Technical Plasma: Theoretical side

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Outline

- Introduction (some devices and applications)
- Challenges of plasma simulation
- Kinetic Simulation
- Fluid Simulation
- Global models and hybrid models
- Examples & Conclusion

Introduction

- **Analytical Solution (exact solutuion)**

$$\sin(x) = 0.5 \qquad x^2 = 9$$

- **Numerical solution (approximate solution)**

$$\sin(x) + \cos(x) = 0.5$$

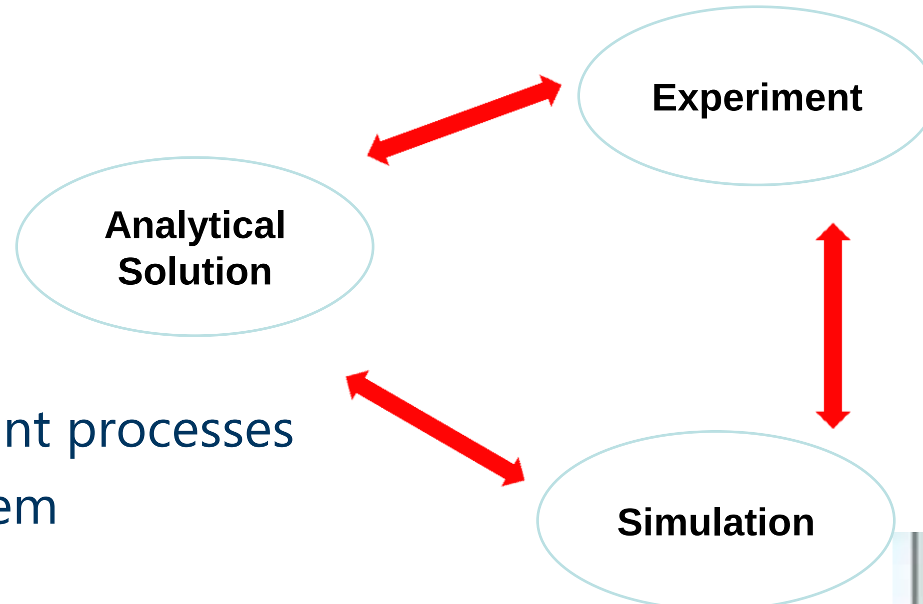
- **Round off errors & Truncation error**

$$2/3 = 0.666666666666666666666666666666....$$

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!}....$$

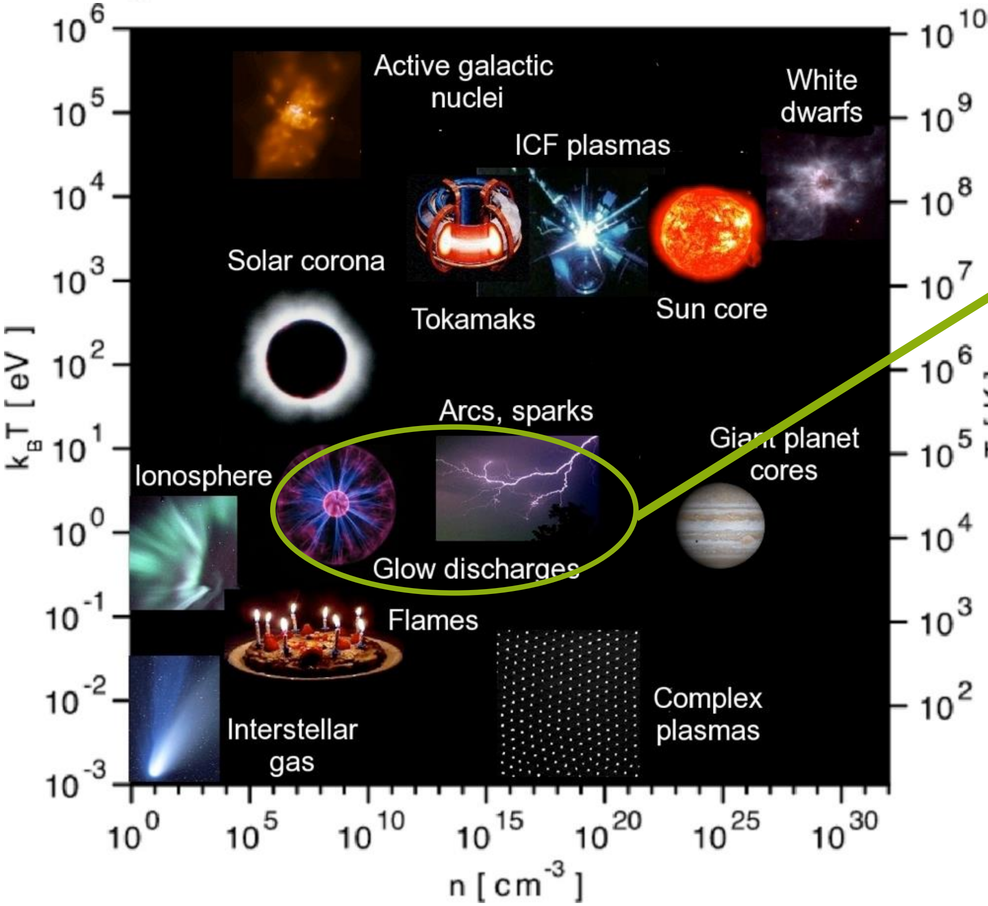
Do we need simulation?

- Simulations are useful
  - For checking theoretical results
  - For cases wher no theoretical results are available
  - For understanding experimental observations

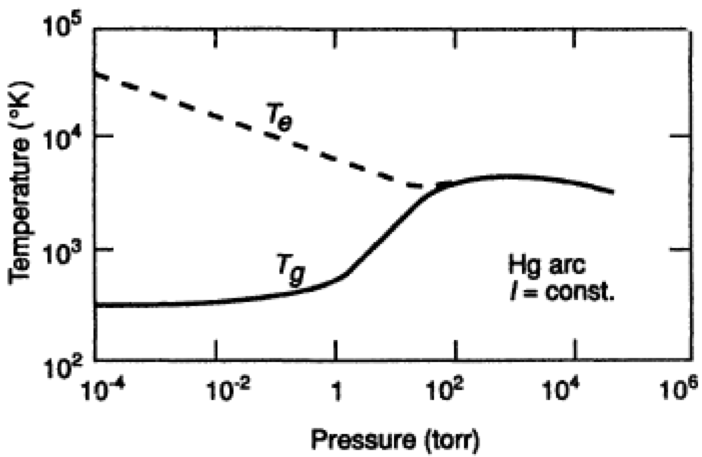


- Simulations allow :
  - Identification of important processes
  - Visualization of the system

Low Temperature Plasma

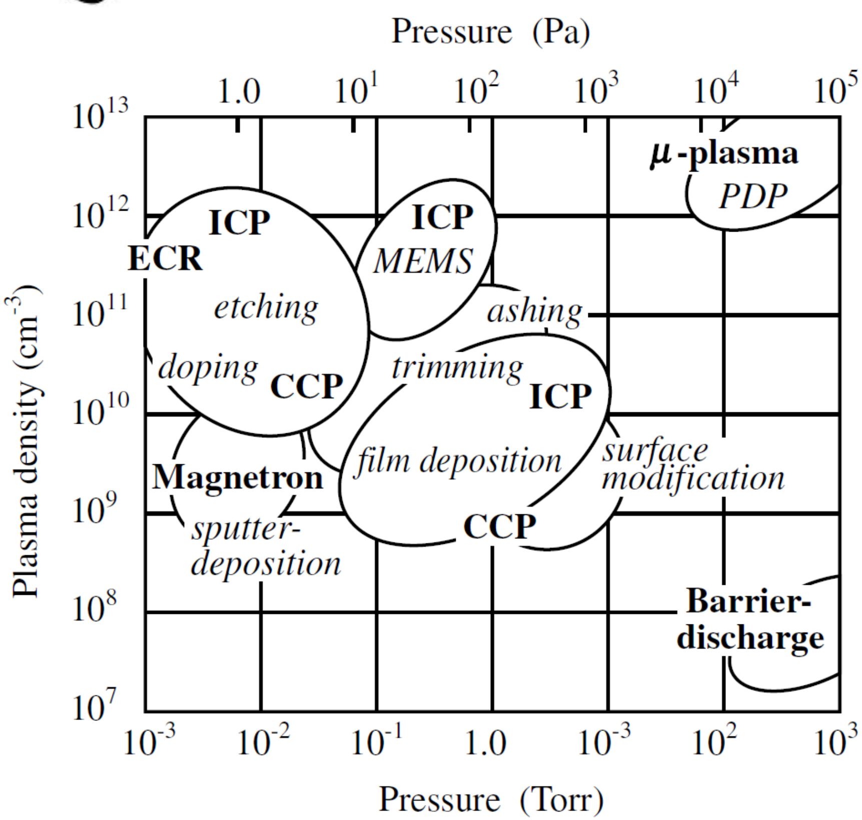


- Low degree of ionization
- Neutral background 10^6 the ion and electron density
- Collisions with the background gas is dominant compared to electron ion collisions



- Non-equilibrium plasmas at low pressures

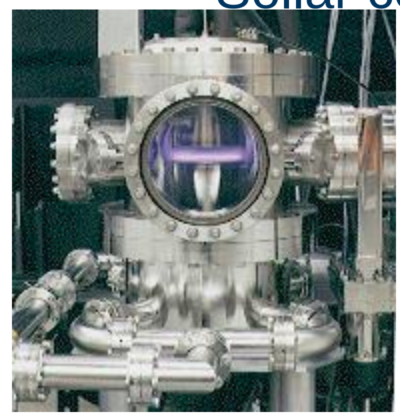
Devices and applications

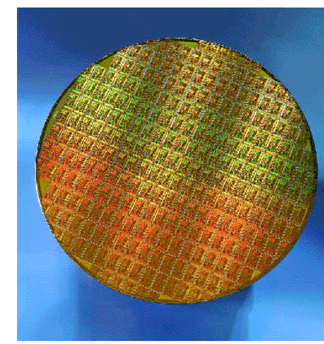


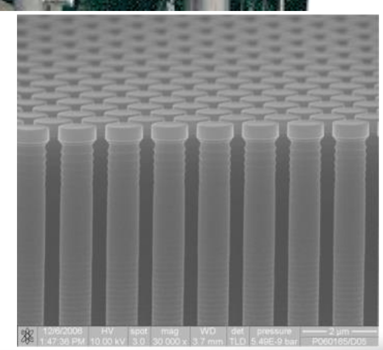
Plasma electronics,

Applications in Microelectronic Device Fabrication

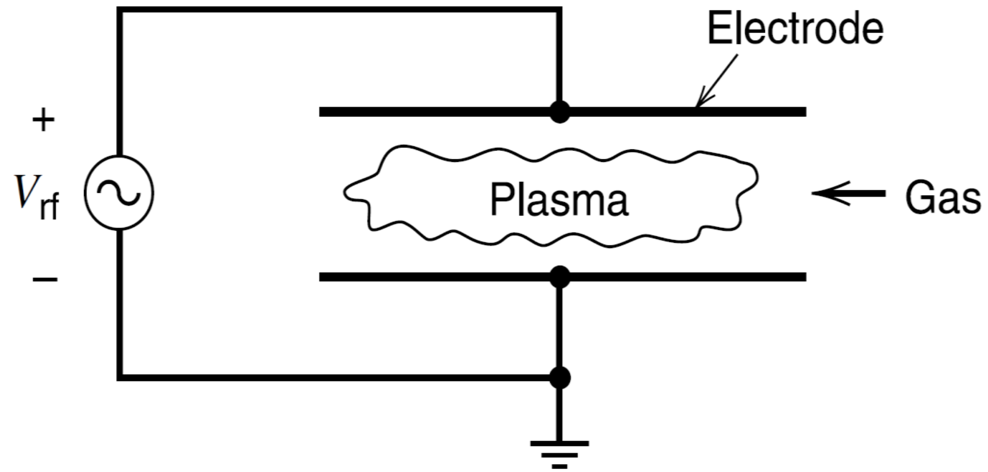
- **Capacitive coupled plasma** are used in plasma etching and deposition process for production of:
  - Integrated circuits
  - Sollar cells

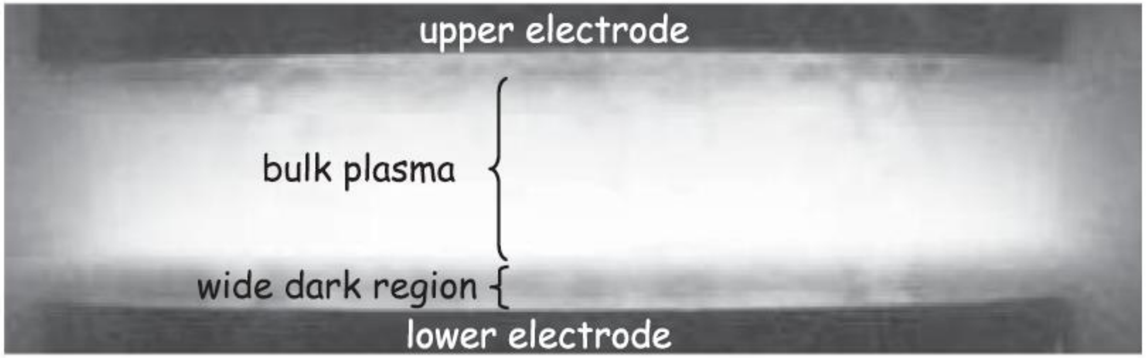






CCP:Symmetric discharge





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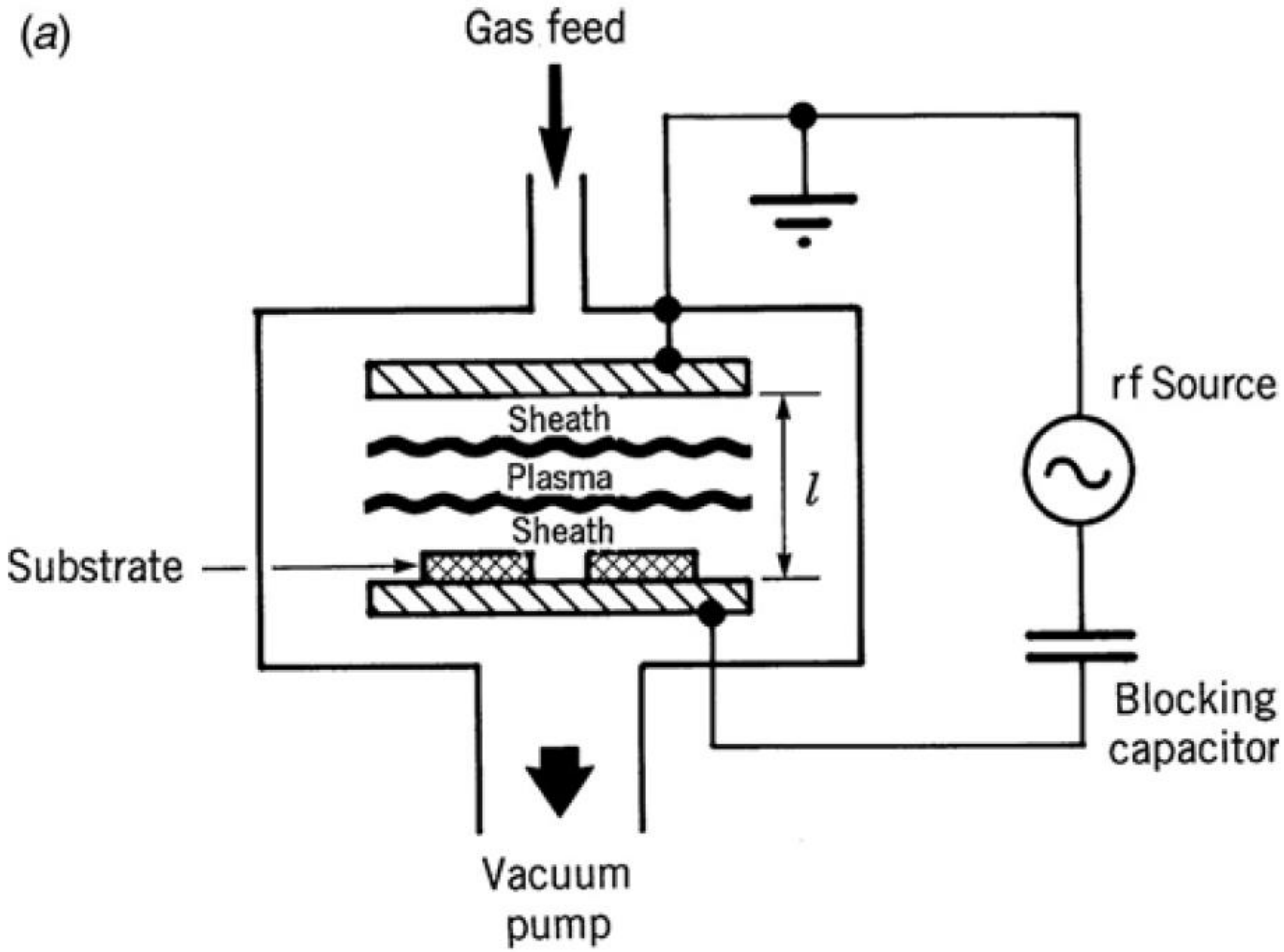
- **The ion flux increases and the ion energies decreases by increasing the driving frequency. !!!!?**

CCPs & blocking a Capacitor



Geometrically Asymmetric

- **The RF current is constant.**
- **But the ground electroge**

Area is greater than the powered electrode area.

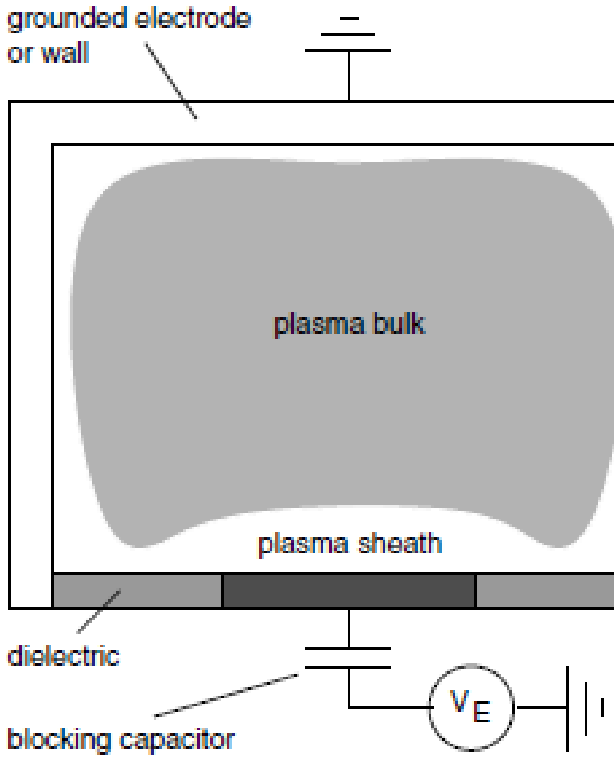
$$J_{\mathrm{g}} = I_{\mathrm{rf}}/A_g$$

$$J_{\mathrm{p}} = I_{\mathrm{rf}}/A_p$$

$$J_{\mathrm{p}} \gg J_{\mathrm{g}}$$

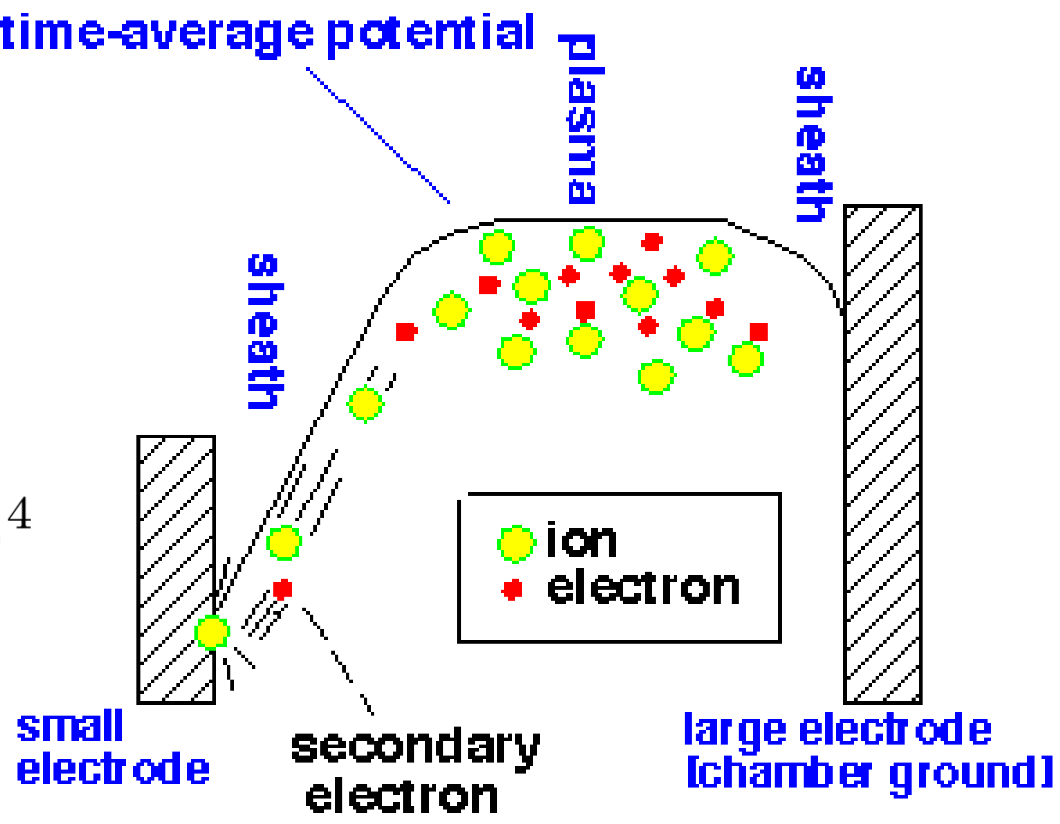
- The blocking capacitor blocks DC currents:

