Effect of miniaturization on ring-type plasma actuators

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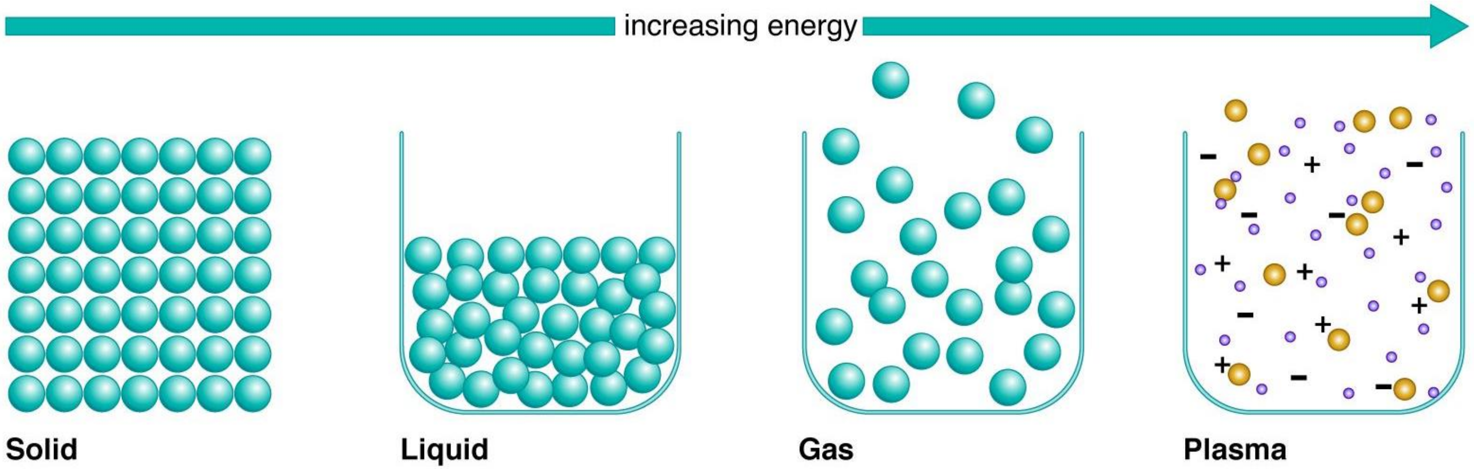
Outline

- Introduction
- Motivation
- Experimental setup
- Methodology
- Observation
- Numerical simulations
- Conclusion and outlook

What is plasma?

- Most common medium found in the observable universe
- Widely regarded as the fourth state of matter



Potter, Simeon and Ehlers, Ernest G.. "phase". Encyclopedia Britannica, 29 Mar. 2024

Natural plasmas



www.wikipedia.org

What is plasma?

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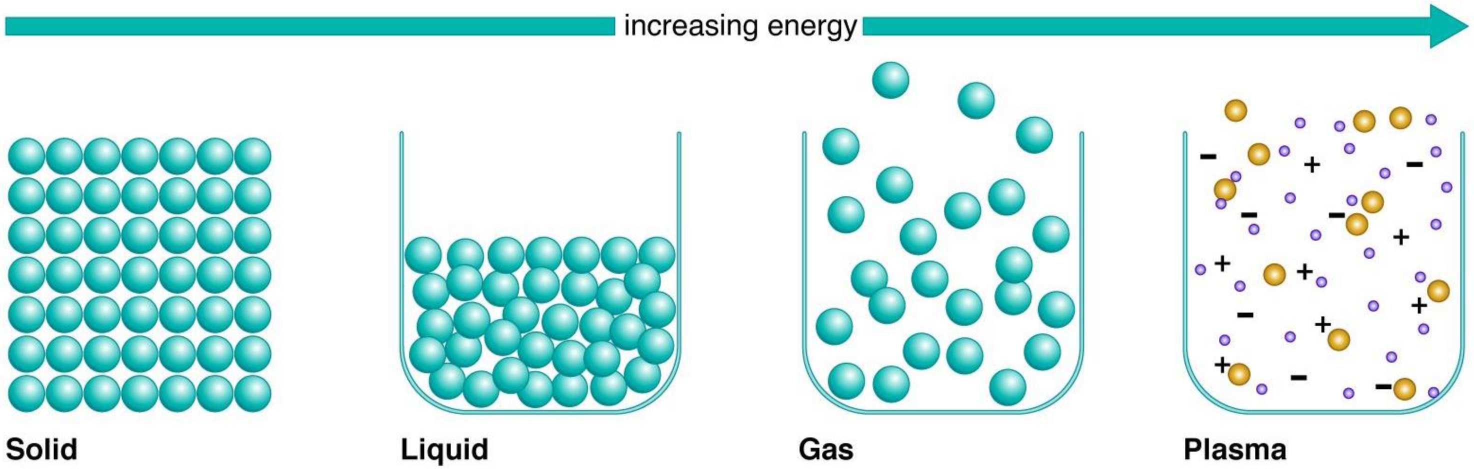
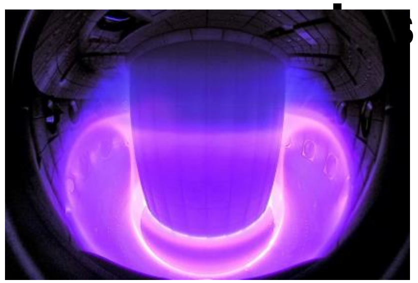


Potter, Simeon and Ehlers, Ernest G.. "phase". Encyclopedia Britannica, 29 Mar. 2024

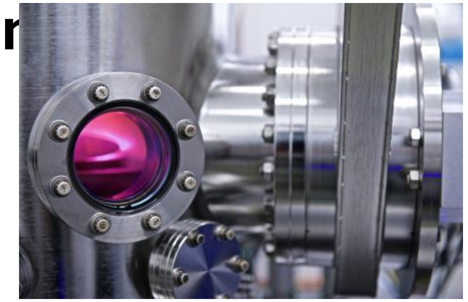
Rigorous definition:

it is a quasineutral gas of charged and neutral particles which exhibits collective behaviour

