Roles and Physical Processes of Anodes in the Initial Stage of Vacuum Breakdowns

Zhipeng Zhou[1,2], Andreas Kyritsakis[2], Zhenxing Wang[1], Yingsan Geng[1], Flyura Djurabekova[2]

1 Xi'an Jiaotong University, Xi'an, China

2 University of Helsinki, Helsinki, Finland

September 17, 2019 @Padova, Italy

OUTLINE

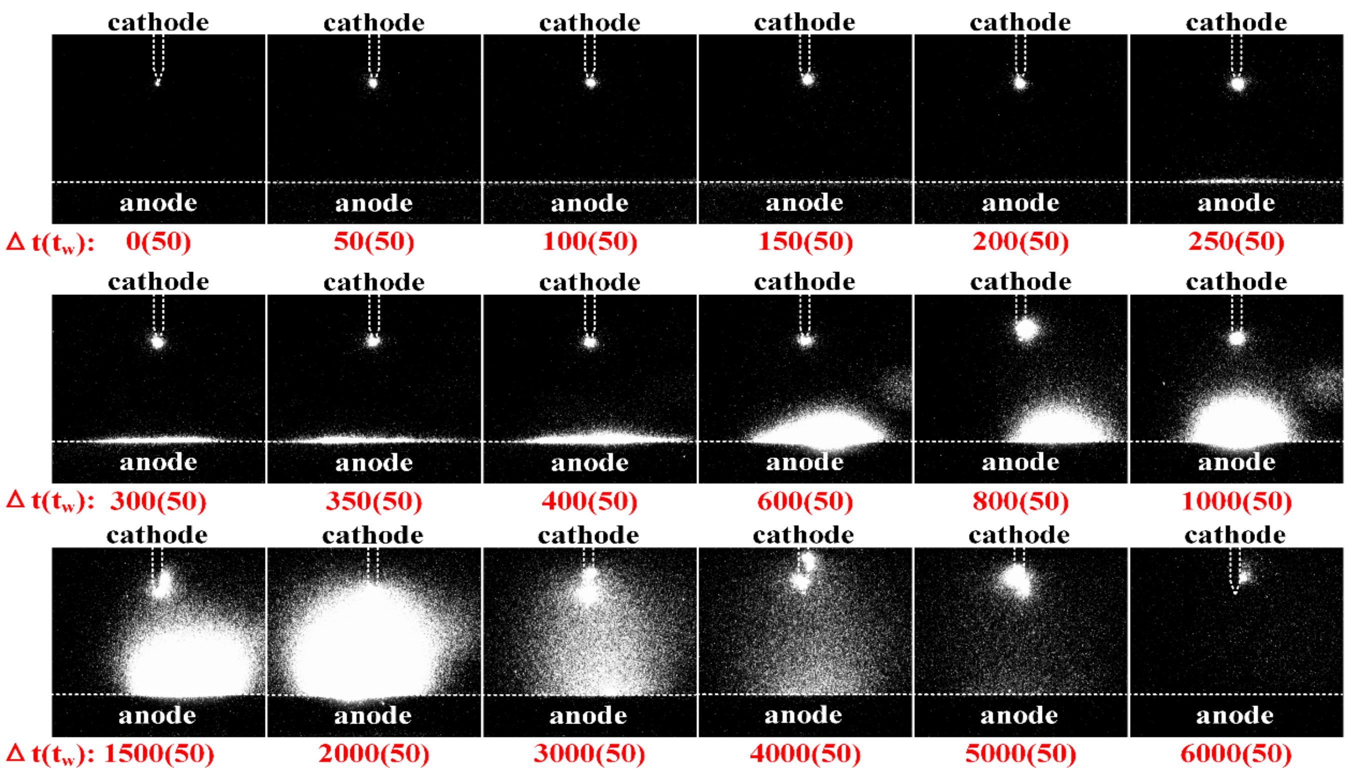
- Background and Motivation
- Experimental Setup
- Results
- Discussion
- Conclusions

BACKGROUND

Stage I: Cathode glows right after a BD occurs.