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{g}}} = (\frac{A_{\mathrm{g}}}{A_{\mathrm{p}}})^4$$



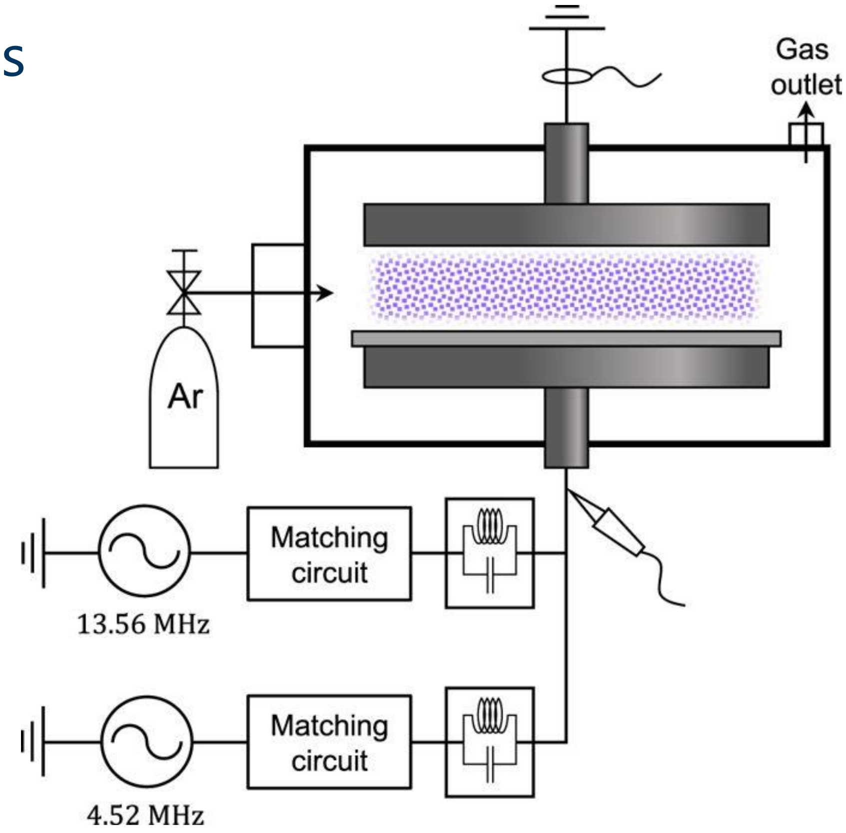
Particle and Potential distribution

$$\frac{V_p}{V_g} = (\frac{A_g}{A_p})^4$$

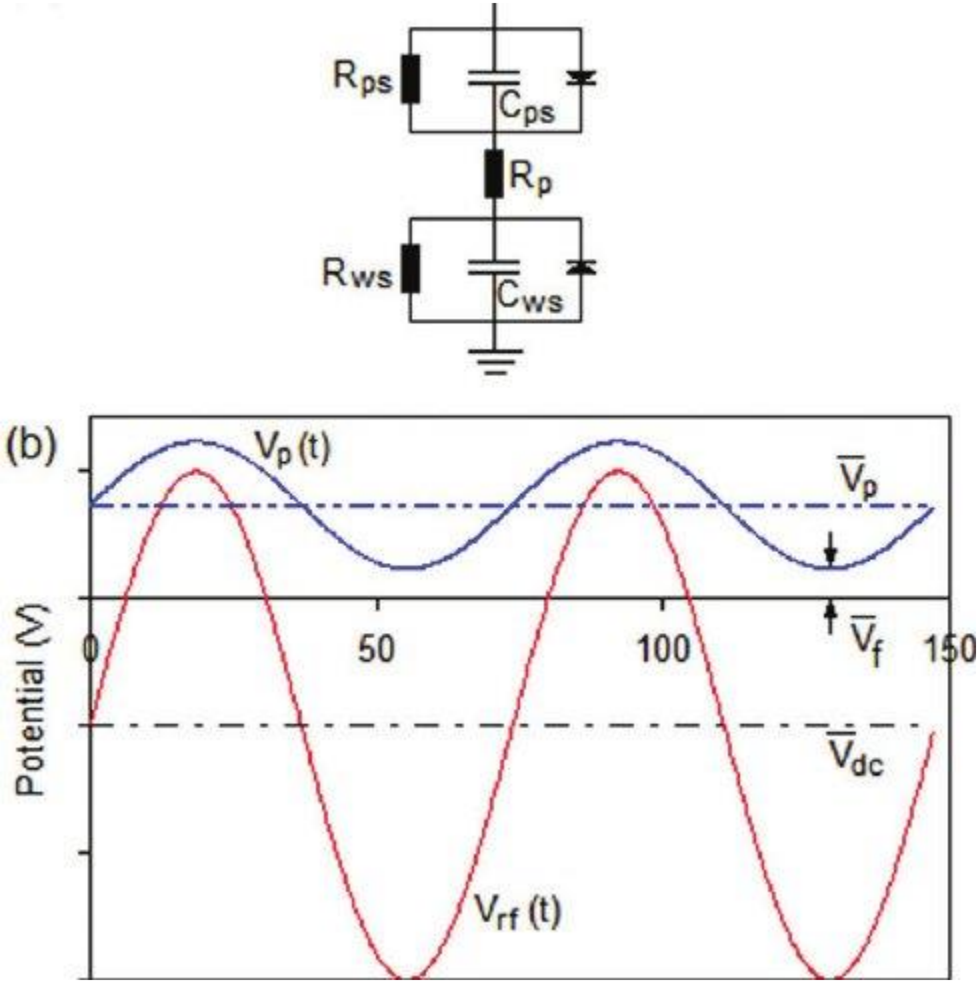


Electrically Asymmetric

- The high frequency controls the ion plasma bulk (ion flux).
- The lower frequency controls the plasma sheath voltage.
- The phase shift between the two sources controls also the sheath potential.
- The independent control is not always perfect.

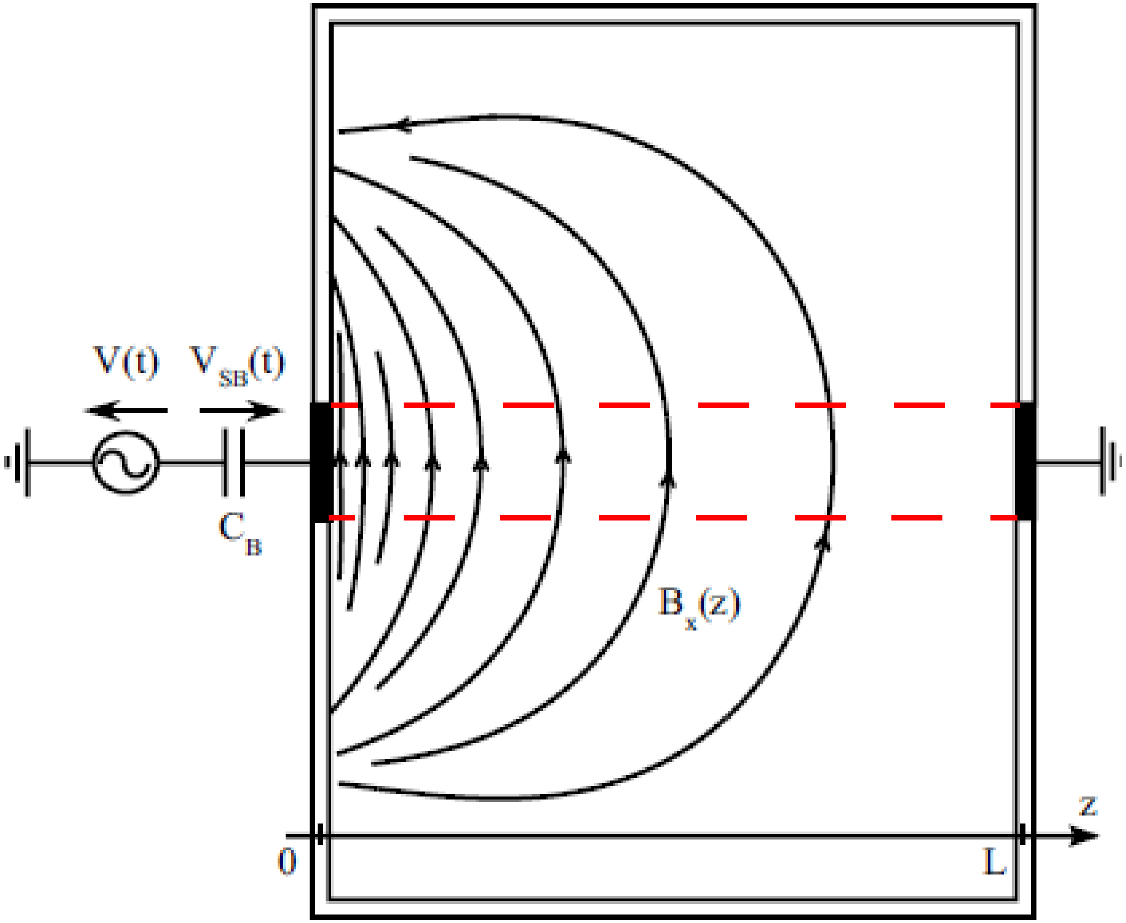


Electrically asymmetric CCP discharges

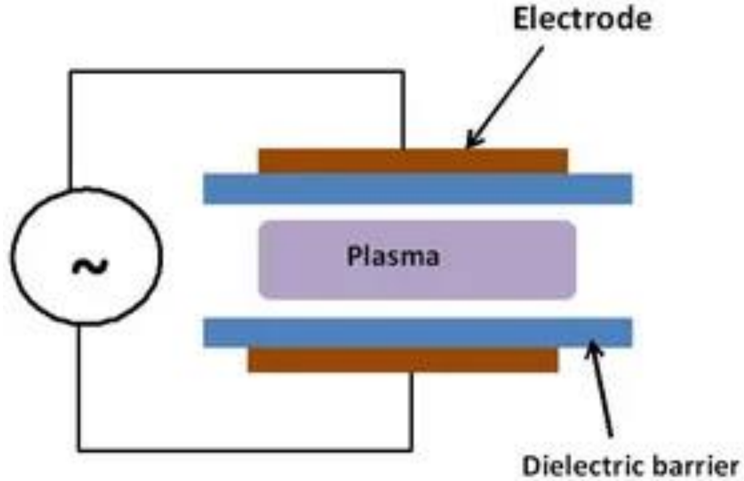


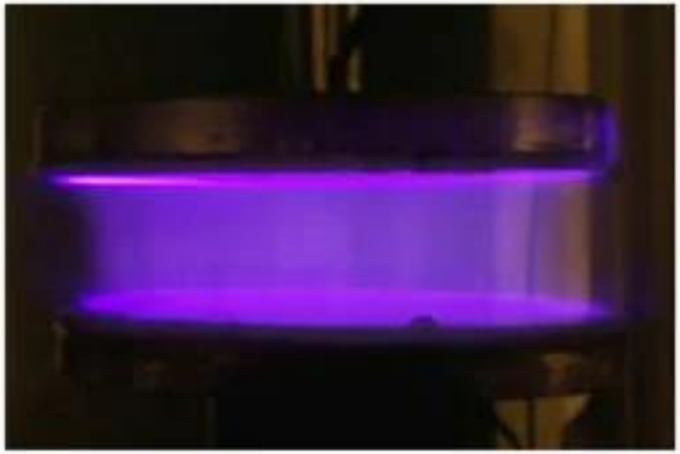
J. Schulze et al, Ruhr University Bochum

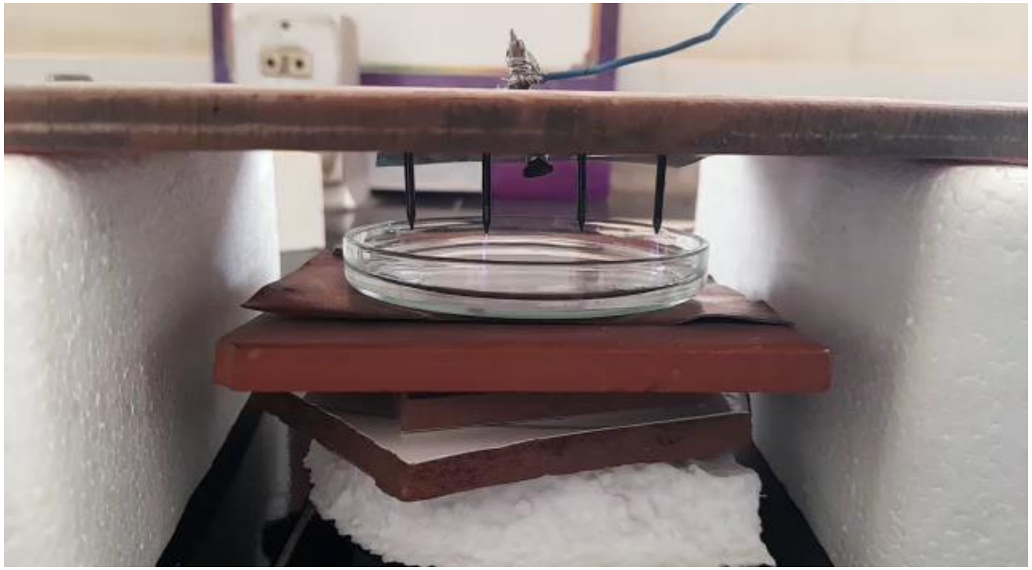
RF Magnetron



Dielectric barrier discharge







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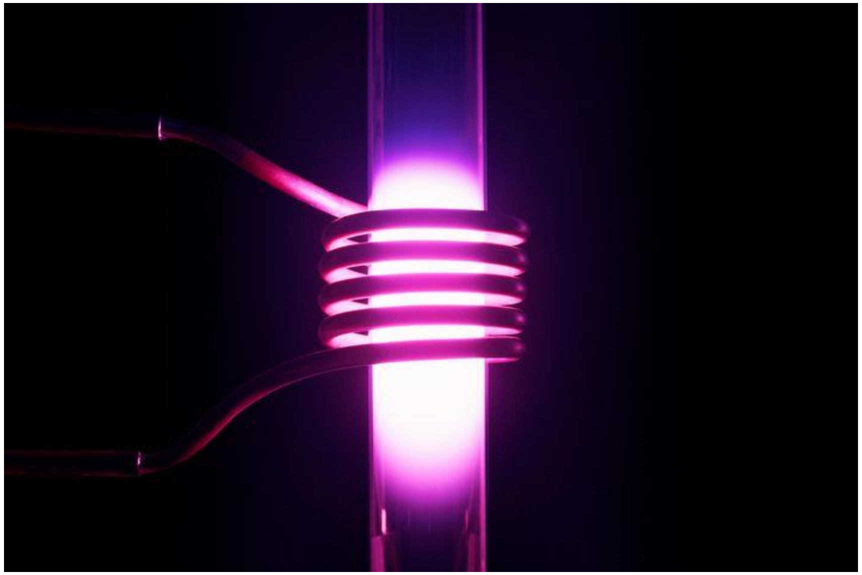
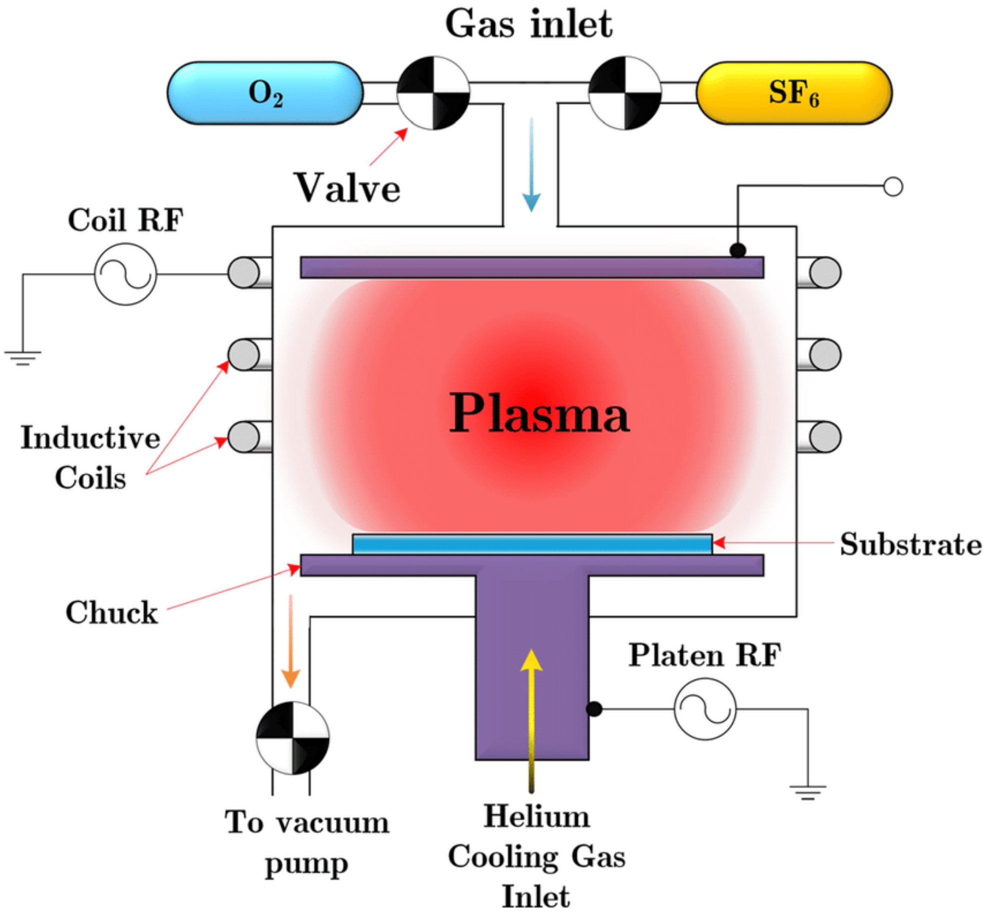
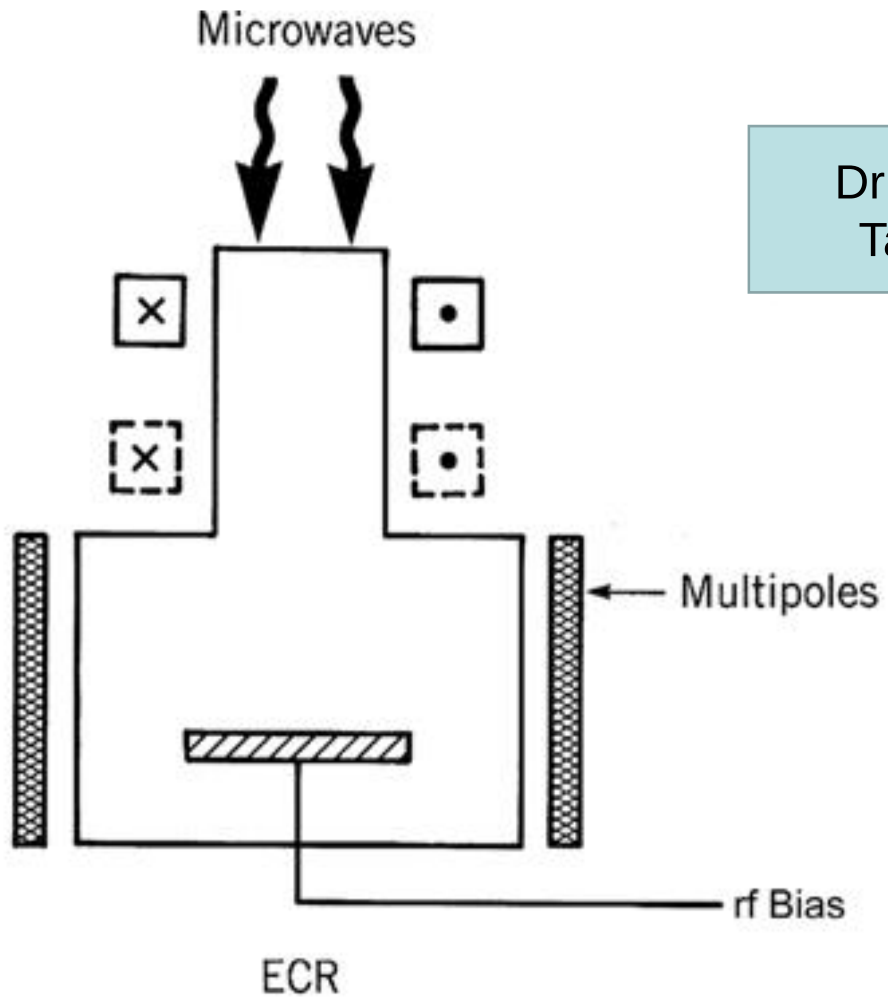
Inductive coupled plasma





High density sources (ECR)