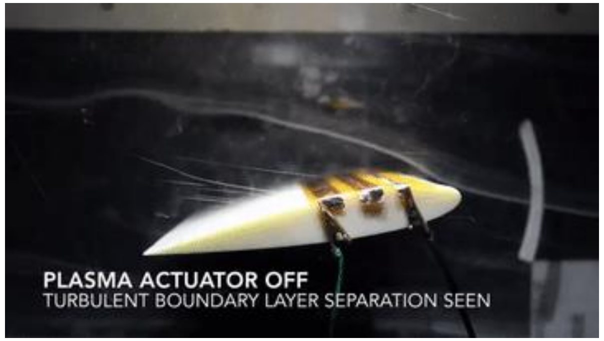
Man-made



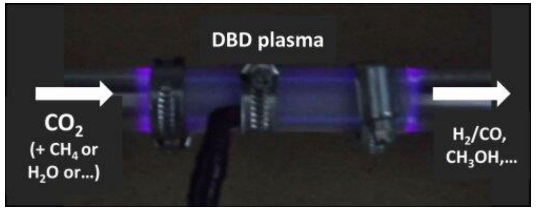
www.newscientist.com



https://www.physik.uni-konstanz.de/



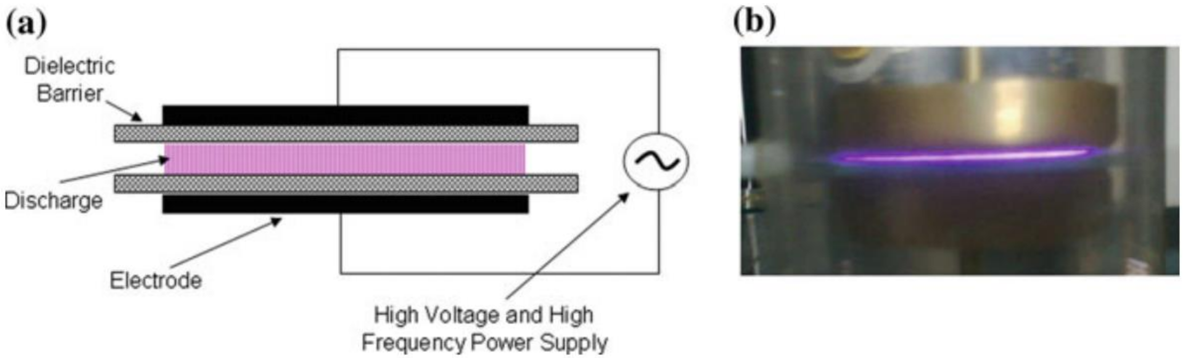
Prince Ghosh (www.youtube.com)



www.uantwerpen.be/en/research-groups/plasmant

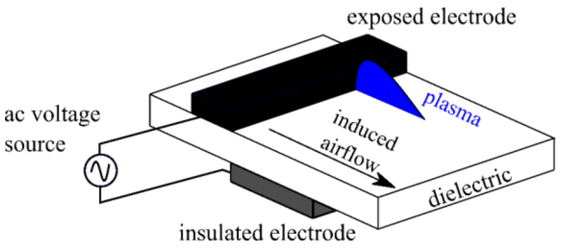
Dielectric Barrier Discharge (DBD)

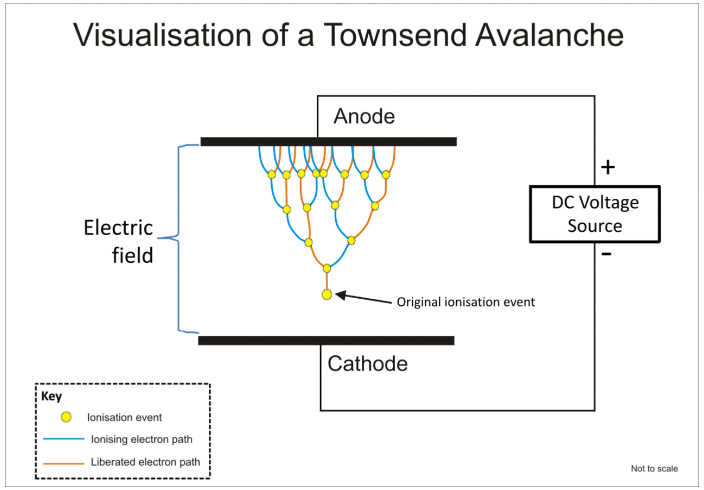
Volumetric (VDBD)



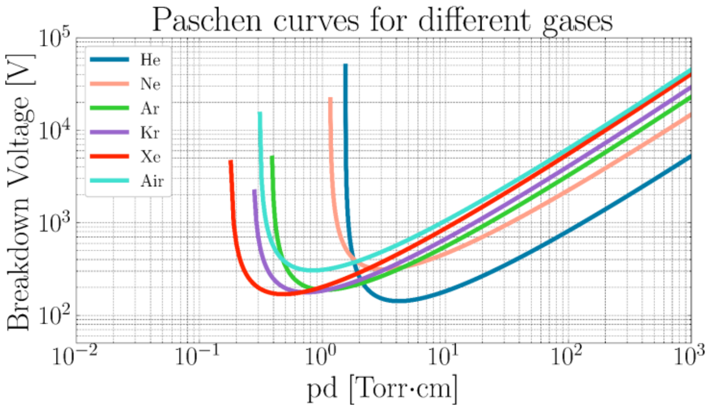
Subedi, D.P., et al., Dielectric Barrier Discharge (DBD) Plasmas and Their Applications. Plasma Science and Technology for Emerging Economies (2017)

