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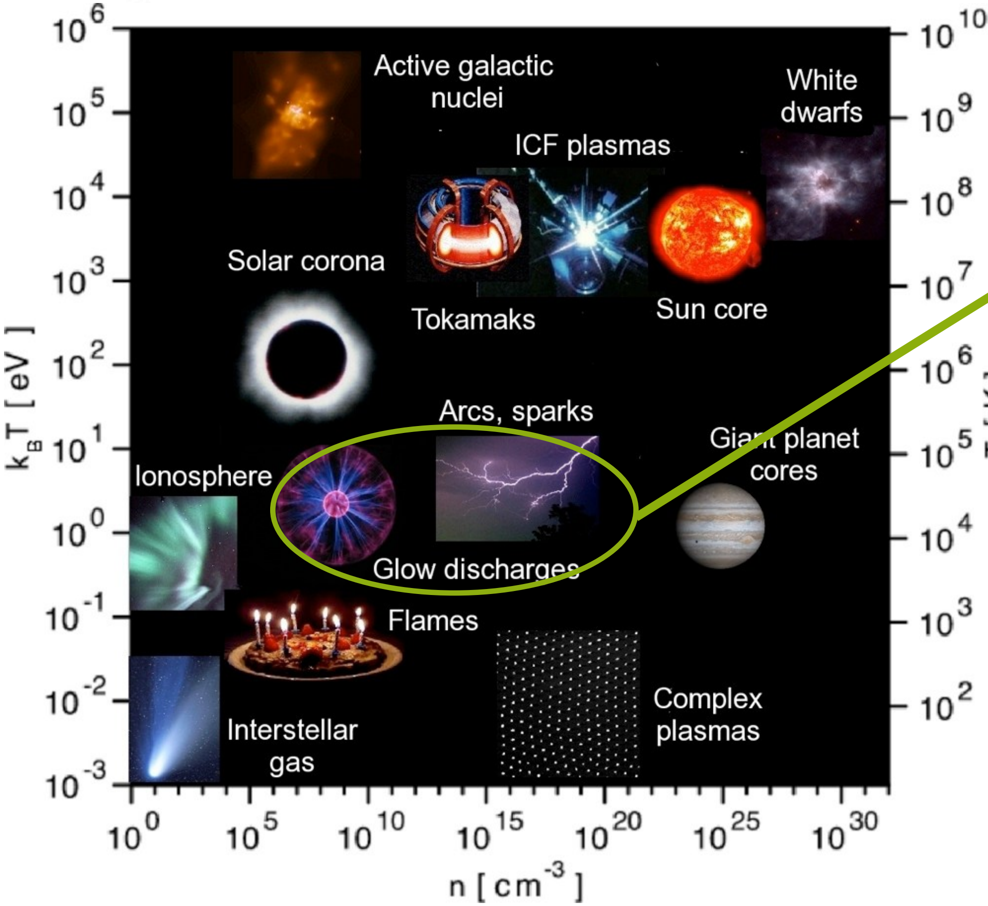
Technical Plasma

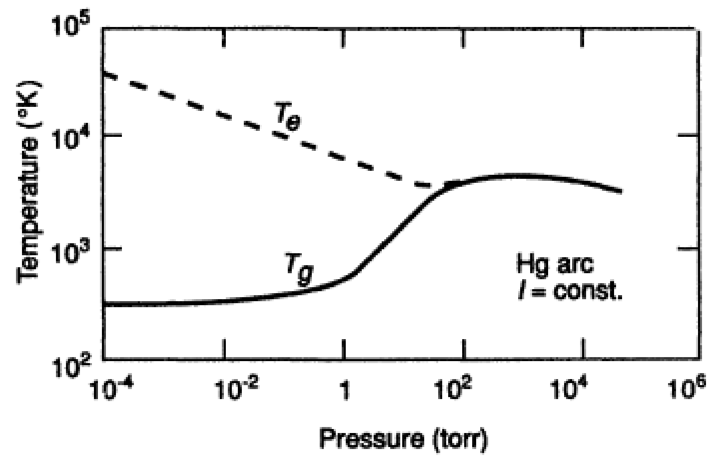
Prof. Dr. Mohammed Shihab

Plasma Technology

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

$T_e = 11000 - 60000\text{K}$ $\quad T_e = 1 - 5\text{eV} \quad T_i = 300\text{K}$

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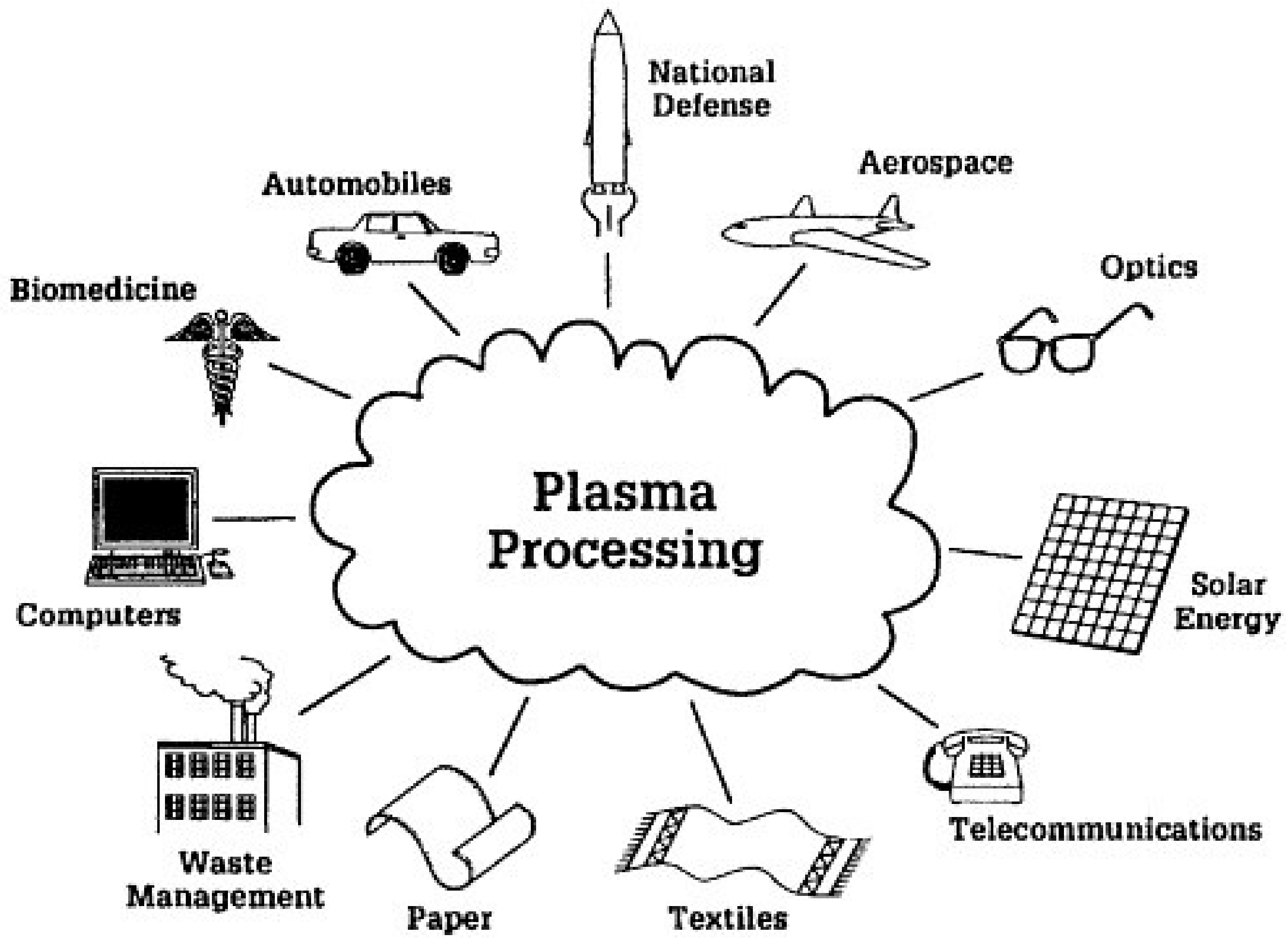
Various applications



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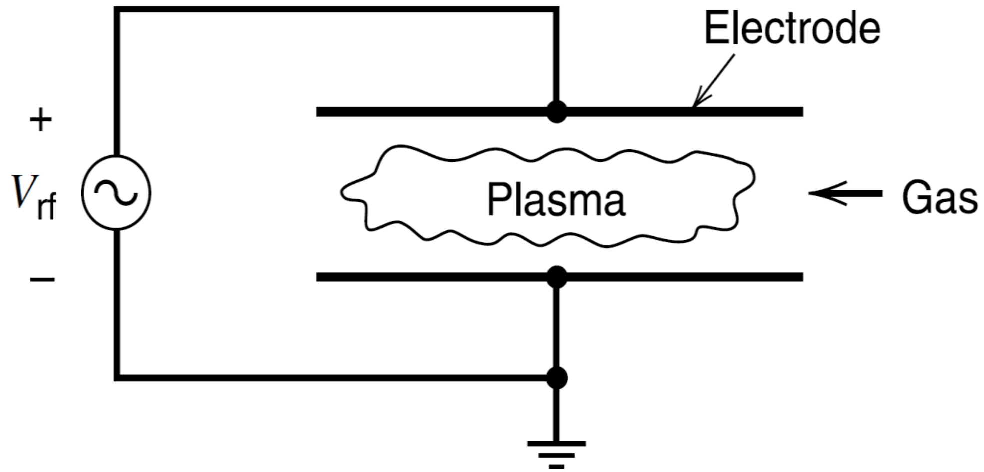
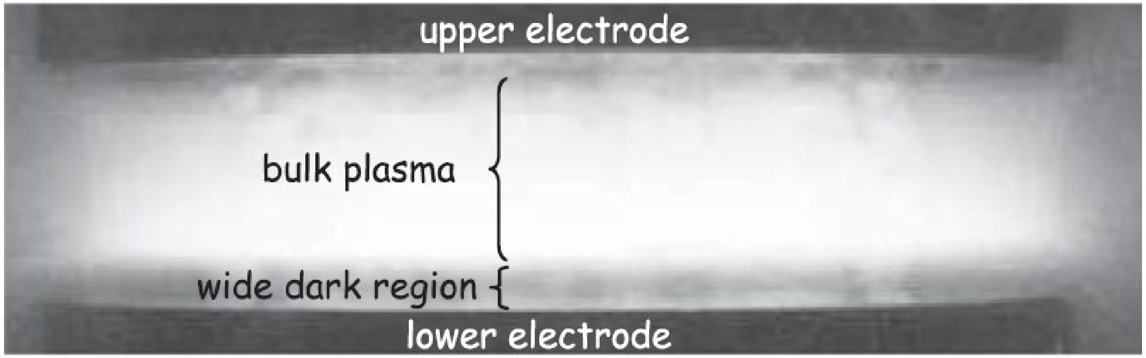
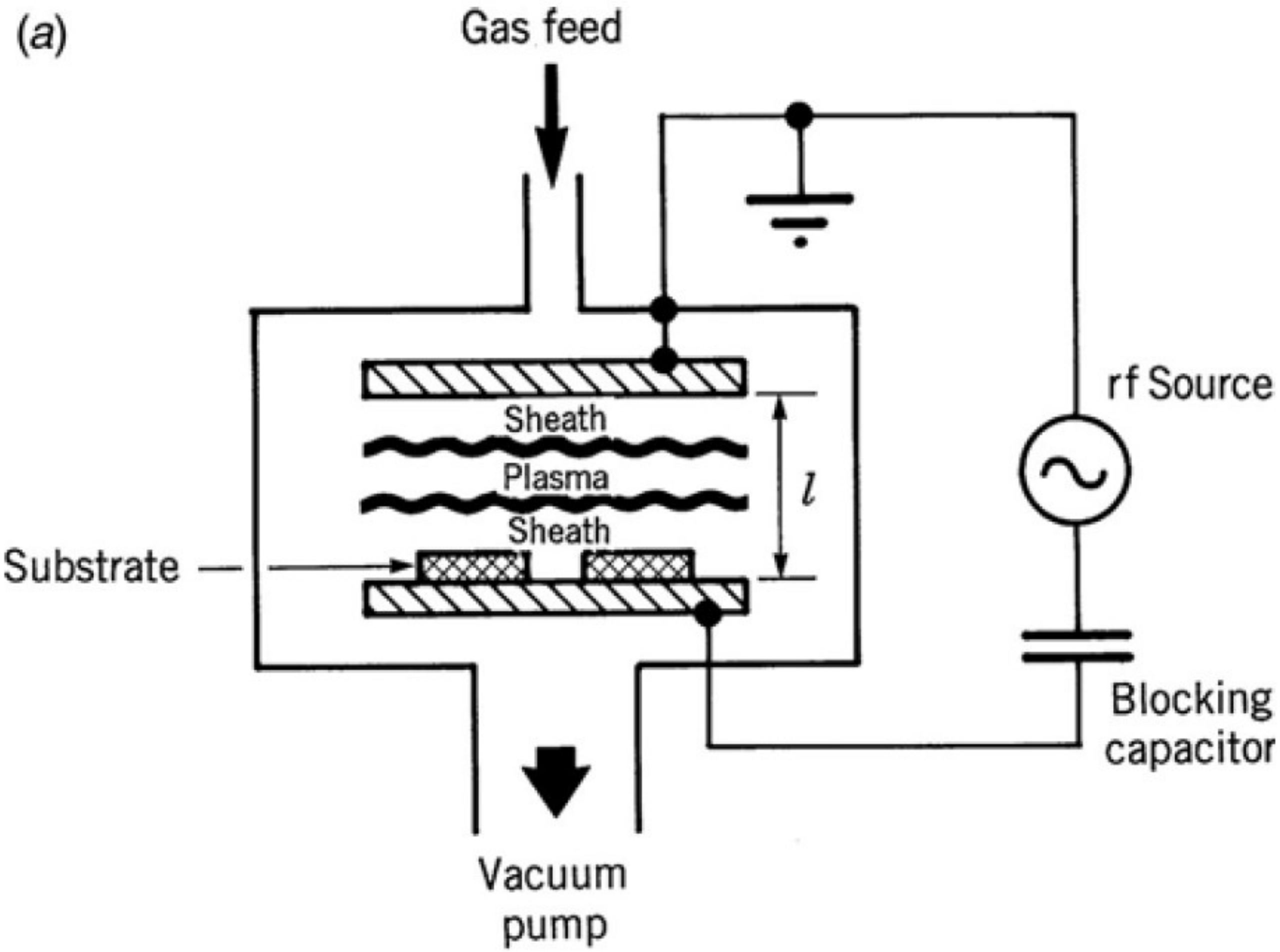
Symmetric CCP discharge





- **The ion flux and the ion energies increase (decreases) by increasing (decreasing) the dreving frequency.**

CCPs & blocking a Capacitor



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Geometrically Asymmetric

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

Area is greater then the powered electrode area.

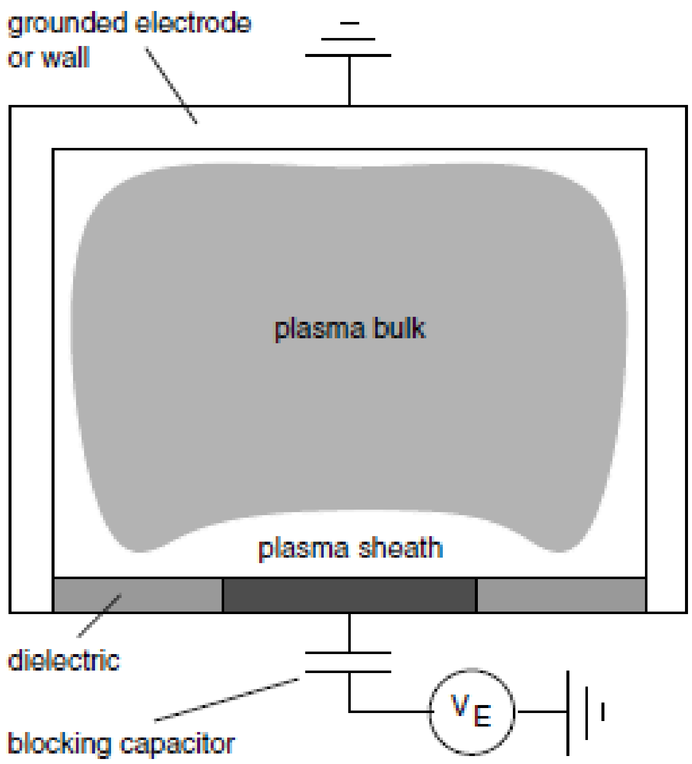
$$J_{\mathrm{g}} = I_{\mathrm{rf}}/A_g$$

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

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

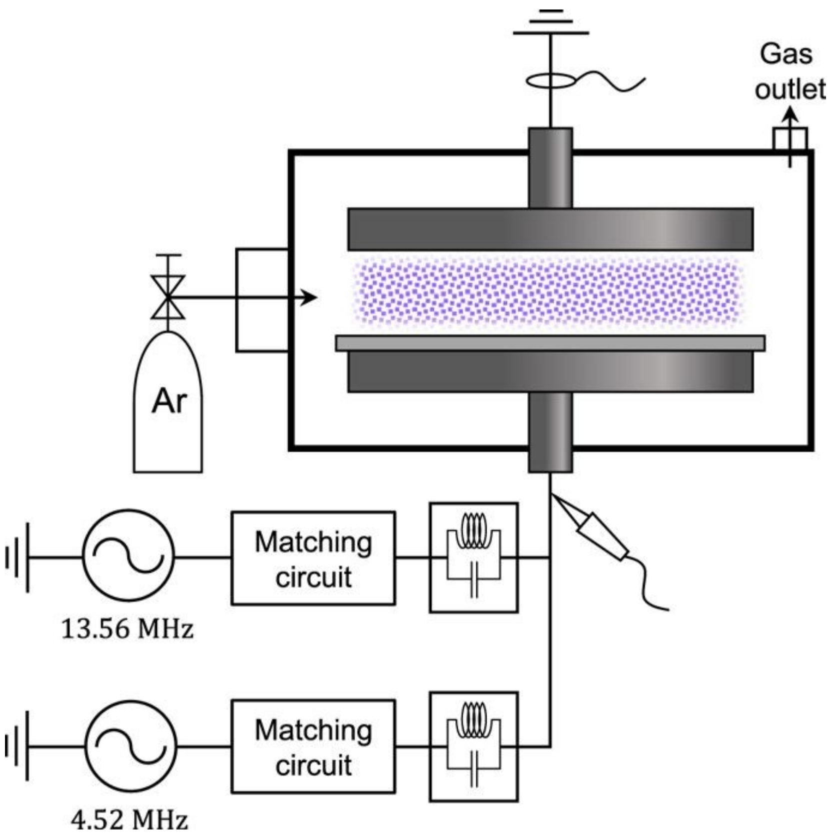
- The blocking capacitor blocks DC currents:

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

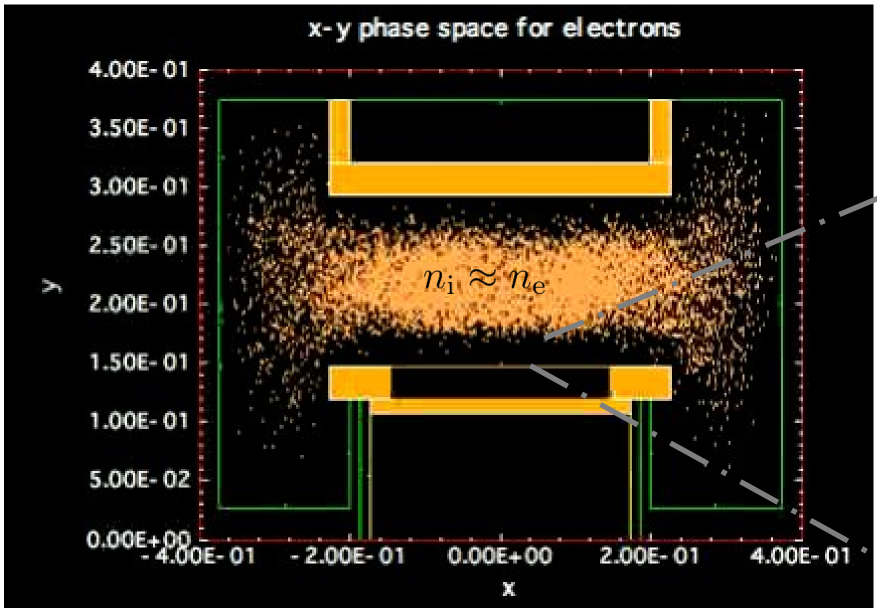


Electrically Asymmetric

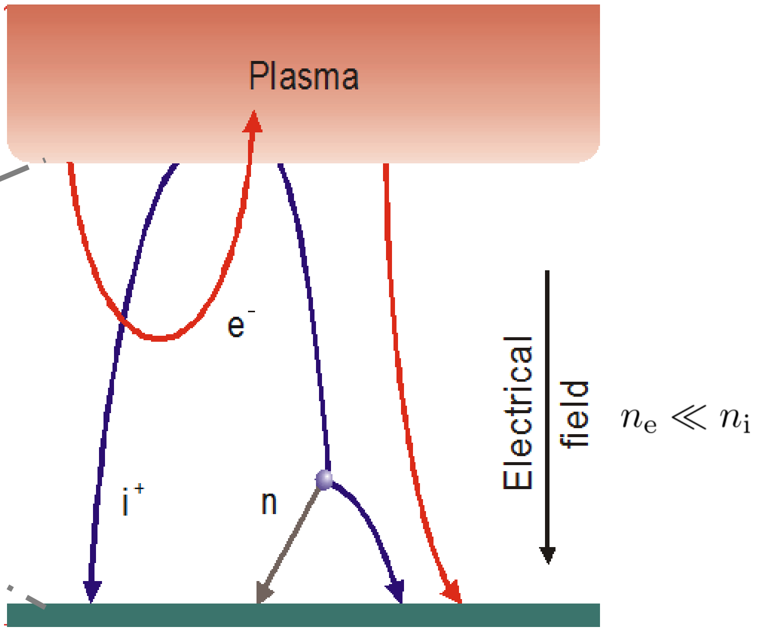
- The high frequency controls the ion plasma bulk (ion flux).
- The lower frequency controls the plasma sheath.
- The phase shift between the two sources controls also the sheath potential.
- The independent control is not always perfect.



Plasma Sheaths



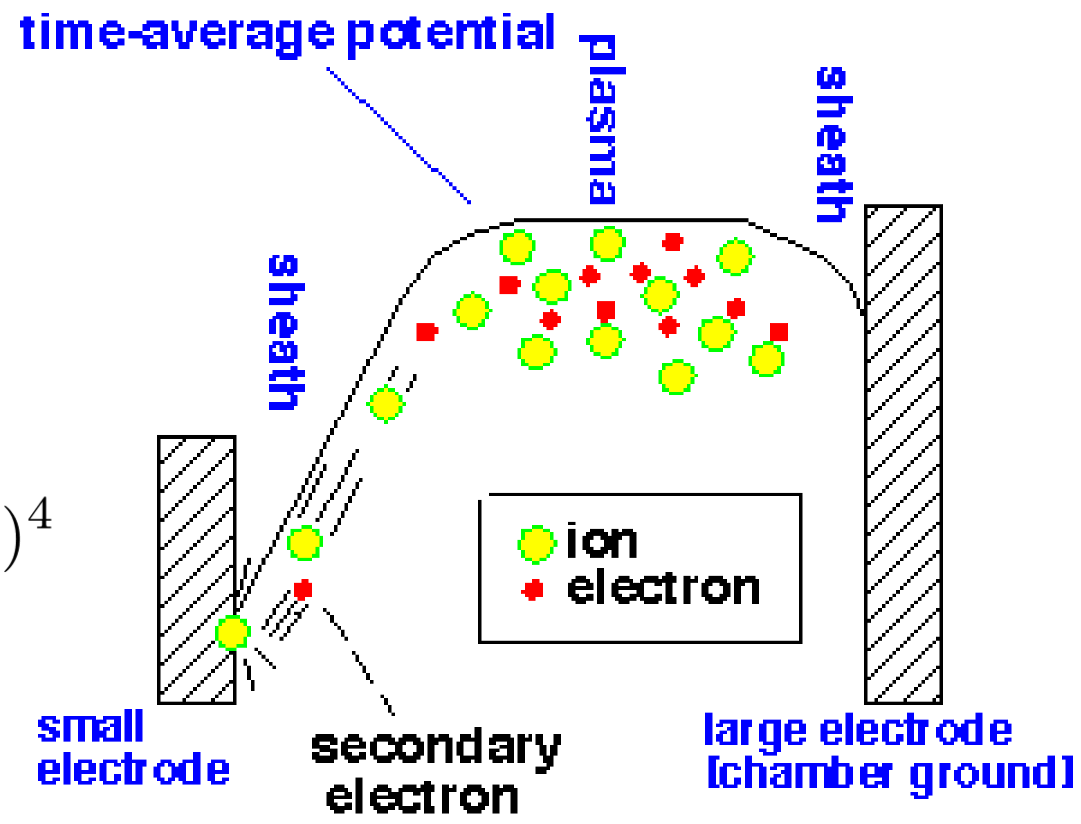
TET



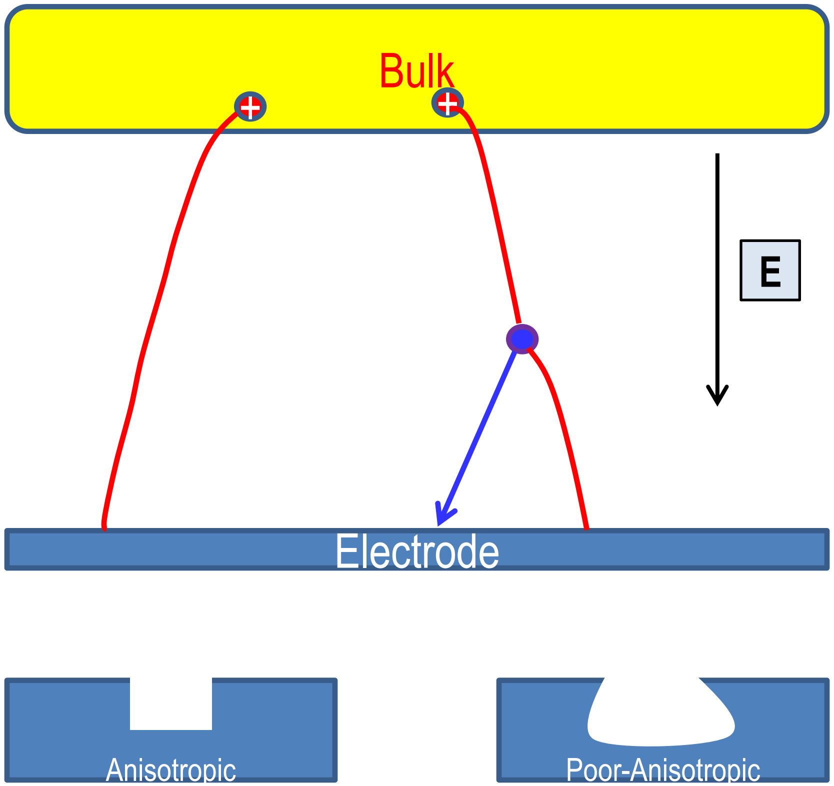
- RF sheaths:
  - High frequency regime $\omega_{RF} \gg \omega_{pi}$ $n_i(x) \Leftrightarrow \bar{E}(x)$
  - Intermediate frequency regime $\omega_{RF} \approx \omega_{pi}$
  - Low frequency regime $\omega_{RF} \ll \omega_{pi}$ $n_i(x,t) \Leftrightarrow E(x,t)$

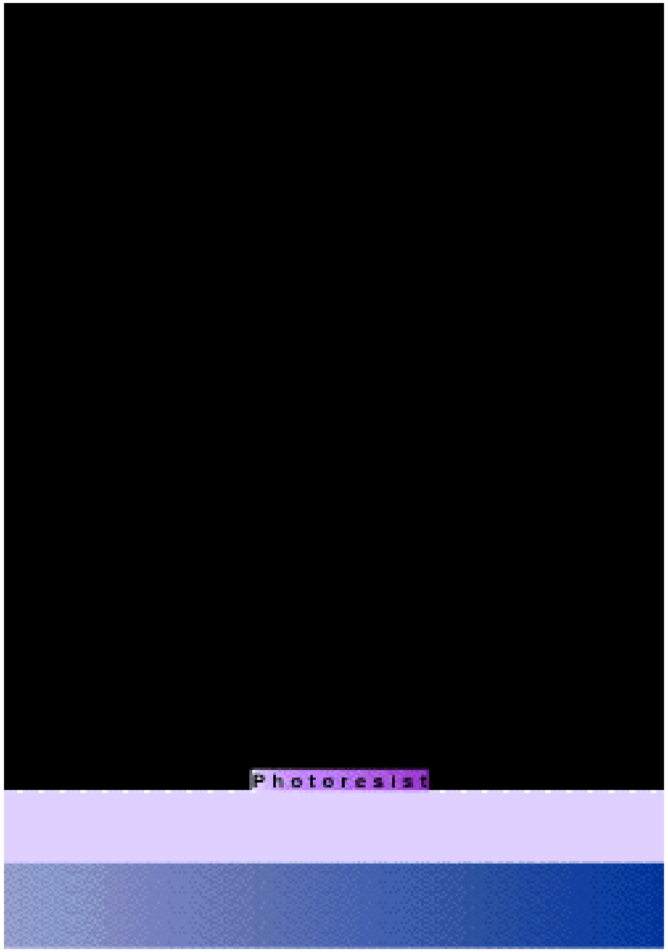
Particle and Potential distribution

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



Plasma Processing

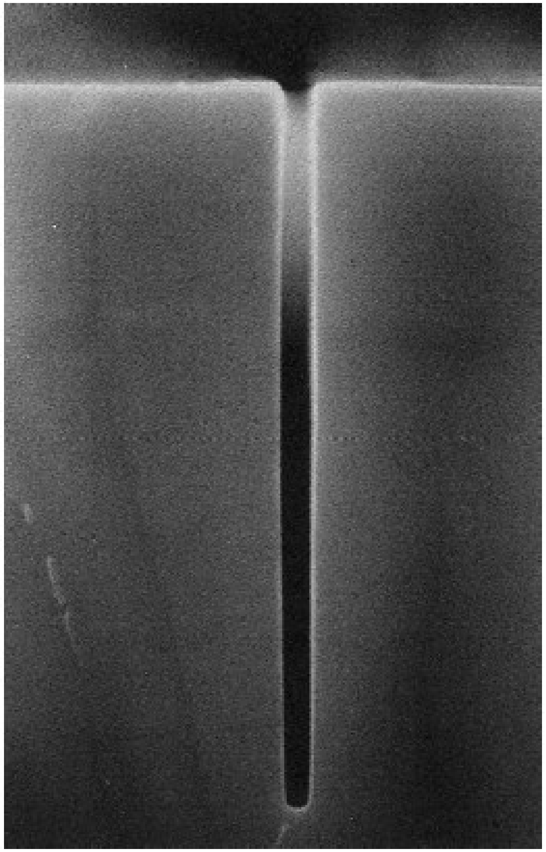




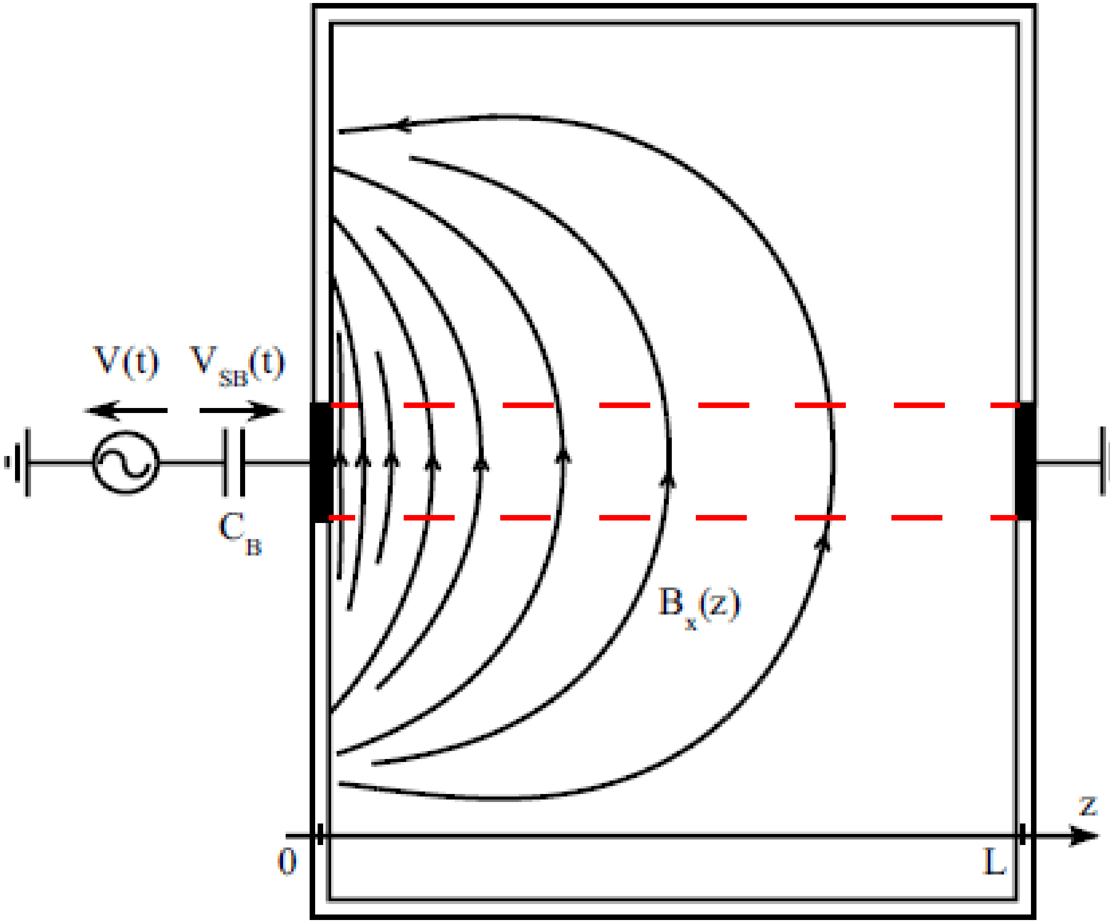
Intel

Plasma Etching

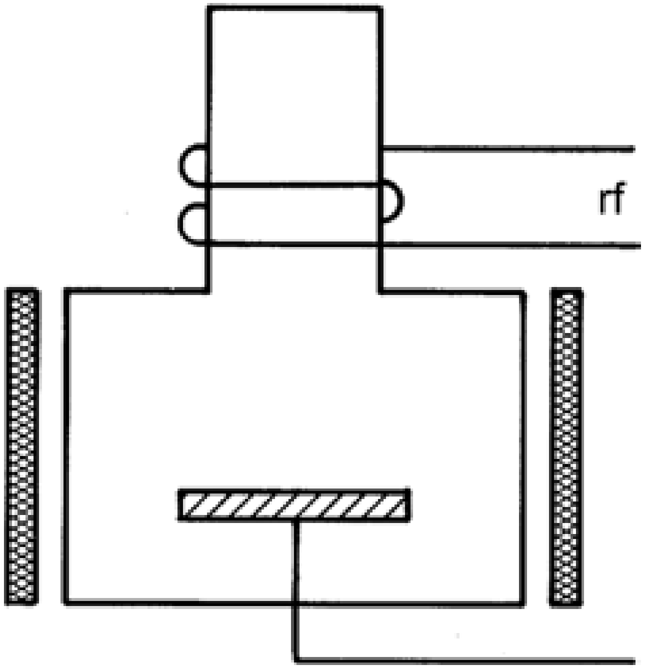
- An etched profile with
  - 0.5 micrometer (500 Nanometer) wide
  - 4 micrometer (4000 nanometer)
- Such profiles are used for device isolation and charge storage capacitores.
- Human hair is 50-100 micrometer in diameter.