Dr Shrouk Elashry
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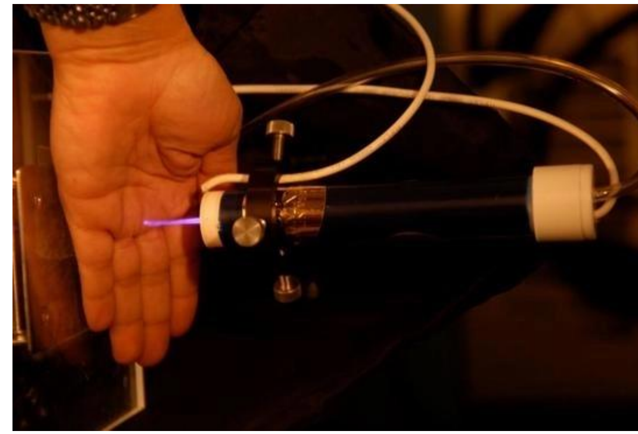
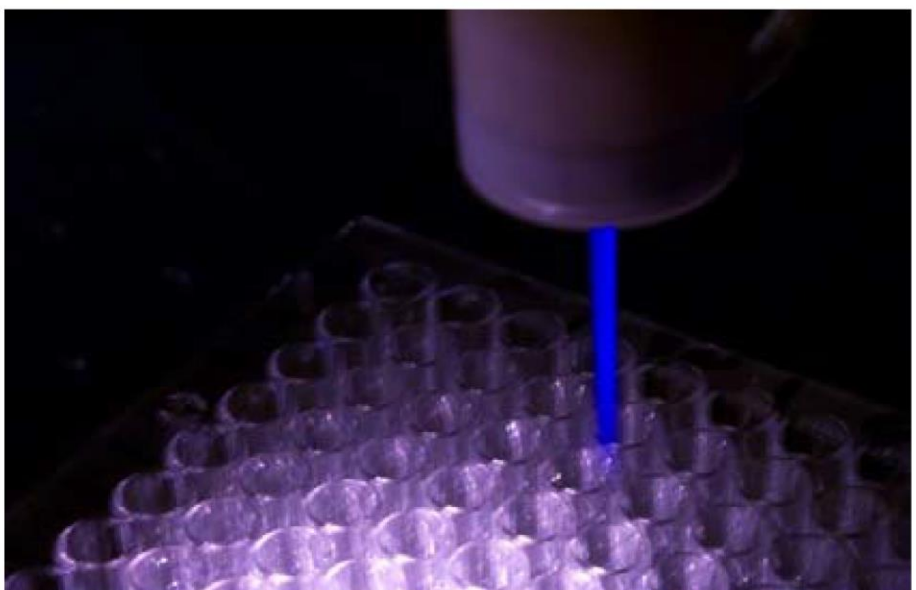
Plasma jets

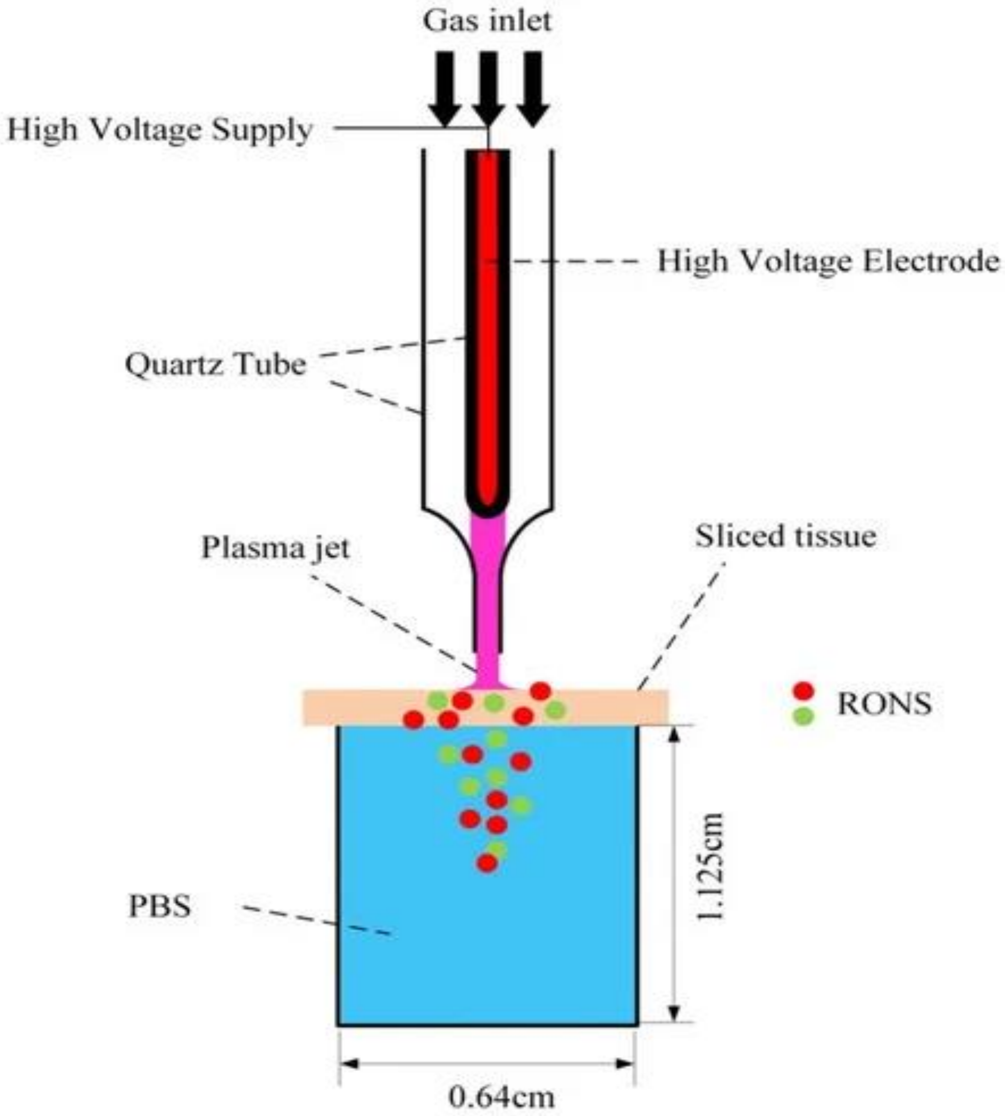




(a)

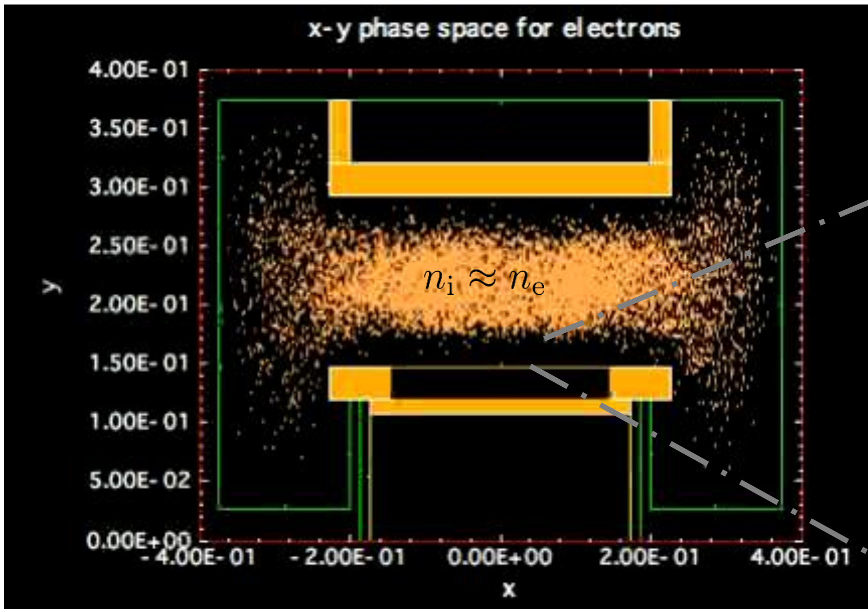
(b)

Plasma jets

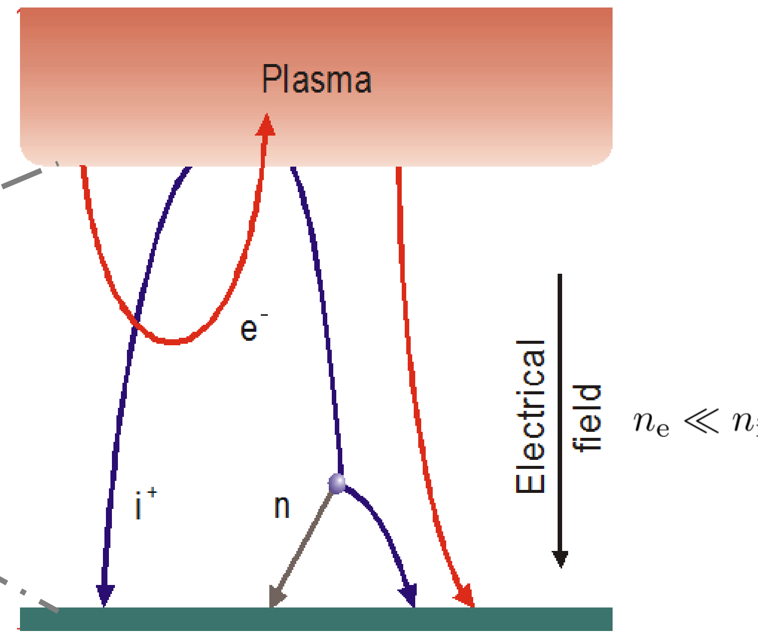


Gas inlet
High Voltage Supply
High Voltage Electrode
Quartz Tube
Plasma jet
Sliced tissue
RONS
PBS
1.125cm
0.64cm

Plasma sheaths



TET



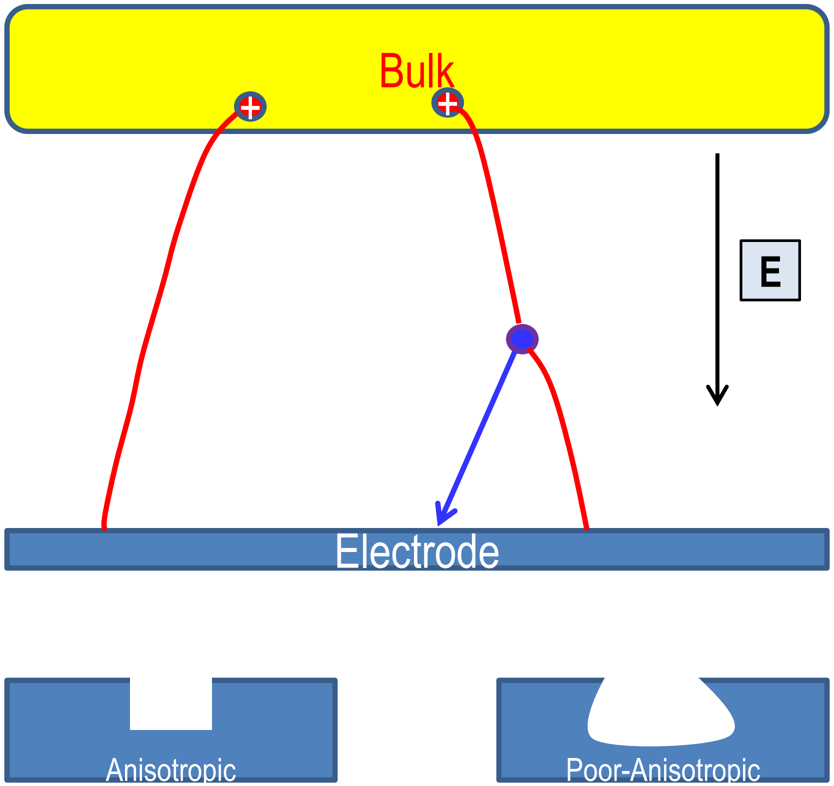
- RF sheaths:
  - High frequency regime
  - Intermediate frequency regime
  - Low frequency regime

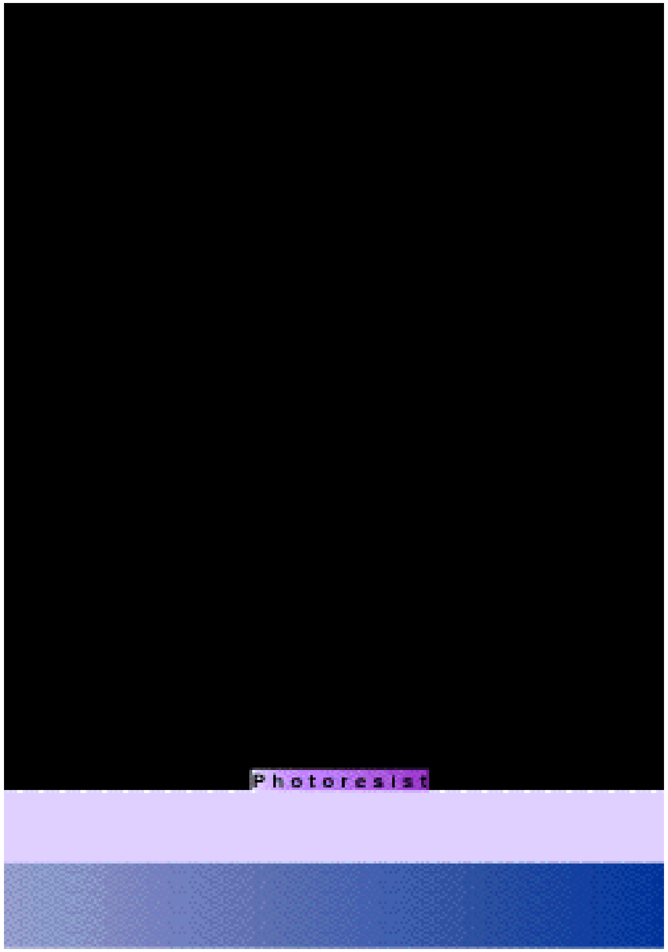
$$\omega_{RF} \gg \omega_{pi} \qquad n_i(x) \Leftrightarrow \bar{E}(x)$$

$$\omega_{RF} \approx \omega_{pi}$$

$$\omega_{RF} \ll \omega_{pi} \qquad n_i(x,t) \Leftrightarrow E(x,t)$$

Plasma Processing





Intel

Plasma Chemistry

- **Dissociation of feedstock gas into active neutral free radicals:**

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$$e^- + CF_4 \rightarrow CF_2 + 2F + e^-$$

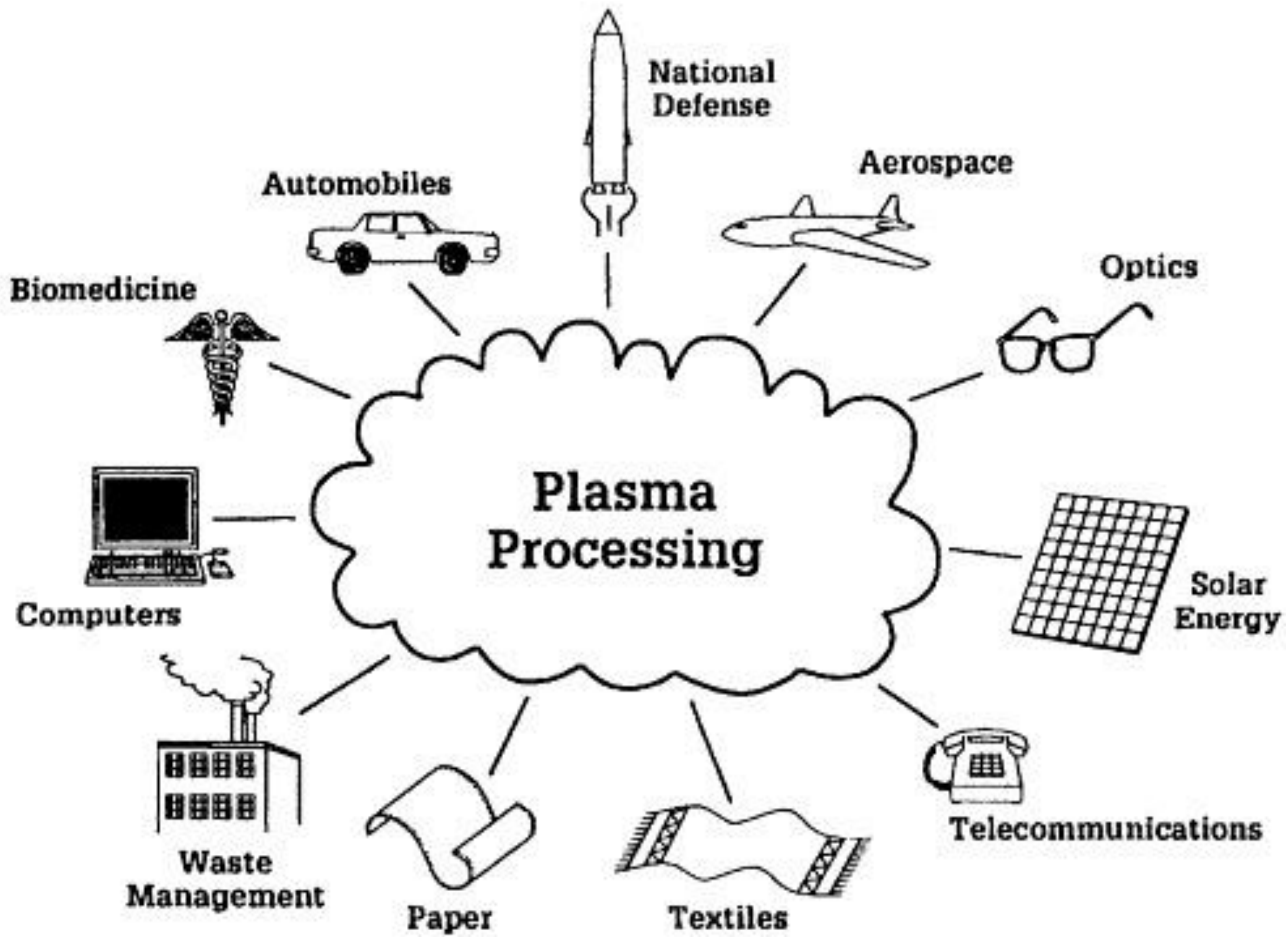
$$e^- + CF_4 \rightarrow CF + F_2 + F + e^-$$

