Plasma sources for high-current electron beam generation

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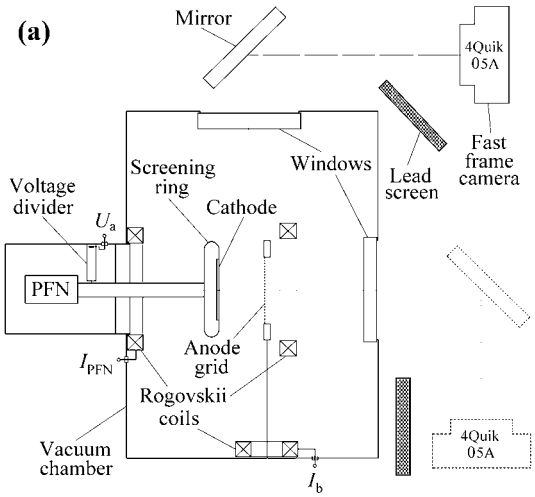
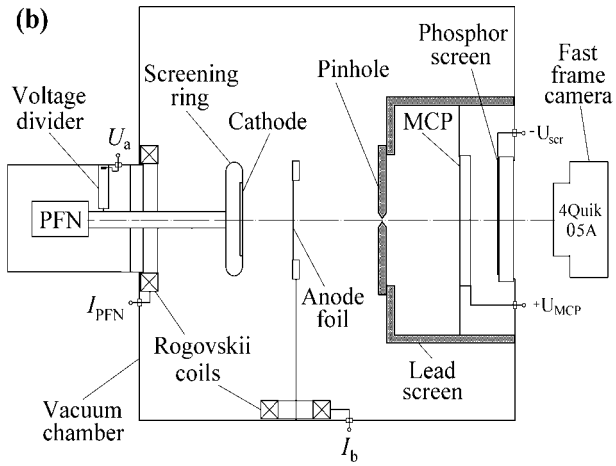
- Introduction
- Passive plasma cathodes
- Active plasma cathodes
- Summary

Experimental setups

Fast framing photography of light emission



Fast framing photography of X-ray image of the anode foil

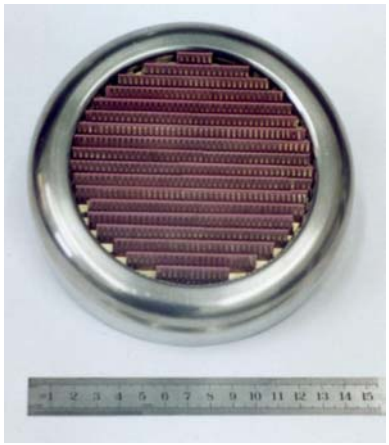


Marx generator (12 stages PFN)	***Diagnostics***
❖ Internal impedance: $Z = 84\ \Omega$ ❖ Voltage amplitude: $\varphi_m \leq 300\ kV$ ❖ Current amplitude : $I_m \leq 3.5\ kA$ ❖ Pulse FWHM: $\tau = 250\ ns$ ❖ Rise time of the voltage: $\tau_f = 10 - 120\ ns$ ❖ Time jitter: $\delta = \pm 10\ ns$ ❖ Repetition rate: $f \leq 10\ Hz$	❖ Active voltage dividers and Rogovsky coils ❖ Fast framing camera (frames of ≥ 0.2 ns) ❖ Time and space resolved X-ray image ❖ Multi-pinhole camera ❖ Movable array of collimated Faraday cups ❖ Movable Faraday cup ❖ Fast Penning probes

Cathodes

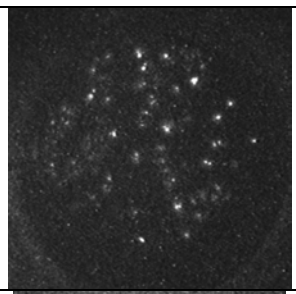
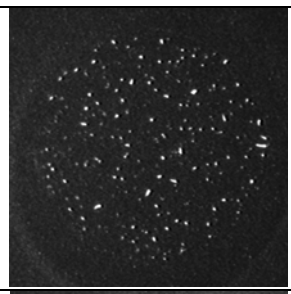
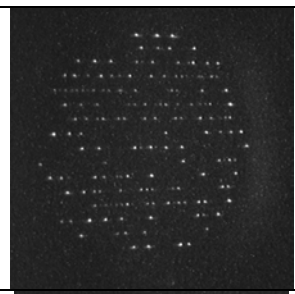
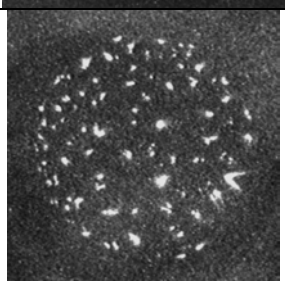
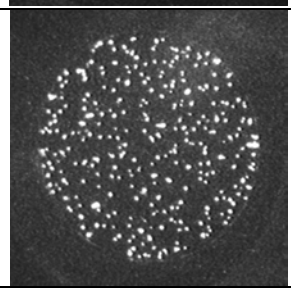
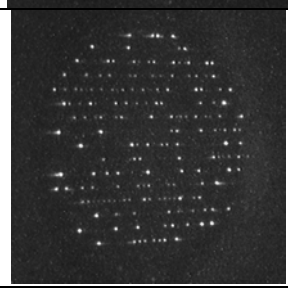
Metal-ceramic, carbon fabric,carbon fibers (with and without CsI coating), velvet, corduroy. *Active area of all cathodes – 100 cm^2*

