The 22nd International Conference on Numerical Simulation of Plasmas

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IONIZATION-FRONT PROPAGATION IN NANO-SECOND PULSED PLASMAS NEAR ATMOSPHERIC PRESSURE

—ANALYSES BY PARTICLE-IN-CELL (PIC) SIMULATION —

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Outline

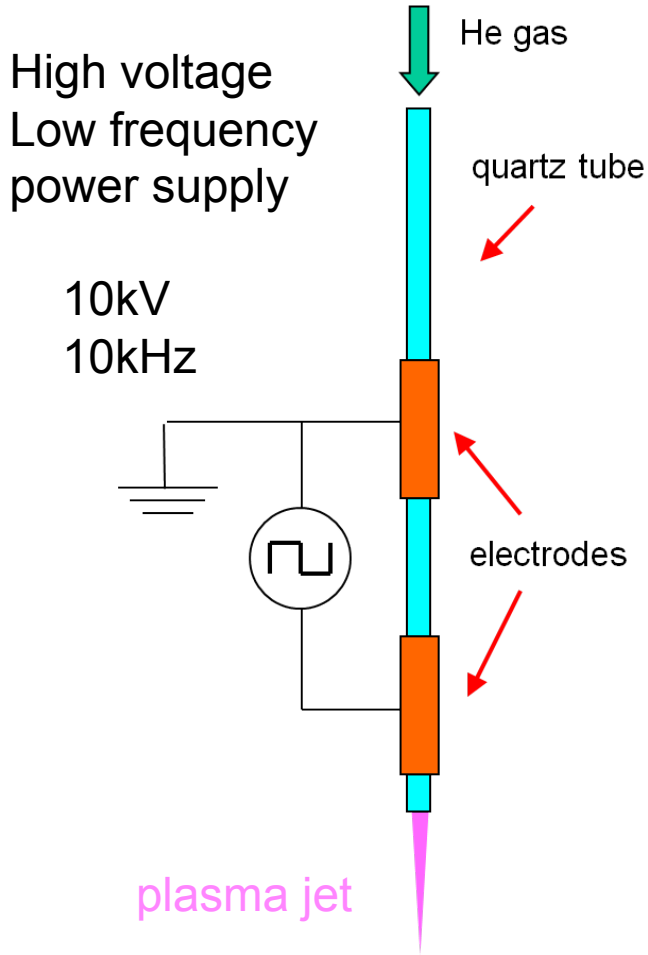
- Background: atmospheric pressure plasmas
- Motivation: mechanism of discharge
- Experiments for nano-second discharge
- PIC/MCC simulation results
- Summary

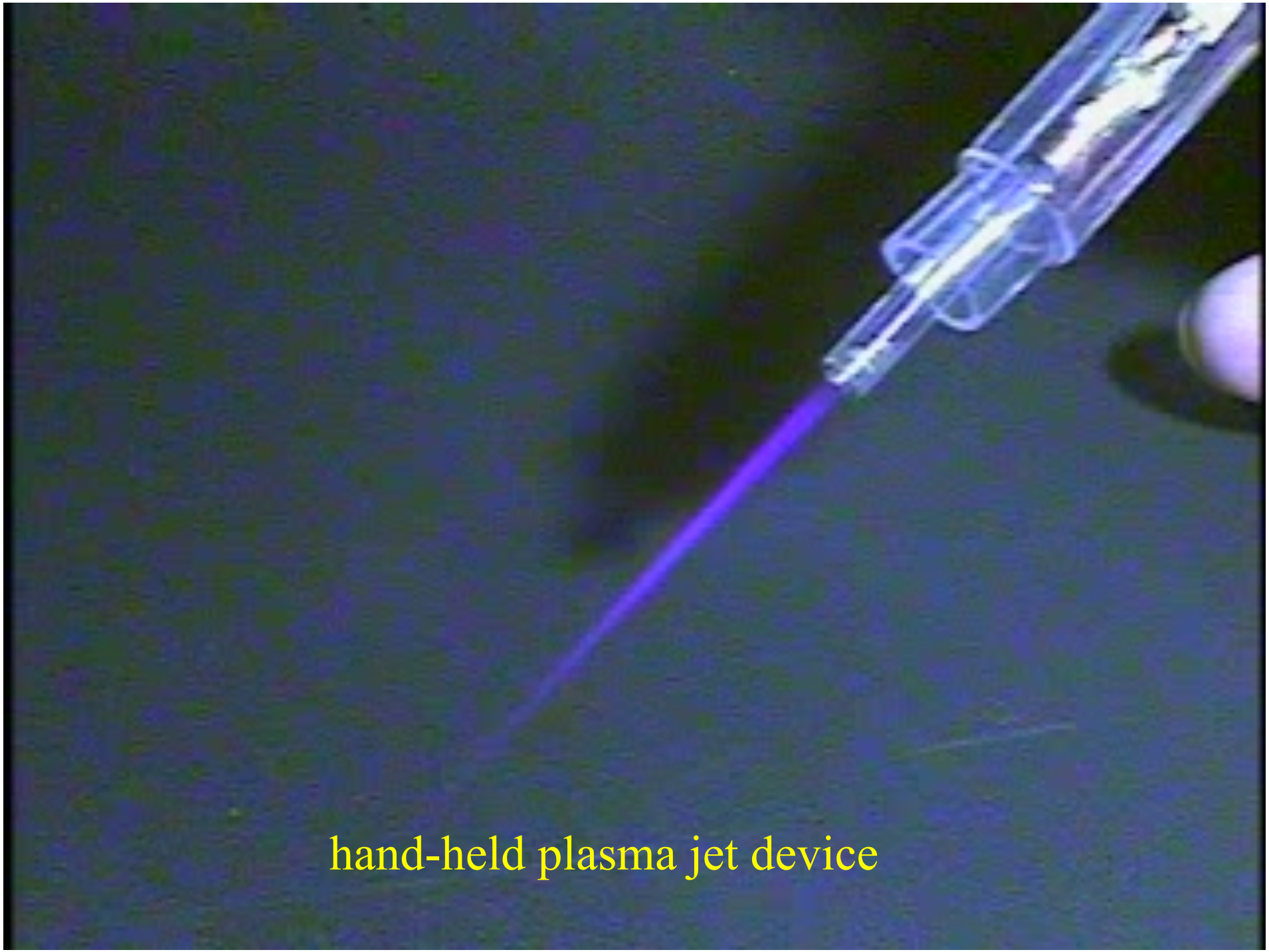
Background

Low Temperature Atmospheric Pressure Plasmas (APP)

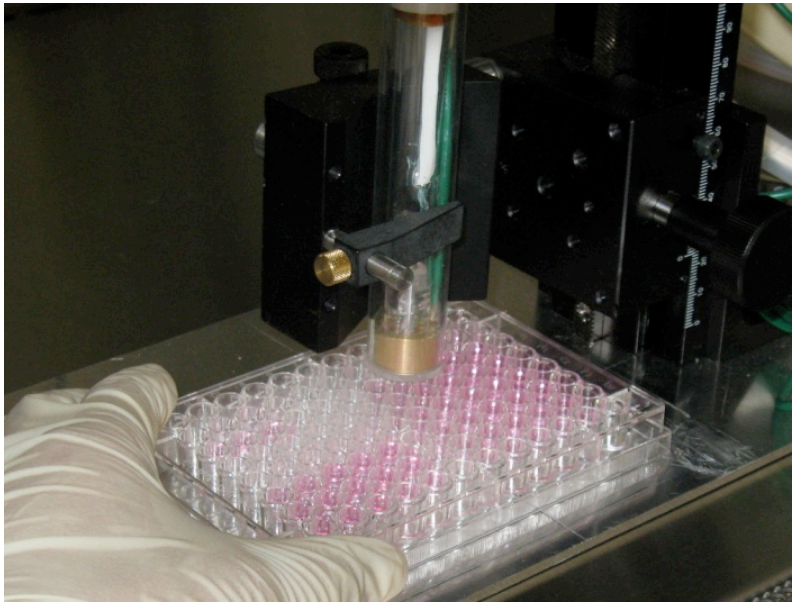
hand-held APP jet system

(Experiments by K. Kitano)