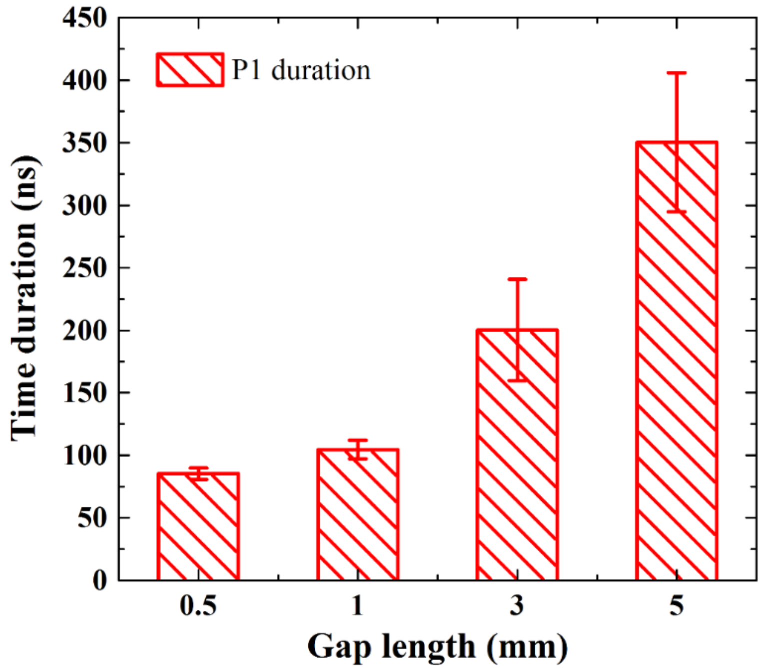
Stage II: Anode starts to glow and expand to the cathode.

Stage III: Light emission near the anode decay gradually, while the cathode glow remains until the end of the voltage pulse.



Scientific Reports. 2019;9(1):7814.

- The voltage collapses **well before** the gap is bridged by the expansion of anode light.
- The expansion of anodic glow seems **NOT** contribute much to the formation of the conductive channel.



Time instants when gap voltages drop to zero.

Gap Length	Stage II		
	Start	End	Duration
5 mm	250	2050	1800
3 mm	150	850	700
1 mm	40	300	260
0.5 mm	10	150	140

Anode glow starts (Start column)

Gap bridged by the glow (End column)

Time instants of anode glow

MOTIVATION

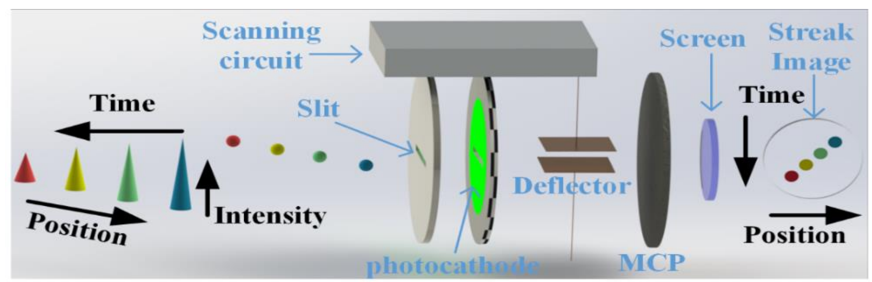
There are two questions left by the previous paper:

- Do anode materials have significant affect on the glowing process?
- Which physical processes contribute more to the anode glow?

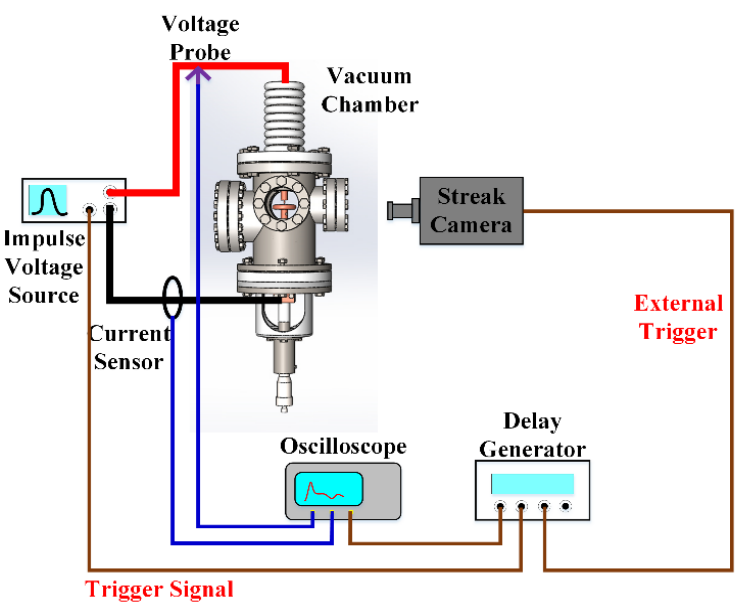
Experimental Setup

General description

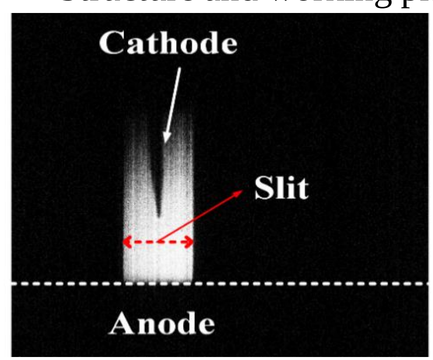
- Electrical discharges occurred in a demountable stainless steel chamber;
- The chamber was pumped to a pressure of $2.5*10^4$ Pa;
- A pair of tip-to-plane electrodes were installed with a variable gap length;
- The impulse voltage source provided a negative high voltage ranging from 0 to -50kV with a pulse width between 1 µs to 5 µs;
- The anode material varied among Al, Cr, Cu, Mo, Ni and W, while the cathode material was always Cu.



