Physics of high-current diode

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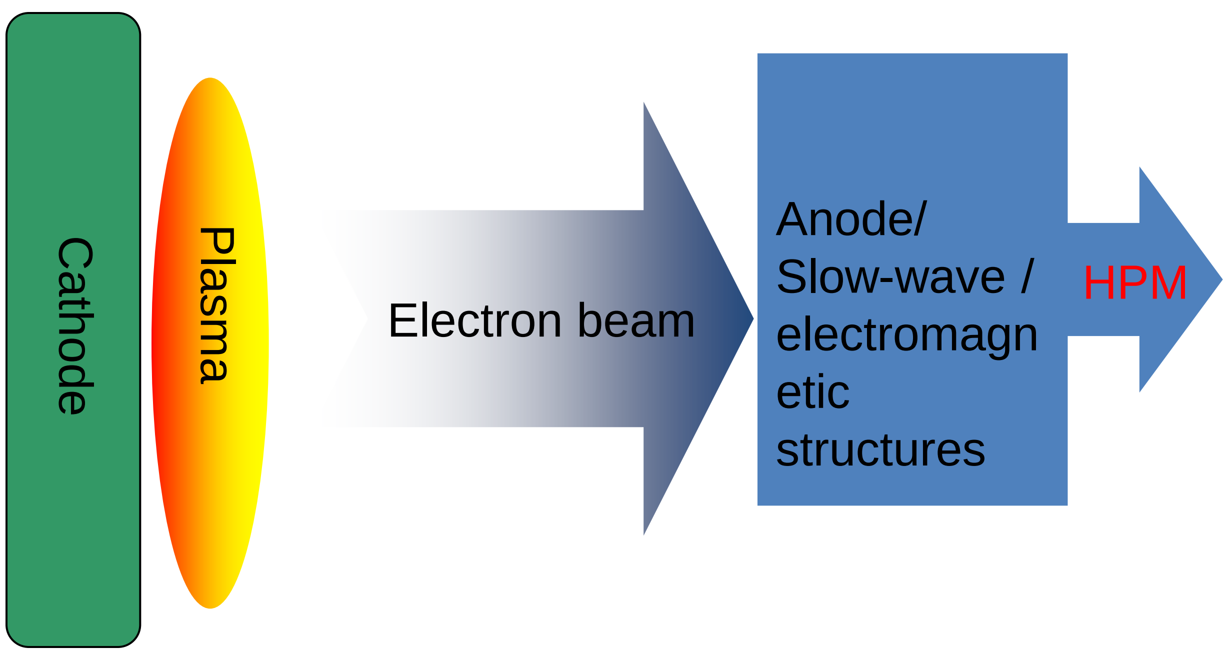
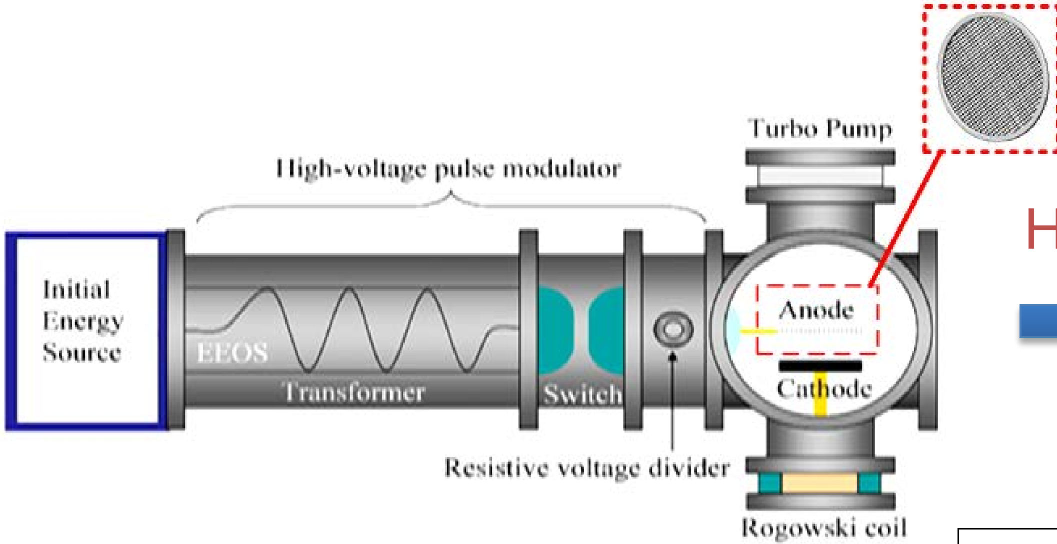
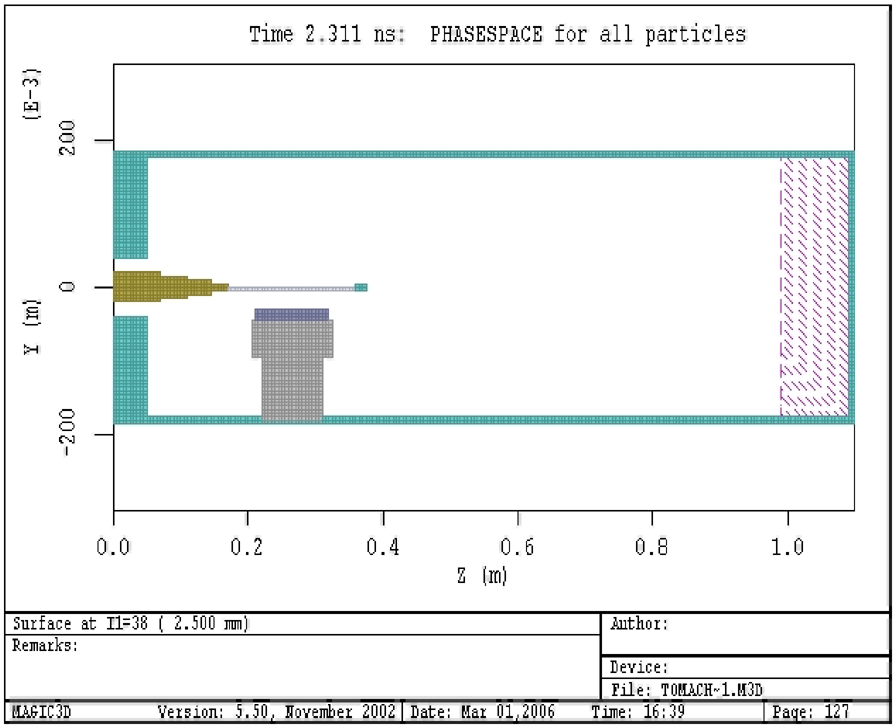


Schematic of high-current diode

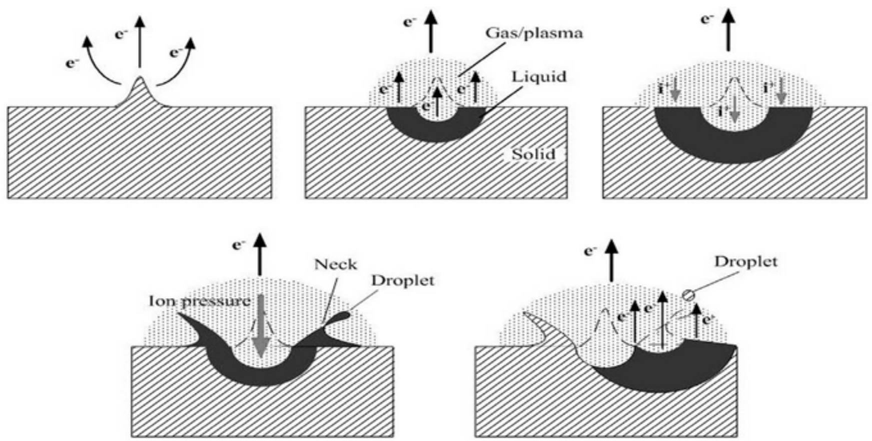


High-power microwave

PIC simulation

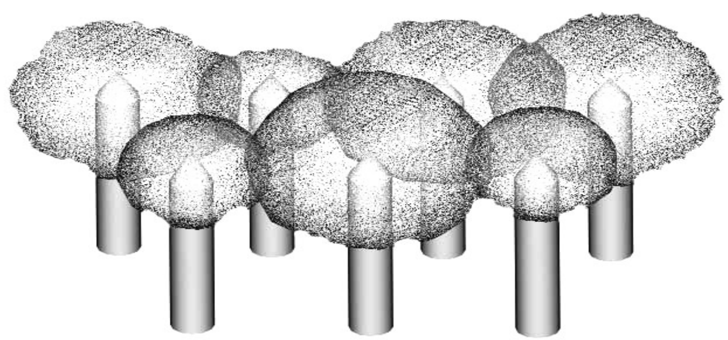


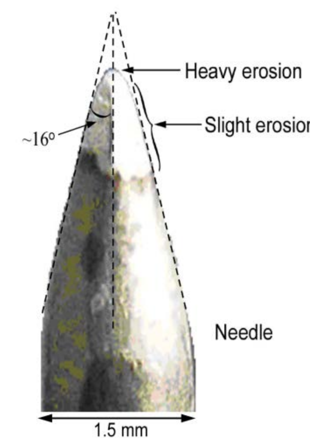
1. Cathode emission physics



$$E \sim \sigma \sim r^{-2}$$

Explosive electron emission only

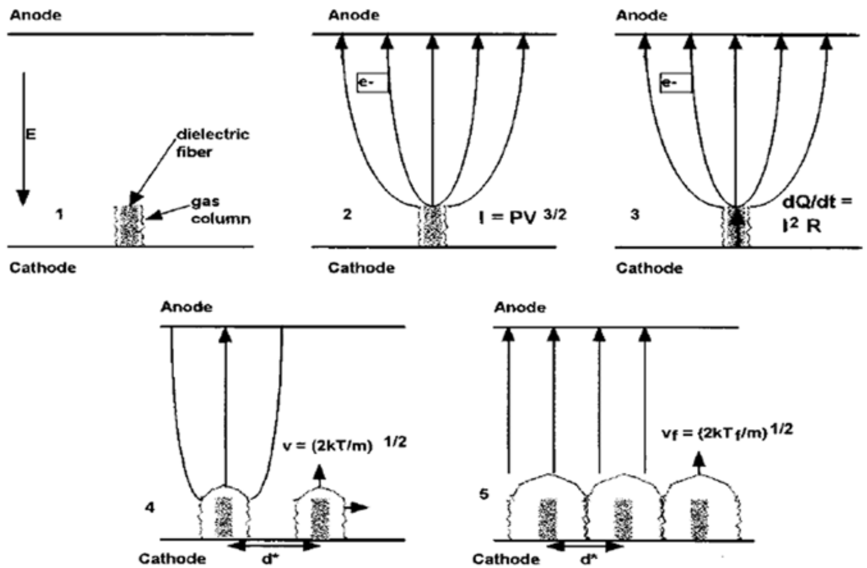




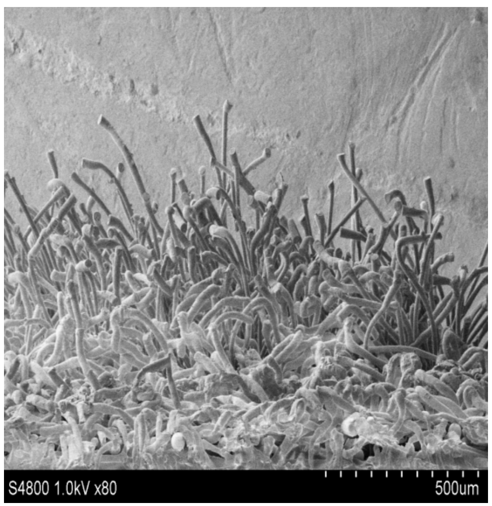
Metal cathode

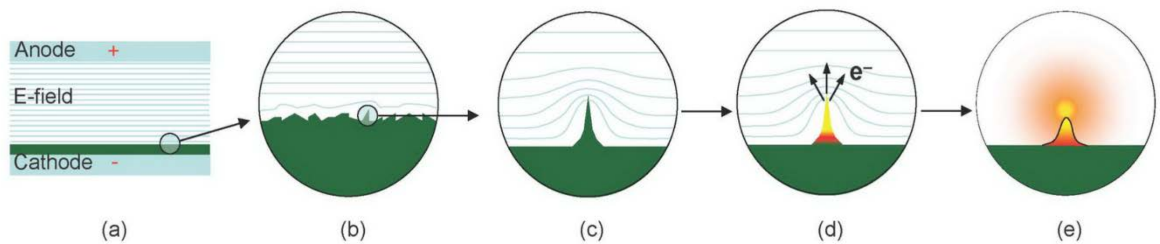
- Fast plasma expansion velocity
- Time delay in plasma appearance
- Non-uniformity in plasma distribution