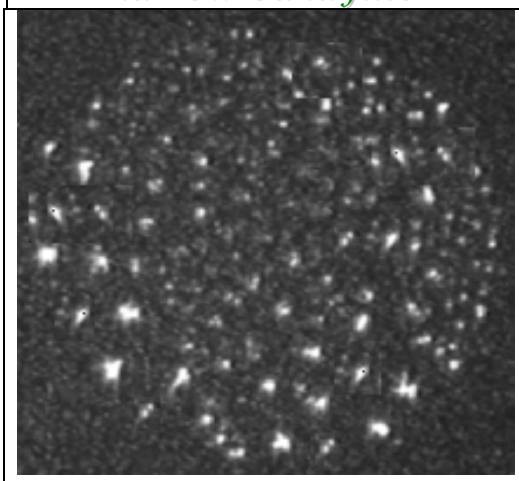
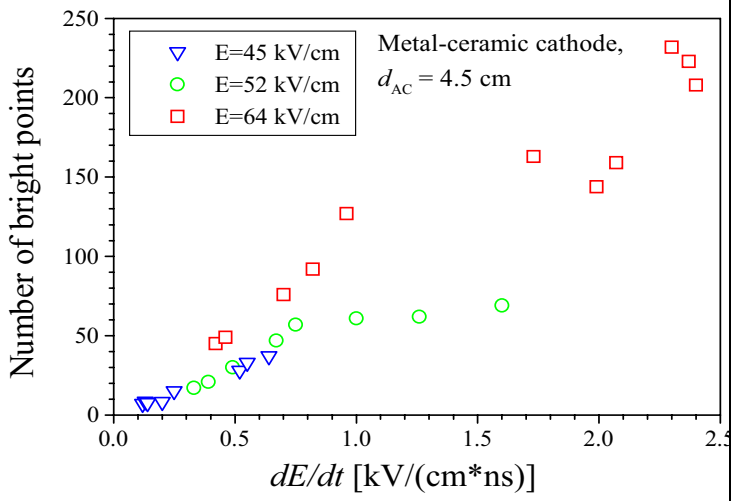
Metal – ceramic cathode Carbon fibers cathode



Front view images

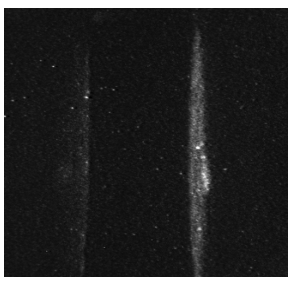
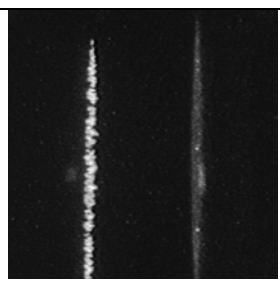
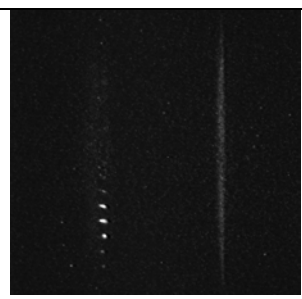
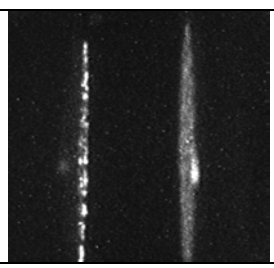
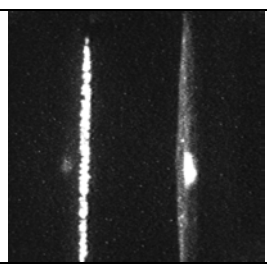
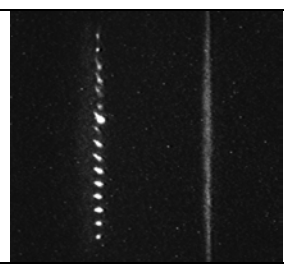
Frame duration of 10ns, d_{AC} =35mm; U_a=190±10kV; I_a=1.7±0.2kA.

Time delay	Velvet	Carbon fabric	Metal-ceramic
0 ns			
200 ns			

Velvet cathode *Front view image with H_α narrow-band filter*	*The number of the bright points vs. the accelerating electric field growth rate*
	

Side view images

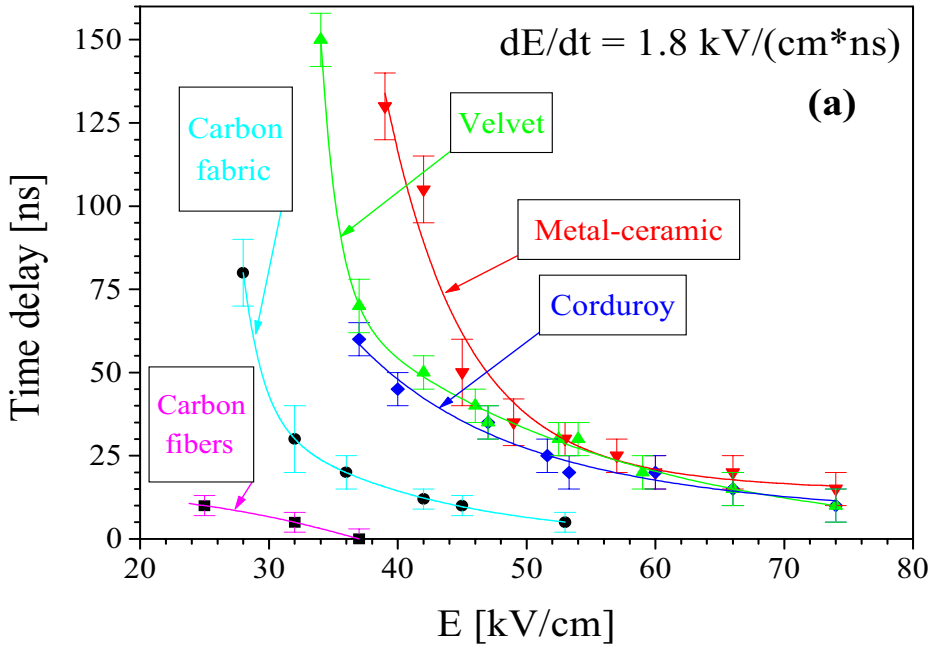
Frame duration of 10ns, d_{AC}=35mm; U_a=190±10kV; I_a=1.7±0.2kA

