Technical Plasma: Experimental Side

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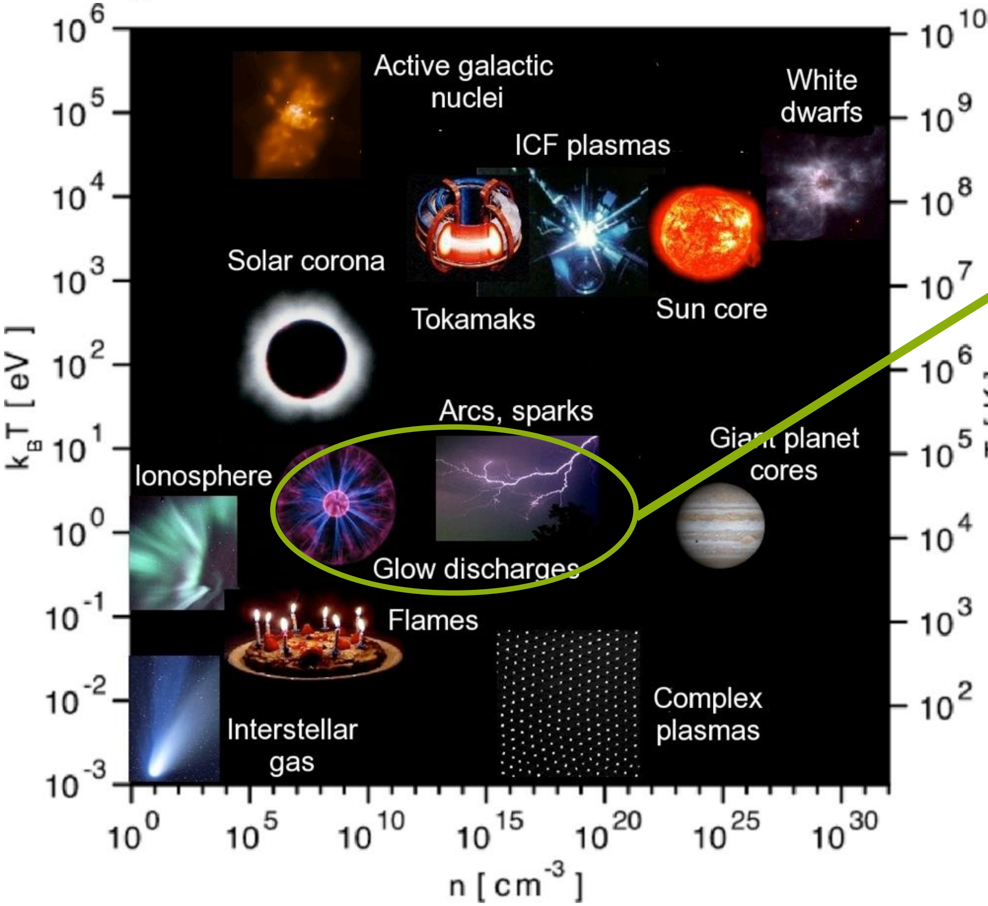
Outline

- Introduction.
  - Low temperature plasmas.

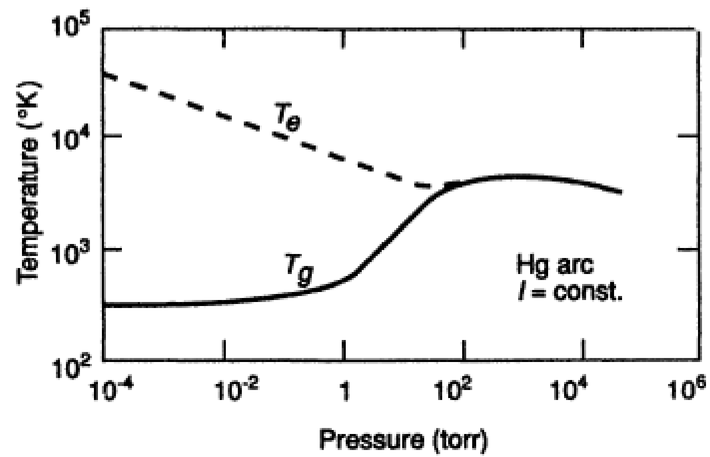
  - Measurements:
    - Voltage
    - Current
    - Density
    - Temperature

- Conclusion.