G. A. Mesyats, *Explosive Electron Emission*, URO Press (1998)



Surface flashover

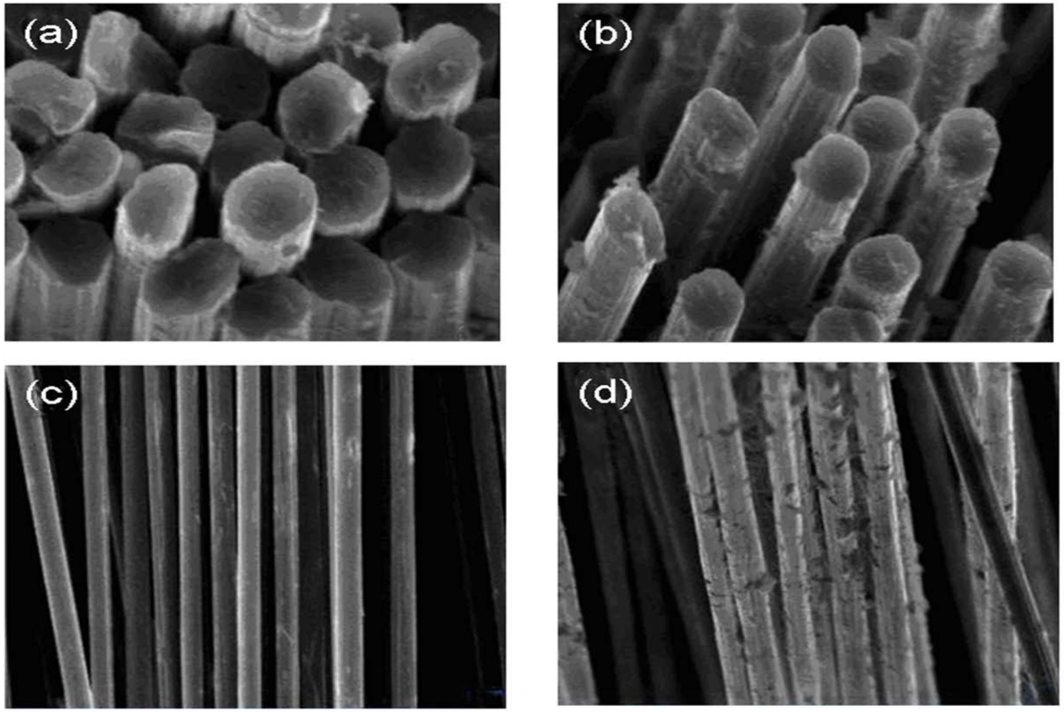




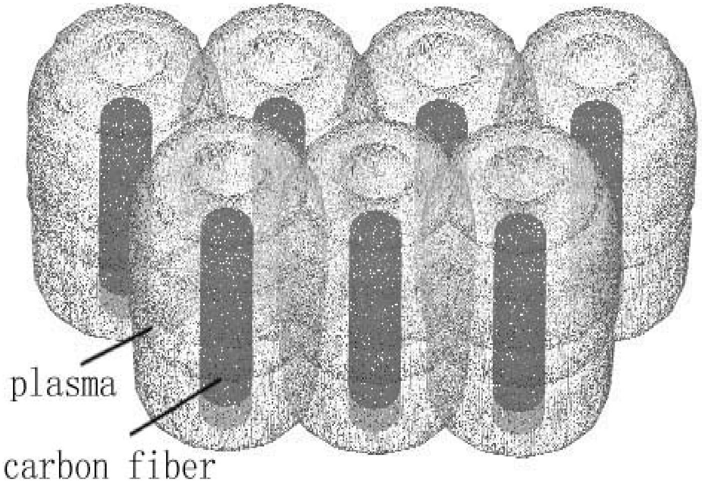
Polymer velvet cathode

- Low electric field threshold of electron emission (few kV/cm)
- Quasi-constant diode impedance behavior
- CsI coating superior diode operation

Before emission After emission



Tracking of emission



Carbon fiber cathode

1. Explosive electron emission
2. Surface flashover
3. Additional photo-electron emission with CsI coating

Lie Liu,et al., *High Power Laser and Particle beams*, Vol. **17**, pp. 1205-1209 (2005)

Hybrid emission mechanisms

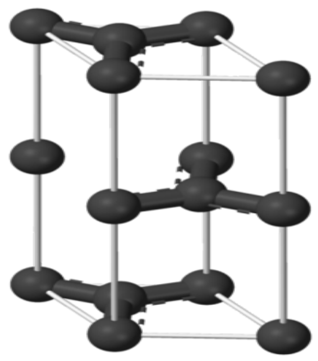
Carbon Fiber Cathode

1. *Explosive electron emission*
2. *Surface flashover*
3. *Additional photo-electron emission for CsI (good UV emitter) coating*

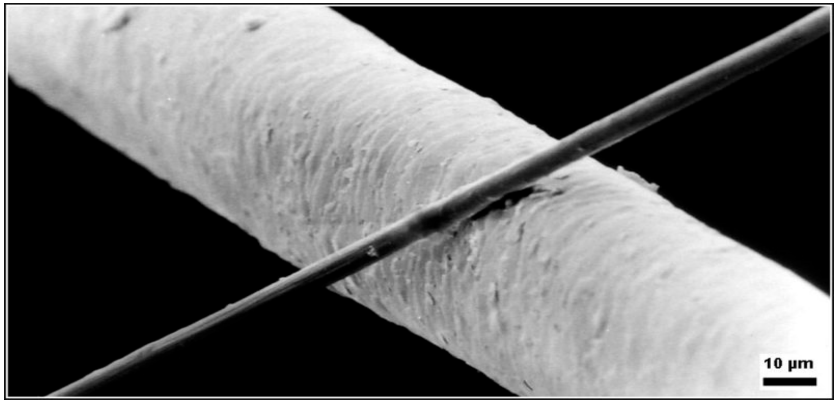
Thus, we can conclude that an optimized cathode should have several electron emission mechanisms, and thus the uniformity of the whole electron emission surface of the cathode may be increased.

Property of carbon fiber

1. Light weight, high strength, high modulus
   carbon fiber density: 1.6~2.15g/cm^3
   tensile strength: >2.2GPa
   modulus: >230GPa
2. Low coefficient of thermal expansion
   Room temperature: (-0.5~-1.6)$\times 10^{-6}$/K，
   at 200~400℃: zero
   at <1000 ℃: 1.5$\times 10^{-6}$/K
3. Electric property between metal and non-metal
4. Boiling Point/Range: >3600^{o}C
   Melting Point/Range: Not available
5. Excellent chemical resistance



Carbon unit cell



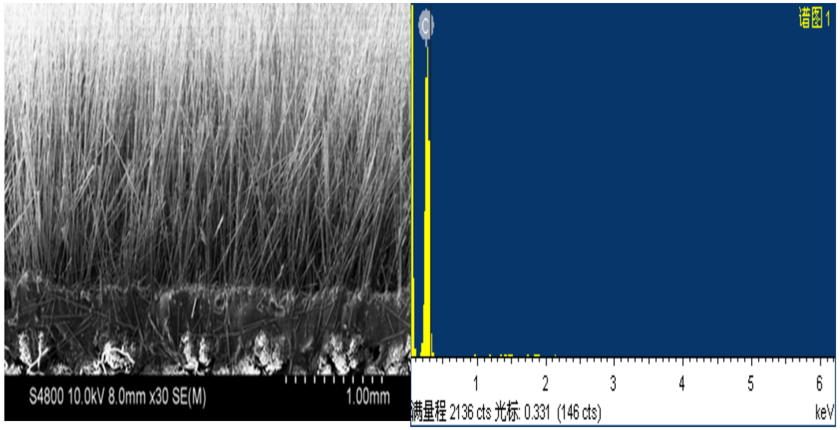
Thickness of carbon fiber and hair

How to construct carbon fiber cathodes?

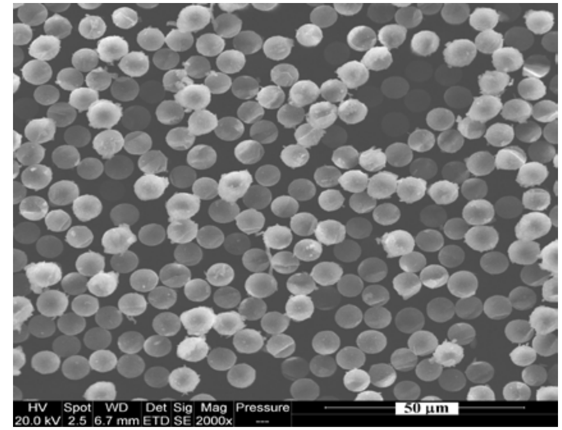
Robust (long life), easily shaped, and free-epoxy
(Invention Patent No. 200310102051.7)

The advantages carbon-fiber cathode for electron emission:

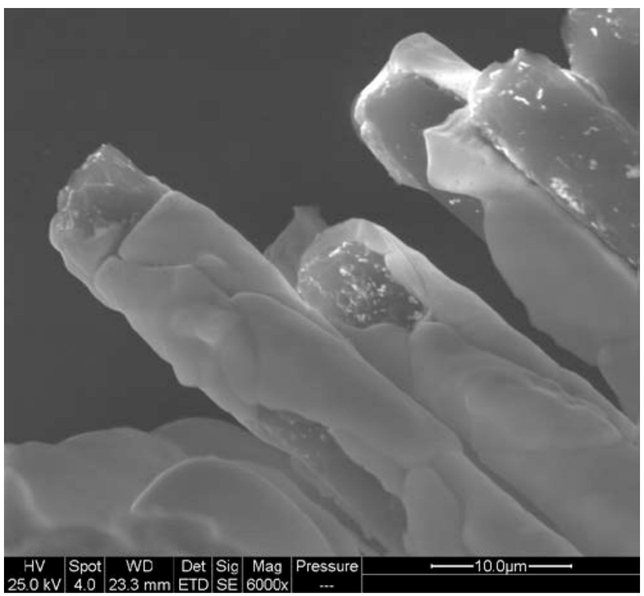
- larger field amplification factor.
- lower turn-on field and threshold field for emission.
- higher intensity of electrical current.
- better uniformity in emission
- lower plasma expansion velocity .
- stronger to stand against the bombardment (long life)



Scanning electron microscope (SEM) image of carbon fiber cathode (side)



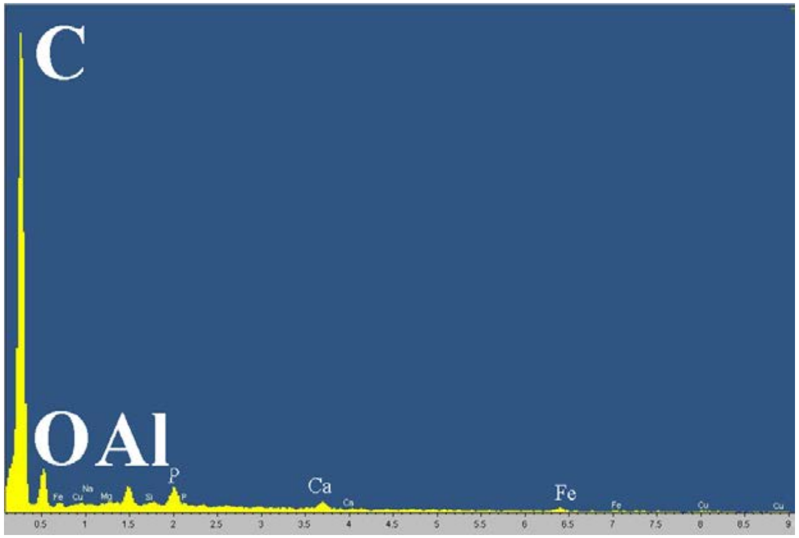
Scanning electron microscope (SEM) image of carbon fiber cathode (top)



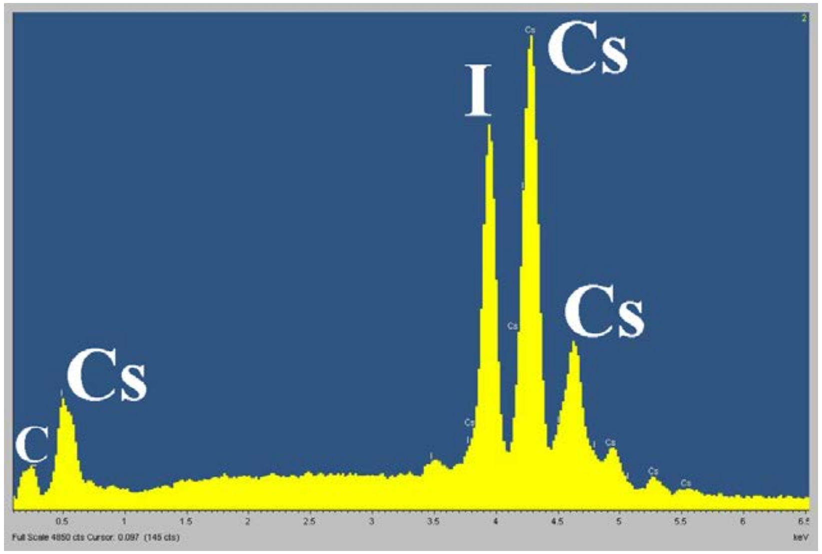
Scanning electron microscope (SEM) image of carbon fiber cathode (side) with CsI Coating

Cathode with CsI coating

Energy distribution spectrum (EDS) of the materials on the carbon fibers with and without CsI coating