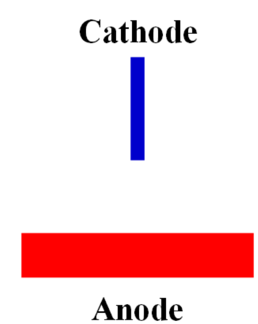
Structure and working principle for a streak camera



Schematic diagram of the experimental setup

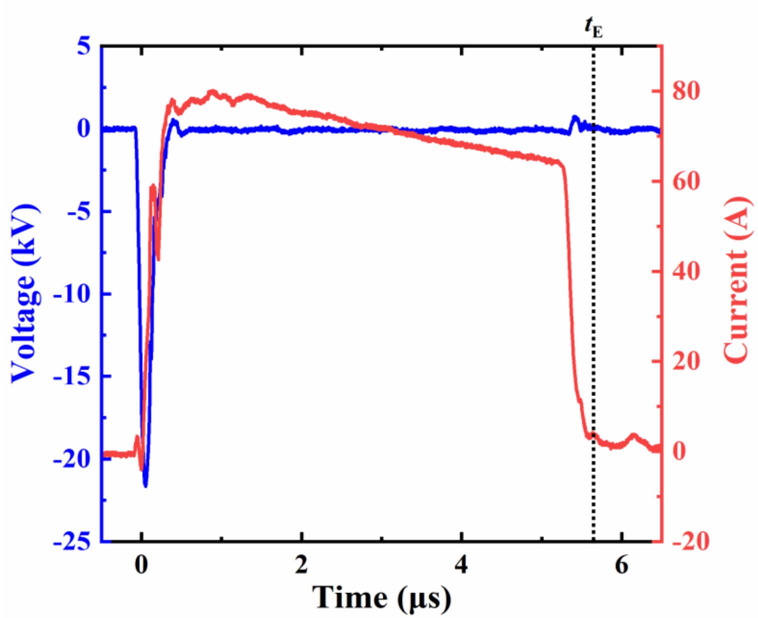


Sample image of the electrodes and gap

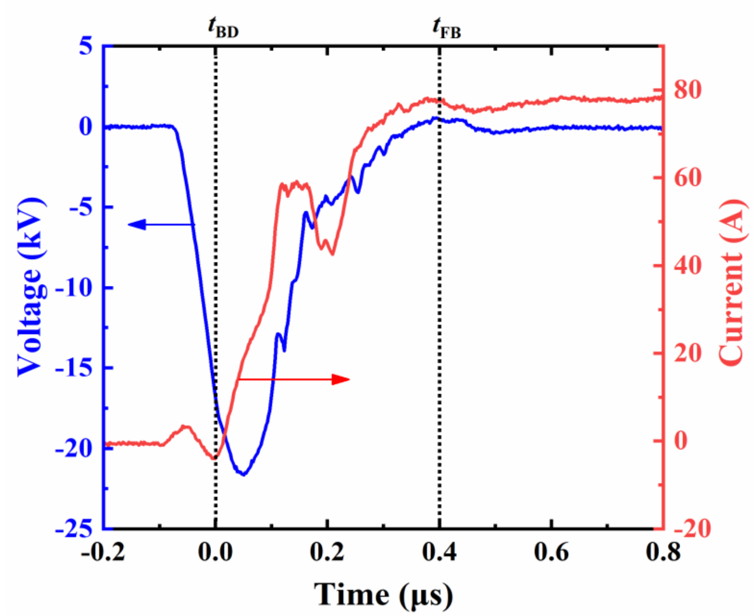


Electrode configuration

I: Typical electrical waveforms



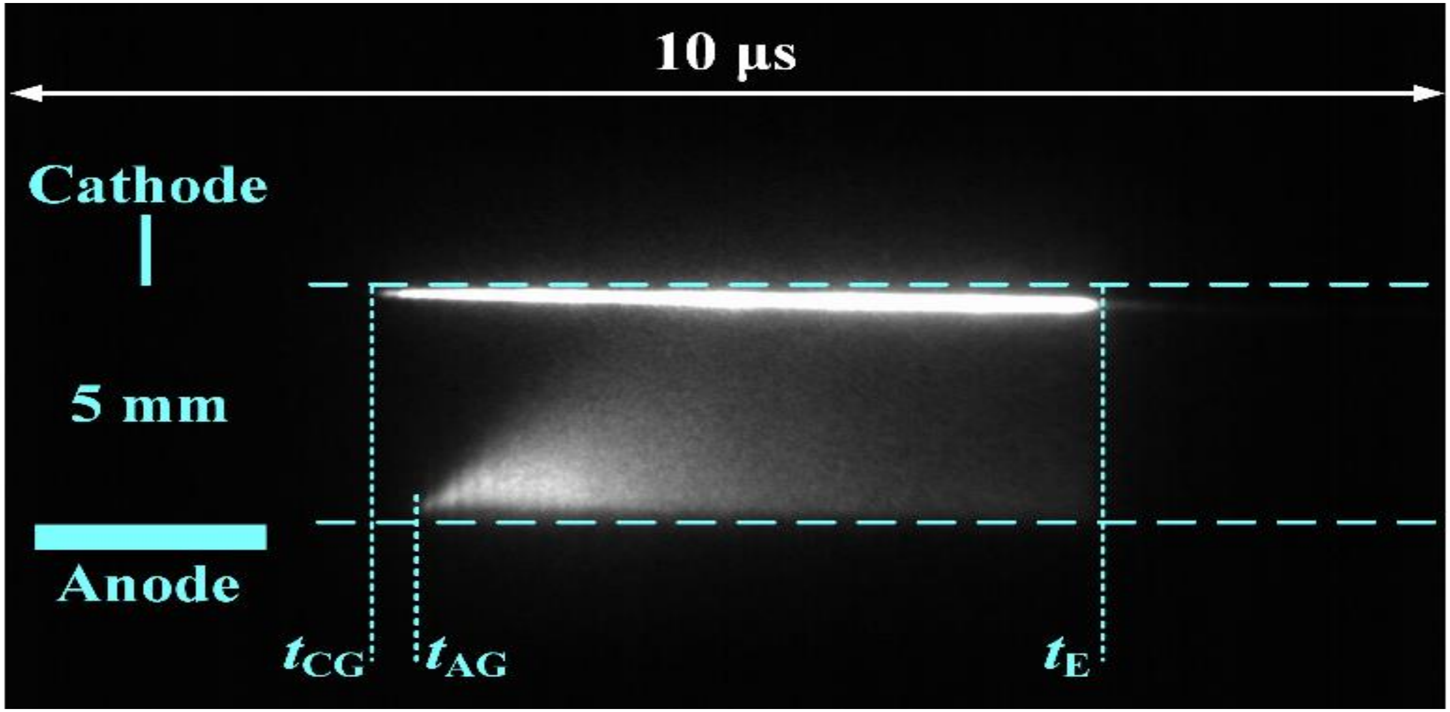
