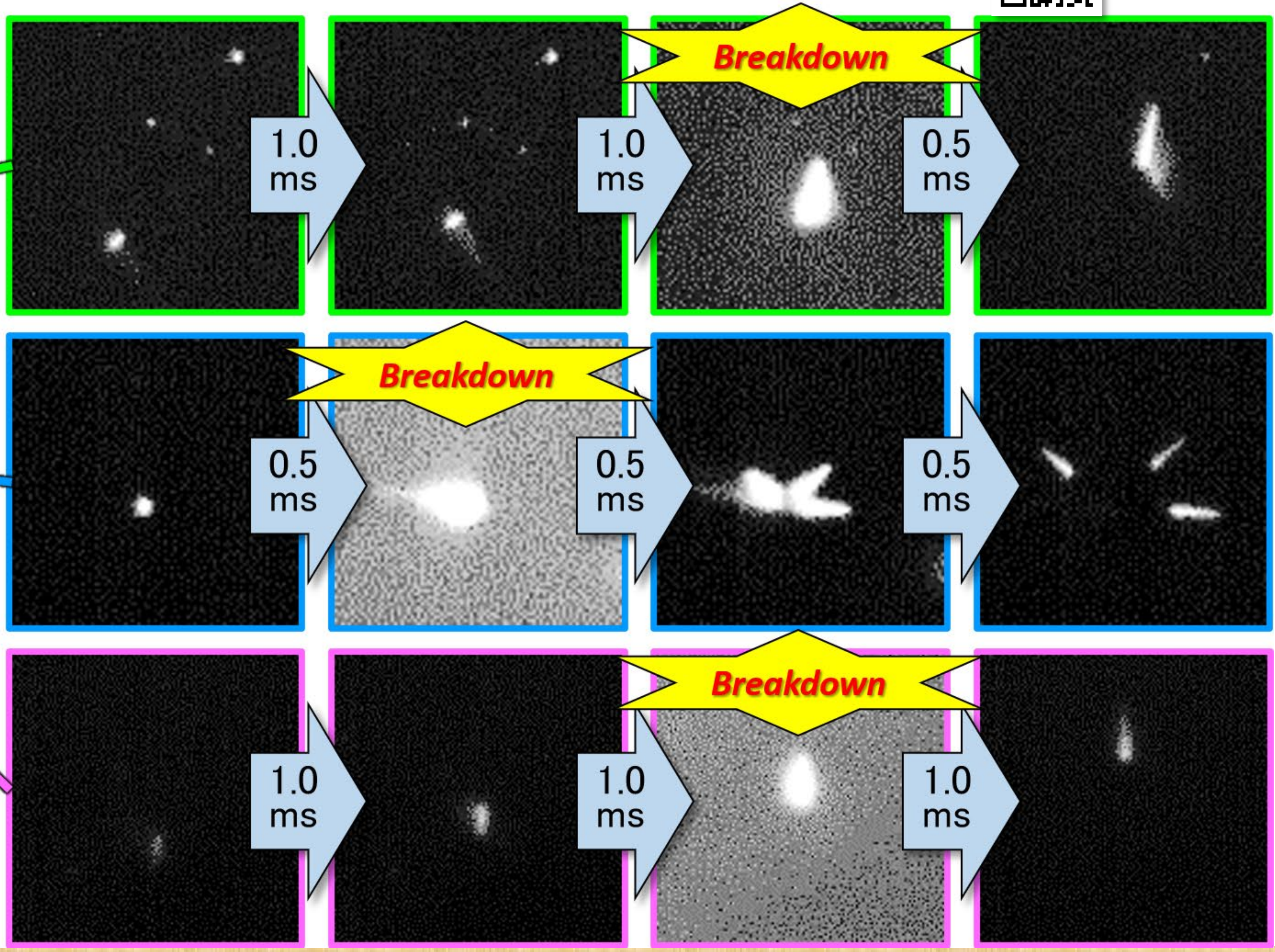
(g) Frame No. 4450
↓
1 ms
↓
(h) Frame No. 4454
↓
1 ms
↓
(i) Frame No. 4455
↓
1 ms
↓
(j) Frame No. 4456



Other flying fireballs

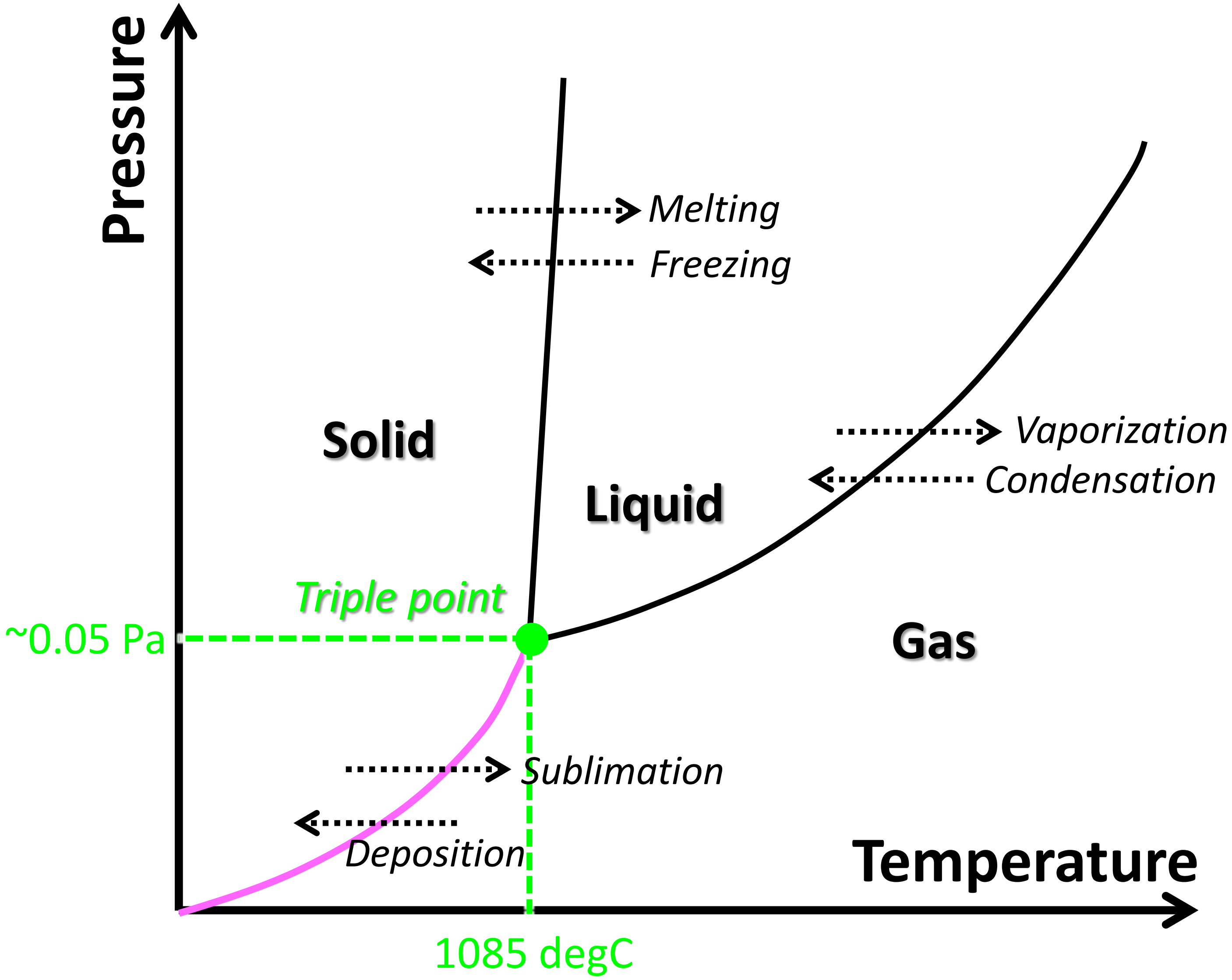
https://youtu.be/MqFYk4EVr7w



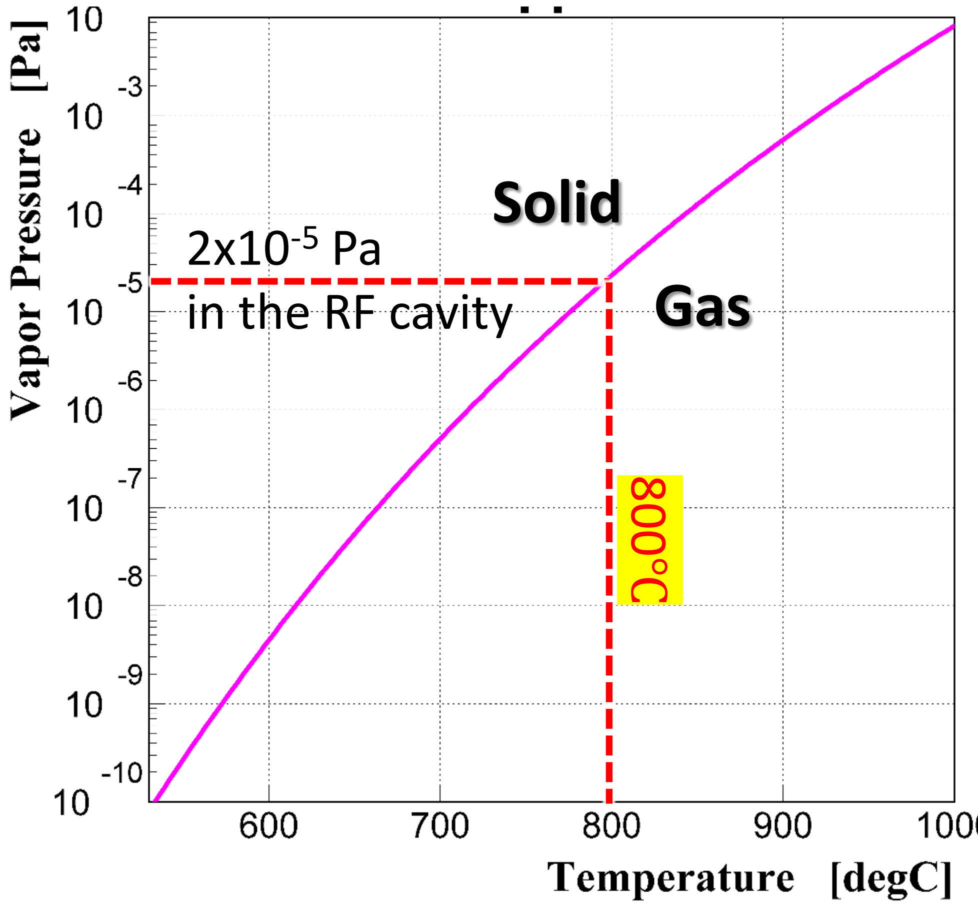


What is the fireball made of?

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 > days.**

➔ 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	

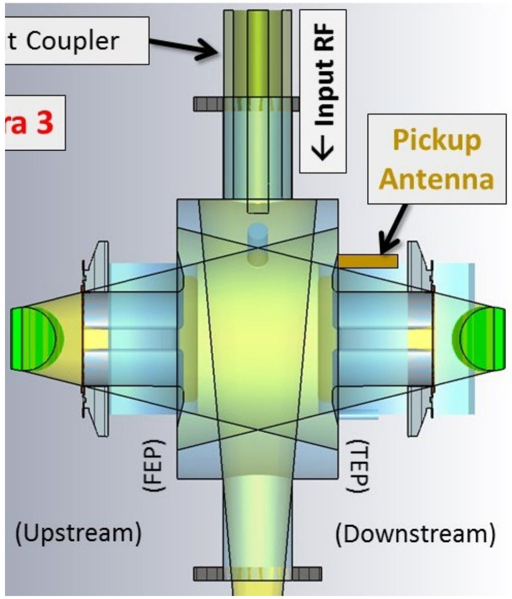
Data from https://www.iap.tuwien.ac.at/www/surface/vapor_pressure

Physics in Fireball Breakdown

Breakdown observable A: Fast drop of the accelerating field

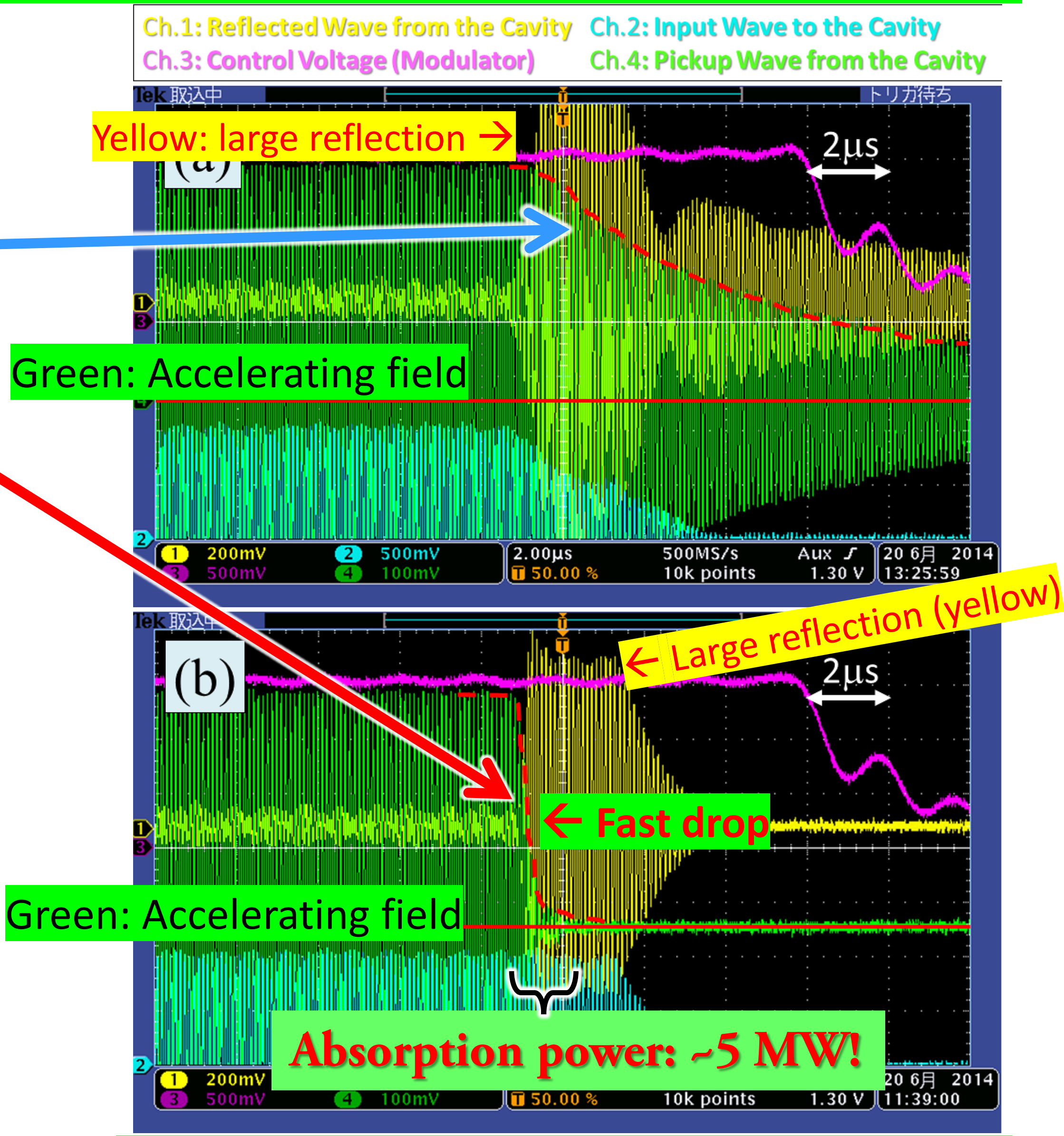
Decay time:

- 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.



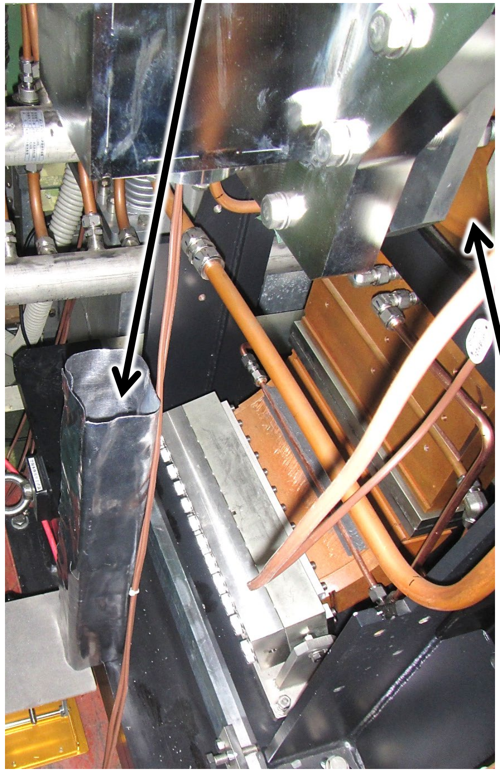
Q_L=13000@509MHz ⇒ Fill time: 8 μs

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

Breakdown Observable B: Current flash

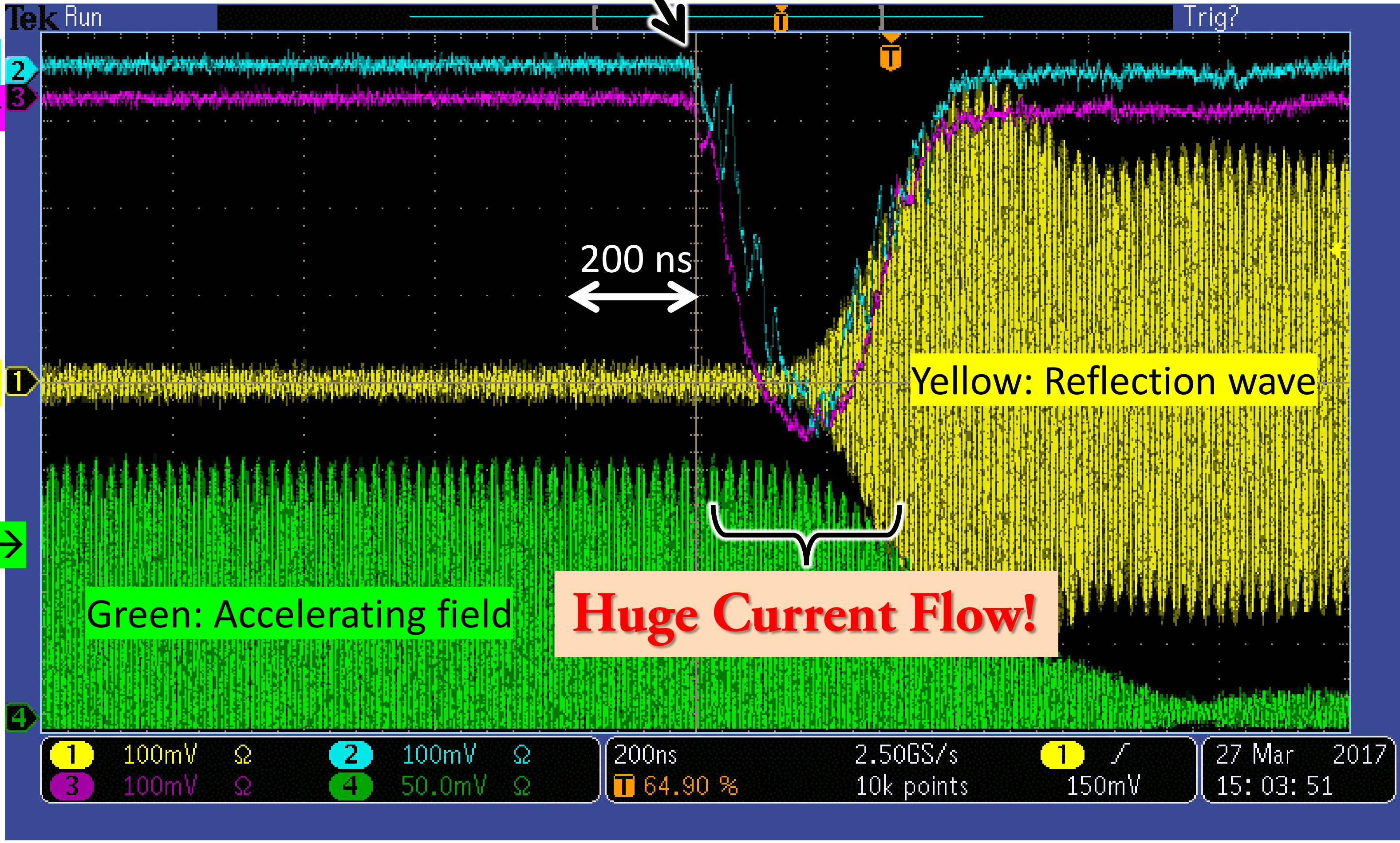
X-ray detector
(plastic scintillator + PMT)