Without CsI coating



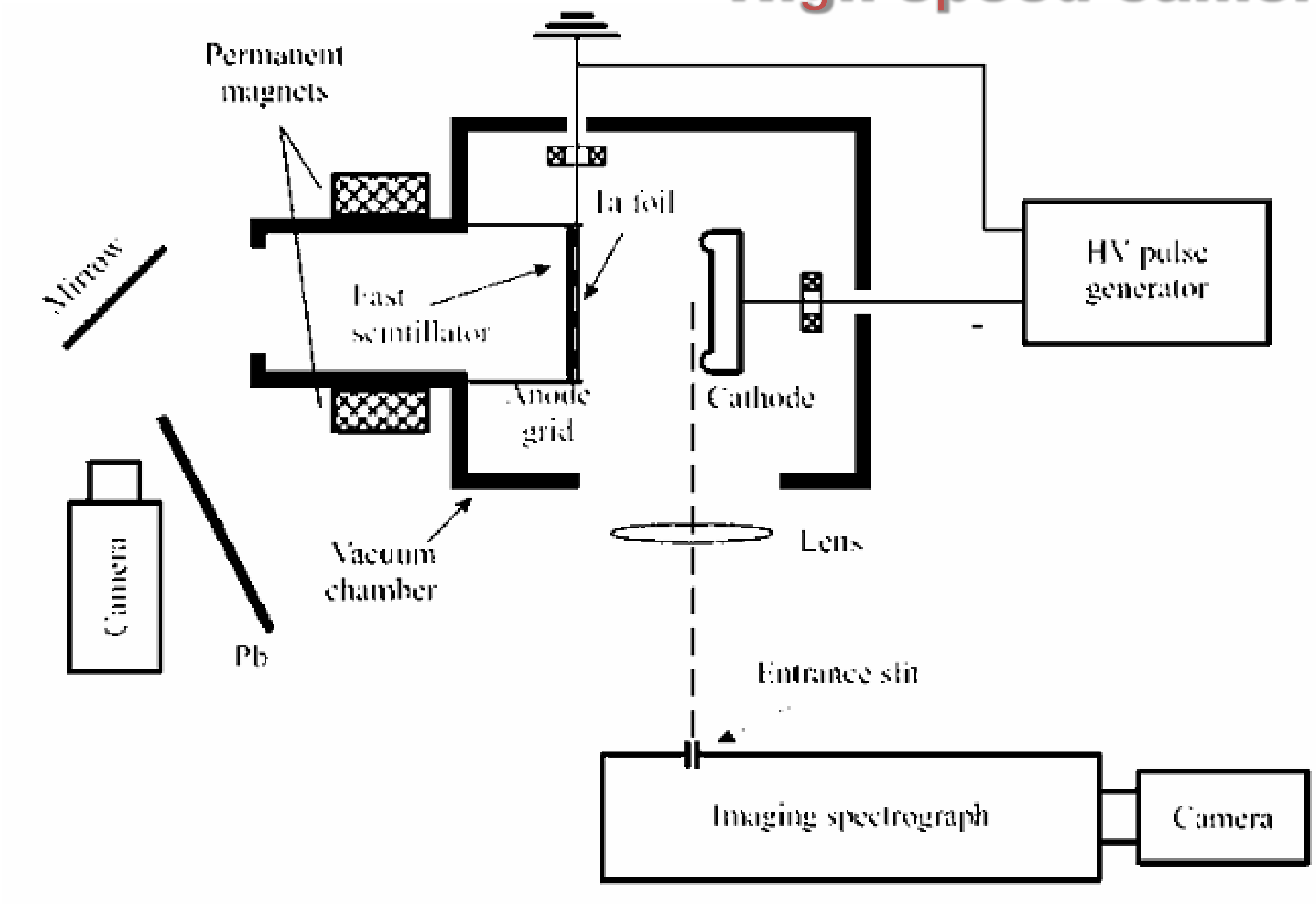
With CsI coating

Properties of ideal pulsed electron source

- Low electric field threshold for electron emission (<50 kV/cm)
- Nanosecond timescale turn-on
- Long life-time (>10^7 pulses)
- High current densities (kA/cm^2)
- Quasi-constant perveance of the diode, a slow plasma expansion rate
- Uniformity and arbitrary cross-section
- Vacuum (10^{-4} – 10^{-5} Torr) compatibility, low outgassing rate
- Low power consumption

2. Diagnostics in diode

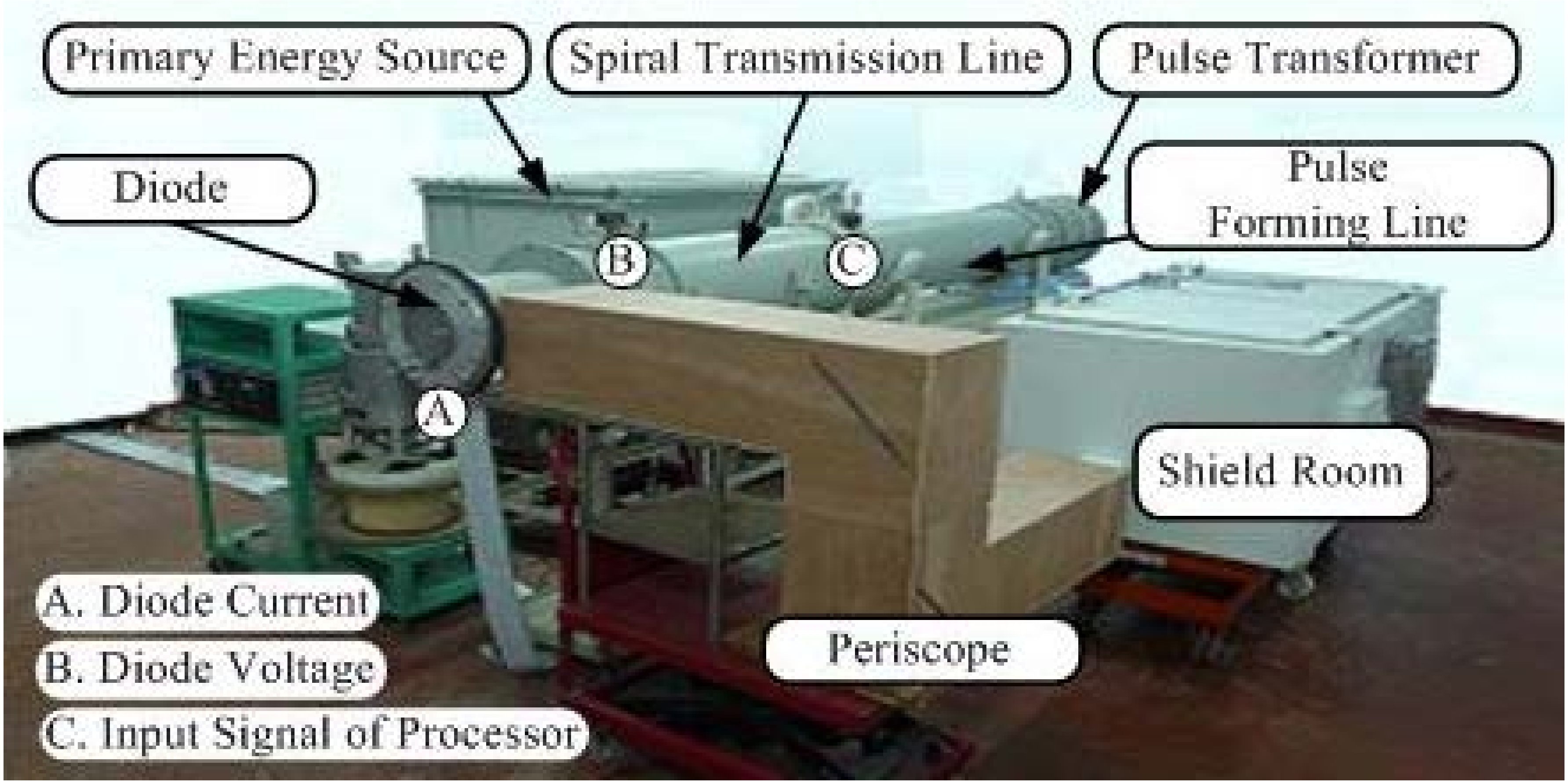
High-speed camera

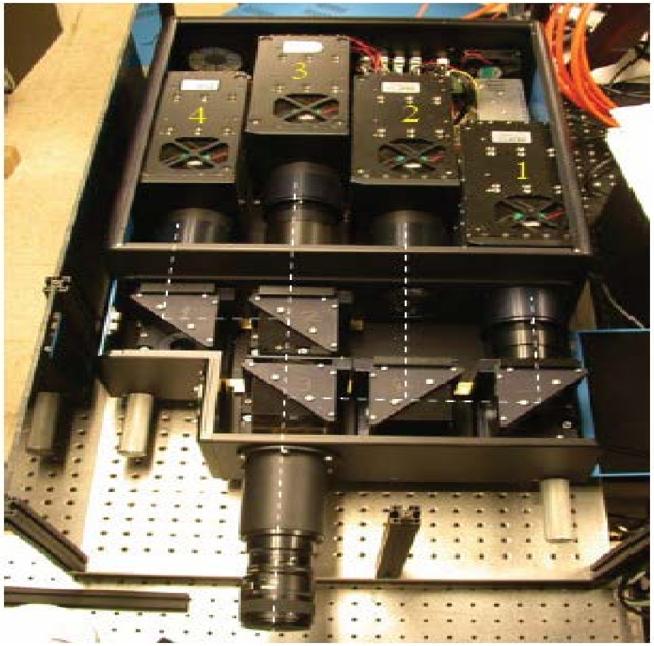


Testing system of optical assistant diagnostics

Lie Liu, et al., *Chinese Physics B,* Vol. 18, pp. 3367-3372 (2009)

Testing system of diagnostics



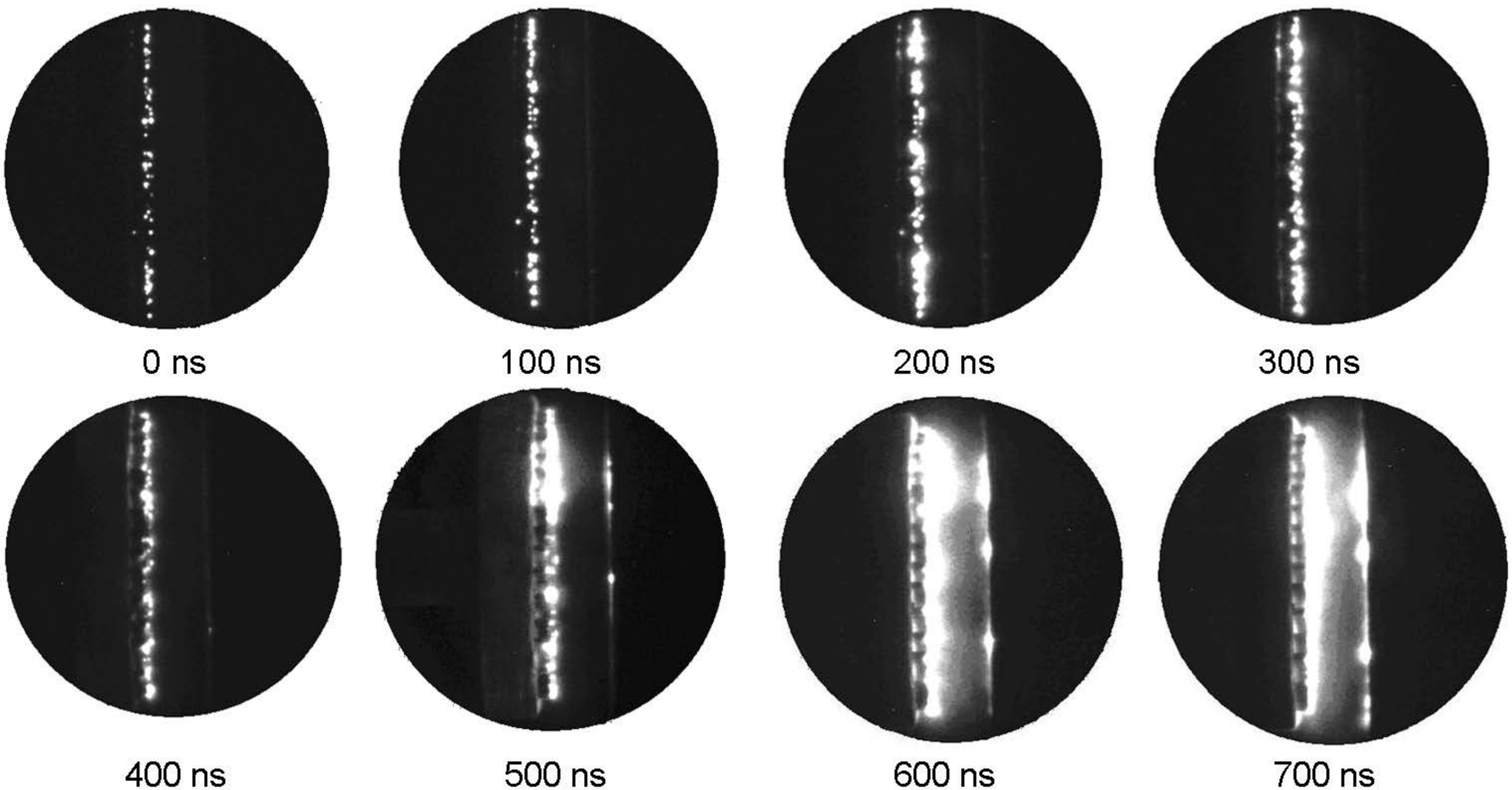


HSFC-PRO
(High Speed Framing Camera)

A Mach-Zehnder interferometer was designed and used to measure the plasma density in the diode.