- **Dissociation of the free radicals**

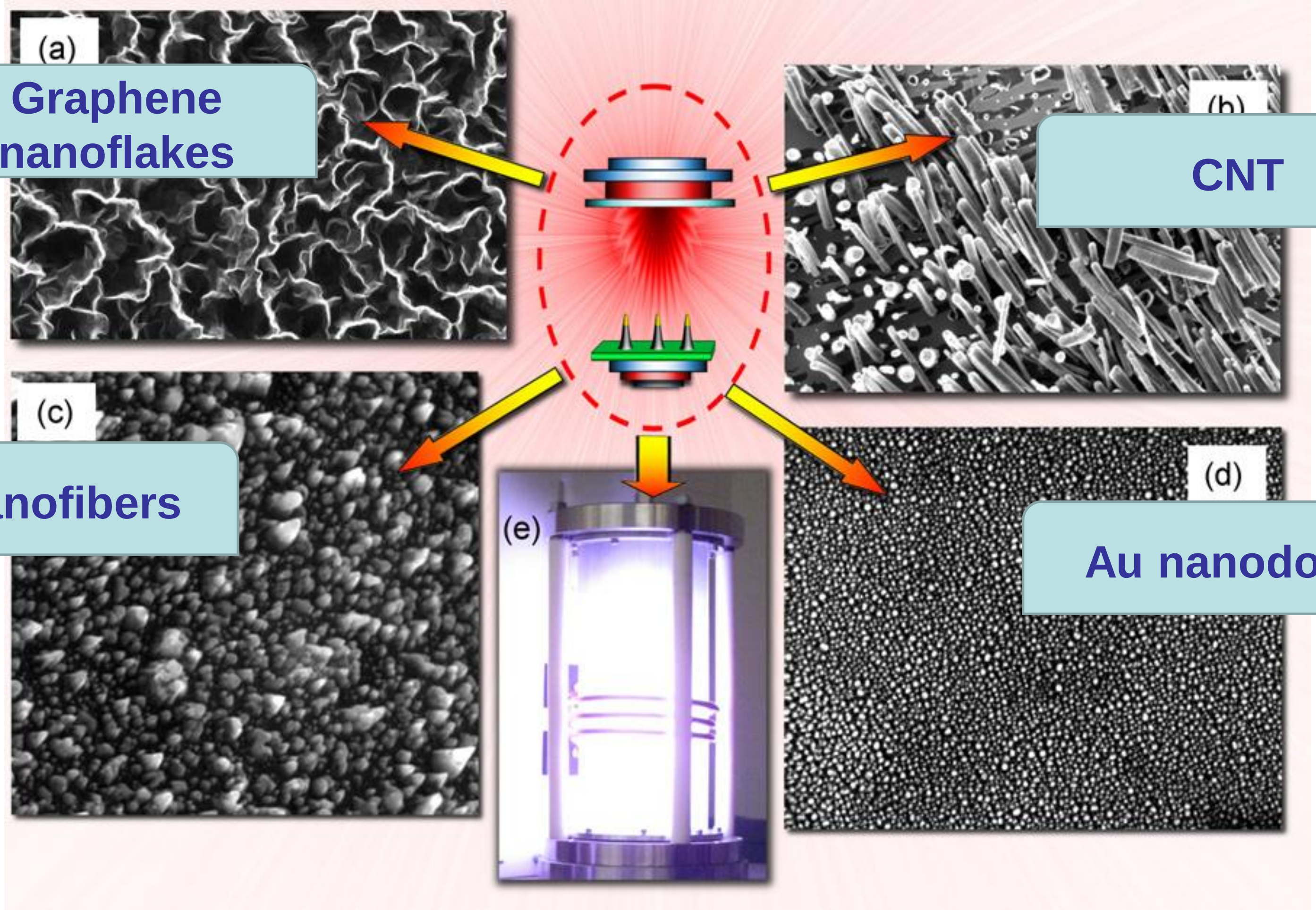
$$e^- + CF_3 \rightarrow CF_2 + F + e^-$$

$$e^- + CF_2 \rightarrow CF + F + e^-$$

Various applications

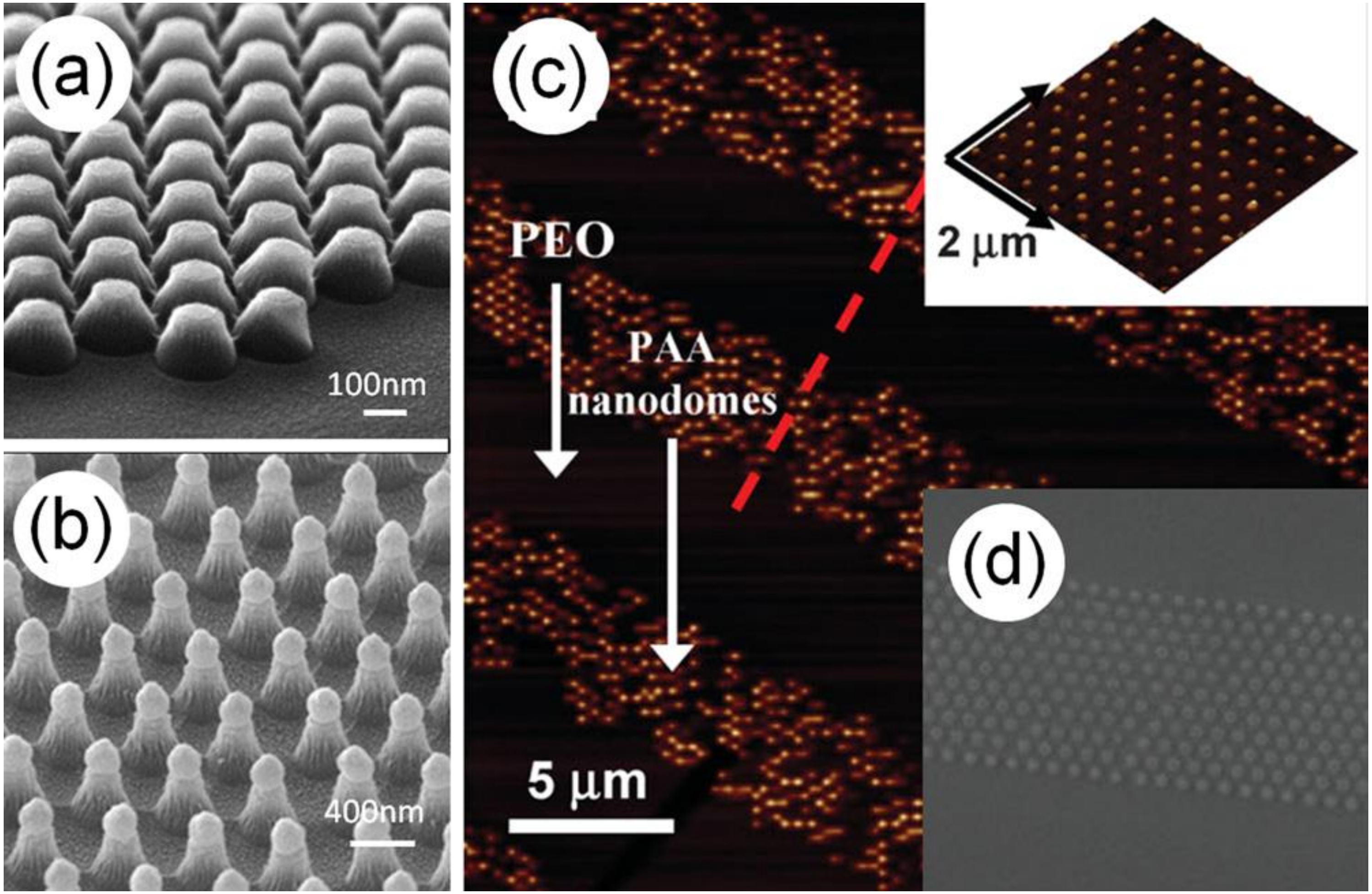


Plasma & Nanotechnology



Han etal, J. Phys. D: Appl. Phys. **44** (2011) 174019

Nano-Patterns



Ostrikov etal, J. Phys. D: Appl. Phys. **44** (2011) 174001

Challenges of plasma simulation

- The most accurate method is to solve the equation of motion of each particle in the plasma.

$$m\frac{d\vec{v}_k}{dt} = e\vec{E}_k + e\vec{v}_k \times \vec{B}_k$$

- No. of particles is very very large $n = 10^9 - 10^{13}\mathrm{cm}^{-3}$
- Maxwell equations

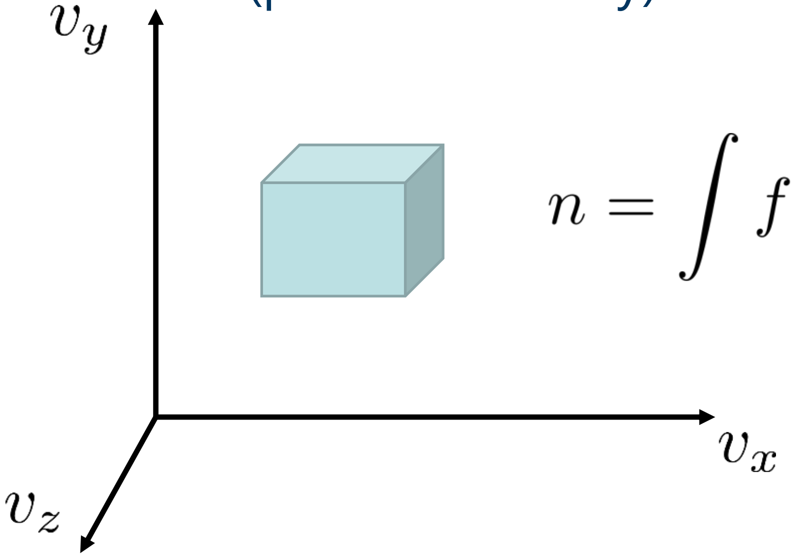
$$\vec{\nabla} \cdot \vec{D} = \rho_v \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{H} = \vec{J} + \epsilon\frac{\partial \vec{E}}{\partial t}$$

- The collective behaviour and the huge number of particles make the solution impossible in such way.

The distribution function

- The distribution function gives the number of particles per unit volume (particles density) with speed v as a function of time.



$$n = \int f(r, v, t) d^3 v$$

- The kinetic equation is an integro- deffrential equations in 7 parameters

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f + \vec{a} \cdot \vec{\nabla}_v f = \text{collision} \;\; \text{terms}$$

Macroscopic description

- Instead of known the physical parameters of each particle, one can calculate the average values for the whole plasma system.

- Average plasma density

$$\bar{n} = \int f(r, v, t) d^3 v$$

- Average speed

$$\bar{v} = \int v f(r, v, t) d^3 v / \bar{n}$$

- Kinetic energy

$$\bar{E}_k = \int \frac{1}{2} m v^2 f(r, v, t) d^3 v / \bar{n}$$

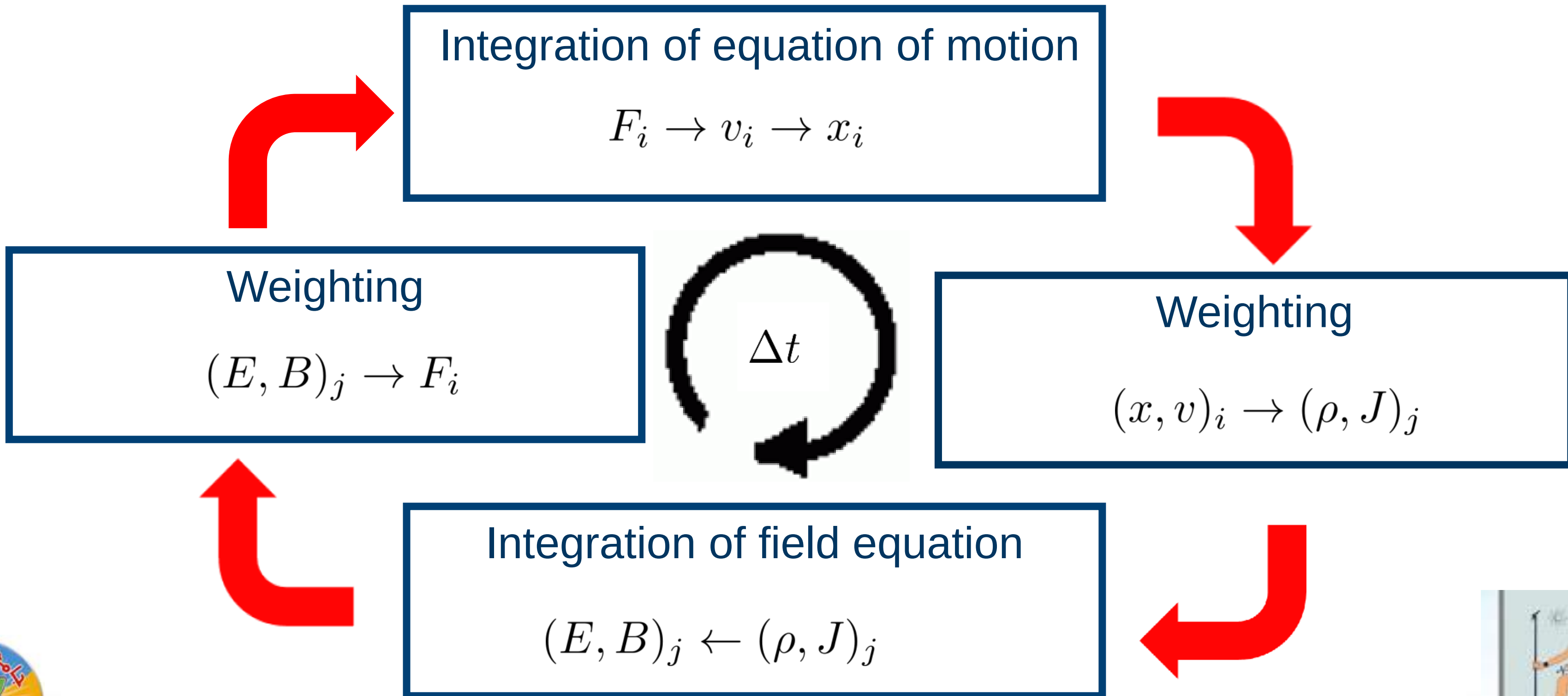
- Avergaes over Boltzman equation

$$m v^q \left(\frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f + \vec{a} \cdot \vec{\nabla}_v f\right) = \text{collision terms}$$

$$q = 0, 1, 2, 3, \ldots$$

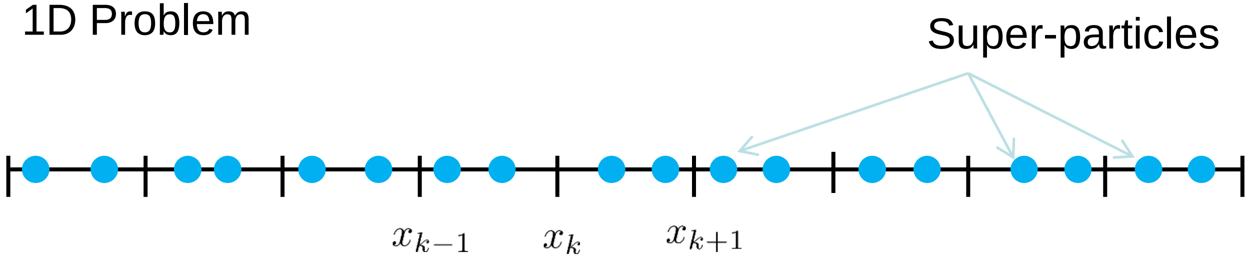
Kinetic Description

- Kinetic means „of or relating to motion“.
  - It is impractical to solve the equation of motion of all plasma particles.
  - Boltzman equation is an integro-differential equation.
- Particle-in-Cell : Super particle $10^6 - 10^9$ real particles.

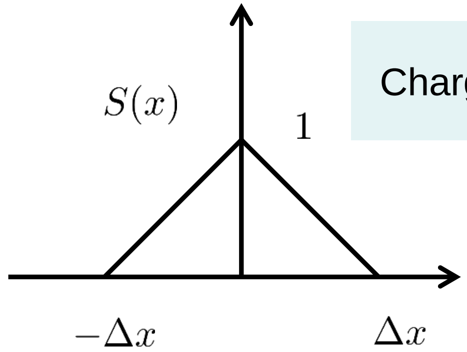


Particles

1D Problem

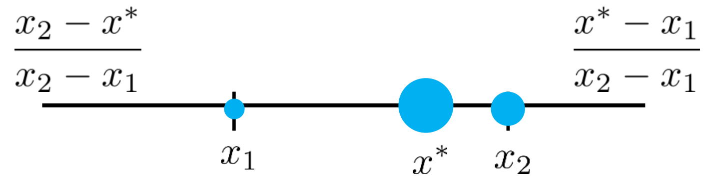


Simulation domain



Charge cloud

First order wieghting



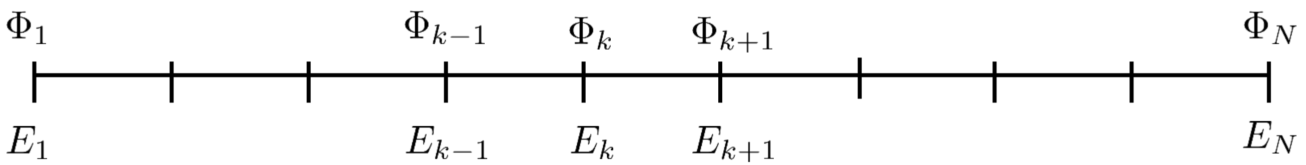
Fields

Poisson's eq.

$$\nabla^2\Phi = -\frac{\rho}{\epsilon} \quad \longrightarrow \quad \frac{\Phi_{k+1} - 2\Phi_k + \Phi_{k-1}}{\Delta x^2} = -\frac{\rho}{\epsilon}$$

Boundary condition

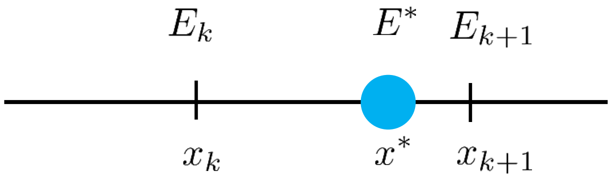
Boundary condition



$$E_1 = -\frac{\Phi_2 - \Phi_1}{\Delta x} - \rho_1 \frac{\Delta x}{2\epsilon} \qquad E_k = -\frac{\Phi_{k+1} - \Phi_{k-1}}{2\Delta x} \qquad E_N = -\frac{\Phi_N - \Phi_{N-1}}{\Delta x} + \rho_N \frac{\Delta x}{2\epsilon}$$

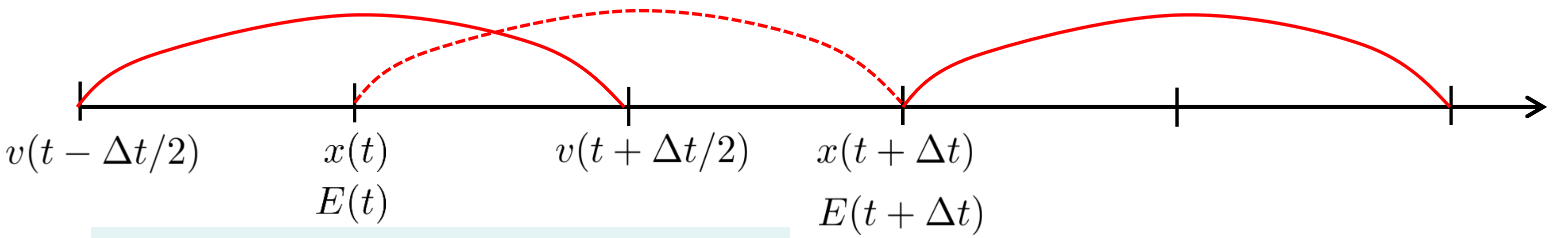
Interpolation of the fields to the particle positions

$$E^* = \frac{x^* - x_k}{\Delta x} E_{k+1} + \frac{x_{k+1} - x^*}{\Delta x} E_k$$



Pushing particles

„Leapfrog“
scheme



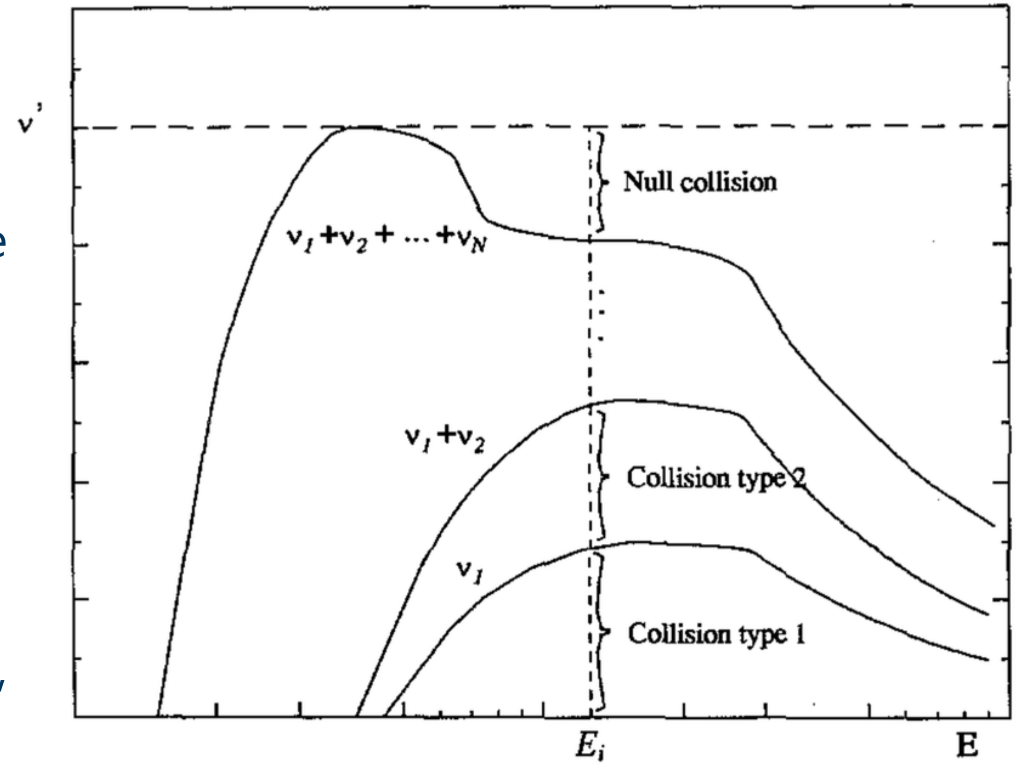
Descritization of equation of motions

$$\frac{v(t+\Delta t/2)-v(t-\Delta t/2)}{\Delta t}=\frac{q}{m}E(t)$$

$$\frac{x(t+\Delta t)-x(t)}{\Delta t}=v(t+\Delta t/2)$$

Monte-Carlo Scheme is required for collisions

Monte Carlo: null collision method



- Many collisions take place:
  impact ionization, charge exchange
  hard-shere, …
- Let the probability of them
  P1,P2,P3,P4, …
- Claculate the total probabilities PT
- Calculate relative probabilities
  P1/PT, P2/PT, P3/PT, P4/PT,

- Generate a random number between [0,1]
- if P1/PT= < The randum number<(P1+P2)/PT
- Event 1 takes place
- If not
  (P1+ P2)/PT= < The randum number<(P1+P2+P3)/PT
- ……..