Surface (SDBD)





www.wikipedia.org

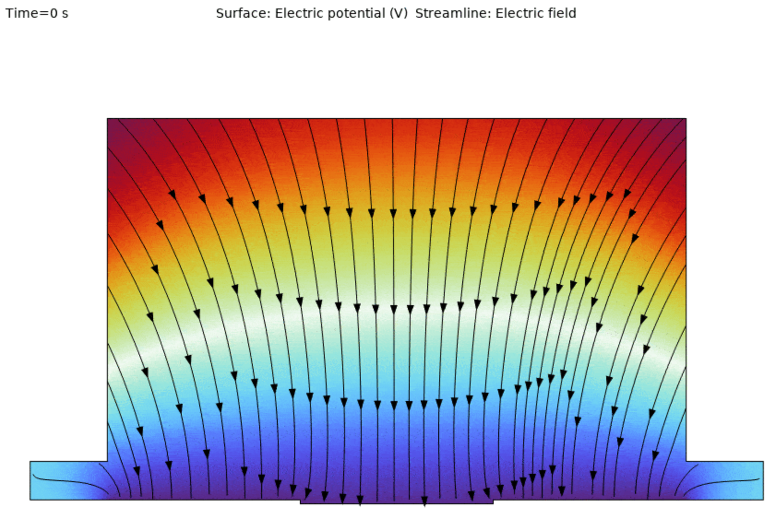


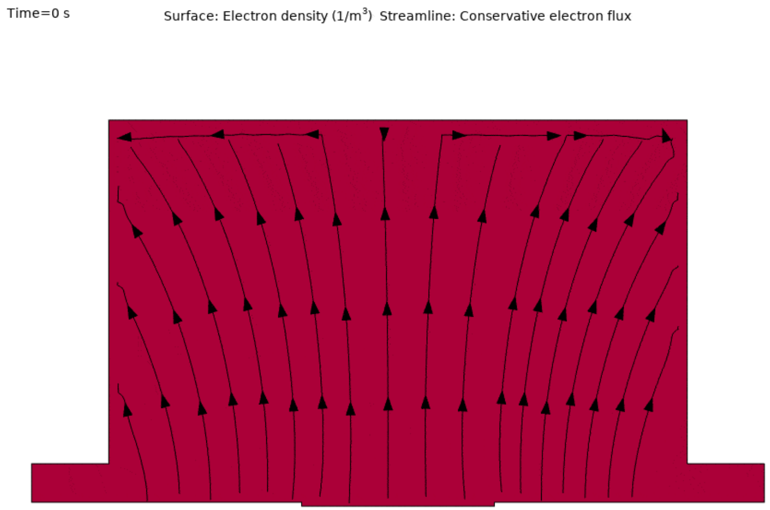
Ionic wind

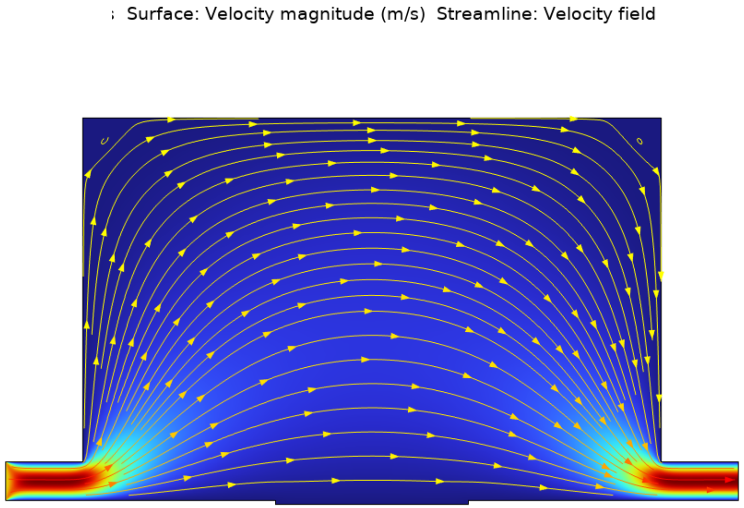
$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

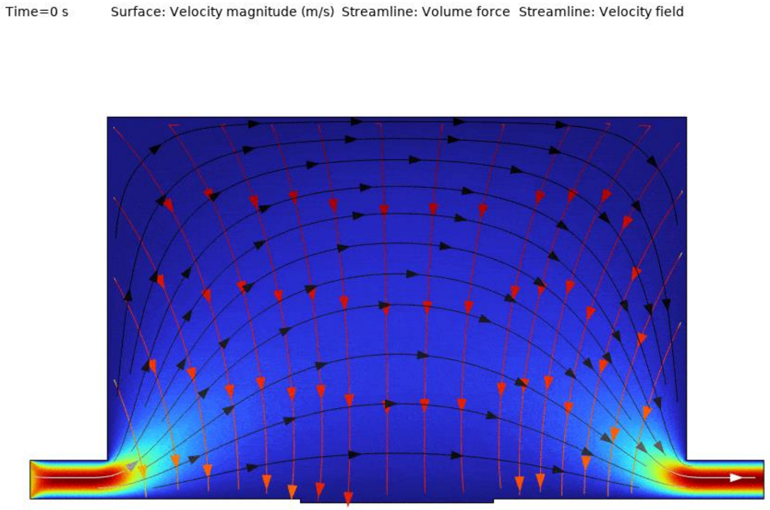
$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \vec{\nabla})\vec{v} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + \vec{f}_{EHD}$$