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

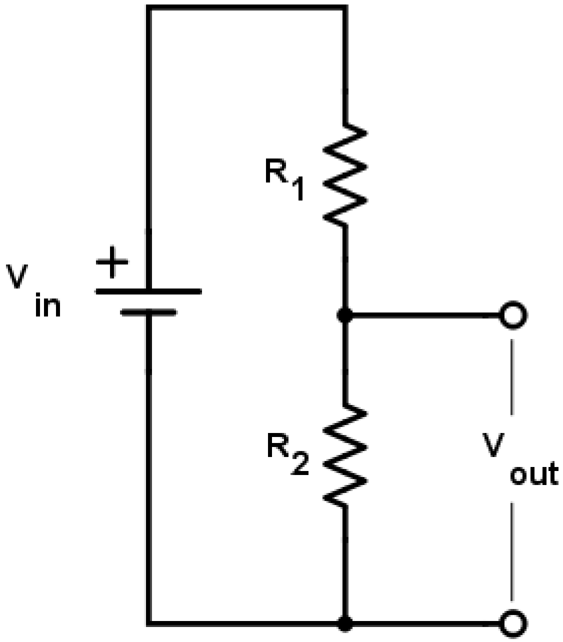


- Non-equilibrium plasmas at low pressures

$$T_e = 1 - 5\mathrm{eV} \qquad T_i = 300\mathrm{K}$$

High Voltage Probe

High Voltage Probe



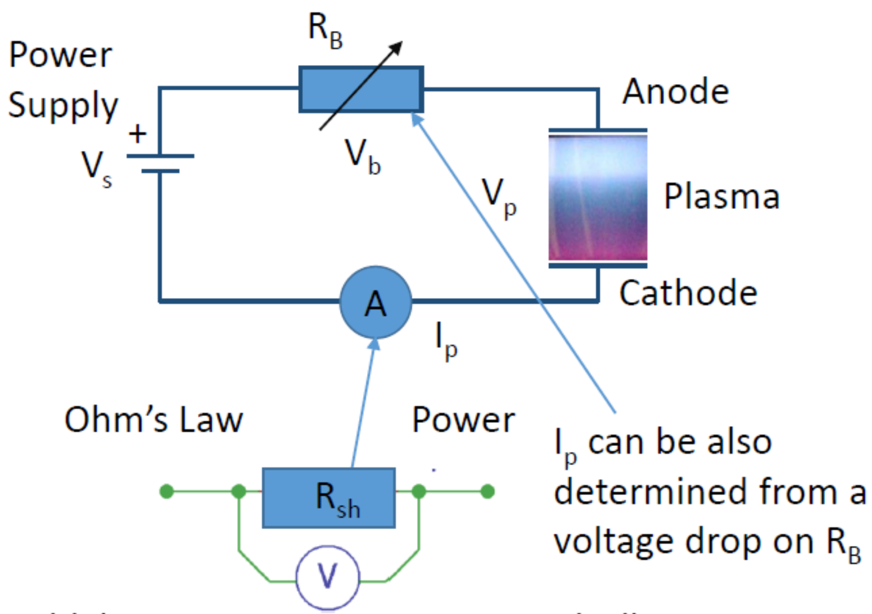
$$V_{in} = I(R_1 + R_2)$$

$$V_{out} = IR_2$$

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

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

DC Current Measurements



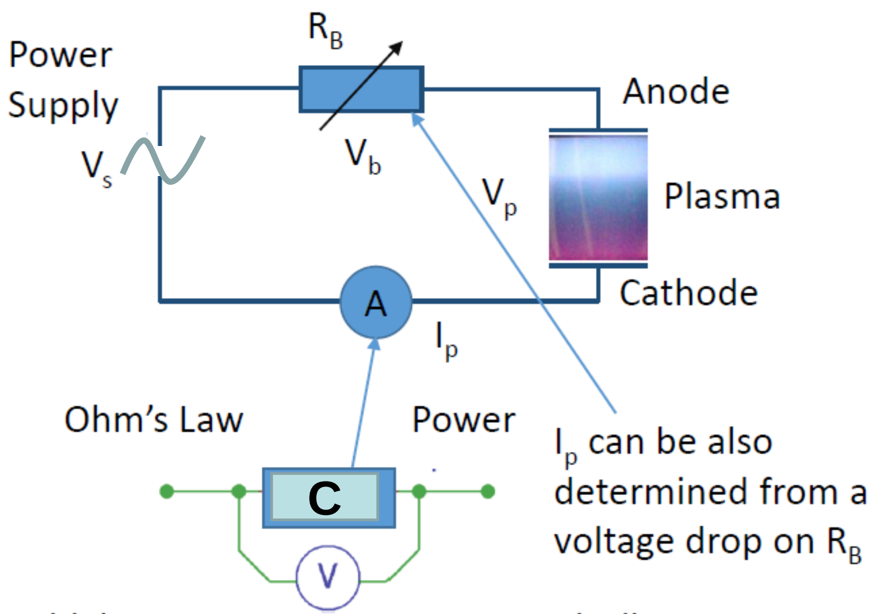
Shunt resistor for DC: V=IR

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

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

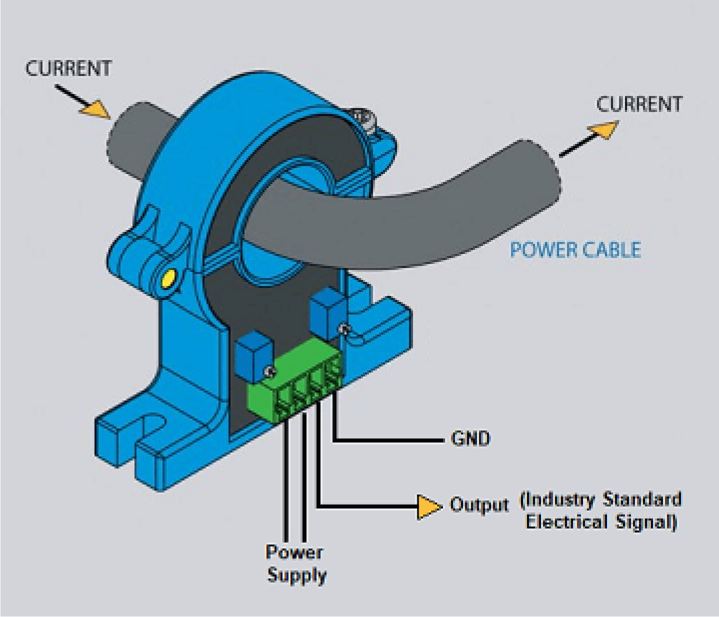
For AC, replace the resistance with capacitor