Waveforms of the entire process



Enlarged graph of the initial stage

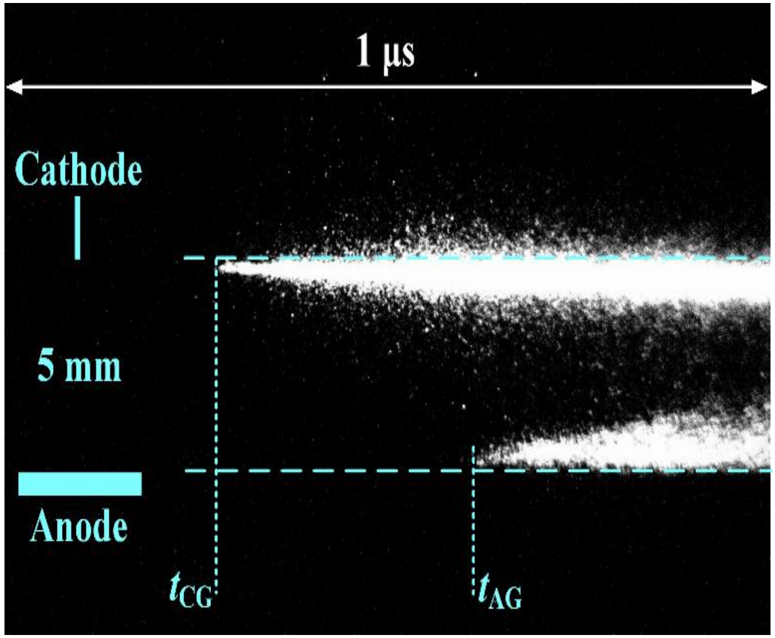
- ✓ **The gap length was 5mm, and the steady current was 60A 80A;**
- ✓ **The starting point t_{BD} of a breakdown is defined as time zero;**
- ✓ **The end point t_{FB} indicates the transition from vacuum flare to vacuum arc and a fully conductive electrical path was formed.**