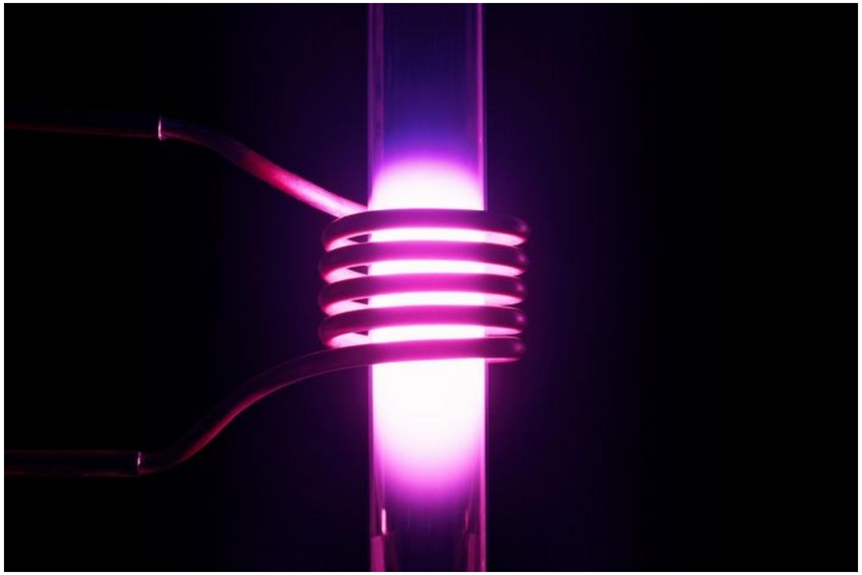
Magnetron



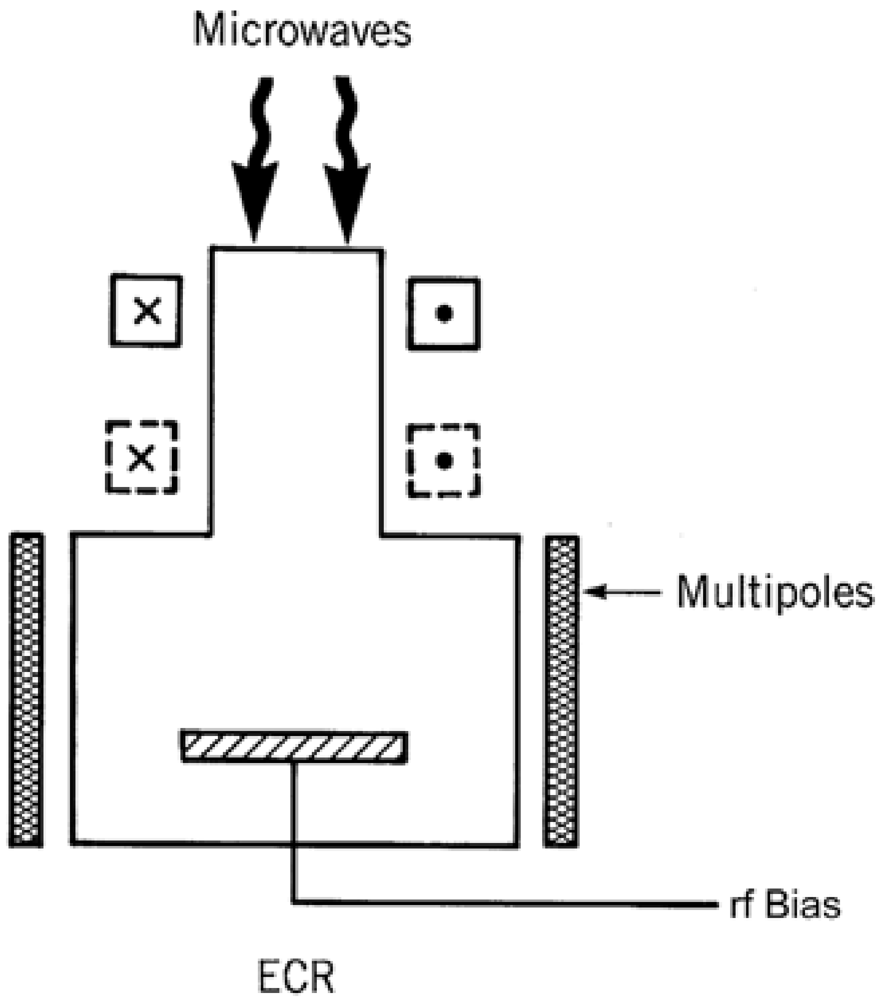
High density sources (ICP)



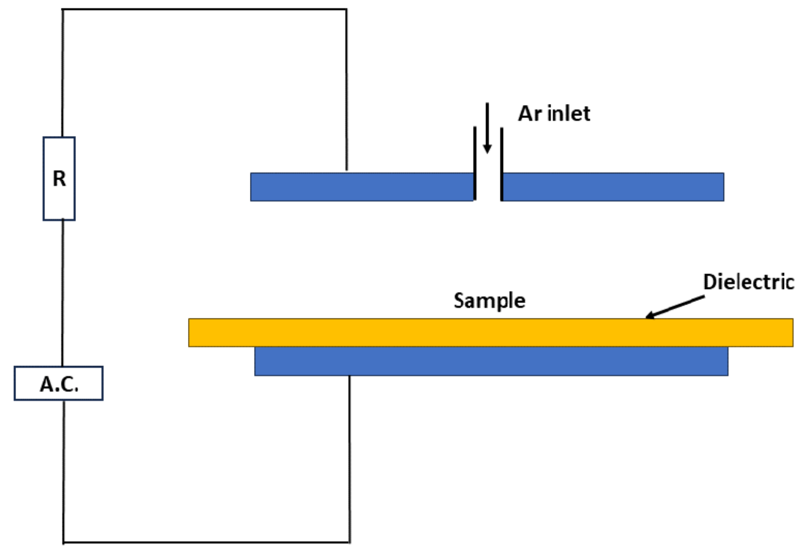
Inductive

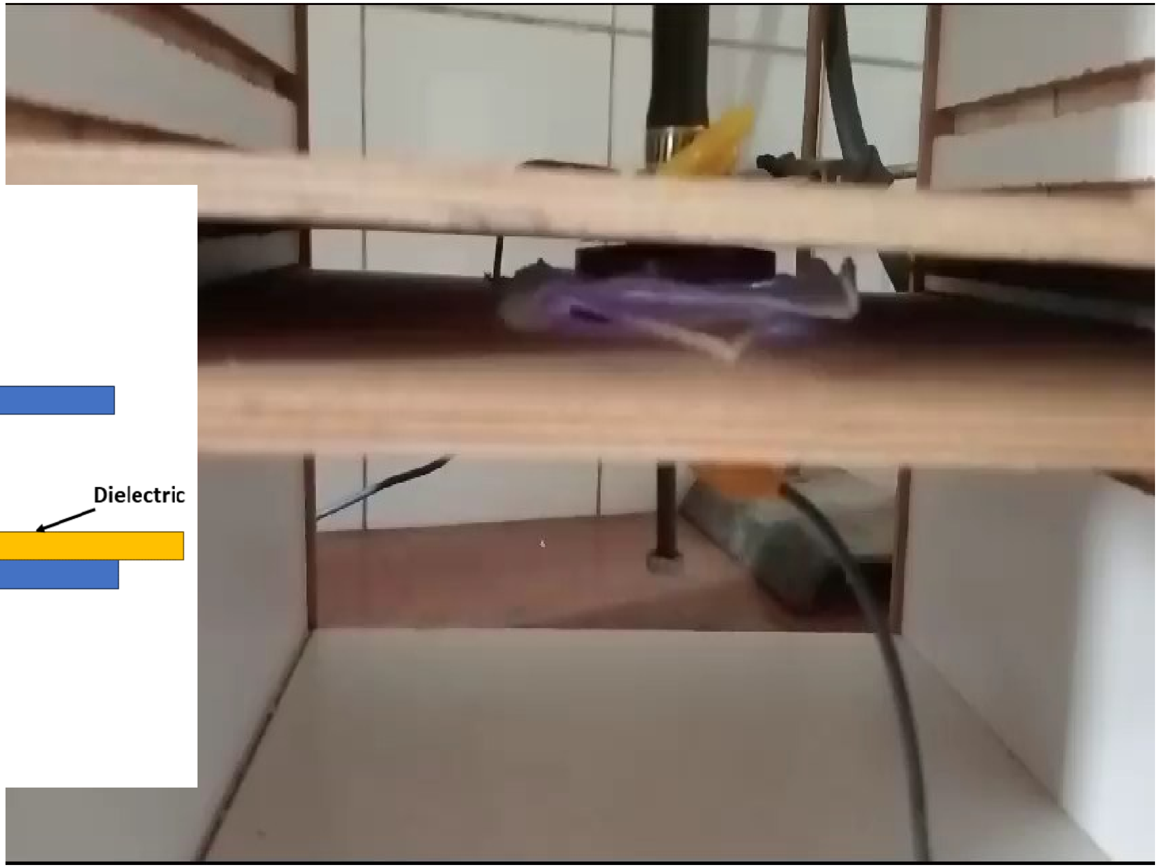


High density sources (ECR)

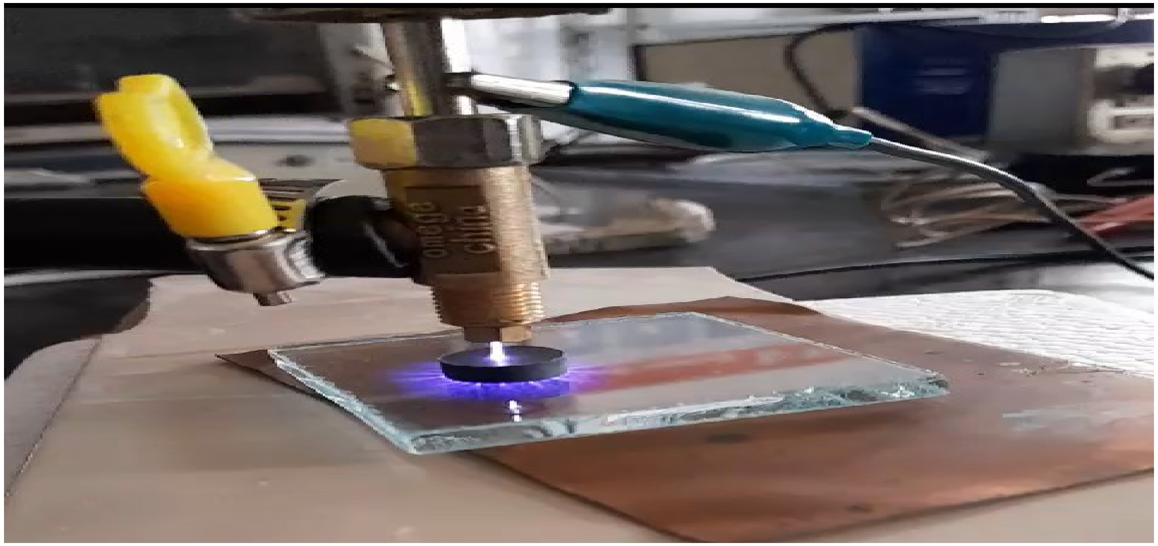


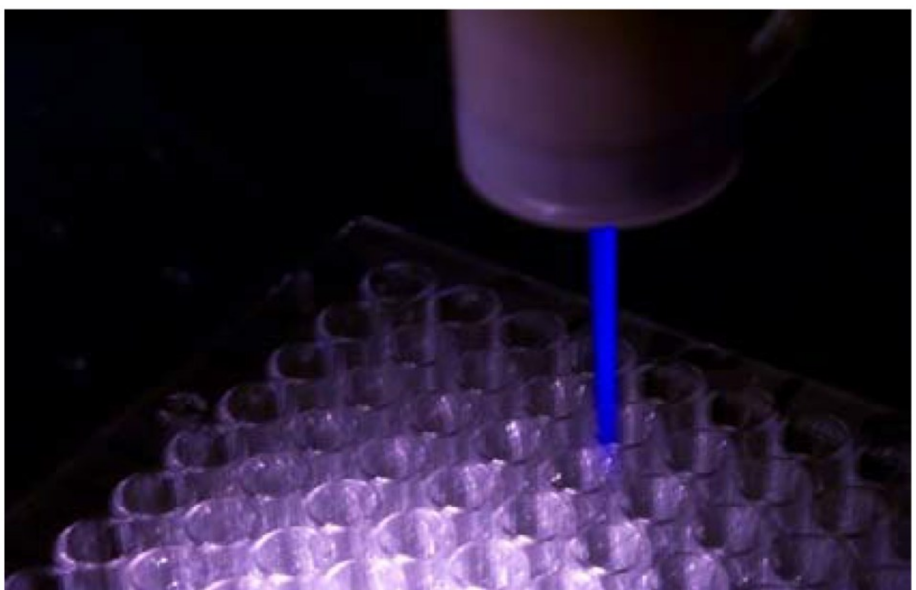
Home-made Devices
DBD-JET





Atmospheric Plasma Jet

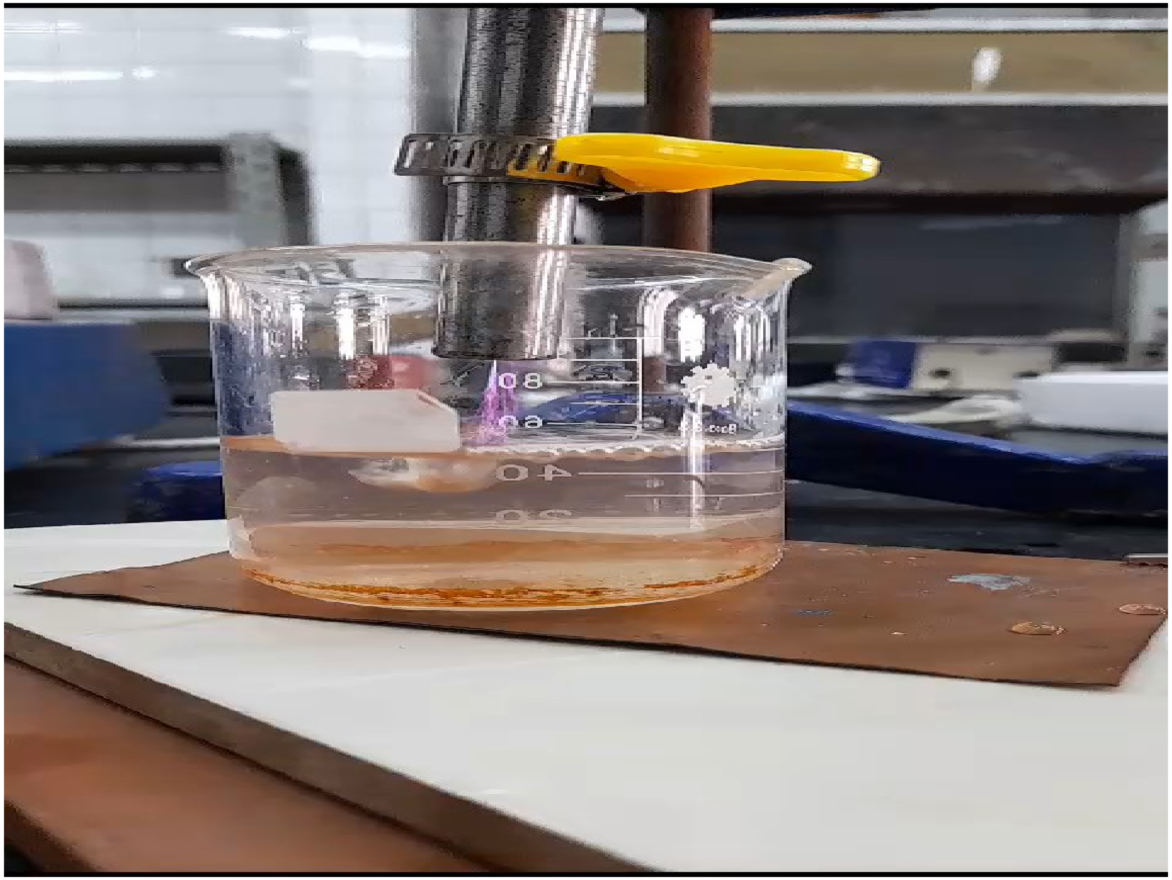




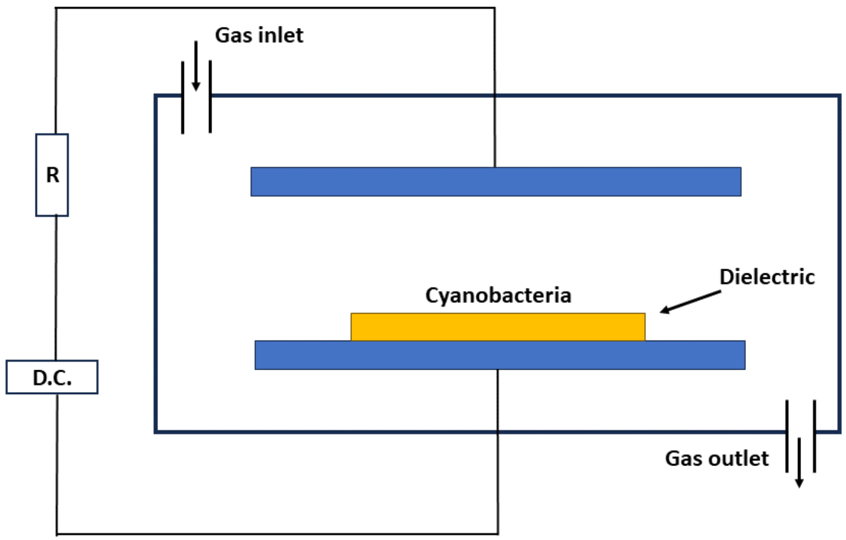
(a)