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



RF cavity
for the e+ DR

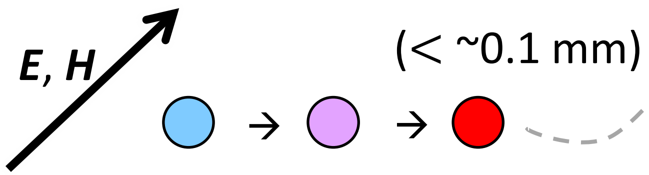
(During the high-power test of the RF cavity for the DR)



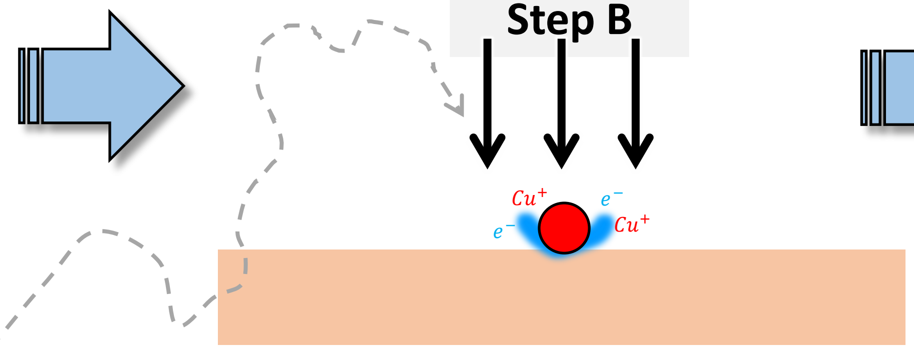
Physical process of FB BD revealed by the observations

Step A

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

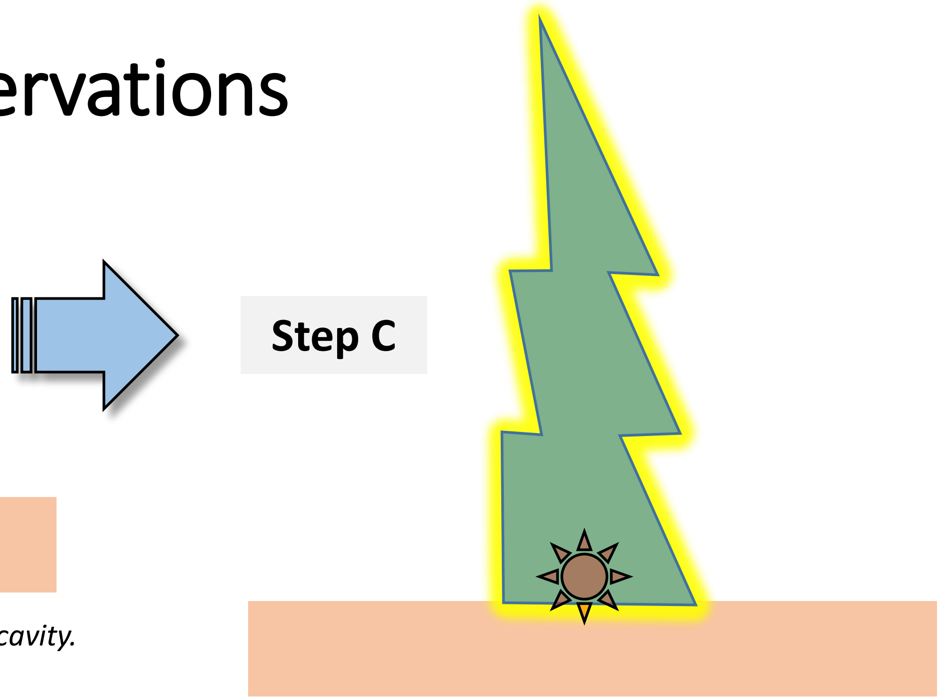


Step B

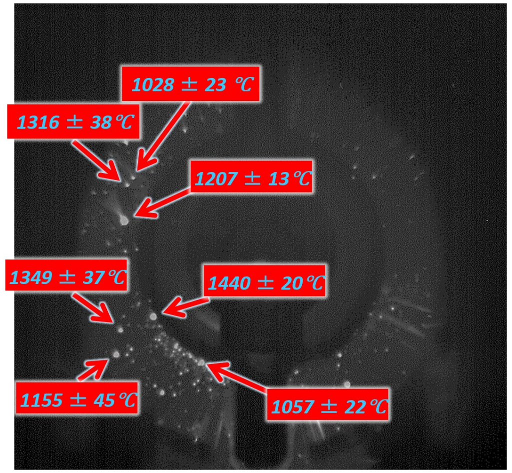


Plasma is generated with eating the RF field in the cavity.

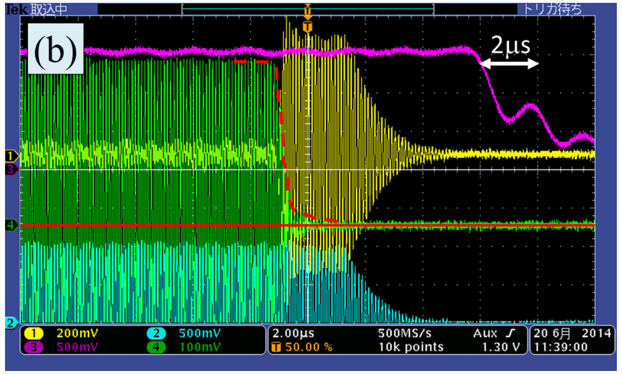
Step C



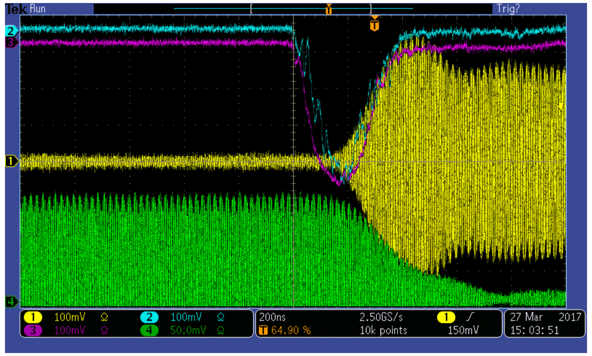
Huge current flow leads to vacuum breakdown.



Temperature measurements



Very high power density of ~GW/cm²



Huge X-ray detected

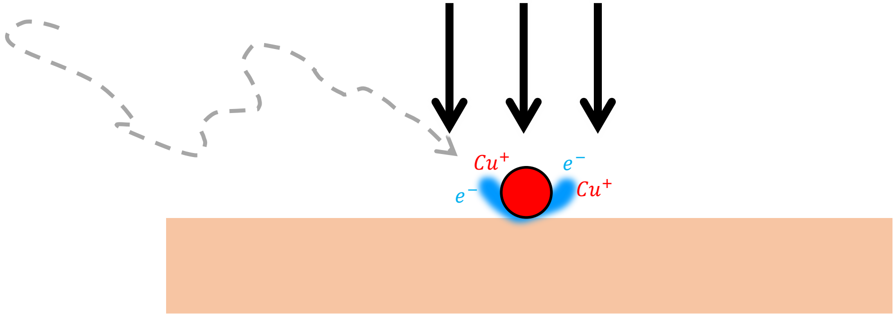
(Plasma generation and its exponential growth are needed for vacuum breakdown.)

Essential Condition for FB BD

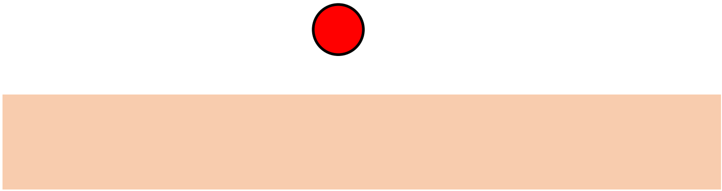
Coexistence of different materials with largely different sublimation/melting points in the same place

Step B

$v \approx 10$ m/s

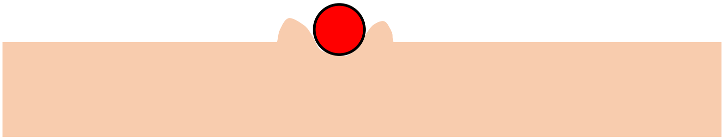


Step B-1

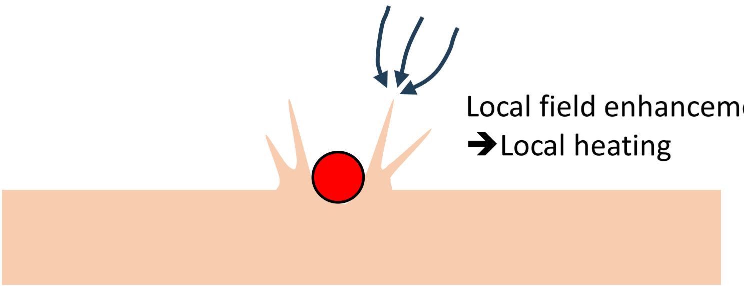


If (fireball temperature) > (sublimation/melting point of the cavity material)

Step B-2



Step B-3



Local field enhancement
➔Local heating

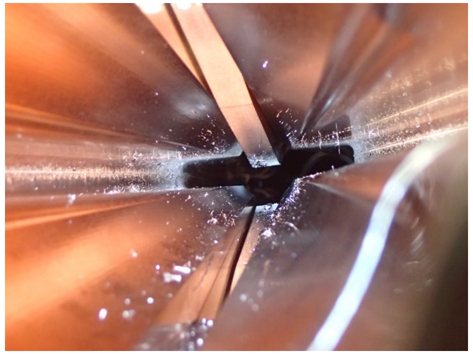
(my speculation)

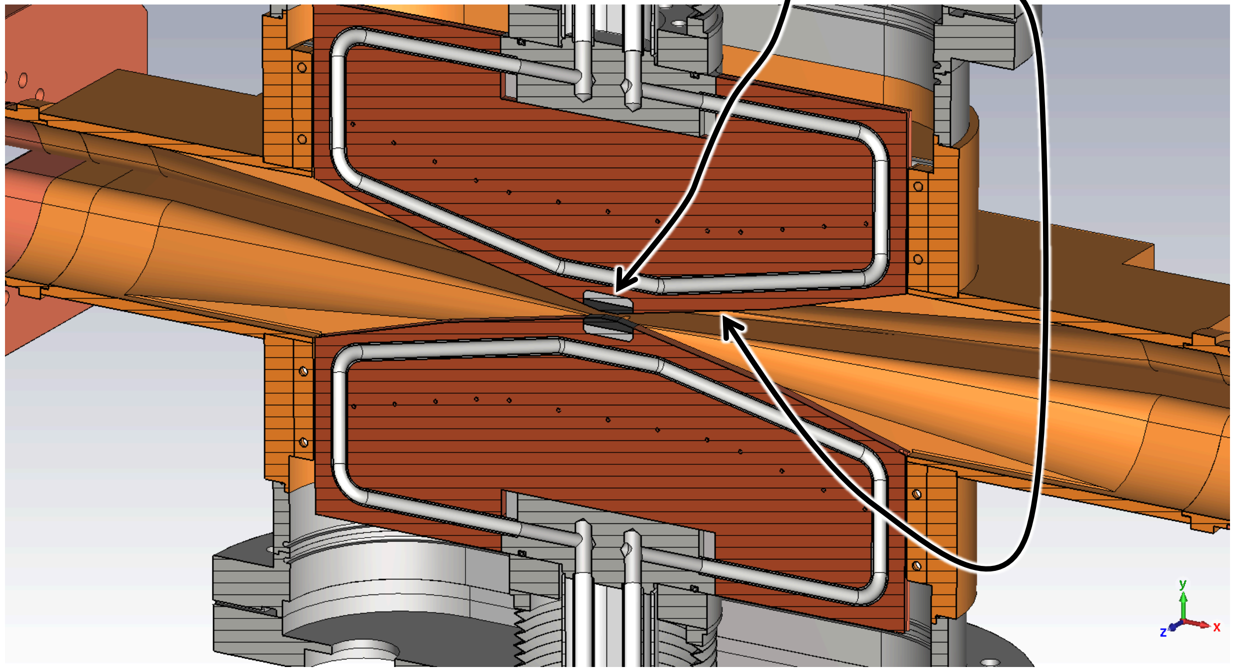
Essential Condition for FB BD

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





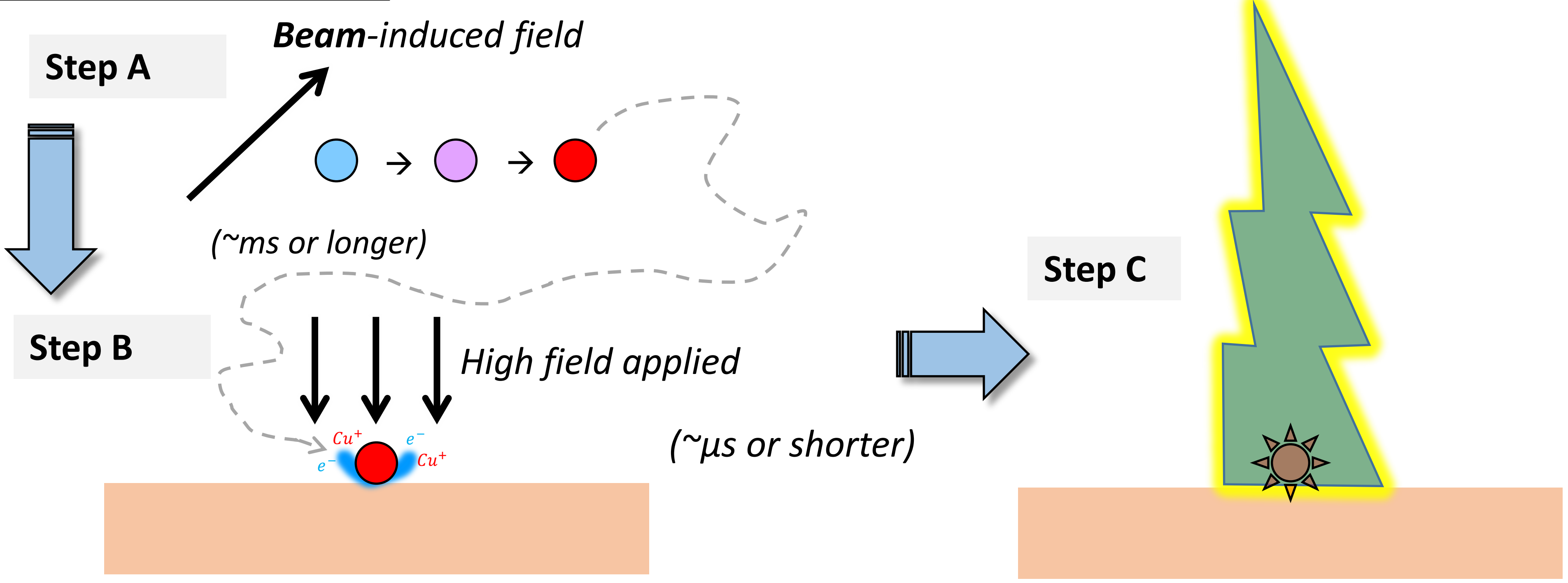
SuperKEKB beam collimator

Phenomena similar to FB BD can occur around collimators.

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.

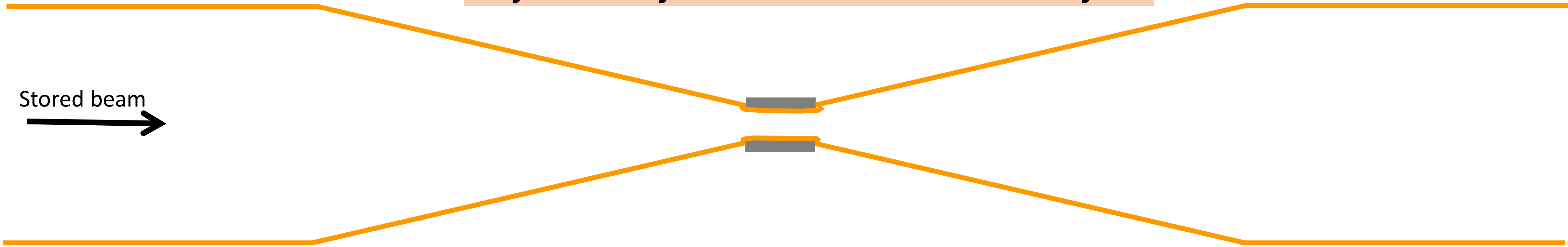
Sudden significant kick of beam bunches?



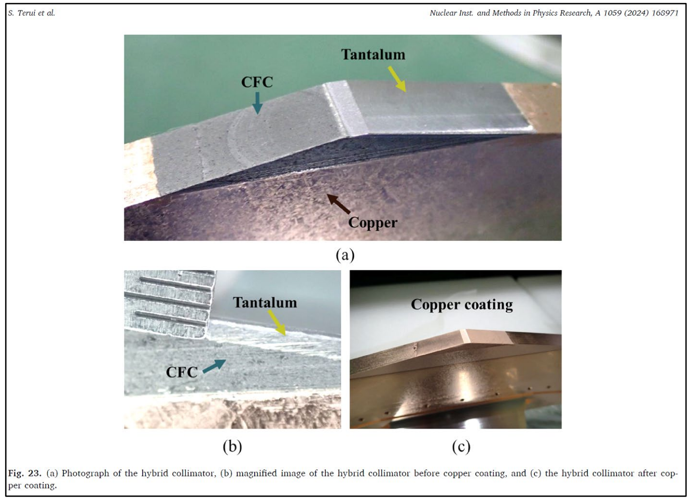
Aperture: ±1mm at min. at SuperKEKB

Cu coating applied to all the collimator heads during LS1

- ✓ ***Only the single material (Cu) seen by the beam***
- ✓ ***Confinement of FB candidates on the head surfaces***



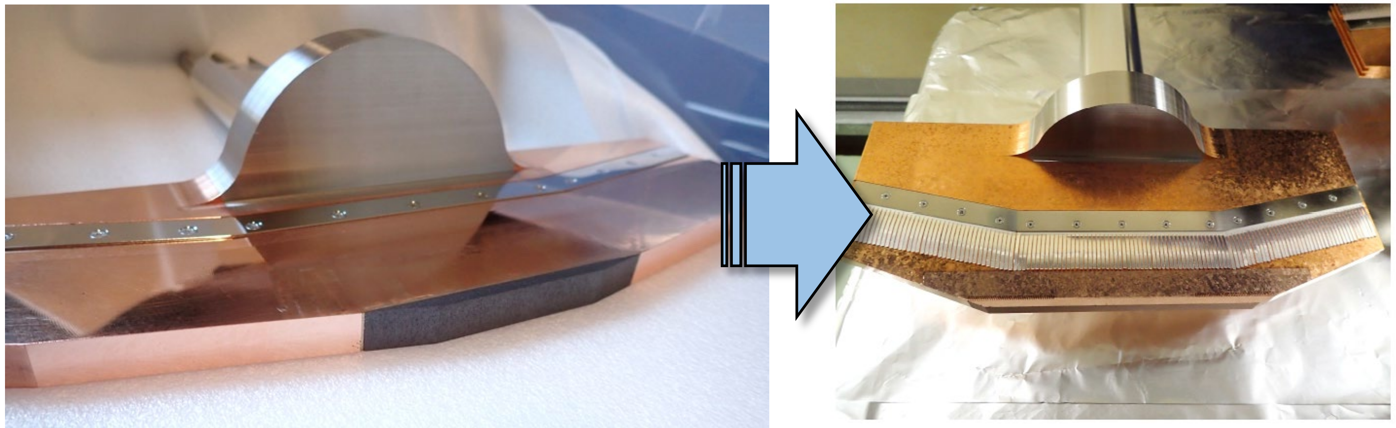
Like the hybrid collimator


S. Terui et al. — Nuclear Inst. and Methods in Physics Research, A 1059 (2024) 168971

Tantalum
CFC
Copper
(a)
Tantalum
CFC
(b)
Copper coating
(c)

Fig. 23. (a) Photograph of the hybrid collimator, (b) magnified image of the hybrid collimator before copper coating, and (c) the hybrid collimator after copper coating.