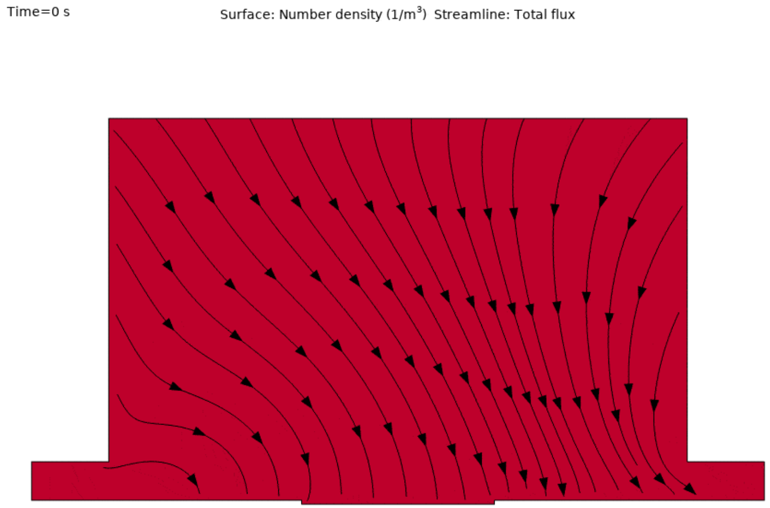
$$= e(n_i - n_n - n_e)\vec{E}$$







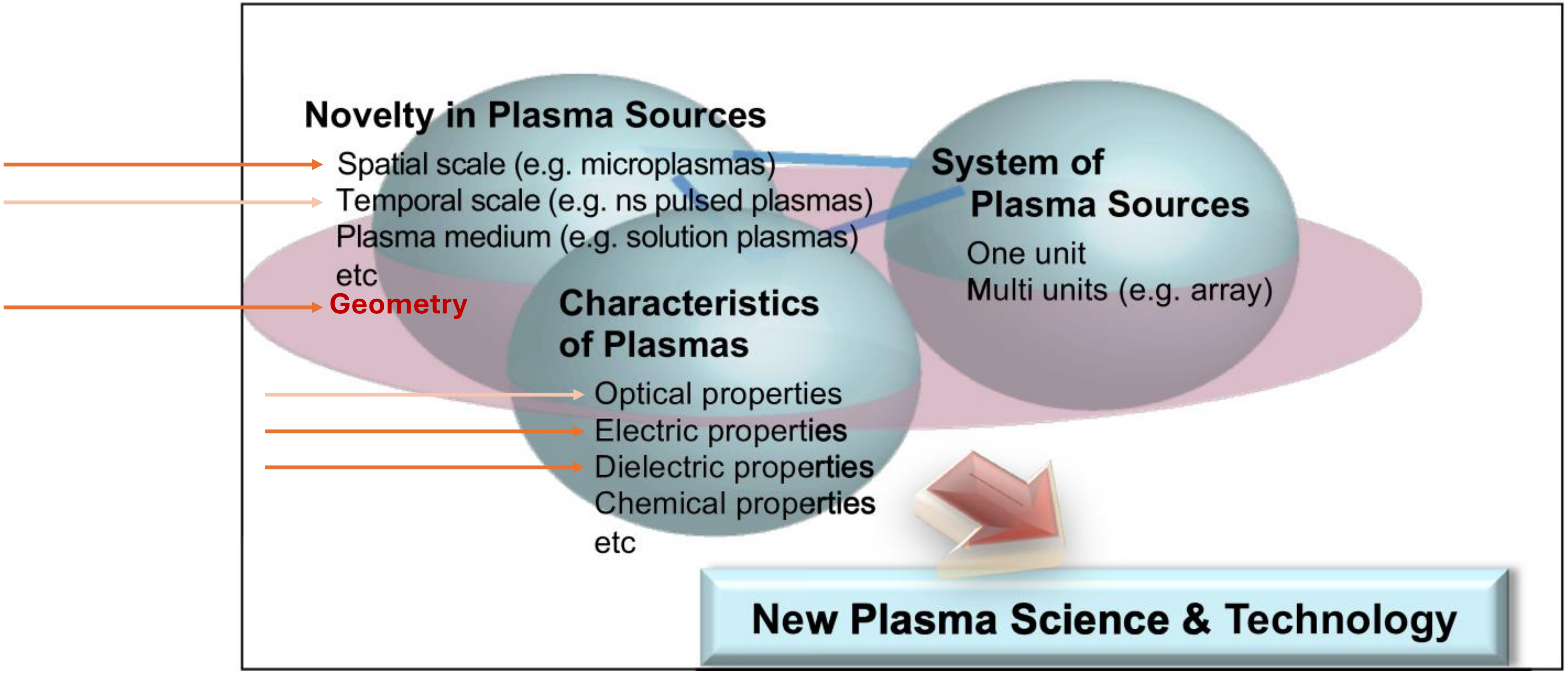




Without plasma

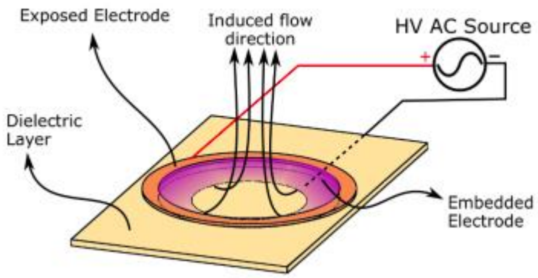
With plasma

Driving force behind new plasma applications and technologies

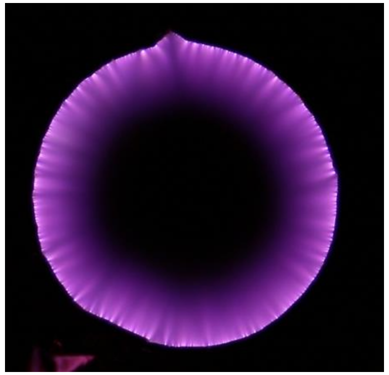


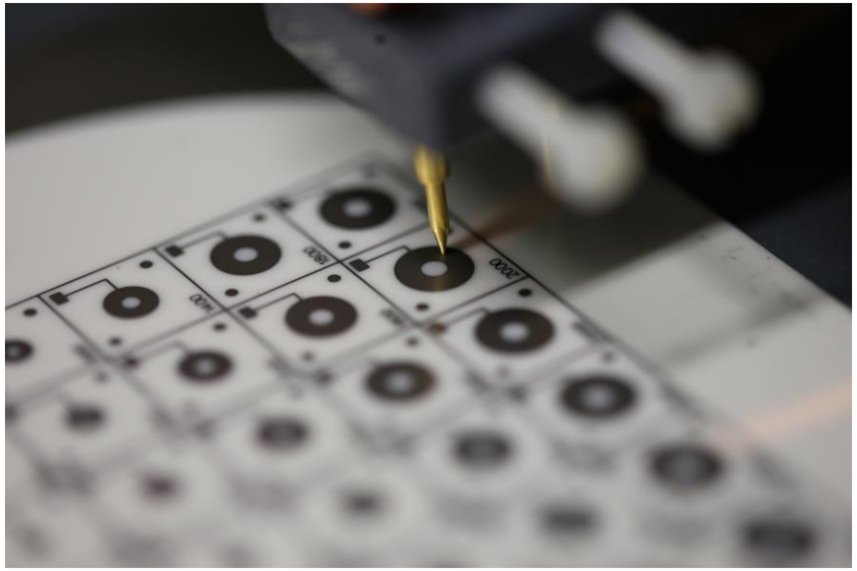
J. Gary Eden and Kazuo Terashima, New plasma sources and regimes, 2017 Plasma Roadmap

Miniaturized ring-type SDBDs



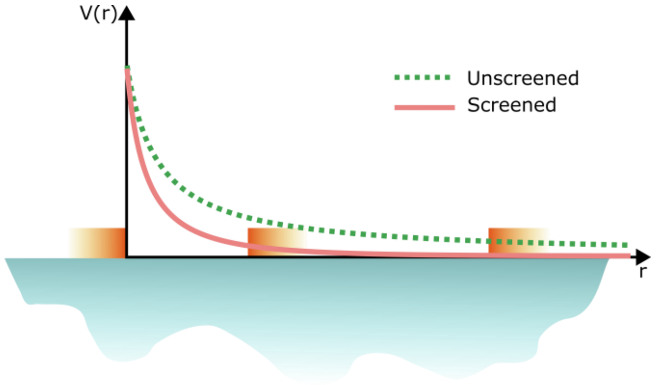
Rodrigues, F., Páscoa, J., pages 1–33. 02 2023