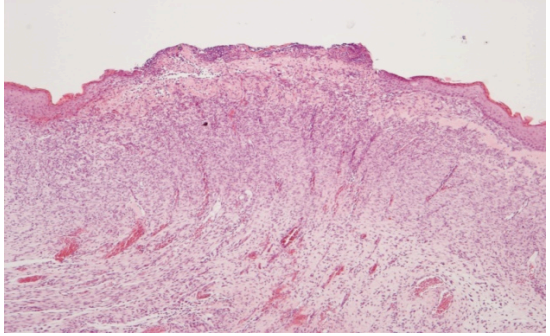



hand-held plasma jet device

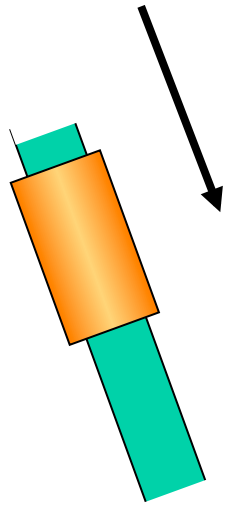
wound healing



cell proliferation



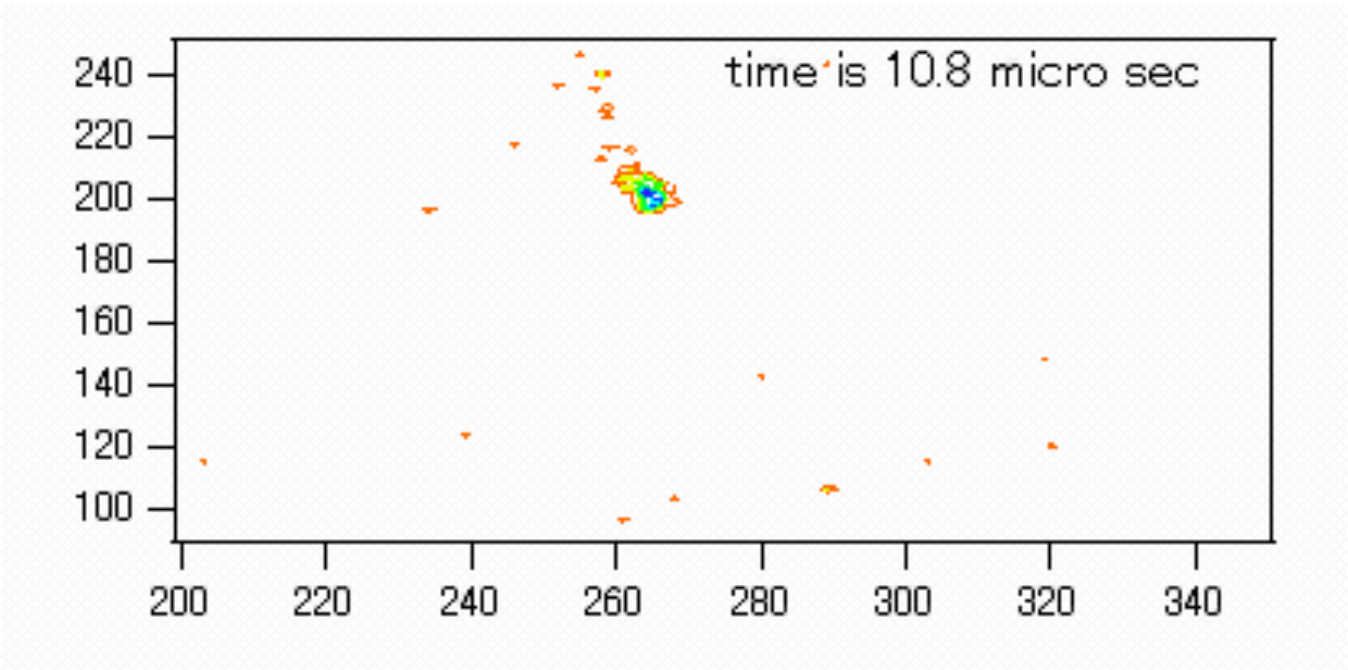
High-speed camera observation

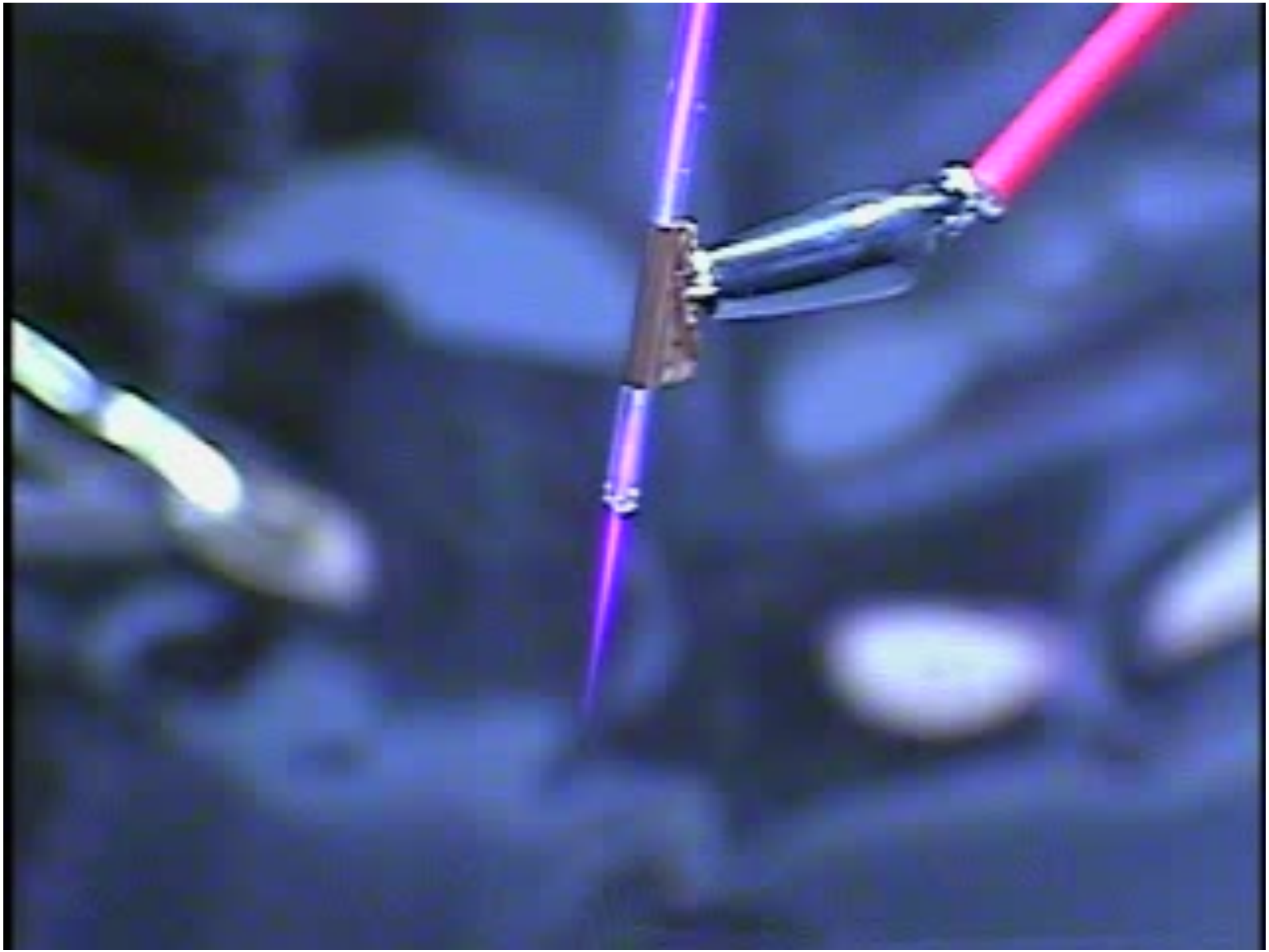


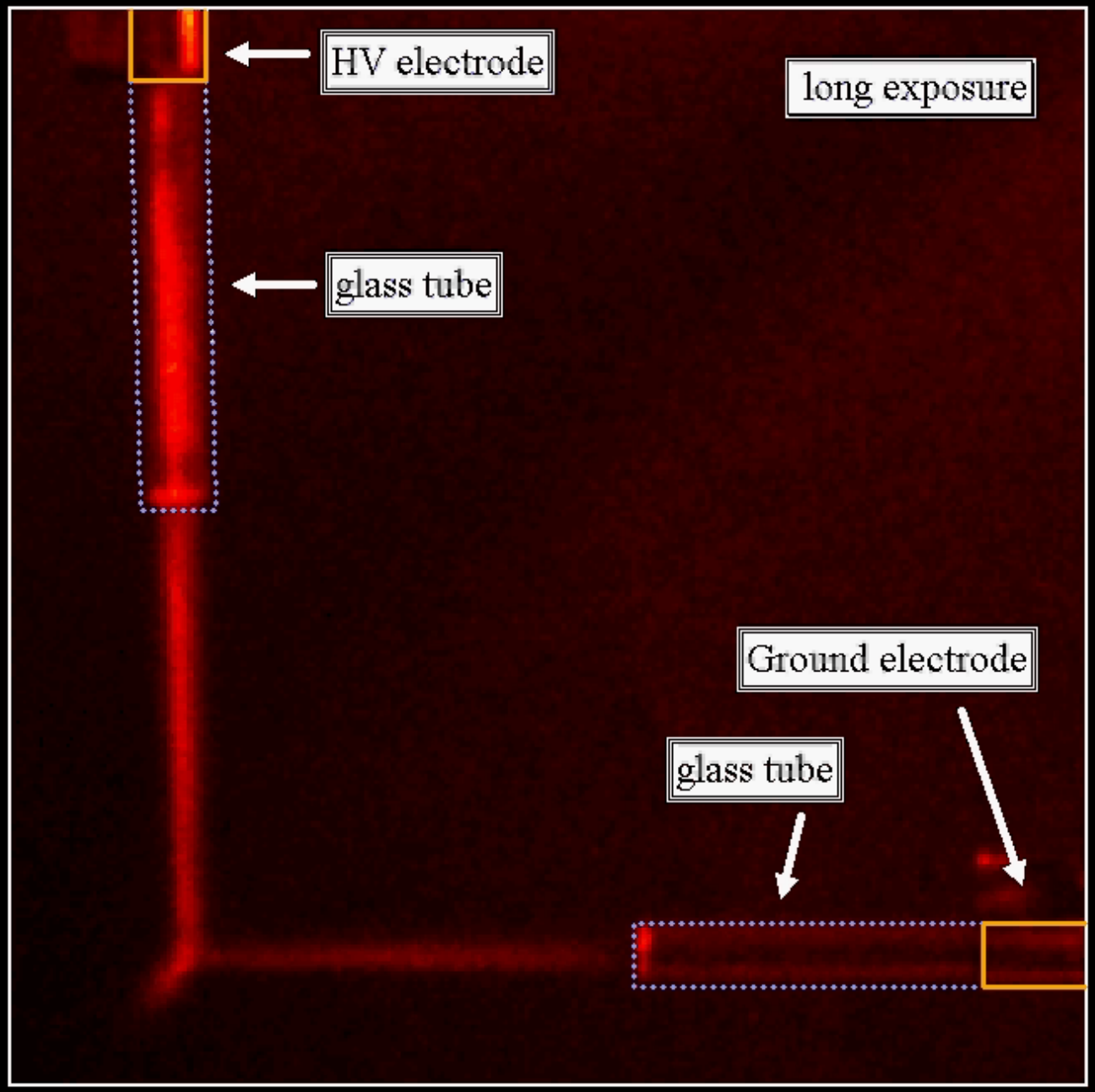
direction of plasma jet injection

plasma bullet : speed（ ≒10km/s）≫ gas velocity

exposure time: 0.1μs
shot at every 0.2μs



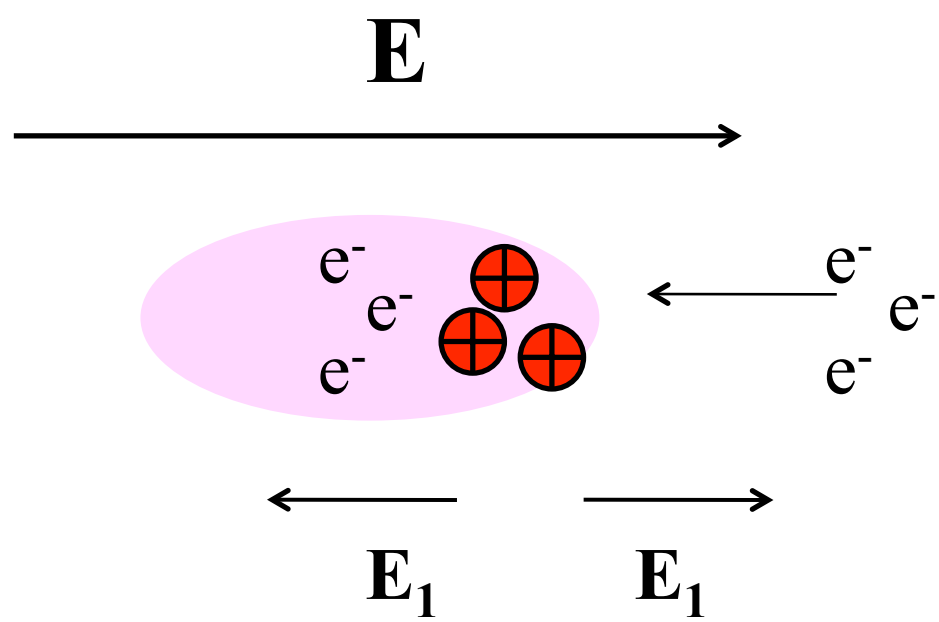



HV electrode
long exposure
glass tube
Ground electrode
glass tube

Mechanism of
low temperature atmospheric pressure plasma

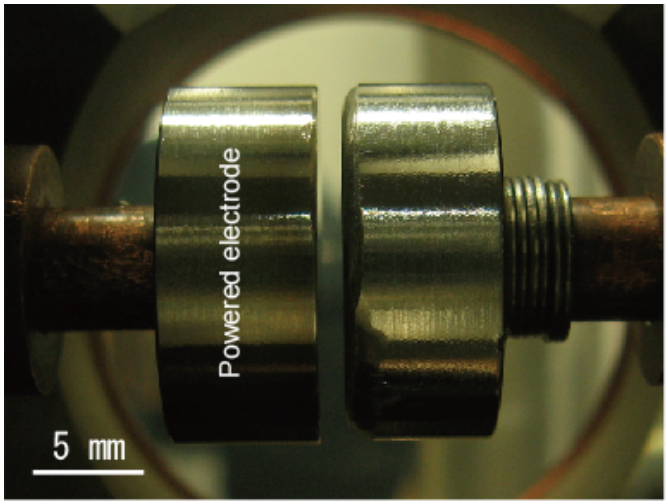
- ionization wave propagation

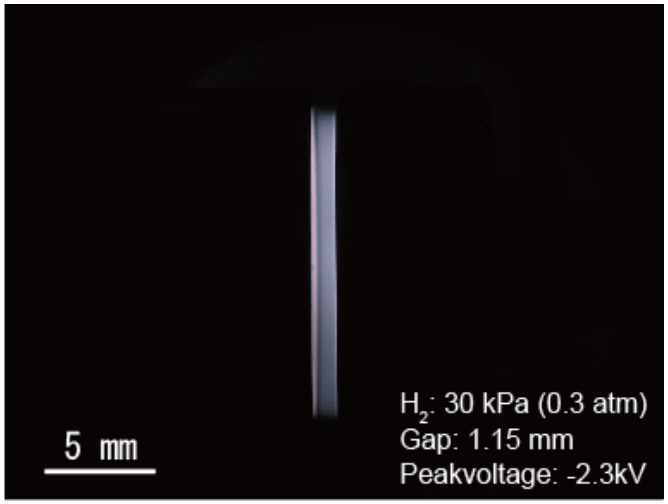
time scale of discharge
~ 10 – 100 nsec



locally enhanced field :3D effect

How about the 1 D case?





parallel plate discharge

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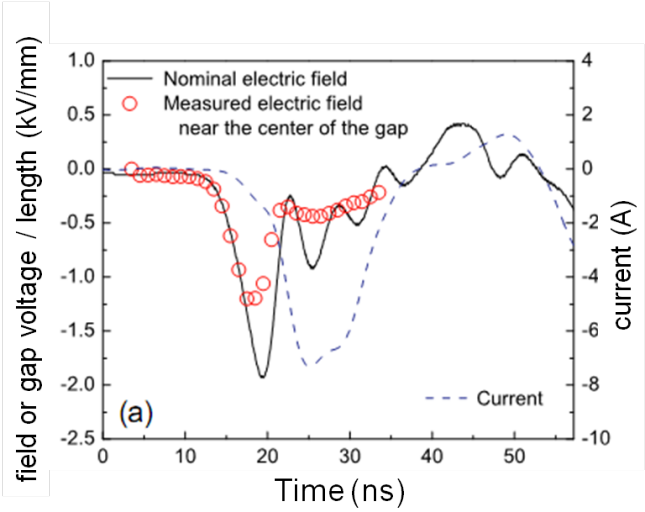
J. Phys. D: Appl. Phys. 43, 1 (2010)



Temporal profile of E-field
(experiments*)

Motivation

- What is the formation mechanism?

—The usual Townsend mechanism for discharge formation cannot explain such nano-second discharge.