Time delay	Velvet	Carbon fabric	Metal-ceramic
0 ns			
200 ns			

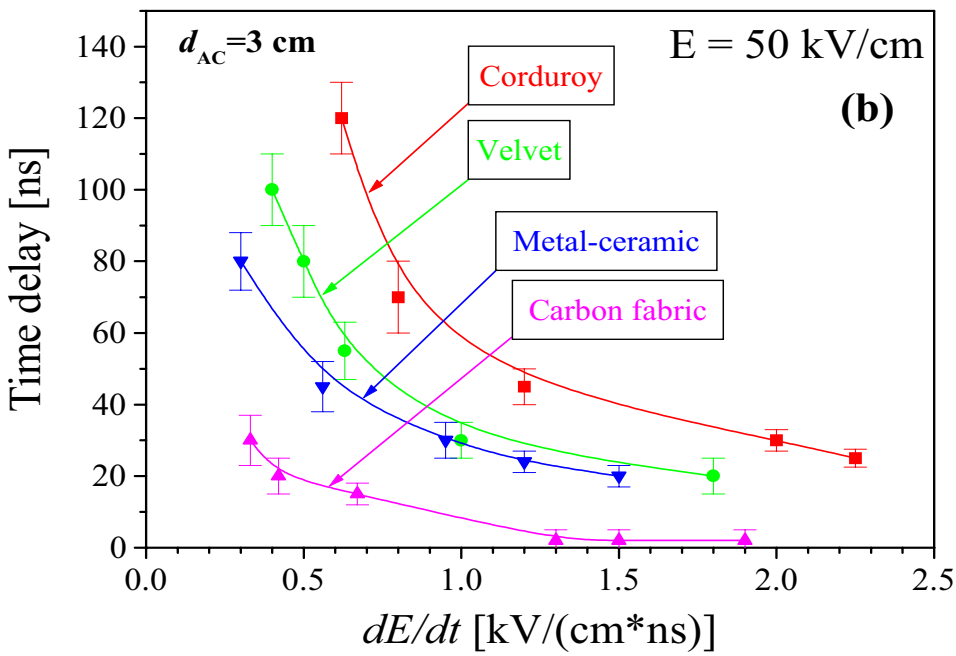
Time delay

of the appearance of the electron emission

- versus accelerating electric field:



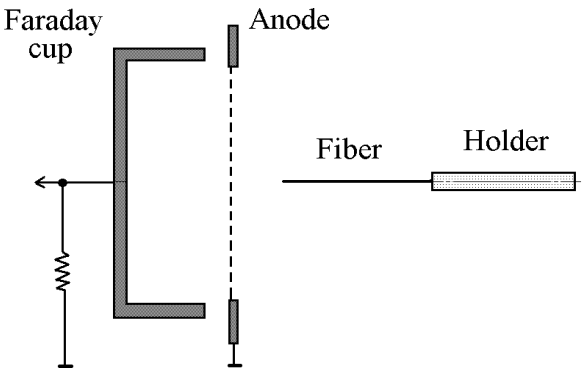
- versus growth rate of the accelerating electric field:

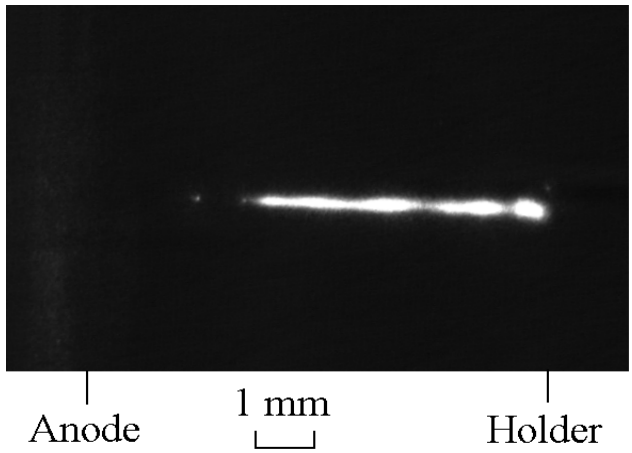


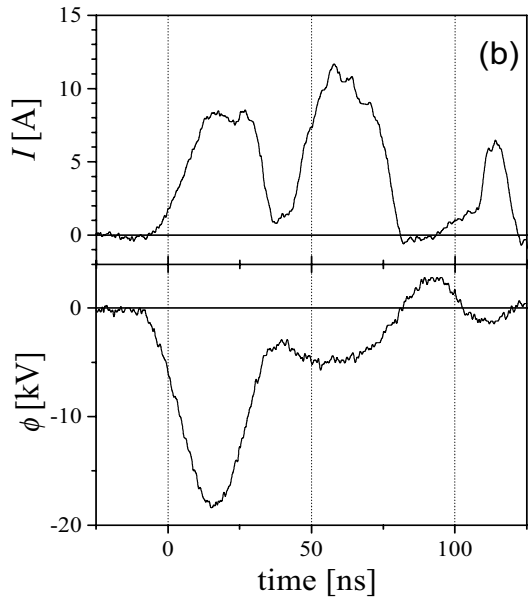
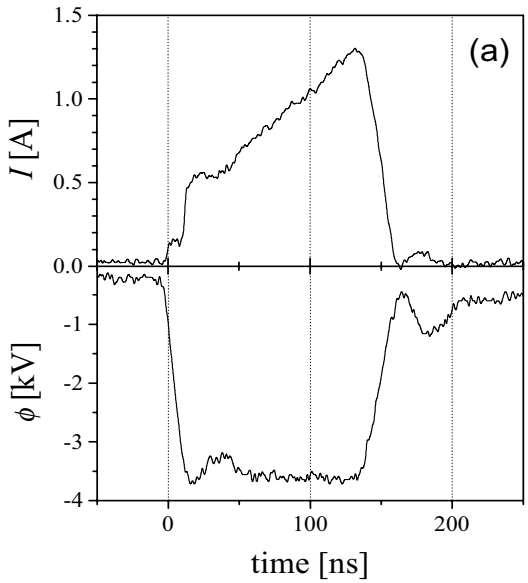
Single Carbon Fiber

Distance anode -fiber 2.2 mm,
Fiber length 6 mm.

20 ns frame duration. 8kV, 10A.



