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The Experimental Study on Vacuum Breakdowns by Optical Diagnosis

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March 22, 2017

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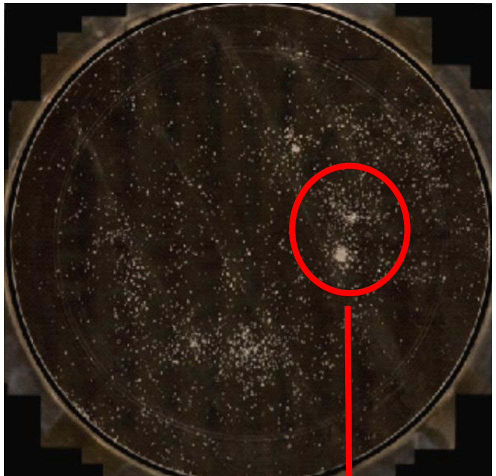
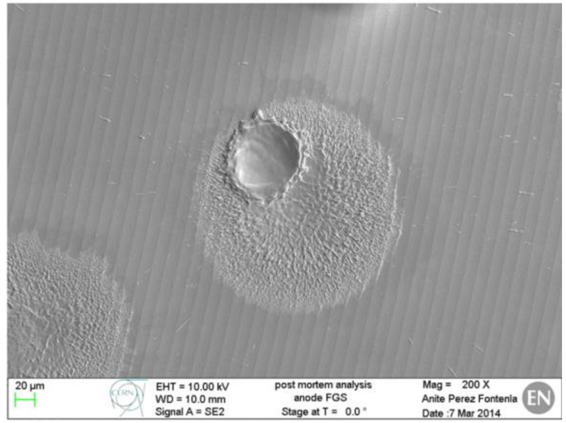
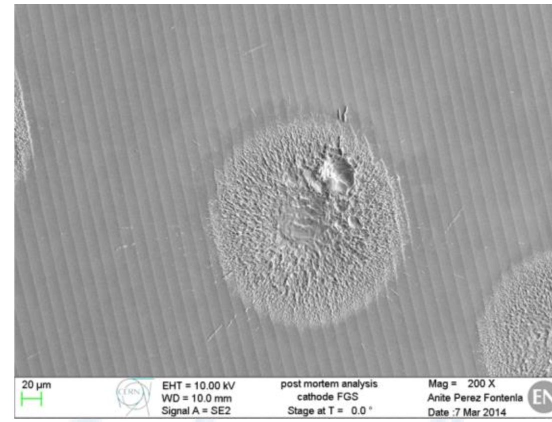
Introduction

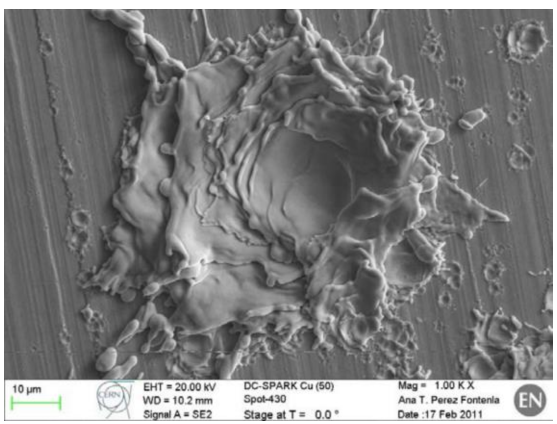




Anode Surface



Cathode Surface



N. C. Shipman, "Experimental Study of Dc Vacuum Breakdown and Application to High-Gradient Accelerating Structures for Clic," The University of Manchester, 2014.

- Micrometer-size craters can be always found on the surface after vacuum breakdowns.
- Not only the cathode but also the anode is affected by breakdowns.
- Sometimes, the crater on the anode seems to be even larger than that on the cathode.
- The craters are the remains of breakdowns, but cannot provide detail information of the physical processes.
- Before we move on, a basic question should be answered: **What role do the cathode and anode play in the processes, respectively?**

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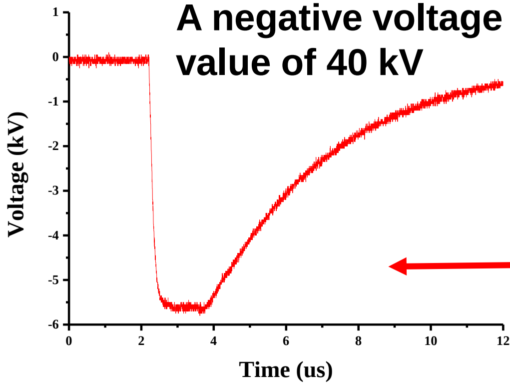
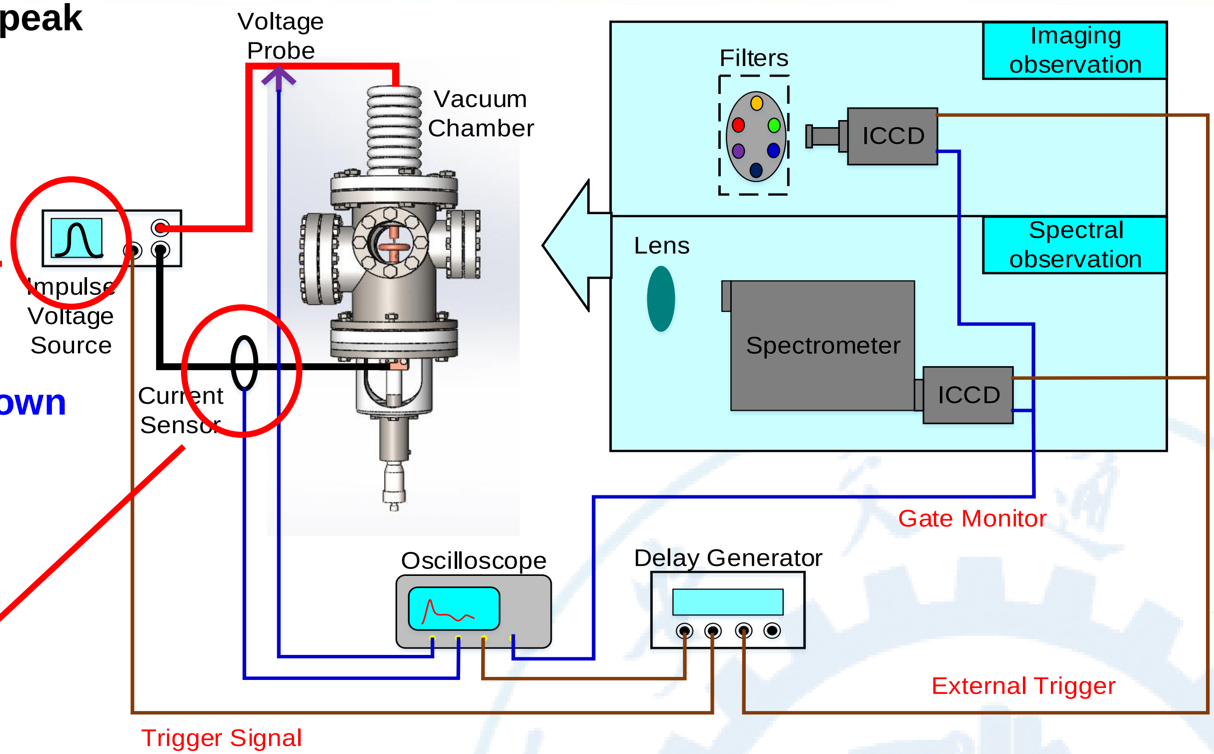
Experimental Setup