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

Current Sensors

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

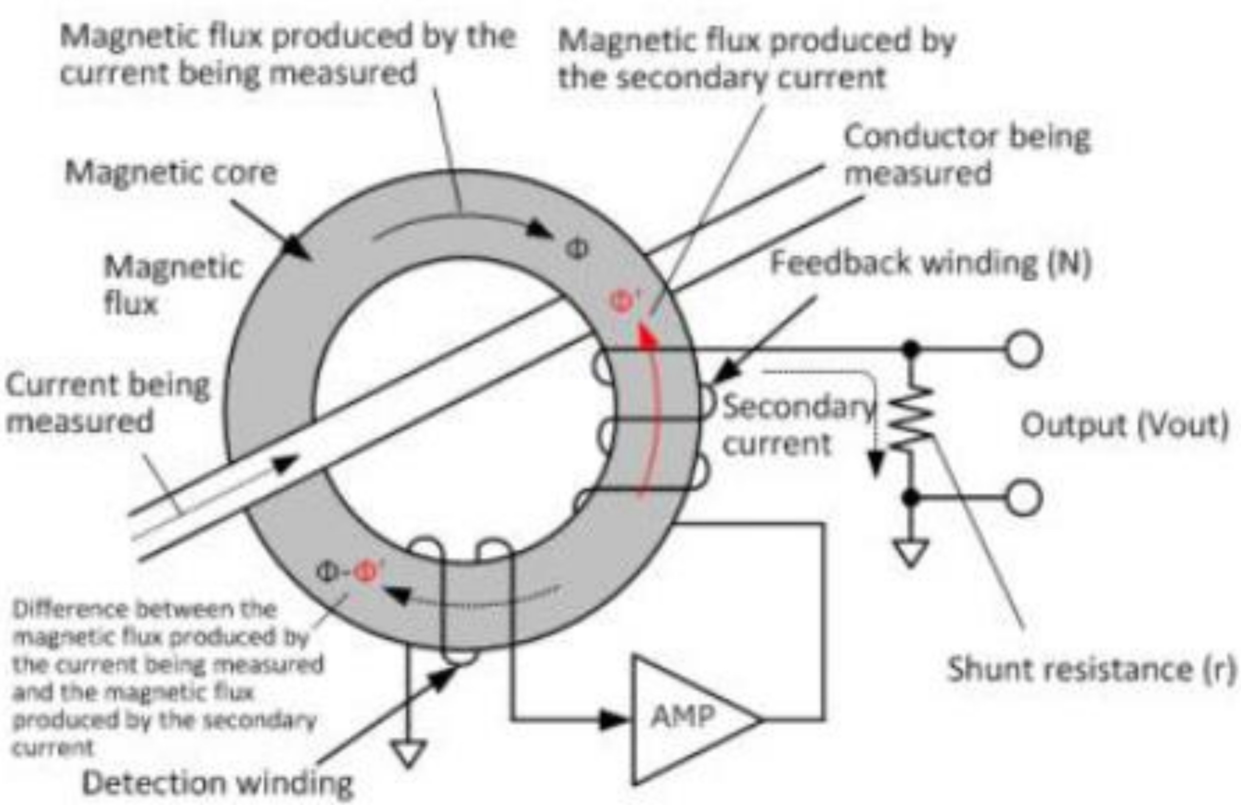
<u>Current transducer</u>



Current Sensors

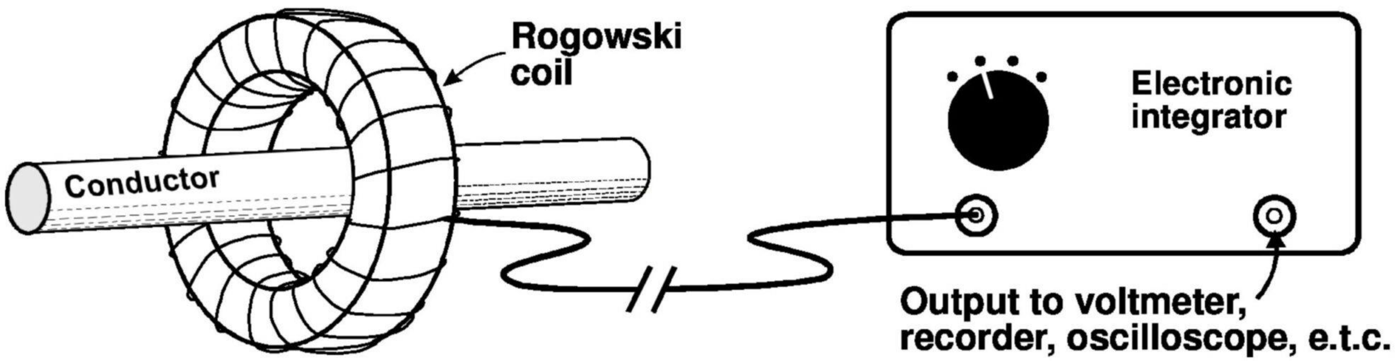
A current sensor is a dvice that detects and converts current to an easily measure output voltage

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.

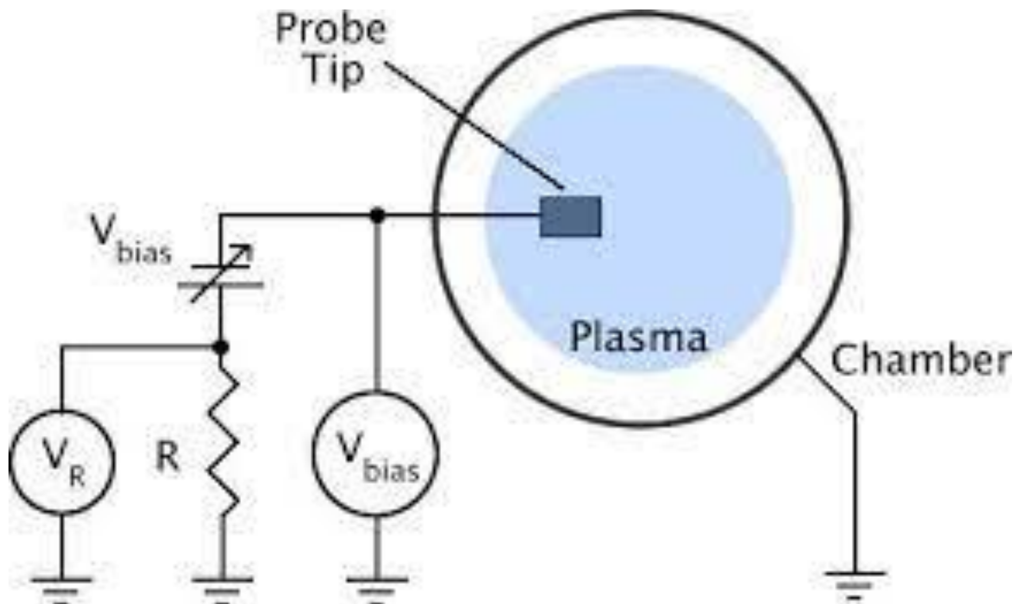
$$V = M\frac{dI}{dt}$$

Langmuir Probe

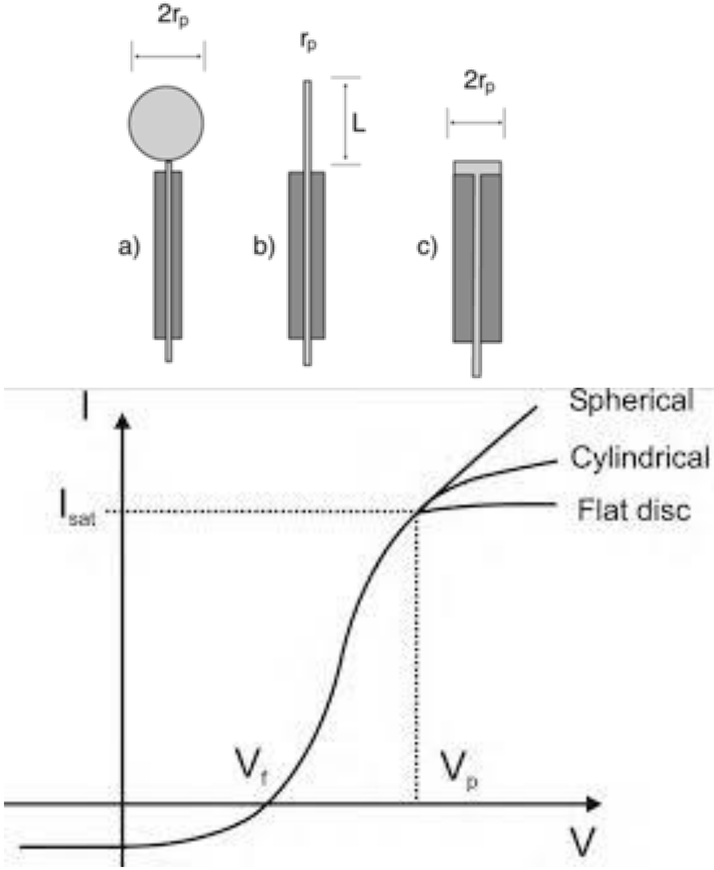
One of the most frequently employed methods for plasma diagnostics is Langmuir probes.