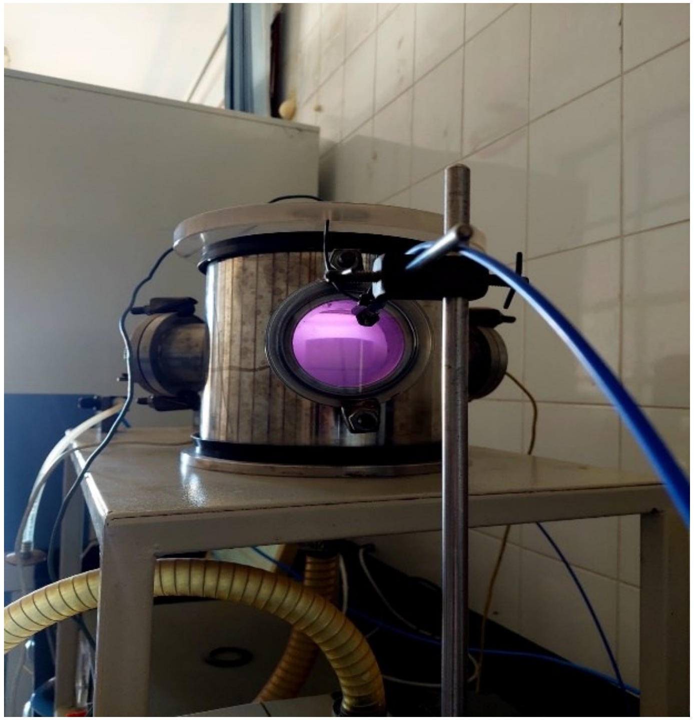
(b)

Devices



Capacitive Coupled Plasma





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Theoretical Side

Prof. Dr. Mohammed Shihab

Plasma Technology

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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

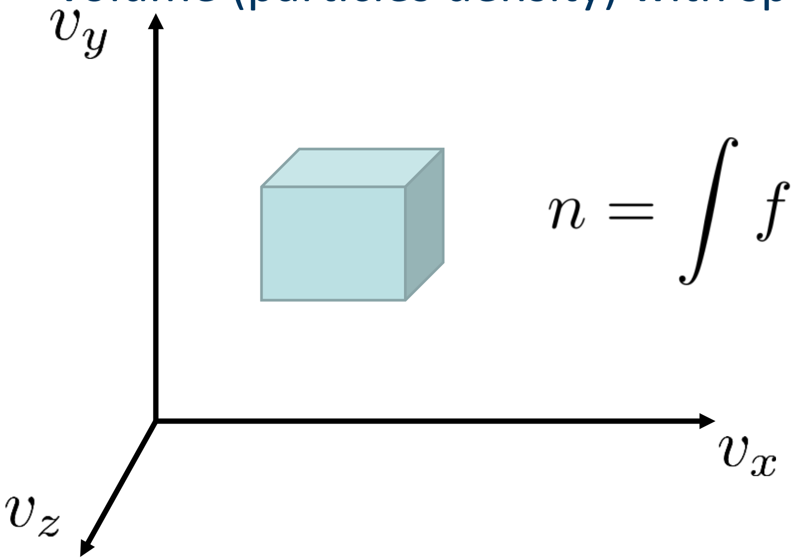
$$\vec{\nabla} \cdot \vec{D} = \rho_v \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

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

- 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

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

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

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

- Average speed

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

- Kinetic energy

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

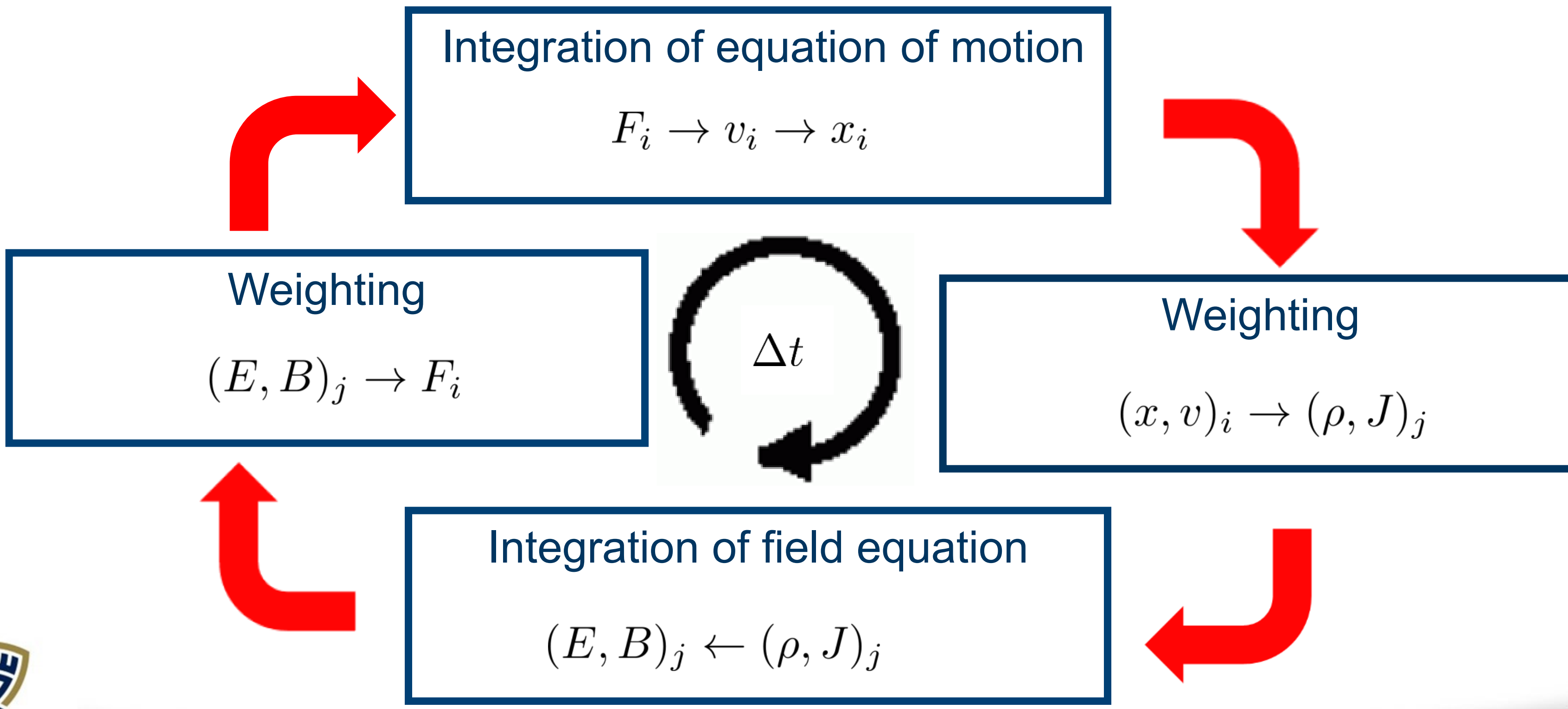
- Avergaes over Boltzman equation

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

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

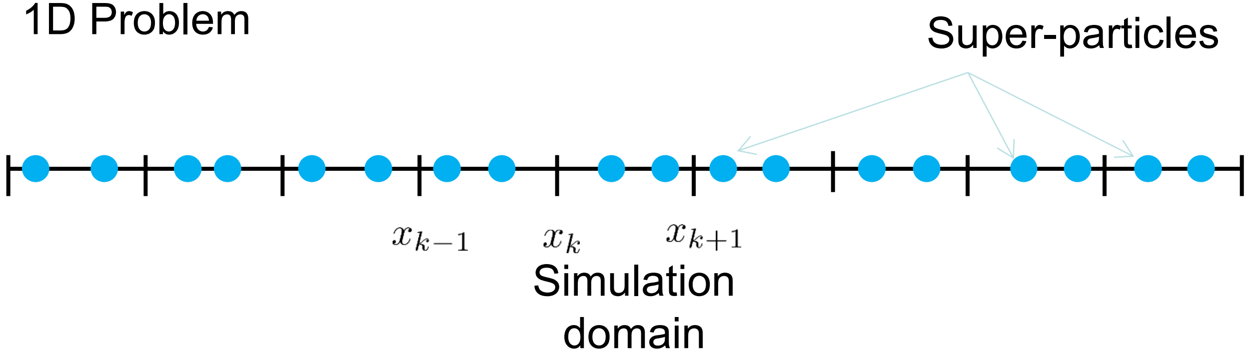
Particle in Cell Simulation

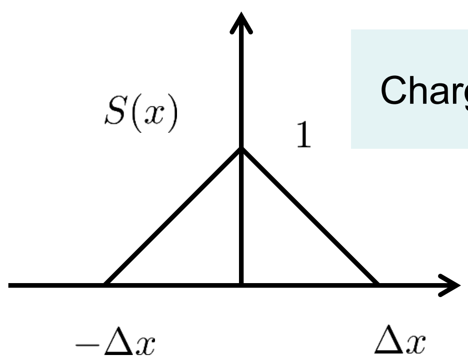
- Kinetic means „of or relating to motion“.
  - It is impractical to solve the equation of motion of all plasma particles.
  - Boltzman equation is an integro-differential equation.
- Particle-in-Cell : Super particle $10^6 - 10^9$ real particles.



Particles

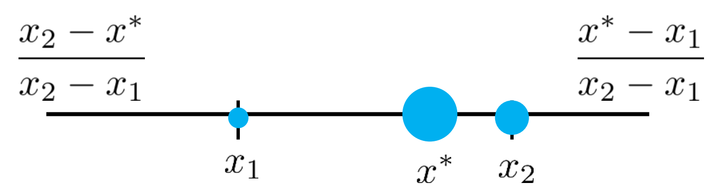
1D Problem





Charge cloud

First order wieghting



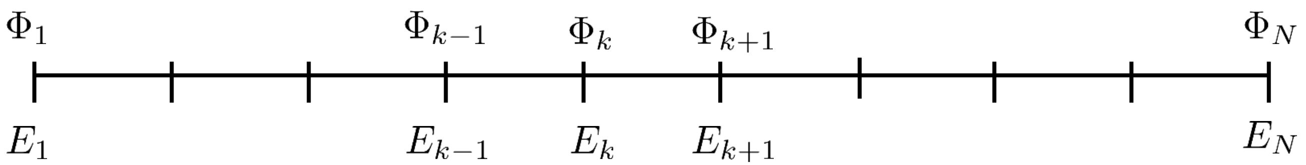
Fields

Poisson's eq.

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

Boundary condition

Boundary condition



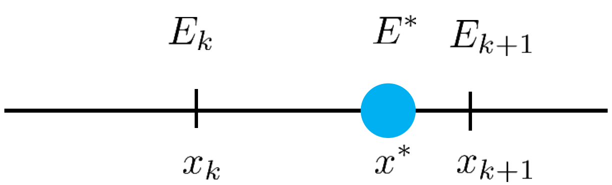
$$E_1 = -\frac{\Phi_2 - \Phi_1}{\Delta x} - \rho_1 \frac{\Delta x}{2\epsilon}$$

$$E_k = -\frac{\Phi_{k+1} - \Phi_{k-1}}{2\Delta x}$$

$$E_N = -\frac{\Phi_N - \Phi_{N-1}}{\Delta x} + \rho_N \frac{\Delta x}{2\epsilon}$$

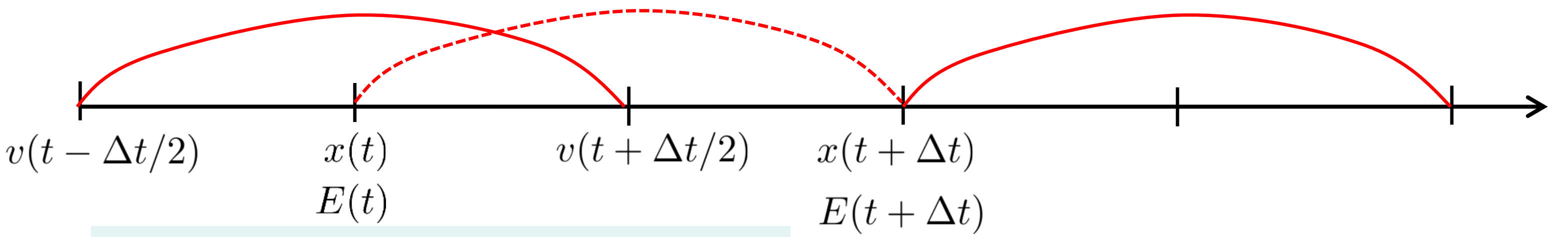
Interpolation of the fields to the particle positions

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



Pushing particles

„Leapfrog“ scheme



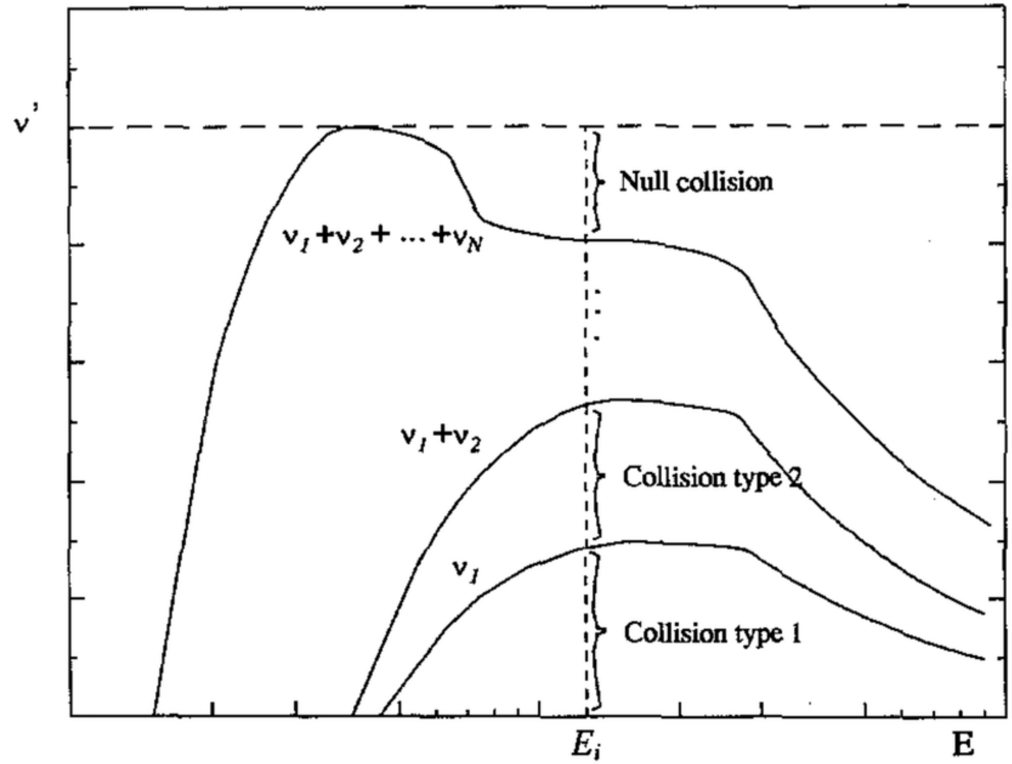
Descritization of equation of motions

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

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

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 $N_{\mathrm{D}} \gg 1$

- Keep the probabilty for collisions small

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

- 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}

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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}