Townsend Theory

$$\frac{dn_e}{dz} = \alpha n_e$$

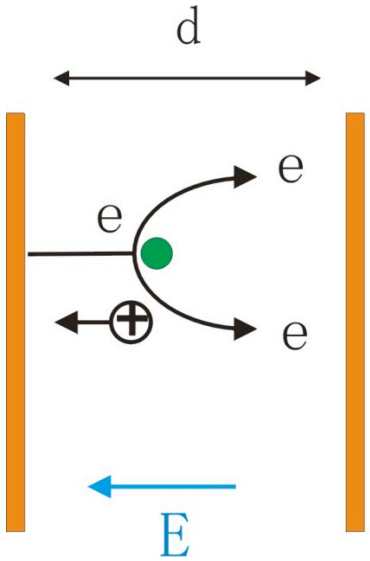
α: The first Townsend coefficient

$$\Rightarrow \quad n_e(z) = n_0 \exp(\alpha z)$$

for a single electron emitted from the surface,

$$\exp(\alpha d) - 1$$

ions are created in the gap

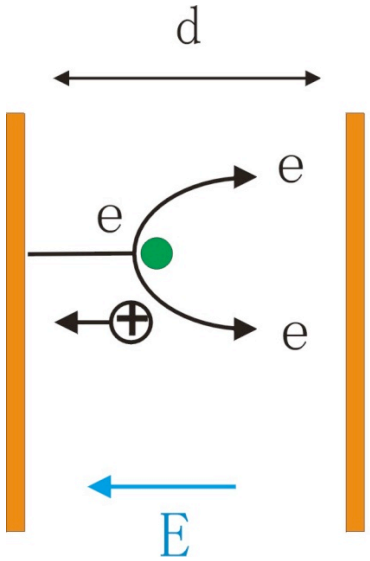


Townsend Theory

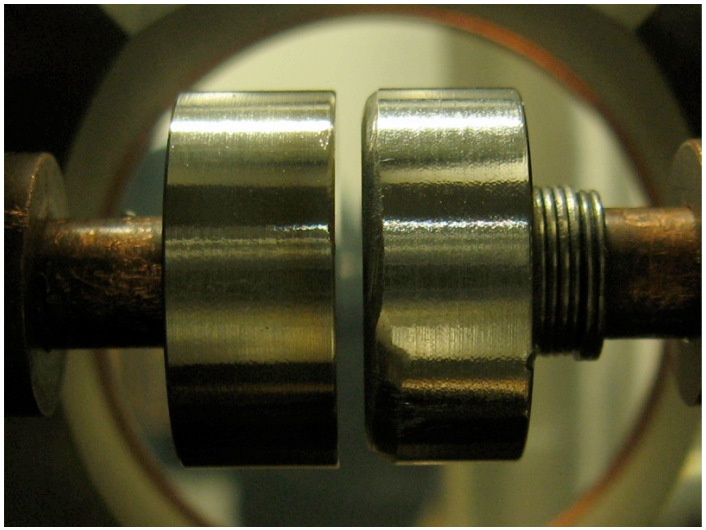
the condition that current continues to flow

$$\gamma\left(\exp\left(\alpha d\right)-1\right)=1$$

γ: secondary electron emission coefficient
(the second Townsend coefficient)



Electric Field Measurement



PS: -2 kV, 5ns at FWHM, 10 kHz

gap distance: 1.15 ± 0.05 mm

gas pressure = 0.3 atm

Coherent Raman Scattering (CRS)

Intensified CCD

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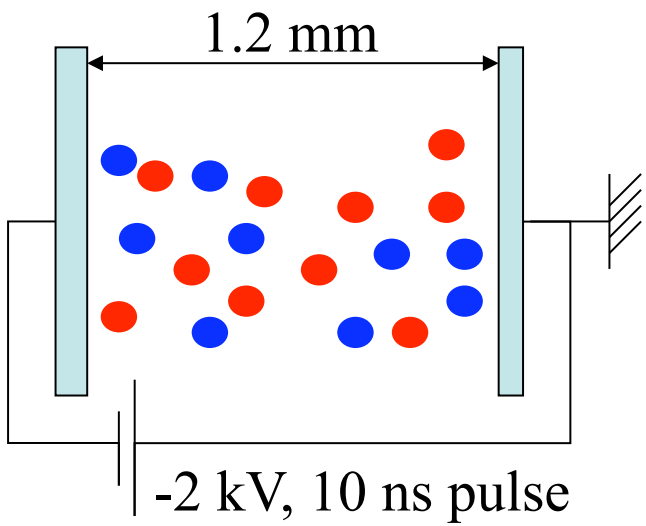
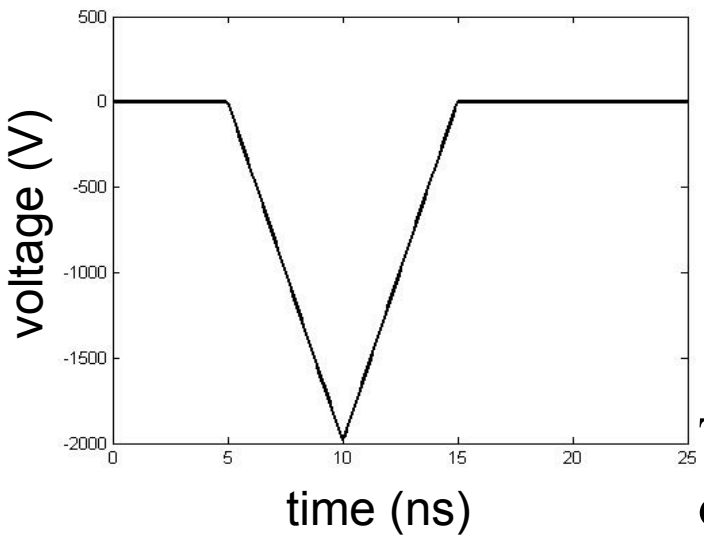
Numerical Model





Temporal profile of applied voltage

1d2v electrostatic PIC/MCC simulation

Initial Conditions

- initial plasma density = 10^{10} cm^{-3}
- Initial number of particles = 20000 for each species