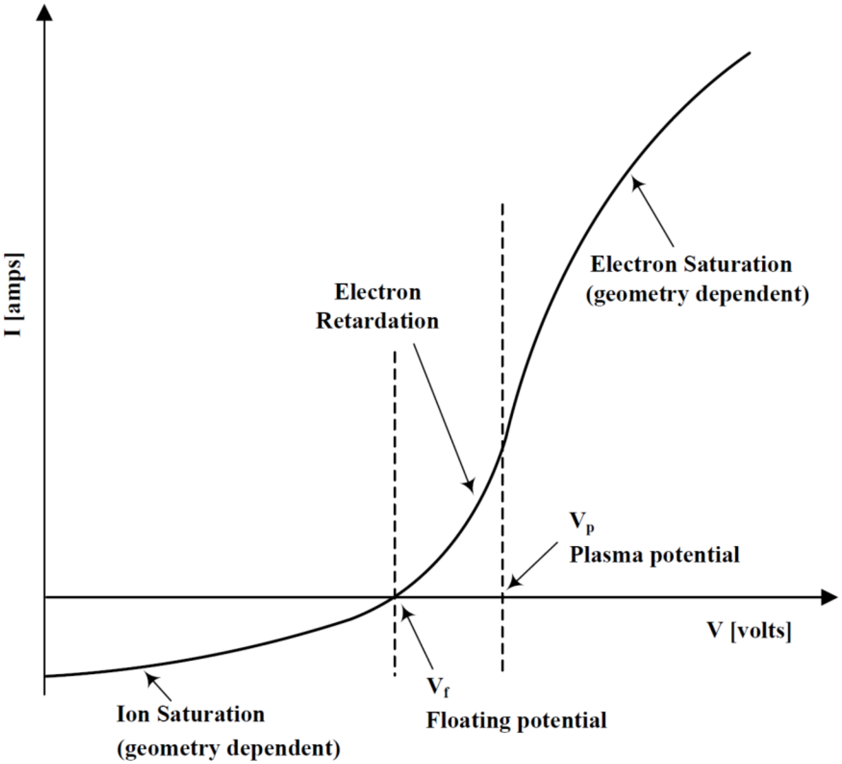
Plasma parameters

Plasma density (n_e, n_i) | Temperature (T_e) | EEDF | Ion flux | Plasma potential



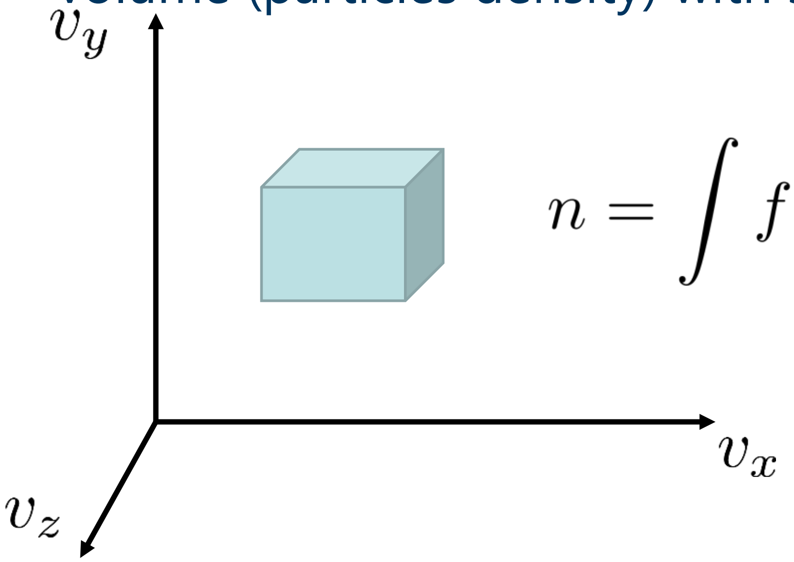
Langmuir Probe





The distribution function

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



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

- 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

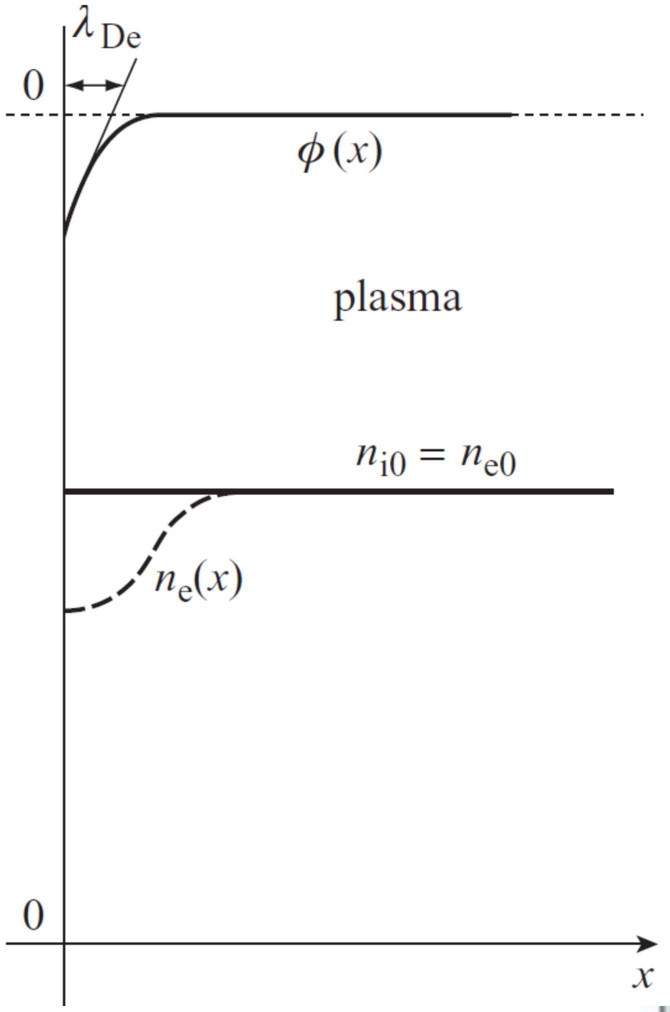
$$J_e = -e\Gamma_e = -\frac{1}{4} e n_e \bar{v}_e = -e n_e \sqrt{\frac{kT_e}{2\pi m}},$$

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

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*

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

$$n_i > n_e$$



Floating Sheath

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

$$e(n_{\mathrm{i}} - n_{\mathrm{e}}) = en_{\mathrm{e0}}\left[1 - \exp\left(\frac{e\phi}{kT_{\mathrm{e}}}\right)\right] \simeq -\frac{e^2 n_{\mathrm{e0}}\ \phi(x)}{kT_{\mathrm{e}}},$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = \frac{e^2 n_{\mathrm{e0}}\,\phi}{\varepsilon_0 k T_{\mathrm{e}}}.$$