Challenges of PIC simulation

- Numerical instabilities:
  - Accuracy criterion $\omega_p \Delta t \leq 0.2$
  - Courant criterion $v_{\max} \Delta t \leq \Delta x$
  - The computational grid has to resolve the Debye lenght $\Delta x \leq \lambda_D$

- In order to have a good statistics, a resonable high number of particles per Debye lenght must be used $N_D \gg 1$

- Keep the probabilty for collisions small

$$P_{\text{coll}} = 1 - e^{-\nu t} \leq 0.1$$

- Alternatives:
  - Implicit schems
  - Parrallilization

Fluid Models

- Continuity, momentum, and energy equations are closed with Poisson's equation

$$\frac{\partial n_{\mathrm{e,i,m}}}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_{\mathrm{e,i,m}} = G_{\mathrm{e,i,m}} - L_{\mathrm{e,i,m}},$$

$$\vec{\Gamma}_{\mathrm{e,i,m}} = \mathrm{sign}(q_{\mathrm{e,i,m}})\ n_{\mathrm{e,i,m}}\ \mu_{\mathrm{e,i,m}}\ \vec{E} - D_{\mathrm{e,i,m}} \vec{\nabla} n_{\mathrm{e,i,m}},$$

$$\frac{\partial n_{\mathrm{e}} T_{\mathrm{e}}}{\partial t} = -\vec{\nabla} \cdot \left(\frac{5}{3} T_{\mathrm{e}} \vec{\Gamma}_{\mathrm{e}} - \frac{5}{3} n_{\mathrm{e}} D_{\mathrm{e}} \vec{\nabla} T_{\mathrm{e}}\right) - e\vec{\Gamma}_{\mathrm{e}} \cdot \vec{E} - n_{\mathrm{e}} n_{\mathrm{G}} k_{\mathrm{loss}},$$

and

$$T_{\mathrm{i}} = T_{\mathrm{m}} = 0.026\ eV.$$

Fluid Models

Ar atomic processes considered in the simulation

Equation of Reaction	Rate of Reaction Coefficient	
$e + Ar \rightarrow Ar^{+} + 2e$	impact-ionization	$K_{ei} = 1.253 \times 10^{-7} \exp(-18.618/T_e)\ cm^3/s$
$e + Ar \rightarrow Ar^{*} + e$	collisional-excitation	$Kex = 3.712 \times 10^{-8} \exp(-15.06/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar^{+} + 2e$	impact-ionization	$K_{mi} = 2.05 \times 10^{-7} \exp(-4.95/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar + e$	collisional-deexcitation	$K_{em} = 1.818 \times 10^{-9} \exp(-2.14/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar^{r} + e$	radiative-deexcitation	$K_r = 2 \times 10^{-7}\ cm^3/s$
$Ar^{*} + Ar^{*} \rightarrow Ar^{+} + Ar + e$	collisional-ionization	$K_{mm} = 6.2 \times 10^{-10}\ cm^3/s$
$Ar^{*} + Ar \rightarrow 2Ar$	collisional-deexcitation	$K_{2q} = 3.0 \times 10^{-15}\ cm^3/s$
$Ar^{*} + 2Ar \rightarrow Ar + Ar_2$	attachment	$K_{3q} = 1.1 \times 10^{-31}\ cm^6/s$

Main reactions and the corresponding rate coefficients in the Ar/CF_4 discharge plasma.

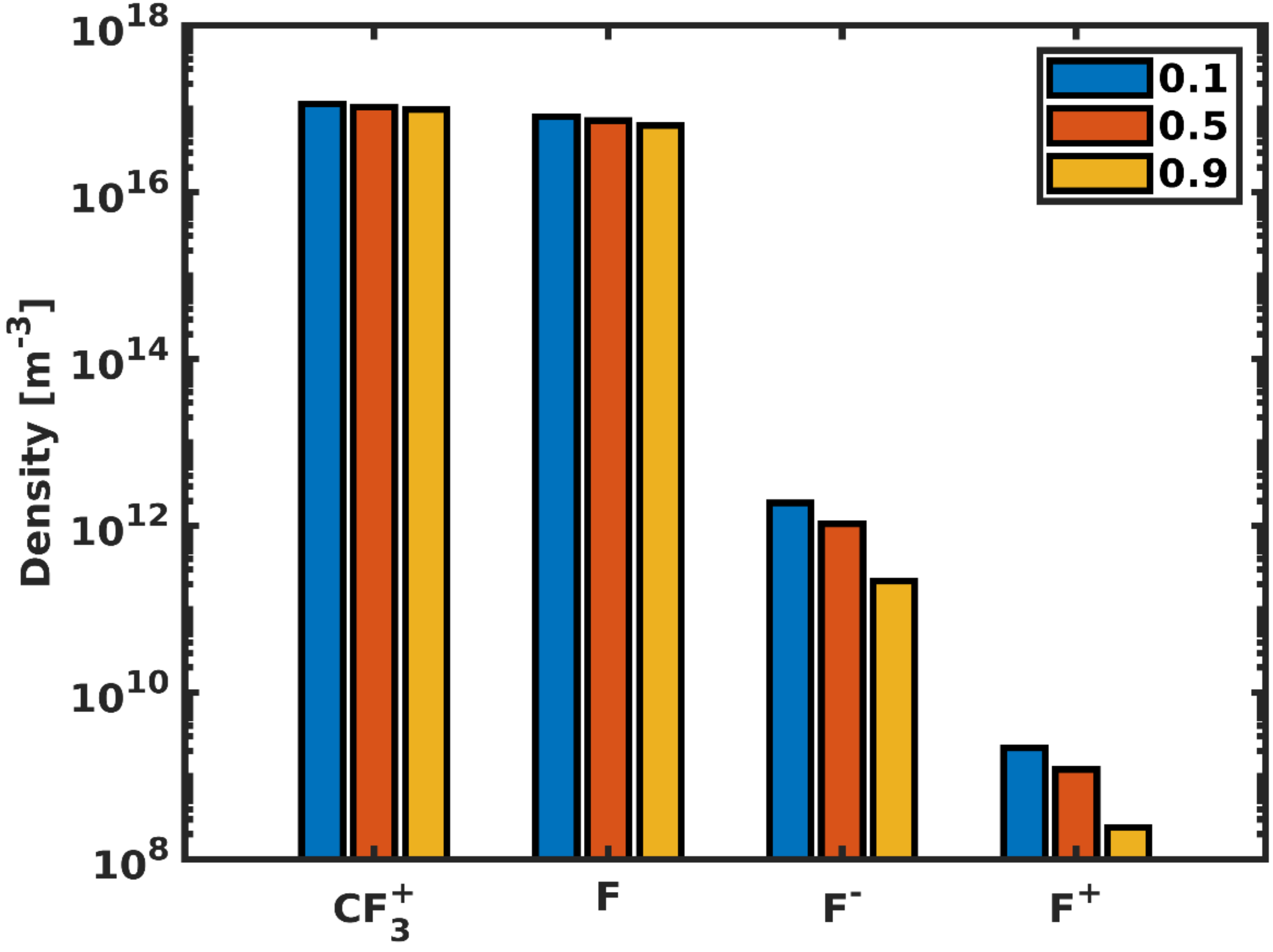
Reaction equation	Reaction rate coefficient
$CF_3^- + Ar^+ \rightarrow CF_3 + Ar$	1×10^{-7} cm^3 s^{-1}
$F^- + Ar^+ \rightarrow F + Ar$	1×10^{-7} cm^3 s^{-1}
$CF_4 + Ar^+ \rightarrow CF_3^+ + F + Ar$	9.58×10^{-10} cm^3 s^{-1}
$Ar + CF_3^+ \rightarrow CF_3 + Ar^+$	1×10^{-9} cm^3 s^{-1}

Chengjie Bai *et al* 2018 *J. Phys. D: Appl. Phys.* 51 255201

Main reactions and the corresponding reaction rate coefficients in the CF_4 discharge plasma.

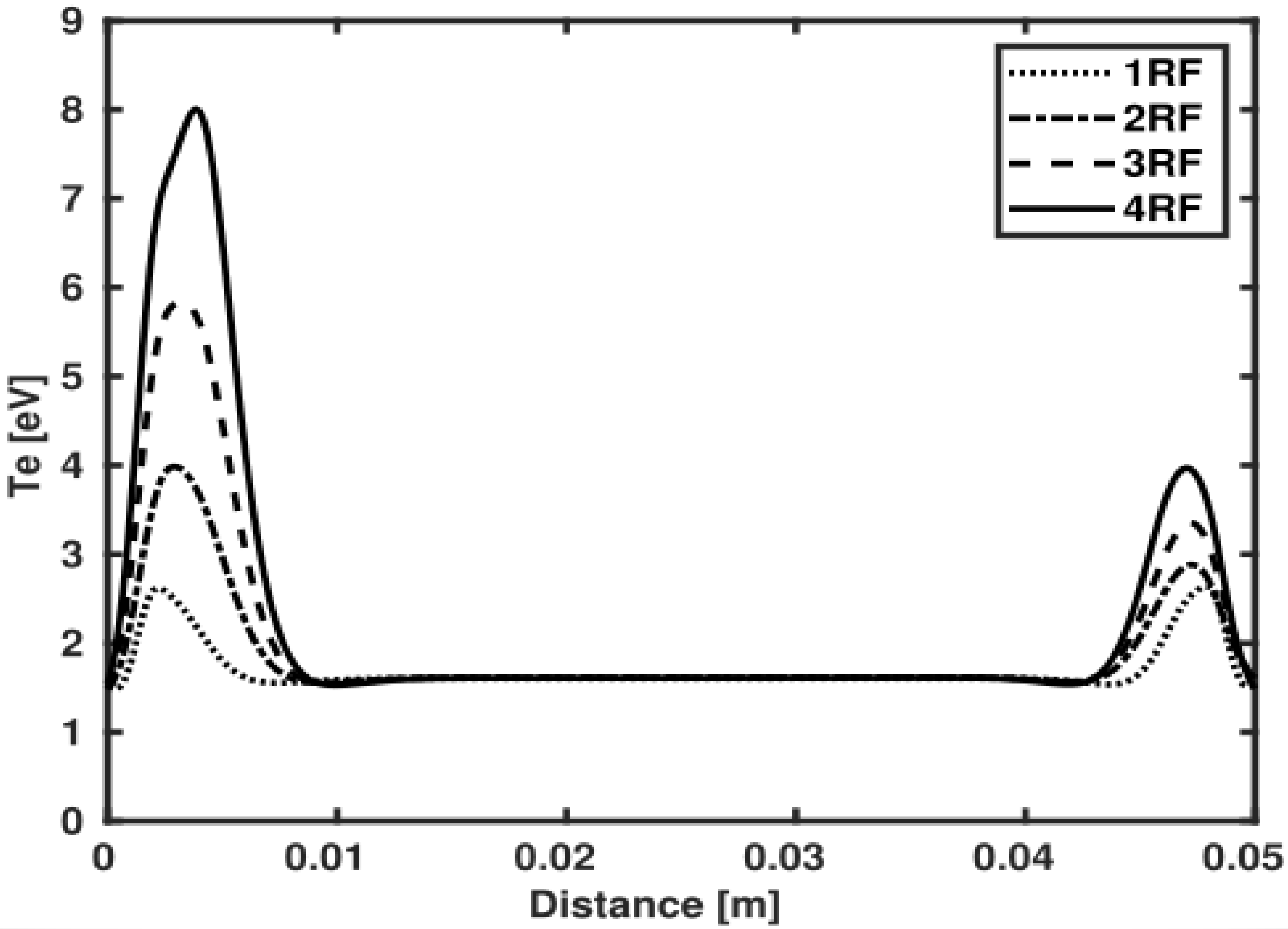
Reaction equation	Reaction rate coefficient
$CF_4 + e \rightarrow CF_4^+ + 2e$	Calculated by BOLSIG+
$CF_3 + e \rightarrow CF_3^+ + 2e$	$1.4 \times 10^{-11}(11\,605 \times T_e)^{0.6481}\exp(-9.8/T_e)$ cm^3 s^{-1}
$F + e \rightarrow F^+ + 2e$	$7.489 \times 10^{-13}(11\,605 \times T_e)^{0.8595}\exp(-17.6/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_4^*(12.5\,eV) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4^*(8\,eV) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4(V13) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4(V24) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_3^+ + F + 2e$	$1.159 \times 10^{-11}(11\,605 \times T_e)^{0.7645}\exp(-17.2/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_2^+ + F_2 + 2e$	$2.886 \times 10^{-11}(11\,605 \times T_e)^{0.5108}\exp(-22.8/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF^+ + F_2 + F + 2e$	$2.296 \times 10^{-14}(11\,605 \times T_e)^{1.09}\exp(-27.0/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3 + F^+ + 2e$	$1.482 \times 10^{-13}(11\,605 \times T_e)^{0.9375}\exp(-34.7/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3 + F + e$	$2 \times 10^{-9}\exp(-13/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_2 + 2F + e$	$5 \times 10^{-9}\exp(-13/T_e)$ cm^3 s^{-1}
$CF_3 + F^- \rightarrow CF_4 + e$	5×10^{-10} cm^3 s^{-1}
$CF_2 + F^- \rightarrow CF_3 + e$	5×10^{-10} cm^3 s^{-1}
$CF + F^- \rightarrow CF_2 + e$	5×10^{-10} cm^3 s^{-1}
$CF_3 + F \rightarrow CF_4$	2×10^{-11} cm^3 s^{-1}
$CF_2 + F \rightarrow CF_3$	1.3×10^{-11} cm^3 s^{-1}
$CF + F \rightarrow CF_2$	5.2×10^{-15} cm^3 s^{-1}
$CF_3^- + CF_3^+ \rightarrow 2CF_3$	4×10^{-7} cm^3 s^{-1}
$F^- + CF_3^+ \rightarrow F + CF_3$	4×10^{-7} cm^3 s^{-1}
$F^- + CF_2^+ \rightarrow F + CF_2$	$1 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$F^- + CF^+ \rightarrow F + CF$	$1 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$F^- + F^+ \rightarrow F_2$	$4 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$CF_2^+ + e \rightarrow CF + F$	4×10^{-8} cm^3 s^{-1}
$CF^+ + e \rightarrow C + F$	4×10^{-8} cm^3 s^{-1}
$CF_3^+ + e \rightarrow CF_3$	9.6×10^{-7} cm^3 s^{-1}
$F^+ + e \rightarrow F$	4×10^{-8} cm^3 s^{-1}
$CF_4^+ \rightarrow CF_3^+ + F$	3.3×10^{5} s^{-1}
$CF_4 + e \rightarrow CF_3 + F^-$	4.8×10^{-12} cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3^- + F$	3.28×10^{-11} cm^3 s^{-1}
$CF_2 + F_2 \rightarrow CF_3 + F$	4.56×10^{-13} cm^3 s^{-1}
$CF_3 + F_2 \rightarrow CF_4 + F$	1.88×10^{-14} cm^3 s^{-1}
$CF_3^- + F \rightarrow CF_3 + F^-$	5×10^{-8} cm^3 s^{-1}
$2CF_4^*(12.5\,eV) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4^*(8\,eV) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4(V13) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4(V24) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}