Other Parameters

- Number of grids = 500
- dt ≅ 10^{-14} second
- $\gamma_{SE} = 0.2$

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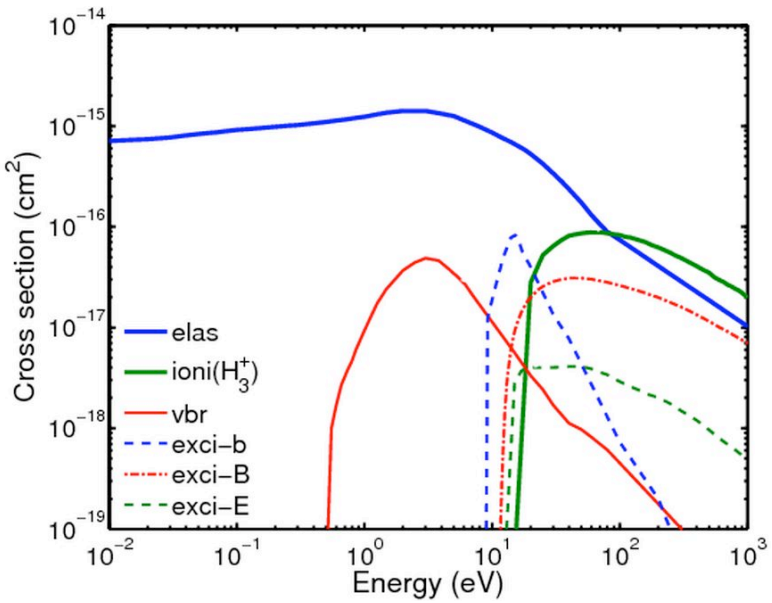
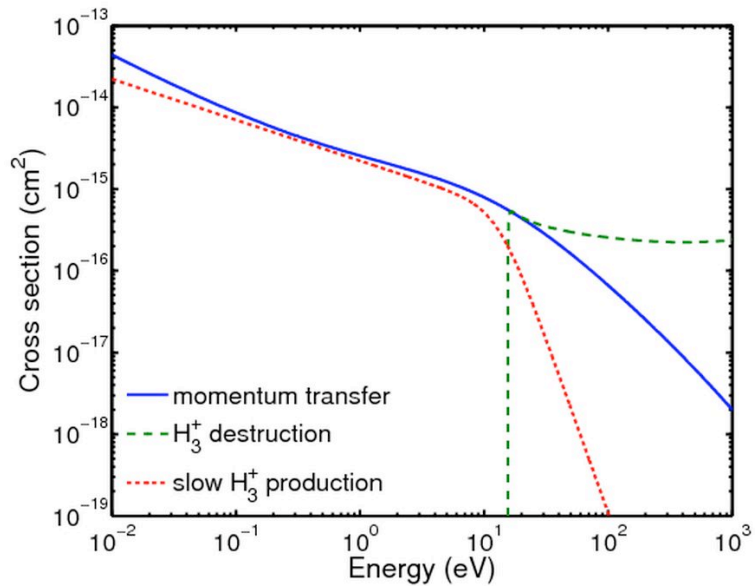
Collisions

ions in the simulation : H_3^+ only

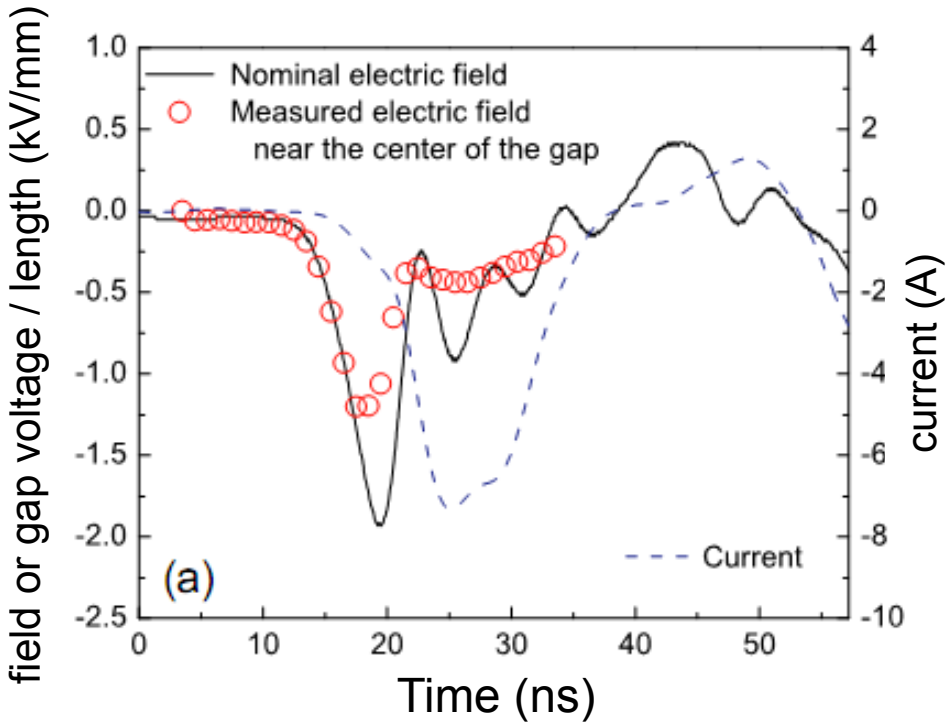


electron-neutral

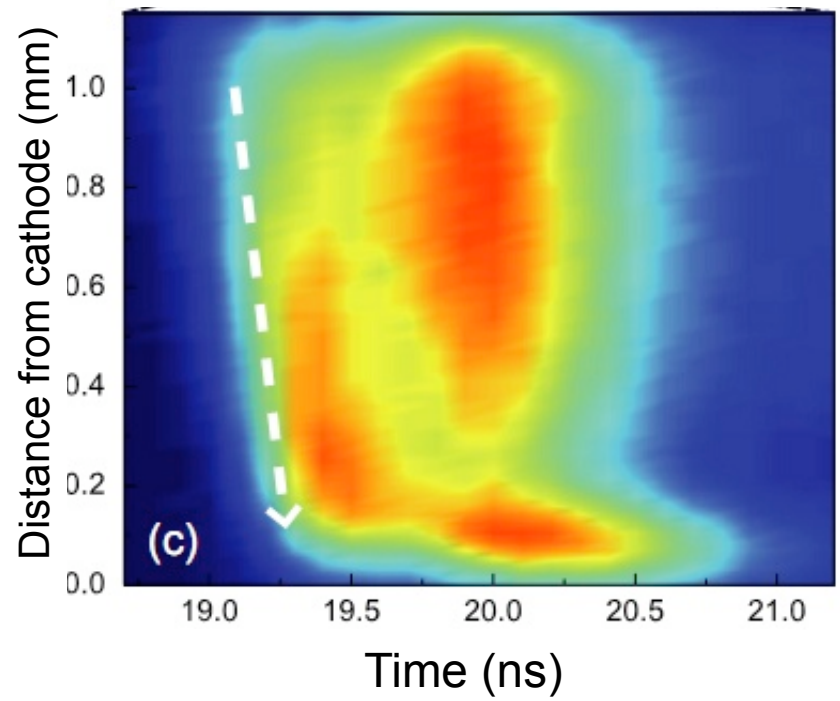


ion-neutral

Propagation of Ionization Front



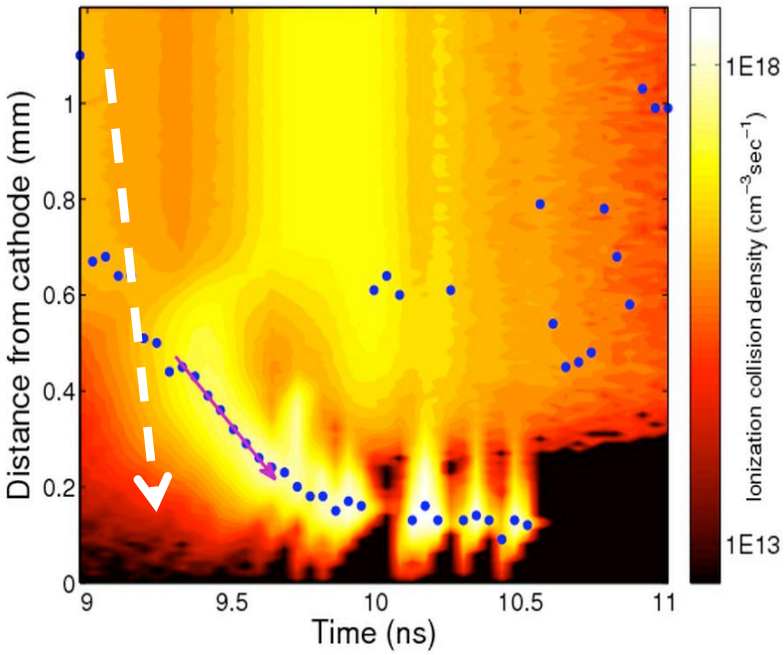
Temporal profile of E-field (experiments*)



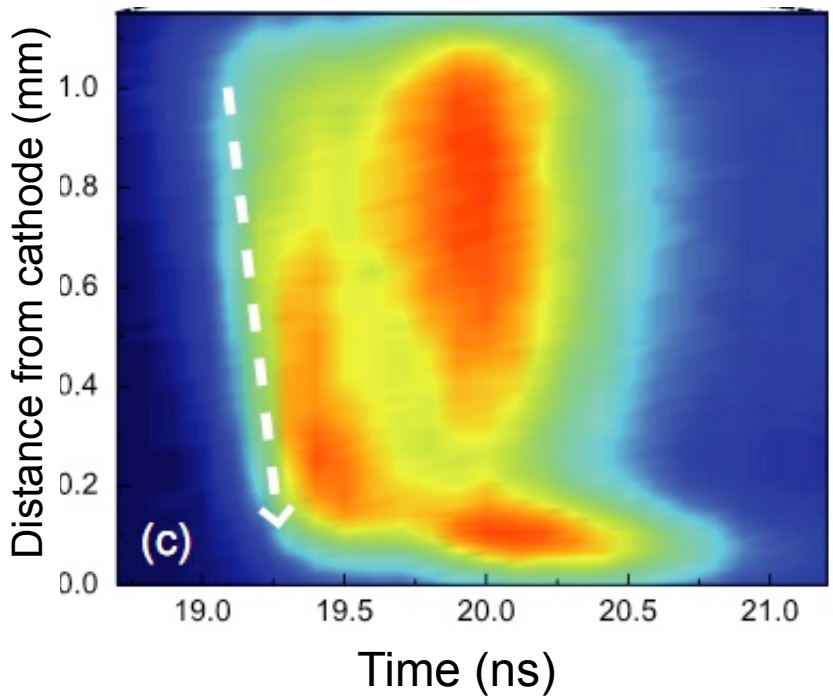
Emission intensity distribution (experiments*)

*T. Ito, *et al*., J. Phys. D: Appl. Phys. 43, 1 (2010)