Extracted from [Shinji TERUI et al,, NIMA 1059 (2024) 168971]



Like the robust carbon collimator

Dust (microparticle) charging and lofting in Accelerators

https://indico.cern.ch/event/1272104/


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

Jun 13 – 15, 2023
CERN
Europe/Zurich timezone

Enter your search term

- Overview
- Timetable
- Program Committee
- Registration
- Contribution List
- Participant List
- Useful Information
  - How to create an Indico Account
  - Link to the MapCERN mobile applications
  - Link to CERN maps
  - How to get to CERN
  - In case of emergency
  - How to get from the CERN hotel to Building 30

Support
claudia.dupraz@cern.ch
+41754118222

Workshop Objectives

- Improve understanding of beam-dust interactions in particle accelerators, in particular, of dust-charging and release mechanisms.
- Improve understanding of evolution of beam-dust interaction rate as a function of beam and other parameters.
- Present modelling work on beam-dust interactions and their consequences.
- Present research on dust issues in space applications.
- Improve understanding of the behaviour of dust particles in accelerator hardware systems (Vacuum, RF, treated surfaces...) and their consequences.
- Improve understanding of mechanisms of dust migration into sensitive devices, such as high field gradient superconducting cavities, and ways to prevent this migration.
- Identify synergies between particle-accelerator and space-research communities.
- Define next research steps and possible collaborations.

Participation is by invitation only.

The final report available at the CERN Document Server:
https://cds.cern.ch/record/2884112

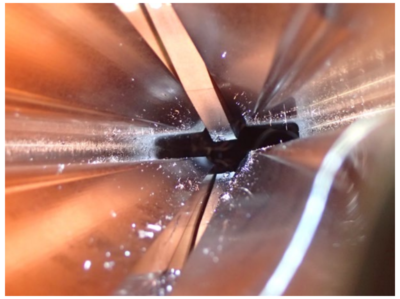
5.1 Dust charging mechanisms in accelerators, P. Belanger, TRIUMF, link to presentation

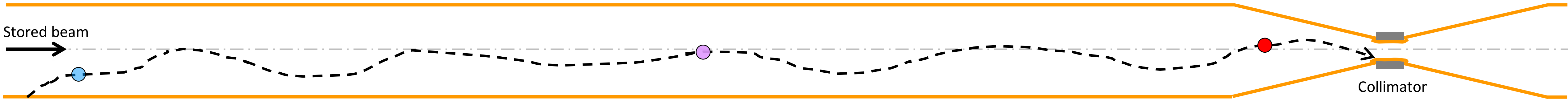
5.2 Dust charging lofting experiments at LASP, X. Wang, LASP, University of Colorado, link to presentation

There is a possibility that microparticles (debris) from the damaged heads, which are far from collimators, could be charged, lofted, and moved along the beam direction.

➔ Fireball?

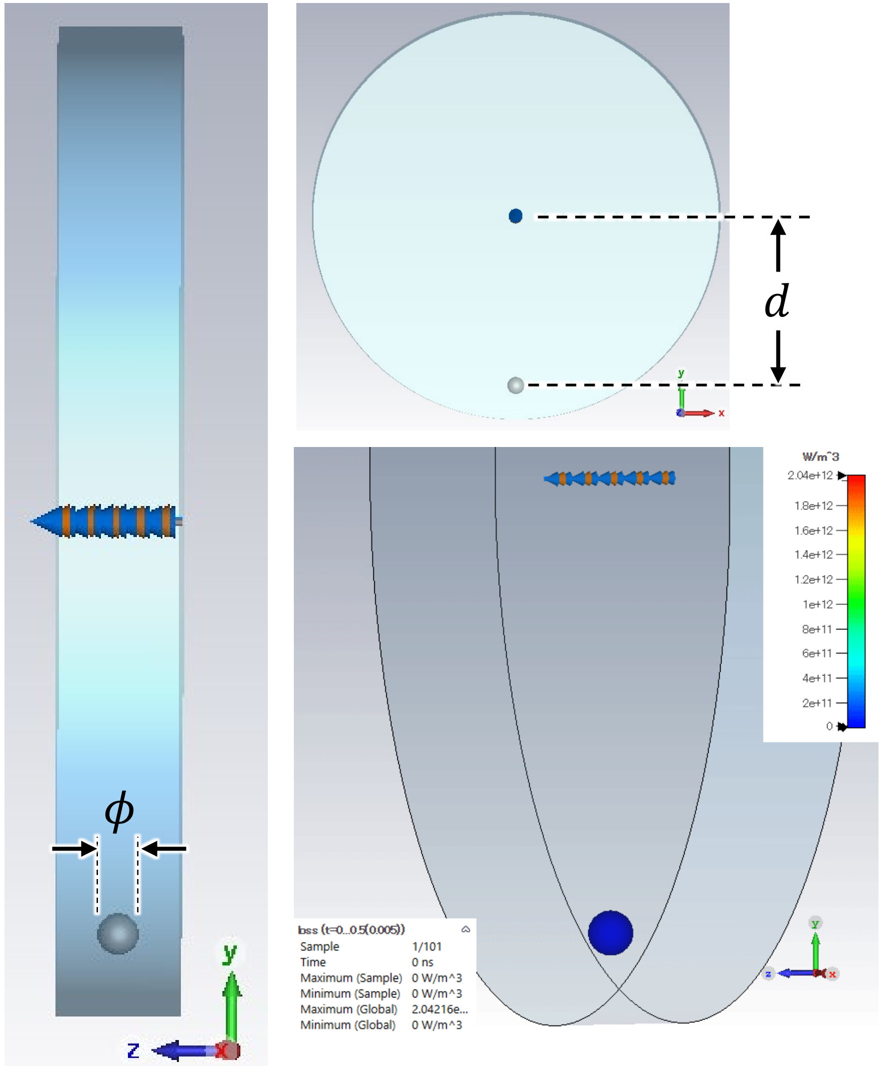
➔ SBL?





[Step A] Beam-induced field can generate fireballs?

Simulation using a first-principle simulator (CST Wakefield Solver)



For a bunch length of 6 mm, total current of 900 mA, and 1272 bunches per ring, which is a typical set of operational parameters for sudden beam losses at SuperKEKB/LER.

<Results>

Table 1: Simulated equilibrium temperatures in Celsius of spherical microparticles made from tungsten. The time in second to reach 1000 °C from 30 °C is also shown in parentheses. ϵ_e and ϕ indicate emissivity and diameter of the microparticle, respectively. d indicates the transverse distance between the beam bunch and the center of the microparticle.

	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	1019 (0.4)	595	842	467	748	400
0.05	1600 (0.7)	802	1253 (0.7)	597	1079 (0.9)	495
0.10	1542 (1.6)	767	1194 (1.9)	567	1022 (2.6)	469
0.50	1670 (6.6)	819	1293 (7.3)	607	1107 (8.5)	503
1.00	1704 (12)	763	1322 (13)	558	1133 (15)	458

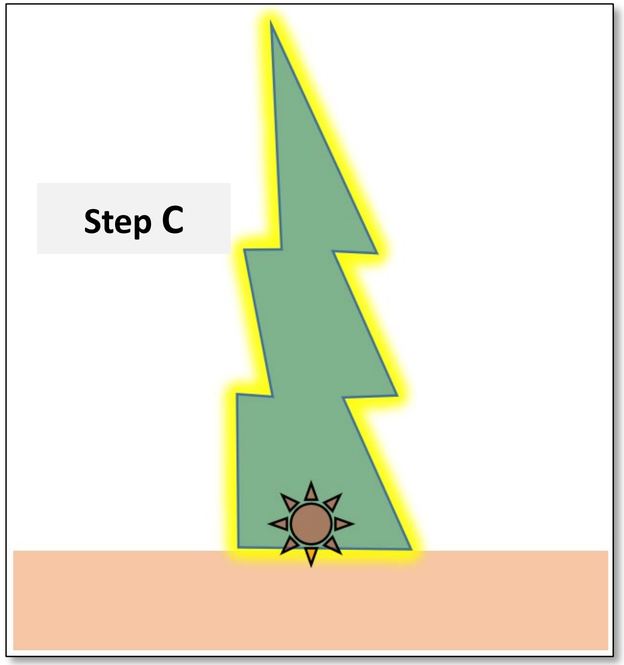
Table 2: The same as in Table 1 for tantalum.

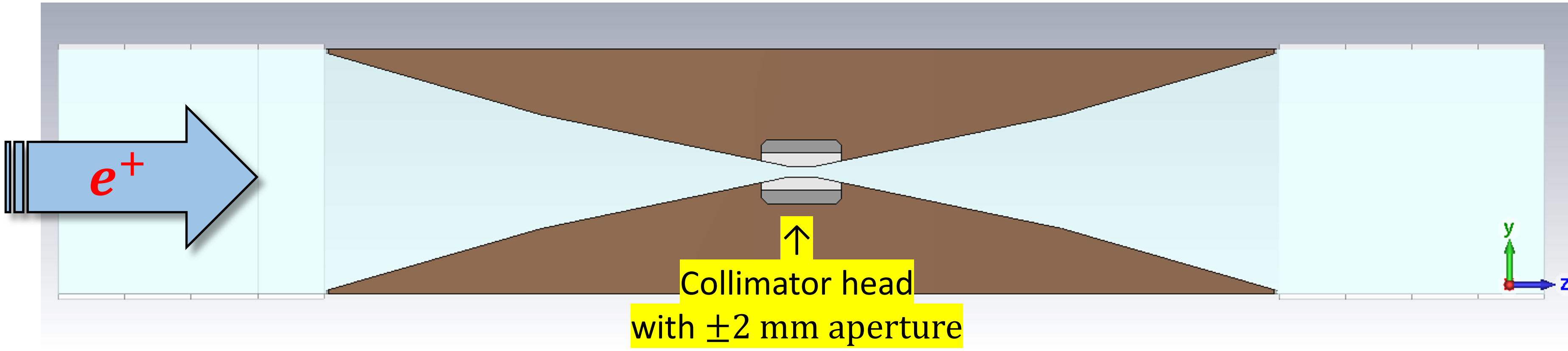
	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	923	534	759	421	673	362
0.05	1687 (0.4)	904	1347 (0.4)	695	1175 (0.5)	589
0.10	1625 (1.0)	877	1284 (1.1)	668	1113 (1.3)	564
0.50	1799 (3.7)	940	1423 (4.0)	718	1235 (4.3)	607
1.00	1830 (7.0)	896	1449 (7.4)	679	1258 (7.9)	570

The results show that fireballs can be generated realistically if a submillimeter or smaller micro-particle gets to a few millimeters from beam bunches for a second with a low emissivity of the fireball material.

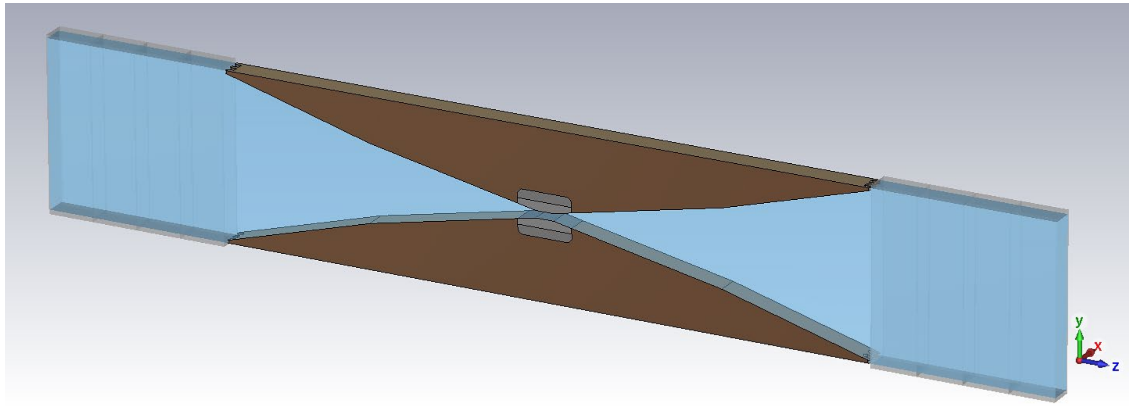
[Step C] Large transverse kick?

Simulation using a first-principle simulator CST / **P**article-**I**n-**C**ell (**PIC**) Solver

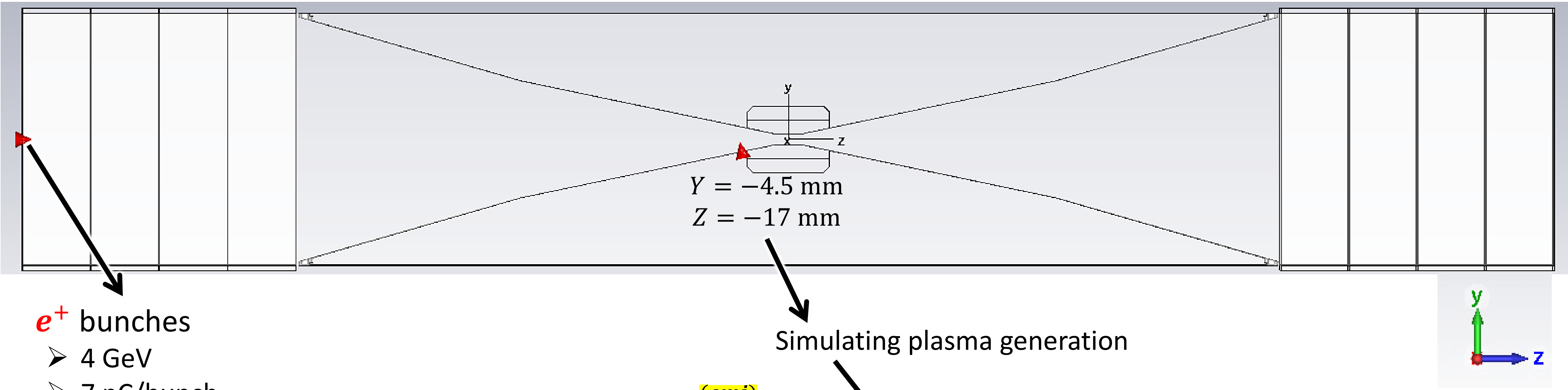




SuperKEKB Collimator Model

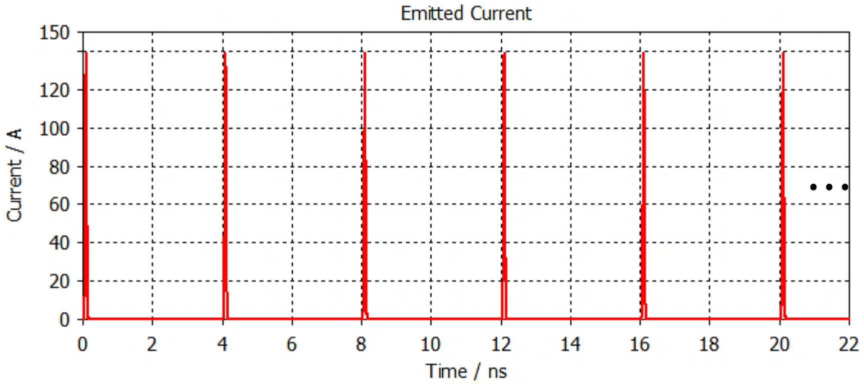


CST PIC Simulation / Particle Sources



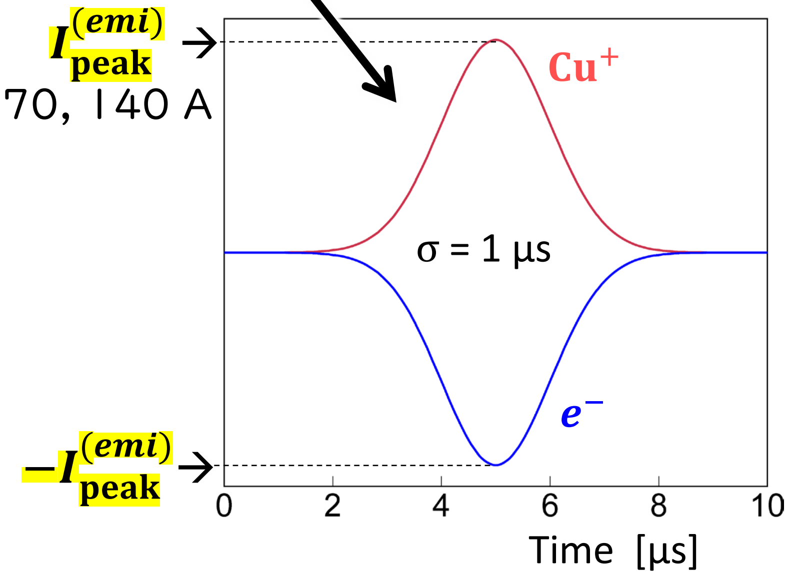
$Y = -4.5$ mm
$Z = -17$ mm

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



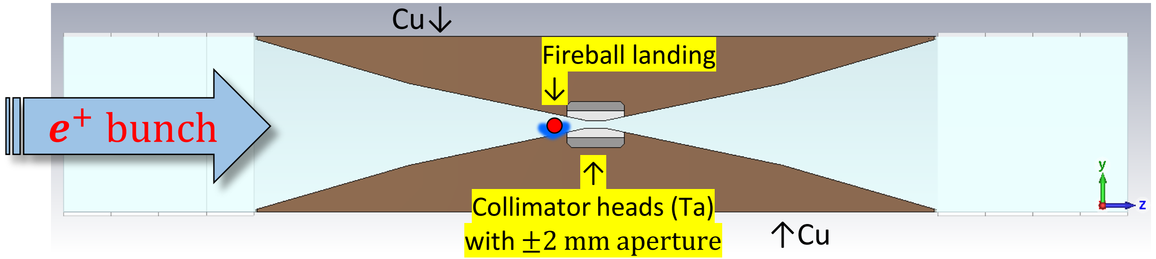
Simulating plasma generation

$I_{\mathrm{peak}}^{(emi)}$ = 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

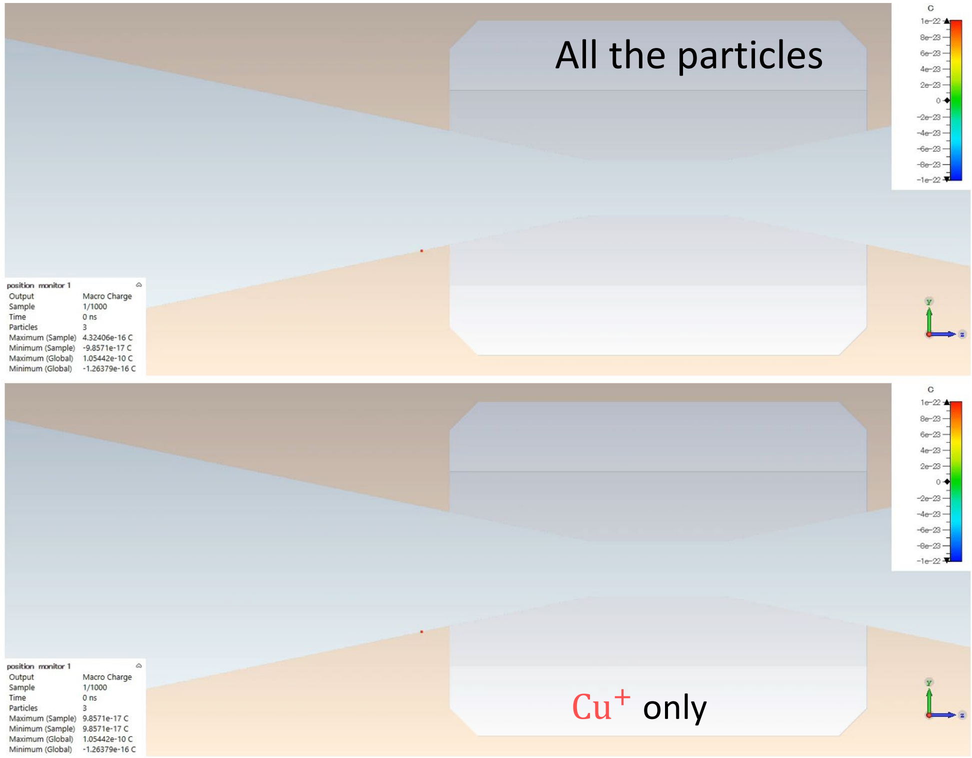


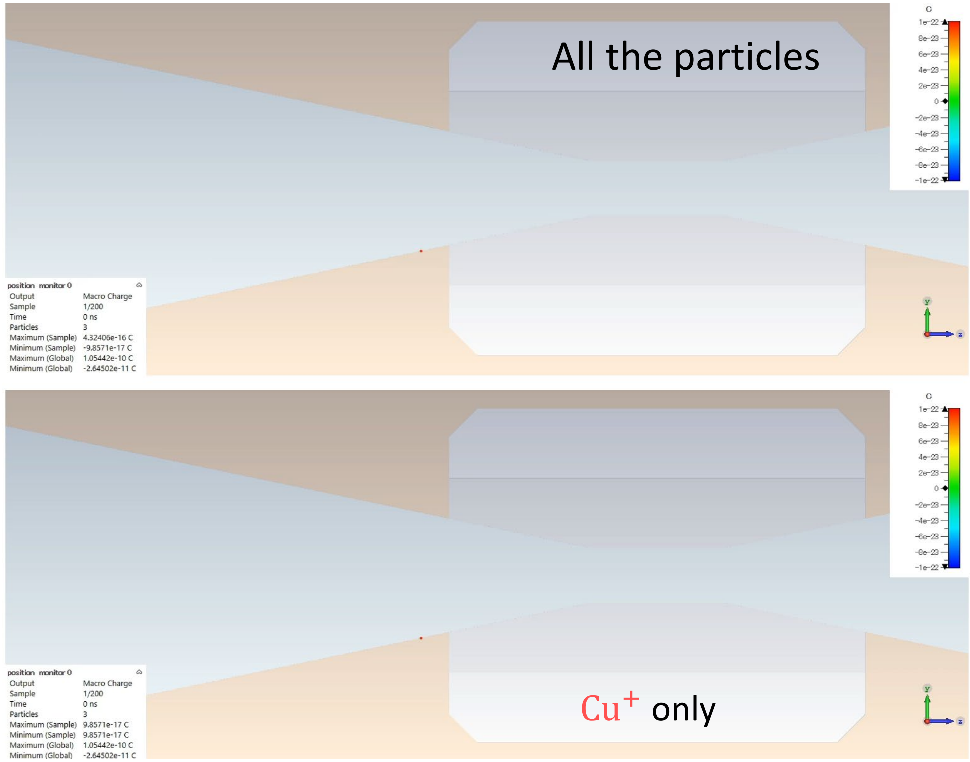
Full simulation of the dynamics of the LER e^+ and emitted e^- , Cu^+ and interactions among them