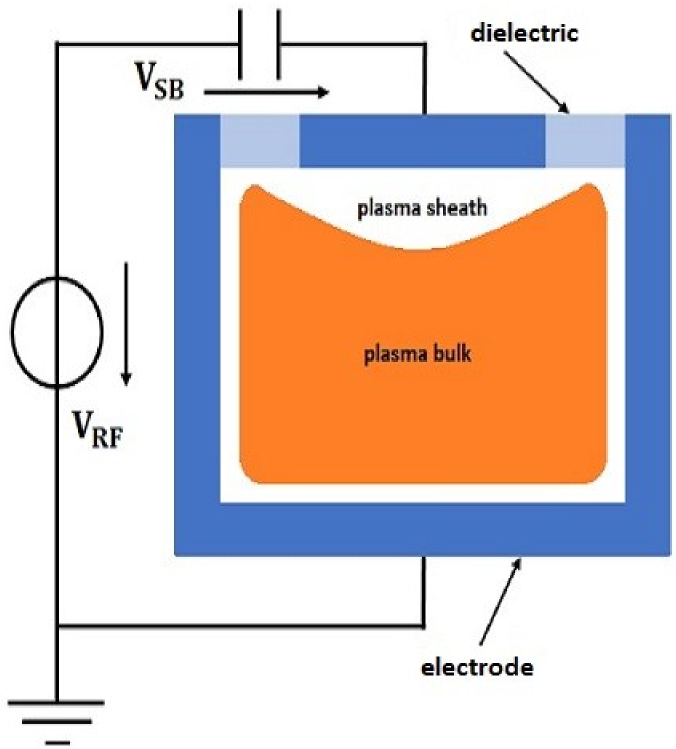
Global model:
Zero-dimensional model

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

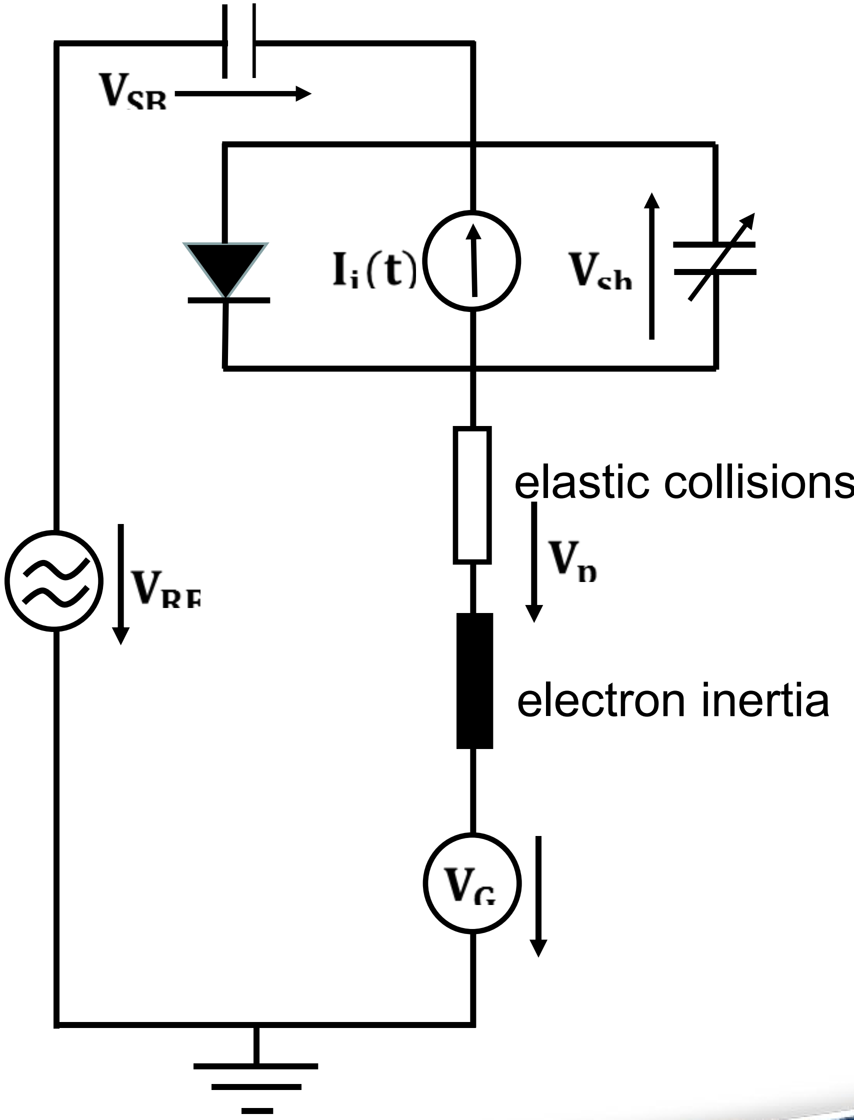
Note

- 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



TOGETHER FOR BRIGHT FUTURE

Experimental Side

Prof. Dr. Mohammed Shihab

Plasma Technology

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Outline

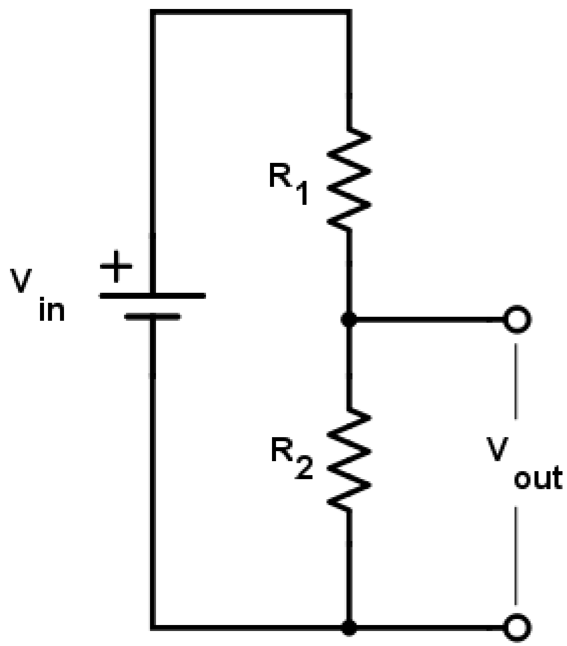
- Introduction.
  - Low temperature plasmas.

  - Measurements:
    - Voltage
    - Current
    - Density
    - Temperature

- Conclusion.

High Voltage Probe

High Voltage Probe



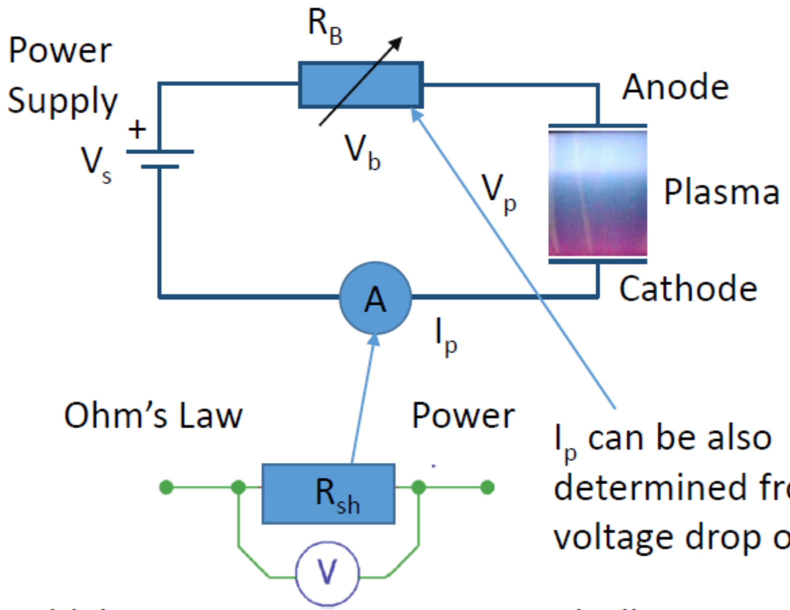
$$V_{in} = I(R_1 + R_2)$$

$$V_{out} = IR_2$$

$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_1 + R_2}$$

When $R_2 \ll R_1$ Then $V_{out} \ll V_{in}$

DC Current Measurements



I_p can be also determined from a voltage drop on R_B

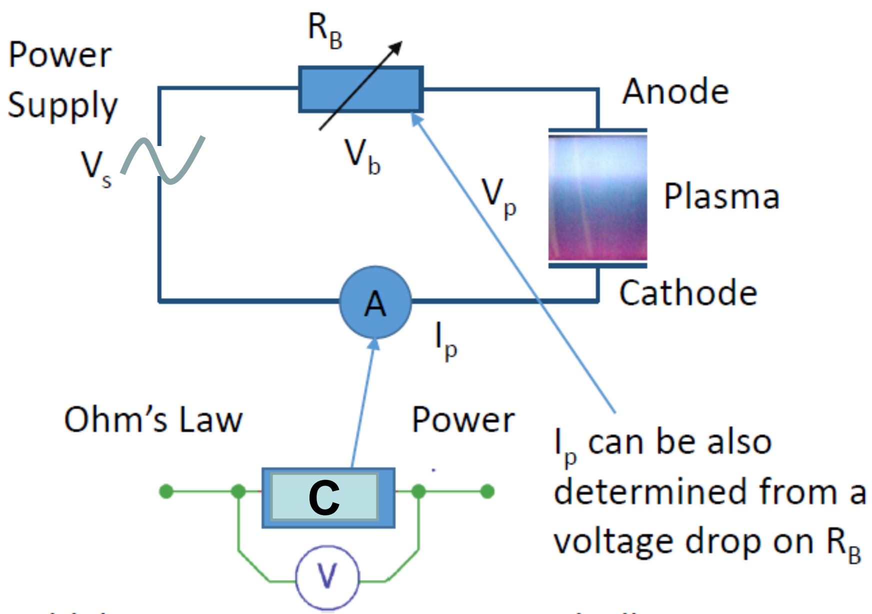
Typical accuracy ~1%
Range V: mV to kV
Range A: mA to A

34465A

Typical accuracy ~0.01%
Range V: mV to kV
Range A: microA to A

Shunt resistor for DC: V=IR

AC Current



Typical accuracy ~1%
Range V: mV to kV
Range A: mA to A

34465A

Typical accuracy ~0.01%
Range V: mV to kV
Range A: microA to A

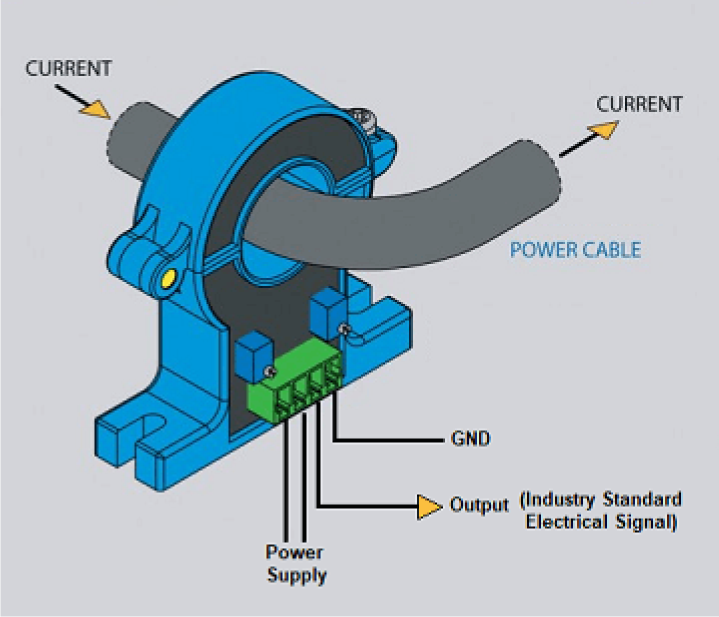
For AC, replace the resistance with capacitor

$$V = Q/C \qquad I = C\frac{dV}{dt}$$

Current Sensors

A current sensor is a dvice that detects and converts current to an easily measure output voltage

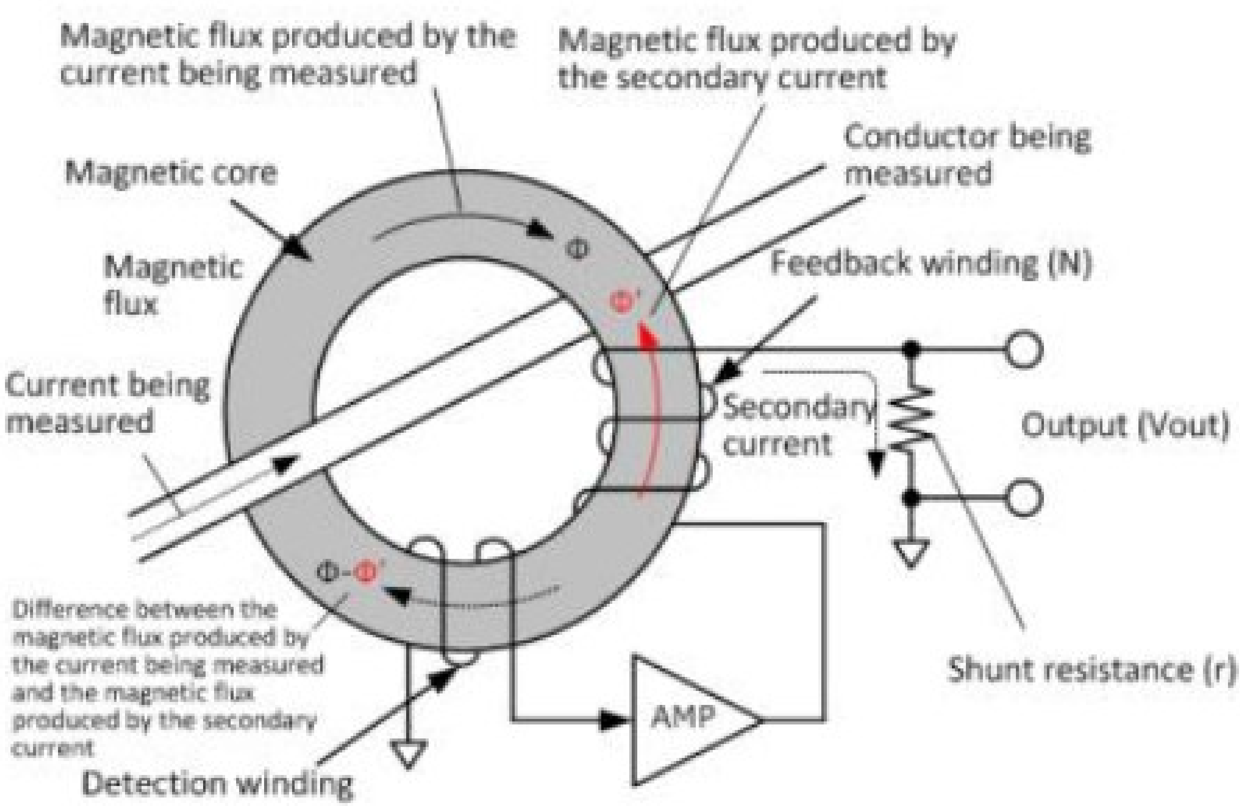
Current transducer



Current Sensors

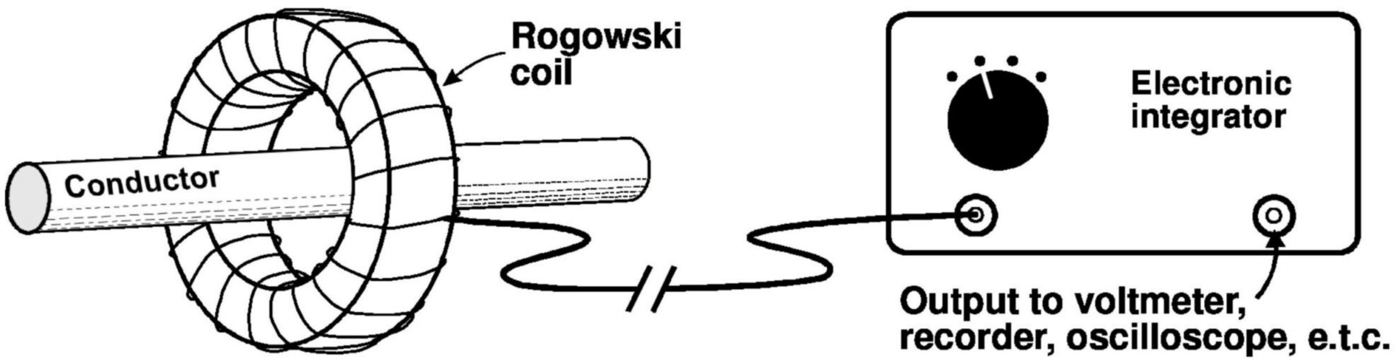
A current sensor is a dvice that detects and converts current to an easily measure output voltage

Zero-flux type (AC)



Current Sensors

A current sensor is a dvice that detects and converts current to an easily measure output voltage



A Rogowski coil is an 'air-cored' toroidal coil placed round the conductor. The alternating magnetic field produced by the current induces a voltage in the coil which is proportional to the rate of change of current.

$$V = M\frac{dI}{dt}$$

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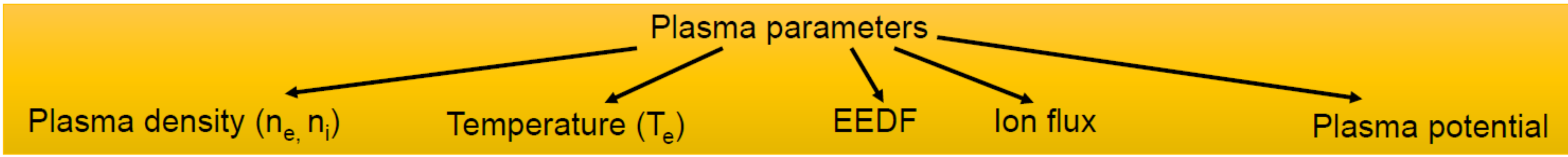
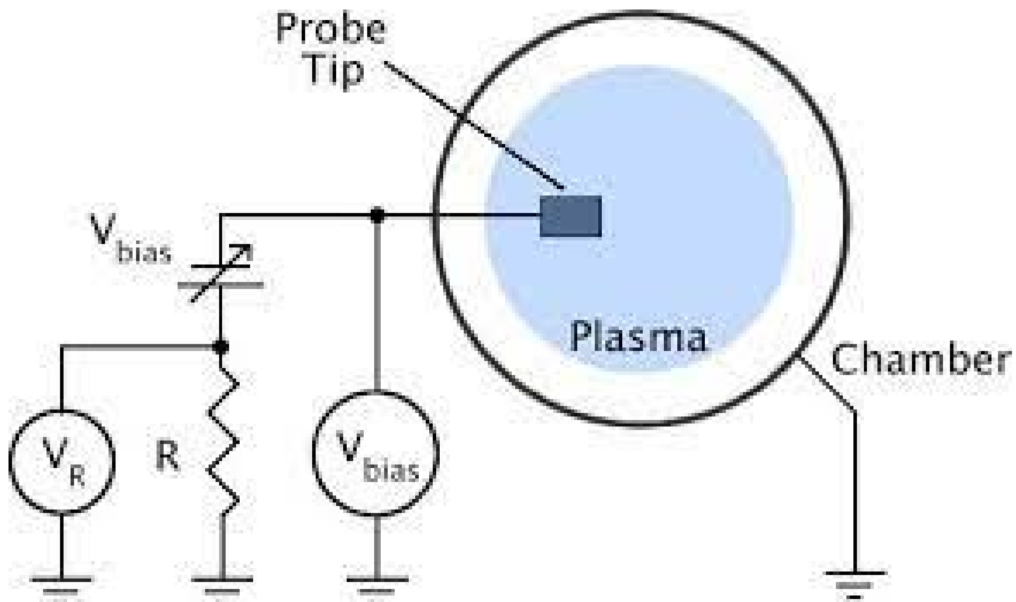
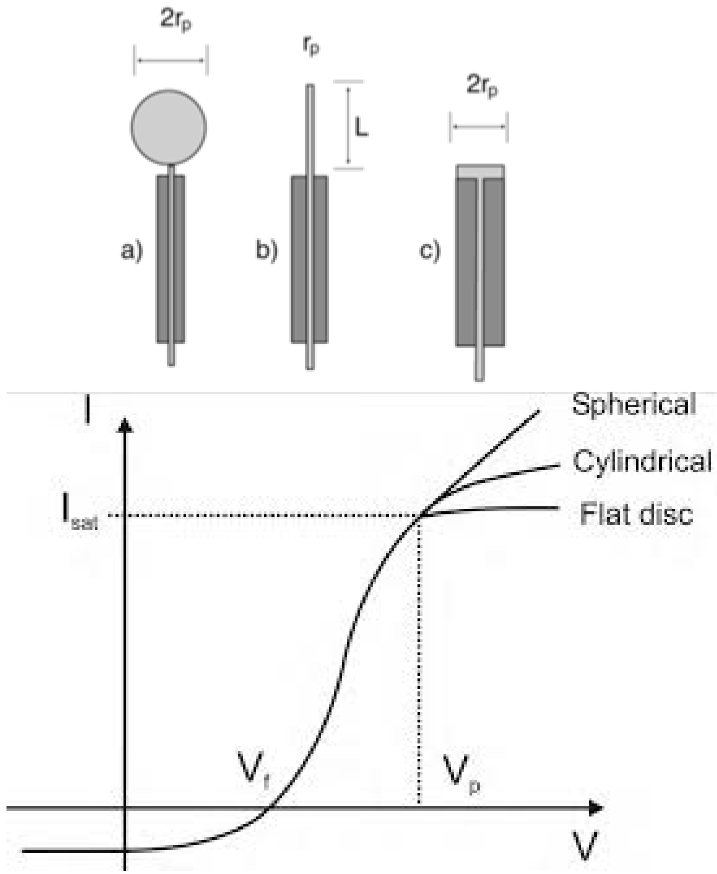
Langmuir Probe