Propagation of Ionization Front



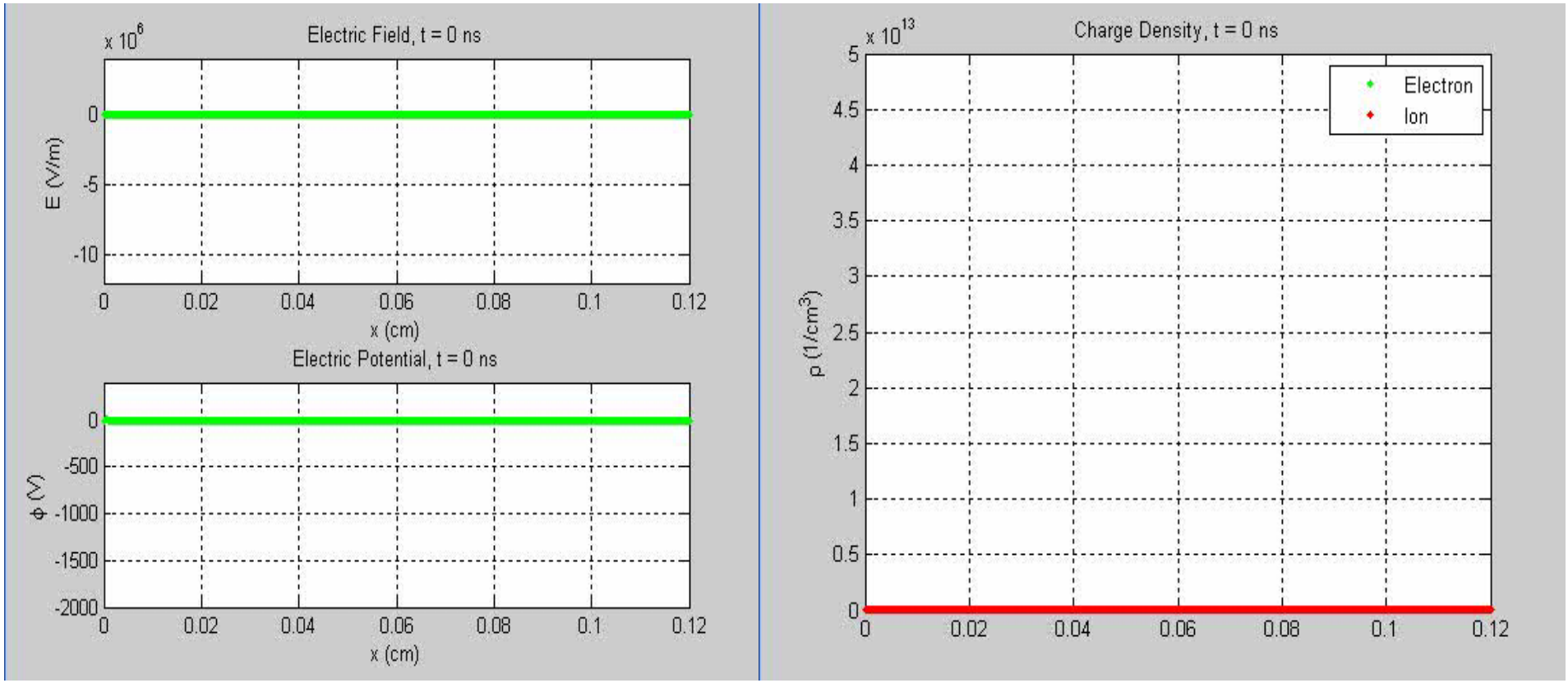
Ionization collision density
(simulation)



Emission intensity distribution
(T. Ito, *et al*, J. Phys. D: Appl. Phys. 43, 1 (2010))

Good agreement between the experiment and simulation

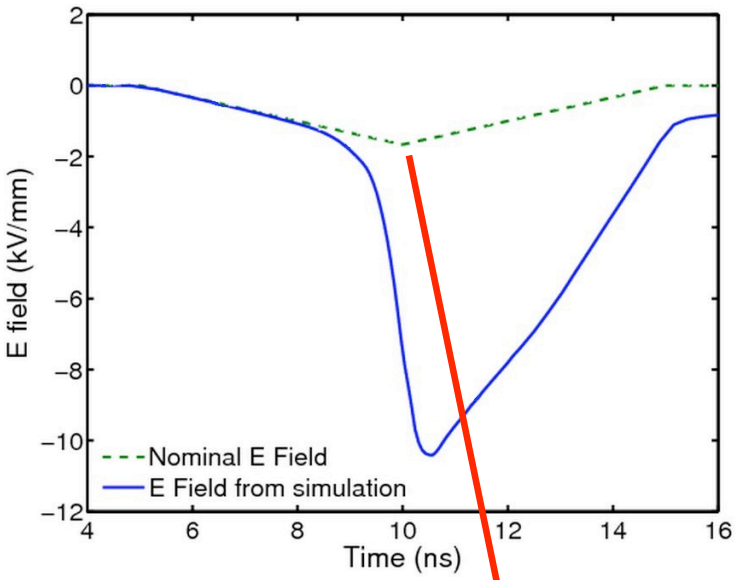
Evolution of E-field and Plasma Density

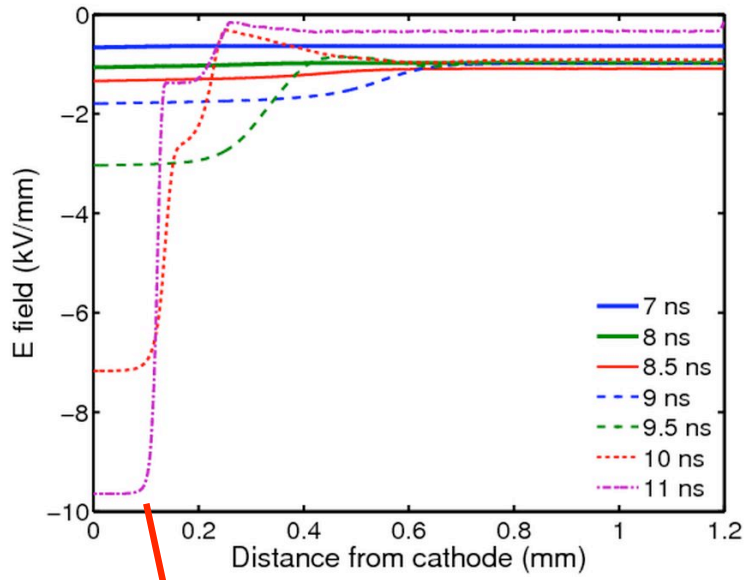


density front propagation toward the cathode

Strong enhancement of E field at the cathode

=> increase secondary electron emission coefficients ?

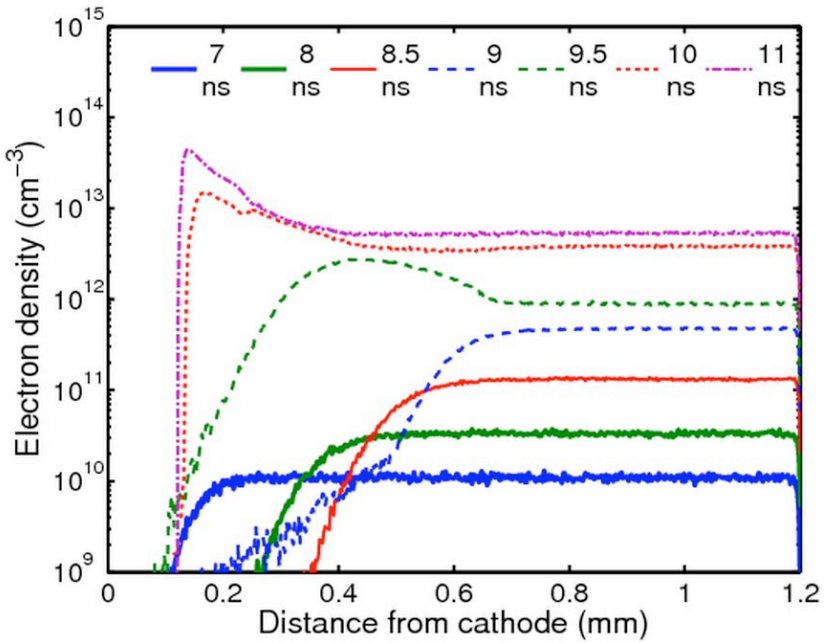




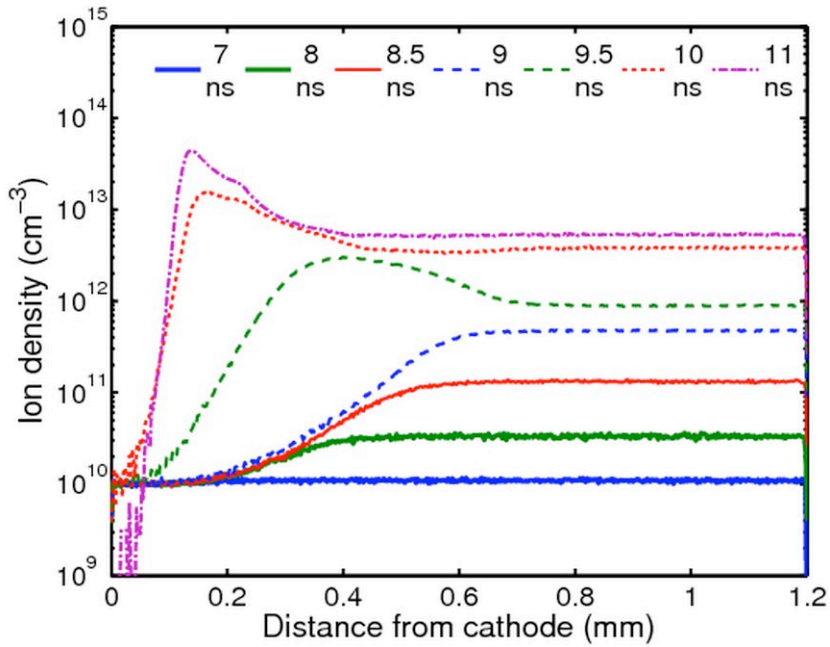
only 1.7kV/mm nominal E-field at the peak

close to -10kV/mm

Plasma densities in log scale



electron density profiles



ion density profiles

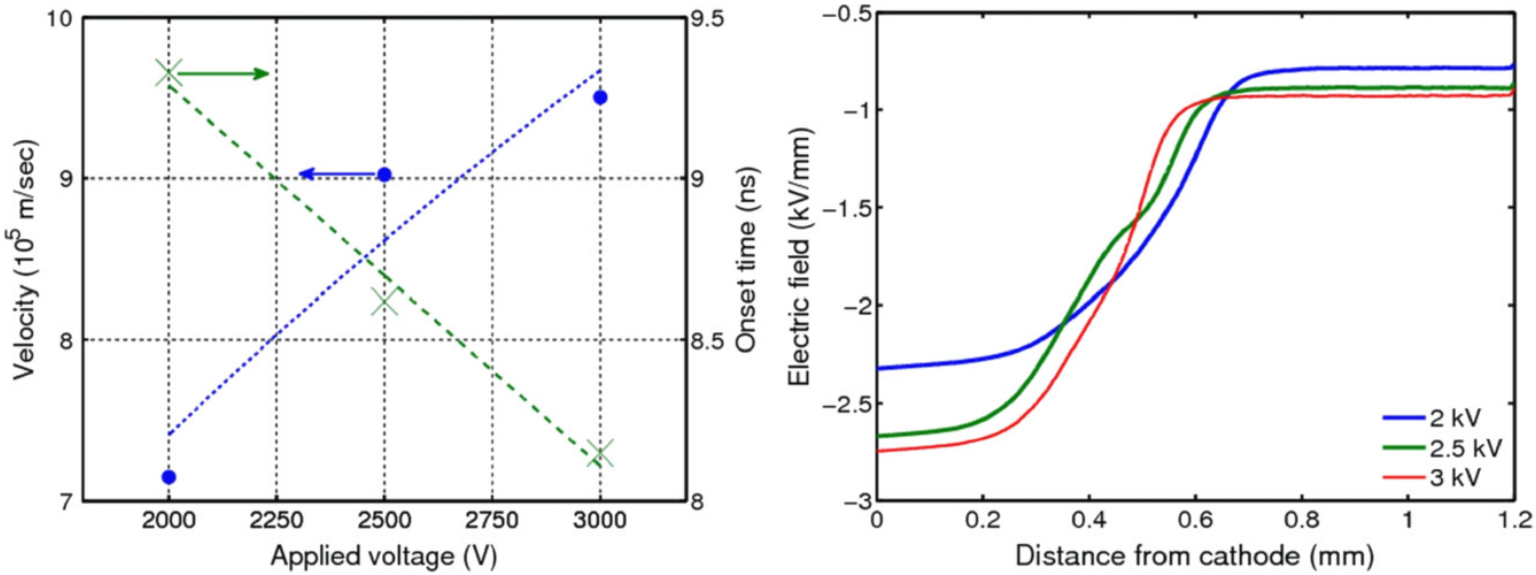


Figure 6. Peak-voltage dependence of discharge characteristics. (*a) Dependence of the propagation velocity (filled circle) and onset time*
(cross) of an ionization front on the peak voltage of the applied field. Here the dotted and broken lines are drawn as a guide to the eye.
(*b) The profile of electric field at the onset of an ionization front for each peak voltage*