The effect of Ar ratios

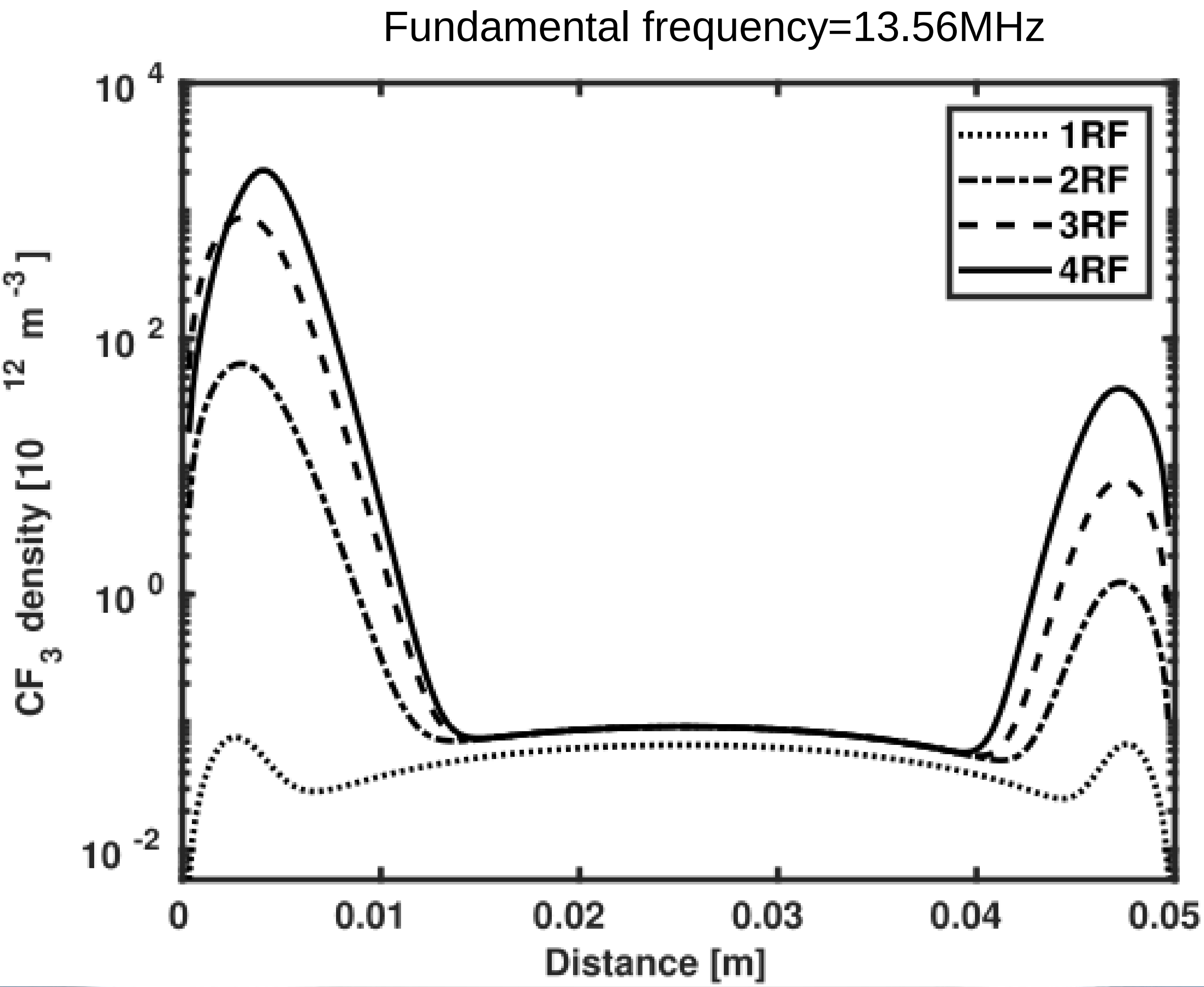


The electron temperature

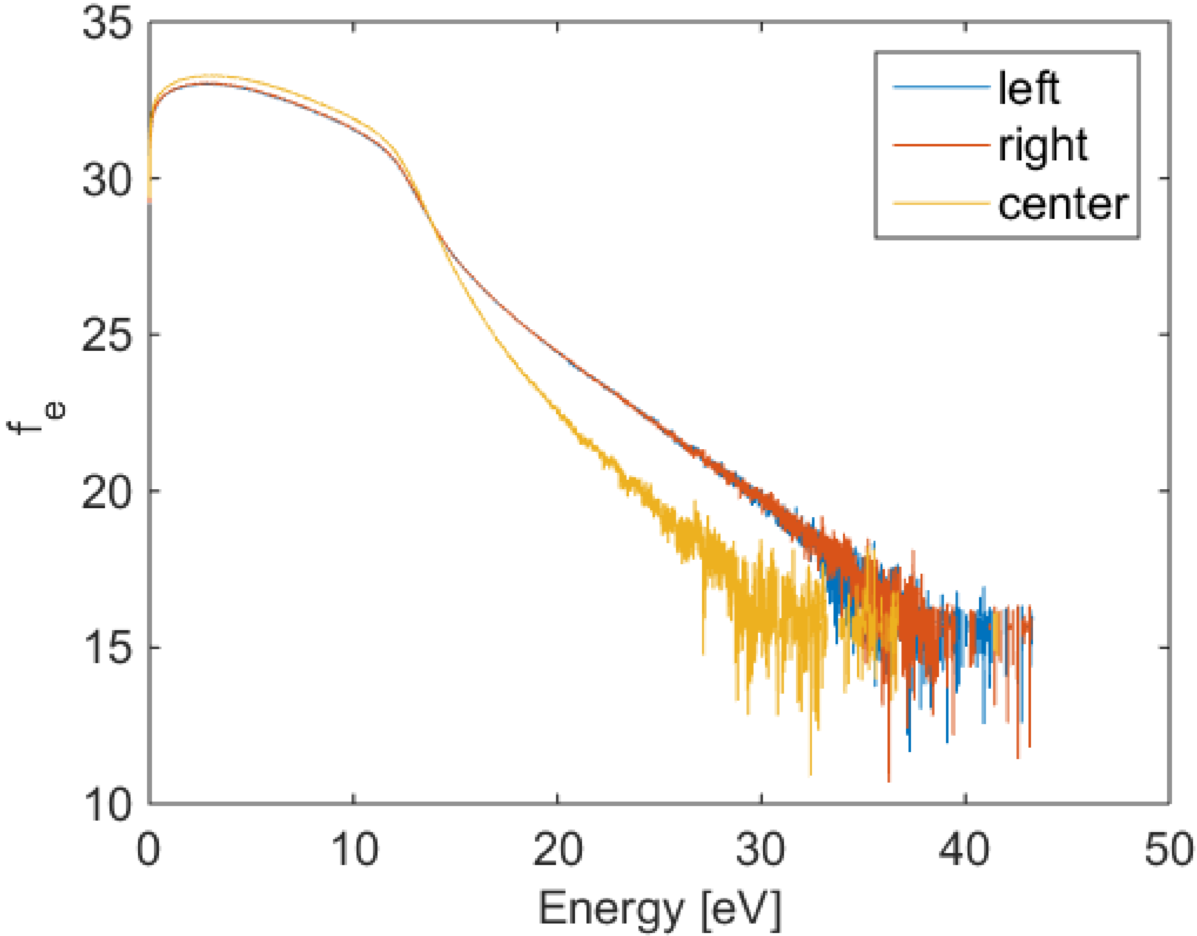
Fundamental frequency=13.56MHz



The density of CF3 Species



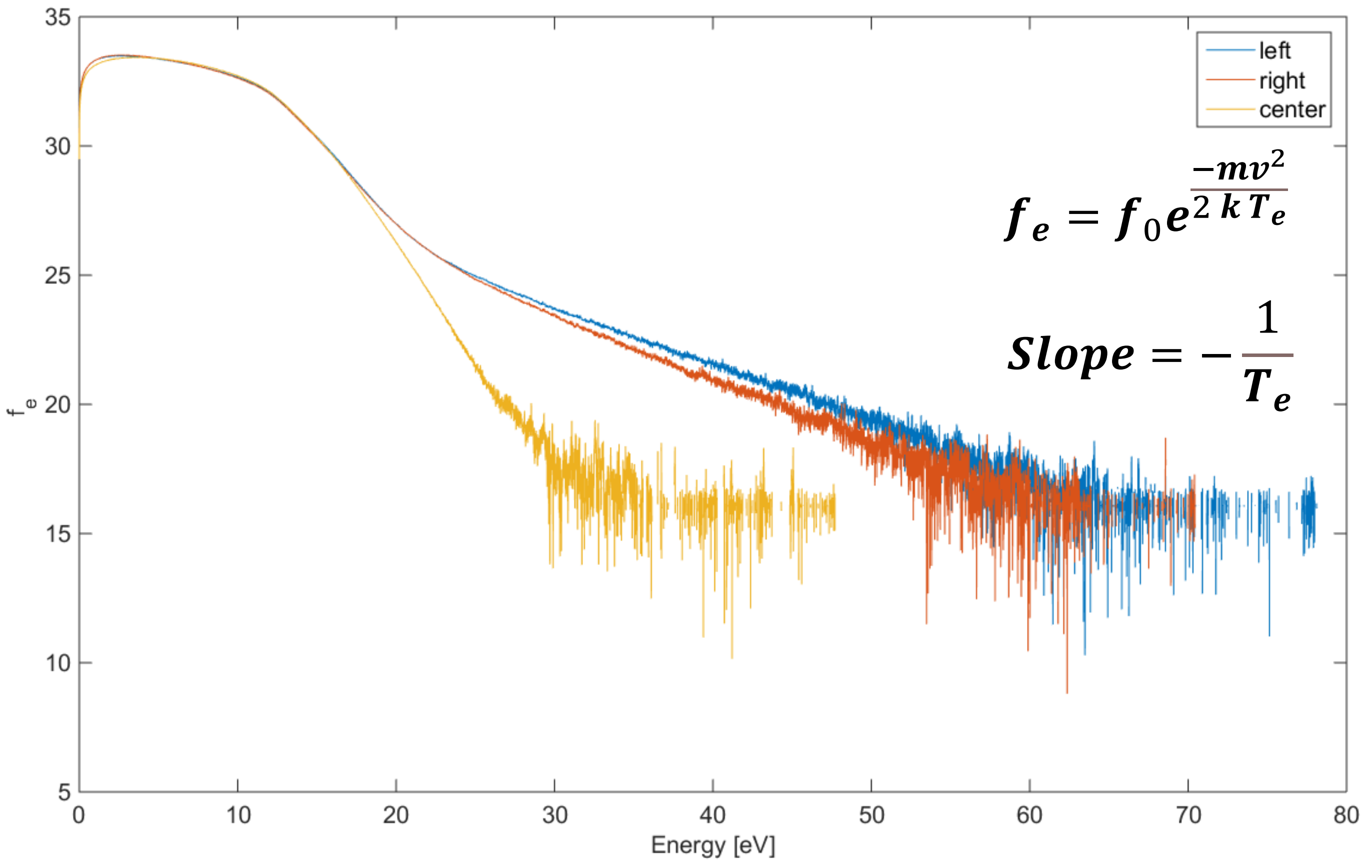
Kinetic Confirmation-Symmetric discharge



$$f_e = f_0 e^{\frac{-mv^2}{2\,k\,T_e}}$$

$$Slope = -\frac{1}{T_e}$$

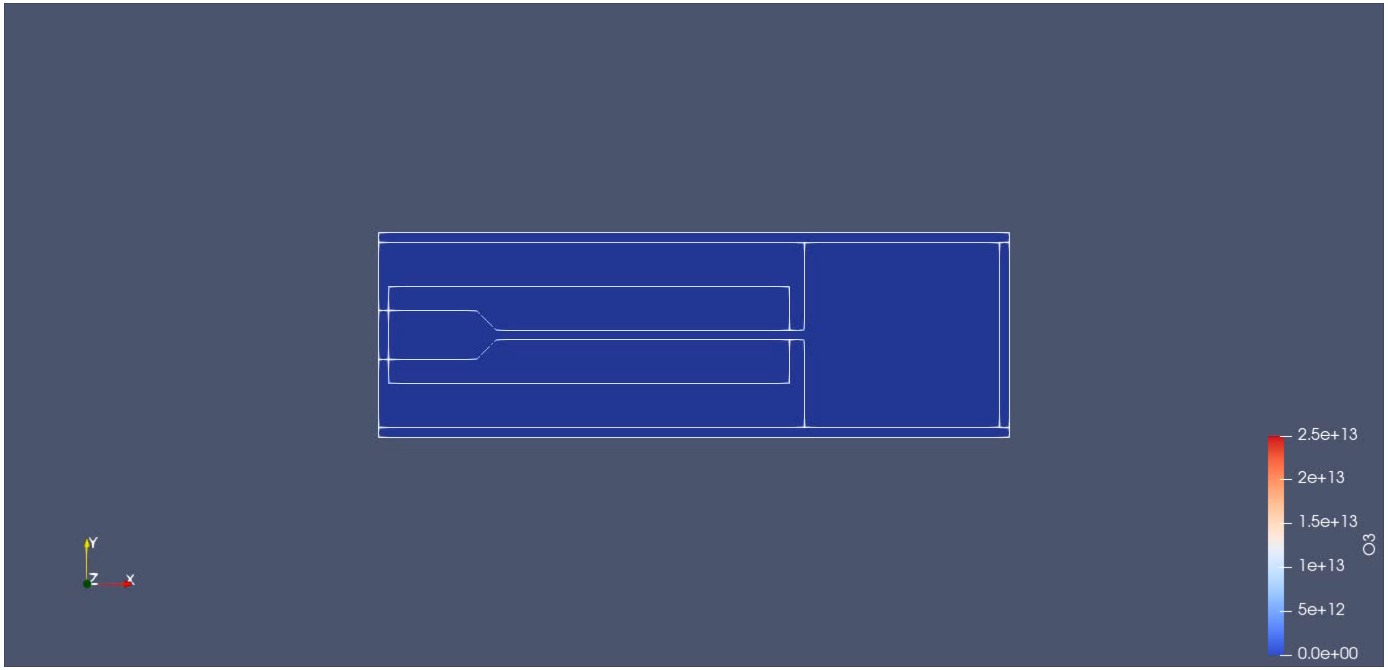
Kinetic Confirmation-Asymmetric discharge



$$f_e = f_0 e^{\frac{-mv^2}{2\,k\,T_e}}$$

$$Slope = -\frac{1}{T_e}$$

Plasma Jets



Ruhr-Universität Bochum
Fakultät für Elektrotechnik und Informationstechnik
Lehrstuhl für Angewandte Elektrodynamik und Plasmatechnik (AEPT)

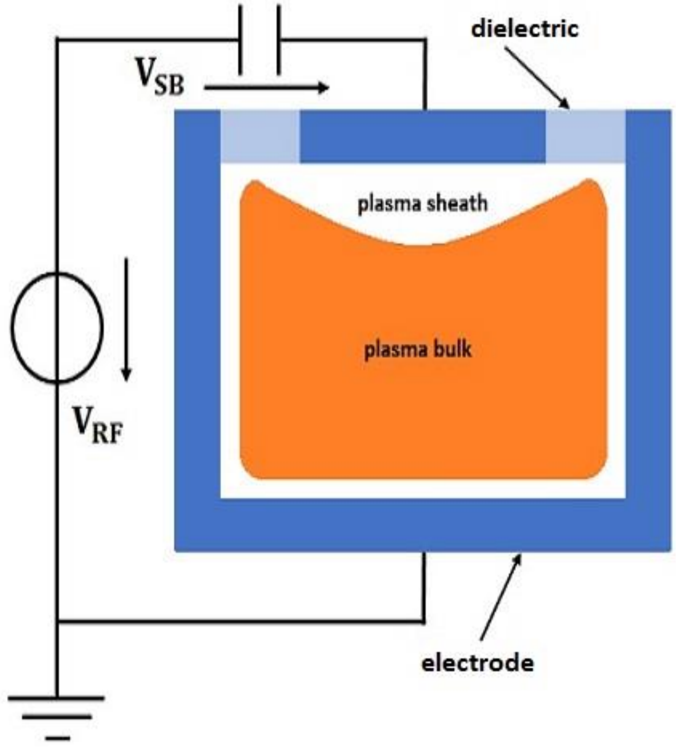
Global model:
Zero dimensional model

$$\frac{\partial n_e}{\partial t} = n_e n_s k_i - n_e n_s k_r - \text{loss term}$$

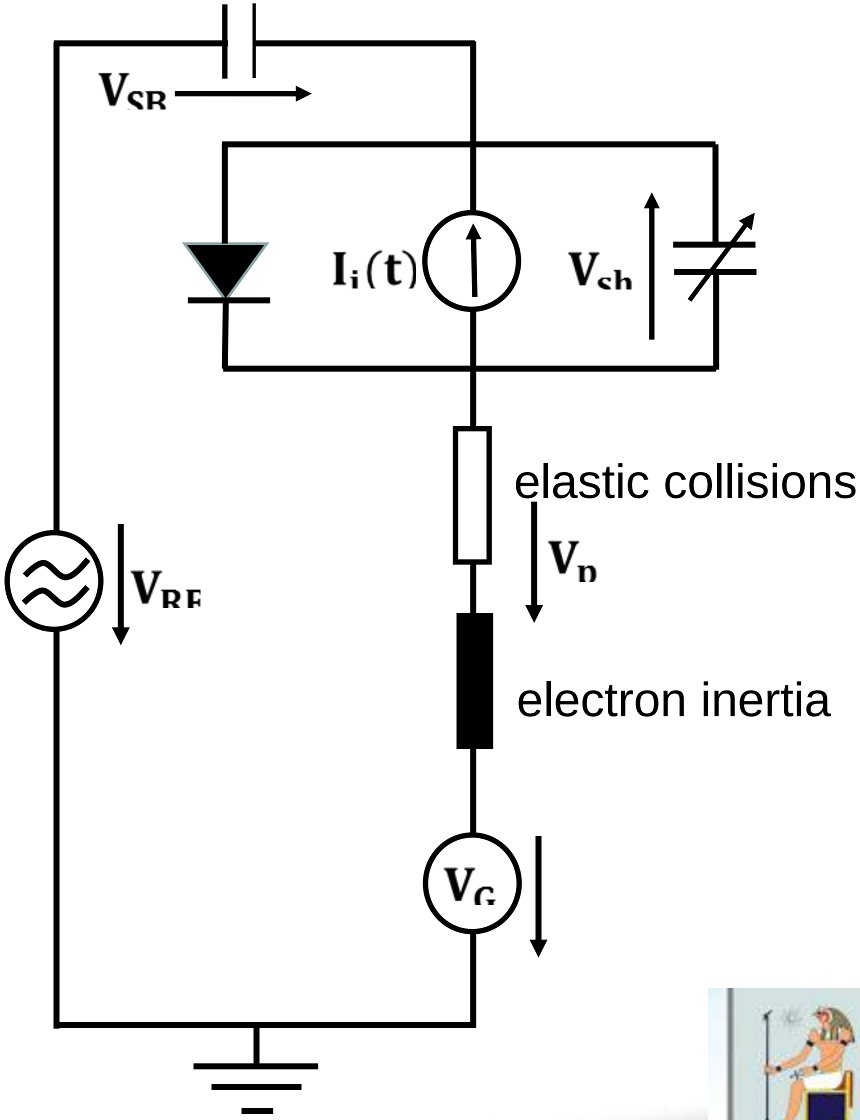
Note

- **If right hand side always positive = Simulation diverge with time**
- **If right hand side always negative= the plasma density vanishes with time**
- **We are looking for balance situation. Comparison with experiments is highely required.**

Global model: Electrical circuit



M. Shihab / Physics Letters A 382 (2018) 1609–1614



Model equations

$$\frac{dQ(t)}{dt} = -I - en_{\mathrm{s}}(t)A_{\mathrm{s}}u_{\mathrm{s}}(t) + en_{\mathrm{B}}\sqrt{(T_{\mathrm{e}}/2\pi m_{\mathrm{e}})}A_{\mathrm{s}}\exp(-eV_{\mathrm{s}}(t)/T_{\mathrm{e}})$$

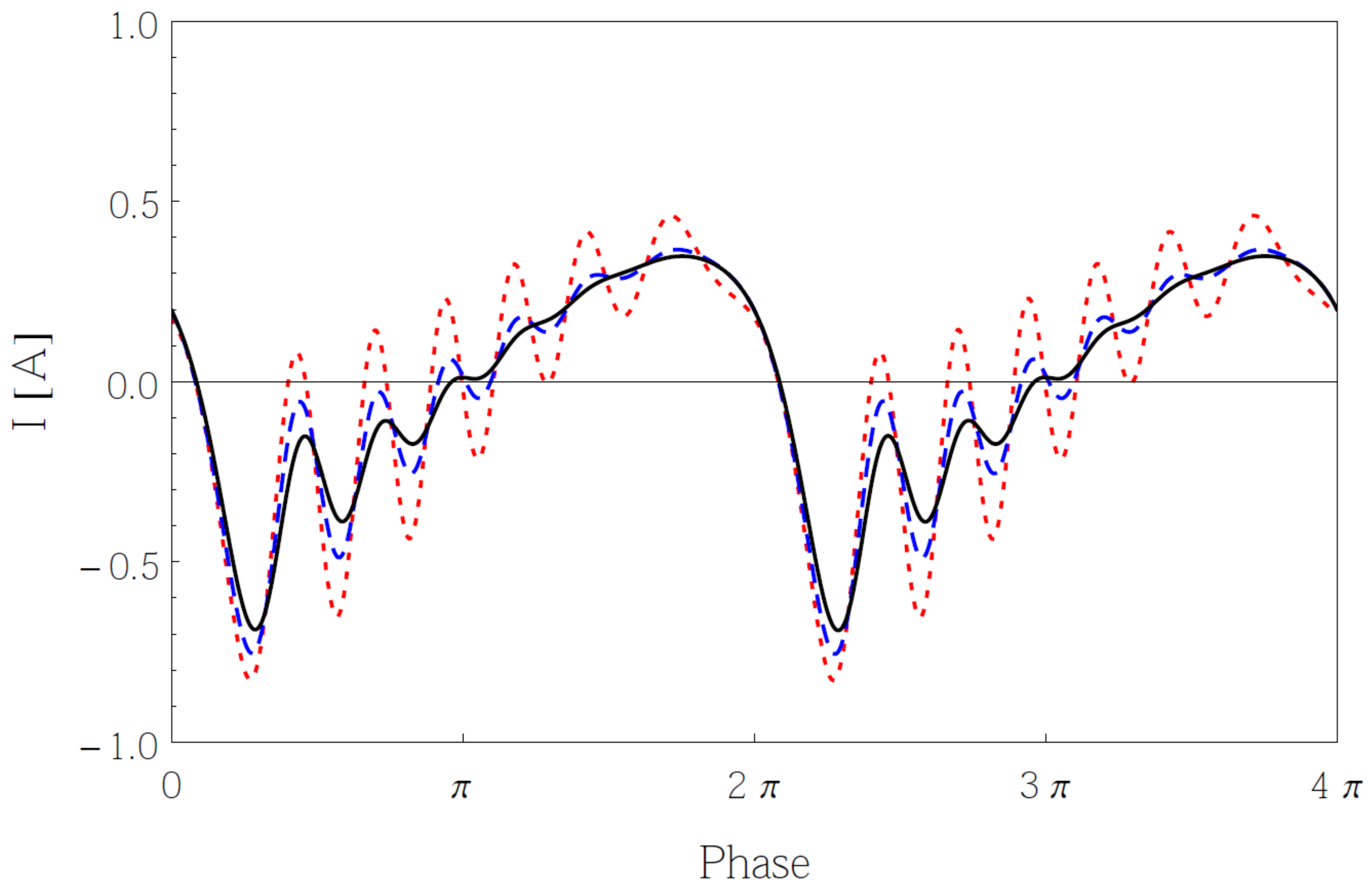
$$V_{\mathrm{s}}(t) = \frac{Q^2(t)}{2\epsilon_0 e n_{\mathrm{s}}(t)A_{\mathrm{s}}^2}$$

$$\frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}}\left(\frac{dI(t)}{dt} + \nu_{\mathrm{eff}}I(t)\right) = V_{\mathrm{s}}(t) - V_{\mathrm{G}} - V_{\mathrm{SB}}(t) + V_{\mathrm{RF}}(t)$$

$$V_{\mathrm{G}} = \frac{T_{\mathrm{e}}}{2e}\ln\left(\frac{m_{\mathrm{i}}}{2\pi m_{\mathrm{e}}}\right)$$

$$C\frac{dV_{\mathrm{SB}}(t)}{dt} = I(t)$$

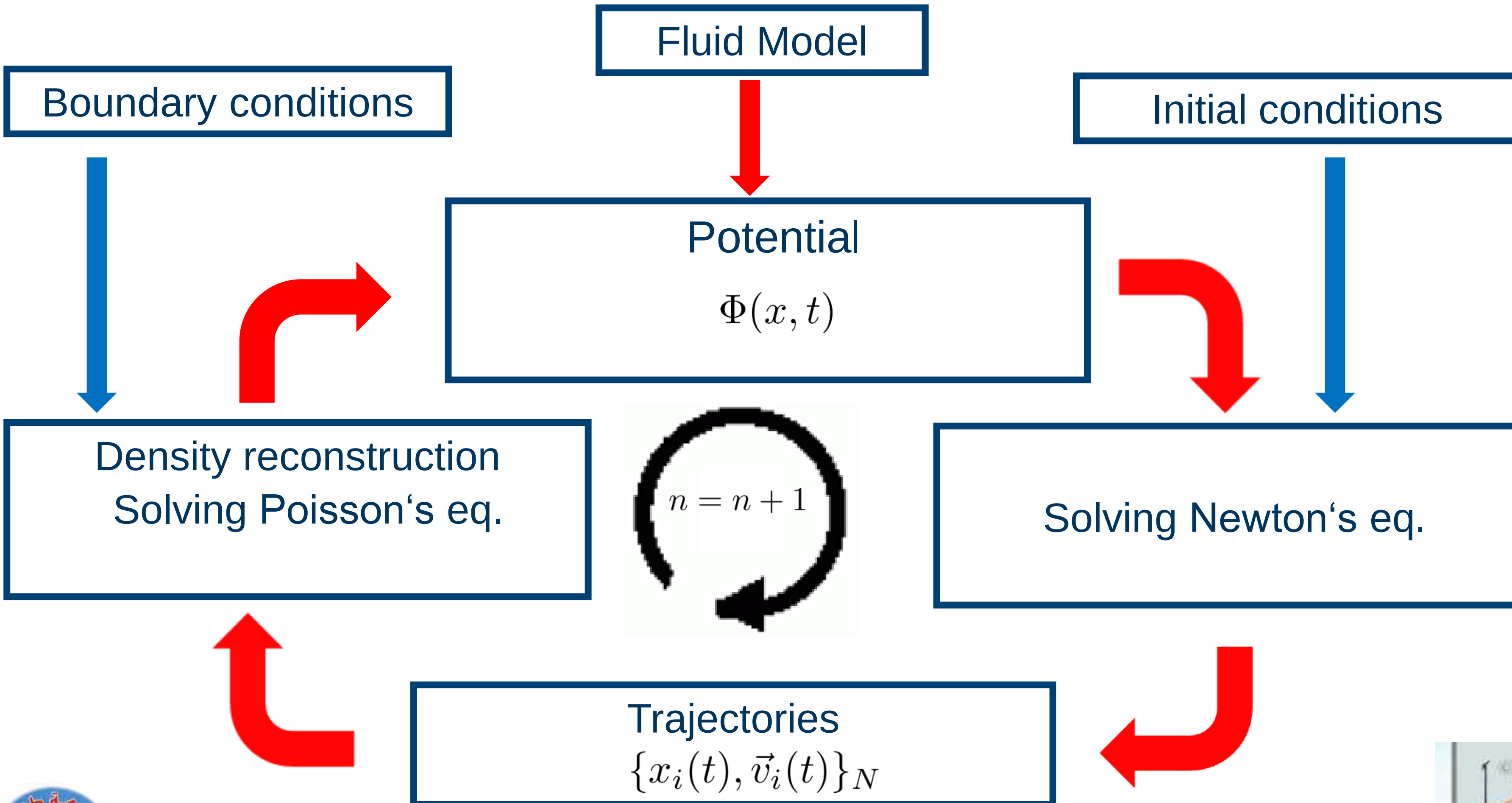
$$P(t) = \frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}}\nu_{\mathrm{eff}}I^2(t) \qquad \bar{P}(t) = \frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}\tau}\int_0^t \nu_{\mathrm{eff}}I^2(t)dt$$