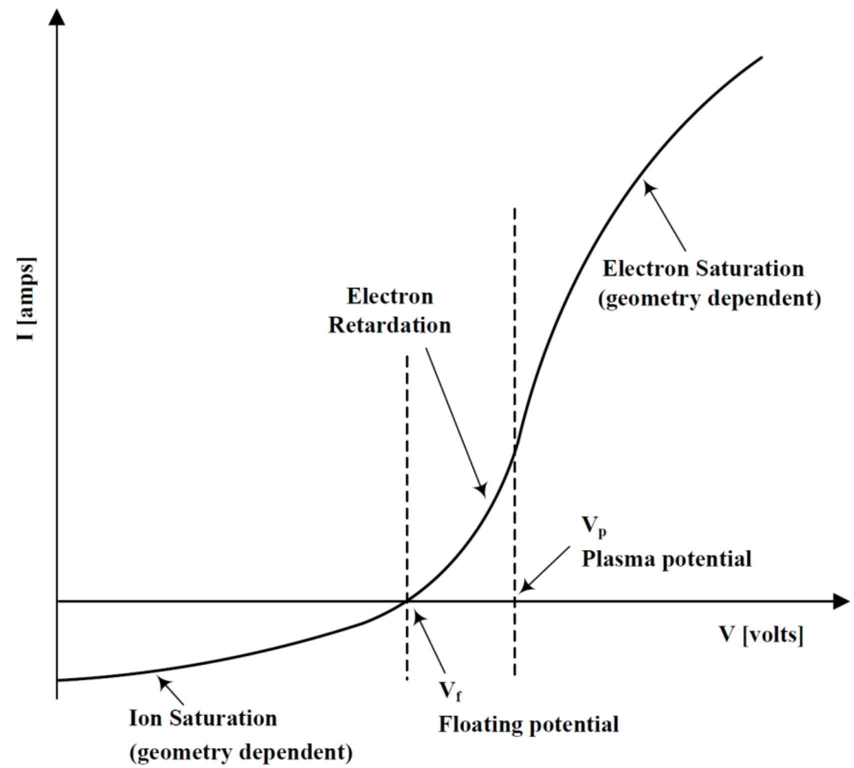
One of the most frequently employed methods for plasma diagnostics is Langmuir probes.





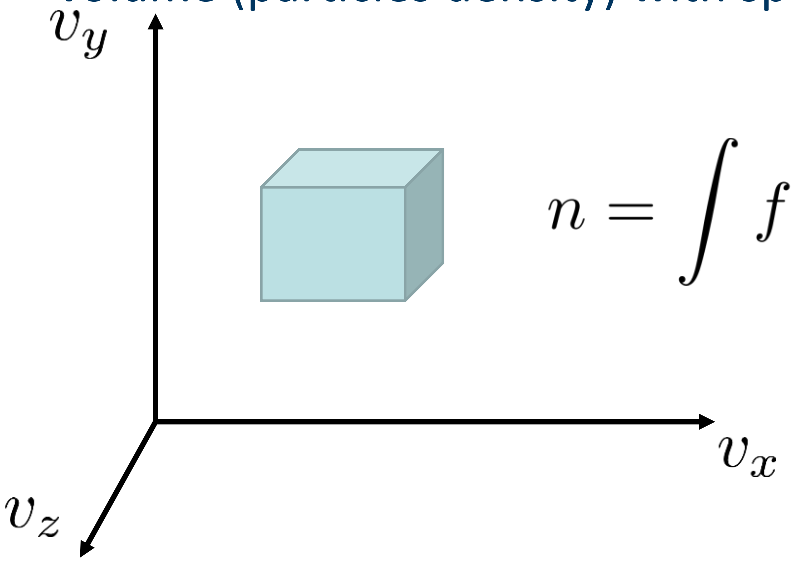
Langmuir Probe





The distribution function

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



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

- At equilibrium

$$f = f_0 \exp\left(\frac{-mv^2}{2k_B T_e}\right) \qquad f = f_0 \exp\left(\frac{-E_k}{k_B T_e}\right)$$

Sheath formation

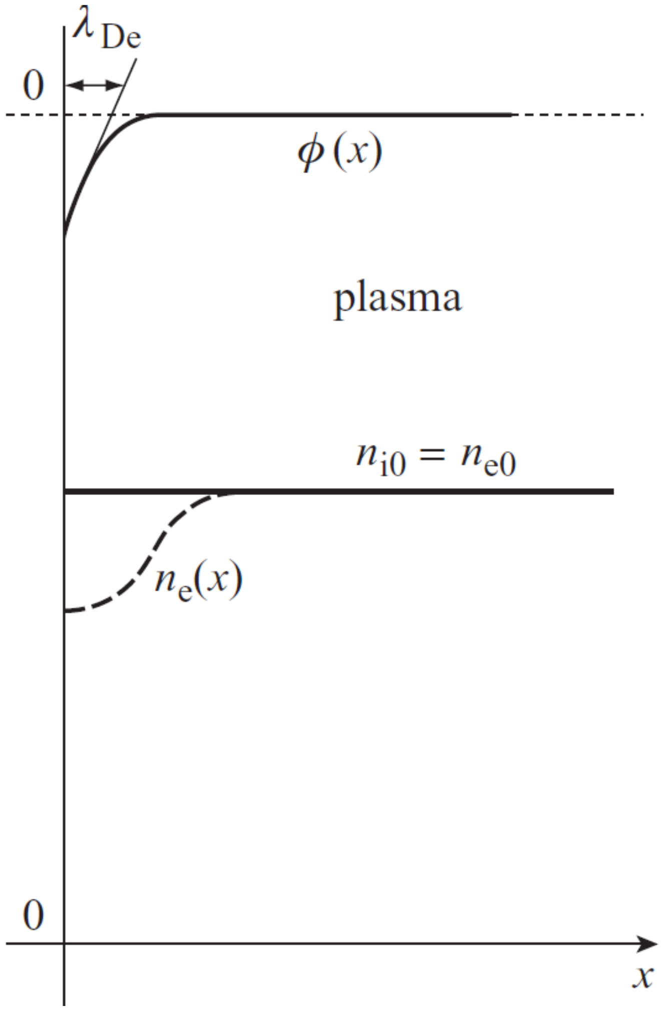
$$J_e = -e\Gamma_e = -\frac{1}{4} e n_e \bar{v}_e = -e n_e \sqrt{\frac{kT_e}{2\pi m}},$$

$$J_i = e\Gamma_i = \frac{1}{4} e n_i \bar{v}_i = e n_i \sqrt{\frac{kT_i}{2\pi M}}.$$

A steady state would be reached when the potential of the object is sufficiently negative for the electron flux to exactly balance that of the positive ions. Such a potential is called the *DC floating potential*. At balance:

$$n_e\sqrt{T_e/m} = n_i\sqrt{T_i/M}$$

$$n_i > n_e$$



Floating Sheath

$$\frac{(n_\mathrm{i} - n_\mathrm{e})e}{\varepsilon_0} = \frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2}.$$

$$e(n_\mathrm{i} - n_\mathrm{e}) = en_{\mathrm{e}0}\left[1 - \exp\left(\frac{e\phi}{kT_\mathrm{e}}\right)\right] \simeq -\frac{e^2 n_{\mathrm{e}0}\ \phi(x)}{kT_\mathrm{e}},$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = \frac{e^2 n_{\mathrm{e}0}\,\phi}{\varepsilon_0 k T_\mathrm{e}}.$$

$$\phi(x) = \phi_0 \exp\left(-\frac{x}{\lambda_{\mathrm{De}}}\right),$$

$$\lambda_{\mathrm{De}} = \sqrt{\frac{\varepsilon_0 k T_\mathrm{e}}{n_{\mathrm{e}0} e^2}}$$

Exercise 3.1: Debye length Calculate the Debye length for a plasma in which the electron density is $n_{\mathrm{e}0} = 1.0 \times 10^{16}\ \mathrm{m}^{-3}$ and $kT_\mathrm{e}/e = 2.0\ \mathrm{V}$.

Floating Potential

$$\Gamma_e = \frac{n_s \overline{v}_e}{4} \exp\left(-\frac{e\Delta\phi}{kT_e}\right).$$

$$\overline{v} = \left(\frac{8kT}{\pi m}\right)^{1/2}$$

The formation of the sheath retards electrons with a temperature T_e, Only electrons with energy greater than $e\Delta\phi$ can reach the electrode.

$$\Gamma_e = \Gamma_i$$

$$\Delta\phi = -V_f$$

$$\frac{n_s \overline{v}_e}{4} \exp\left(\frac{eV_f}{kT_e}\right) = n_s u_B$$

Bohm Speed: $$u_s = \left(\frac{kT_e}{M}\right)^{1/2}$$

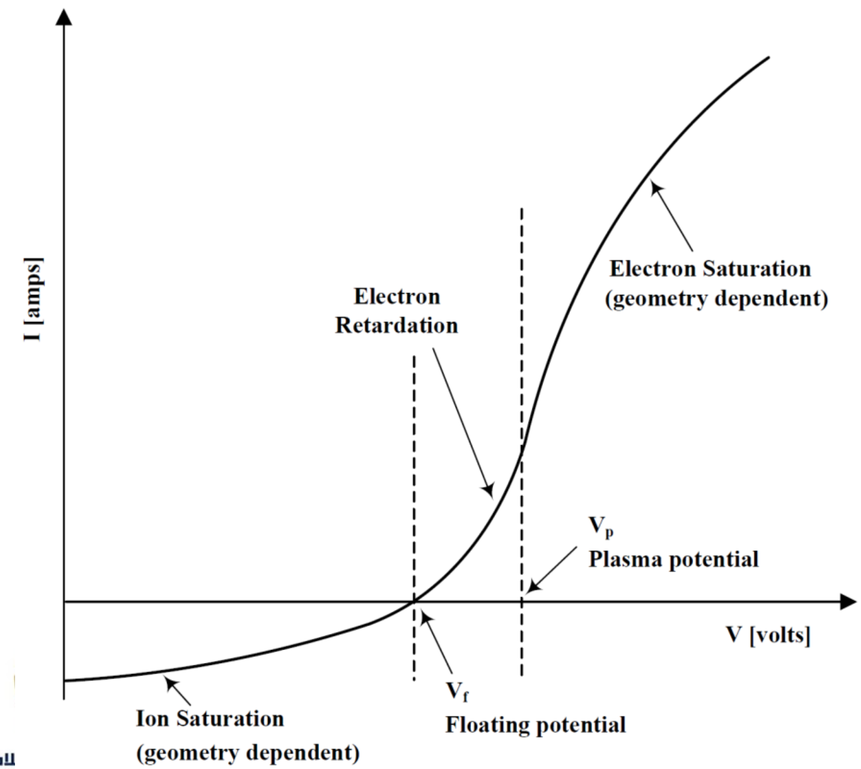
$$V_f = \frac{kT_e}{e} \frac{1}{2} \ln\left(\frac{2\pi m}{M}\right)$$

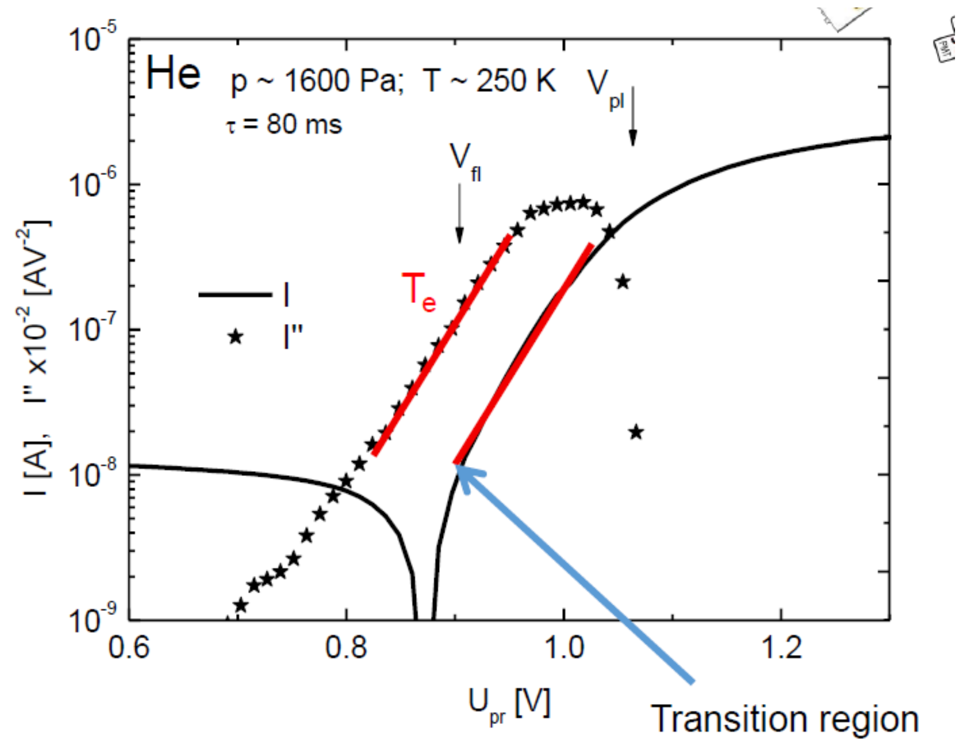
Langmuir Probe

The electron temperature T_e for any plasma is well defined if the EEDF is Maxwellian

$$\ln[I_e(V)] = \ln[I_{e0}] - \frac{e}{kT_e}V$$

$$I_e(V) = I_{e0}\exp\left(-\frac{eV}{kT_e}\right)$$

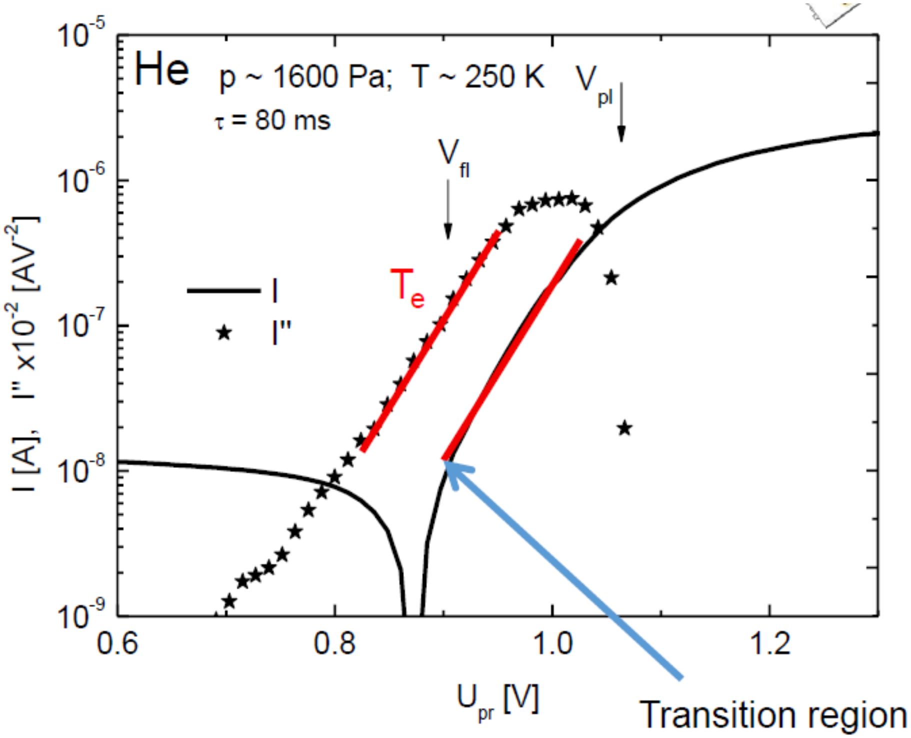




Langmuir Probe:

Druyvesteyn method*

The electron temperature T_e for any plasma is well defined if the EEDF is Maxwellian



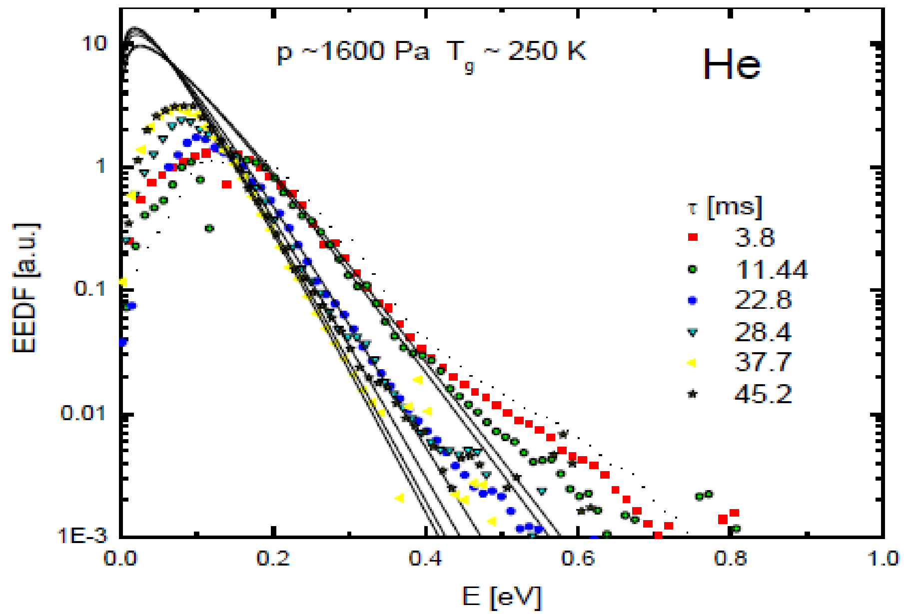
$$\frac{d^2I}{d(V-V_p)^2} = \frac{1}{4}Aq^2\sqrt{\frac{2q}{m_e(V-V_p)}}[f(E)]$$