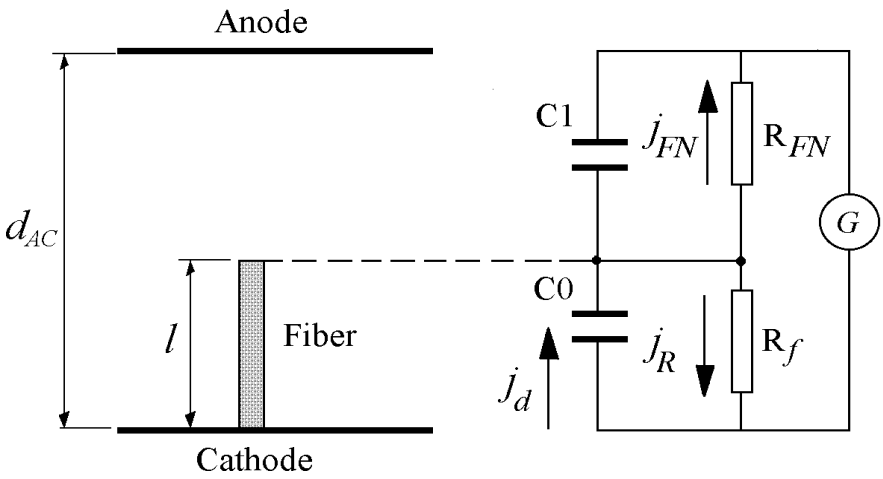


Short duration high amplitude accelerating pulse	Long duration low amplitude accelerating pulse
	

Electron emission begins at E ≥ 8 kV/cm. The voltage and current waveforms strongly indicate that electron emission occurs from ***flashover plasma which expands towards the anode***

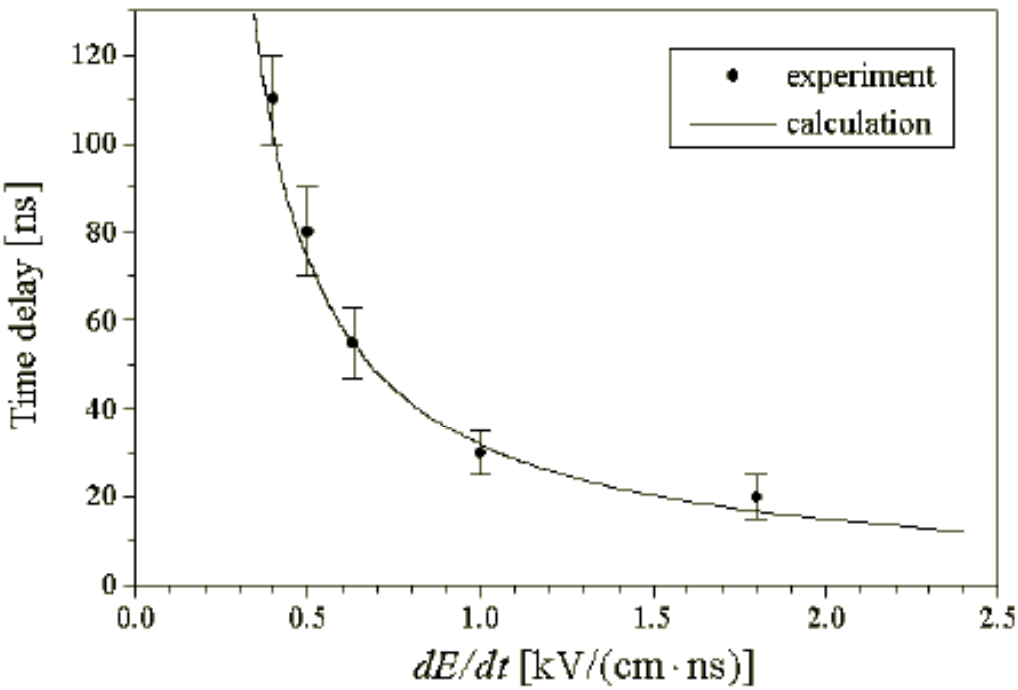
Model of flashover plasma formation

Equivalent scheme



$$\frac{d\varphi}{dt} = \frac{\varphi_m}{\tau_f}\frac{l}{\varepsilon d_{AC}} - \frac{l}{\varepsilon\varepsilon_0} j_{fe}(\varphi) - \frac{1}{\varepsilon\varepsilon_0\eta}\varphi$$

Dependence of the time delay of electron emission appearance versus the growth rate of electric field:



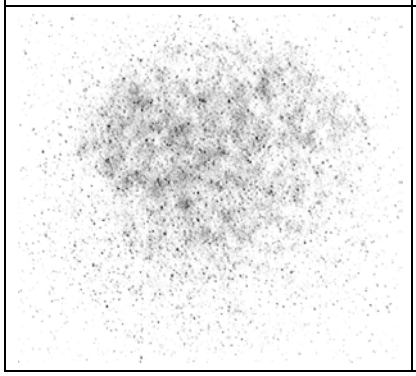
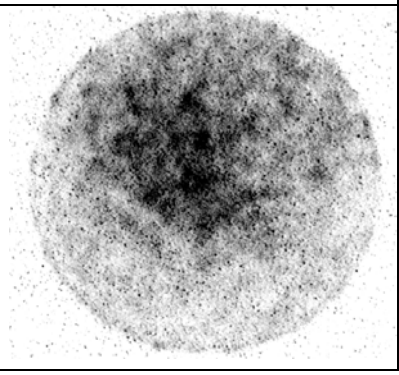
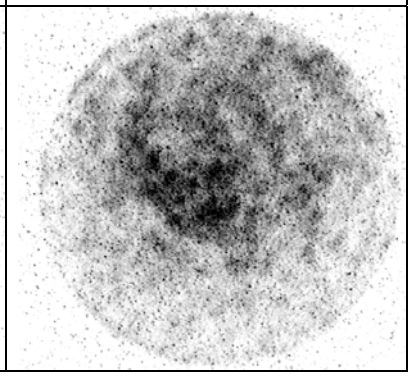
Beam nonuniformity