+ positive charge
– negative charge

(Short time range)

t = 0–50 ns





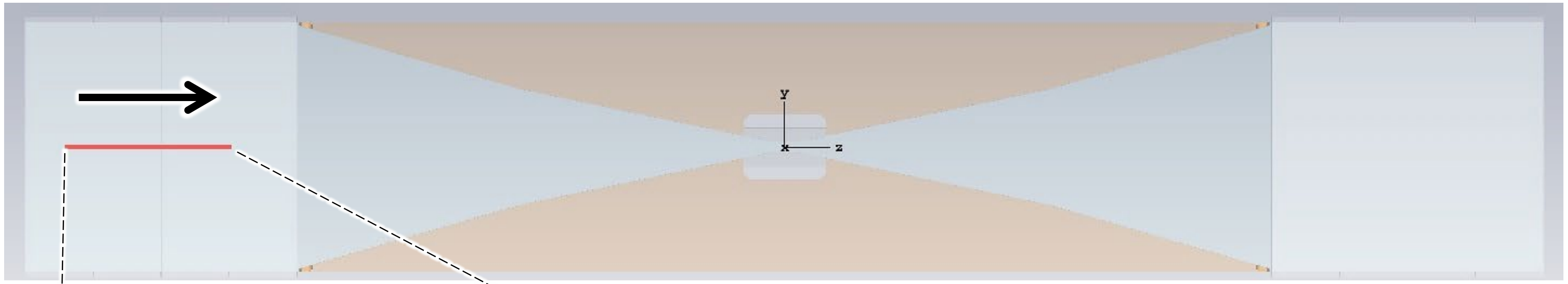
(long time range)

t = 0–10 μs

https://youtu.be/Ow0IX8bEB9g

https://youtu.be/5pHMwFmjSyo

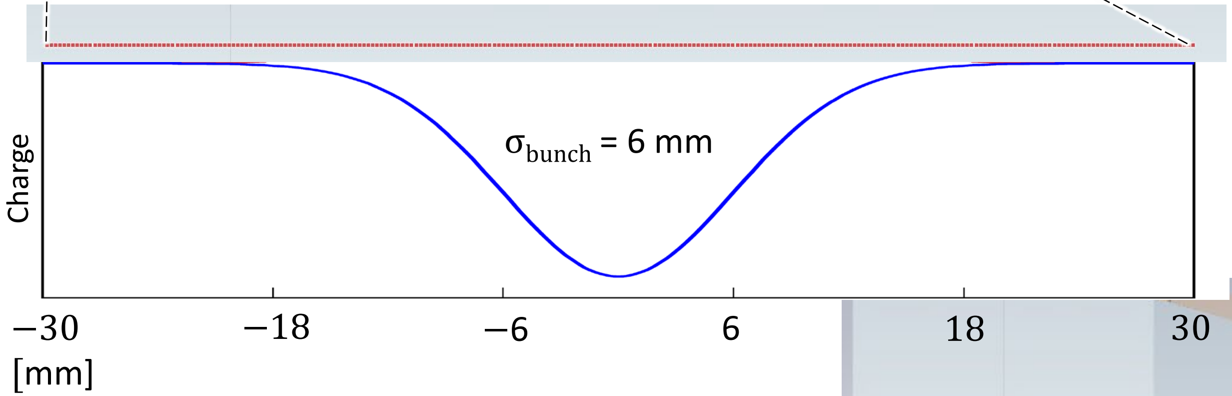
Calculation formula of the transverse kick



Initial state

$p_y^{(i)} = 0$

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



Final state

$$k_y = P_y / P_z$$

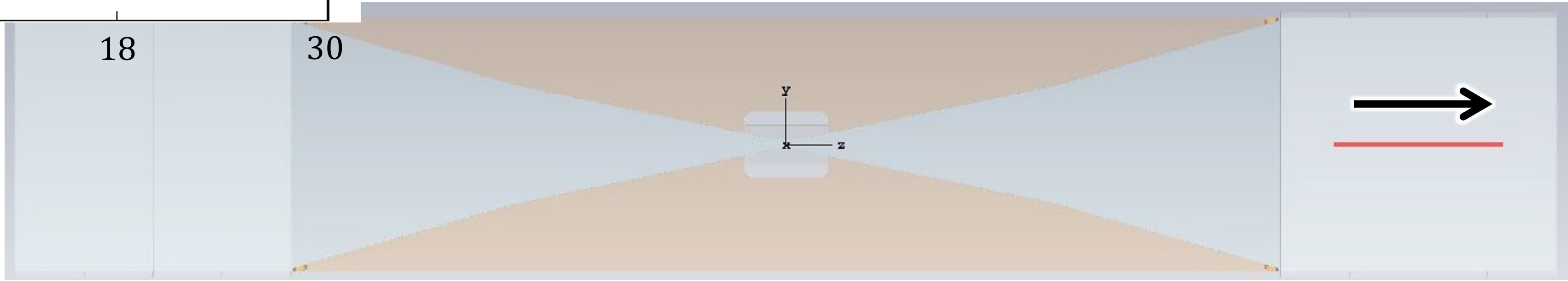
$$P_y = \frac{1}{Q_b} \sum_{i=1}^{N_{\rm mp}} p_y^{(i)} q^{(i)}$$

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

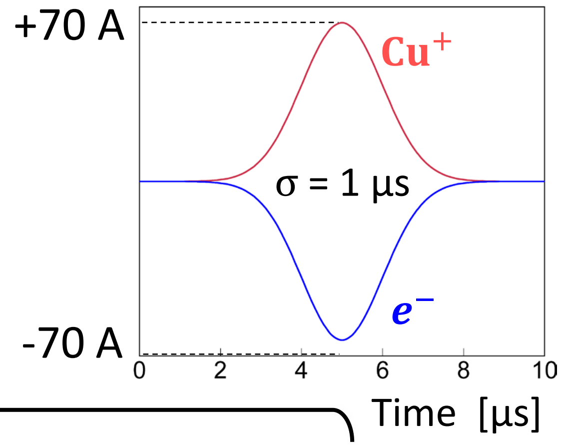
$p_y^{(i)}$: Y-momentum of particles in the i-th macro-particle

$q^{(i)}$: Charge of the i-th macro-particle

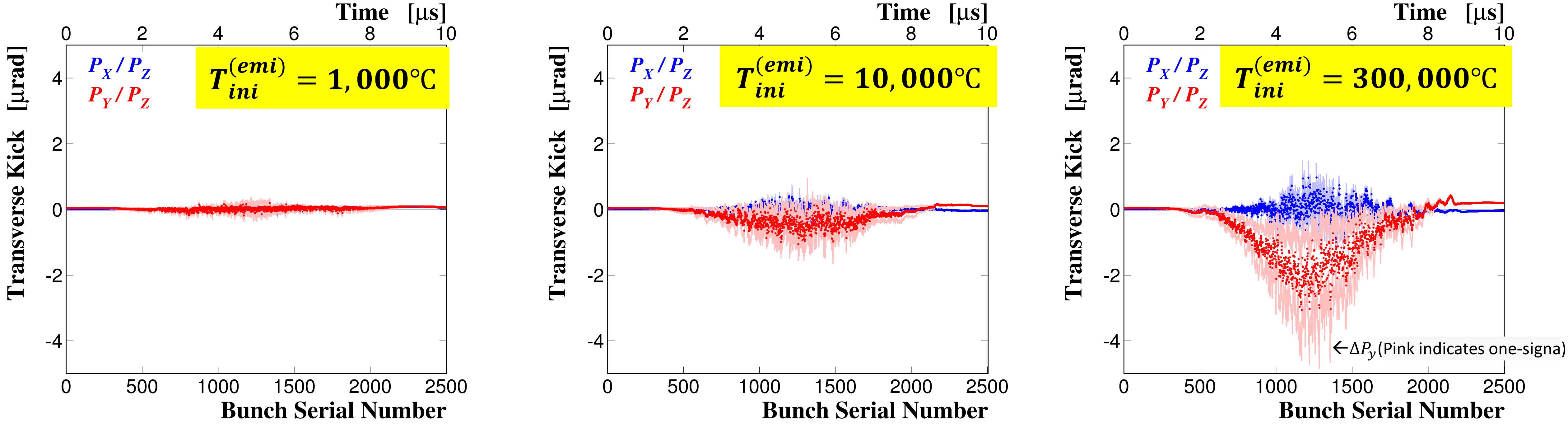
Q_b: Bunch charge



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



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

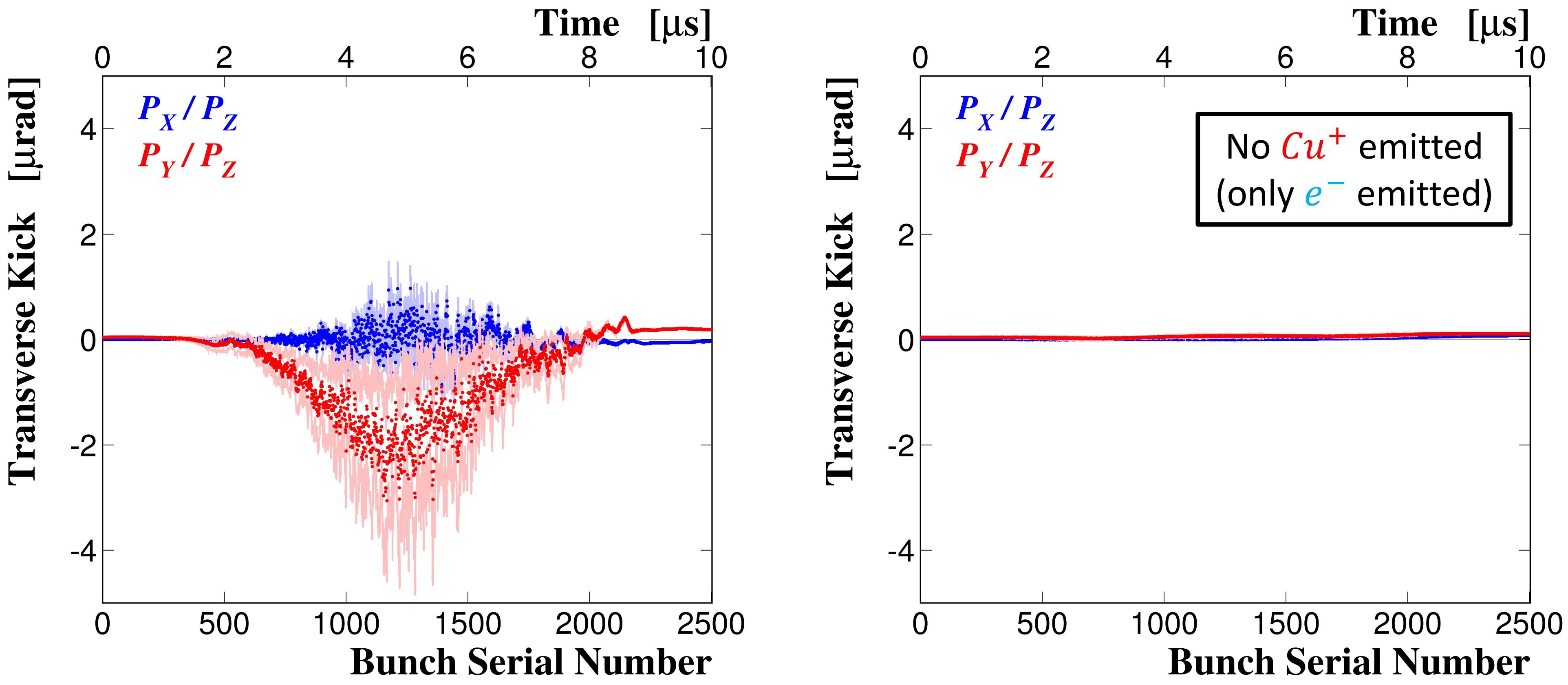


(Kick angle does not increase with any further increase in initial temperature.)

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

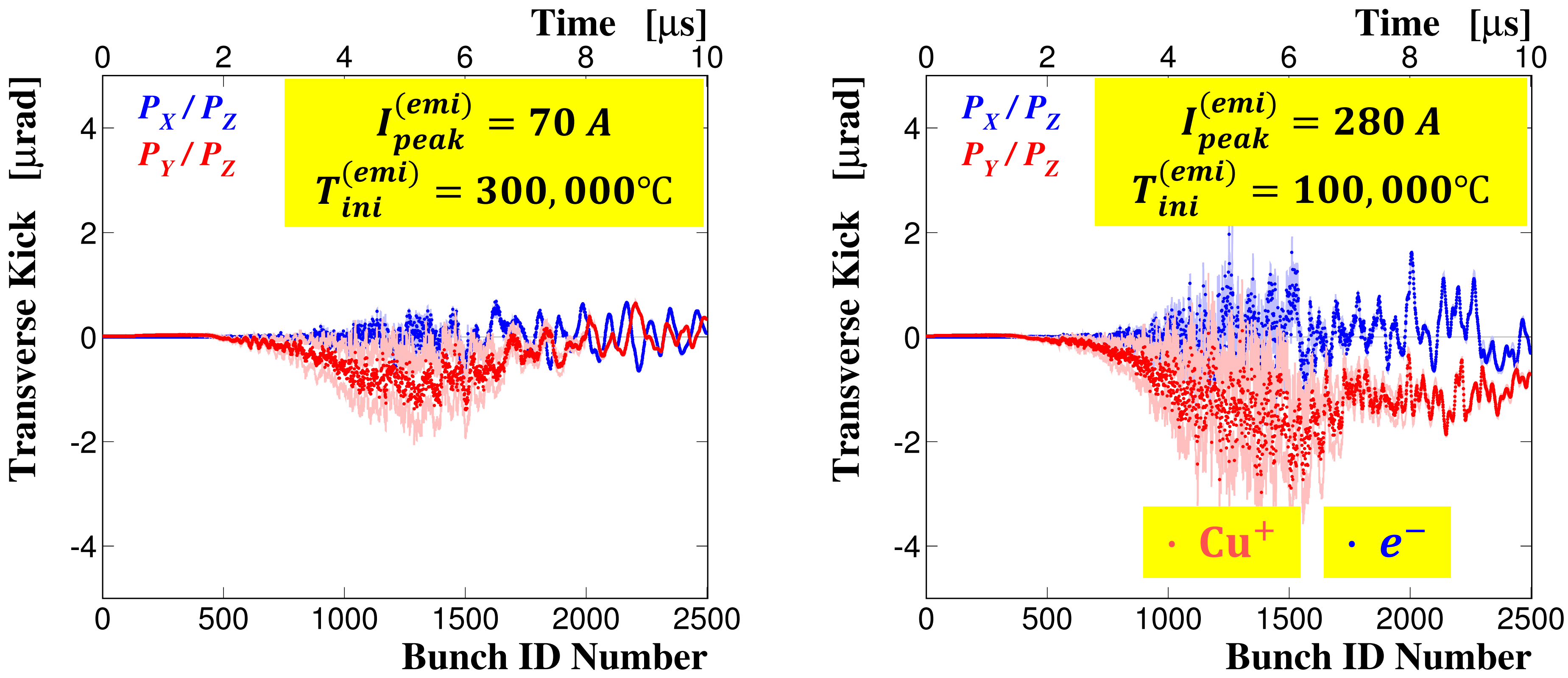
Comparison between w/ and w/o Cu^{+}

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



Cu^{+} pushes up the space charge limit of emitted e^{-}

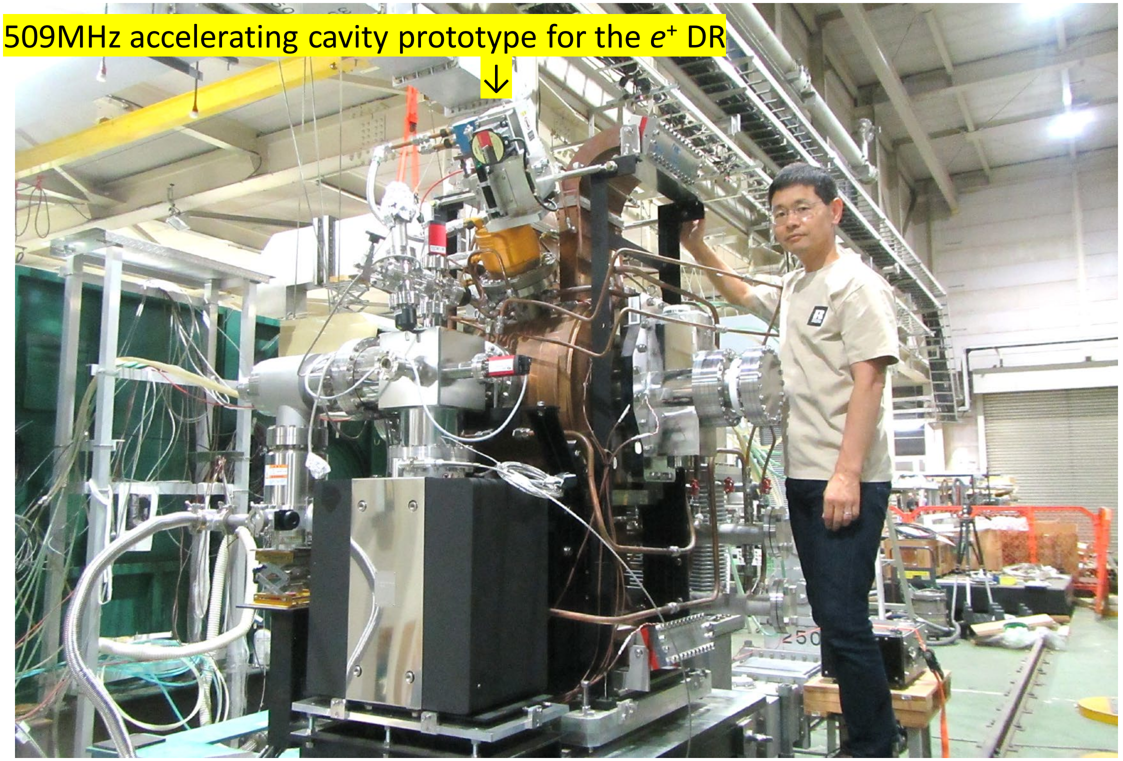
Transverse kicks for HER (e^-) beams bunches



- ✓ Looks different from LER(e^+)
- ✓ Under detailed study

Relevant experiment on-going!