Expansion of Plasma in Diode

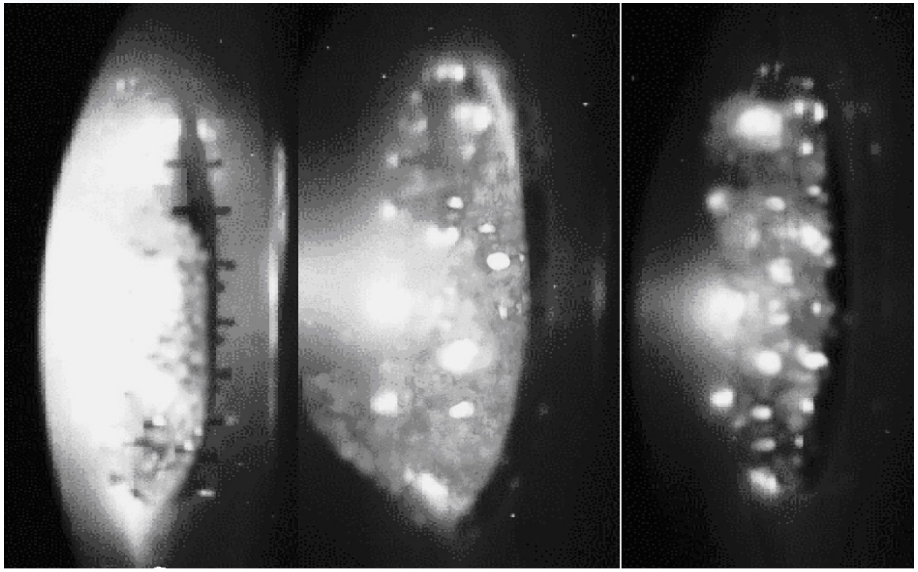
Gap distance 1.9cm



- Cathode turn-on at t=0 ns
- Quasi-equilibrium process during t=0-400 ns
- Inertial characteristic or anode plasma or both after t=400ns

High current densities (kA/cm^2)

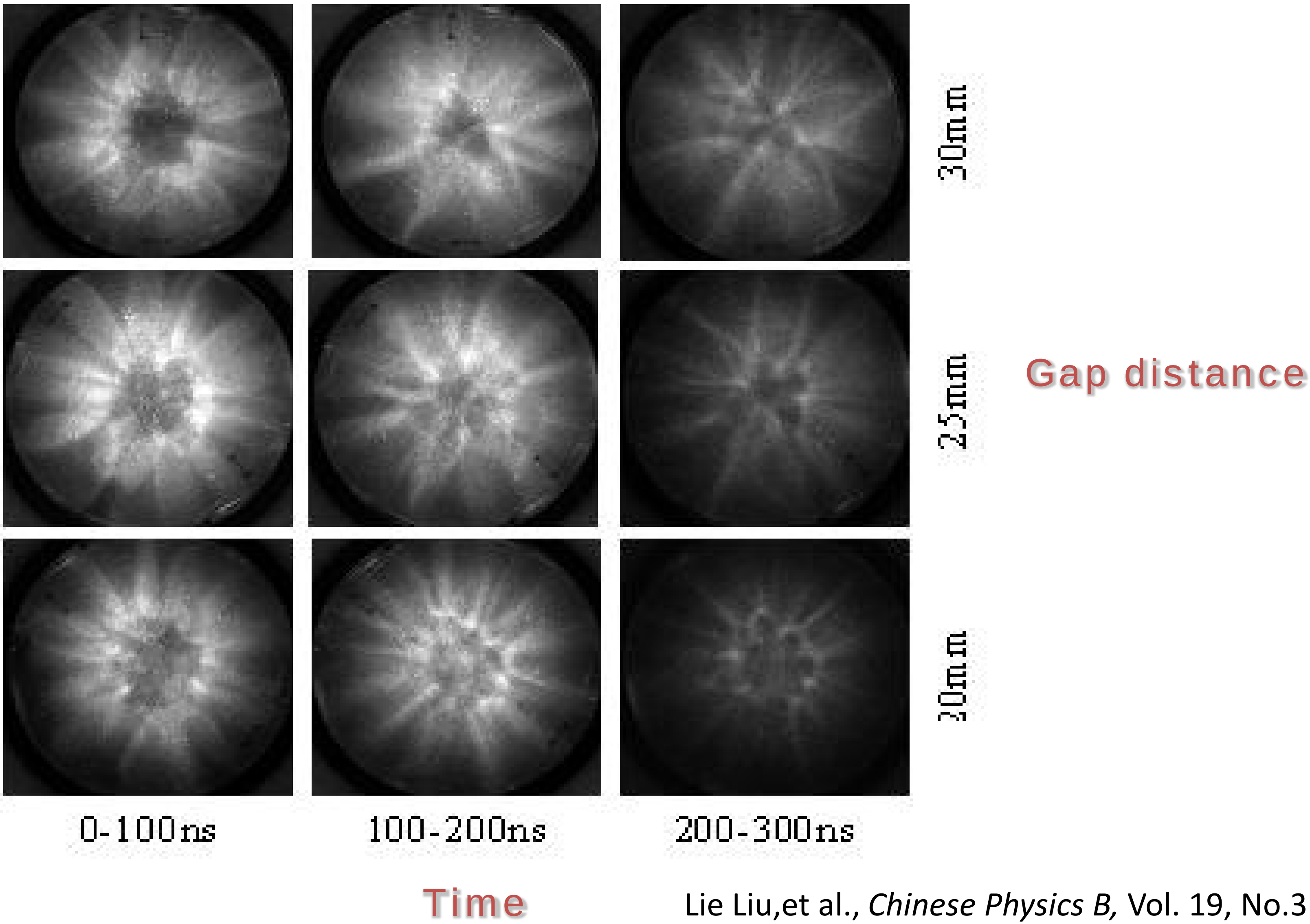
Emitting spots



Time-and-space resolved observations

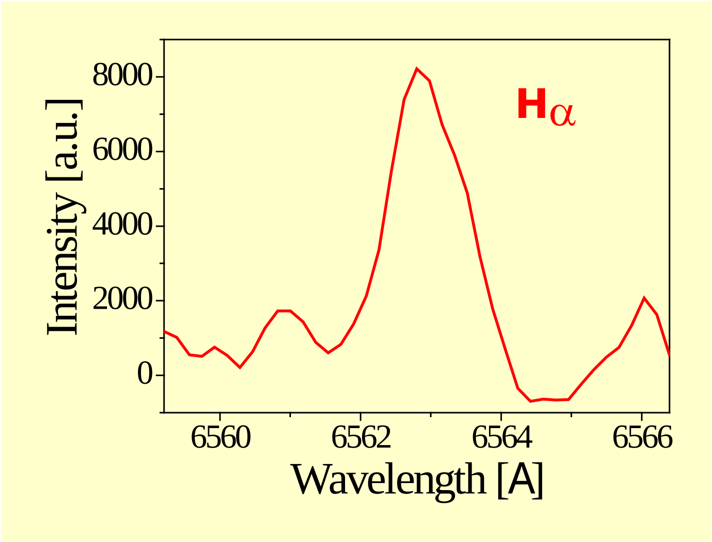
X-ray imaging in time and space

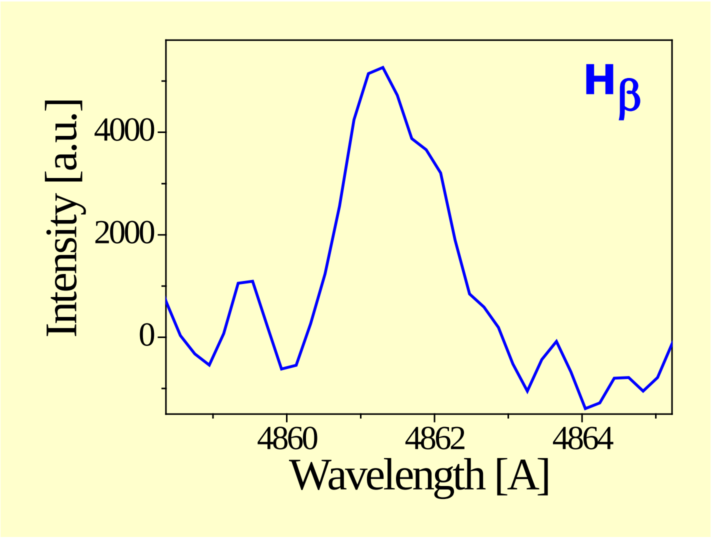
(Scintillator film (EJ-260) attach to anode)



Lie Liu,et al., *Chinese Physics B,* Vol. 19, No.3 (2010)

Spectroscopic diagnostics



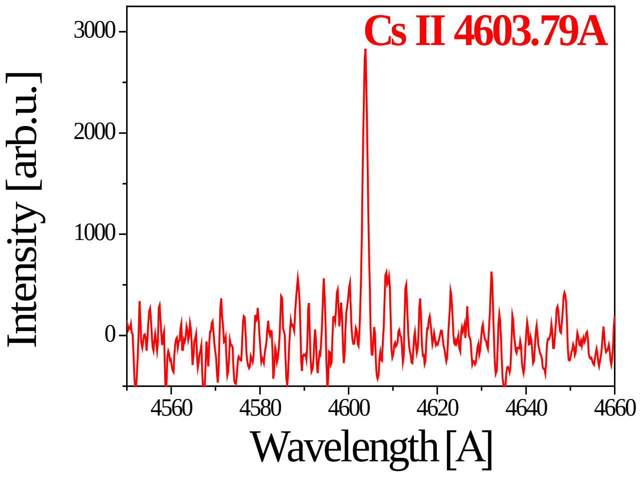


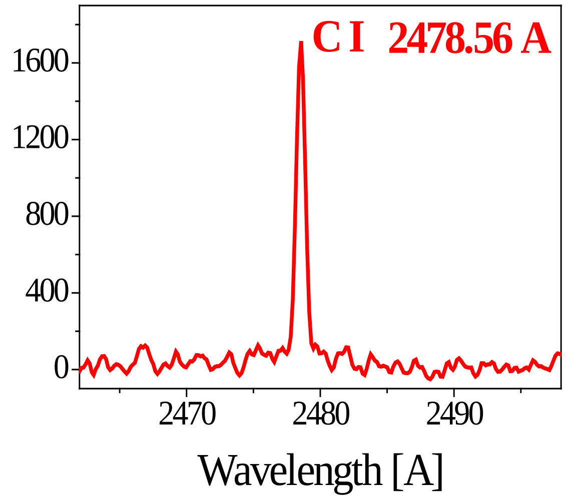
Stark broadening → Plasma density: $(4.5 \pm 1.3) \times 10^{14}\,\mathrm{cm}^{-3}$

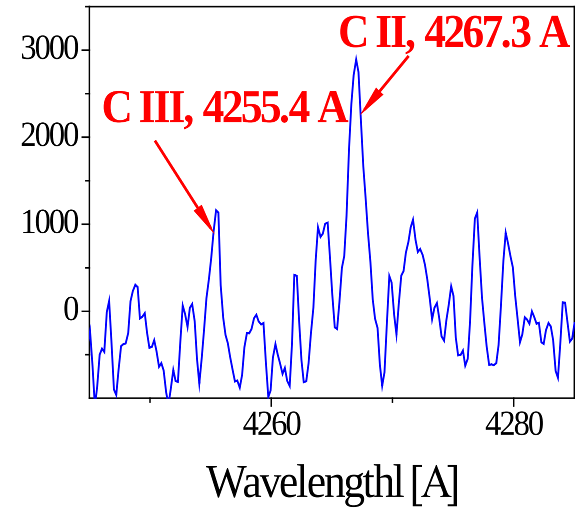
H_α/H_β population ratio ⟷ Collisional radiative modeling

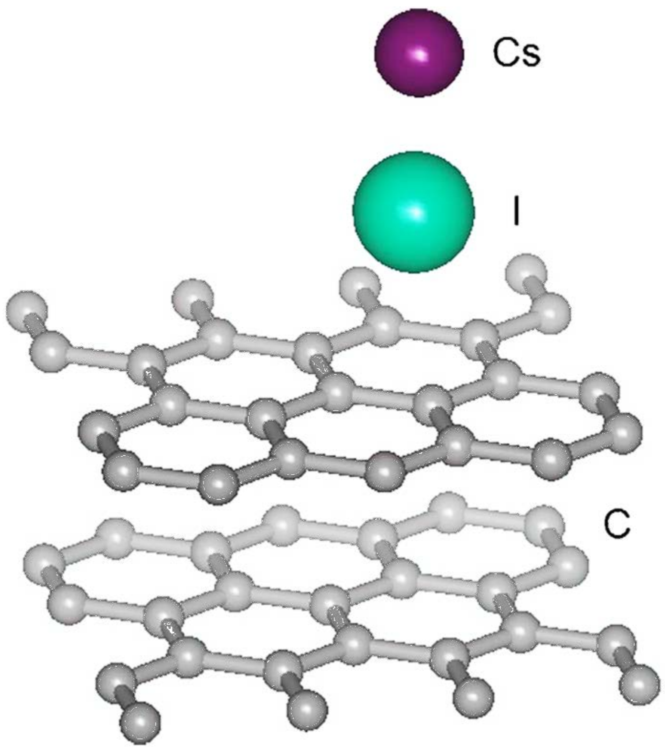
Plasma electron temperature 7 ± 2 eV

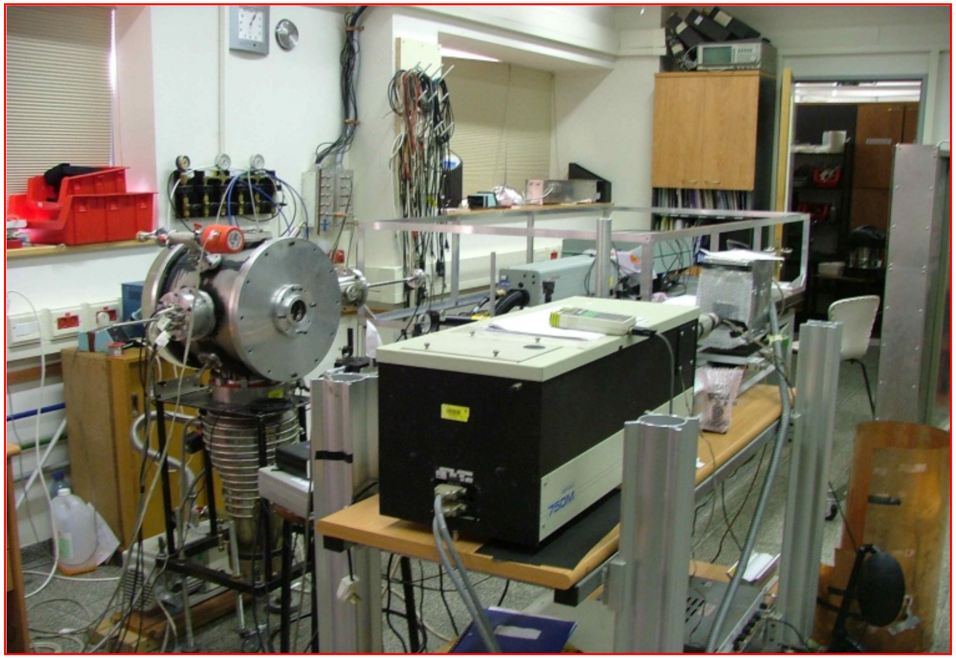
V.Vekselman, J.Gleizer, D.Yarmolich, J.Felsteiner, Ya.Krasik, **Lie Liu**, and V.Bernshtam, ***Appl. Phys. Lett***.,vol. 93, 081503, 2008.