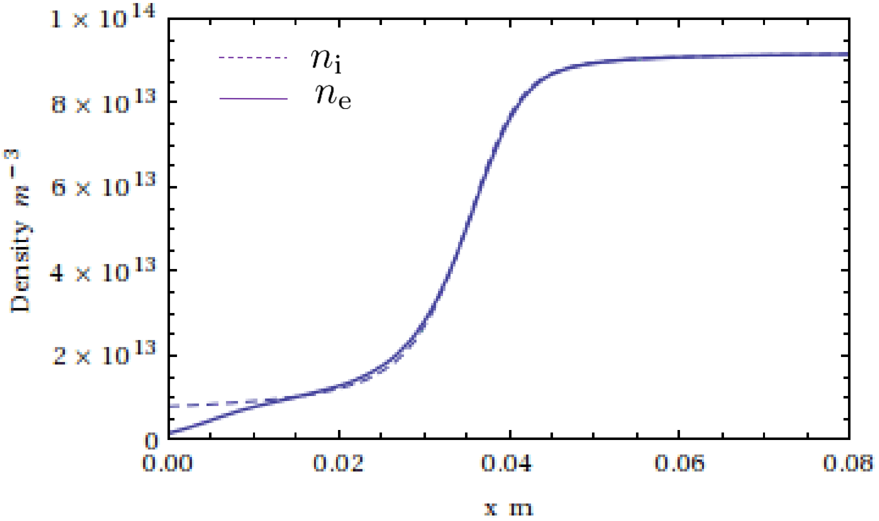
- 50 mTorr Black, 30 mTorr Blue, 10 mTorr Red
- 13.56 MHz

Ensemble-in-Spacetime Kinetic Sheath model

Ensemble in Spacetime

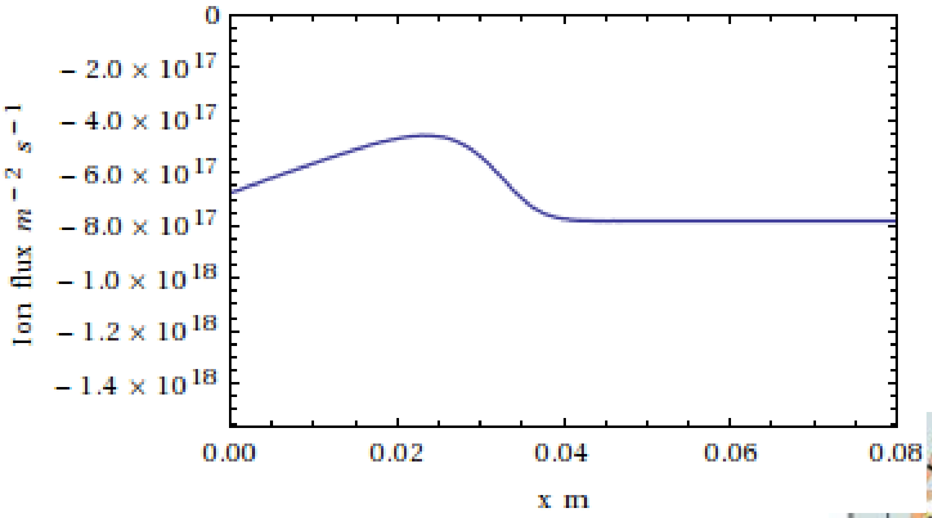


Ion dynamics



- The intermediate regime

$$\omega_{\mathrm{RF}} \approx \omega_{\mathrm{pi}}$$

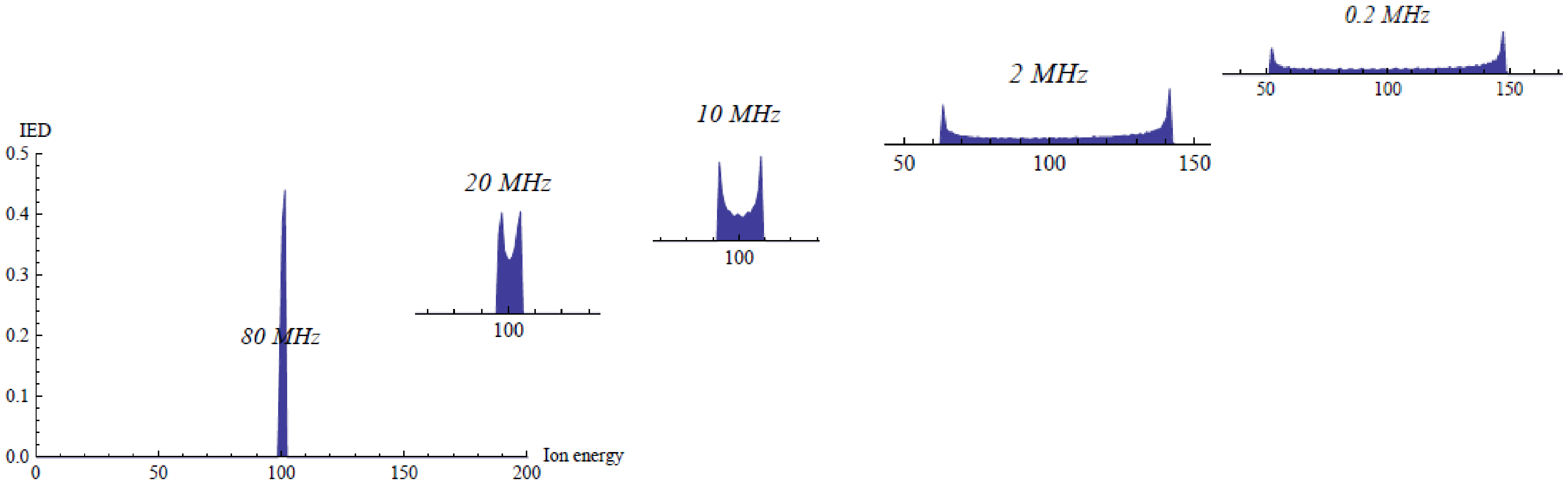


IEDFs

- HF regime $\omega_{\mathrm{RF}} \gg \omega_{\mathrm{pi}}$

IMF regime $\omega_{\mathrm{RF}} \approx \omega_{\mathrm{pi}}$

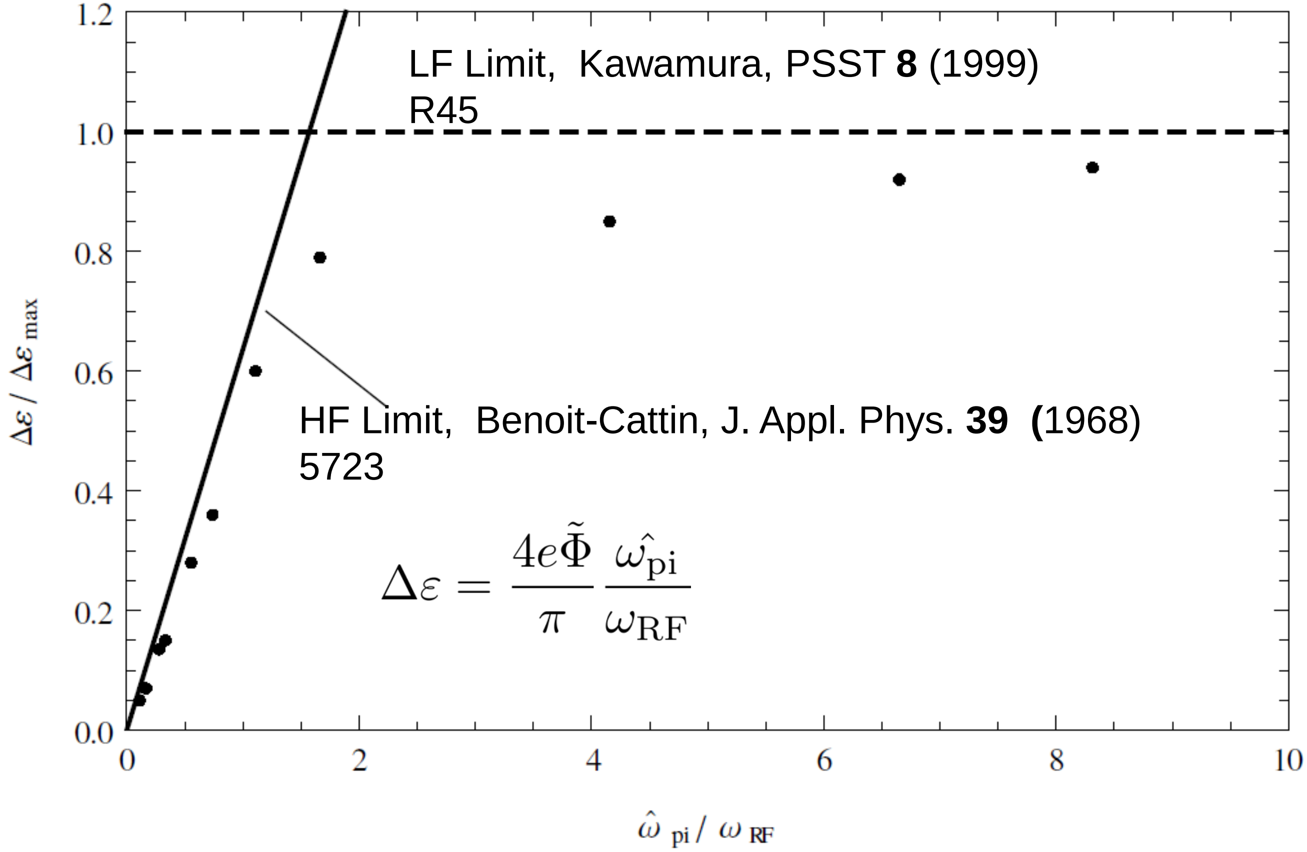
LF regime $\omega_{\mathrm{RF}} \ll \omega_{\mathrm{pi}}$



Argon plasma $n_{\mathrm{i}} = 10^{10}\mathrm{cm}^{-3}$

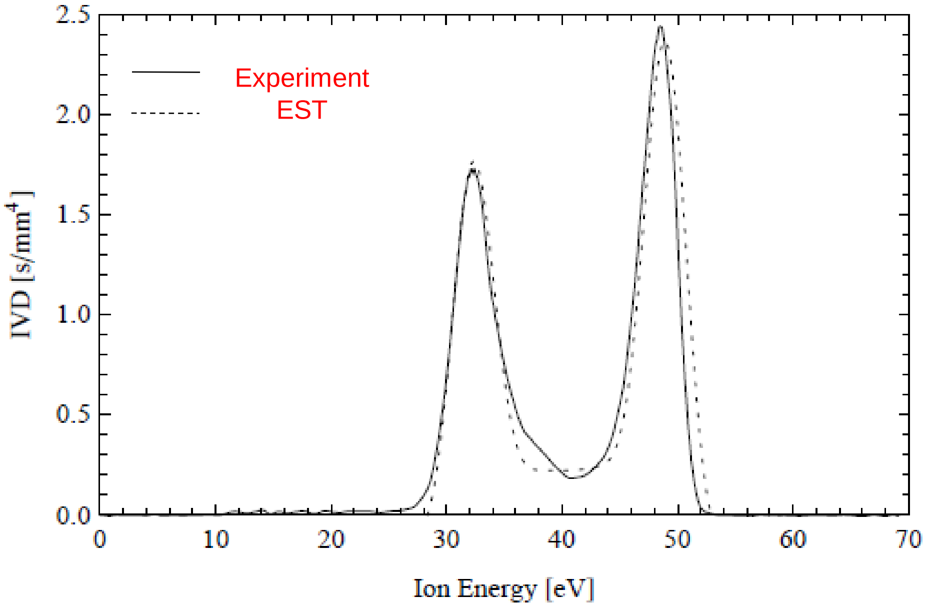
Verification of the EST Model

Compare to analytical models



M. Shihab et al, J. Phys.D: Appl. Phys.**45** (2012) 185202

Comparison to experiment

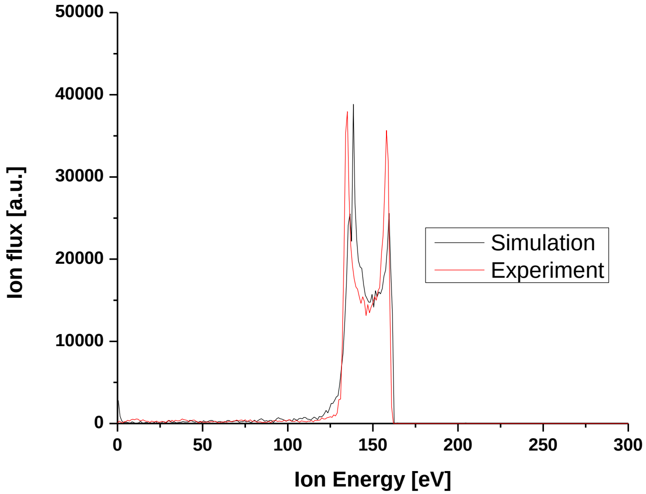


T. Baloniak et al J. Phys. D: Appl. Phys. **43** 335201 2010

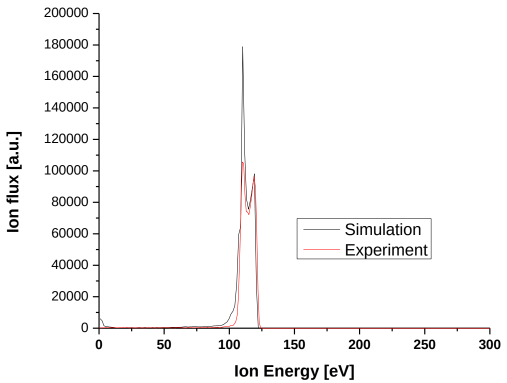
M. Shihab et al. 30th ICPIG, Belfast, UK, 2011

Simulation vs Experiment (privat)

27 MHz, 86 mTorr, 0.2 mA cm^-2, CHF2+ in Ar, Te=4eV



60 MHz, 86 mTorr, 0.2 mA cm^-2, CHF2+ in Ar, Te=4eV

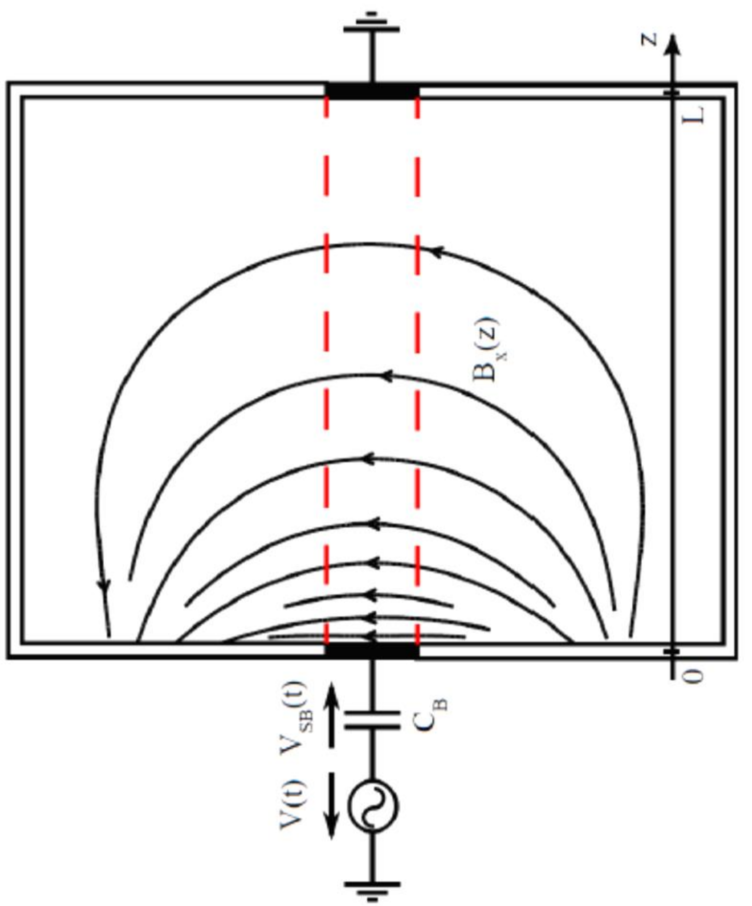


- **The same species under the same conditions except the driven RF frequency.**
- **Decreasing the driven RF frequencies leads to shorter ion transit times with respect to the driven RF period and consequently a wider IED.**

The code may predict an experiment

EST as postprocessing tool

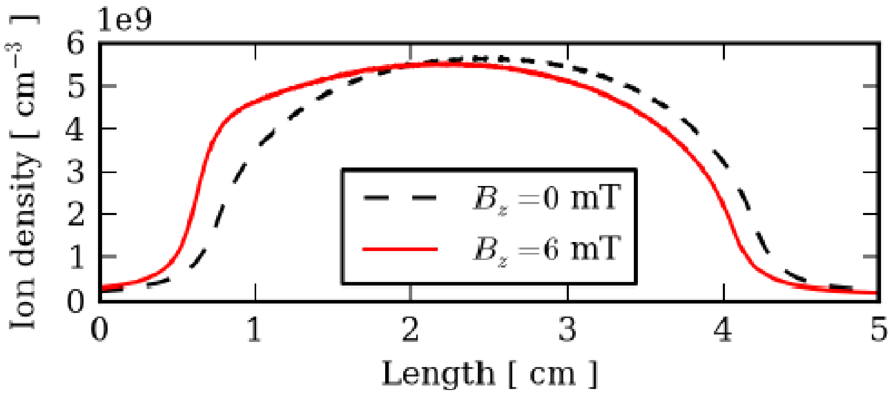
- **Simulation set up.**



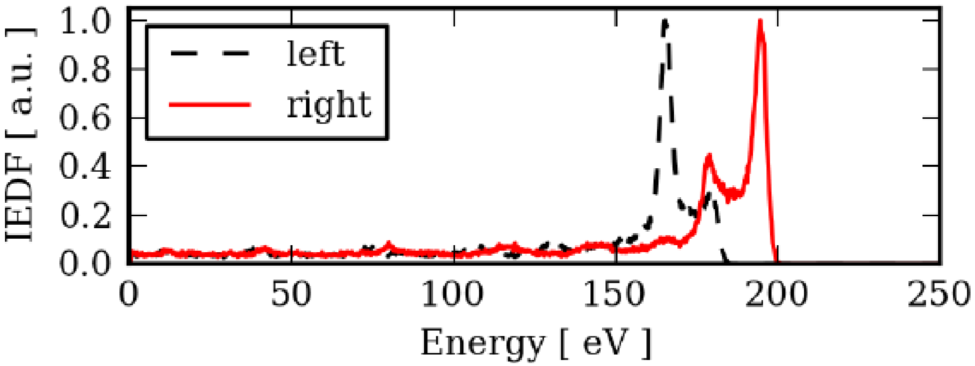
J. Trieschmann, M. Shihab et al J. Phys. D: Appl. Phys. **46** 084016 2013