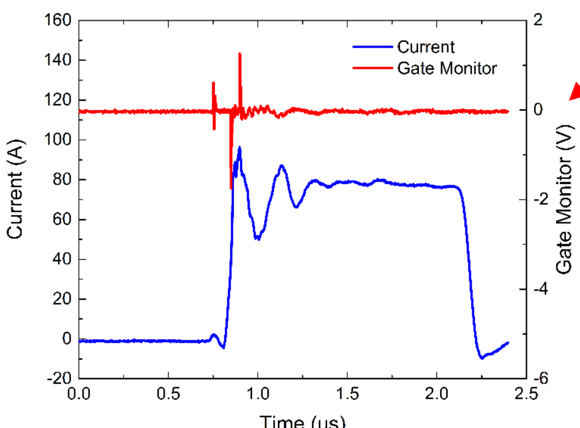
A negative voltage with a peak value of 40 kV



Voltage waveform without breakdown

Measured by PVM-7:
60 kV/100kV, 1000:1, 110 MHz



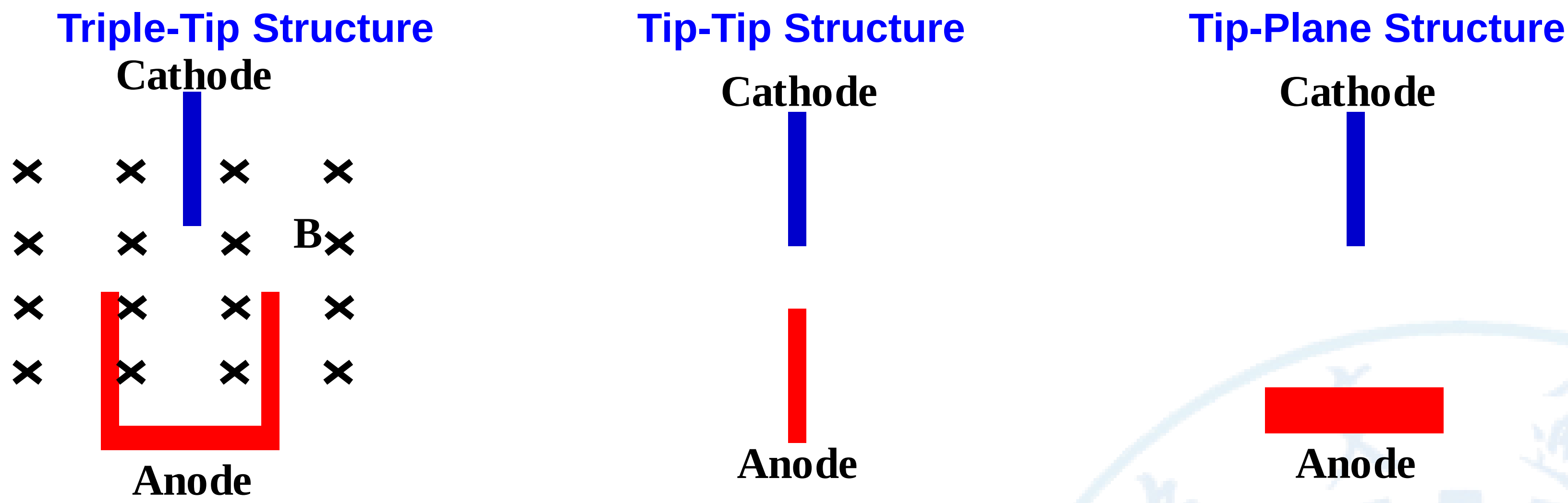


Current waveform during breakdown

Measured by Pearson Current Monitor 6596: 150 MHz

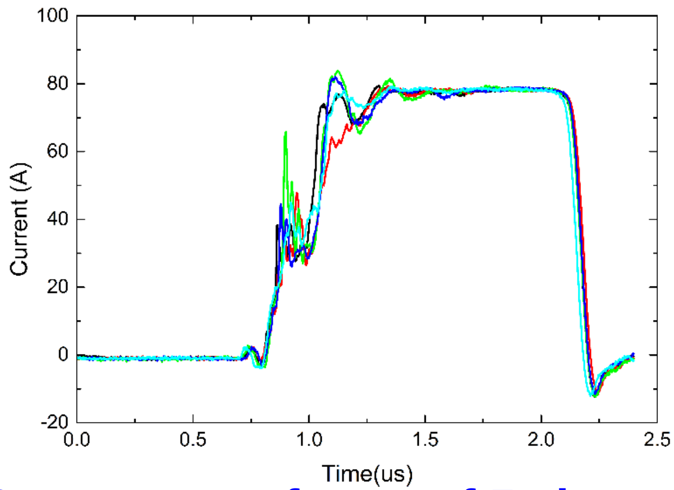
- ❖ **ICCD Camera: Andor DH334T-18U-04**
  Minimum gate time: 2ns
- ❖ **Dual-channel Spectrometer: SOL NP250-2**
  Spectral resolution:0.07nm
- ❖ **Optical filters:**
  Center wavelength: 391.42nm (Cu II)
  Center wavelength: 570.78nm (Cu I)