II: Light emission during vacuum breakdown by the streak image

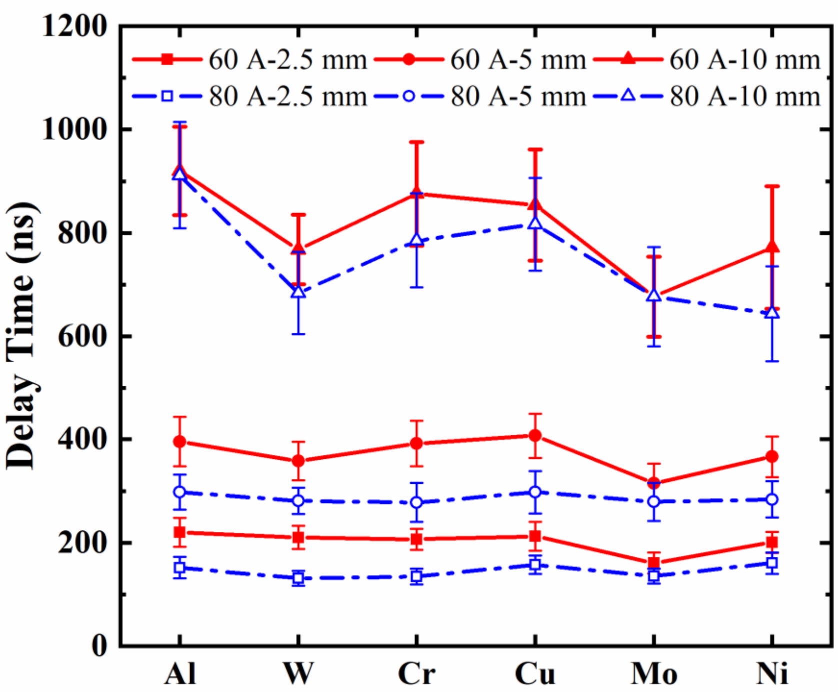


- ✓ The horizontal axis represents time lapsing rather than positions in space;
- ✓ t_{CG}, starting point of cathodic glow; t_{AG}, starting point of anodic glow;
- ✓ t_E, time point of voltage source turn-off;
- ✓ The intensity of anodic glow did not grow continuously but decayed a short time later, while the cathode kept glowing until t_E.

III: Effect of anode materials



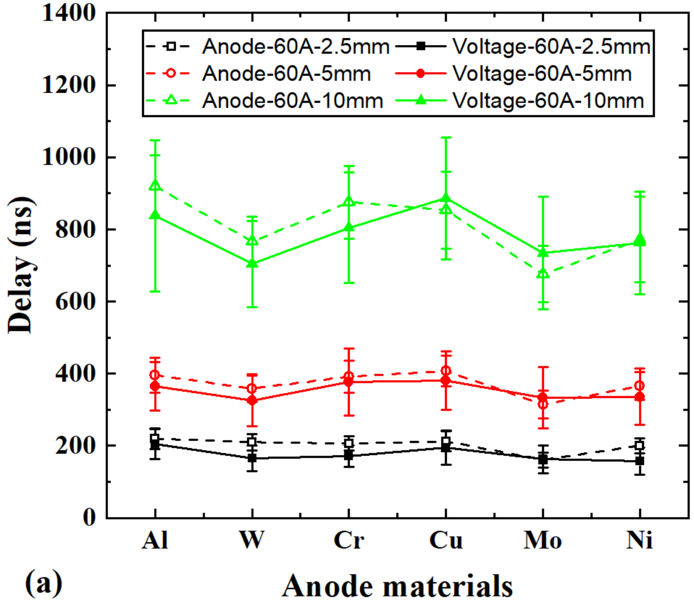
Initial stage of a breakdown



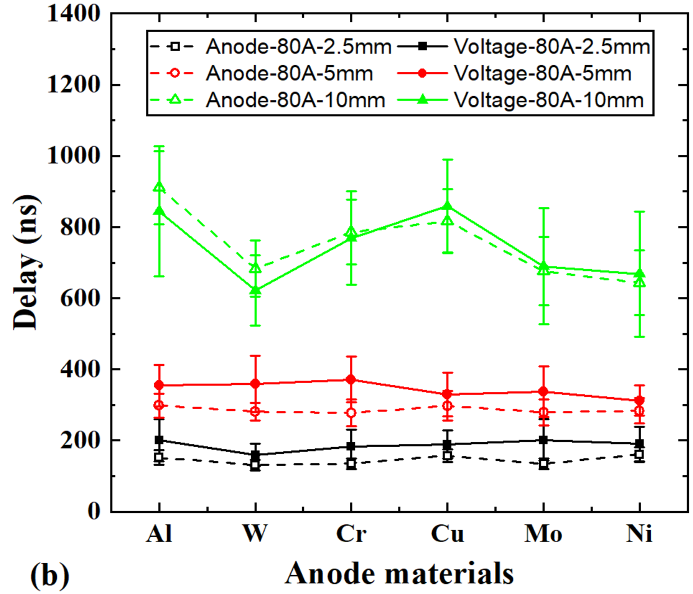
Anodic delay times under different conditions

- ✓ **The anode material seems not to have much effect on the delay for the anodic glow;**
- ✓ **The delay increases almost linearly with the gap length.**