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

$$\lambda_{\mathrm{De}} = \sqrt{\frac{\varepsilon_0 k T_{\mathrm{e}}}{n_{\mathrm{e0}} e^2}}$$

Exercise 3.1: Debye length Calculate the Debye length for a plasma in which the electron density is $n_{\mathrm{e0}} = 1.0 \times 10^{16}\ \mathrm{m}^{-3}$ 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:

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

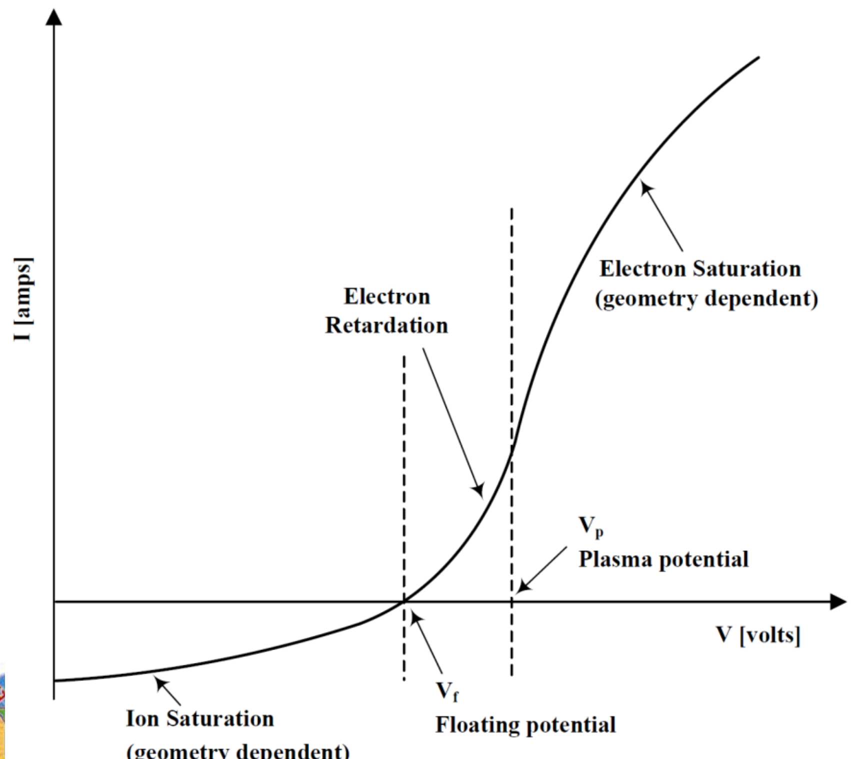
$$V_f = \frac{kT_e}{e} \frac{1}{2} \ln\left(\frac{2\pi m}{M}\right)$$

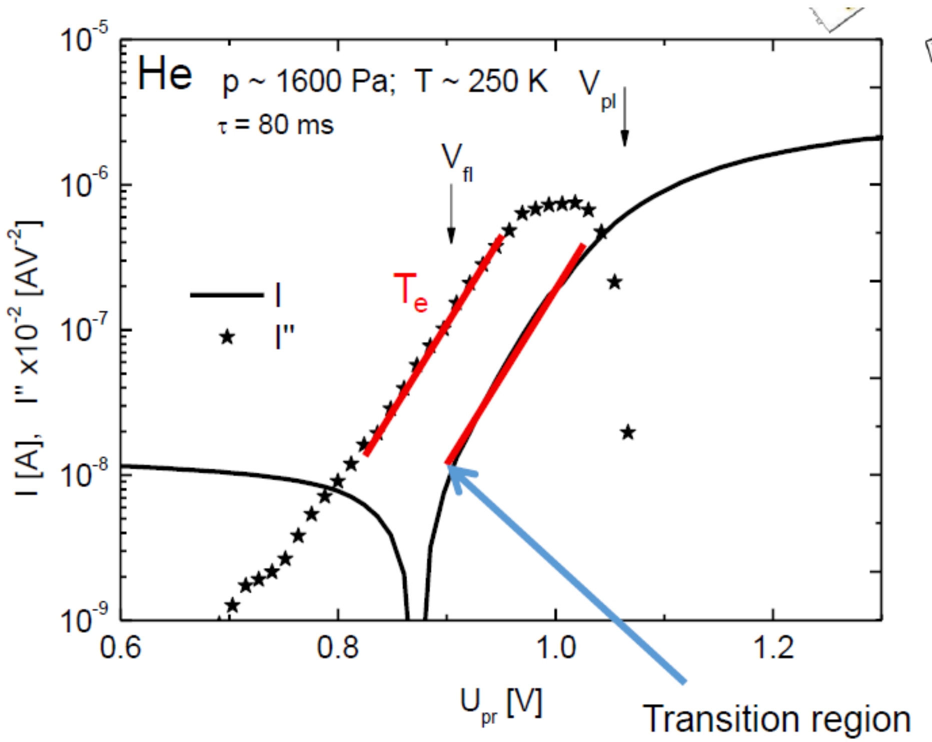
Langmuir Probe

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

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

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

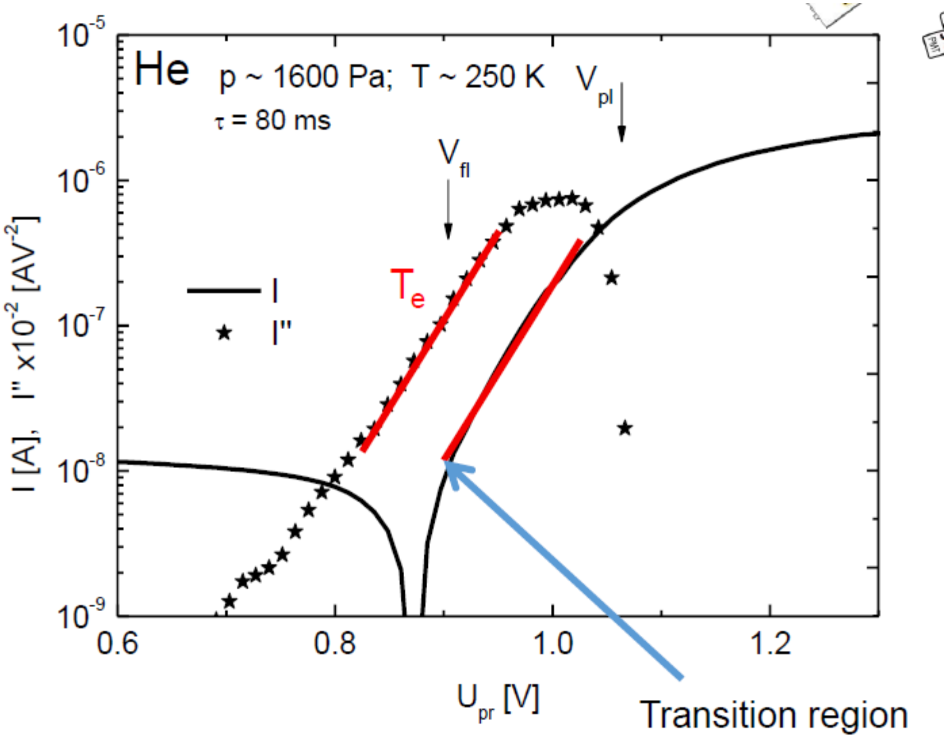




Langmuir Probe:

Druyvesteyn method*

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



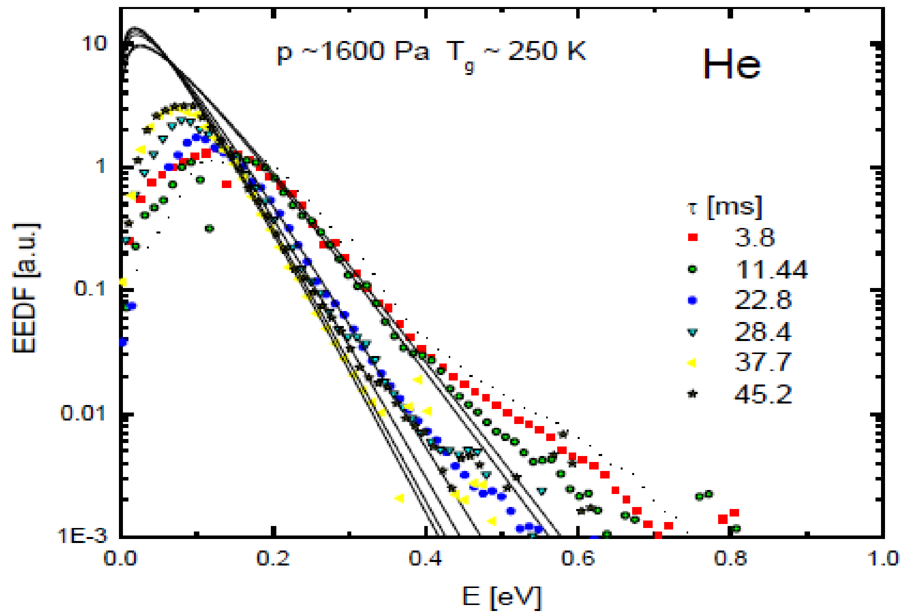
$$\frac{d^2I}{d(V-V_p)^2} = \frac{1}{4}Aq^2\sqrt{\frac{2q}{m_e(V-V_p)}}\left[f(E)\right]$$

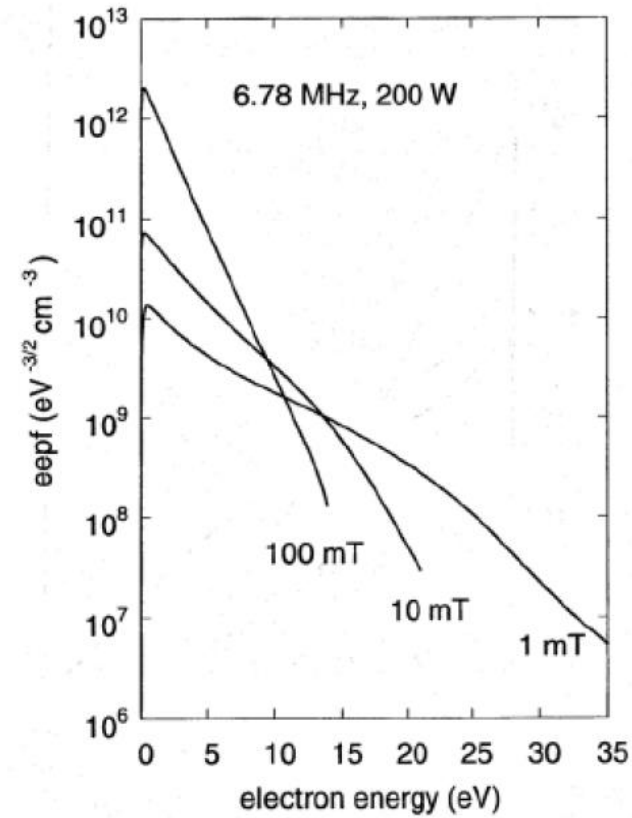
$$\boxed{\frac{d^2I}{d(V-V_p)^2} = \frac{1}{4}Aq^3\sqrt{2\pi m_e}(k_BT_e)^{-3/2}e^{\left[\frac{q(V-V_p)}{k_BT_e}\right]}}$$

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

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

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

$$I^2 = \frac{2(Aqn_e)^2}{\pi^2 m_e}[k_B T_e + q(\mathrm{U_{pr}} - \mathrm{V_{pl}})]$$

Slope of $I^2(U)$

$$n_e = \sqrt{\frac{\pi^2 m_e}{2A^2 q^3} S}$$

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

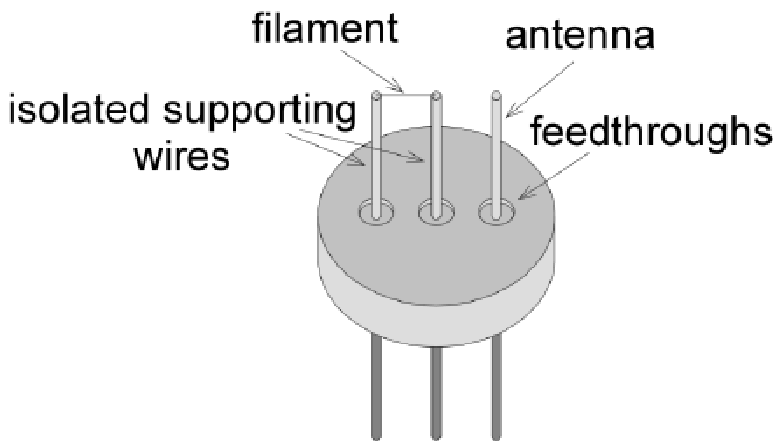
Španěl P.: *Int J. Mass Spectrom and Ion Proces.*, 149/150, 299, 1995

Problems with Langmuir Probes

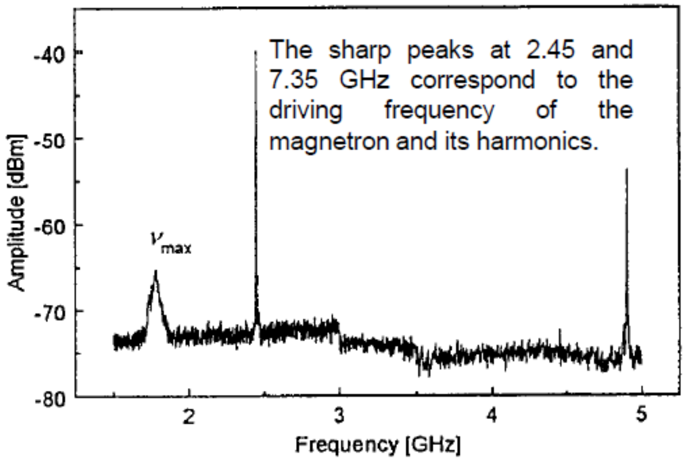
- Melting of the probe
- Contamination of the probe
- Interpretation of the results
- Need physics access to the plasma
- Langmuir probe failed in case of insulator deposition experiments

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.