Parameters of Experiments

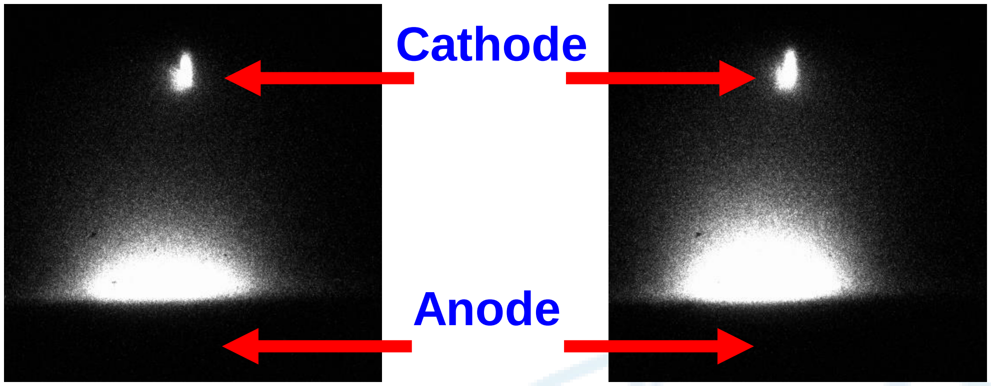


- **Gap structure:** tip-tip, tip-plane and triple-tip (The upper is a cathode and the lower is the anode)
- **Magnetic field**: only adopted with the triple-tip structure
- **Material:** Copper, Aluminum (Aluminum is chose because it can provide much higher intensive light than copper, important for spectrum observation)
- **Gap length:** 0.5-5 mm (can be smaller, but difficult to observe the radiance)
- **Pressure**: 10^{-4} Pa

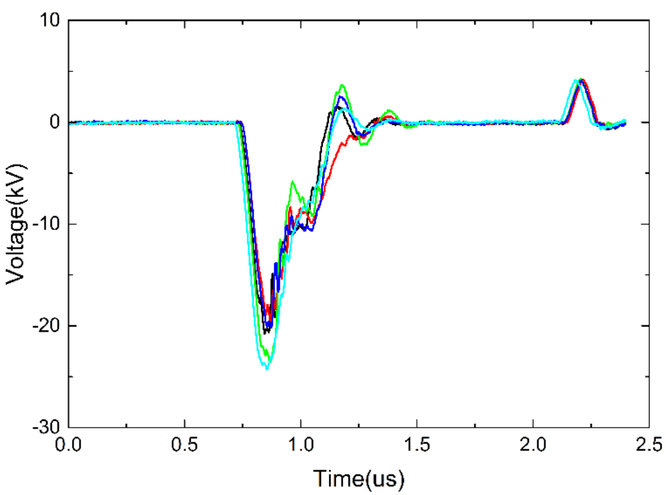
The proof of repeatability



Current waveforms of 5 shots



2 independent shots with a exposure time of 5 us



Voltage waveforms of 5 shots

- ❖ One image is captured at a specific time instant for each shot.
- ❖ After several shots, the whole breakdown process can be presented by joining all the images.
- ❖ The current and voltage waveforms imply that the physical process of vacuum breakdowns is repeatable.
- ❖ The images captured with a exposure time of 5 us, involving a whole process, also indicate the repeatability is good enough.

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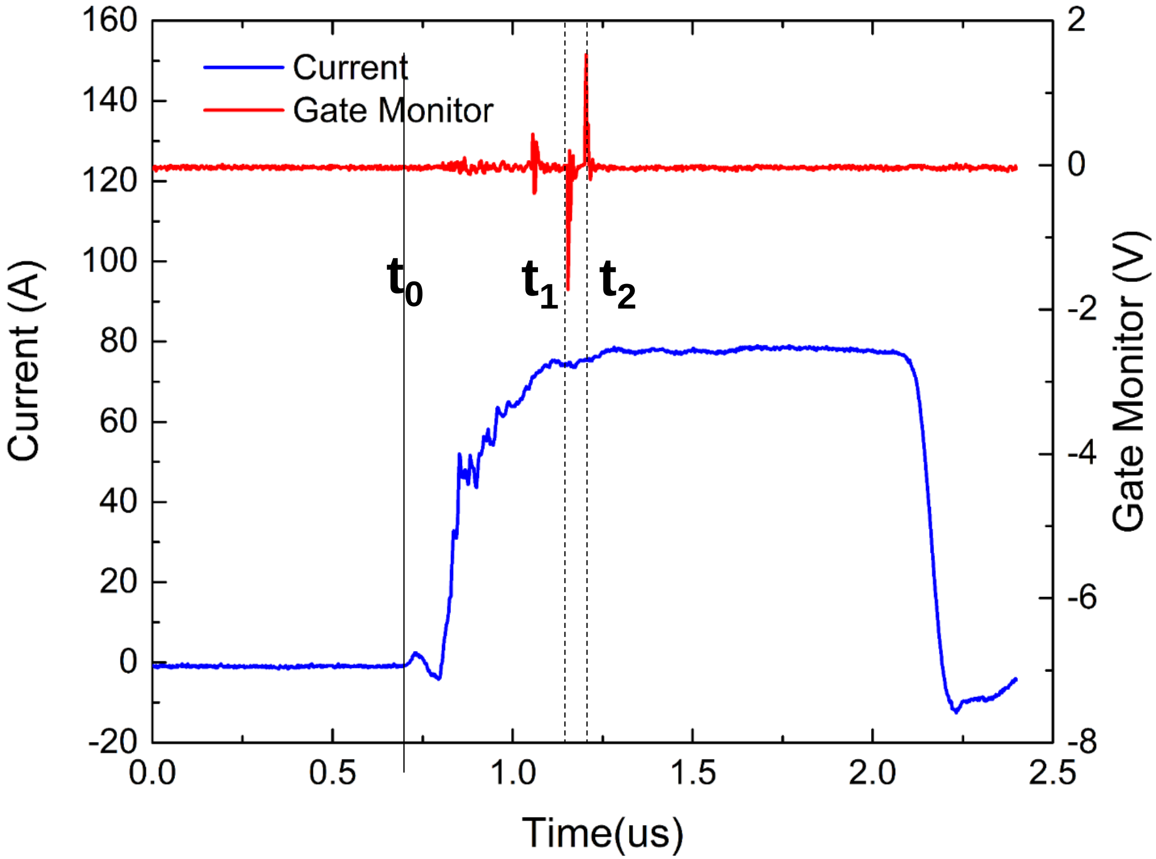
Procedure of Experiments

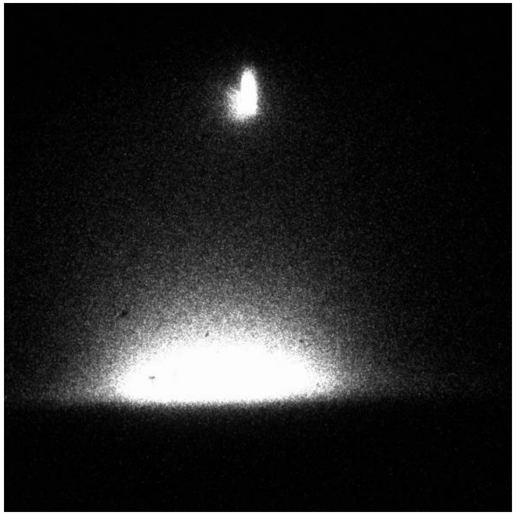


- **t_0**: start point of current rising
- **t_1**: camera gate is opened.
- **t_2**: camera gate is closed.
- **$t_w=t_2-t_1$**: exposure time.
- **$\Delta t=t_1-t_0$**: when the image is captured.