High-power RF-cavity test stand (MR-D1-AT)

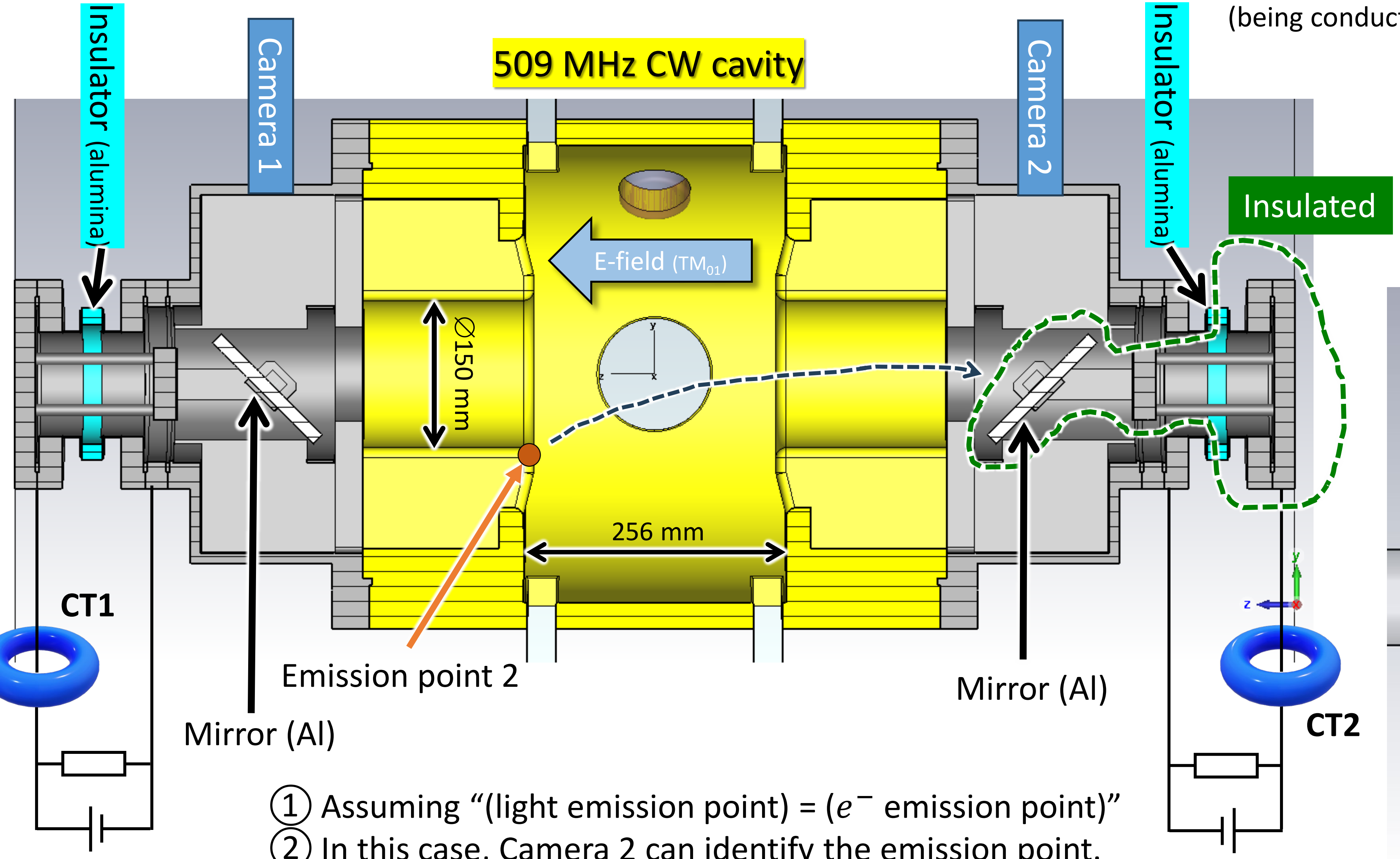


The RF-field level and time structure in the RF cavity are roughly the same as those at the collimators,
so that we can estimate the fundamental parameters of the FB hypothesis from the RF-cavity high-power test.

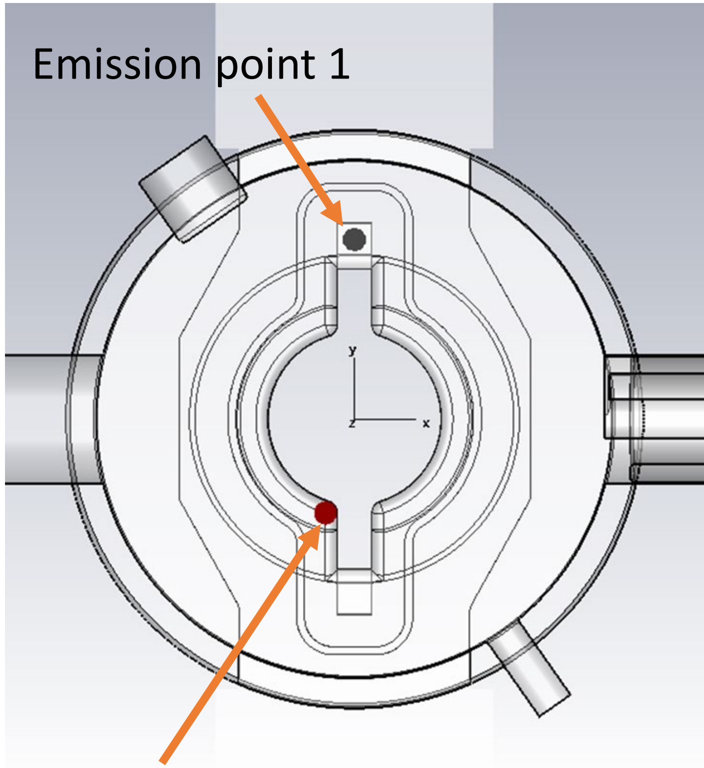
We are now trying to measure "total" breakdown current ($\approx I_{peak}^{(emi)}$)

Measurement of total breakdown current

(being conducted by Takaaki YAMAGUCHI (KEK))



Suggests huge currents (peak)
(> 100A!?)



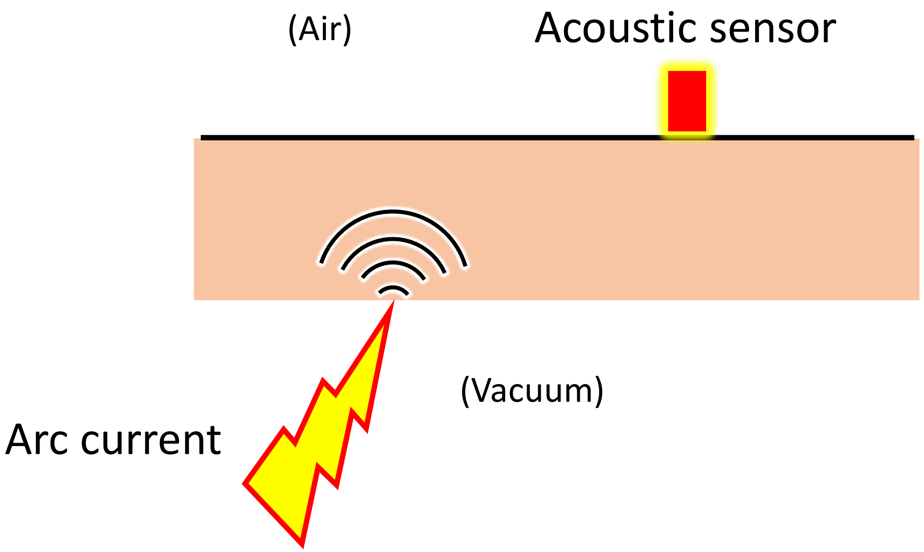
① Assuming "(light emission point) = (e^- emission point)"
② In this case, Camera 2 can identify the emission point.
③ Percentage of e^- reaching the mirror to be estimated with PIC sim.

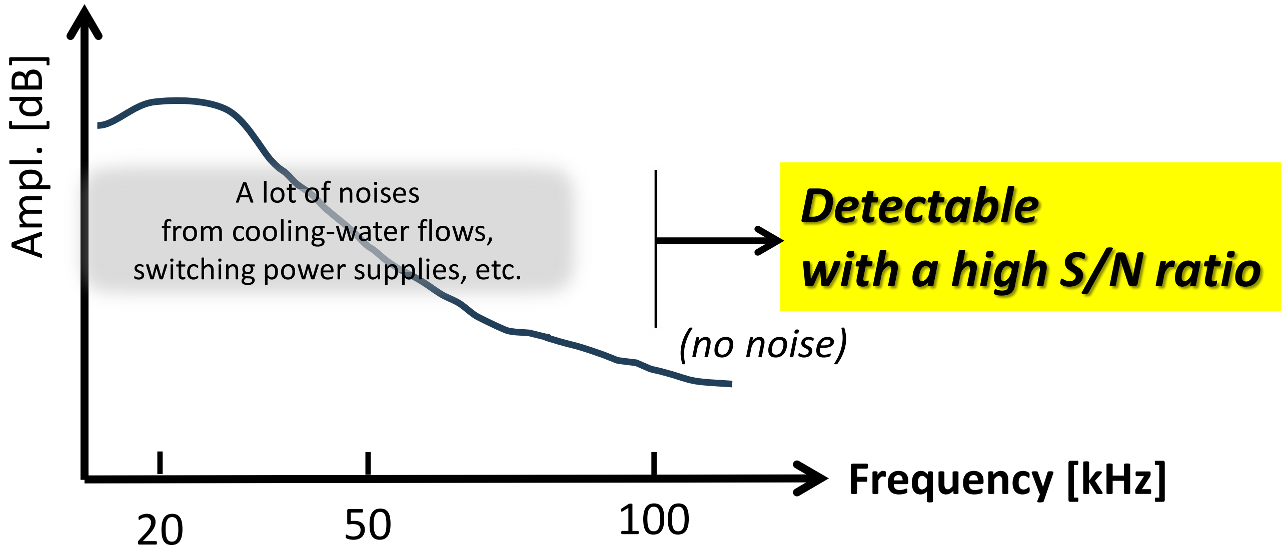
Acoustic Observation to detect vacuum arcs

Why Acoustic Observation?

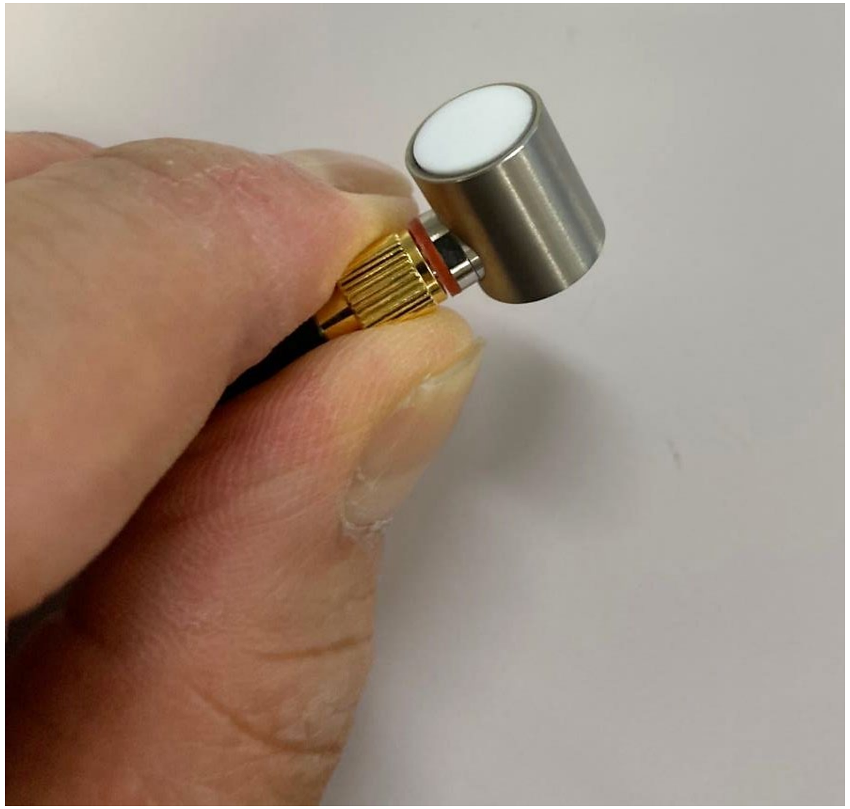
■ How to detect vacuum arcs through:

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.

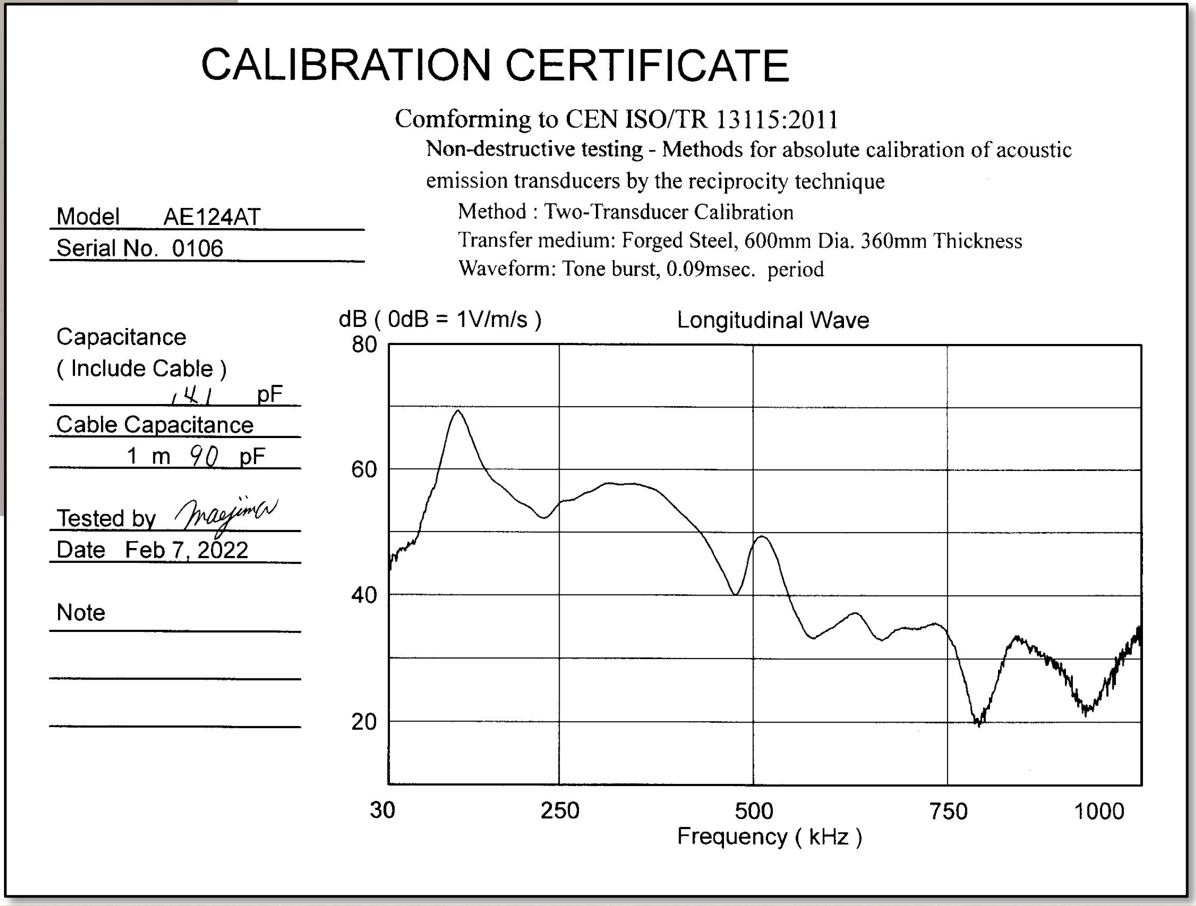




Acoustic sensor used in this observation: AE124AT



- ✓ 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

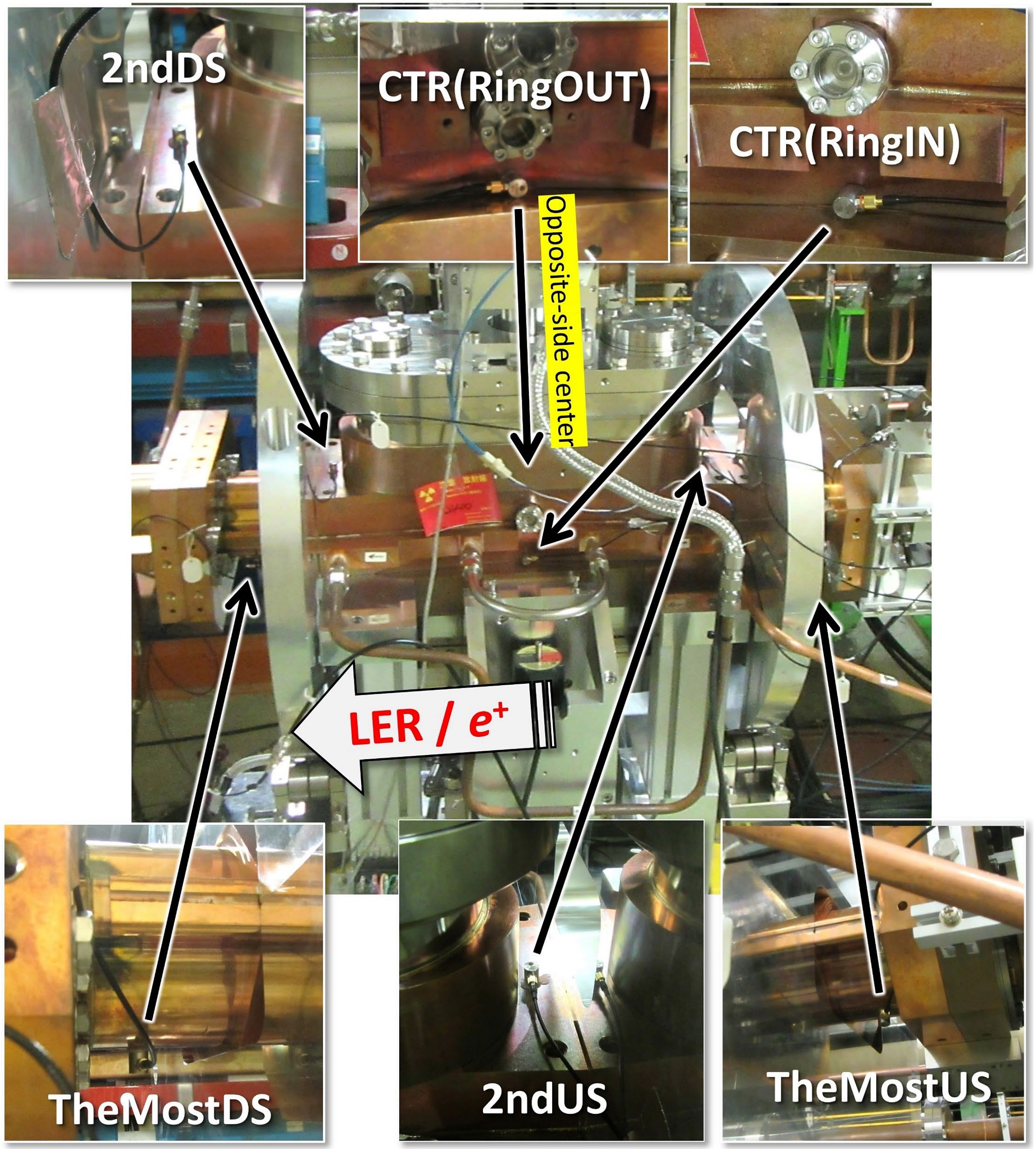
Tested by
Date Feb 7, 2022

Note

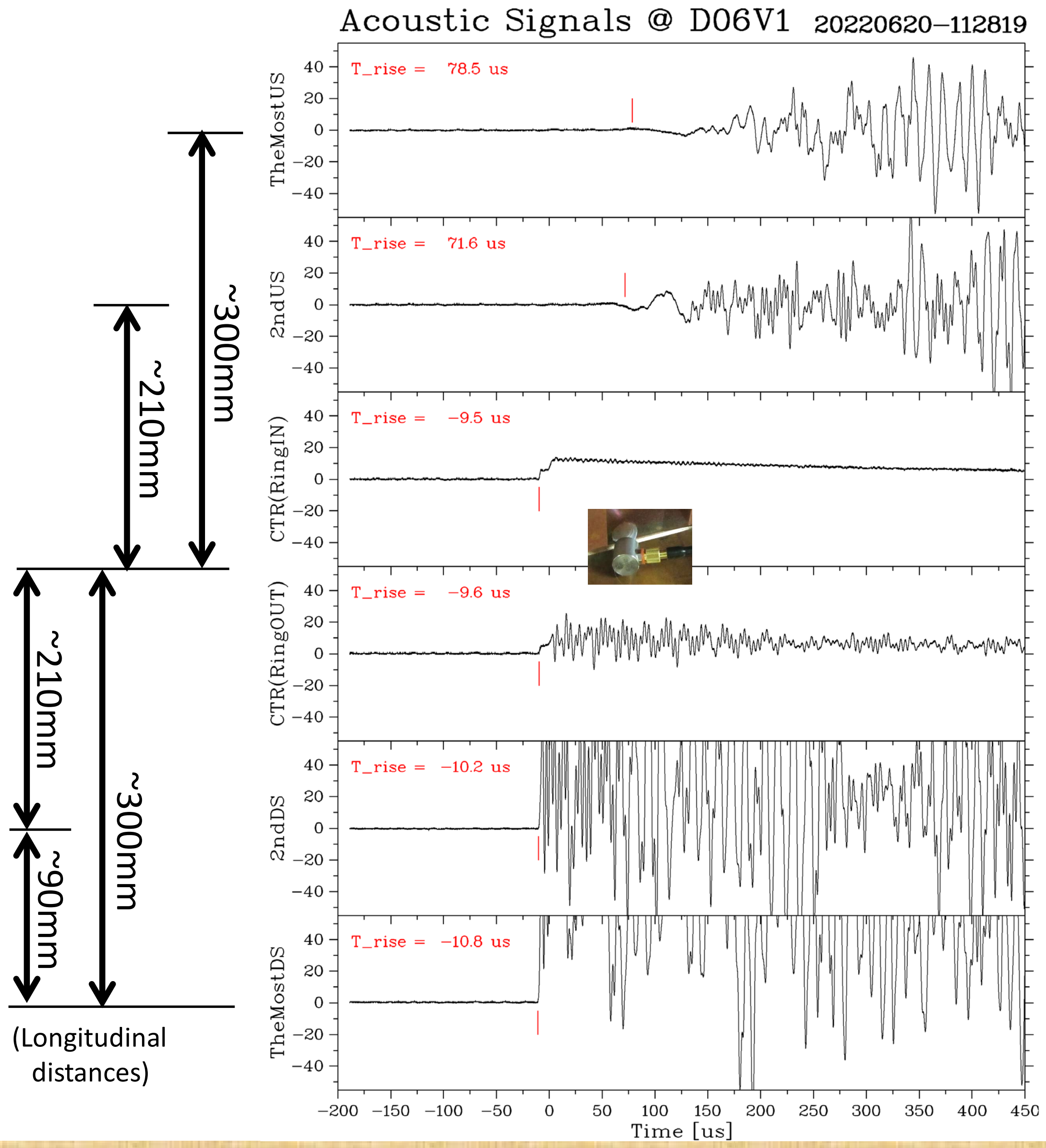
(Selection by Toshiyasu HIGO (KEK/e+e-Linac))