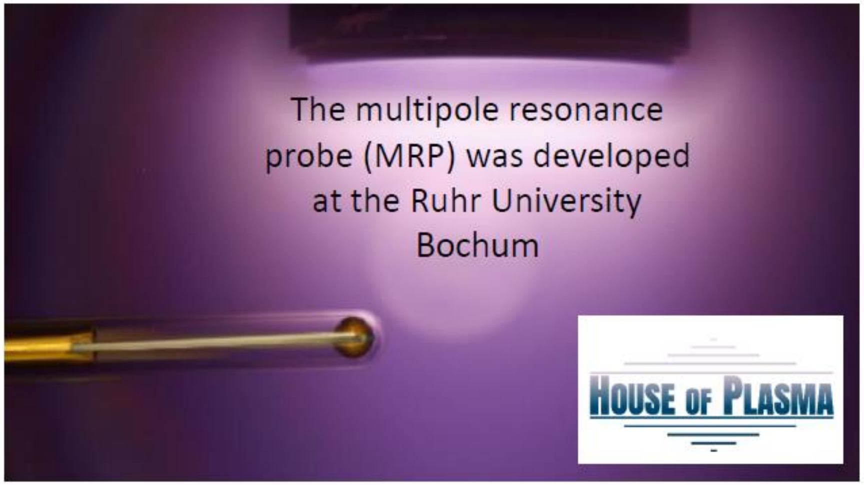
Frequency spectrum in Argon



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

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

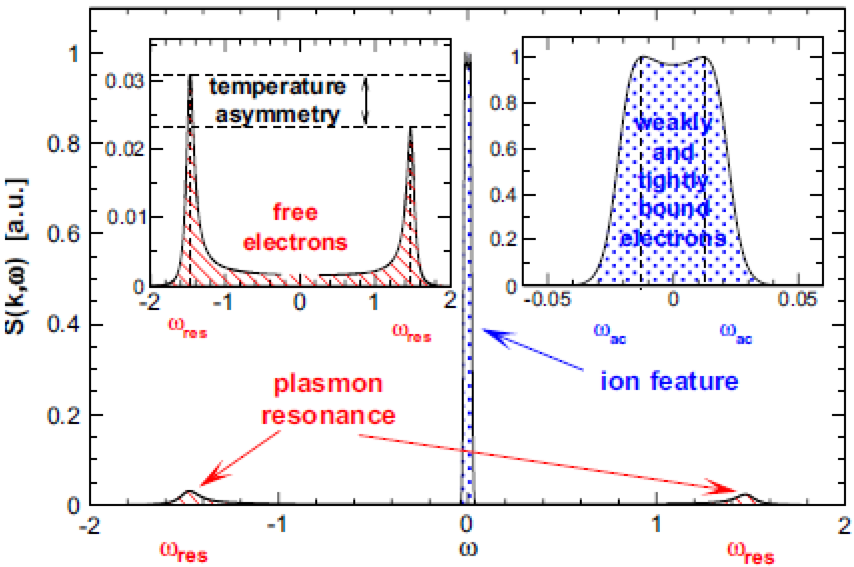
Plasma Absorption Probes



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

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.

X-ray Thomson Scattering



A. Höll et al., HEDP 3, 120(2007)

- Thomson scattering has two distinct features:
  - Inelastic scattering (frequency shifted) from free electrons and bound free transitions
  - Unshifted Rayleigh peak (elastic) due to electrons co-moving with the ions
- The electrons in partially ioized system can be split into bound and free electrons

$$\rho_{\rm e} = \rho_{\rm b} + \rho_{\rm f}$$

- Intermediate scattering function

$$N_{\rm e} F_{\rm ee}^{tot} = \langle \rho_{\rm b}(\vec{k},t)\rho_{\rm b}(-\vec{k},t)\rangle + 2\langle \rho_{\rm f}(\vec{k},t)\rho_{\rm b}(-\vec{k},t)\rangle + \langle \rho_{\rm f}(\vec{k},t)\rho_{\rm f}(-\vec{k},t)\rangle$$

Born-Mermin approximation

- Fluctuation-dissipation theorem :

$$S^0_{\mathrm{ee}}(k,\omega) = -\frac{\epsilon_0 \hbar k^2}{\pi e^2 n_{\mathrm{e}}} \frac{\mathrm{Im}\epsilon^{-1}(\mathrm{k},\omega)}{1-\exp(-\hbar\omega/k_{\mathrm{B}}T_{\mathrm{e}})}$$

- RPA gien by Lindhard:

$$\epsilon^{\mathrm{RPA}}(\vec{k},\omega) = 1 - \frac{1}{\epsilon_0 \Omega_0 k^2} \sum_p e^2 \frac{f^e_{p+k/2} - f^e_{p-k/2}}{\Delta E^e_{p,k} - \hbar(i\omega + i\eta)}$$

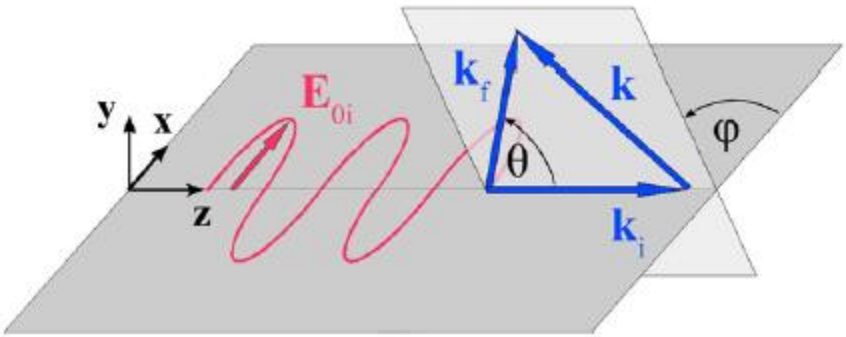
- Mermin ansatz :

$$\epsilon_M(k,\omega) = 1 + \frac{\left(1+\frac{i\nu(\omega)}{\omega}\right)\left[\epsilon^{\mathrm{RPA}}(k,\omega+i\nu(\omega))-1\right]}{1+i\frac{\nu(\omega)}{\omega}\frac{\epsilon^{\mathrm{RPA}}(k,\omega+i\nu(\omega))-1}{\epsilon^{\mathrm{RPA}}(k,0)-1}}$$

- $\nu(\omega)$ is the dynamic collision frequency via Born approximation.