IV: Effect of the voltage collapse



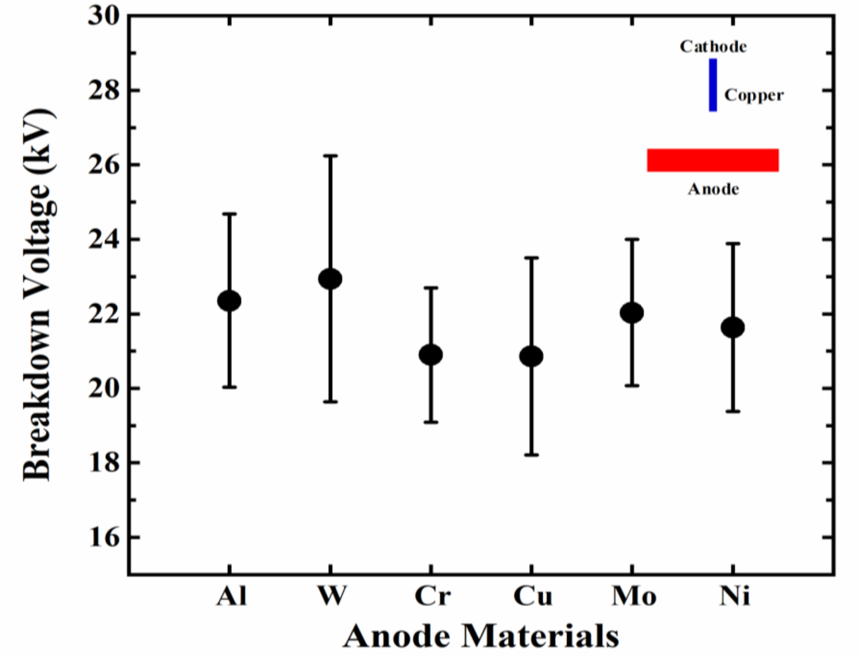
60A



80A

- ✓ The voltage collapse indicates the formation of the conductive channel in the gap;
- ✓ It is easier for an anodic glow to be appeared before a voltage collapse at higher currents and shorter gaps;
- ✓ If the gap length becomes much larger, the anodic glow occurs much later than the moment of the voltage collapse.
- ✓ Anodic glow is NOT the prerequisite for the voltage collapse or the formation of conductive channel.

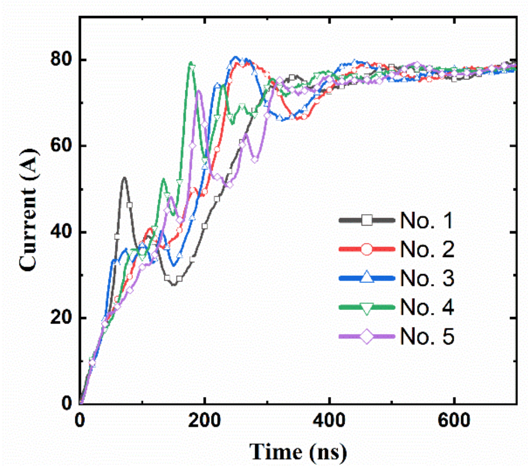
V: Effect of anode materials on breakdown voltages



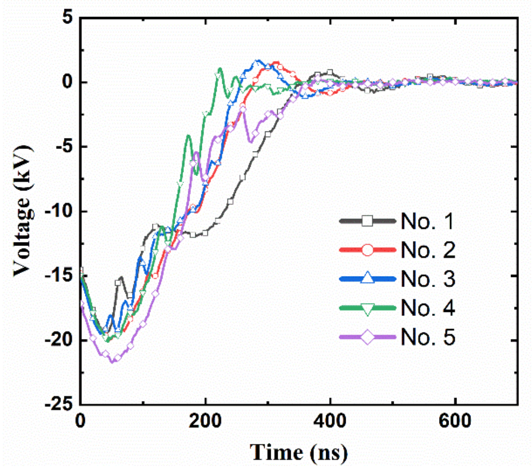
Effect of anode materials on breakdown voltages

- ✓ **The voltage of different cases fluctuate around 21kV, and there is no obvious pattern that can be observed.**
- ✓ **It further proves that the anode does not play a critical role in the initial stage of a vacuum breakdown.**