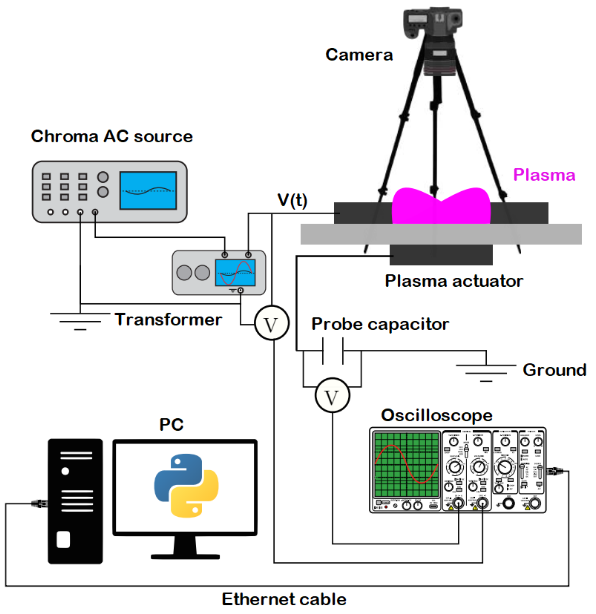


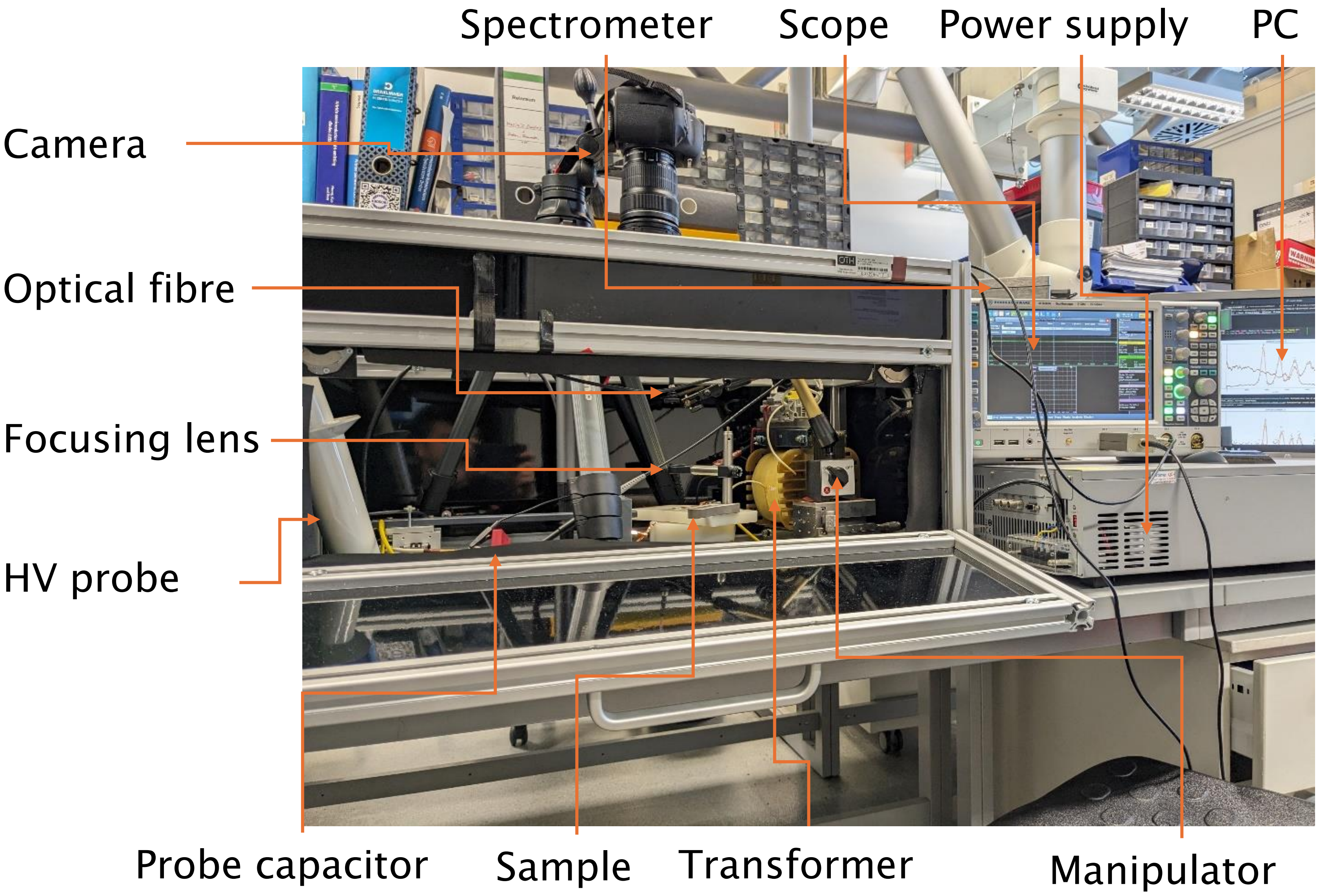
Motivation

- Induce Perpendicular Ionic Flow
- Eliminate edge effects and fringing fields
- Local effects -> Global w.r.t. dimensions

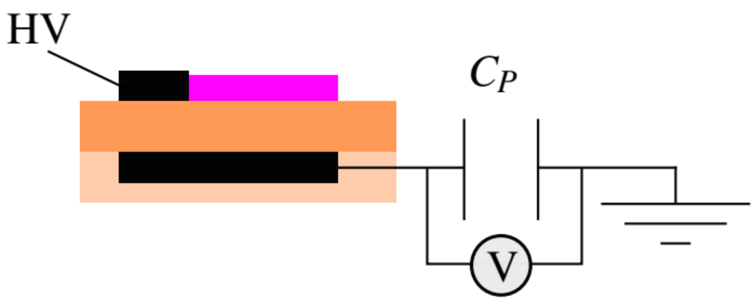


Dielectric material	Dielectric thickness	Electrode material	Electrode thickness	Diameters
Zirconia	150µm	Titanium	550nm	0.4-2 mm

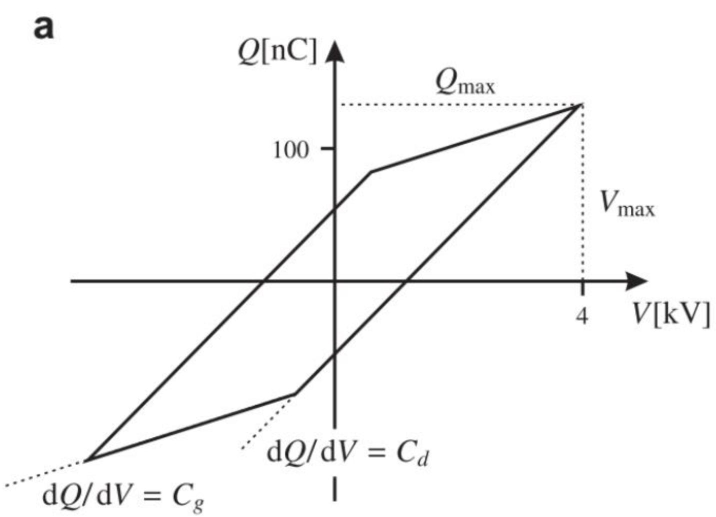

Camera