PIC results

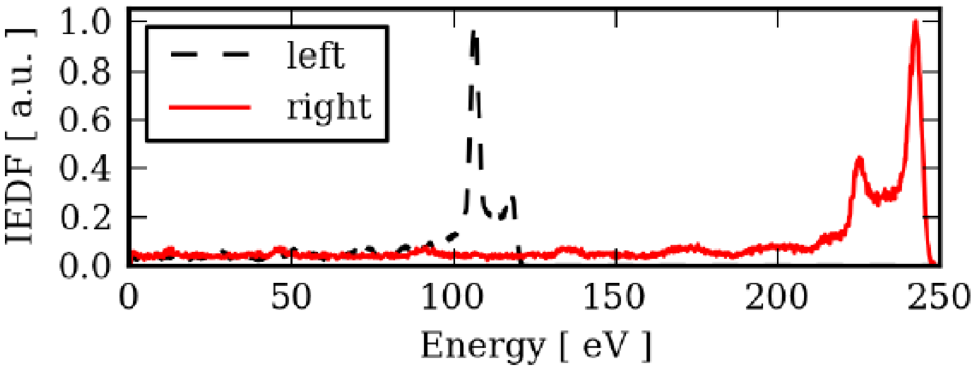
Ion density profile



IED- without B field



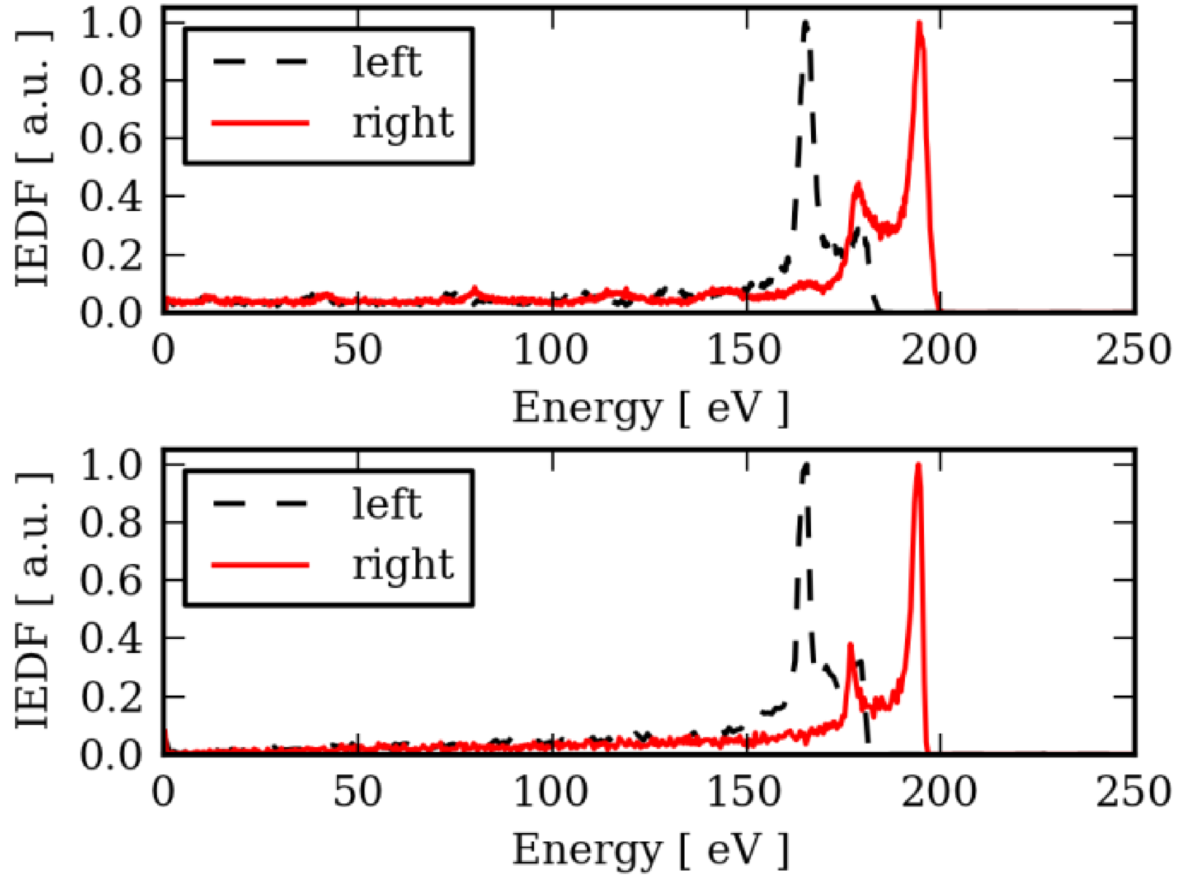
IED- with B field



EST vs PIC

PIC

EST

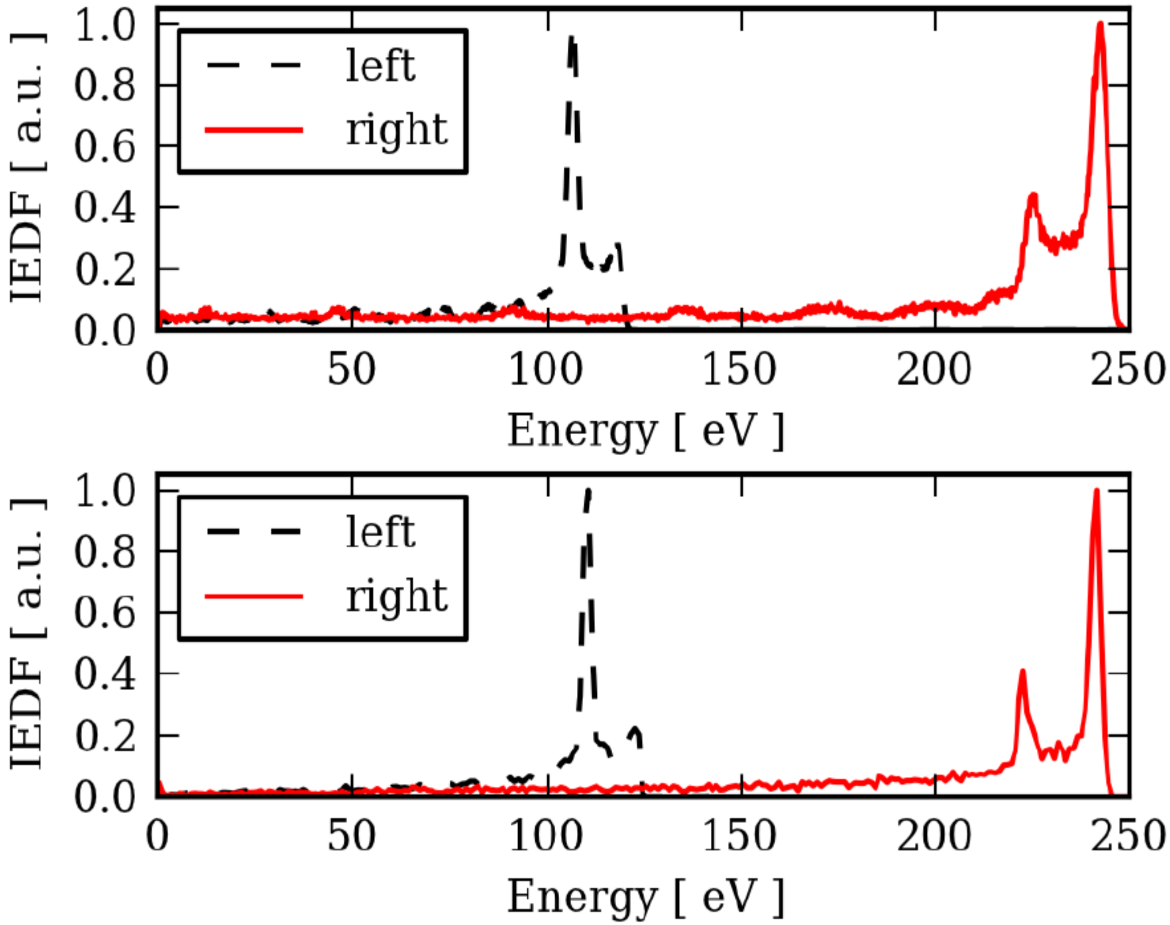


J. Trieschmann, M. Shihab et al J. Phys. D: Appl. Phys. **46** 084016 2013

EST vs PIC

PIC

EST



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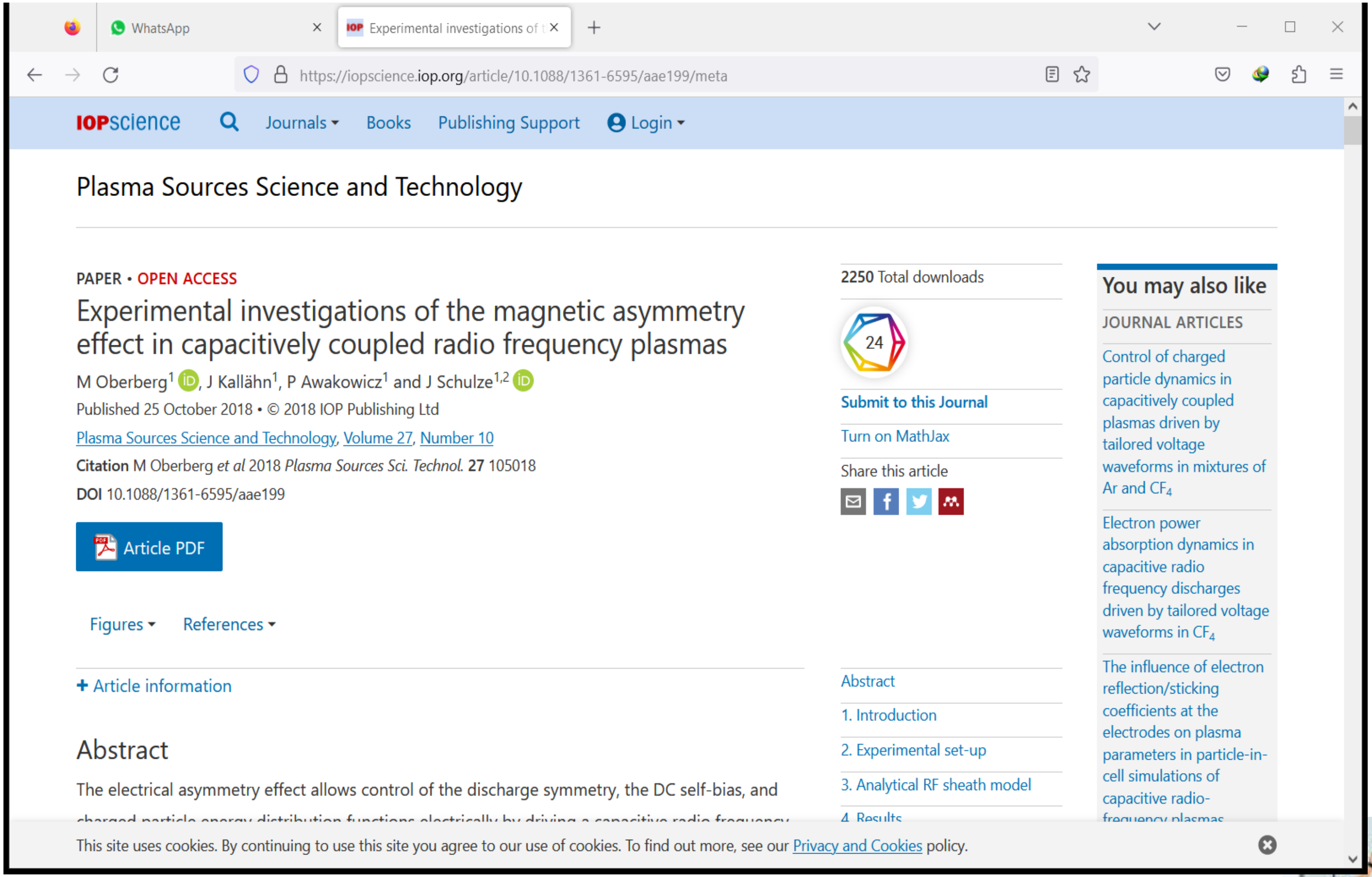
Experimental verification



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Plasma Sources Science and Technology

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Experimental investigations of the magnetic asymmetry effect in capacitively coupled radio frequency plasmas

M Oberberg[1], J Kallähn[1], P Awakowicz[1] and J Schulze[1,2]

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DOI 10.1088/1361-6595/aae199

Article PDF

Figures | References

+ Article information

Abstract

The electrical asymmetry effect allows control of the discharge symmetry, the DC self-bias, and charged particle energy distribution functions electrically by driving a capacitive radio frequency

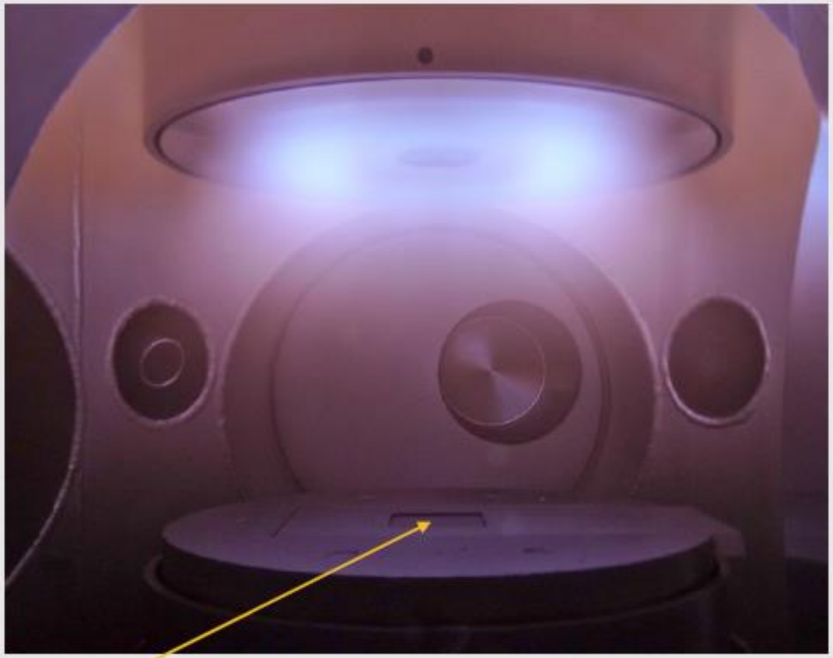
The code may be a part in the experiment

Deposition of Al_2O_3

The film stoichiometry is a function of the energy per deposited atom $\bar{E}$.

- Alumina is widely used:
  - microelectronics
  - hard coating
  - absorbent
  - catalyst

- Alumina is an insulator.
- IED can not be measured, then Simulation.

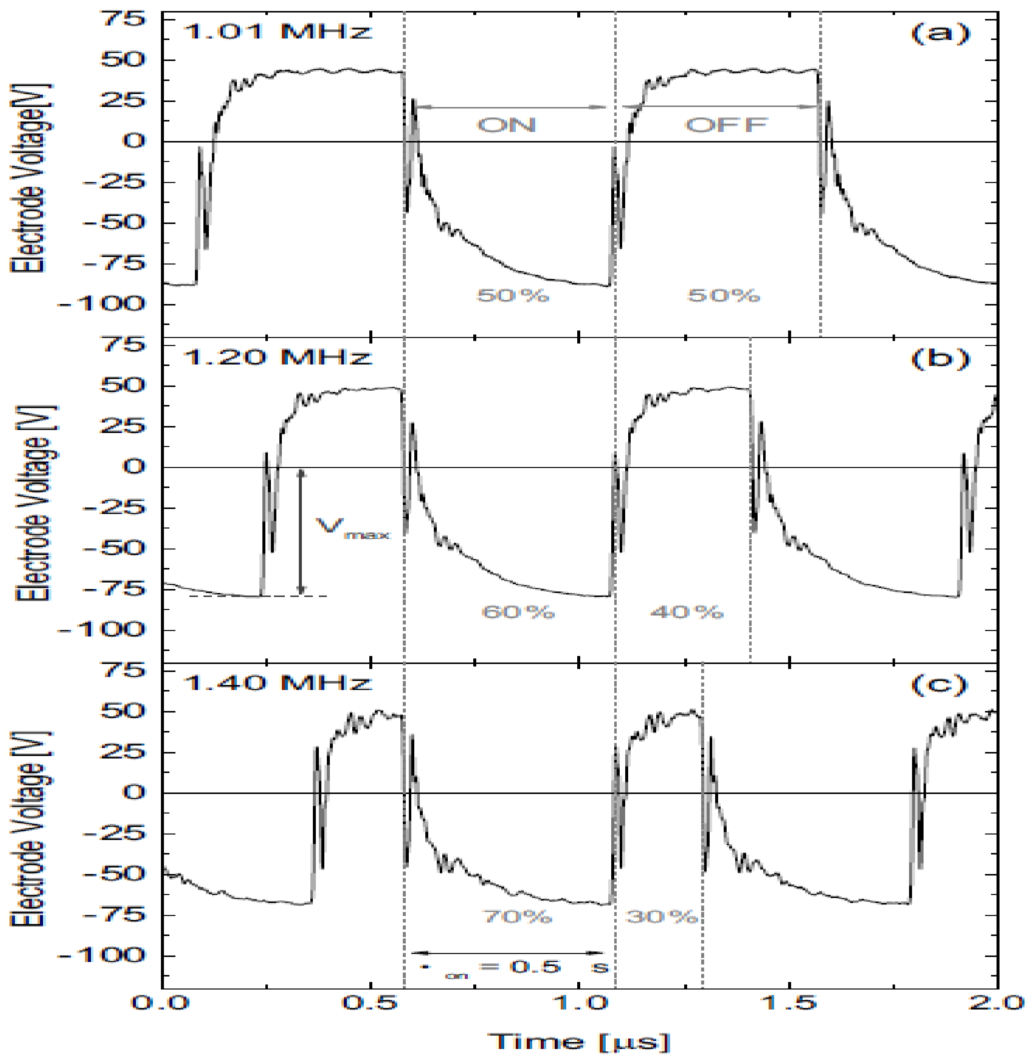


(Al + O_2 + Ar) on Si substrate

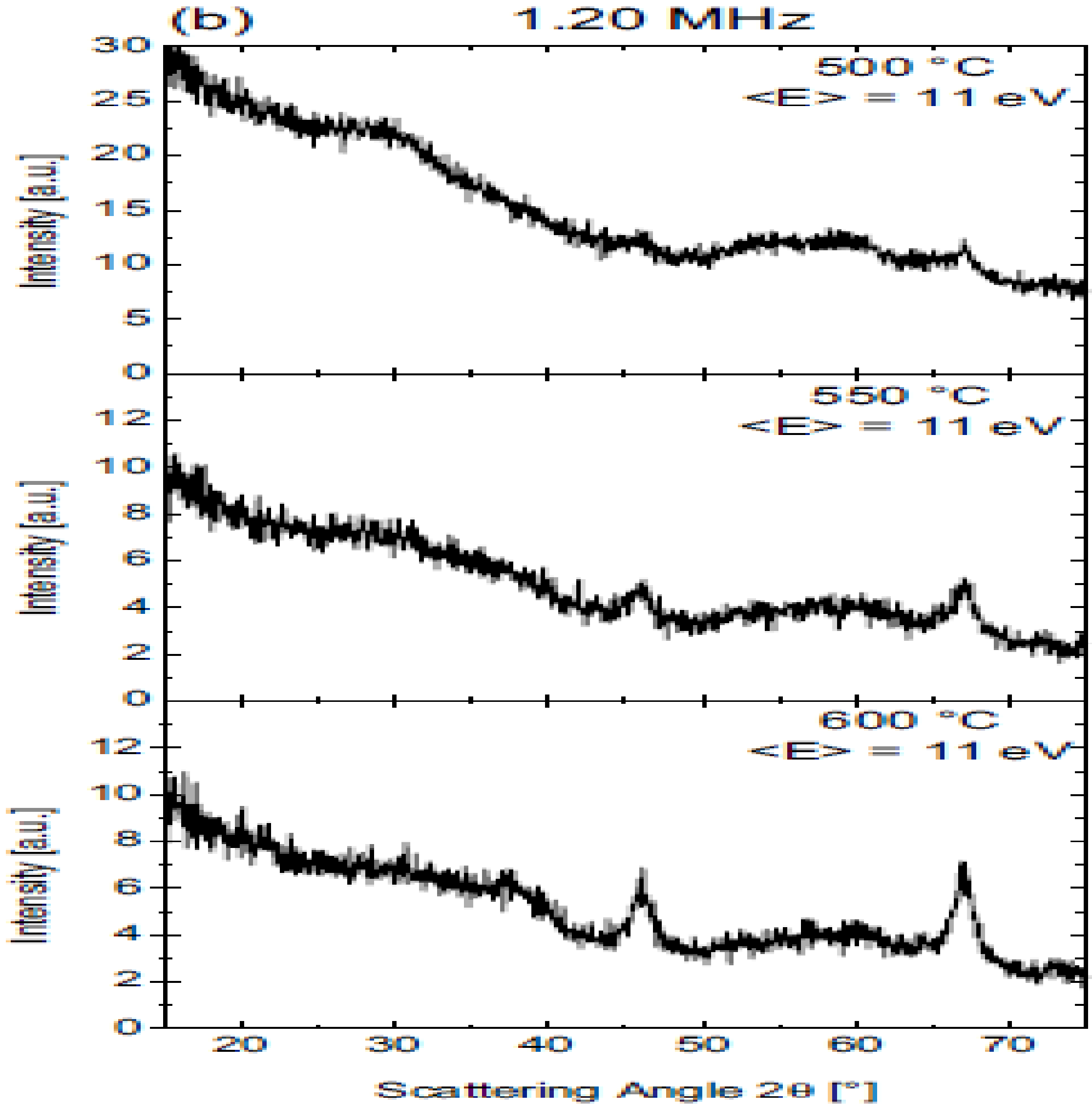
Prenzel, Ruhr University Bochum

M. Prenzel , … M. Shihab et al J. Phys. D: Appl. Phys. **46** (2013) 084004

Aluminum Oxide Deposition I



Aluminum Oxide Deposition II



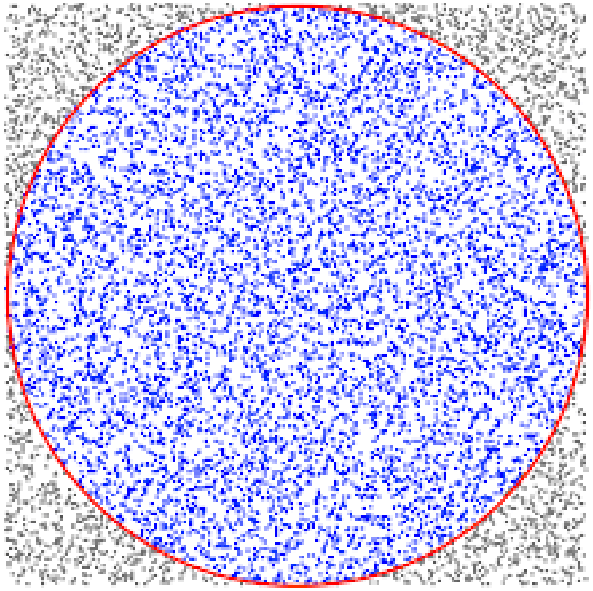
Conclusion

- The simulation gives approximate solution.
- There are different models: Kinetic models as PIC, Fluid models, global models, and hybrid models
- The results must be compared with analytical or exprimental or simulated results.
- We should do calculations to interpret the experiment results, explain phenomena, or even propose an experiment.

Thanks!

Monte-Carlo Simulation

- Use random numbers to solve problems.
- Are numbers really random?



$$\frac{A_{sq}}{A_{sh}} = \frac{l^2}{\pi r^2}$$

$$\frac{A_{sq}}{A_{sh}} = \frac{4r^2}{\pi r^2} = \frac{N_{sq}}{N_{sp}}$$

$$\pi = 4 * N_{sp}/N_{sq}$$