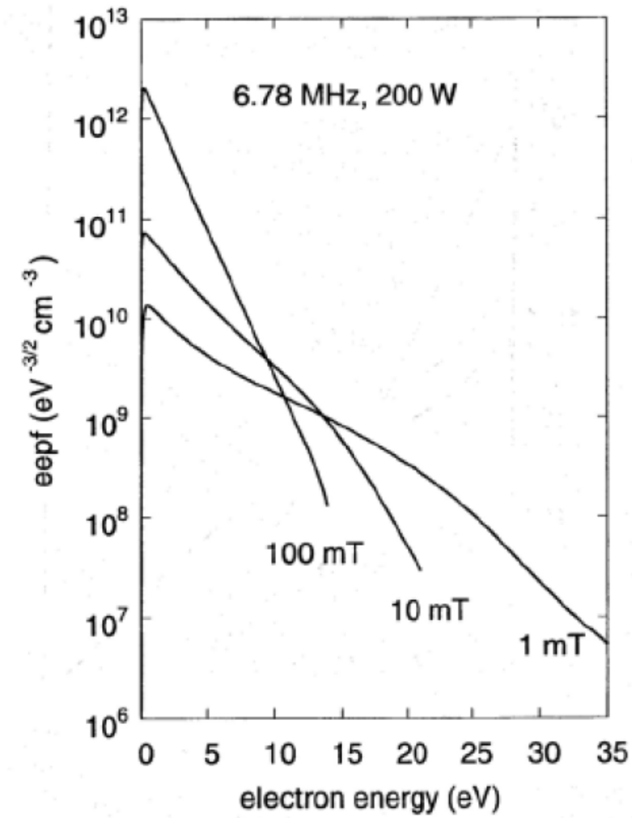
$$\frac{d^2I}{d(V-V_p)^2} = \frac{1}{4}Aq^3\sqrt{2\pi m_e}(k_BT_e)^{-3/2}e^{\left[\frac{q(V-V_p)}{k_BT_e}\right]}$$

Maxwellian EEDF

*Druyvesteyn M.J., *Z. Physik* **64**(1930)781

Maxwellian versus Bi-Maxwellian





V. I. Demidov and C. A. DeJoseph Jr. Rev. Sci. Instrum. 77, 116104 (2006)

F.F. Chen Langmuir probe diagnostics, IEEE-ICOPS meeting, Jeju, Koreja, 2003

V. Godyak and R. Piejak, Phys. Rev. Lett. 65, 996 (1990)

Electron Density

By EEDF integrating over all energies

$$n_e = \int_0^{\varepsilon_{\max}} f(\varepsilon)\,d\varepsilon \quad \Leftrightarrow \quad n_e = \int_0^{-\infty} f(U)\,dU$$

From I_e

$$n_e = \frac{1}{S_{probe}\,q}\sqrt{\frac{2\pi m_e}{kT_e}}\,I_e(U_{pr} = V_{pl})$$

V_{pl} ! T_e!

J. D. Swift and M. J. R. Schwar. *Electrical probes for plasma diagnostics. London Iliffe books Ltd., 1970.*

I-squared method

Slope of $I^2(U)$

$$I^2 = \frac{2(Aqn_e)^2}{\pi^2 m_e}[k_B T_e + q(U_{pr} - V_{pl})] \qquad n_e = \sqrt{\frac{\pi^2 m_e}{2A^2 q^3} S}$$

Španěl P.: *Int J. Mass Spectrom and Ion Proces.*, 149/150, 299, 1995

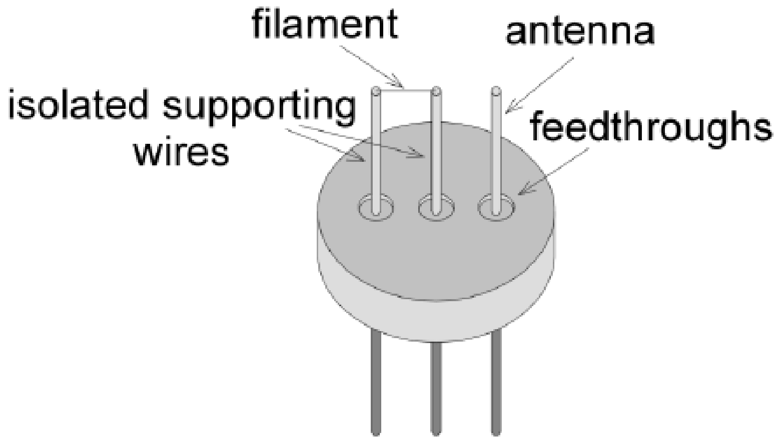
The concentration of electrons can be easily obtained without the need to determine accurate values of V_{pl} and T_e

Problems with Langmuir Probes

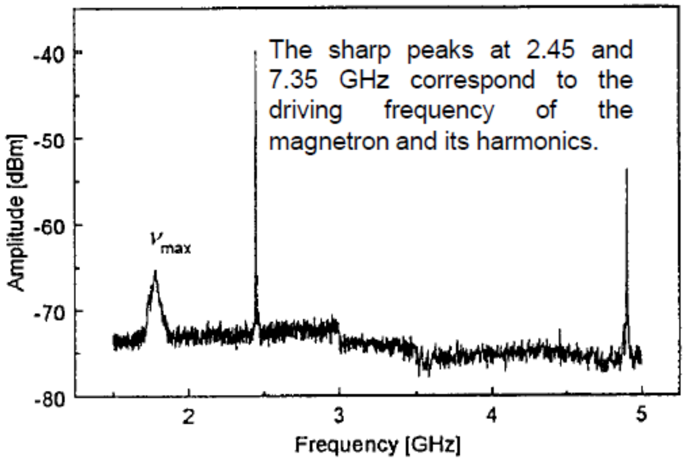
- Melting of the probe
- Contamination of the probe
- Interpretation of the results
- Need physics access to the plasma
- Langmuir probe failed in case of insulator deposition experiments

Plasma Oscillation Probes

In the plasma oscillation method a weak electron beam injected into the plasma excites electrostatic electron waves oscillating at the electron plasma frequency, which is proportional to the square root of the electron density.



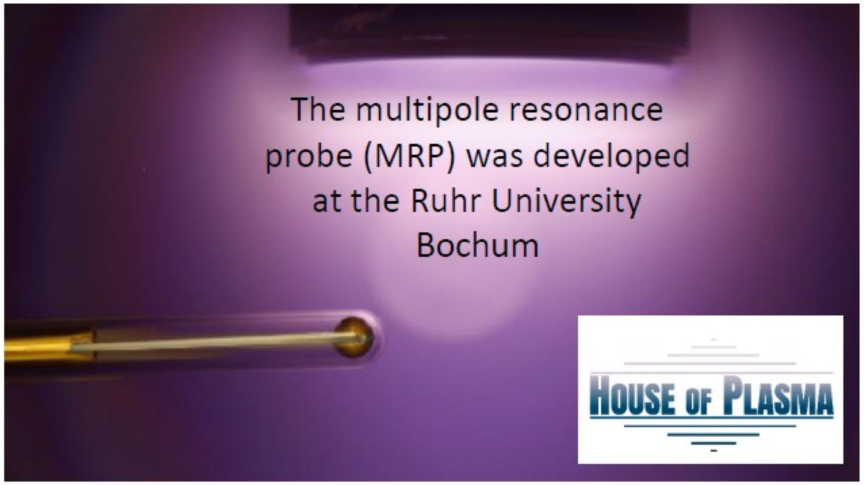
Frequency spectrum in Argon



$$\nu_{\max} \approx \omega_{pe} = \sqrt{\frac{q^2 n_e}{\varepsilon_0 m_e}}$$

A Schwabedissen, Plasma Sources Sci. Technol. 8 (1999) 440–447

Plasma Absorption Probes



$$f_{\text{res}} \sim \omega_{\text{pe}} \sim \sqrt{n_e}$$

The measuring principle is based on Active Plasma Resonance Spectroscopy (APRS). The probe is used to couple a highfrequency signal in the megahertz to gigahertz range via a dielectric into the plasma. At a frequency close to the electron plasma frequency, the plasma absorbs the energy of the signal and resonates. The response of the plasma-probe-system – the reflection value – is picked up by the probe and transmitted to an evaluation unit. Due to symmetry of the probe, its behavior can be analyzed mathematically transparent and a formulaic relationship between the resonance frequency and the electron density of the plasma can be specified.

Retarding Field Analyzer

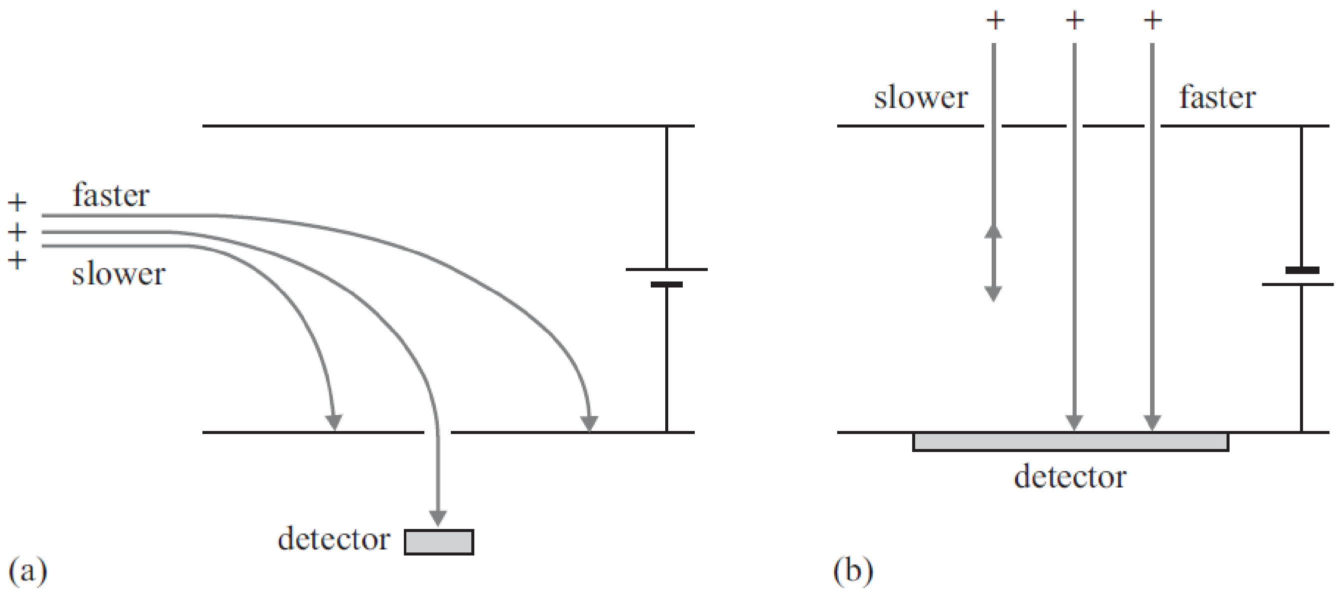
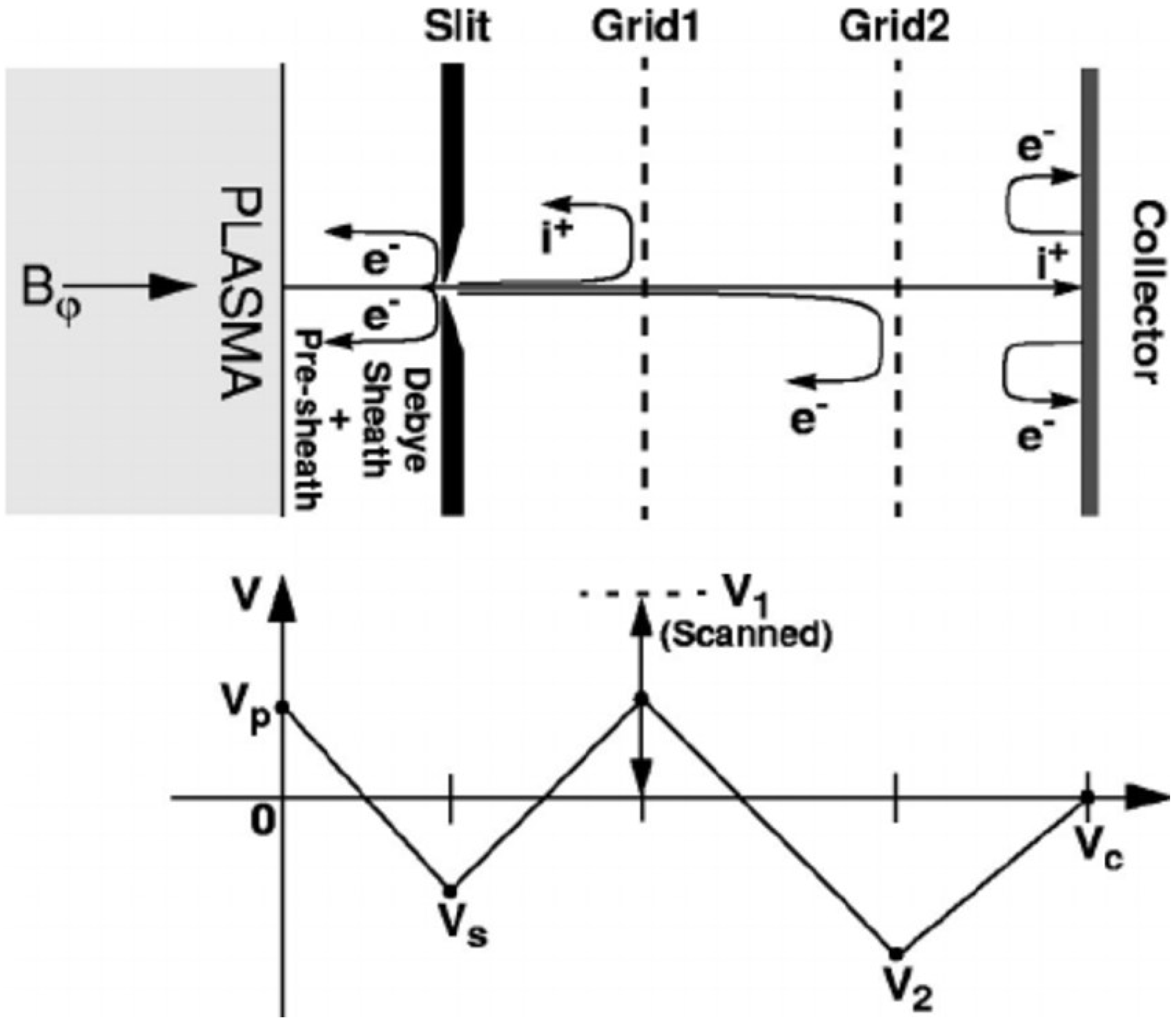


Figure 10.15 (a) A deflecting filter selects particles within a specific (narrow) range of energy; (b) a retarding filter passes particles with energy above a threshold level.

Retarding Field Analyzer



Retarding Field Analyzer

$$I = nevA$$

$$\frac{dI}{d\Phi} = eA\frac{d}{d\Phi}\int vf(v)dv$$

$$nv = \int vf(v)dv$$

$$\frac{dI}{d\Phi} = eA\frac{d}{dv}\frac{dv}{d\Phi}\int vf(v)dv$$

$$\frac{dI}{d\Phi} = eA\frac{dv}{d\Phi}\frac{d}{dv}\int vf(v)dv$$

$$\frac{dI}{d\Phi} = eA\frac{dv}{d\Phi}vf(v)$$

Retarding Field Analyzer

$$\frac{dI}{d\Phi} = eA\frac{dv}{d\Phi}vf(v)$$

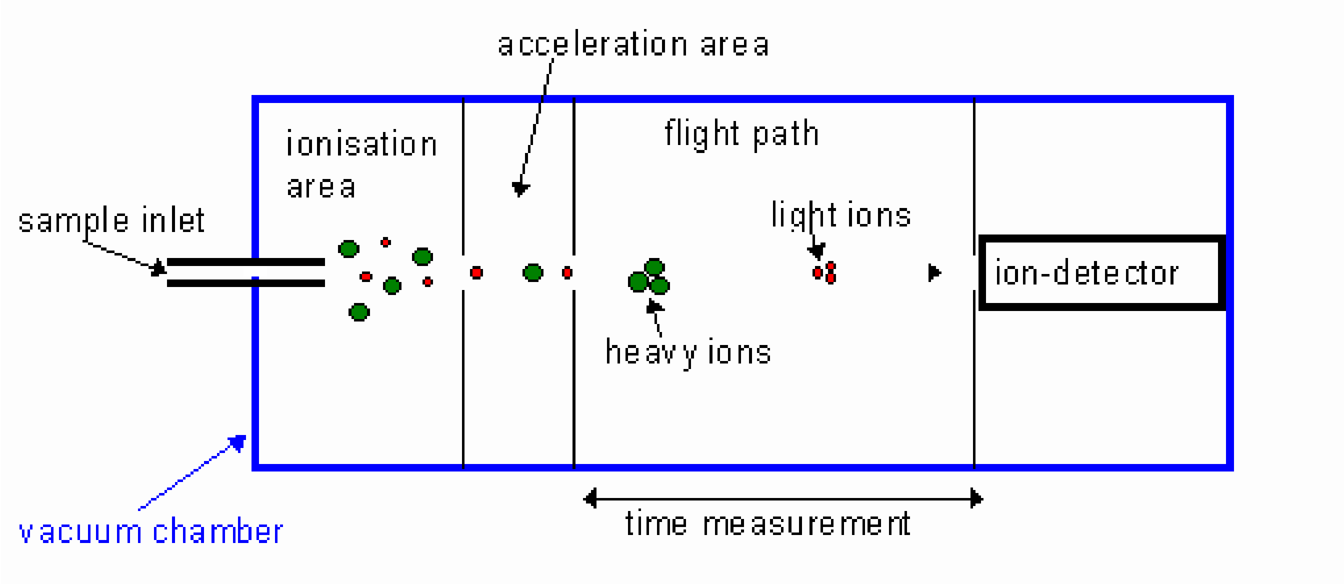
In collisionless plasma

$$e\Phi = \frac{1}{2}mv^2 \qquad ed\Phi = mvdv \qquad \frac{dv}{d\Phi} = \frac{e}{mv}$$

$$\frac{dI}{d\Phi} = eA\frac{dv}{d\Phi}vf(v) \qquad \frac{dI}{d\Phi} = eA\frac{e}{mv}vf(v)$$