Chroma AC source
Plasma
V(t)
Plasma actuator
Transformer
V
Probe capacitor
Ground
V
Oscilloscope
PC
Ethernet cable


Spectrometer
Scope
Power supply
PC
Camera
Optical fibre
Focusing lens
HV probe
Probe capacitor
Sample
Transformer
Manipulator

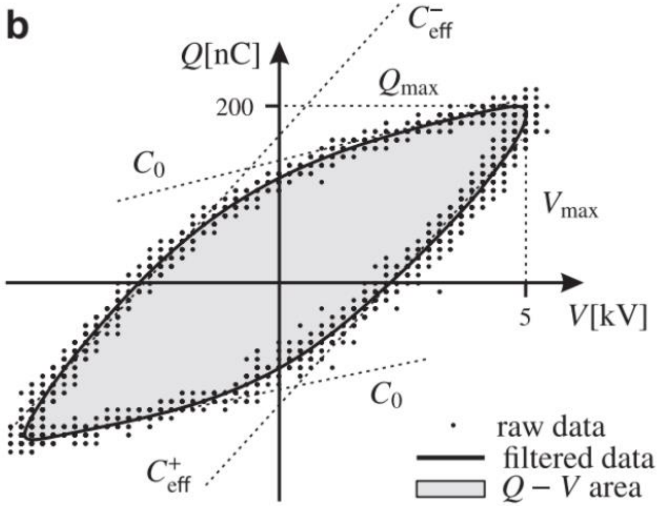
Q-V plots (Lissajous figure)



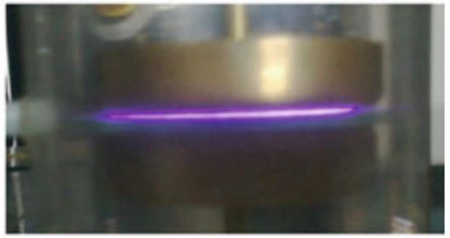
$$C_{eff.}(t) = \frac{\varepsilon_r \varepsilon_0 L \cdot W_{eff.}(t)}{d}$$