Metal-ceramic cathode

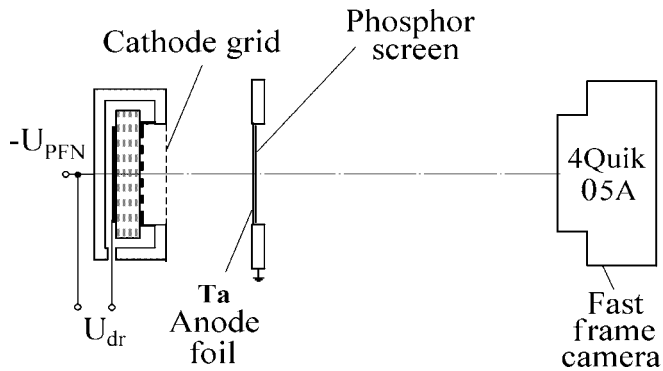
(similar images were obtained for all types of investigated cathodes)

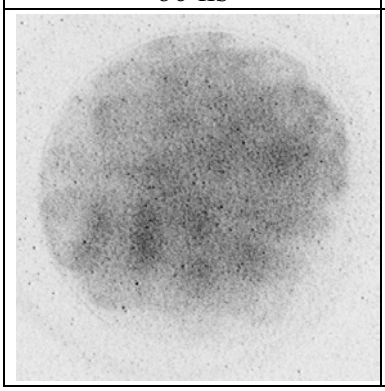
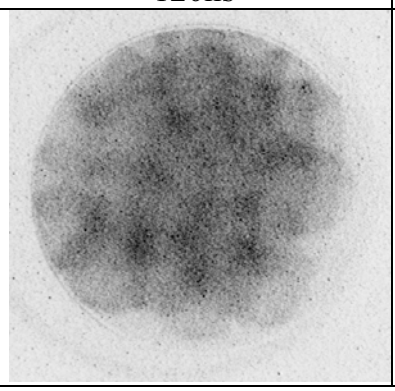
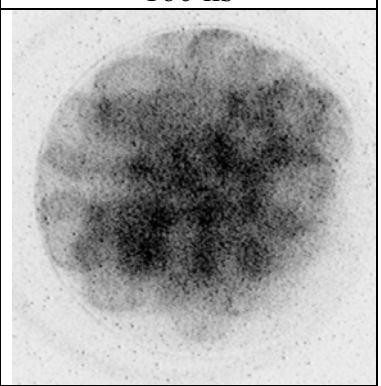
d_{AC} = 3 cm, U_a = 240 kV, I_a = 1.25 kA, frame duration of 40 ns.

Fast time-resolved framing X-ray images of the anode (Ta 125 μm)

0	100 ns	200 ns
		

X-ray space-resolved images of the anode (Ta 125 μm)



60 ns	120ns	160 ns
		

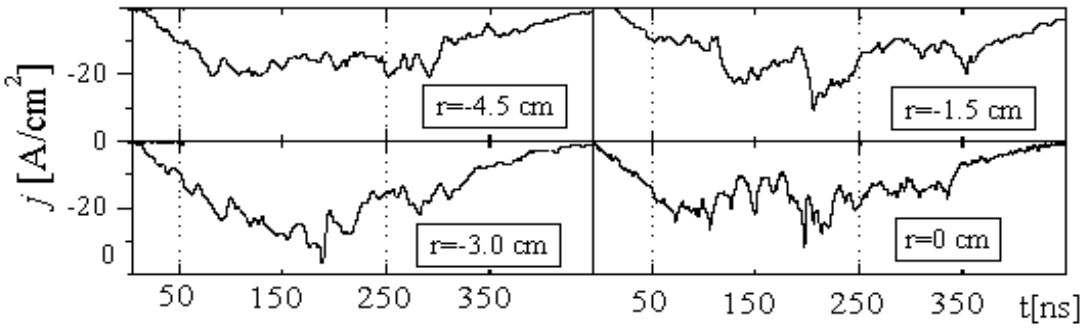
Beam nonuniformity

Waveforms registered by collimated Faraday cups:

Carbon fabric cathode

(similar waveforms were obtained for all types of investigated cathodes)

d_{AC} = 3 cm, U_a = 180 kV, I_a = 2 kA.



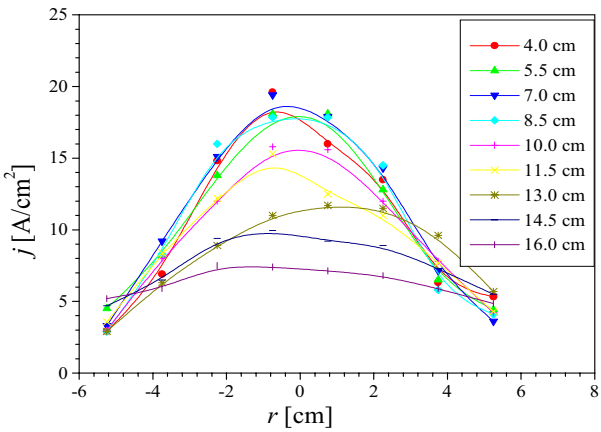
Electron beams have time and space nonuniformity

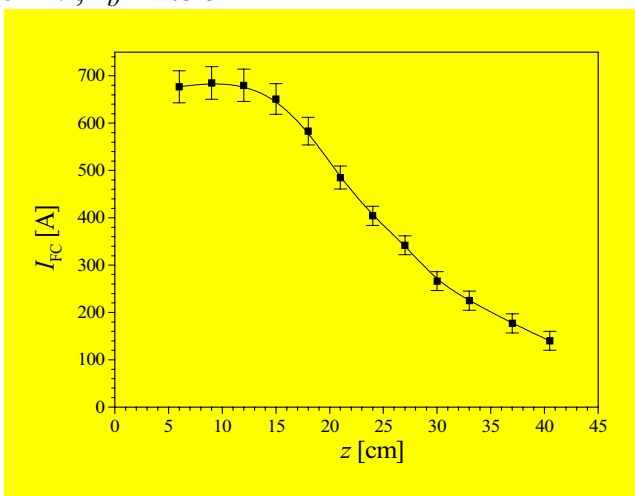
Electron beam divergence

Distribution of the electron beam current density at different distances from the anode