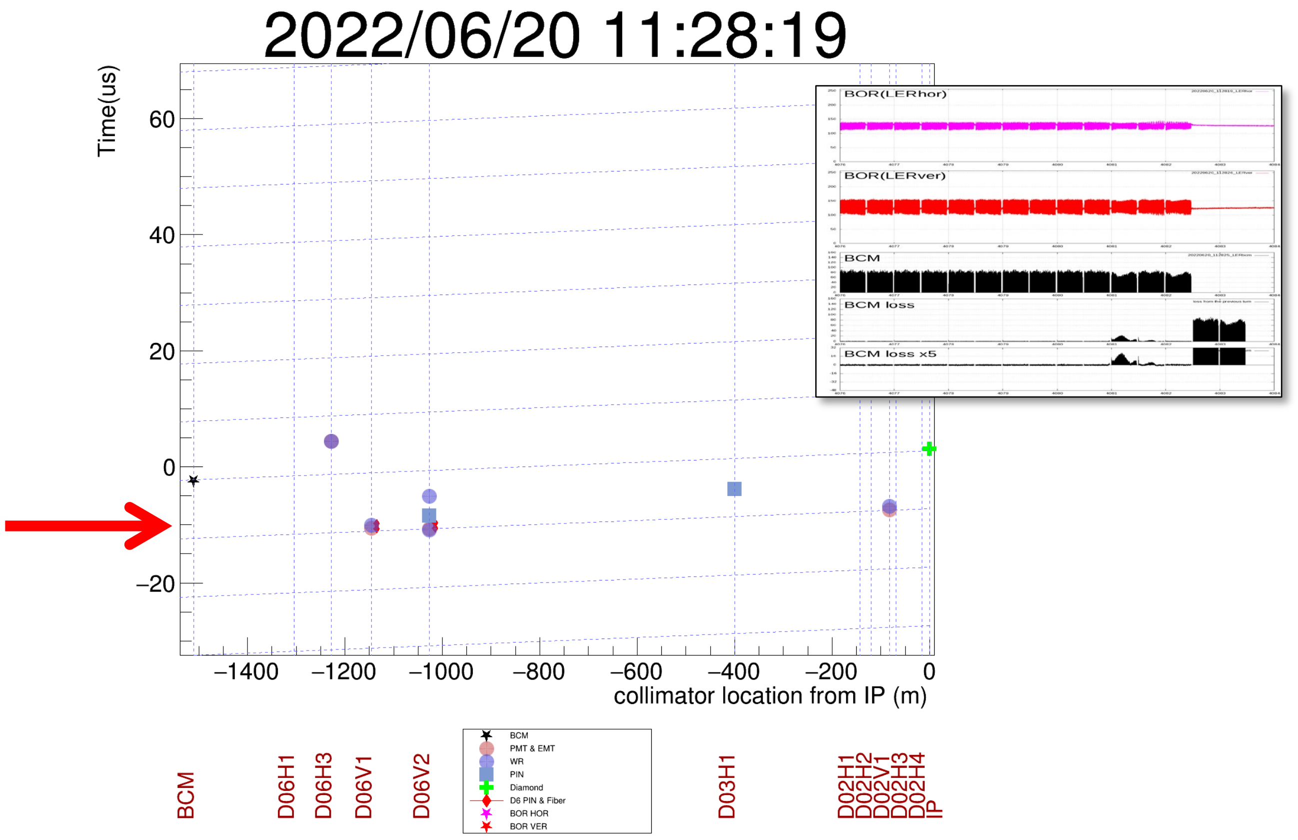
Six sensors attached to LER D06V1 collimator at the end of 2022ab

Hot melt glue was used



2022ab / LER_{1299mA} sudden beam-loss abort : Example (CLAWS and Diamond)





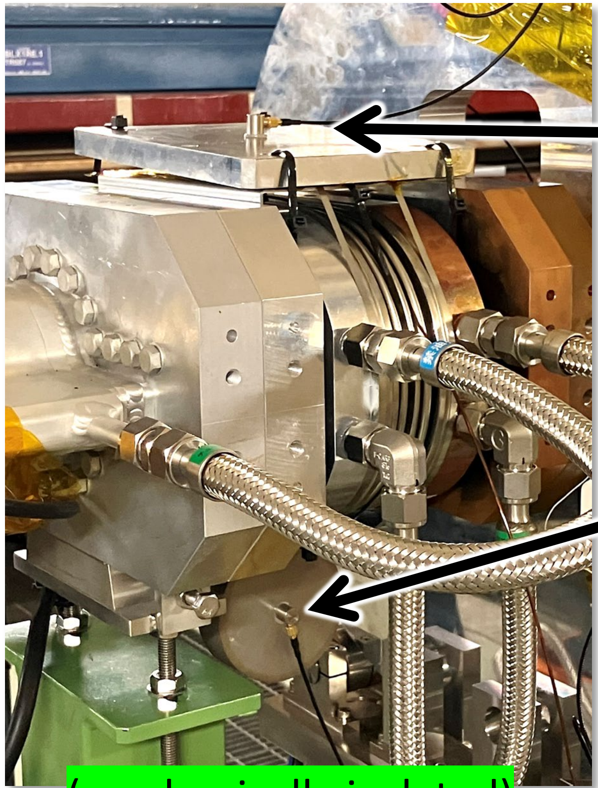
Velocity of acoustic longitudinal (transversal) wave in copper: 4.65 (2.26) mm/us

This data suggests that the particle shower produced at the collimator head generated widespread acoustic wave in the downstream of the head, which propagated upstream.

During LS1, we attached acoustic sensors for D02V1 and D05V1 (NLC) collimator

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

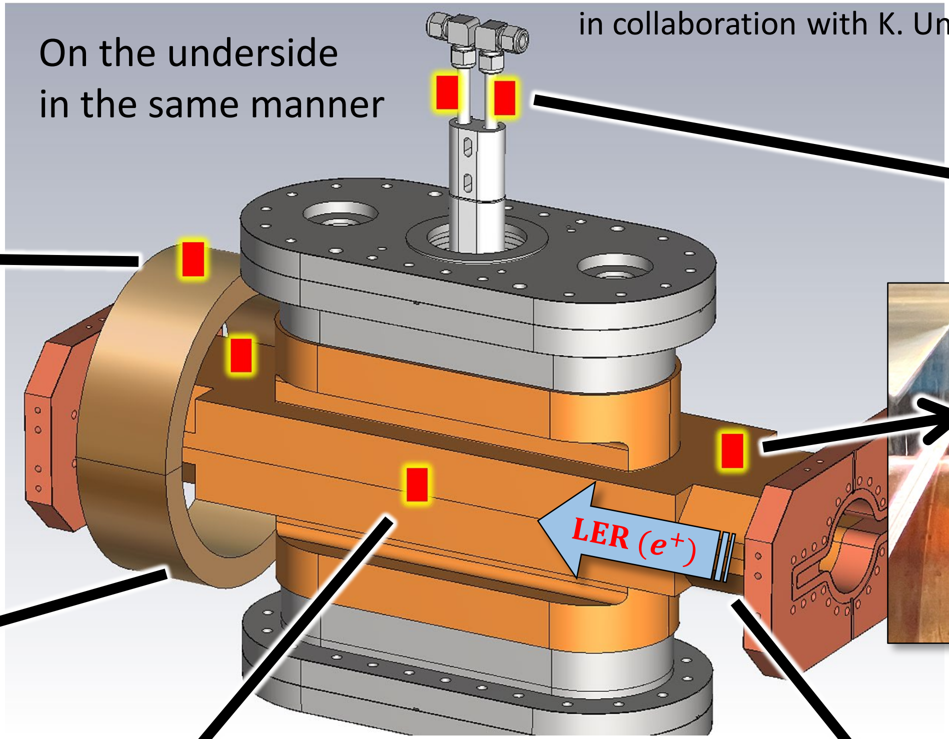
Acoustic loss monitor

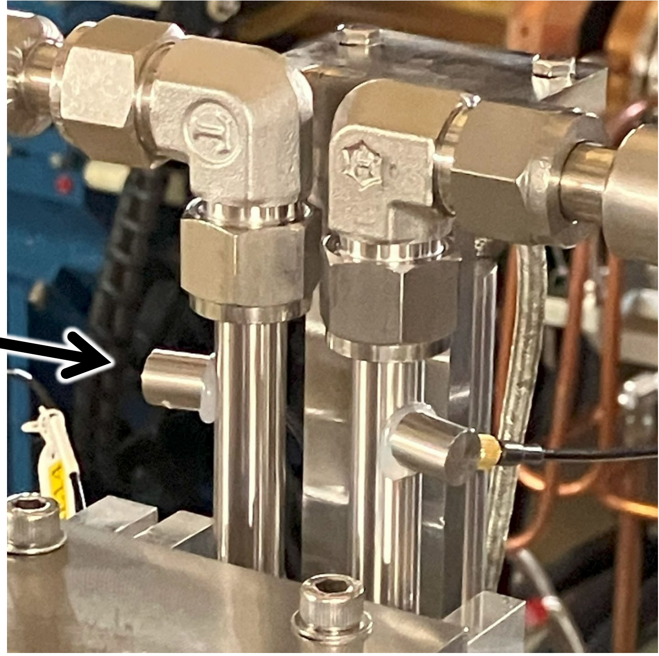


(mechanically isolated)

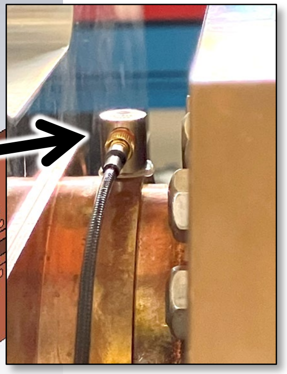
Can hear particle showers

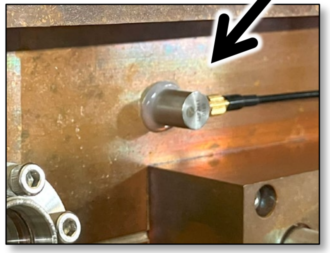
On the underside in the same manner

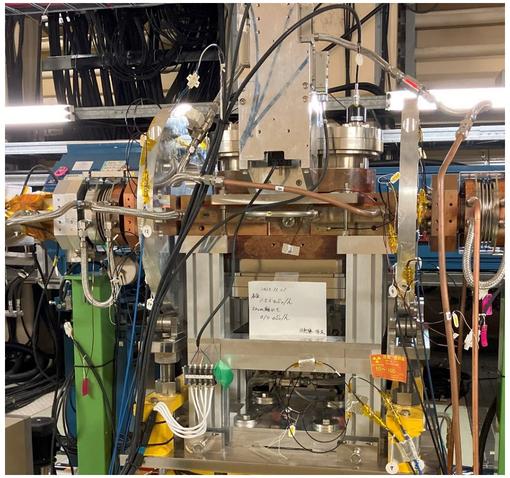


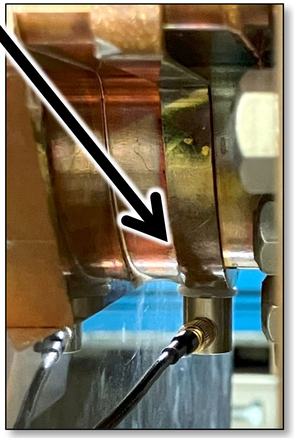


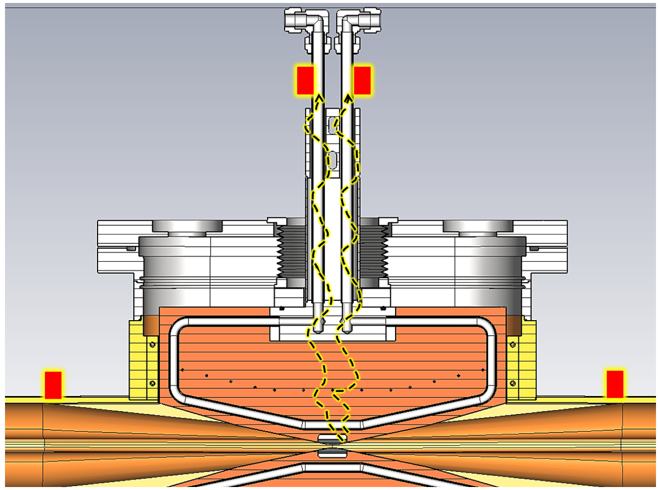
Can hear AE around the head.





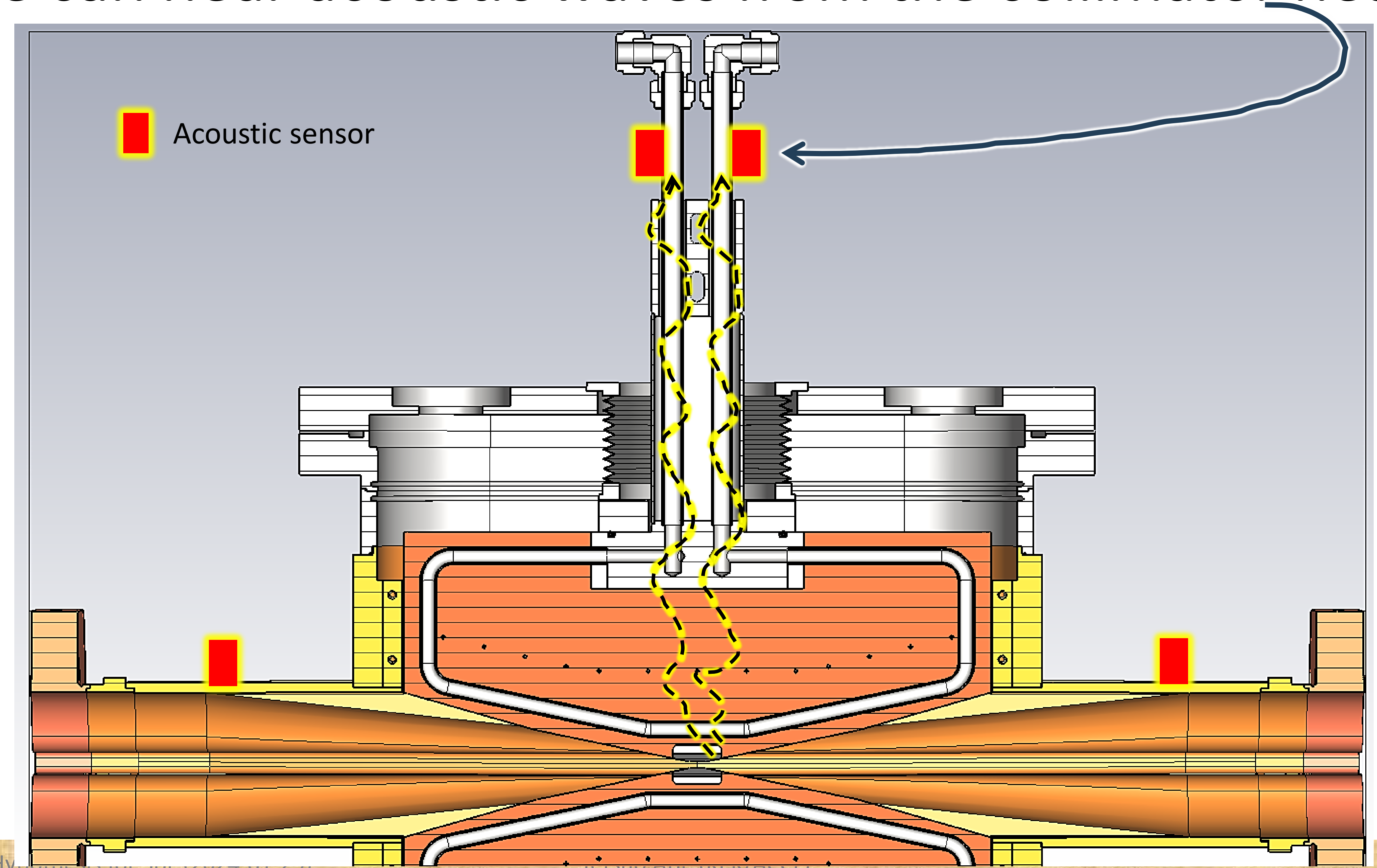






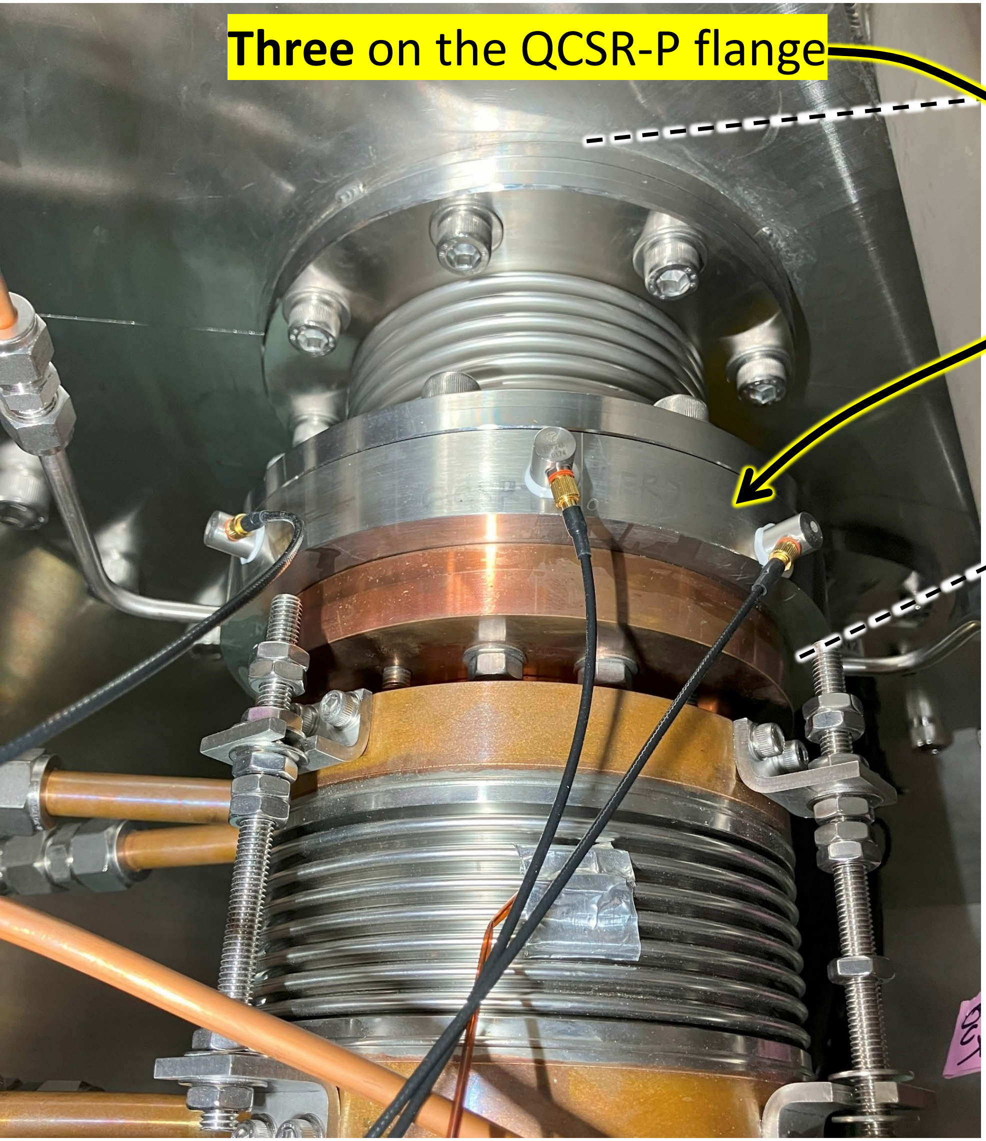
In the same manner for D05V1 collimator (NCL)

We can hear acoustic waves from the collimator head.