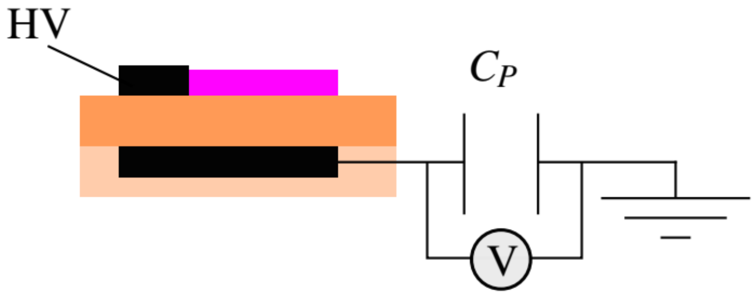
volume discharge (VD);
following Wagner *et al.* [56]



surface discharge (SD);
extracted from Möller [35]



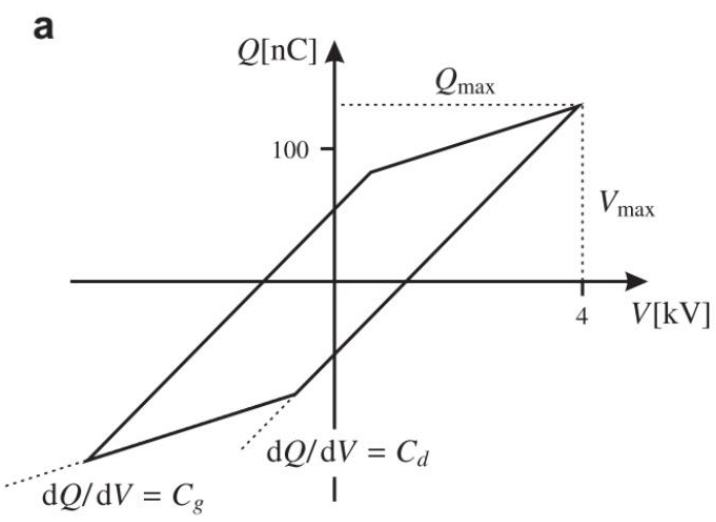
Q-V plots (Lissajous figure)



$$P(t) = V(t) \cdot i(t) = V(t) \cdot C_p \frac{dV_p(t)}{dt}$$

$$P_{avg.} = \frac{1}{T} \oint V(t) \cdot C_p \frac{dV_p(t)}{dt} dt$$

$$= \frac{1}{T} \oint V(t) dQ(t)$$



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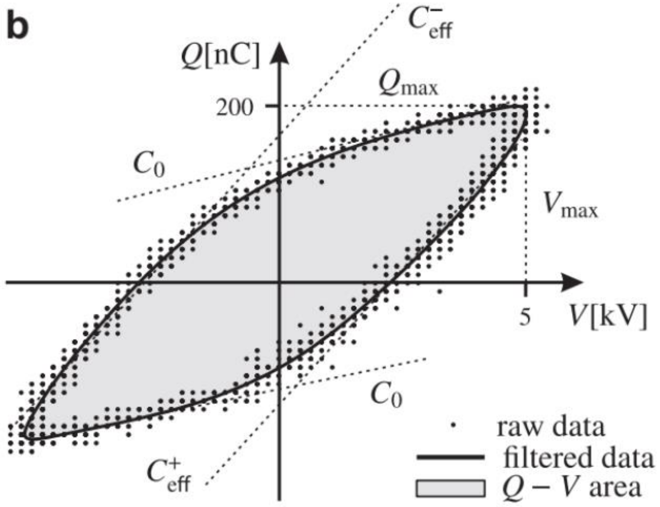

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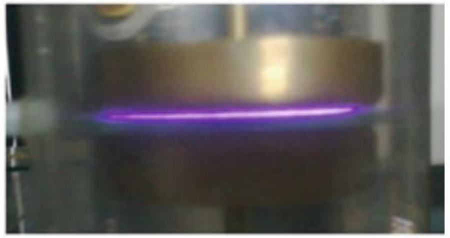


Self-consistent description of a plasma

Lorentz force

$$\vec{E}, \vec{B} \rightarrow \vec{F}_i$$

$$\vec{F}_i = q_i(\vec{E}(\vec{r}_i, t) + \vec{v}_i \times \vec{B}(\vec{r}_i, t))$$

Newton's equation

$$\vec{F}_i \rightarrow \vec{r}_i, \vec{v}_i$$

$$m_i \frac{d^2\vec{r}_i}{dt^2} = \vec{F}_i$$

$$\vec{r}_i, \vec{v}_i \rightarrow \rho, \vec{j}$$

$$\rho = \sum_{i=1}^{N} q_i \delta(\vec{r} - \vec{r}_i)$$

$$\vec{j} = \sum_{i=1}^{N} q_i v_i \delta(\vec{r} - \vec{r}_i)$$

Maxwell's equations

$$\rho, \vec{j} \rightarrow \vec{E}, \vec{B}$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0(\vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t})$$