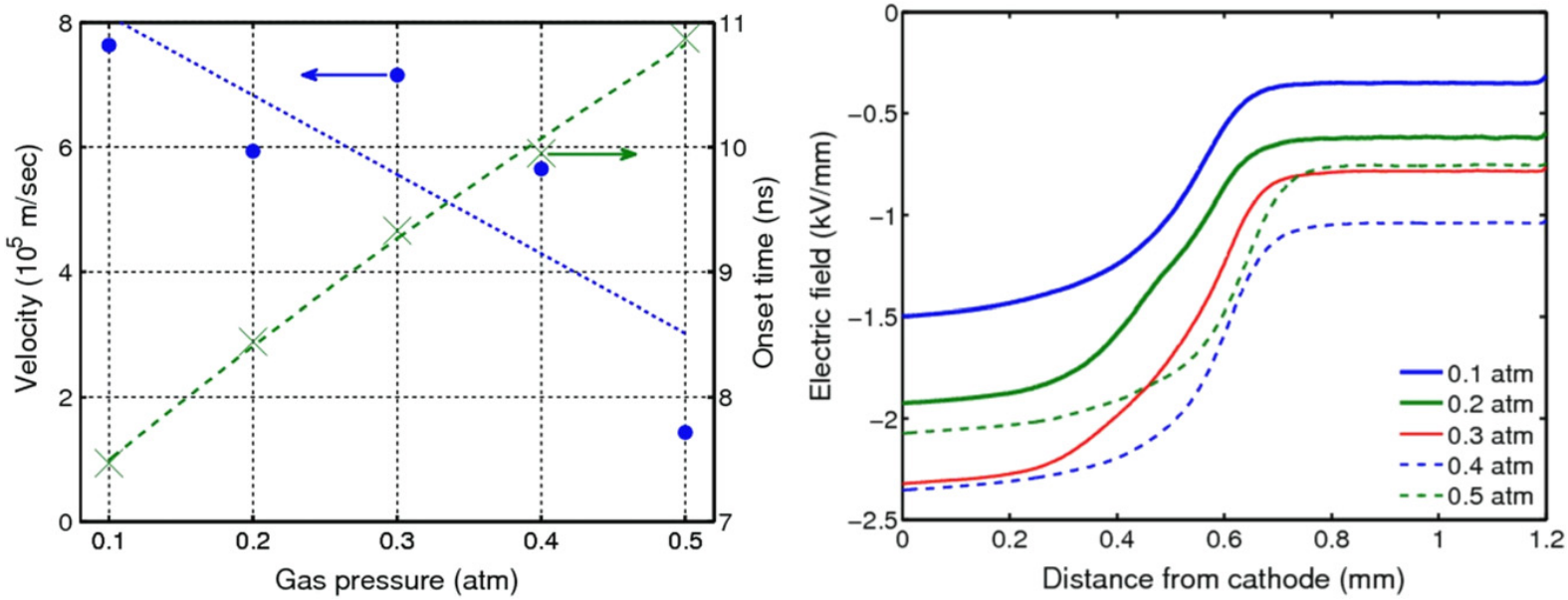


Figure 5. Pressure dependence of discharge characteristics. (*a) Pressure dependence of the propagation velocity (filled circle) and onset* time (cross) of an ionization front. Here the dotted and broken lines are drawn as a guide to the eye. (*b) The profile of electric field at the* onset of an ionization front at each gas pressure

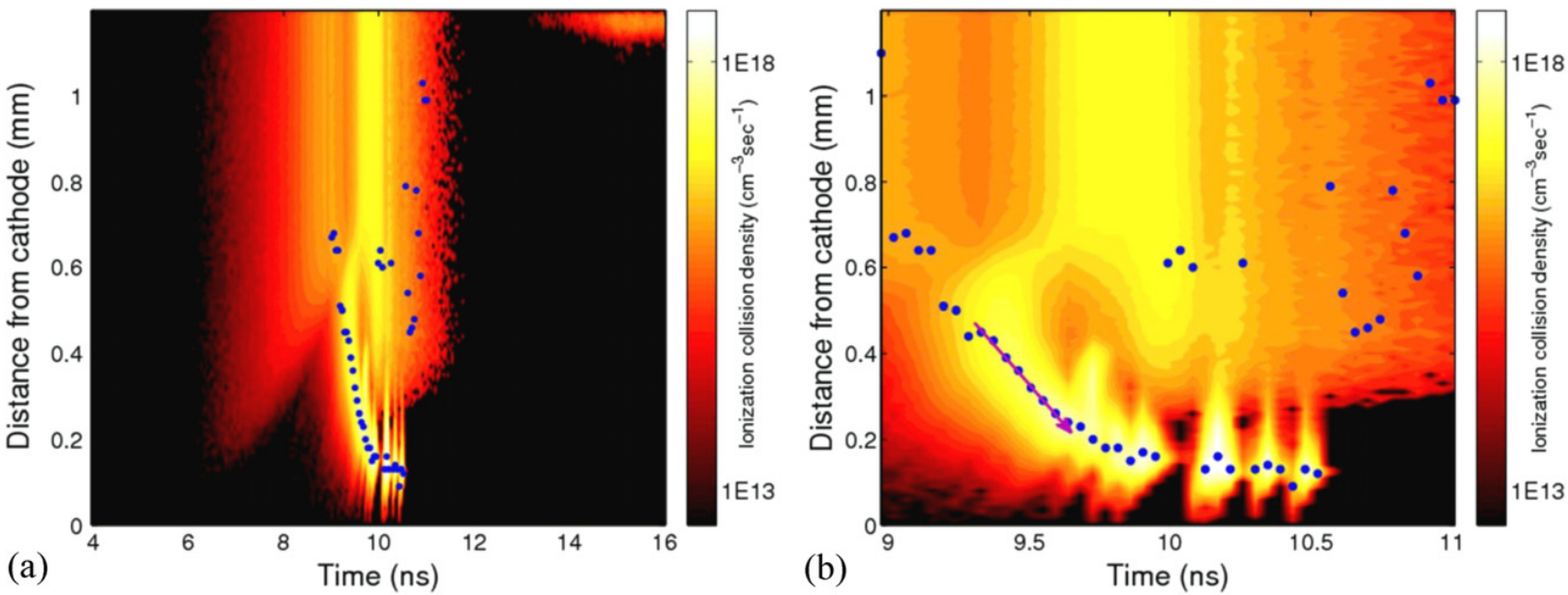
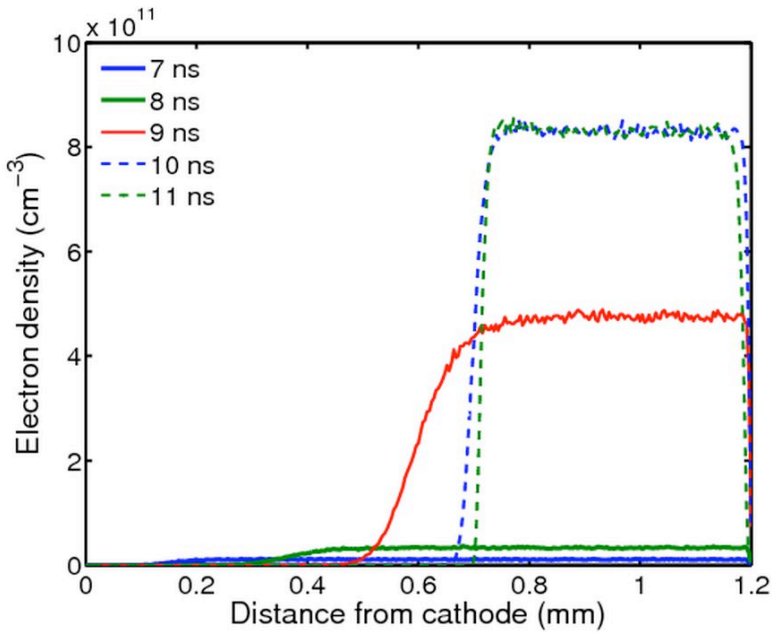
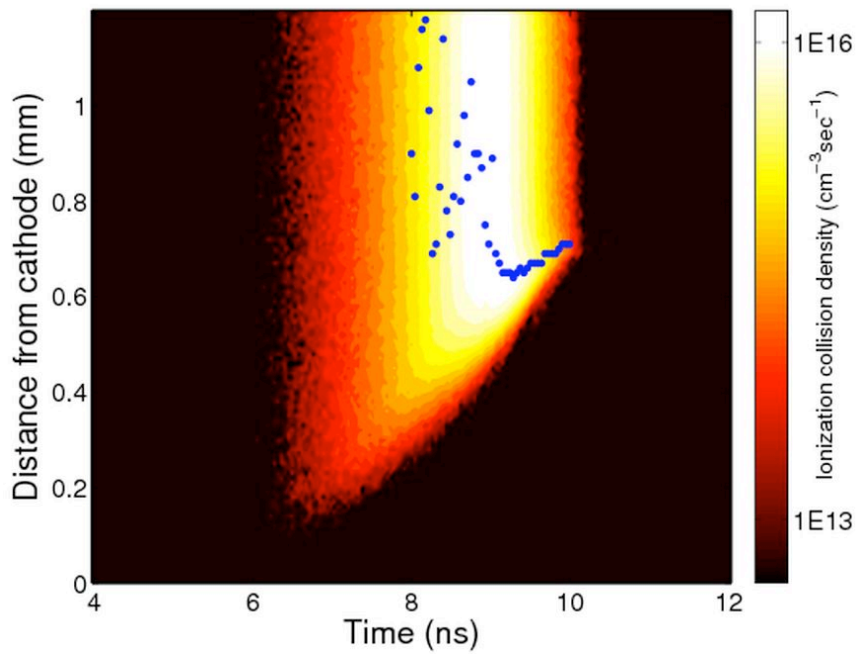


Figure 4. Spatiotemporal distribution of the ionization collision density obtained from the simulation. A magnification of (*a) for*
9 ns *t 11 ns is given in (b). The blue dot indicates the position of maximum ionization collision density at each time instance in*
9 ns *t 11 ns. The arrow in (b) is a guide to the eye that indicates propagation of the ionization front.*