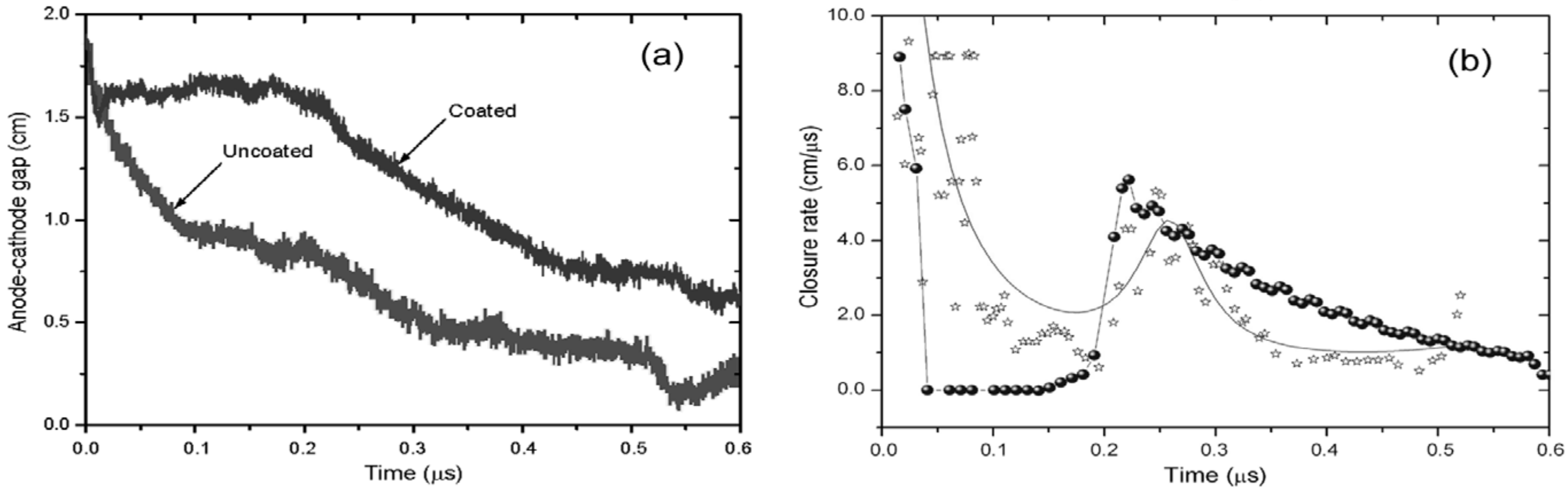

Cs II 4603.79A
Intensity [arb.u.]
3000
2000
1000
0
4560
4580
4600
4620
4640
4660
Wavelength [A]


C I 2478.56 A
1600
1200
800
400
0
2470
2480
2490
Wavelength [A]


C II, 4267.3 A
C III, 4255.4 A
3000
2000
1000
0
4260
4280
Wavelengthl [A]

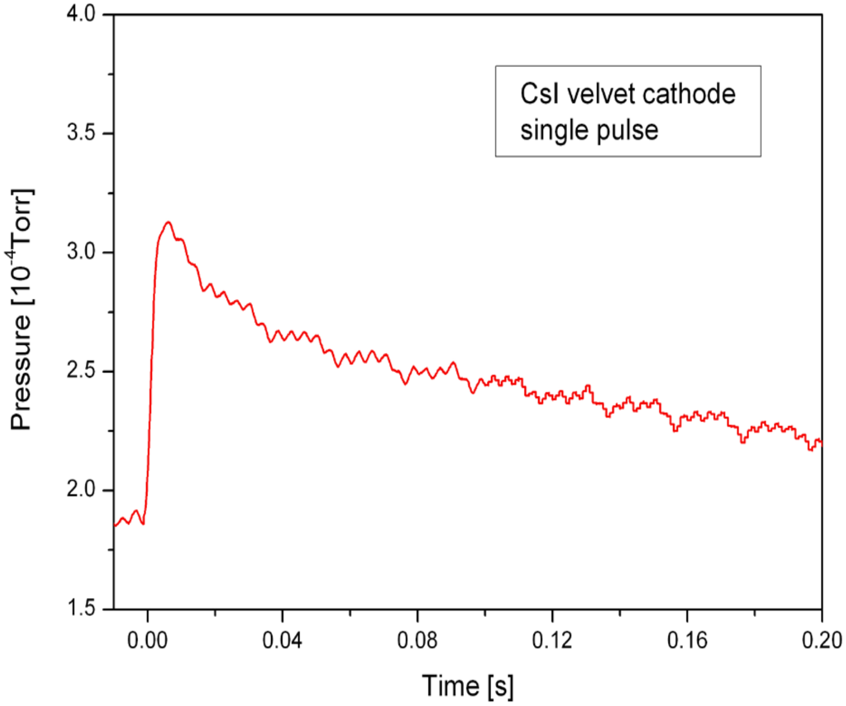

Cs
I
C



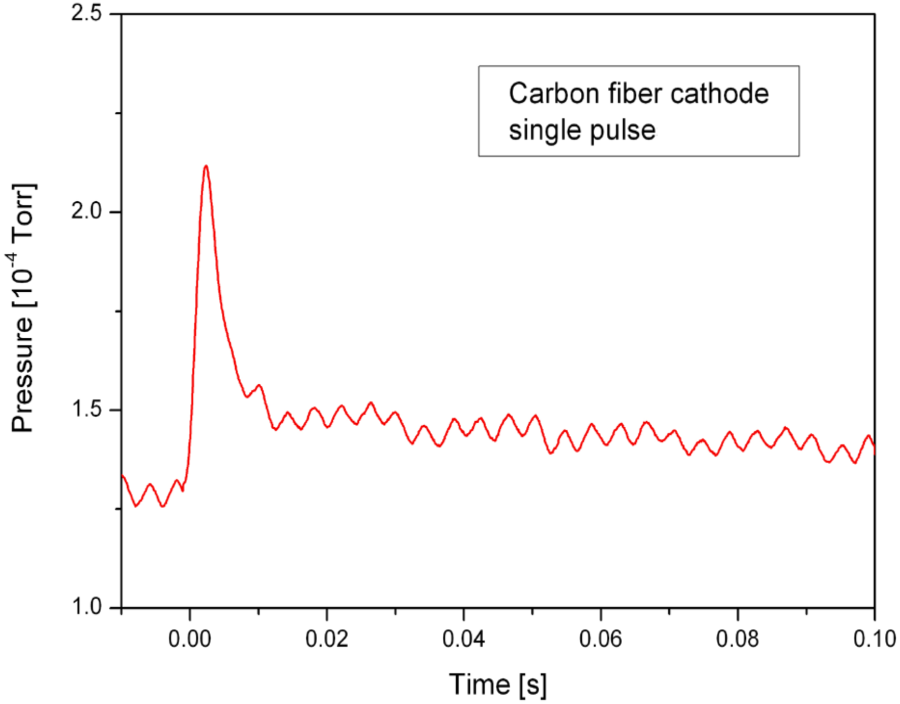


"Cs plasma" remains at the vicinity of the cathode surface, Cs II (4603.8 Å) was obtained only at the distance of 2.5mm from the cathode surface.