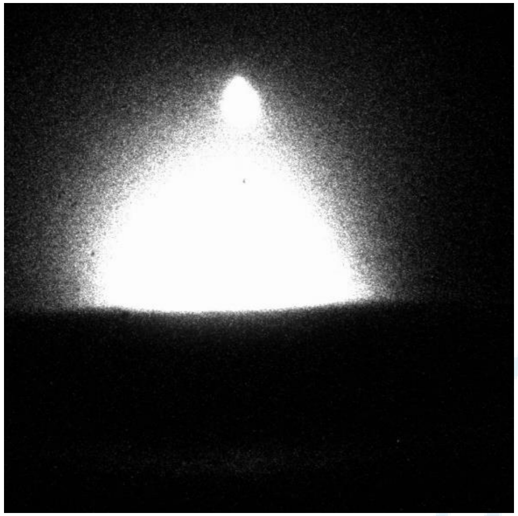
Results

Light emission during a breakdown process

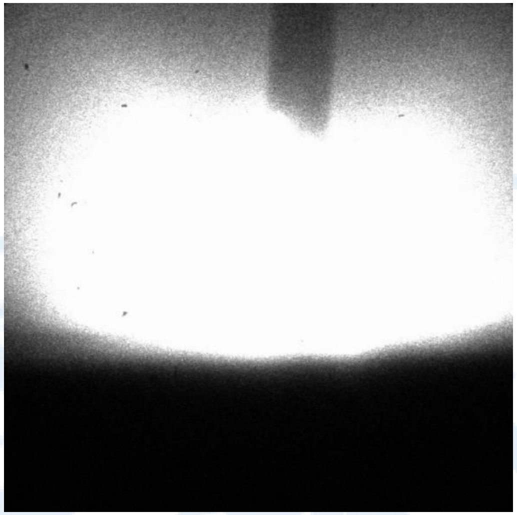
Exposure time: 5 us; Tip-Plane; Copper



Gap length: 5 mm



Gap length: 3 mm



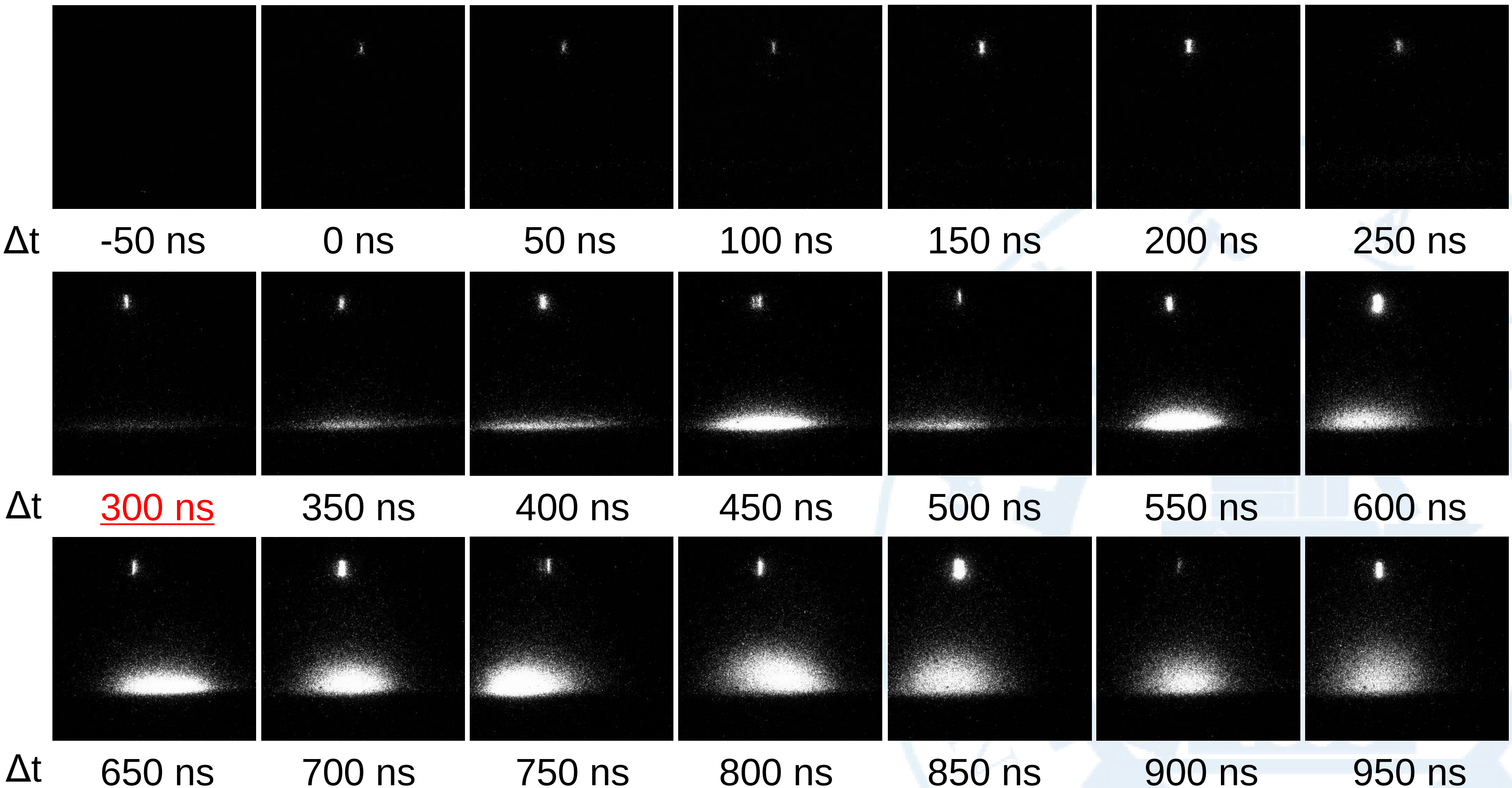
Gap length: 1 mm

- It is difficult to recognize the radiance from a small gap because of the spatial resolution and development speed.
- We tried to perform an experiment with a gap length of 100 um, but the ICCD cannot work well, so did a streak camera with 2 ps time resolution because the light was weak.