Plasma densities in log scale

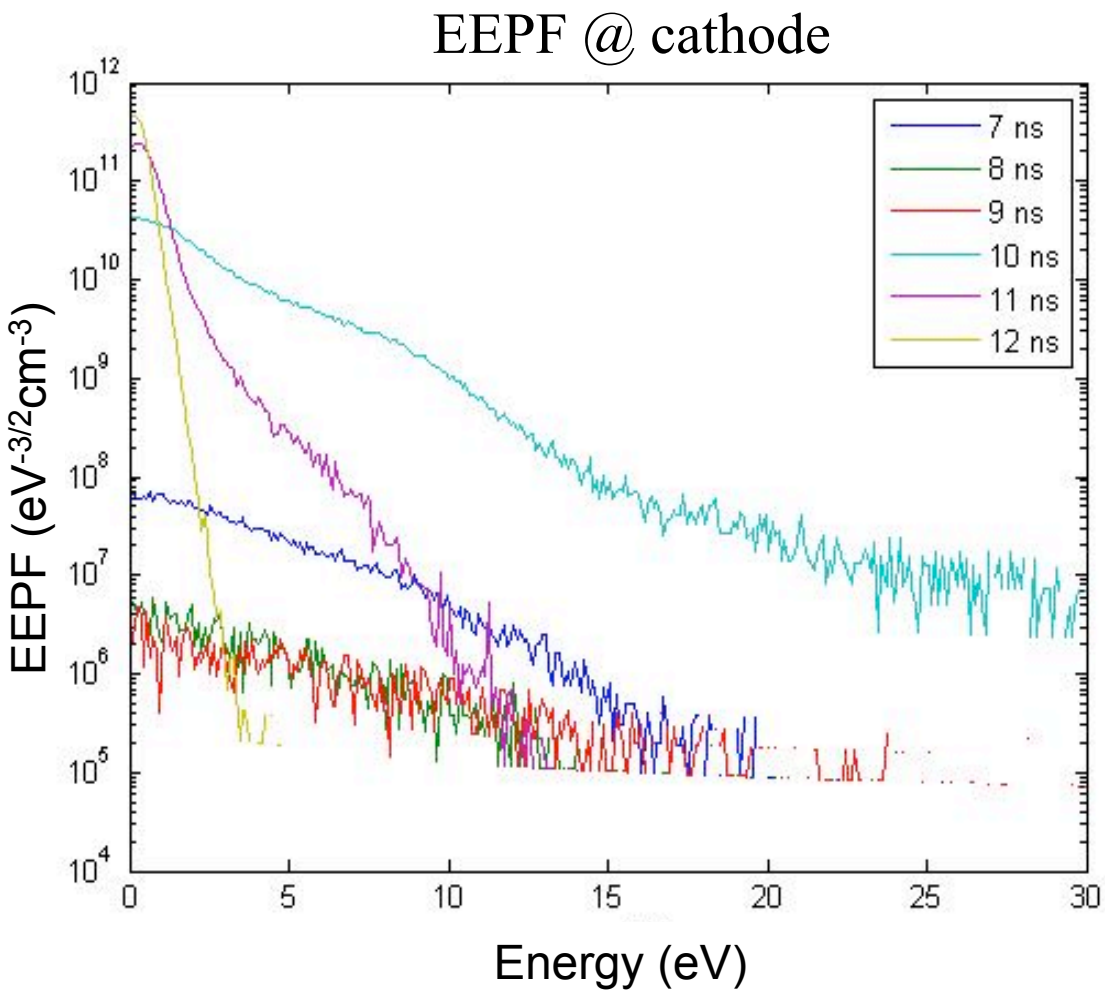


electron density profiles
(in linear scale)



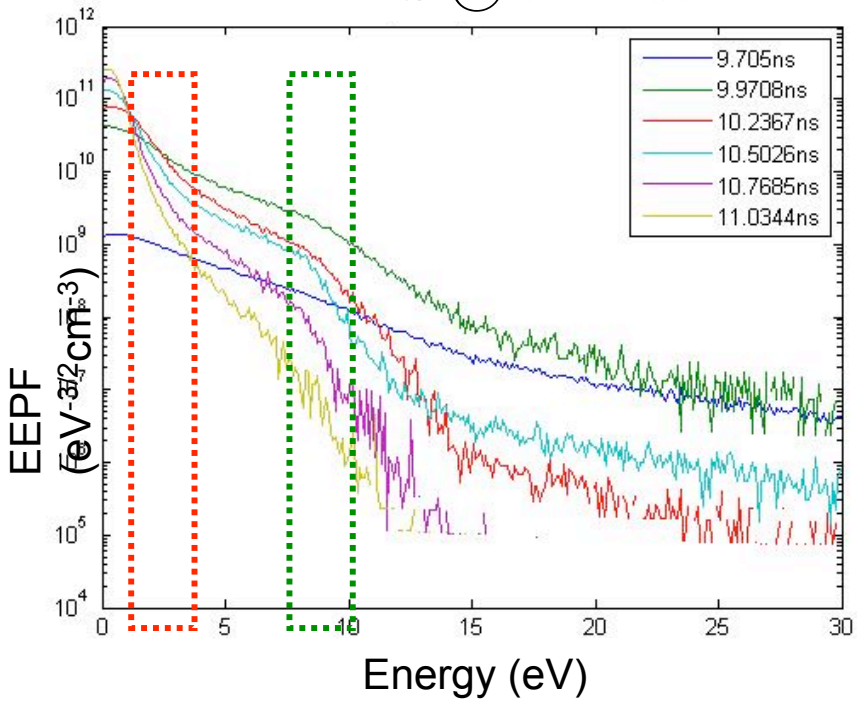
ionization collision density

Electron Energy Probability Functions (EEPF)

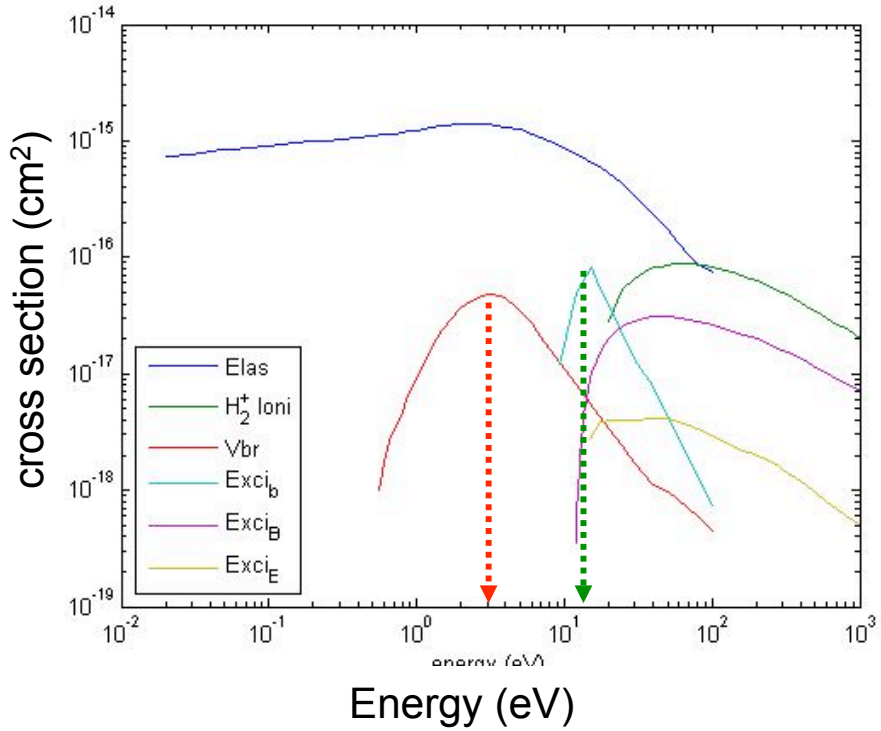


Electron Energy Probability Functions (cont.)

EEPS @ cathode



Electron-Neutral Collisions



Non-Maxwellian shapes of electron energy probability functions are caused by strong electron-neutral vibrational and electronic excitation.

Summary

- The electric field is enhanced at the cathode, which enhances ionization in the sheath.
- Increase of ionization causes ionization front propagation.
- The enhanced E field may increase secondary electron emission coefficient.
- Importance of secondary electron emission; without secondary electrons, no ionization propagation occurs and only a low-density plasma is obtained

Summary (cont'd)

- Non-Maxwellian electron energy probability functions (EEPF) in the region near the cathode are caused by strong electron-neutral vibrational and electronic excitation.

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Acknowledgement

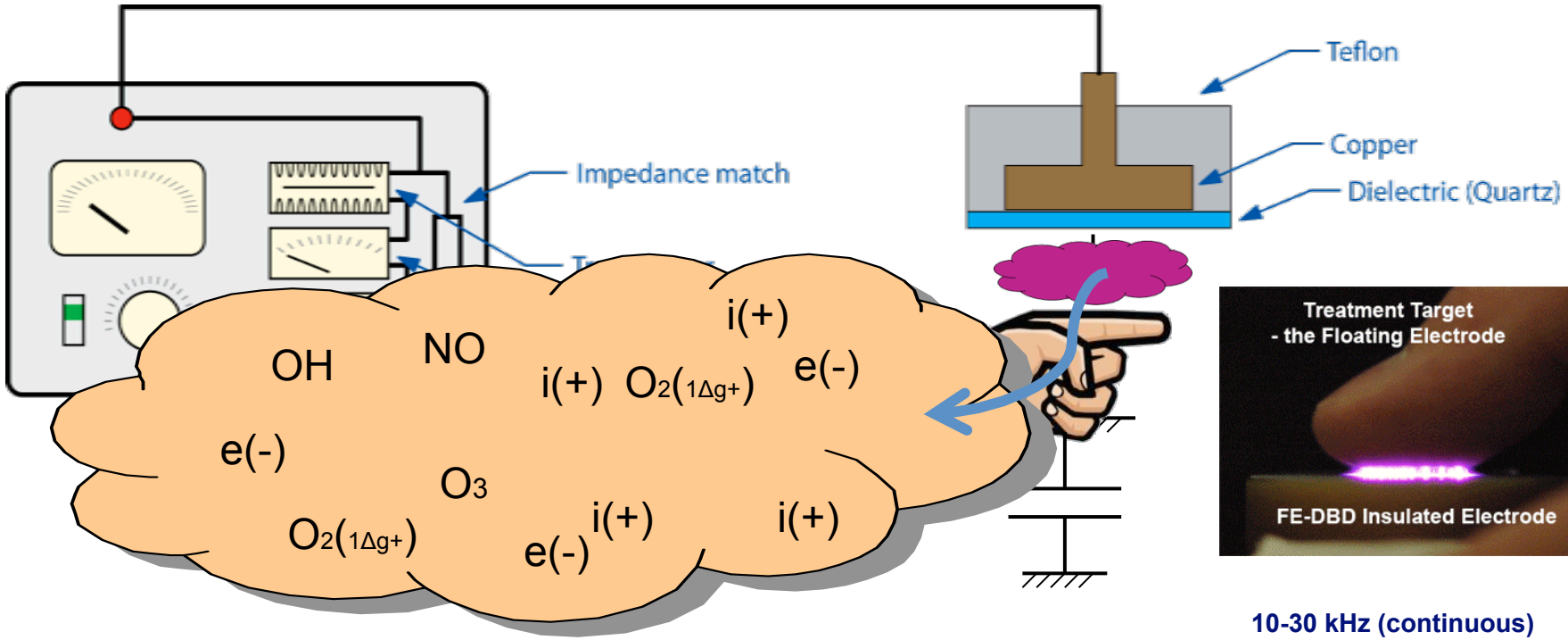
- Experiments: Profs. K. Kitano and T. Ito of Osaka University