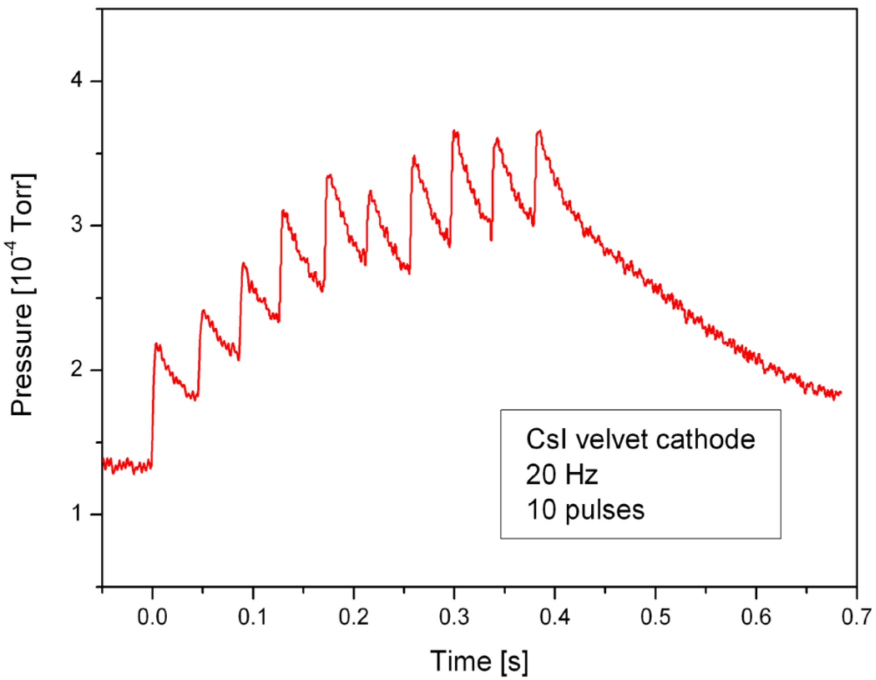
Vacuum compatibility



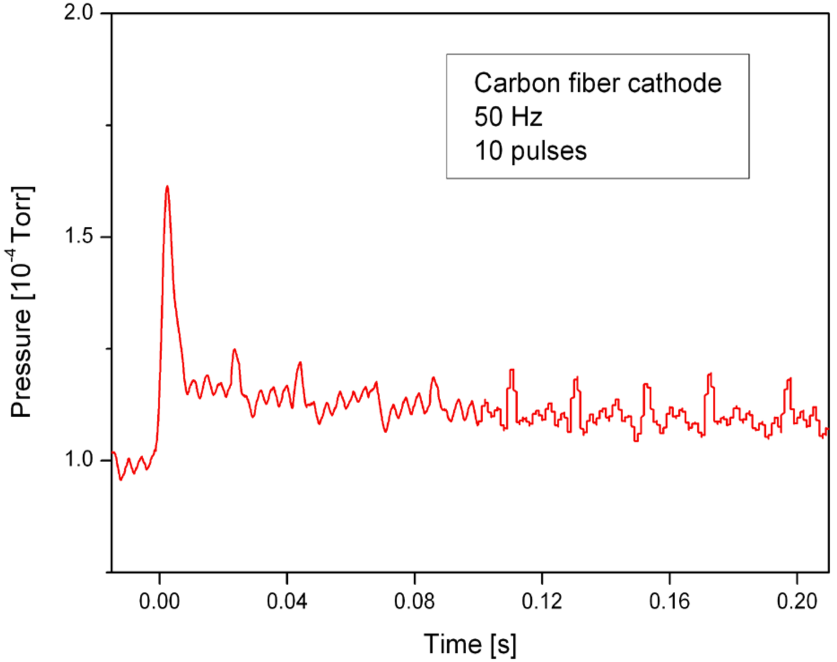
Velvet cathode



Carbon fiber cathode

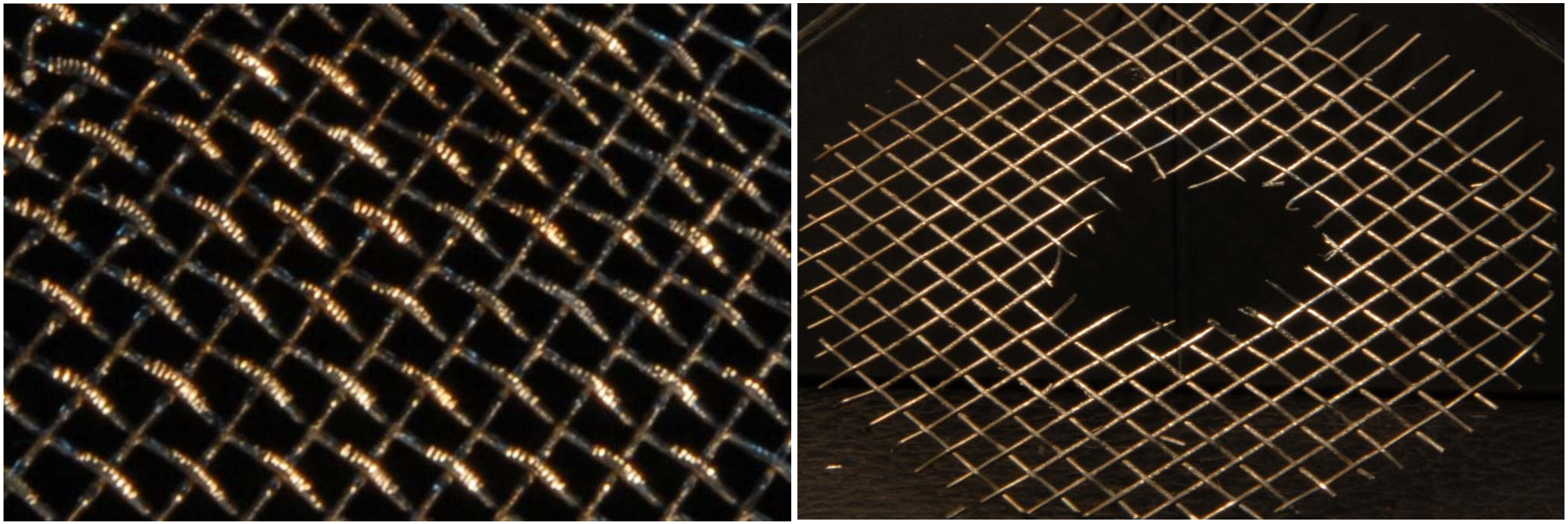


Velvet cathode, 20 Hz, 10 pulses



Carbon fiber cathode, 50 Hz, 10 pulses

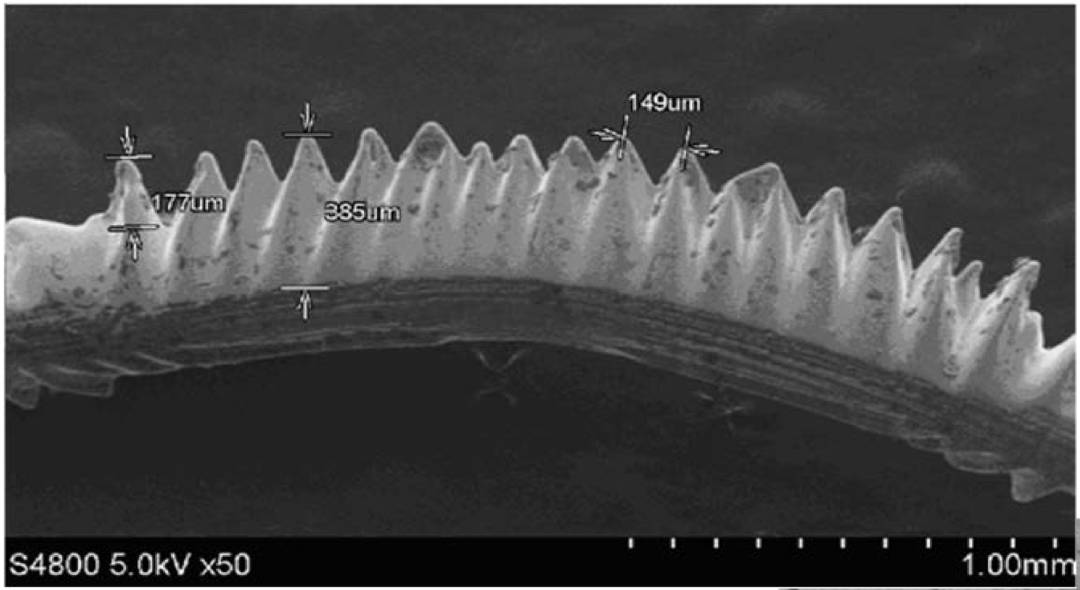
3. Surface morphology of the stainless steel anode-grid irradiated by high-current electron beams



The anode grid is of 21 cm in diameter and 70% transparency.

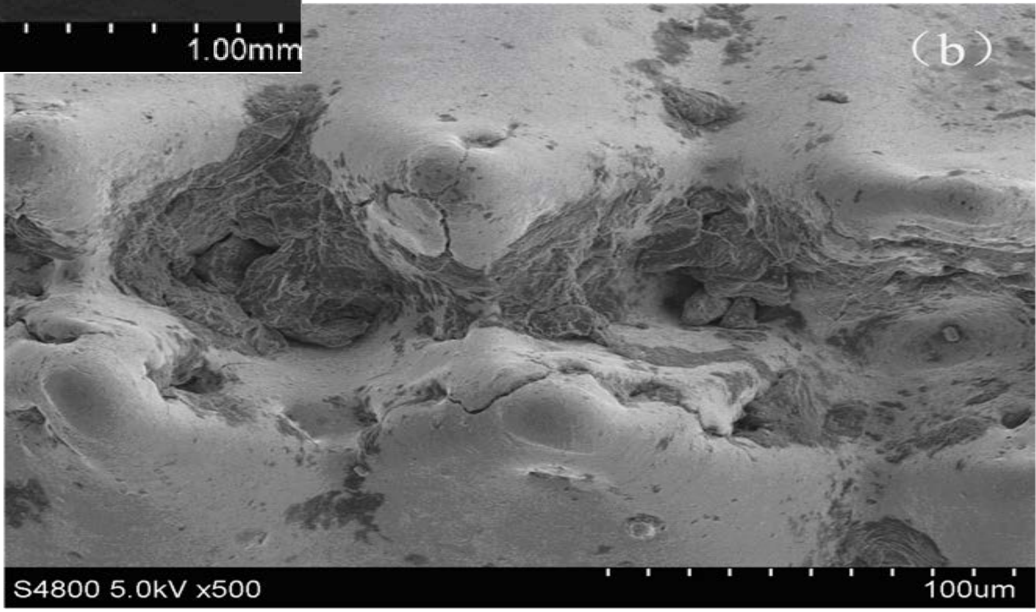
The square grid cell's inner length is about 2.5 mm with cylindrical single wire of 0.3 mm in diameter.

Surface morphology of a single wire observed by a SEM in increasing magnification



Side view

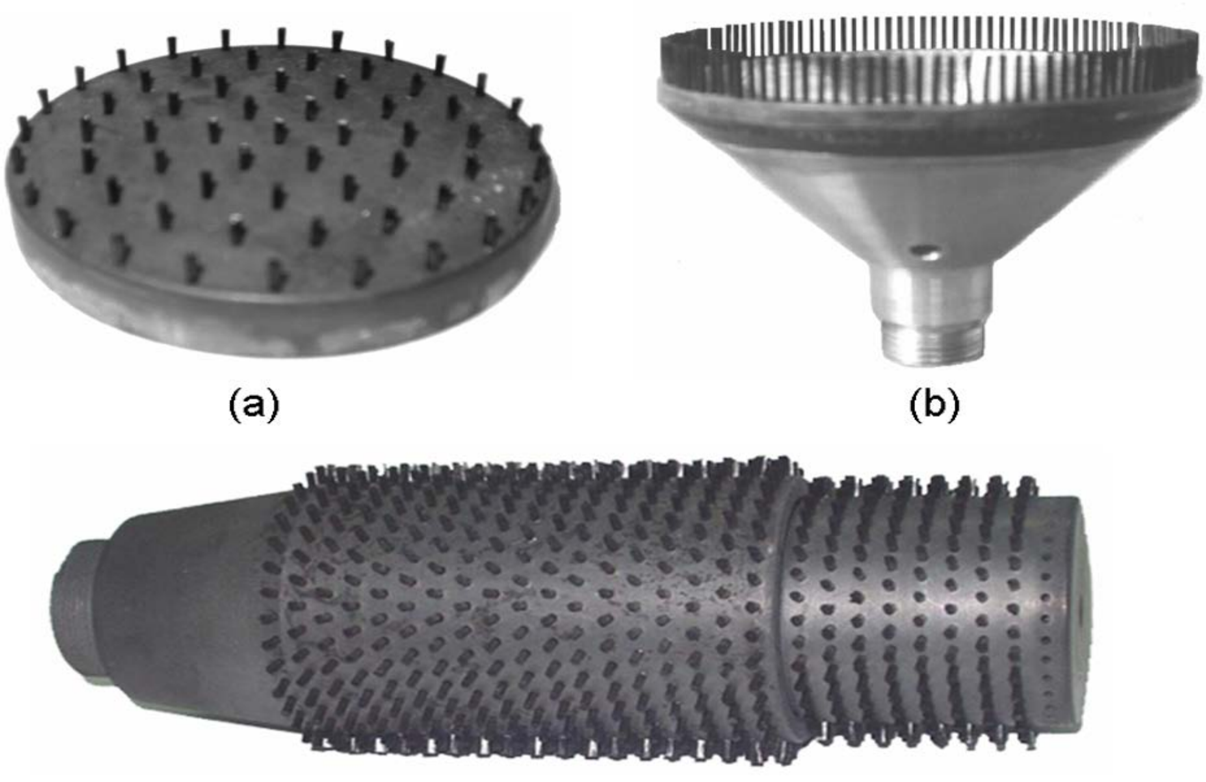
Top view



Question:

Is it Rayleigh-Taylor-like interface instability?

4. A series of tufted carbon fiber cathodes designed for different high power microwave sources

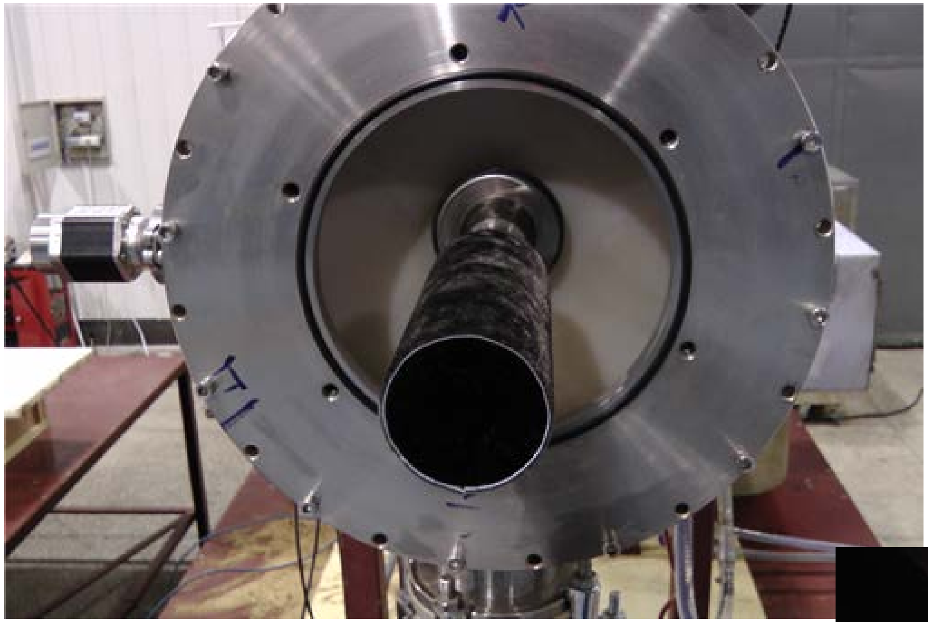


(a) (b) (c)

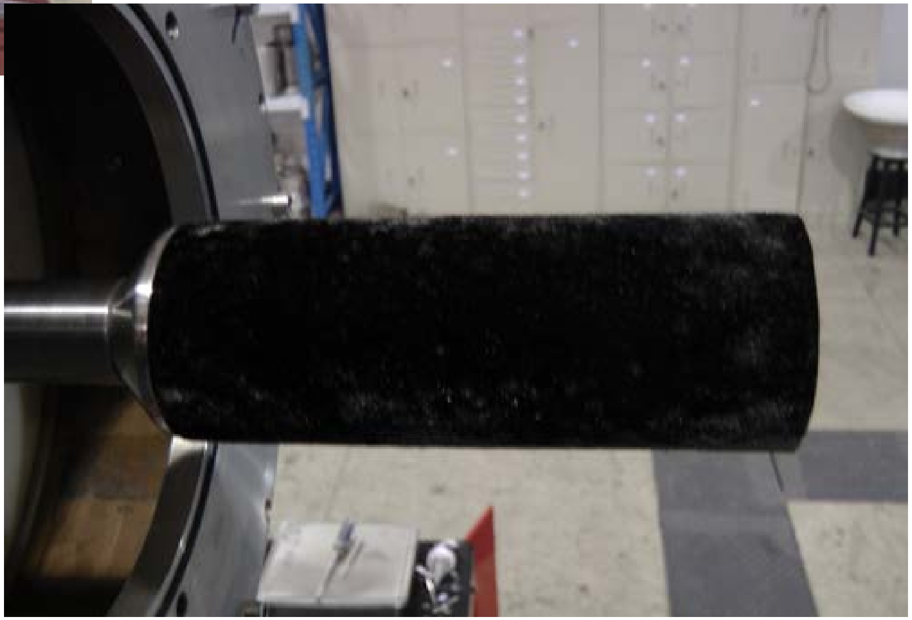
Lie Liu, et al., Rev. Sci. Instrum. Vol. 79, P. 064701 (2008)

Carbon fiber-based cathodes for magnetically insulated transmission line oscillator (MILO) operation

Lie Liu, et al., Applied Physics Letters, vol. 91, p. 161504 (2007)