Fluid drift-diffusion approach

Neutral atom density

Energy density

Rate of electron creation and annihilation

Electron density

Energy source term

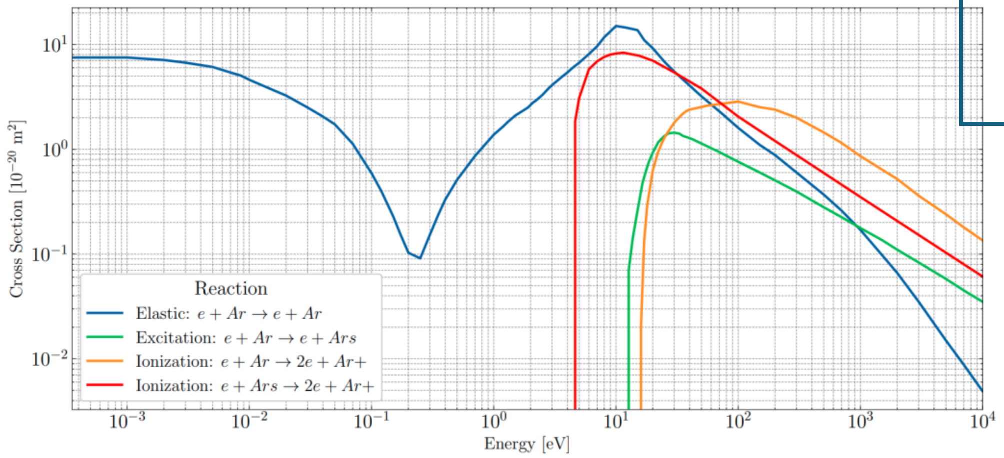
Energy loss/gain

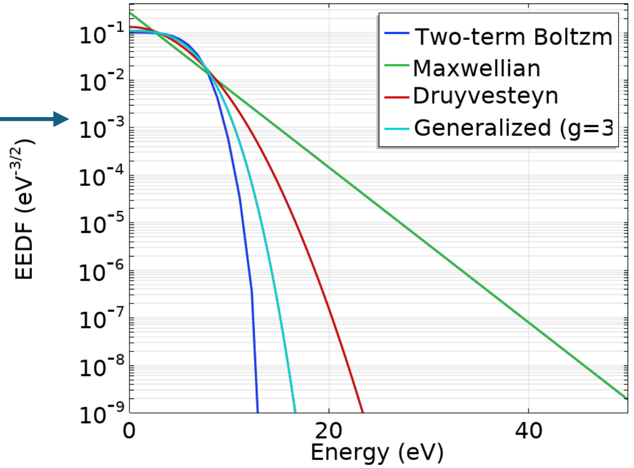
$$R_e = \frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_e = \sum_{j=1}^{M} x_j k_j N_n n_e \qquad S_\epsilon = \frac{\partial n_\epsilon}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_\epsilon = \sum_{j=1}^{P} x_j k_j N_n n_e \Delta$$

Molar fractions

Rate constant

$$k_j = \sqrt{\frac{2e}{m_e}} \int_0^\infty \epsilon \sigma_j(\epsilon) f(\epsilon) d\epsilon \qquad -\nabla^2 V = \frac{\rho_c}{\varepsilon_r \varepsilon_0} \qquad \rho_c = e\left(\sum_{k=1}^{N} Z_k n_k - n_e\right.$$





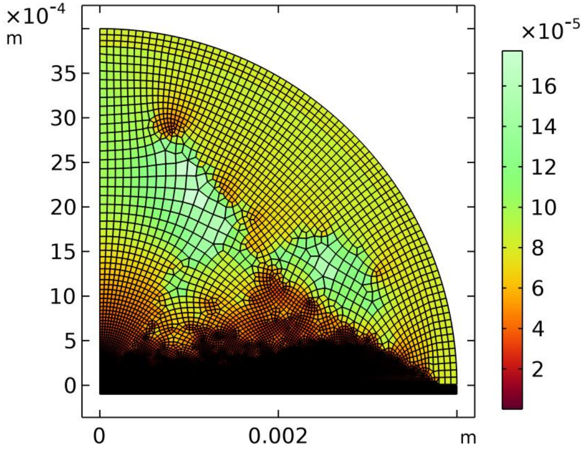
Model

Parameters

- Argon environment
- $V_0 = 500\ V$
- $f_0 = 1\ kHz$
- $\varepsilon_r = 5$
- $t = 100\ \mu m$
- $T_g = 400K$
- $p_0 = 1\ atm$
- $\mu_e N_n = 4 \cdot 10^{24} \frac{1}{V \cdot m \cdot s}$
- Maxwellian

Geometry

COMSOL



Chemistry set

Reaction	Formula	Type	$\Delta\epsilon$ (eV)	Forward rate constant ($m^3/s \cdot mol$)
1	$e + Ar \rightarrow e + Ar$	Elastic	0	Cross-section
2	$e + Ar \rightarrow e + Ars$	Excitation	11.5	Cross-section
3	$e + Ars \rightarrow e + Ar$	Superelastic	-11.5	Cross-section
4	$e + Ar \rightarrow 2e + Ar^+$	Direct ionization	15.8	Cross-section
5	$e + Ars \rightarrow 2e + Ar^+$	Stepwise ionization	4.427	Cross-section
6	$Ars + Ars \rightarrow e + Ar + Ar^+$	Penning ionization	-	3.734×10^8
7	$Ars + Ar \rightarrow Ar + Ar$	Metastable quenching	-	1807

Reaction	Formula	Sticking coefficient	Secondary emission coefficient	Mean energy of secondary electron (eV)
1	$Ar^+ \rightarrow Ar$	1	0.01	2.5
2	$Ars \rightarrow Ar$	1	0	0

Initial and boundary conditions

- Surface charge accumulation along dielectric surface $-\vec{n} \cdot (\vec{D}_g - \vec{D}_d) = \rho_s$ $\frac{d\rho_s}{dt} = \vec{n} \cdot \vec{J}_i + \vec{n} \cdot \vec{J}_e$
- Zero charge along outer boundary $-\vec{n} \cdot \vec{D} = 0$
- Wall condition along surface

Conclusion

- Rich Information in Electrical Signals
- Innovative Applications and Technologies
  - Advanced Plasma Diagnostics
  - Miniaturized ion sources
  - Vertical scaling and heterogeneous integration at the chip-level
- Future work:
  - Perform simulations in air
  - Pressure and gas dependent experiments
  - Different dielectric materials with modified surface properties
  - Correlate with other measurement techniques

Thank you! Questions?