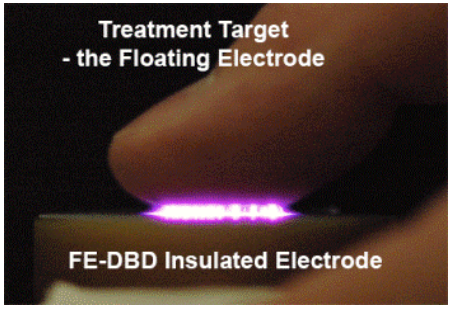
- Theory: Profs K. C. Shaing and Frank C. Z. Cheng of National Cheng Kung University

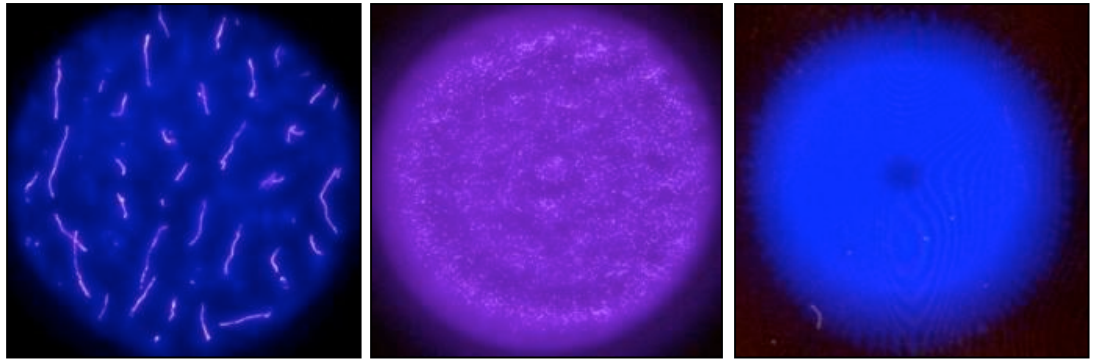
- National Cheng Kung University for the funding for C.-W. Lo

So, What is This Safe Direct Plasma?

Floating Electrode Dielectric Barrier Discharge (FE-DBD)







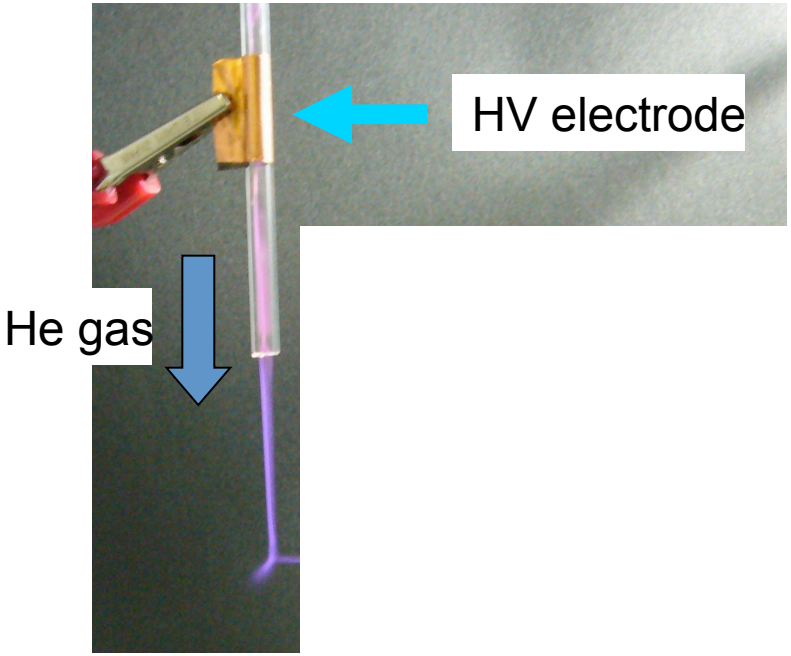
Continuous wave | Microsecond pulse | Nanosecond pulse

10-30 kHz (continuous)
0.1-10 kHz (pulsed)
10-30 kV
0.5-5 mm gap
0.1-10 cm^2 electrode
0.01-2 W/cm^2 plasma power

Electron Temperature: 10,000-20,000 K
Temperature of Ions and Neutrals: 300 K (room)
Plasma Density: 10^12 cm-3
Electron Density in Streamer: 10^13 cm-3

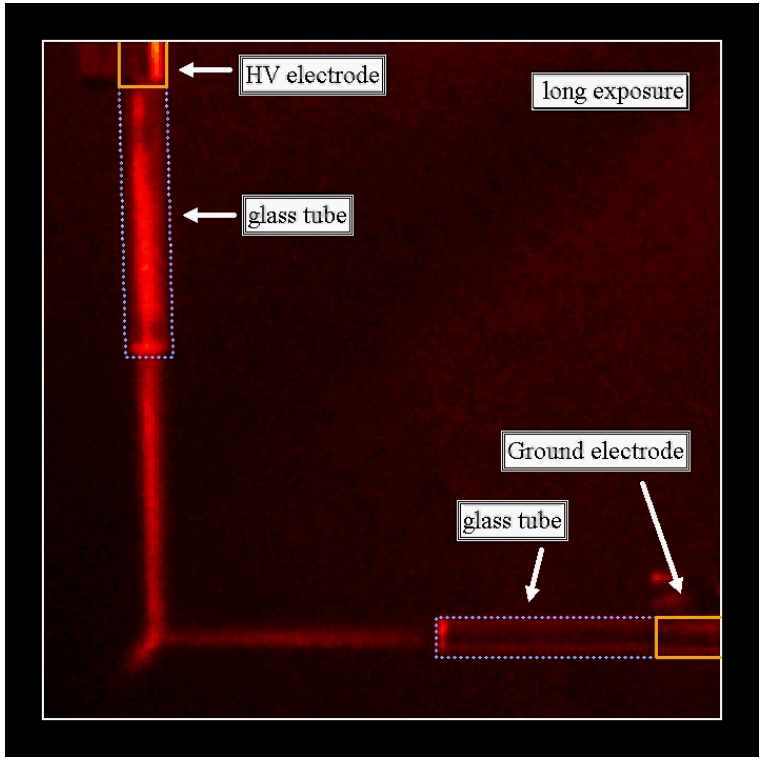
Cross Jet

Cross jet



High speed ICCD camera

Exposure time 50ns
Time step 50ns



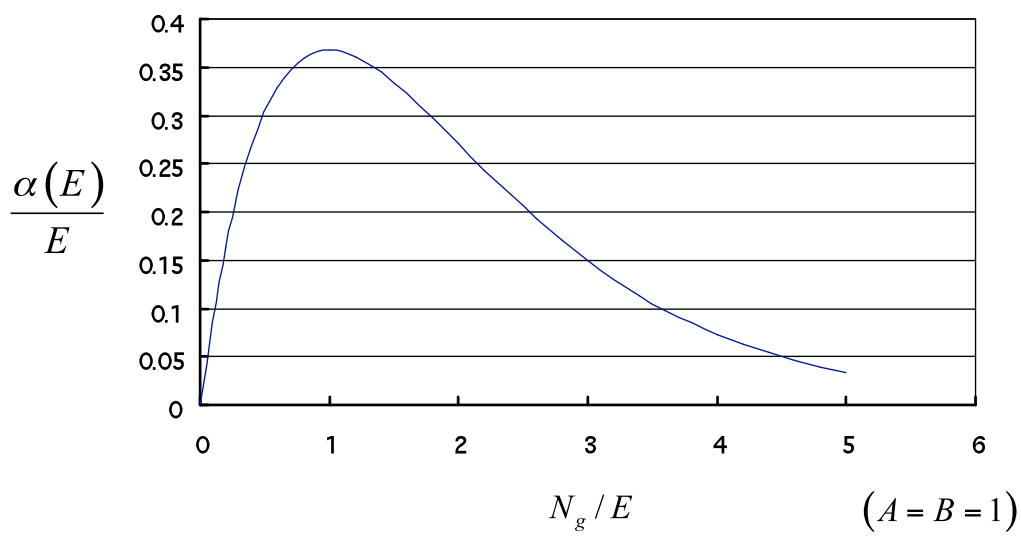
The ionization front travels along the crossing gas flows

Townsend Theory

standard assumption:

$$\alpha(E) = AN_g \exp(-BN_g / E)$$

N_g : gas density, E : electric field, and A, B are constants



the condition that current continues to flow

$$\gamma\left(\exp\left(\alpha d\right)-1\right)=1 \qquad \cdots \quad (1)$$

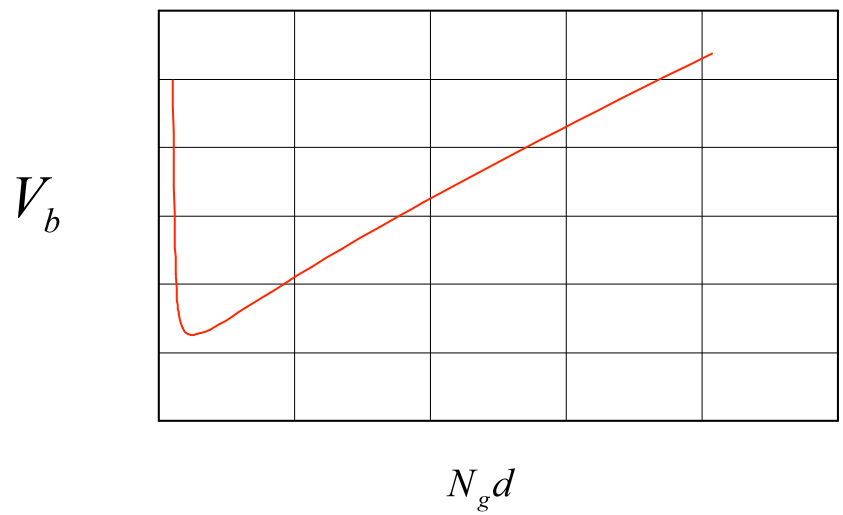
expression for Townsend coefficient

$$\alpha\left(E\right)=AN_g\exp(-BN_g/E) \qquad \cdots \quad (2)$$

$\Rightarrow$ Solve Eqs. (1) and (2) for $V = Ed$ as a function of $N_g d$

$$V_b\left(N_g d\right)=B\frac{N_g d}{\ln(N_g d)+\ln\left(A/\ln\left(1+1/\gamma\right)\right)}$$

Townsend Theory

breakdown voltage

$$V_b\left(N_g d\right) = B\frac{N_g d}{\ln(N_g d) + \ln\left(A/\ln\left(1+1/\gamma\right)\right)}$$