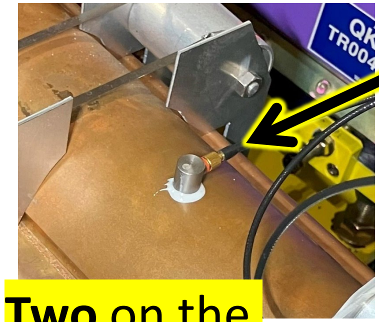


Five Acoustic-Emission (AE) Sensors around QCSR-P

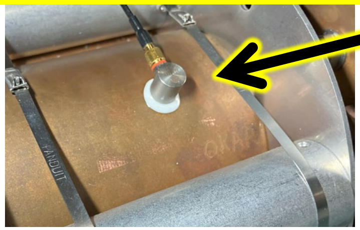
Three on the QCSR-P flange

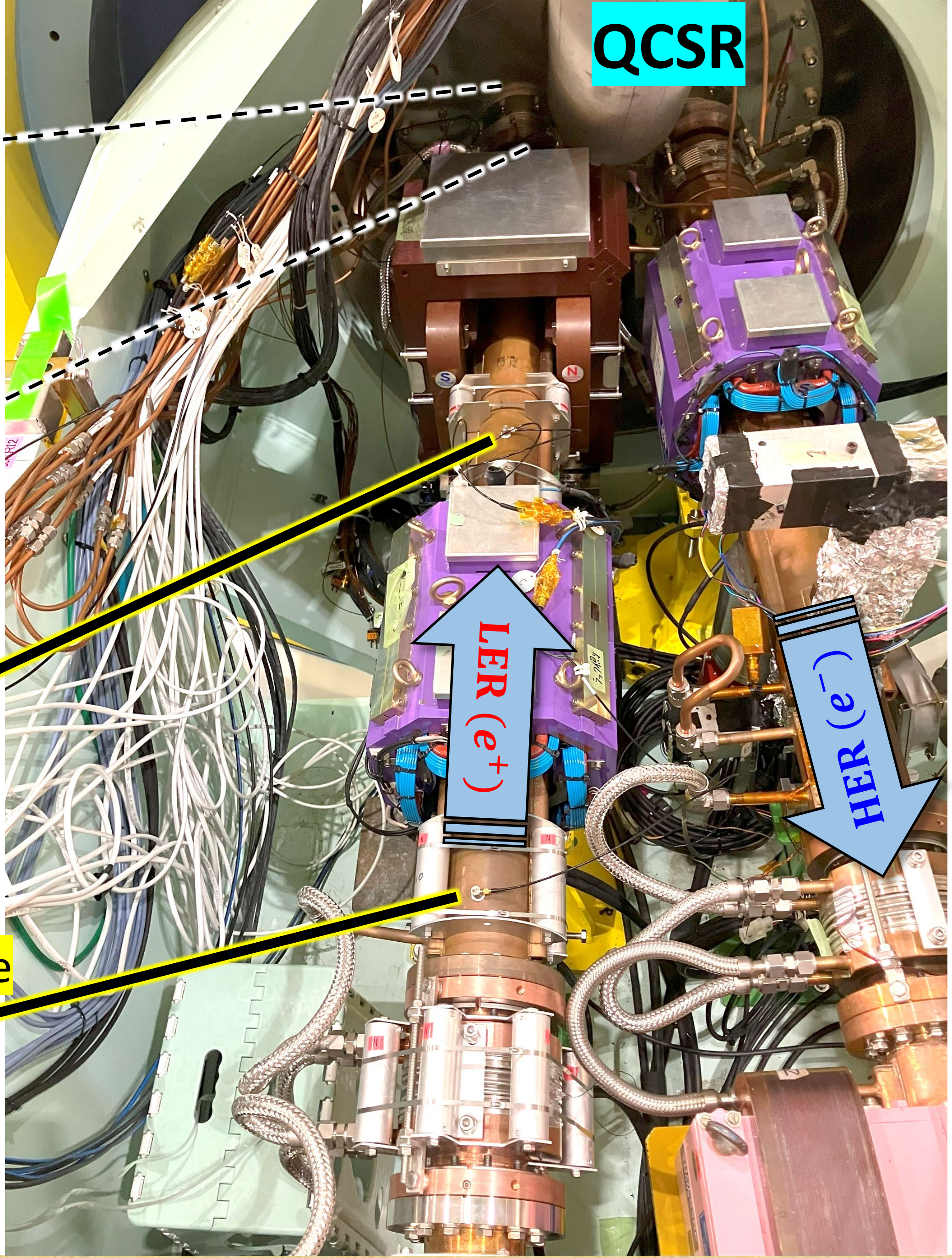


Y. Arimoto,
K. Uno, and
T. Abe



Two on the
upstream beam pipe





Can hear acoustic waves from the beam pipe in QCSR-P

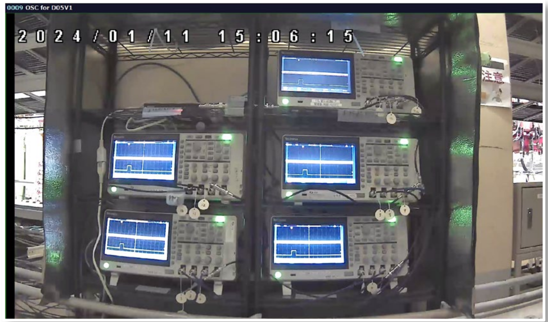
(A possible trigger of vacuum arcs in QCS was noted by Shinji TERUI.)

Oscilloscopes and DAQ

The oscilloscopes to be triggered by the LER beam-abort signal or “Manual signal”

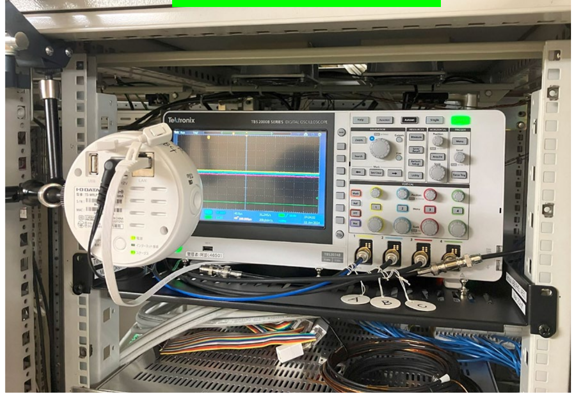
In the D5 sub-tunnel

In the D2 sub-tunnel



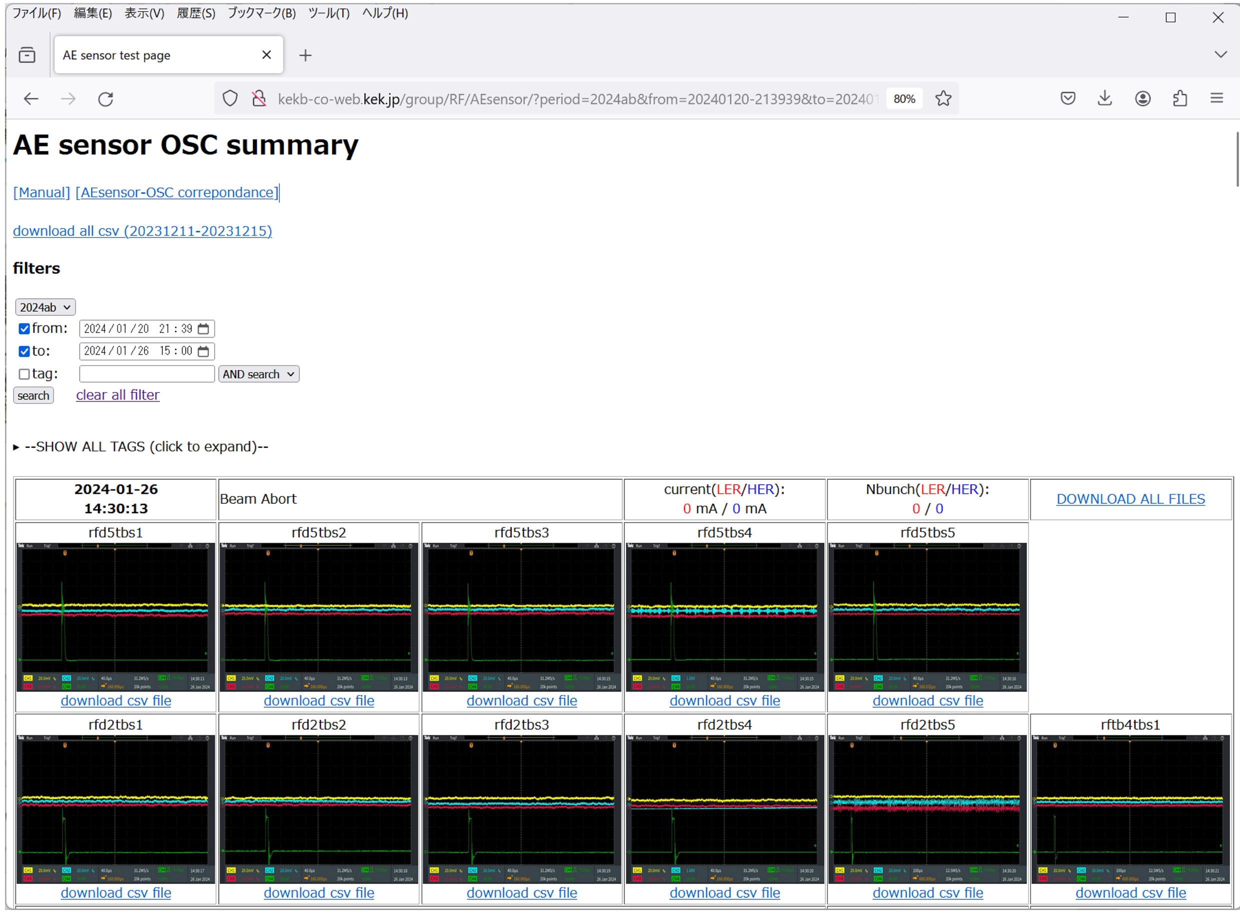
Oscilloscopes should be put near the collimators because of the small analog signals from the acoustic sensors (~0.1 mV at min.)

In Tsukuba B4



✓Created and maintained by Shunto OGASAWARA
✓Updated every LER beam abort (auto.) or “Manual get”

http://kekb-co-web.kek.jp/group/RF/AEsensor/index.php



Summary

- **The SuperKEKB collimators satisfy the occurrence conditions of FB-triggered SBL**:
  - Coexistence of different materials with largely different sublimation/melting points in the same place
  - Small physical apertures ($\pm$ 1 mm at min.)
    - More chance of producing fireballs
- **First principle simulation study of the FB hypothesis** on-going
  - Several μrad kicks at the collimator possible
  - Funakoshi-san's study based on the loss pattern at the SBLs suggests several tens of μrad kicks needed for SBL.
  - Further study with other simulation parameters on-going
- We are conducting the **high-power experiment to measure the fundamental parameters of the fireball hypothesis** to prove it.
- We have established the **acoustic observation system** to detect a vacuum arc when SBL occurs.
  - 25 acoustic sensors attached to the two collimators with a sub-tunnel nearby
    - D02V1 (smallest physical aperture)
    - D05V1 (largest amount of scraped particles?)
  - 5 to the QCSR-P flange and chamber
    - Another mechanism?
  - Just started the observation in the 2024ab beam operation
    - We will make a new strategy for the next step based on observation results early in 2024ab.

Thank you for your attention

For more details on:

The fireball hypothesis

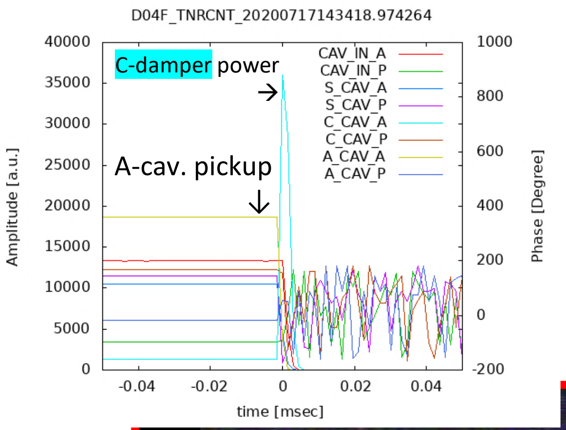
- T. Abe, "*Fireball Hypothesis for the Trigger of Sudden Beam Losses at SuperKEKB*", in Proceedings of the 20th Annual Meeting of Particle Accelerator Society of Japan, PASJ2023-TUP01 (2023).

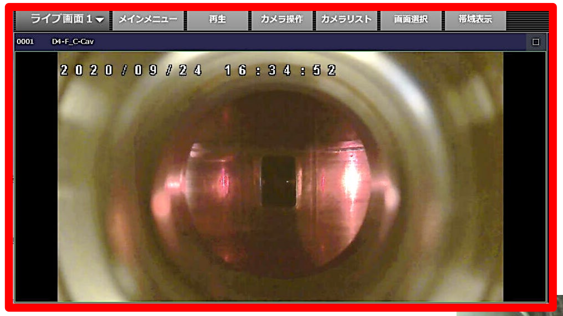
Fireball breakdown of RF cavities

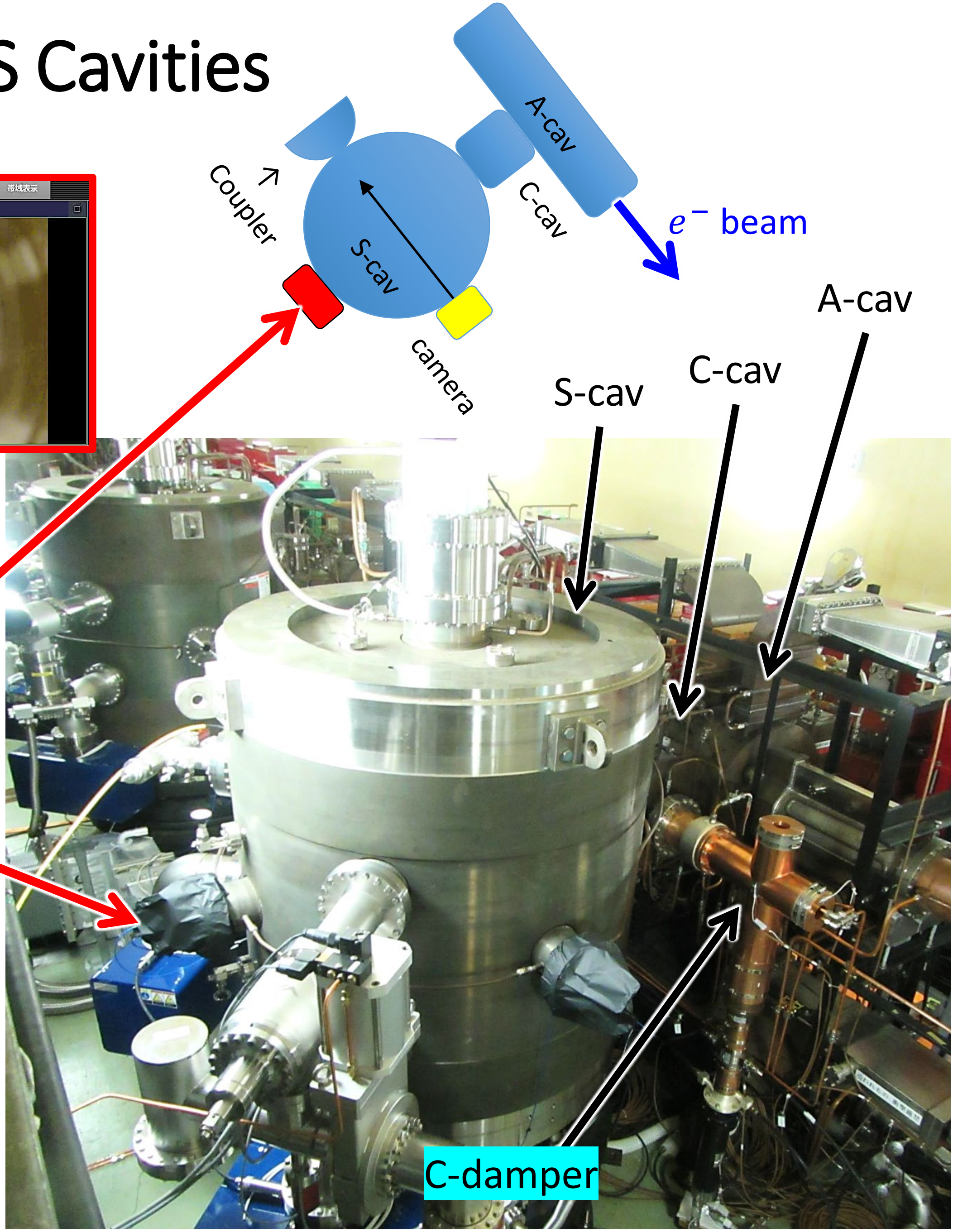
- **KEK Accl. Lab. Topics (web article)**
  - *"Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities"*
    - https://www2.kek.jp/accl/eng/topics/topics190122.html
- **Presentations at Workshops**
  - T. Abe, "*Direct Observation of Breakdown Phenomena in Normal-Conducting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

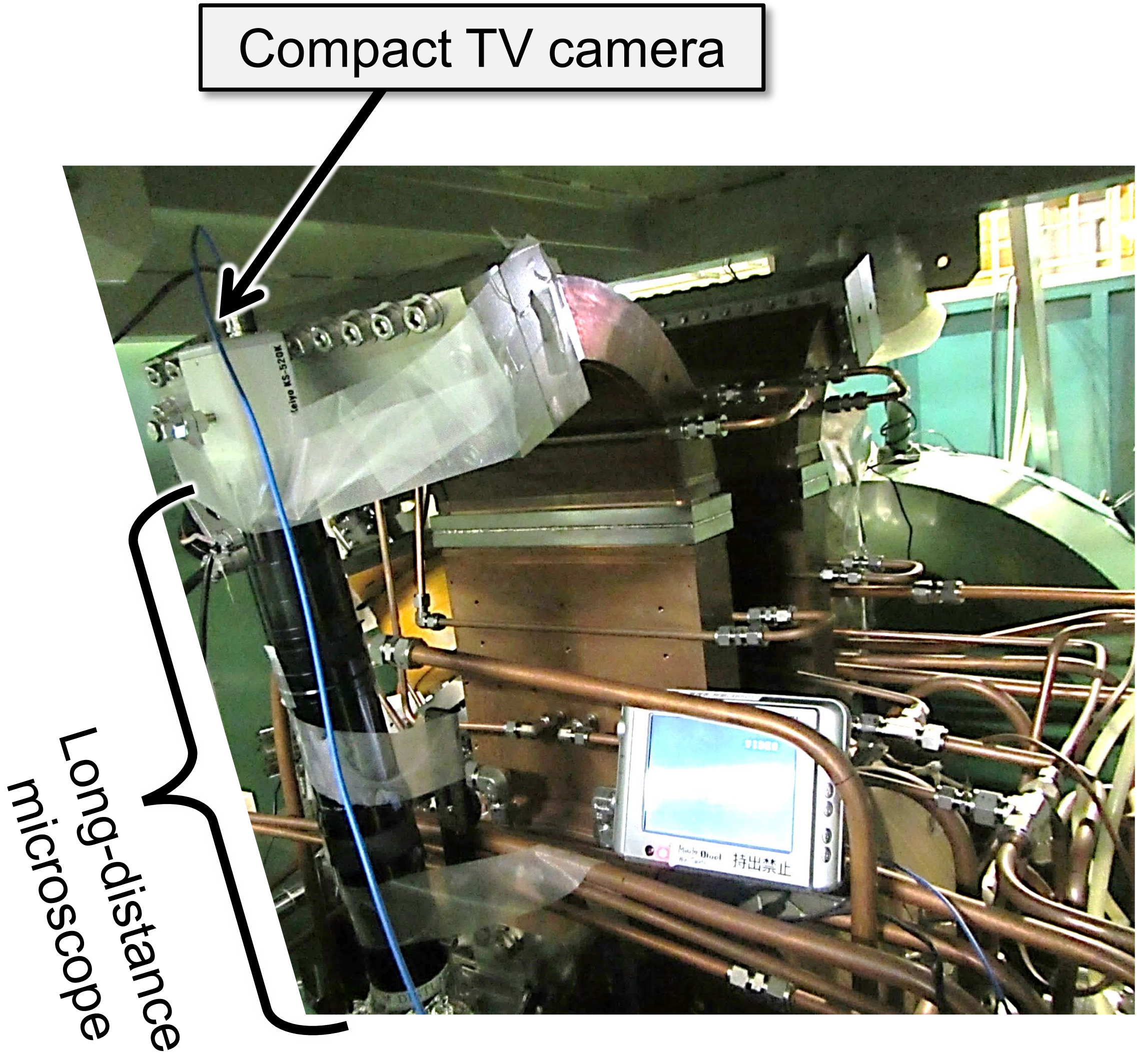






Video file: https://youtu.be/qtIB6kLf2j4

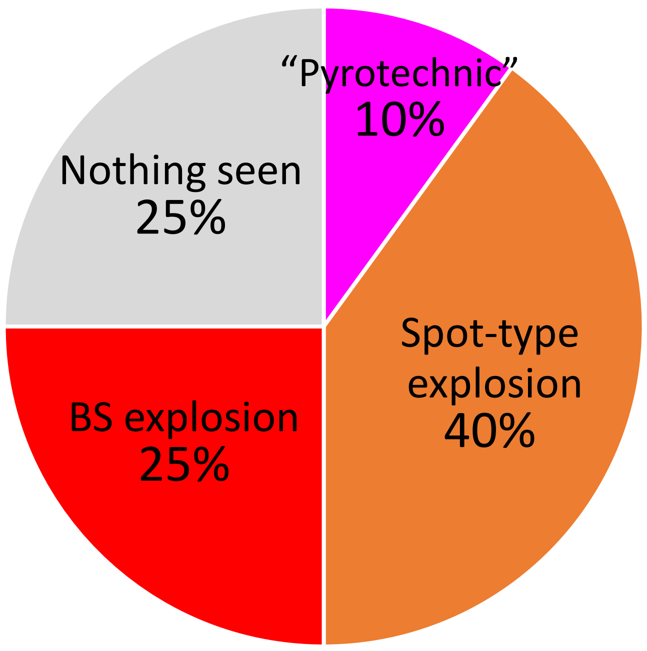
Observation of the FB size



≲ ~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.