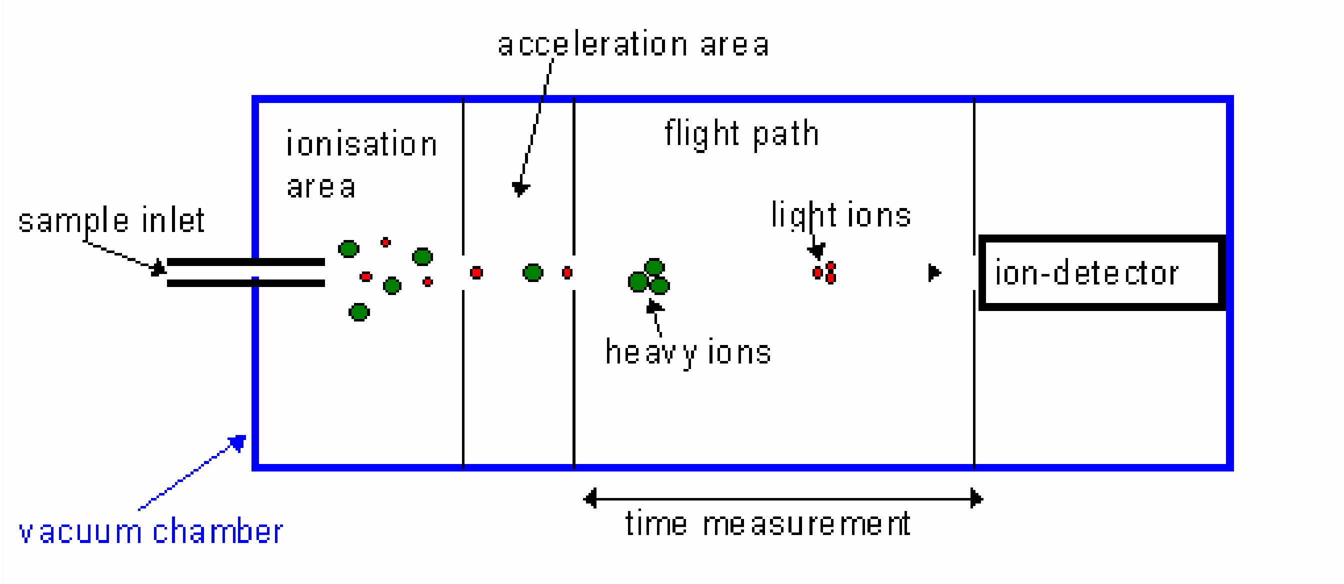
$$\frac{dI}{d\Phi} = A\frac{e^2}{m}f(v)$$

Mass Spectrometer



A **Time-of-Flight Mass Spectrometer** works by **accelerating** an **ionised** sample and calculating **mass per charge** based on how long each ‘object’ is in **flight** for. Since every ‘object’ receives equal force, according to Newton’s Second Law, the acceleration of each ‘object’ will be inversely proportional to its mass.

Mass Spectrometer



The sample is first **ionised** by **bombarding it with electrons**, which also causes **fragmentation** to form smaller groups of atoms. Ions tend to have **+1 charge**, since a bombarding electron will knock an electron out of an atom's shell, so 'mass per charge' can generally be taken as simply '**mass**'.

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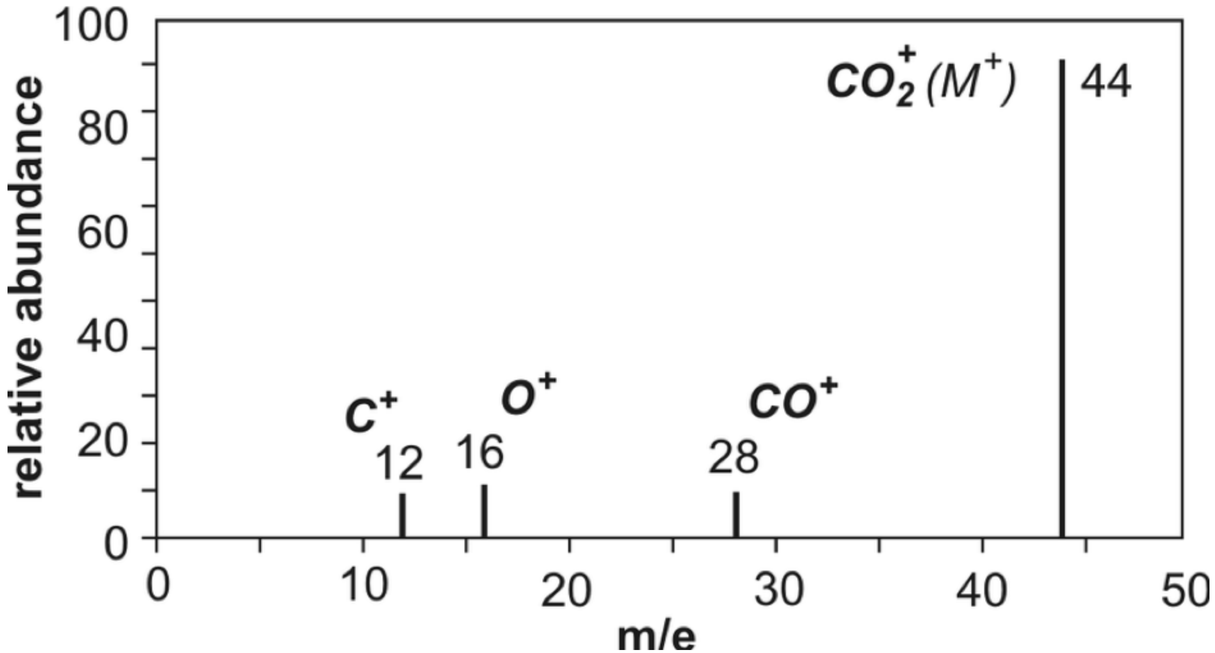
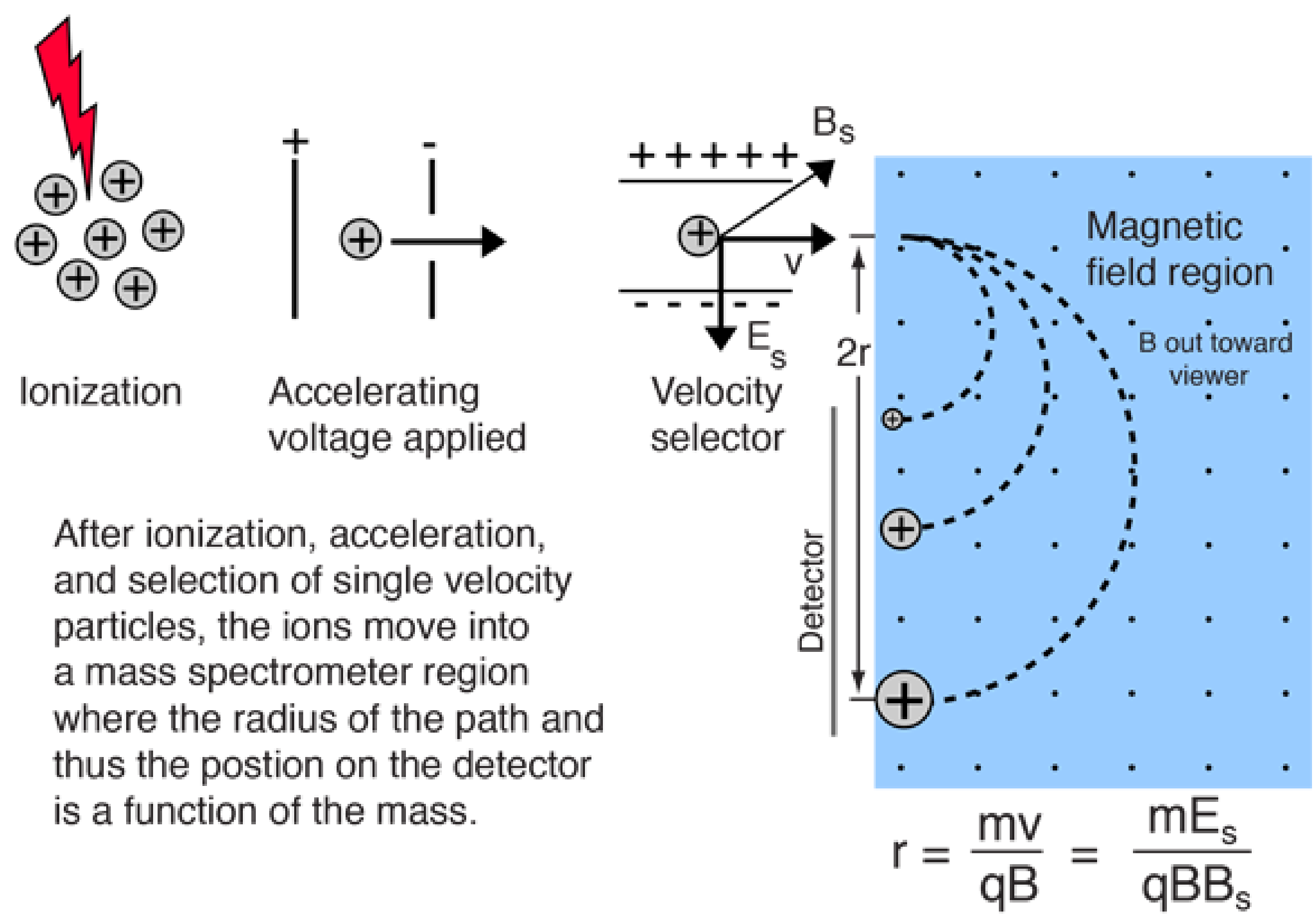
Mass Spectrometer



The ions are then **accelerated** by **Electromagnetic Field** and travel through a **vacuum** area called the **Drift Region**, before being **detected** by the **Ion Detector**.

Mass Spectrometer



The emission Spectrum

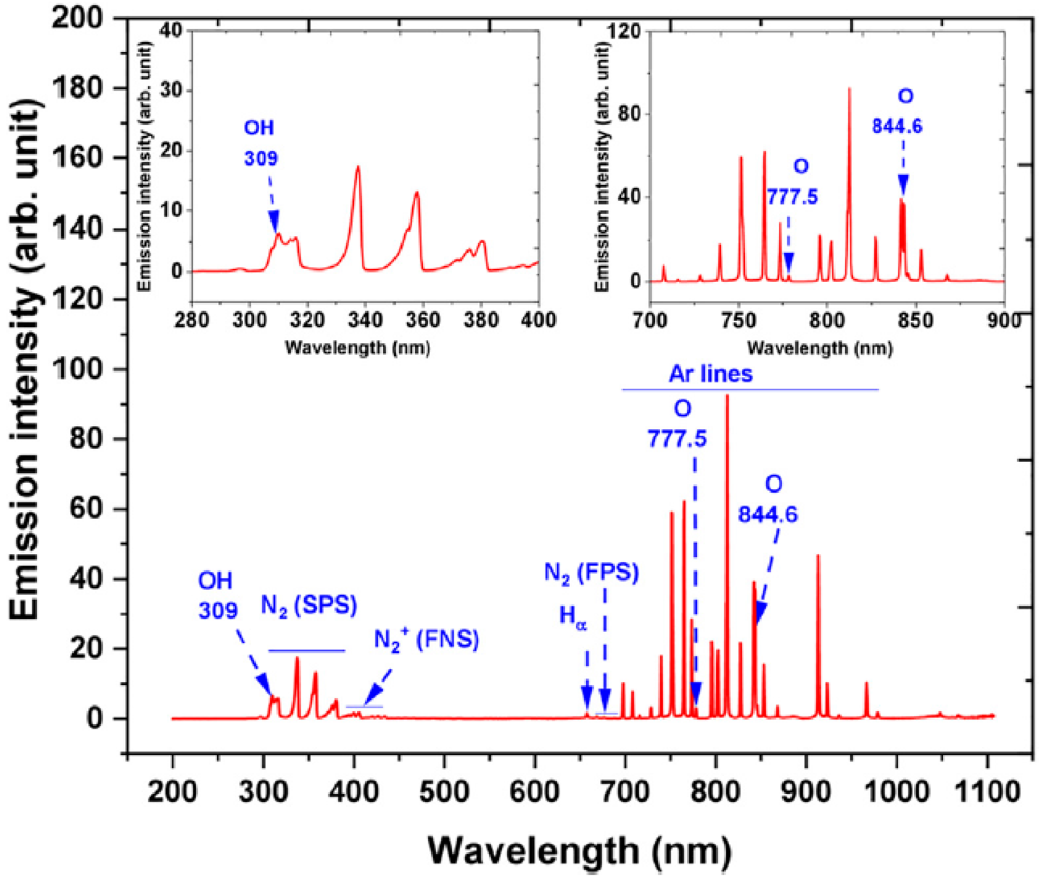


FIGURE 6 | The emission spectrum of Ar—APPJ in contact with ambient air and over a liquid surface. During the diagnostics, AB25 was placed under APPJ, $V_o = 5$ ml, Ar 1 slm, P_{mean} at the sample 11 W. Inset plots show parts of the spectrum zoomed.

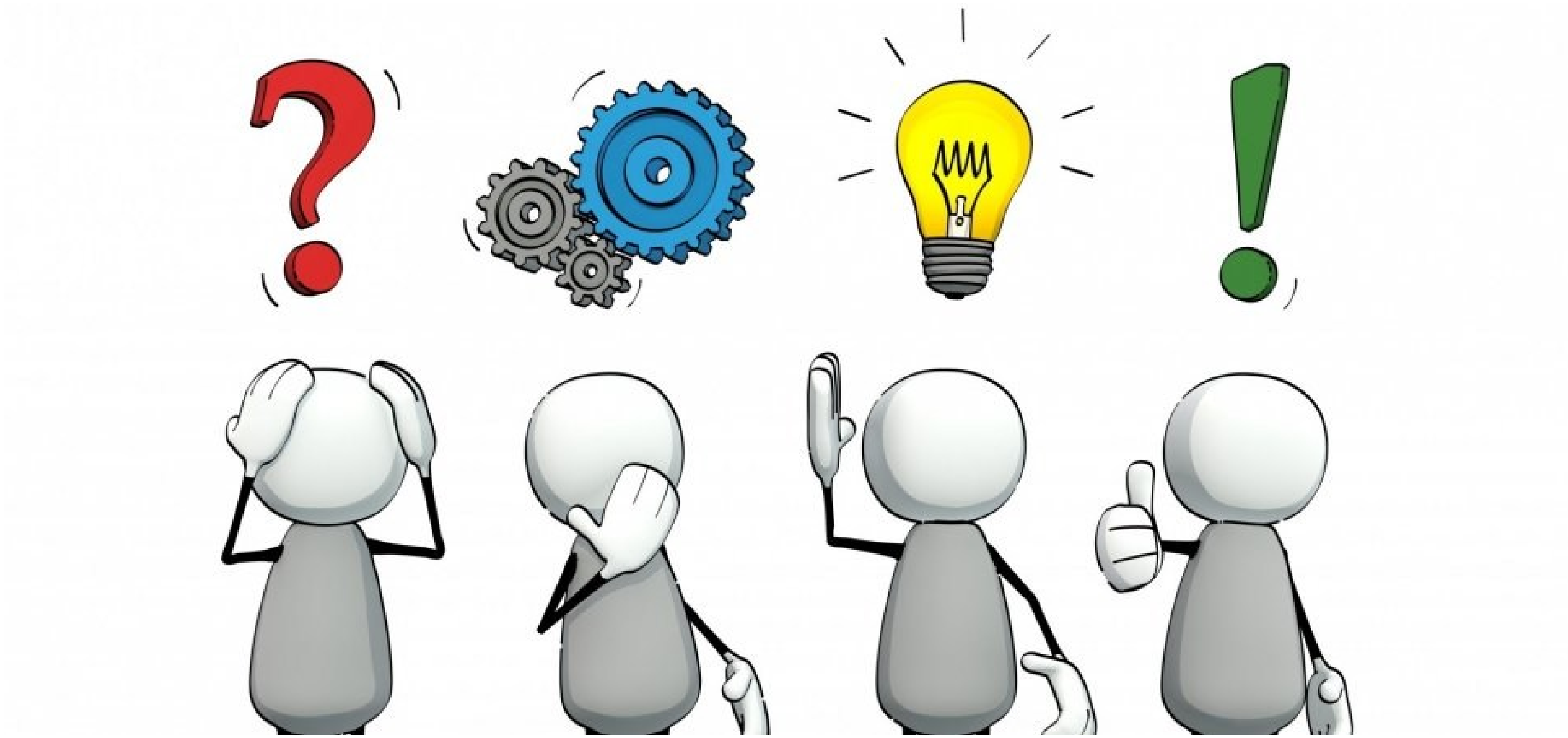
Good and fast Start

- **References:**

- **PRINCIPLES OF PLASMA DISCHARGES AND MATERIALS PROCESSING, MICHAEL A. LIEBERMAN & ALLAN J. LICHTENBERG, John Wiley & Sons, Inc (2005).**

- **PHYSICS OF RADIO-FREQUENCY PLASMAS, PASCAL CHABERT & NICHOLAS BRAITHWAITE, Cambridge University Press (2011).**

- **Spacial issue „ Plasma and Nanotechnology“ : , J. Phys. D: Appl. Phys. 44 (2011)**



Thanks!