Results

Light emission during a breakdown process

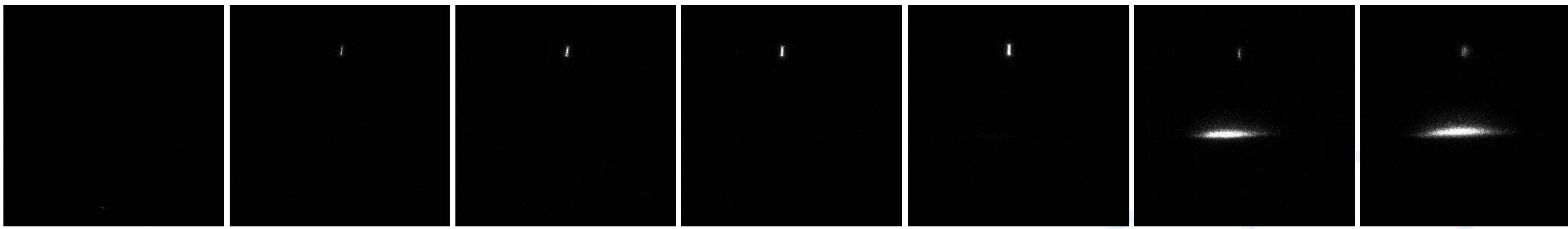
Exposure time: 50 ns; Gap length: 5 mm; Tip-Plane; Copper



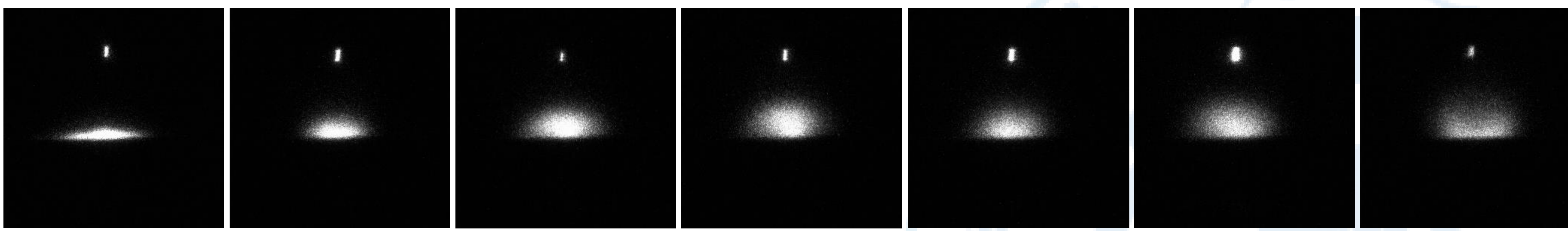
Results

Light emission during a breakdown process

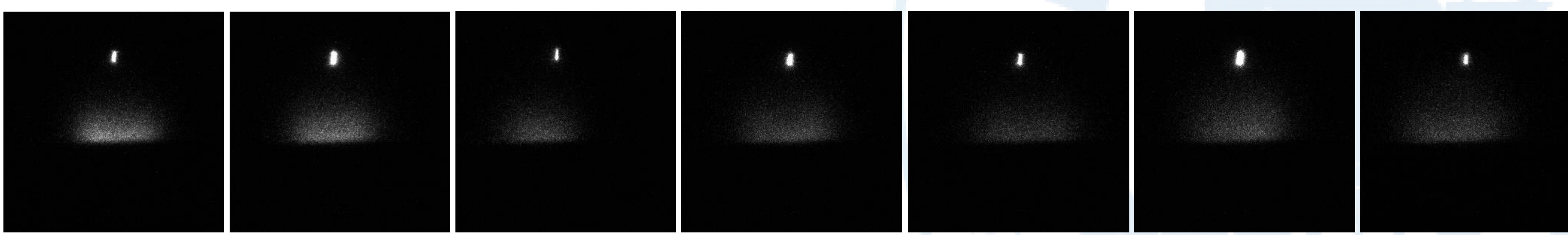
Exposure time: 50 ns; Gap length: 3 mm; Tip-Plane; Copper



Δt -50 ns | 0 ns | 50 ns | 100 ns | 150 ns | 200 ns | 250 ns



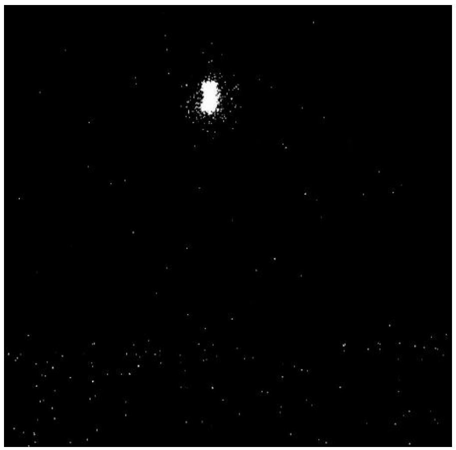
Δt 300 ns | 350 ns | 400 ns | 450 ns | 500 ns | 550 ns | 600 ns



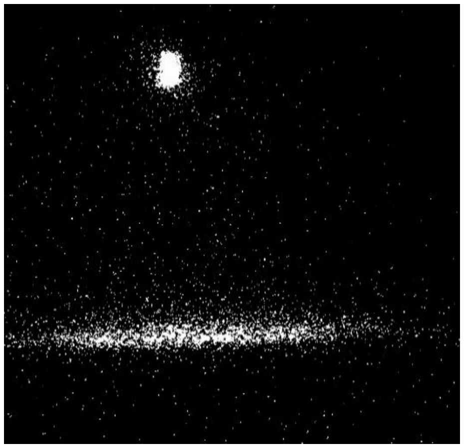
Δt 650 ns | 700 ns | 750 ns | 800 ns | 850 ns | 900 ns | 950 ns

Results

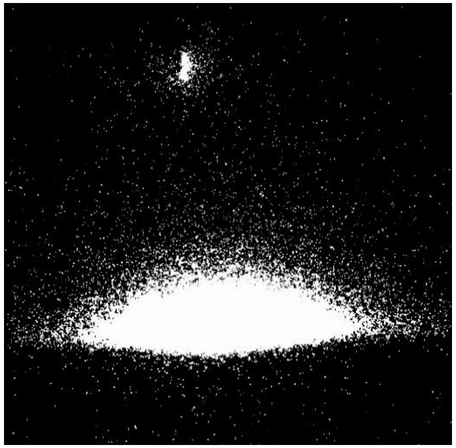
Exposure time: 50 ns; Gap length: 5 mm; Tip-Plane; Copper