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)

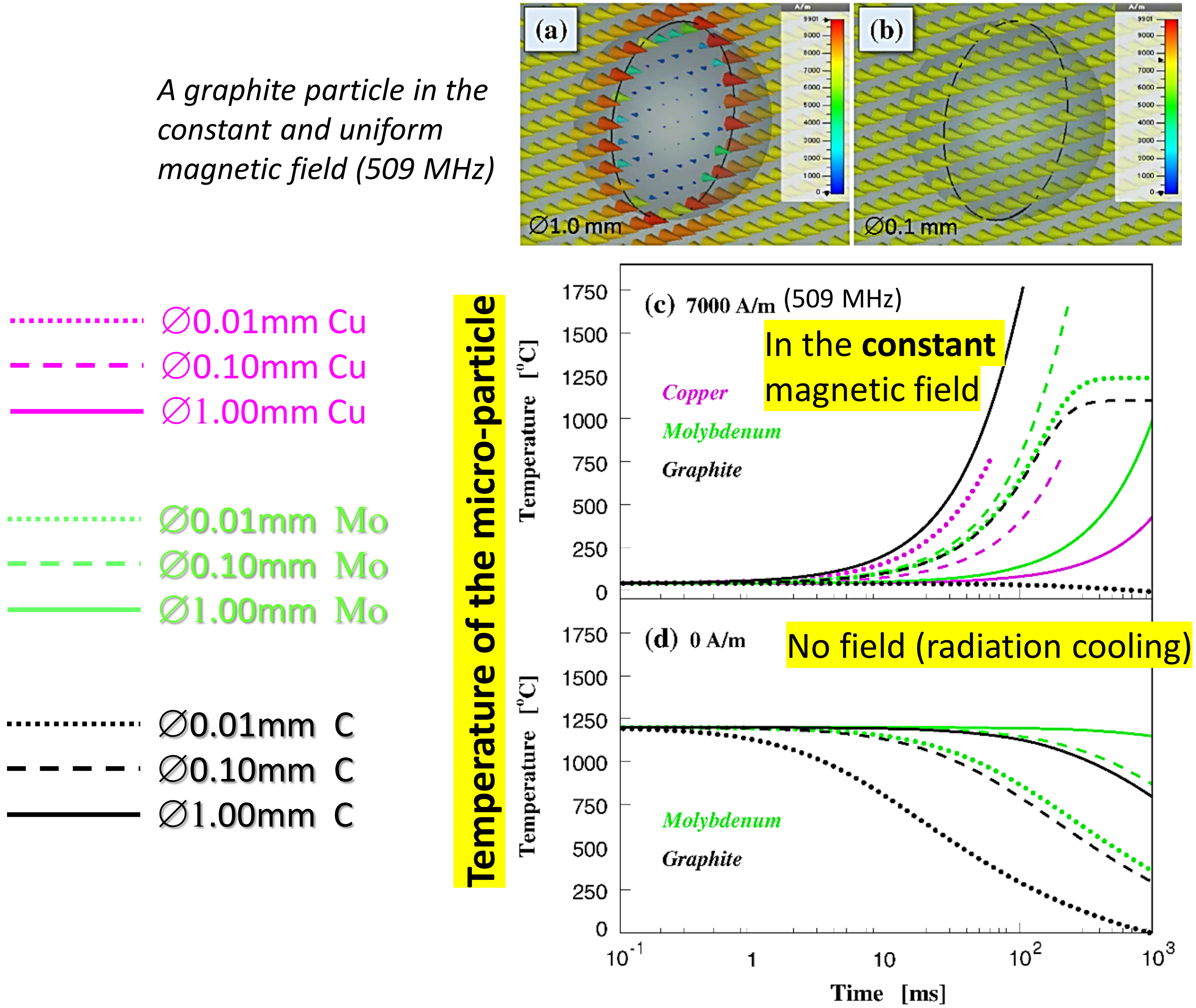
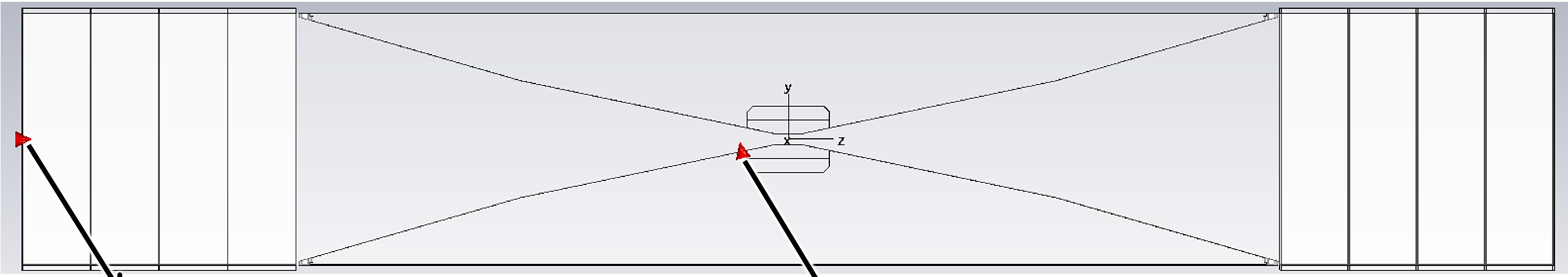


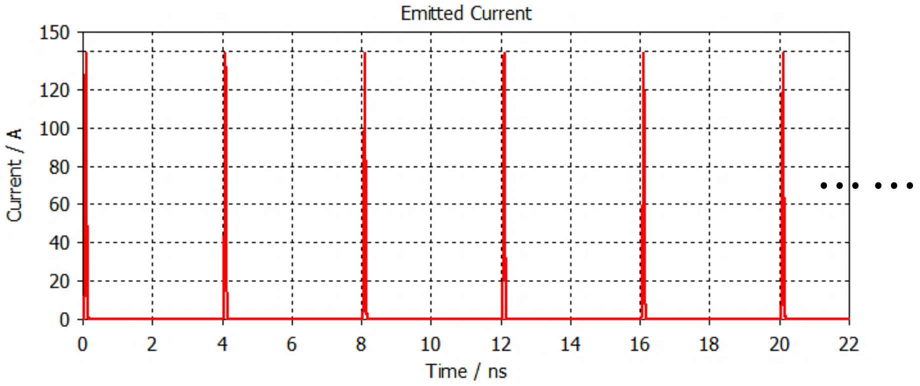
FIG. 22. Simulations of temperatures of spherical microparticles made of graphite (black lines), molybdenum (green lines), and copper (magenta lines) with diameters of 1.0 mm (solid lines), 0.1 mm (dashed lines), and 0.01 mm (dotted lines) located in a vacuum. Radiation cooling was calculated according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

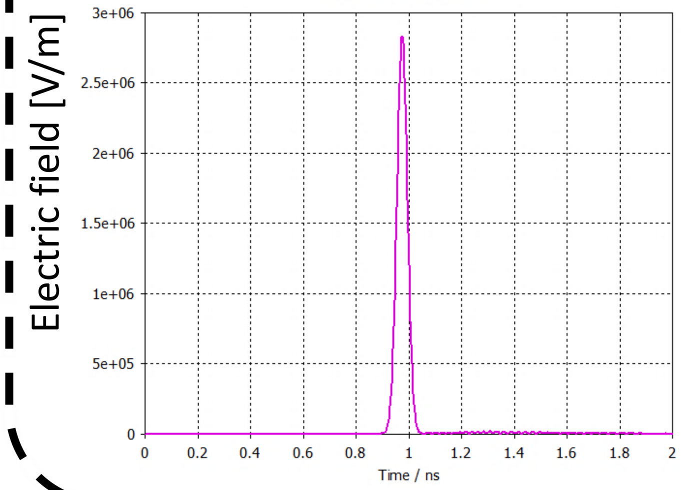


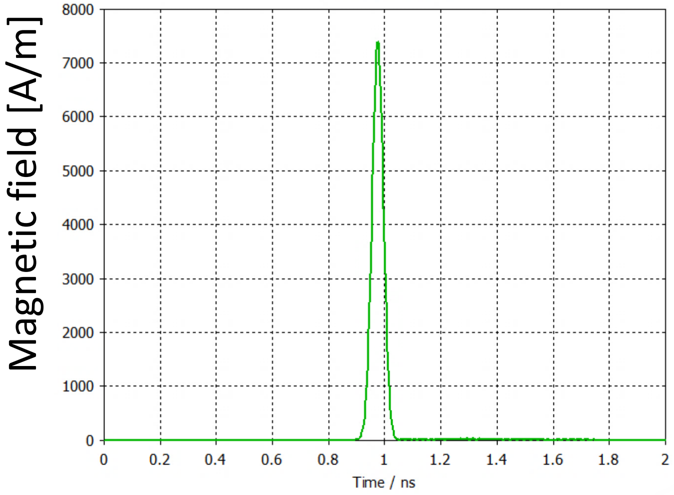
e^+ bunches

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

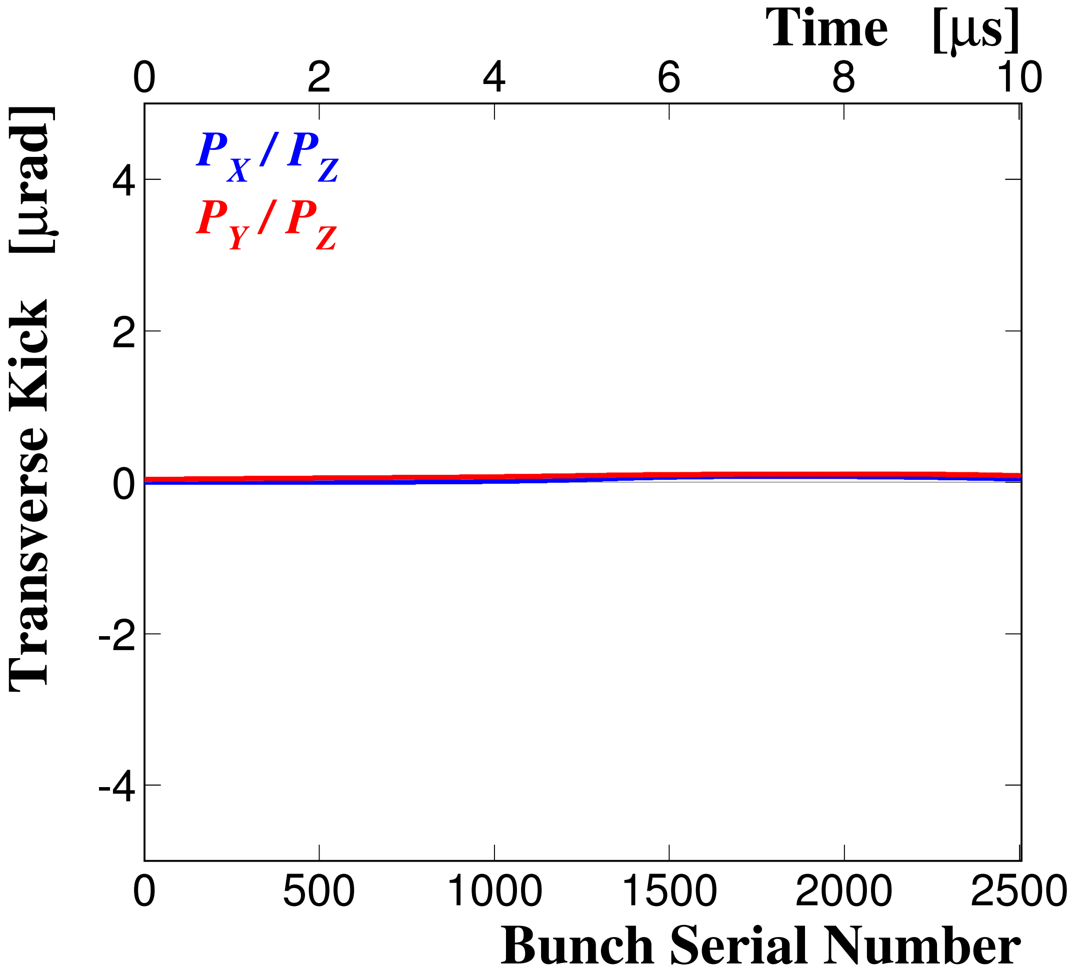


The peak field strength at the FB landing point is comparable with that in the RF cavity.





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

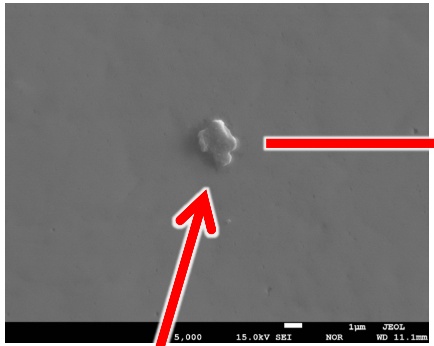


Numerical noise level in the PIC simulation: $\lesssim$ 0.1μrad

An Example of Carbonic Microparticles on Copper Surface

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

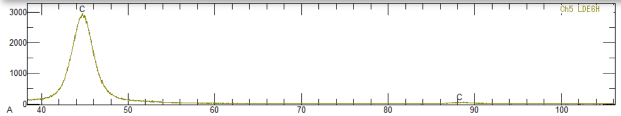
Size of this microparticle： 1 µm

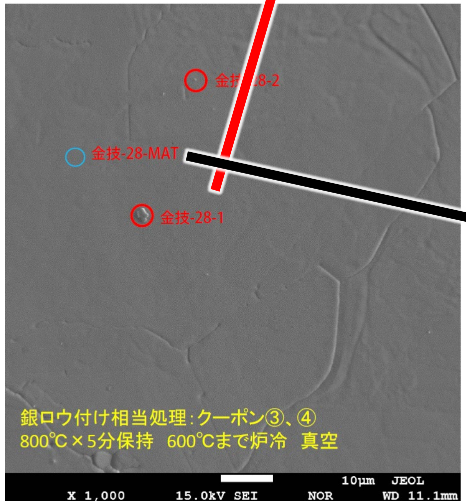


ZAF Metal

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

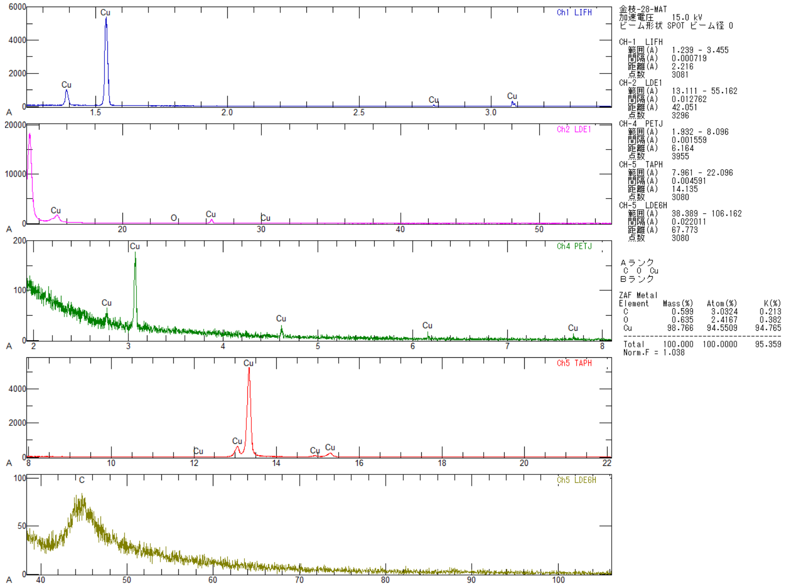
Norm.F = 0.844



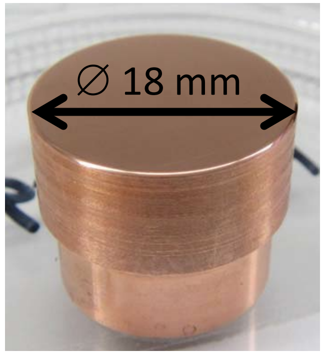


Base

Inspection conducted by T. Higo (KEK)



Copper Coupon



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

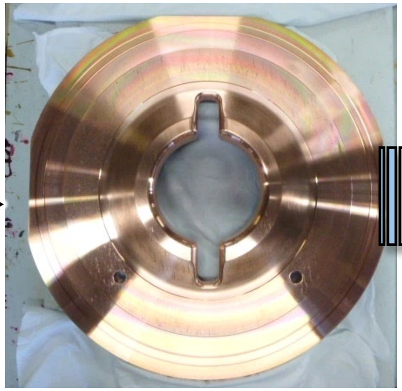
Although carbon cannot be melt in copper,
It can adhere to copper surface.

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

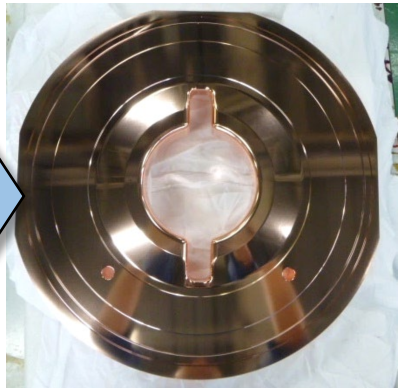
- **Good high-power performance**
  - The breakdown rates are the same as those of other UHF CW cavities
  - The vacuum pressure level is normal during high-power operation.

< Before EP >



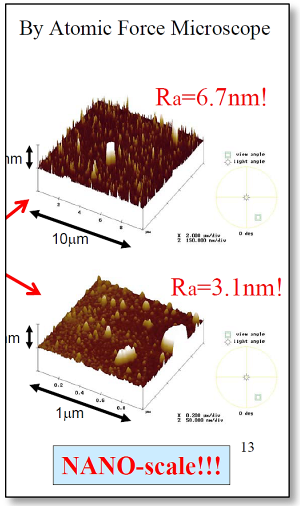
R_a = ~1.5 μm
R_y = ~8 μm

< After EP >



R_a < ~0.2 μm
R_y < ~1 μm

PAC'05, TPPT007→



The results obtained in this study have generality.

End of This File