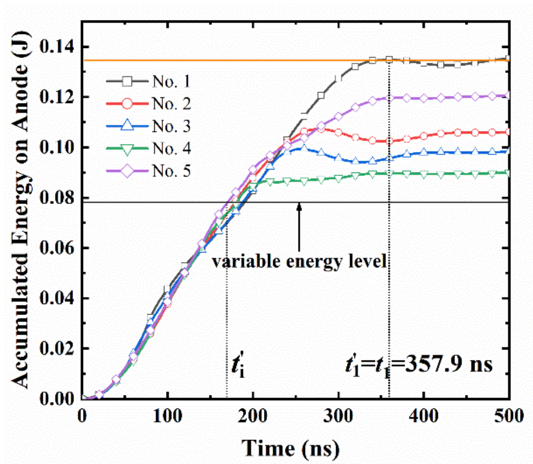
I: Energy deposited by electrons



Current waveforms



Voltage waveforms

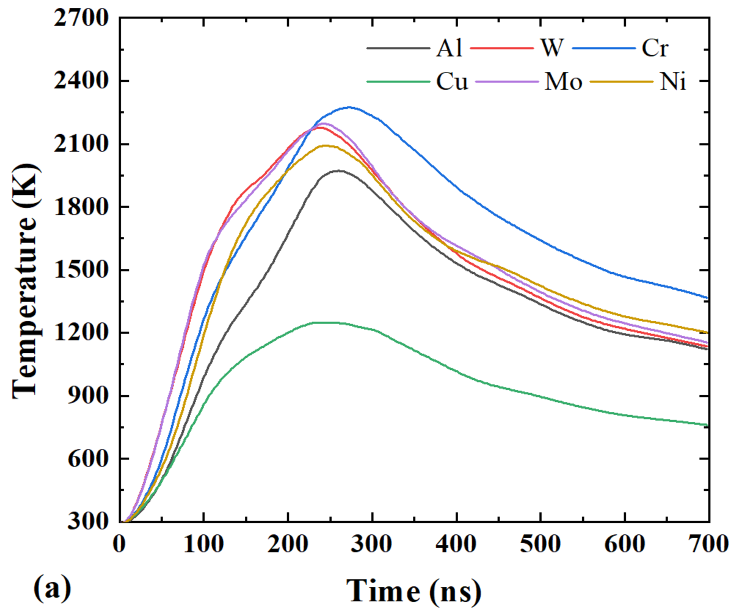


Accumulated deposited energy on the anode surface

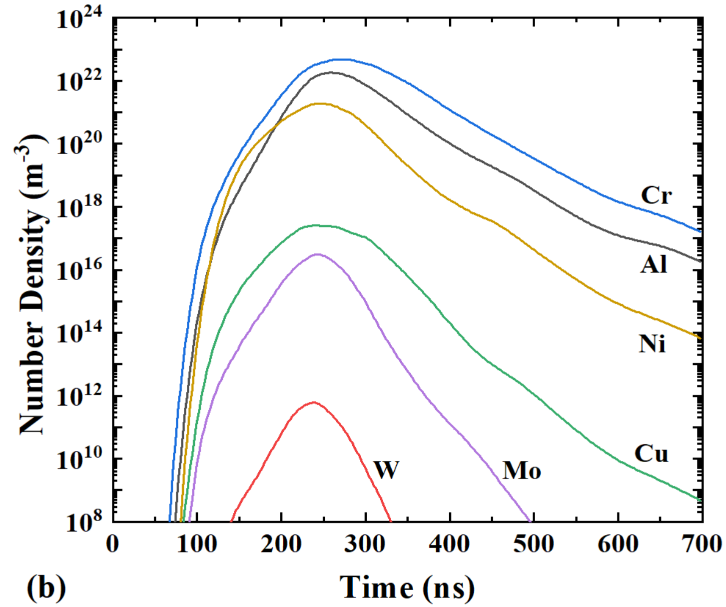
No.	1	2	3	4	5
t_i(ns)	357.9	292.6	256.5	241.7	296.3

- ✓ **The deposited energy on the anode surface by electrons at the initial stage of a vacuum breakdown is calculated:** $E(t)=\int_{t_{BD}}^{t} V(t)\times I(t)\,dt$
- ✓ **We found that there did not exist a specific energy level that could indicate anodic glow.**

II: Evaporation on anode surface



Maximum temperature of anode surface



Evaporated atom densities near andoe

- ✓ We assumed that the electron beam has a Gaussian distribution with $\sigma = 1$ mm. Then the heat source for the anode is calculated as $P(t) = V(t)I(t)/(2\pi\sigma^2)$;
- ✓ The number density of the evaporated atoms is calculated according to the saturated vapor pressure;
- ✓ The great difference in evaporated atom densities for different anode materials would also result in difference in the delay for the anodic glow, if all the atoms in the glow region come from the evaporation of the anode surface.

III: Sputtering process on anode

- Adopting the Binary Collision Approximation method to calculate the sputtered atom velocity

Ion flux density at the anode surface:

$$Q = \frac{I_{\text{ion}}}{e}\frac{1}{2\pi\sigma^2} = 7.96 \times 10^{24}\ \text{m}^{-2}\cdot\text{s}^{-1}$$

Sputtered atom density:

$$n_{\text{sput}} = \frac{QY}{v_{\text{sput}}}$$

Anode materials	Al	W	Cr	Cu	Mo	Ni
Sputtering yield Y	0.164	0.134	0.326	0.591	0.133	0.276
Average sputtered atom energy (eV)	3.49	11	5.12	6	8.01	6
Average sputtered atom velocity (m/s)	4994	3394	4355	4250	4009	4441
Sputtered atom density(m^{-3})	2.61e20	3.14e20	5.96e20	1.11e21	2.64e20	4.95e20