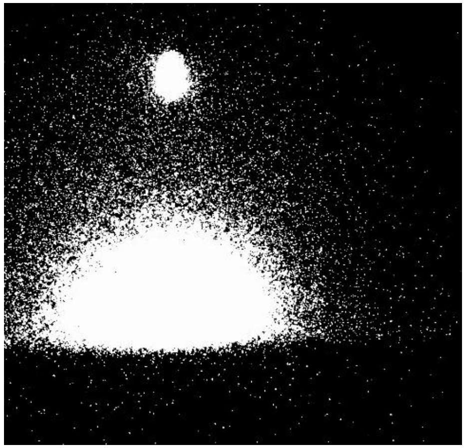
0 ns



300 ns



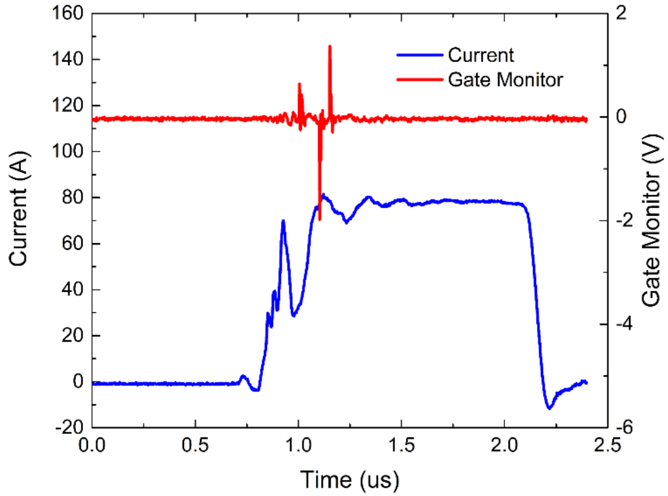
600 ns



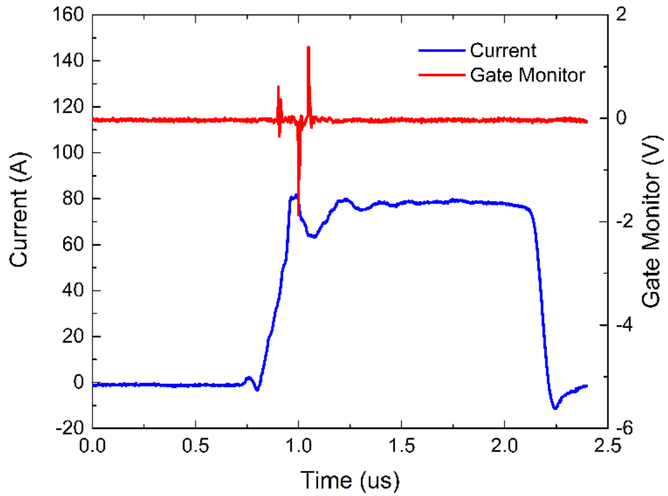
950 ns

- Some information could be hidden by the strongest lighting area, so the contrast ratio is adjusted to make the process clear.
- The process can be divided into 3 stages:
  1) Light was emitted from the cathode tip.
  2) The anode started glowing.
  3) The glowing region near the anode expanded to the cathode.
- The light emitted from the cathode was restricted to a small region around the tip, but, on the contrary, the glowing region gradually covered the anode surface and expanded to the cathode.