Metal-ceramic cathode

d_{AC} = 3 cm, U_a=200 kV, I_b =1.56 kA



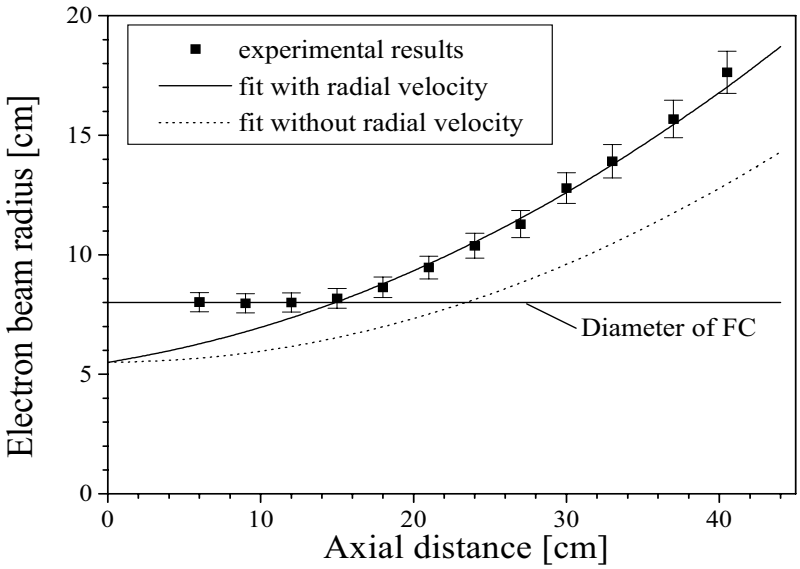


Electron beam divergence

The envelope of the electron beam vs. the distance from the anode

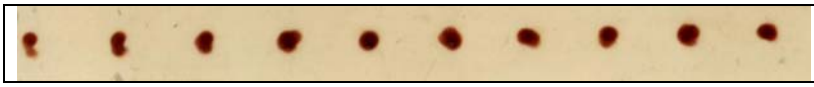
$$r_i(z) = r_0 + \frac{V_{r0}}{V_{z0}} z_i + \frac{eI(z)}{r_{i-1} m_e c^3} \frac{1-\beta_{z0}^2}{\beta_{z0}^3} z_i^2$$

Metal-ceramic cathode: d_{AC} = 3 cm, U_a=200 kV, I_b =1.56 kA.



The fitting of the experimental data gives the V_r about of 8% of V_z

Micro-beam patterns obtained by multi-pinhole camera



Carbon fabric cathode

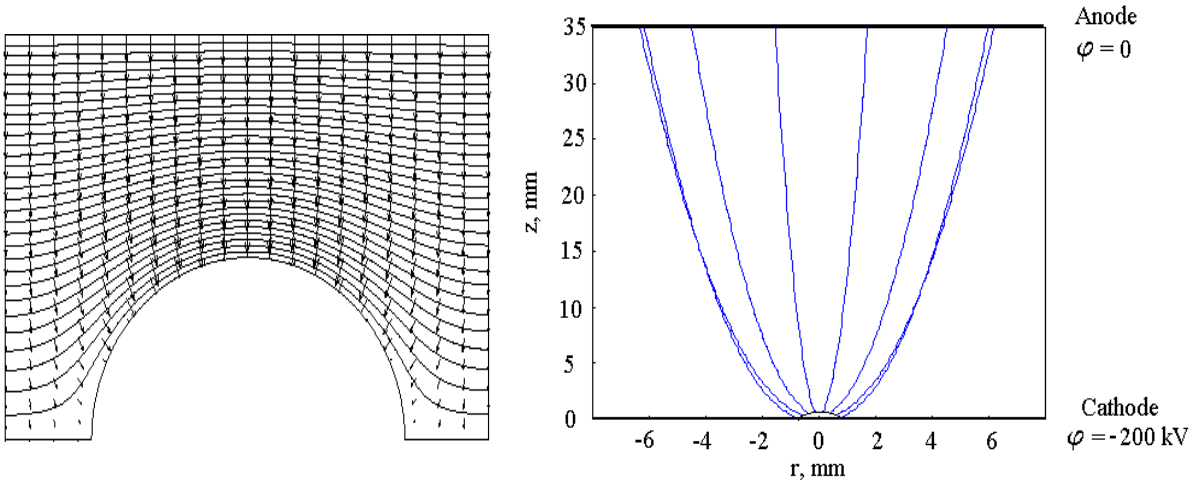
Transverse velocities and estimated distances between single emitters for different cathodes

Cathode type	d_{AC} cm	I_a kA	U_a kV	E kV/cm	$V_\perp/V_\parallel$ %	Δ mm
Metal - ceramic	3	1.8	200	66	**3-9**	3.5
Carbon fabric	3	2.1	180	59	**3-4.5**	2.8
Corduroy	3	1.8	200	65	**9**	5.5
Velvet	3	1.8	200	66	**6**	3

The transverse electron energy could reach a value of ~1 keV for corduroy cathode and ~100 eV for carbon fabric cathode

Electron beam divergence

Potential distribution and electron trajectories in the diode with electron emission from the semispherical plasma "hot point":



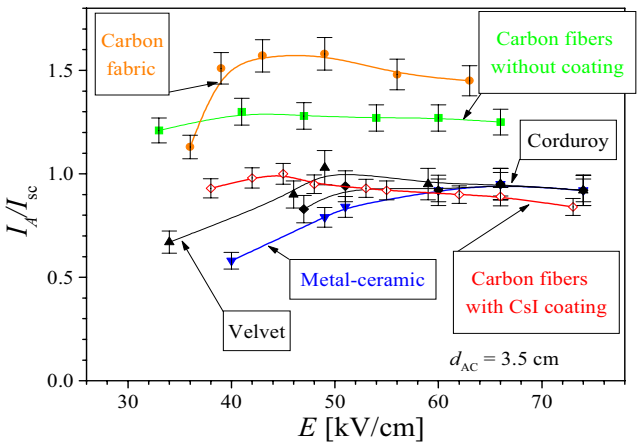
The considered emitting center has a diameter of 1.5 mm (typical size of the observed bright spot) and a height of 2 mm.