IV: Comparison of sputtered and evaporated atoms

Radius	Anode materials	Al	W	Cr	Cu	Mo	Ni
σ=1 mm	Sputtered atom density (m^{-3})	2.61e20	3.14e20	5.96e20	1.11e21	2.64e20	4.95e20
	Evaporated atom density (m^{-3})	1.82e22	6.03e11	4.83e22	2.58e17	3.17e16	1.91e21
σ=2 mm	Sputtered atom density (m^{-3})	6.53e19	7.85e19	1.49e20	2.78e20	6.60e19	1.24e20
	Evaporated atom density (m^{-3})	8.05e4	3.42e-30	2.14e6	9.14e-3	2.28e-14	3.87e3

- ✓ **The sputtering process of anode surface under the impact of cathode ions is an important source for the atoms in the anodic region;**
- ✓ **The contribution of this process may well excess that of the evaporation process for refractory anode materials such as W and Mo;**
- ✓ **Here, we do not discuss the atoms from the cathode. From the spectroscopic experiments, they DO indicate that the cathode materials contribute a lot to the anodic glow. But we need further experimental results to verify this point.**

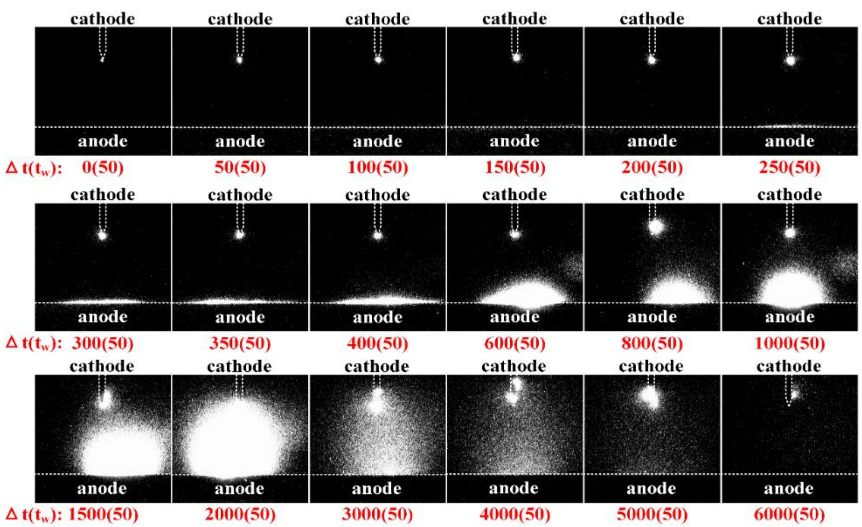
CONCLUSIONS

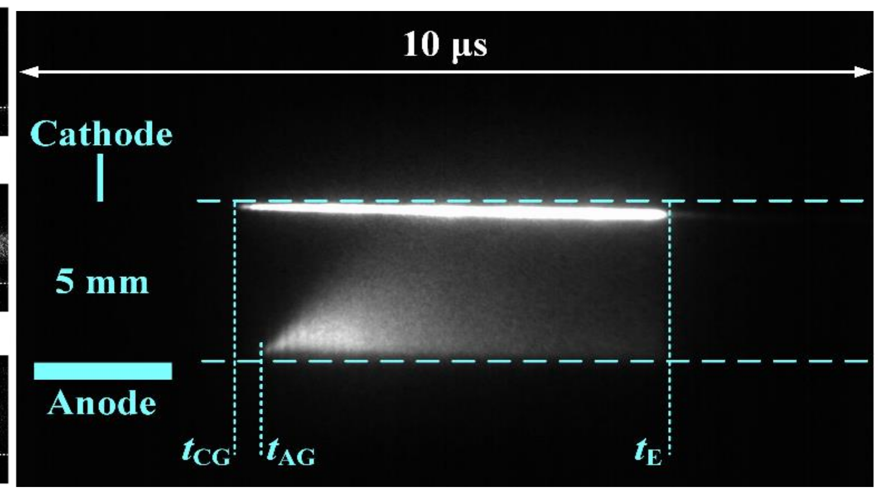
- A fully conductive channel after a vacuum breakdown triggered can be established without contributions from the anode, and the anode material does not affect this process significantly;
- Different anode materials did not affect the delay times between the cathodic and anodic glow obviously as well as the breakdown voltages;
- The evaporation of the anode surface under the heating of electrons can not be the major source generating the vapor atoms in the anodic region;
- The ion sputtering process at the anode surface are important source for the vapor atoms in the anodic glow region;

CONCLUSIONS

- The interaction between the incident ions and the anode surface can produce low speed neutral atom and electrons, and these particles can collide with each other at a higher probability than those in the middle of the gap, resulting in the anodic glow.

- We will verify the contributions of the cathode materials by further experiments.





HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

MeVArc 2019
Padova

西安交通大學
XI'AN JIAOTONG UNIVERSITY

Thank you for your attention !