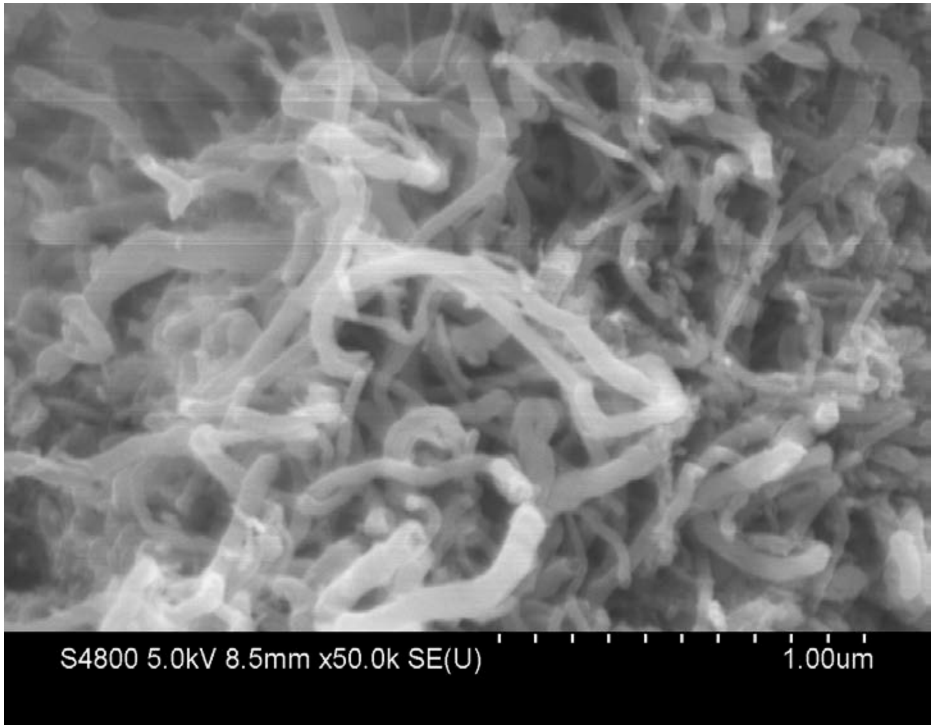
Large-Area
uniformly emitting



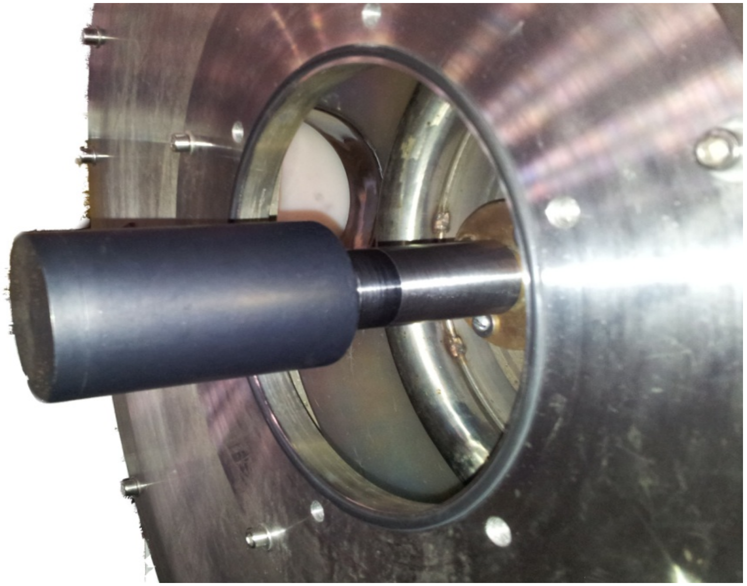
Carbon fiber velvet cathode for MILO operation

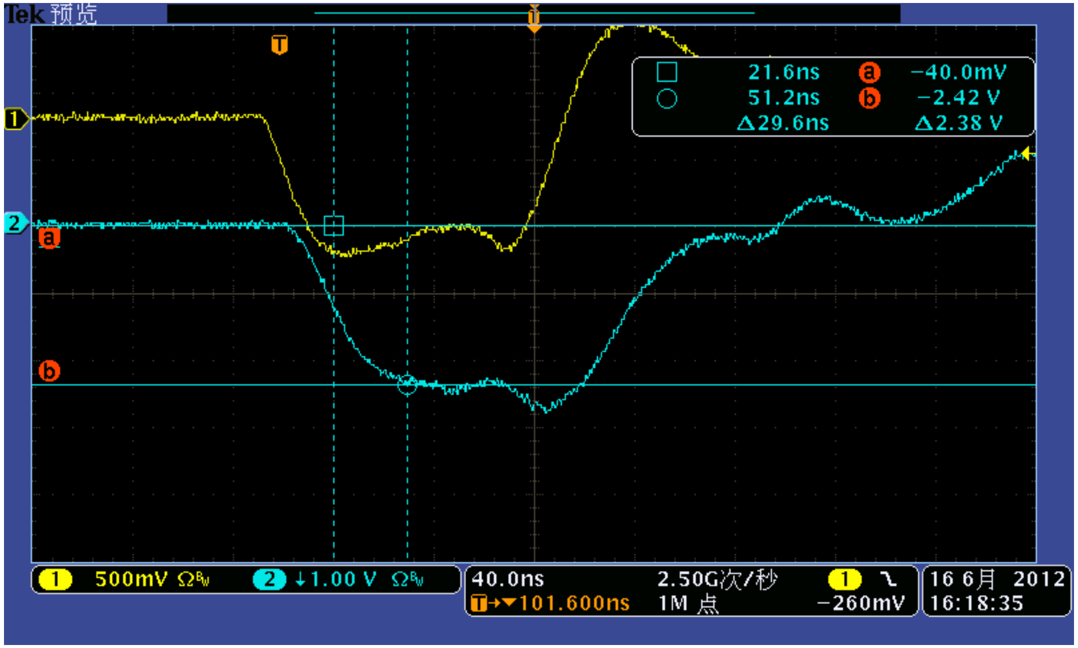
5. On-going research: cathode with carbon nanotube (CNT) coating

Large-area uniformly CNT on cathode surface



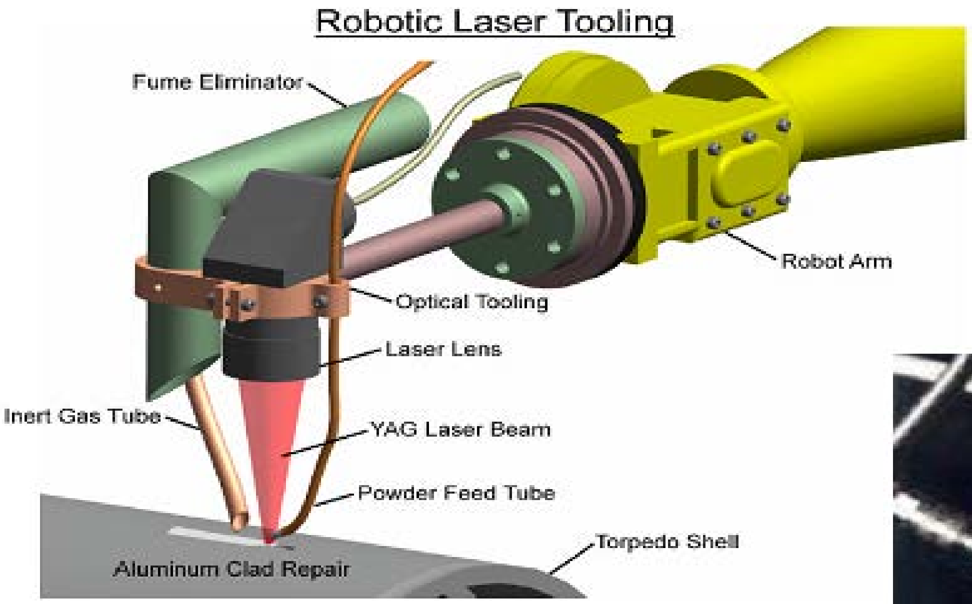
Scanning electron microscope (SEM) image of CNT on cathode surface

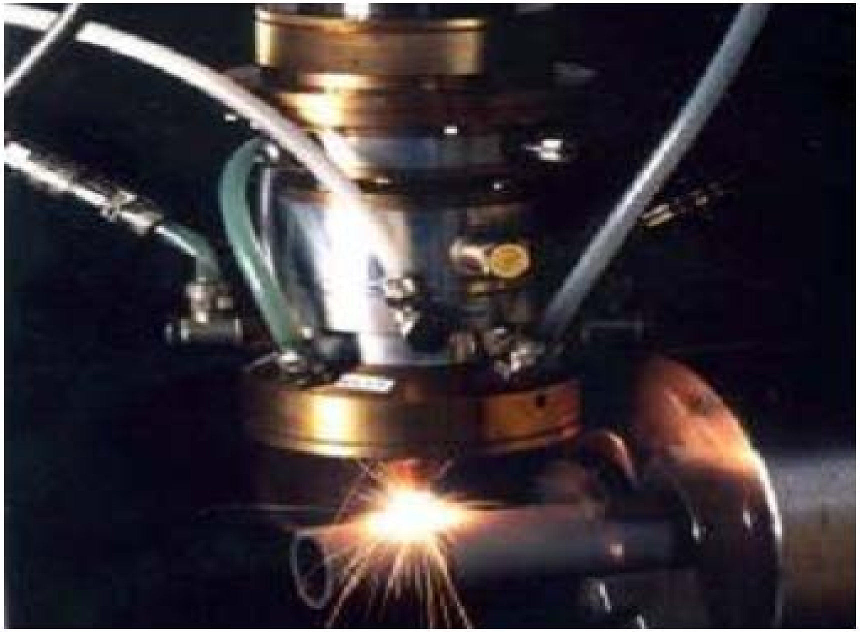




U_d=318kV I_d=84.5kA

Laser cladding (or by high-current electron beams)

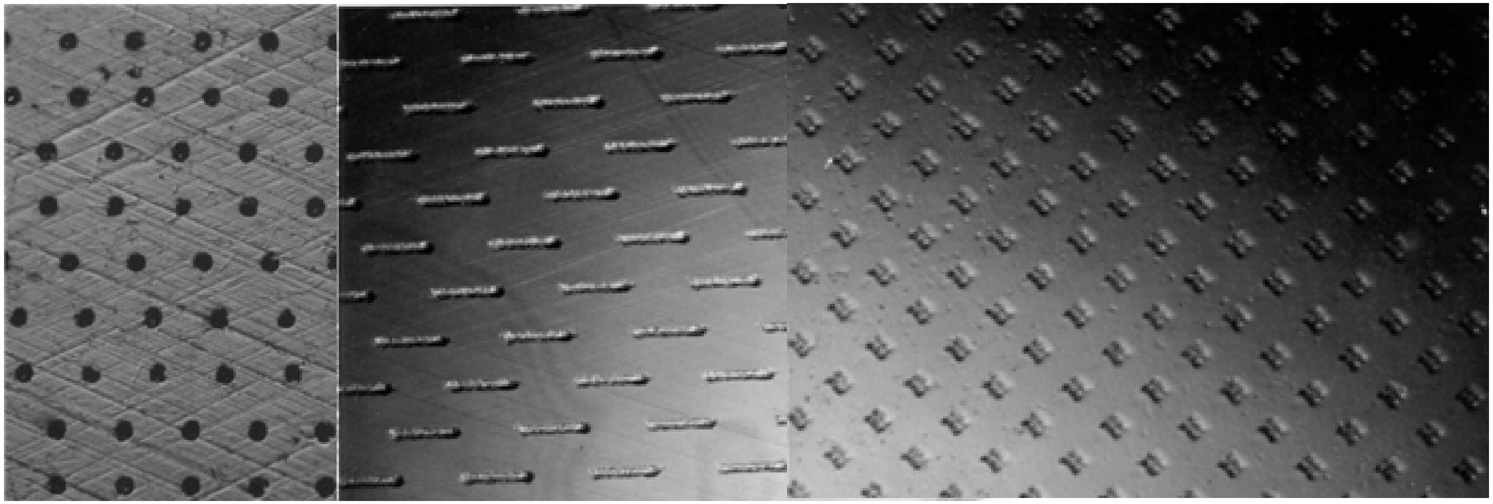


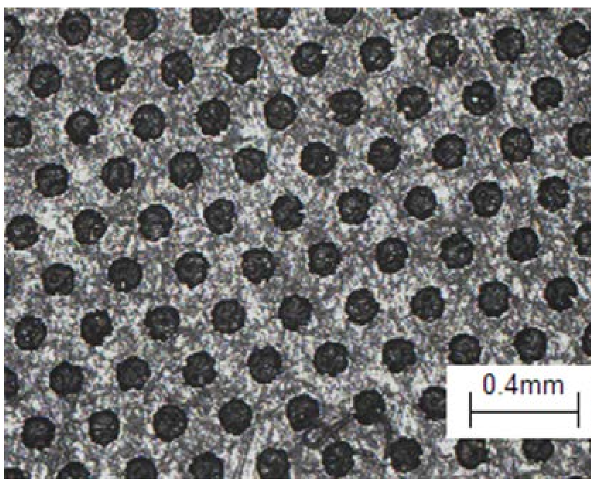


Laser cladding to make carbon nanotube cathode

CNT cathode surface through laser cladding can generate field enhanced EEE and surface-flashover EEE.

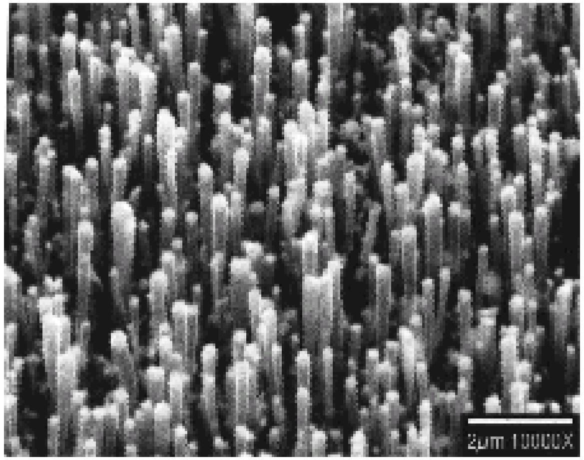
What methods can been used to improve the cladding uniformity of carbon nanotube on a cathode?





- oDigging holes on the surface of cathode uniformly
- oFill carbon nanotube powder into these holes
- oApply laser cladding to combine them together

Recent research breakthroughs include novel methods to precisely fabricate new high current density cathodes and improved understanding of cathode emission physics.