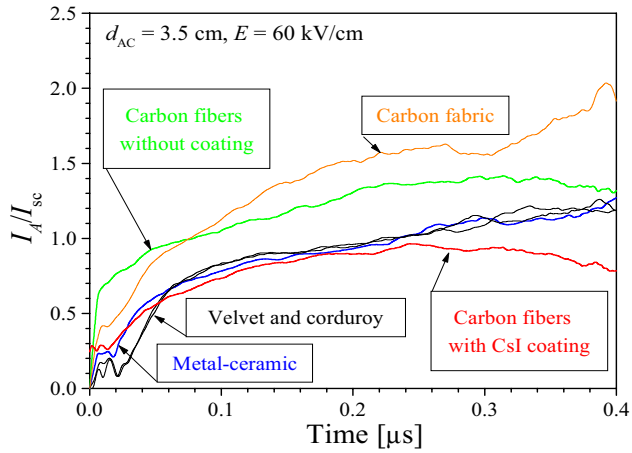
- *the transverse velocity is about of 4-8 % of the longitudinal velocity*
- *the electron micro-beam pattern on the anode has a diameter of 8 - 10 mm*
- *the simulation results coincidence well with the experimental results obtained by micro-beam divergence, X-ray imaging and beam envelope measurements*

The origin of the significant divergence of the electron beams generated in the planar diode with investigated cathodes is a discrete structure of plasma emitters.

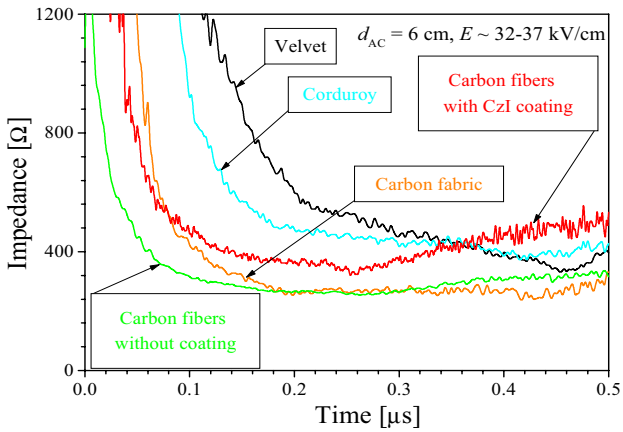
Diode parameters

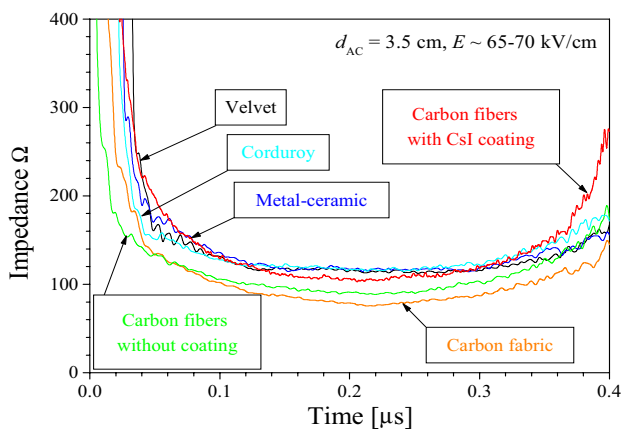
Ratio of the diode current to the space-charge limited current





Temporal behavior of the diode impedance for different cathodes for electric fields of 65 - 70 kV/cm and 32 - 37 kV/cm

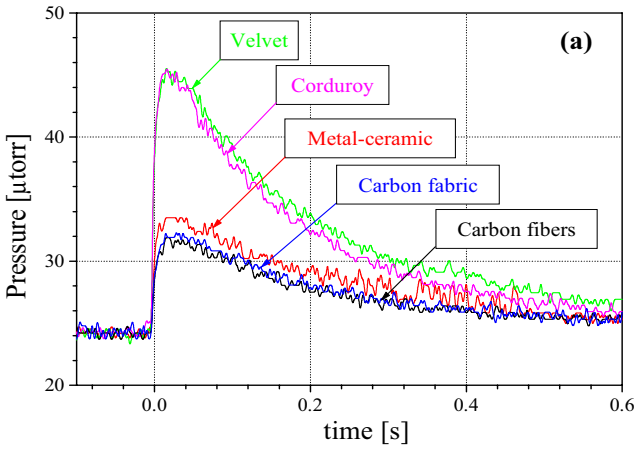




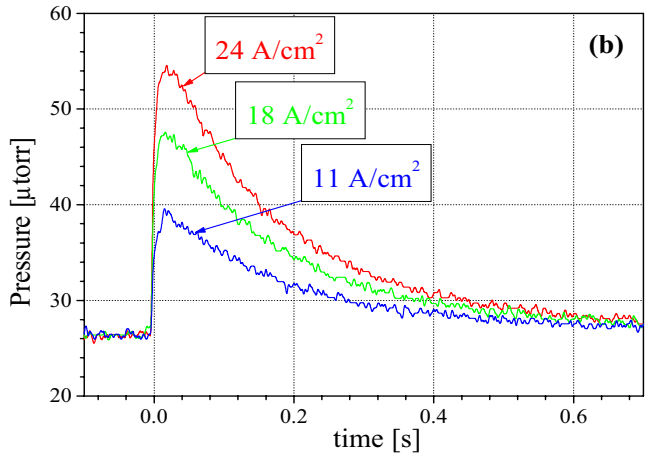
Vacuum deterioration

Waveforms obtained by the Penning probes:

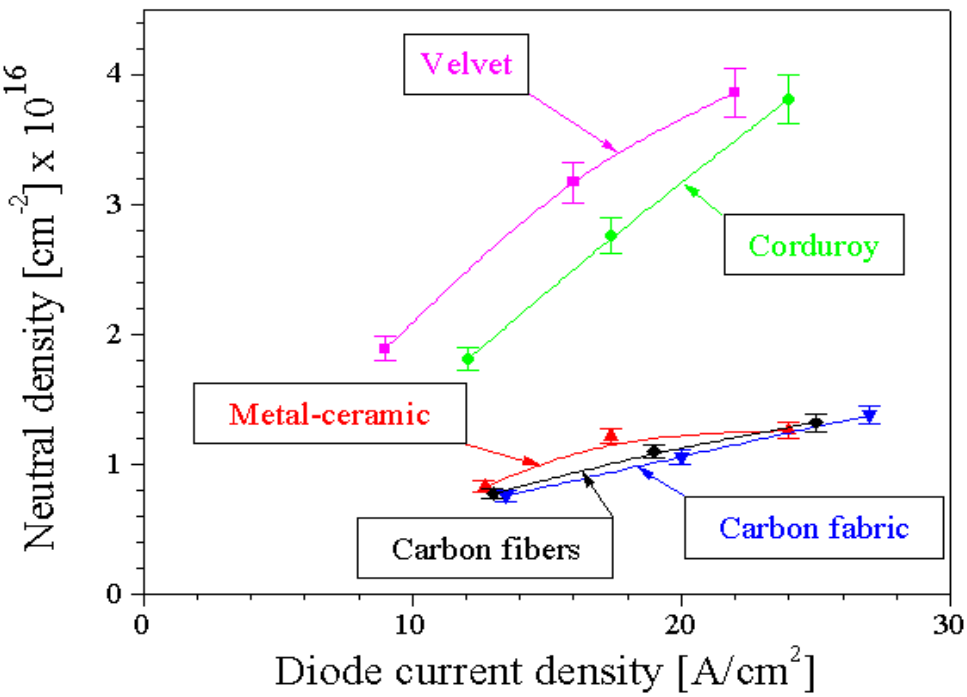
(a) different cathodes at j = 24 A/cm^2



(b) velvet cathode at different current densities



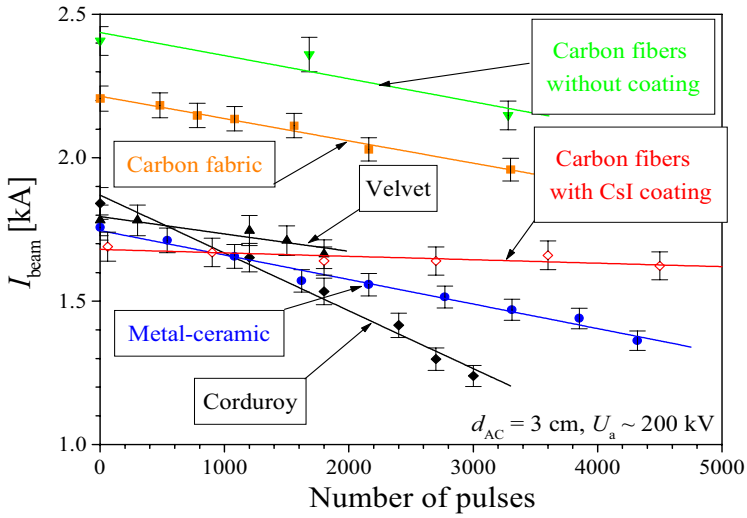
Dependence of the neutral density per cathode unit area per pulse on the diode current density:



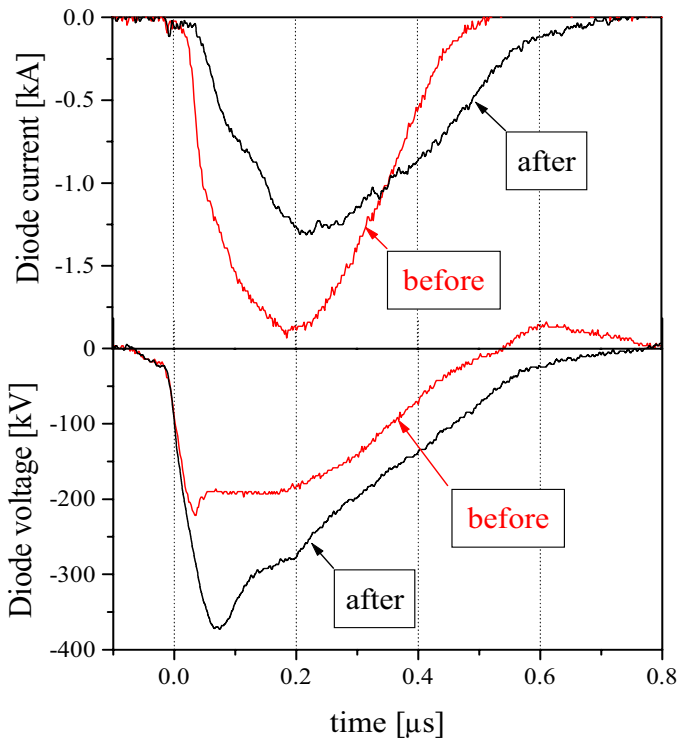
Carbon fabric coated by CsI – about 2×10^{16} particles/(cm^2/pulse)

Lifetime

Diode current vs. the number of the generator pulses



The diode current and the diode voltage at the beginning and at the end of the lifetime test.



Corduroy cathode, d_{AC} = 30 mm.

Conclusions

- The operation of the investigated cathodes is based on the formation of the surface discharge plasma.
- A time delay of the plasma formation and the number of emitting centers are strongly dependent on dE/dt.
- The investigated cathodes allow diode operation with current densities of several tens of A/cm^2 and quasi-constant impedance of the diode.
- A transverse energy of electrons reaches units of percent of the total energy because of discrete type of plasma sources.
- The formation of the surface plasma is accompanied by desorbtion of neutrals which limits the repetition rate of the diode operation.
- The investigated cathodes showed a deterioration of emission properties within 10^5 generator shots.