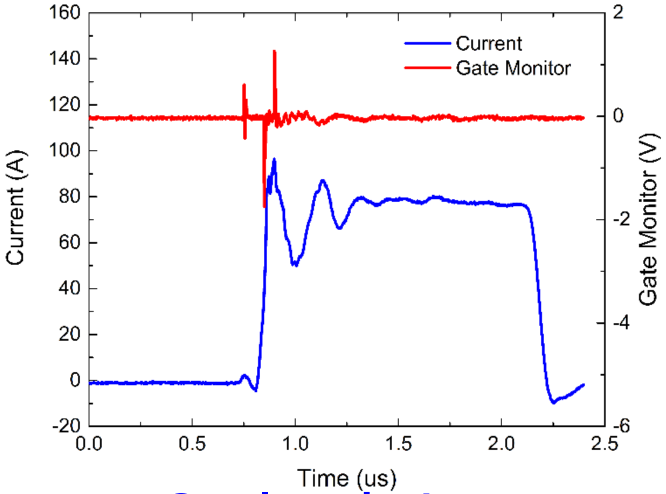
The time point of anode glowing



Gap length: 5 mm



Gap length: 3 mm

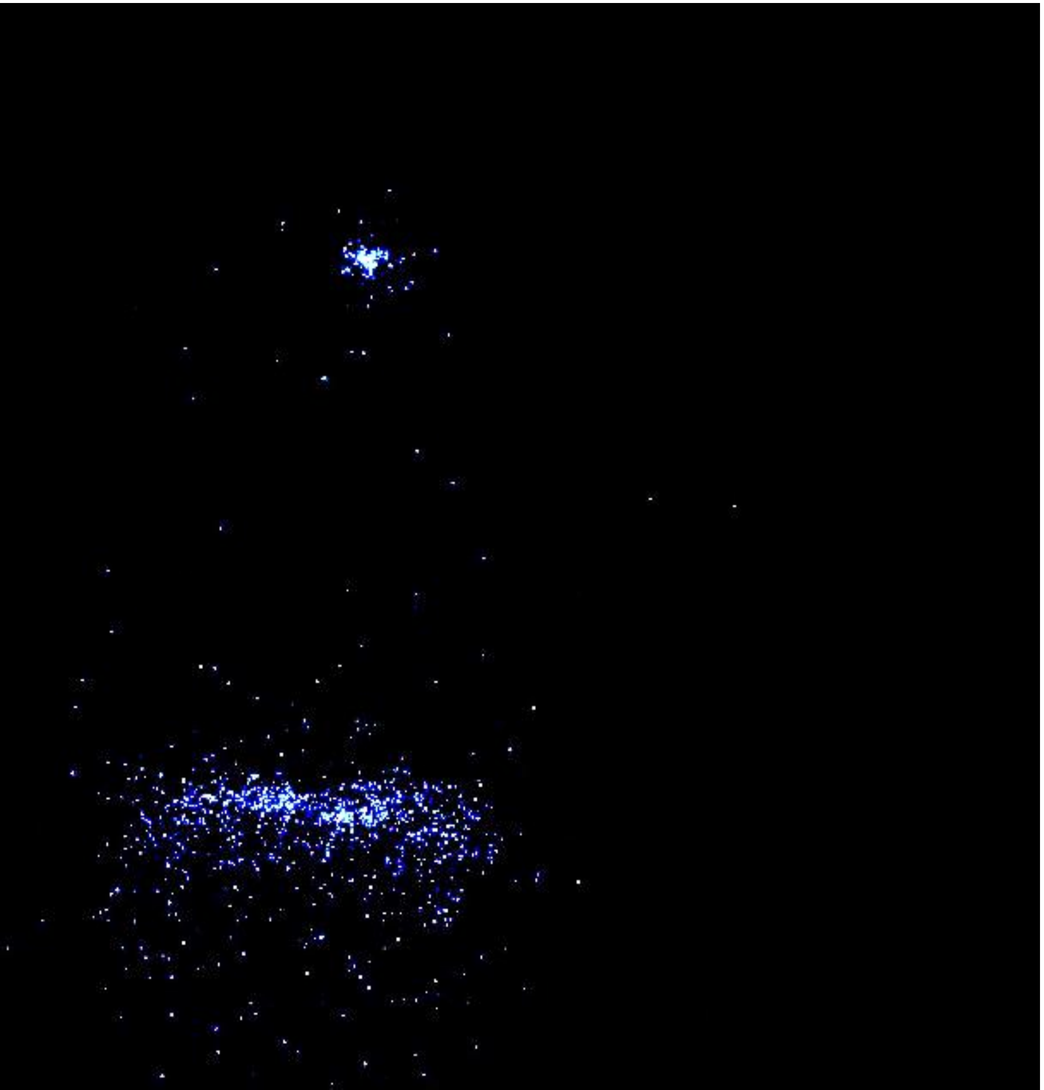


Gap length: 1 mm

- The time point of anode glowing was coincided with the time point when the current ceased rising.
- The stable current amplitudes were the same because of the same external impedance.

Results

Light emission with an optical filter: Cu I

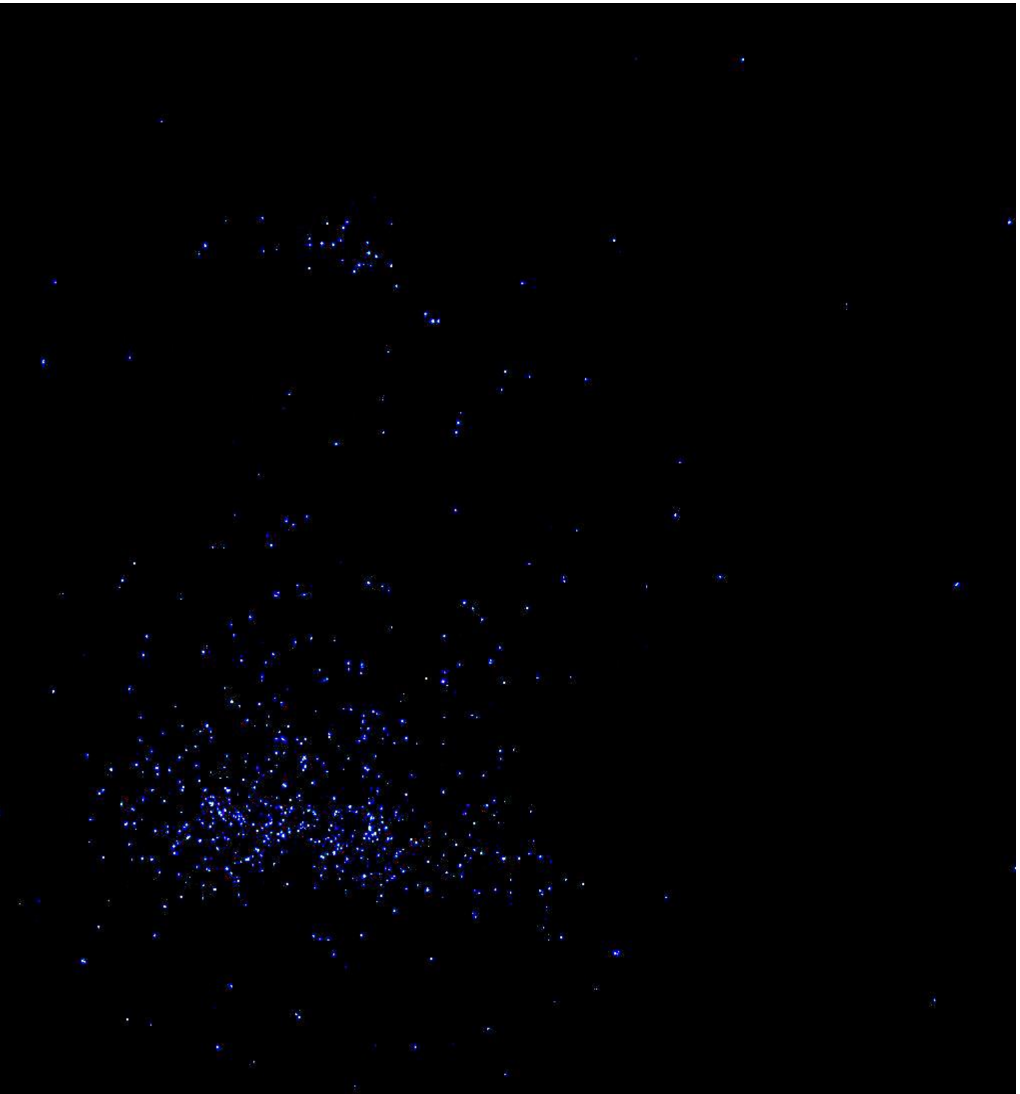


- Center wavelength: 570.78nm (Cu I)
- Copper atoms were observed near the cathode at the initial stage, similar to the previous results as well as the appearing time of copper atoms near the anode.
- The brightness around the cathode is slight higher than that around the anode.