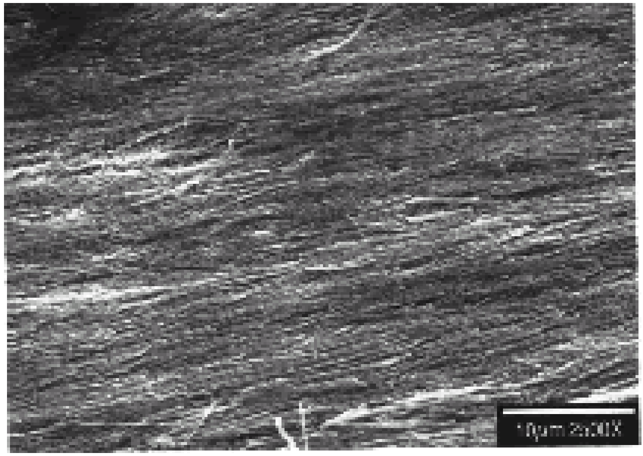


a)

90^0

(b)

45^0



(c)

0^0

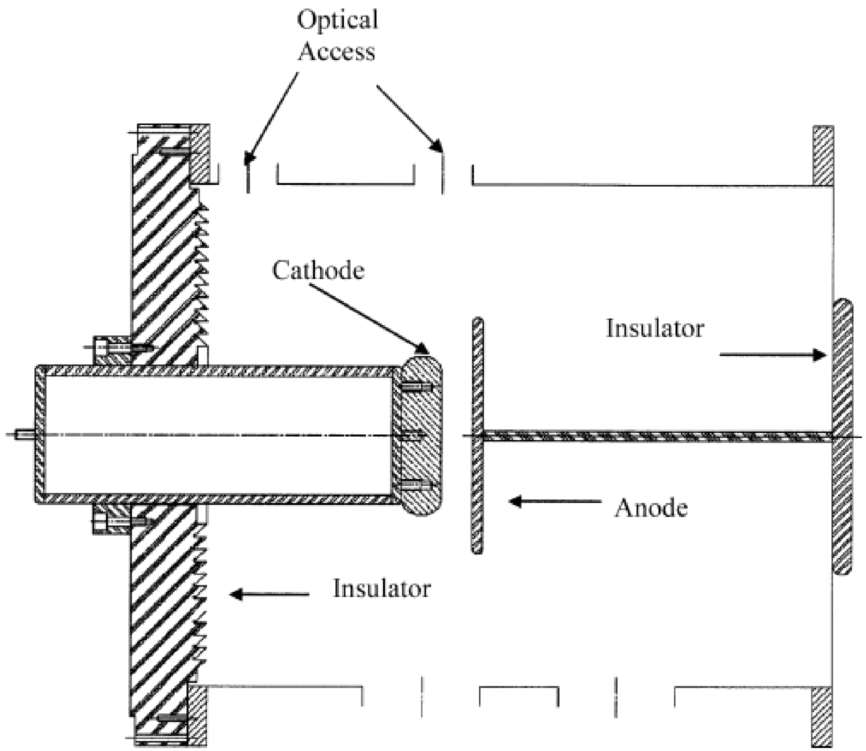
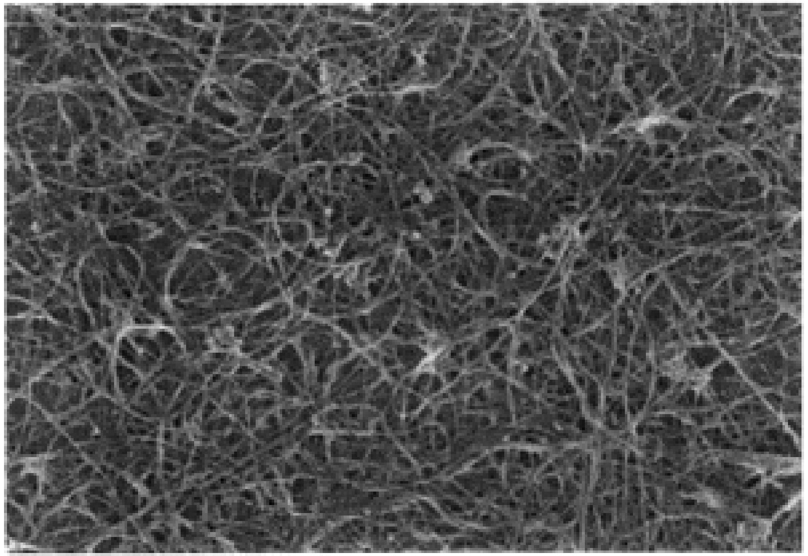


Fig. 1. Experimental configuration for cathode tests.



Results from US Air Force Research Lab

D. Shiffler et al., *IEEE transaction on Plasma Science*, Vol. 32, pp. 2152-2154 (2004)

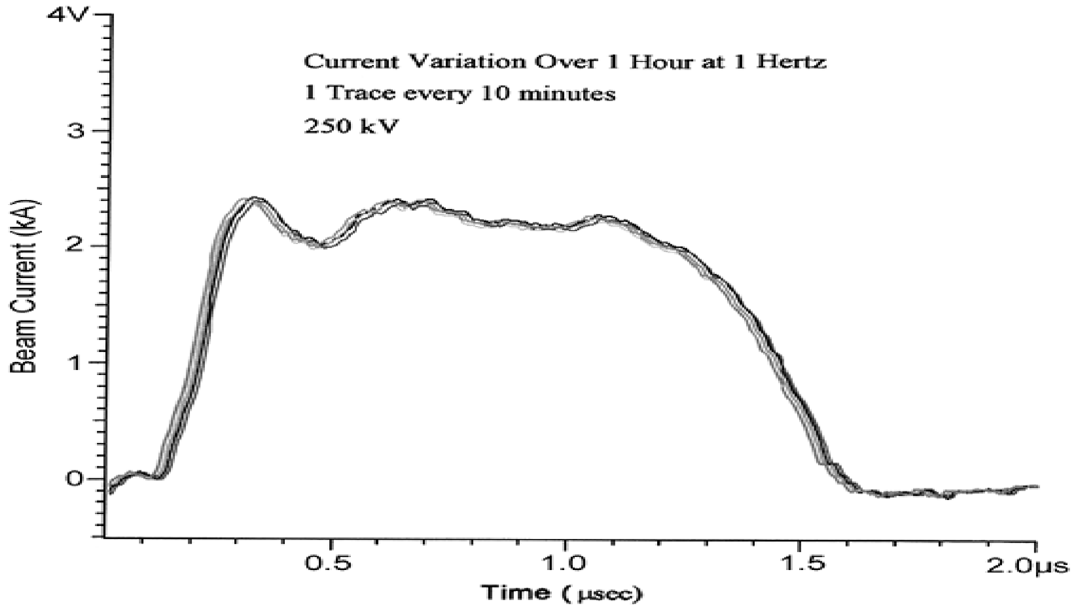


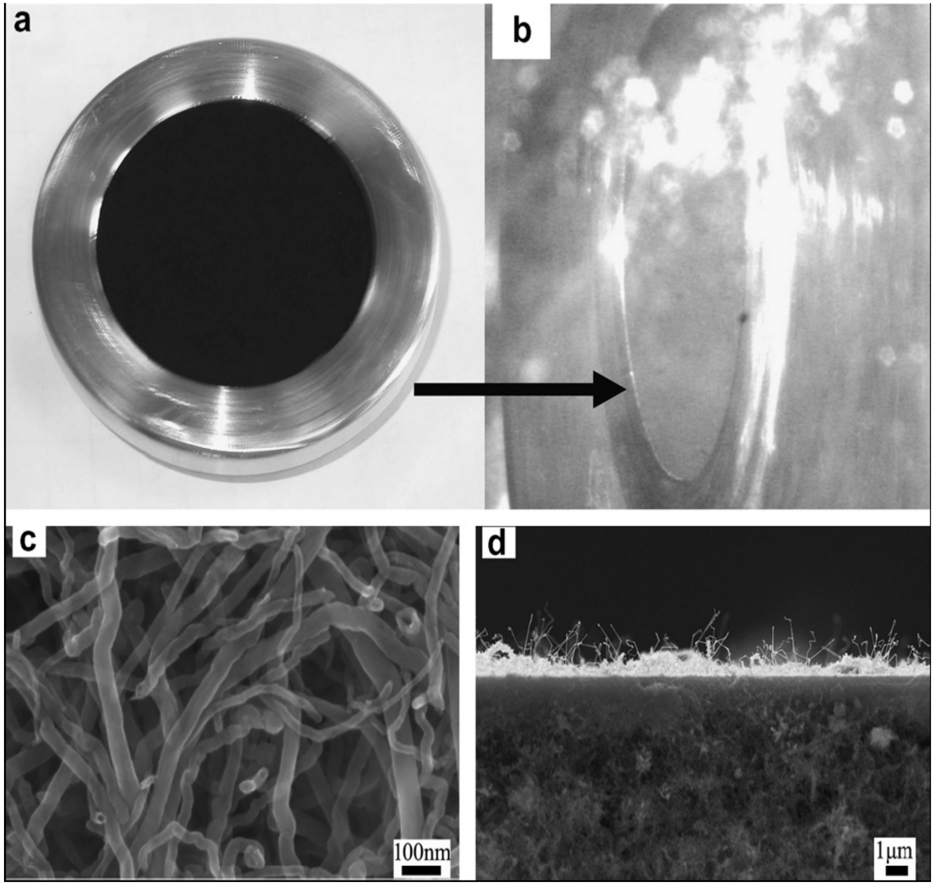
Fig. 4. Current obtained for operation at 250 kV over a period of 1 h. We acquired current data every 10 min. Current remains very stable throughout operation.

TABLE I

VOLTAGE, CURRENT, CURRENT DENSITY, AND SHOT NUMBERS FOR CNT CATHODE. NOTE THAT AVERAGE CURRENT DENSITY OVER MACROSCOPIC REACHES 50 A/cm^2

Voltage (kV)	Current (kA)	Current Density (A/cm^2)	Number of Shots
137.5	0.8	12.5	5,000
165	1.3	20.3125	5,000
192.5	1.5	23.4375	5,000
220	1.7	26.5625	5,000
247.5	2.2	34.375	5,000
275	2.5	39.0625	5,000
302.5	3	46.875	5,000
330	3.3	51.5625	3,321

Results from China Academy of Engineering Physics & University of Science Technology Beijing



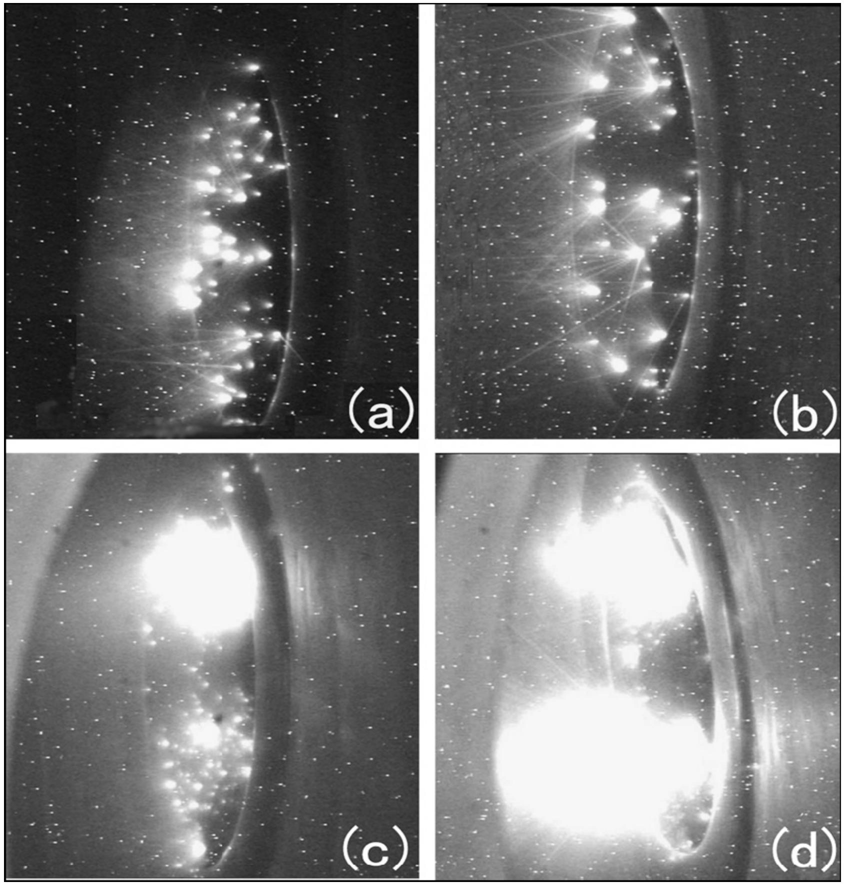


Image of CNT on cathode surface

Explosive field emission(1 MV) and plasma expansion

Q Liao et al., *ACTA PHYSICA SINICA*, Vol. 57, pp. 2328-2333 (2008)

What one can get from the Project

1. Paper __ physics and more discussion

(Comments from APL referees about my papers)

Paper Interesting: Yes	Original Paper: Yes	Sufficient Physics: Yes
Well Organized: Yes	Clear and Error Free: Yes	Conclusions Supported: Yes
Appropriate Title: Yes	Good Abstract: Yes	Satisfactory English: No
Adequate References: Yes	Clear Figures: Yes	

2. Applications __ fabrications and materials

The cathode material:
Low electric field (<50 kV/cm) for electron emission, Nanosecond timesacle turn-on,
Long life-time (>10^7 pulses), High current densities (kA/cm^2)
a slow plasma expansion rate (coating technique), Uniformity and arbitrary cross-section
Vacuum (10^{-4} – 10^{-5} Torr) compatibility (low outgassing rate), Low power consumption
The fabrication process and cathode structure: How to construct cathodes,
Robust (long life), easily shaped, free-epoxy and surface treatment technique of cathodes

Overall rating → Something new and detailed

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