Exposure time: 50 ns;
Gap length: 3 mm;
Tip-Plane;
Copper

Results

Light emission with an optical filter: Cu II

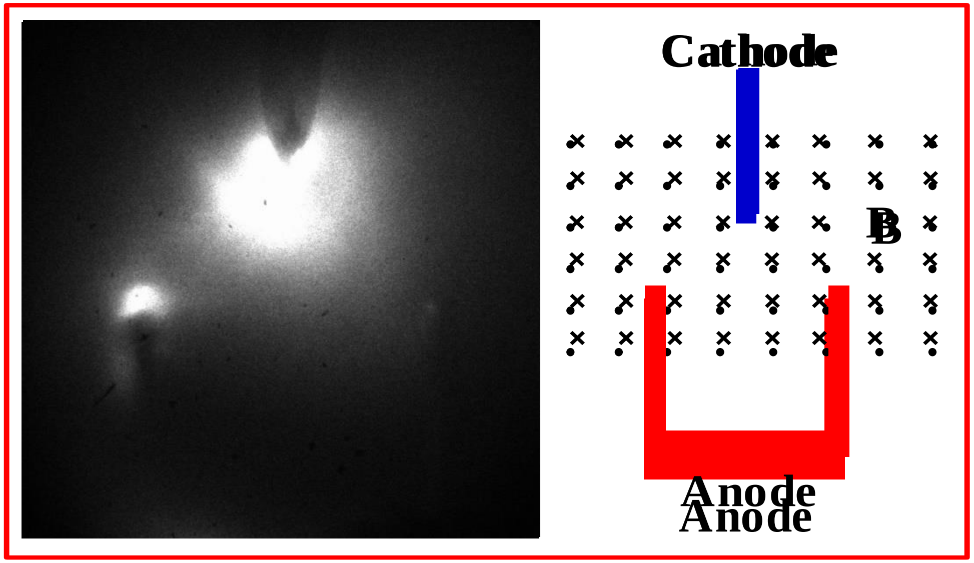


- Center wavelength: 391.42nm (Cu II)
- It seems that the distribution of single-charged copper ions is similar to that of copper atoms, but more scattered.
- The brightness around the cathode is not higher than that around the anode, even lower than that.

Exposure time: 50 ns;
Gap length: 3 mm;
Tip-Plane;
Copper

Results

The effect of magnetic field



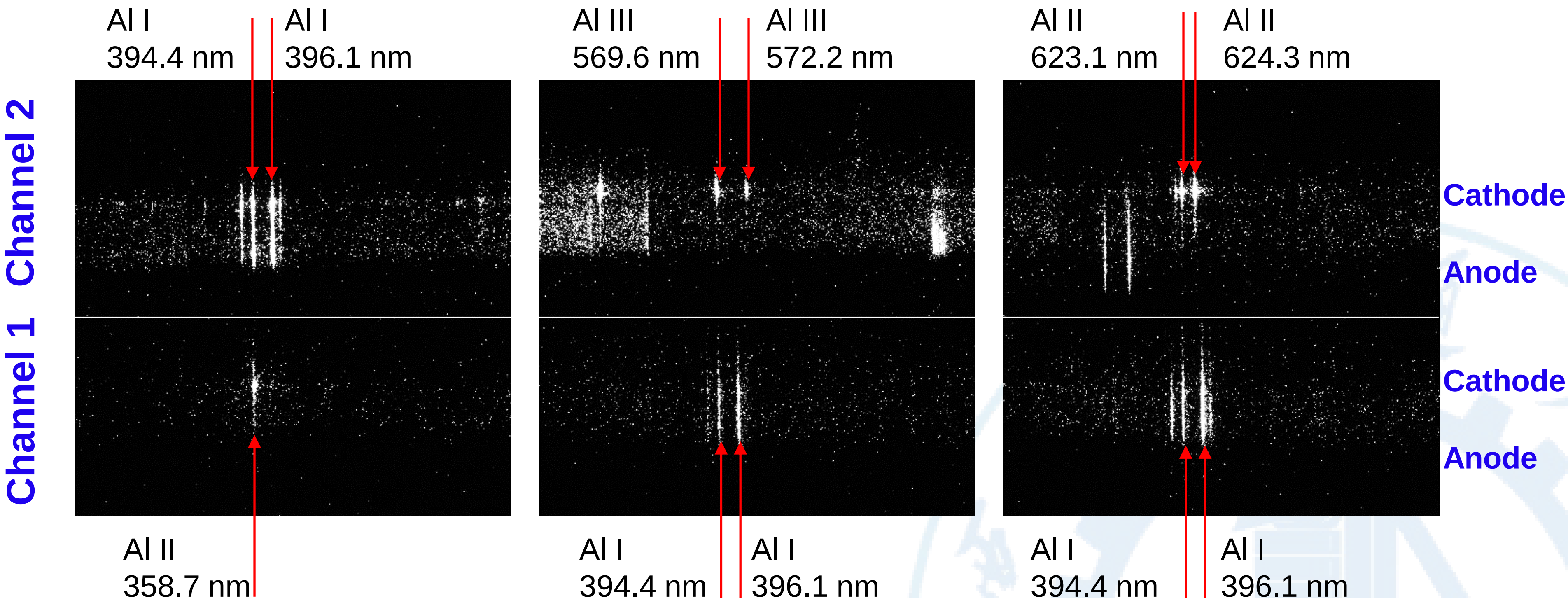
- A triple-tip structure combined with a magnetic field was adopted to verify which kind of particles, electrons or ions, are responsible for the anodic glowing.
- We assumed that all the initial particles come from the cathode tip.
- Apparently, electrons caused the anode glowing based on the estimation of Lorentz force.
- A stronger magnetic field could make this phenomena more clearly.

Exposure time: 5us;Gap length: 3 mm; Magnetic field: 280 mT; Triple-tip; Copper

Results

The spectra during breakdown

Gap length: 3 mm; Tip-plane; Aluminum



- A dual-channel spectrometer was adopted to detect the spectral lines in different wavebands instantaneously.
- The spectral lines of Al I indicate that the distribution of Al atoms is uniform.
- The multi-charged ions, Al II and Al III, are concentrated near the cathode.
- **However**, we also observed some contradictions when the material was not aluminum, so further experiments are required.

Discussion

- The electrons emitted from the cathode are responsible for heating up the anode, leading to evaporation on it.
- Anode glowing is attributed to the evaporation of the anode material otherwise a clear glowing bridge should be observed as well as atom distribution.
- For a gap within a millimeter level, the atoms from the anode is important for forming a stable discharging tunnel
- For a very tiny gap, forming a stable discharging tunnel does not require the evaporation from the anode because the vapor from the cathode can reach the anode even the radiance near the cathode is restricted to a small region.
- Therefore, the craters on the anode could be caused by the plasma from the cathode or evaporation on it.

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Conclusion

- A breakdown is triggered on the cathode, and the anode also plays a crucial role in forming a stable discharging channel.
- The light is restricted to a small region near the cathode tip in a breakdown process.
- The light near the anode, after the light emission of the cathode, gradually intensifies and expands to the cathode.
- The electrons from the cathode heat up the anode, leading to an anode glowing.

Future plan:

- Adopting an interferometer to quantitatively measure the parameters of the plasma during breakdown.

Thank you for your attention !