Glenzer and Redmer, RMP 81, 1625(2009)

Back and forward scattering



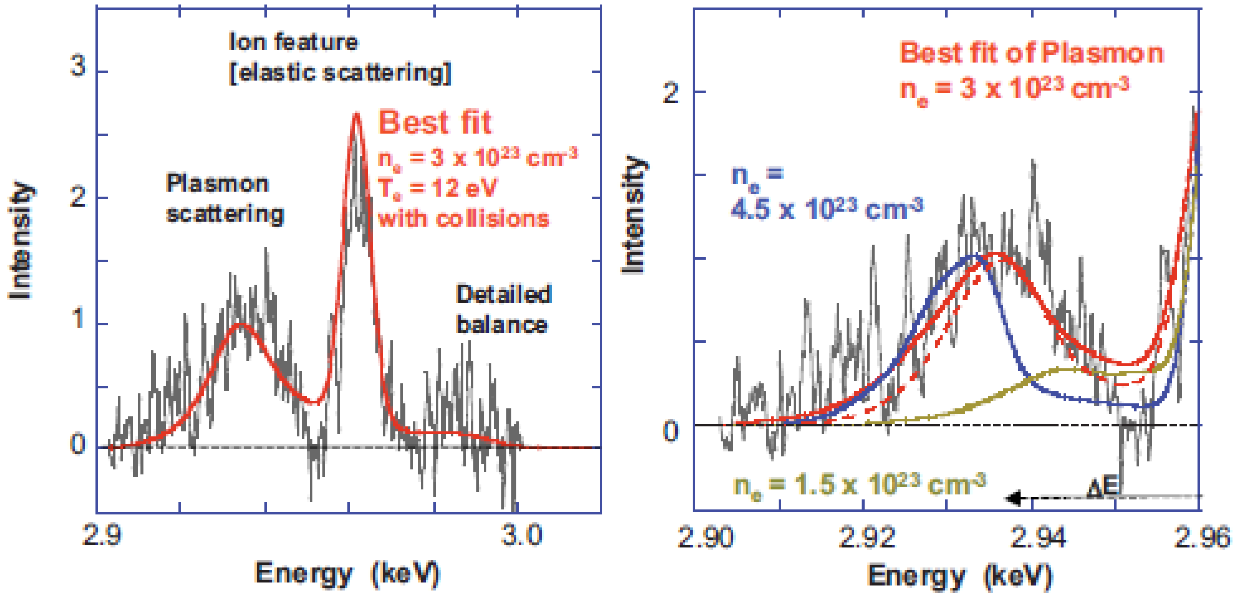
- The momentum transfer depends on the scattering angle

$$k = |k_f - k_i| = \frac{4\pi}{\lambda_i} sin(\theta/2)$$

- Dimensionless scattering parameter $\alpha = \frac{1}{k\lambda_{sc}} = \frac{l}{2\pi\lambda_{sc}}$
  - l is the electron density fluctuation
  - λ_{sc} is the screening length
- Collective scattering: ($\alpha > 1$)
  - the scattering reflects the electron density fluctuations
  - Plasmon features
- Non-collective scattering:($\alpha < 1$)
  - the scattering reflects the velocity distribution of electrons
  - Compton features

Glenzer and Redmer, RMP 81, 1625(2009)

Experimental results and



- **Forward scattering:** collective behavior
- Dispersion relation determines the electron density
- Detailed balance gives the electron temperature

Glenzer et al., PRL 98, 065002(2007)

Retarding Field Analyzer

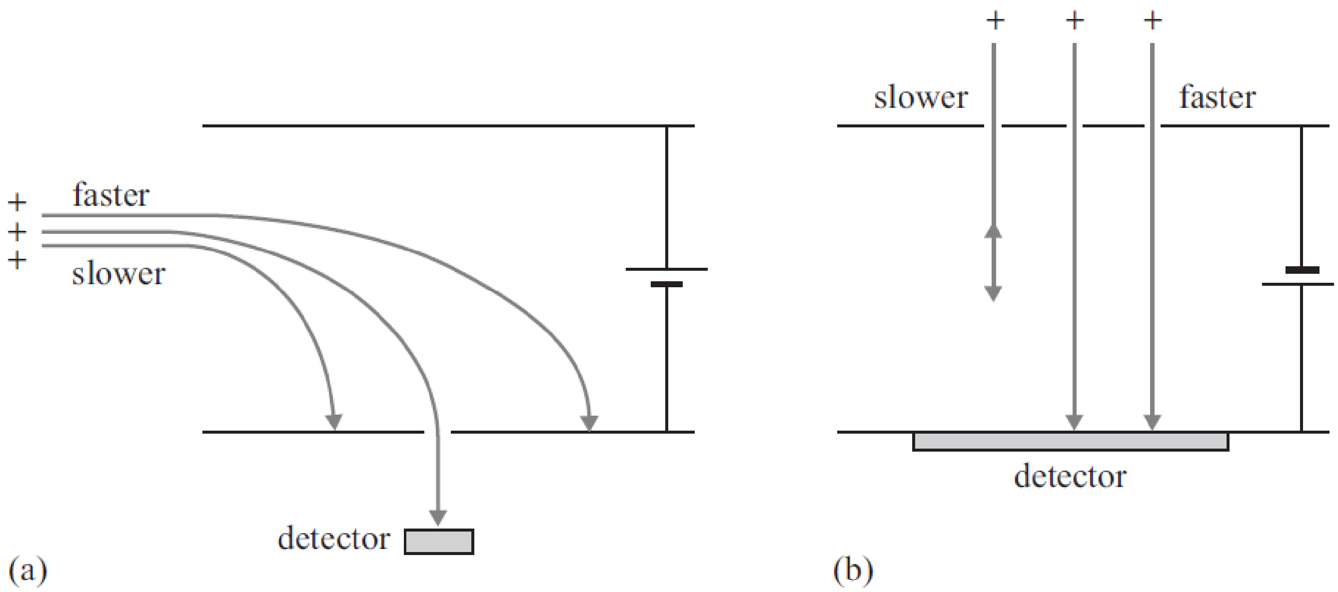
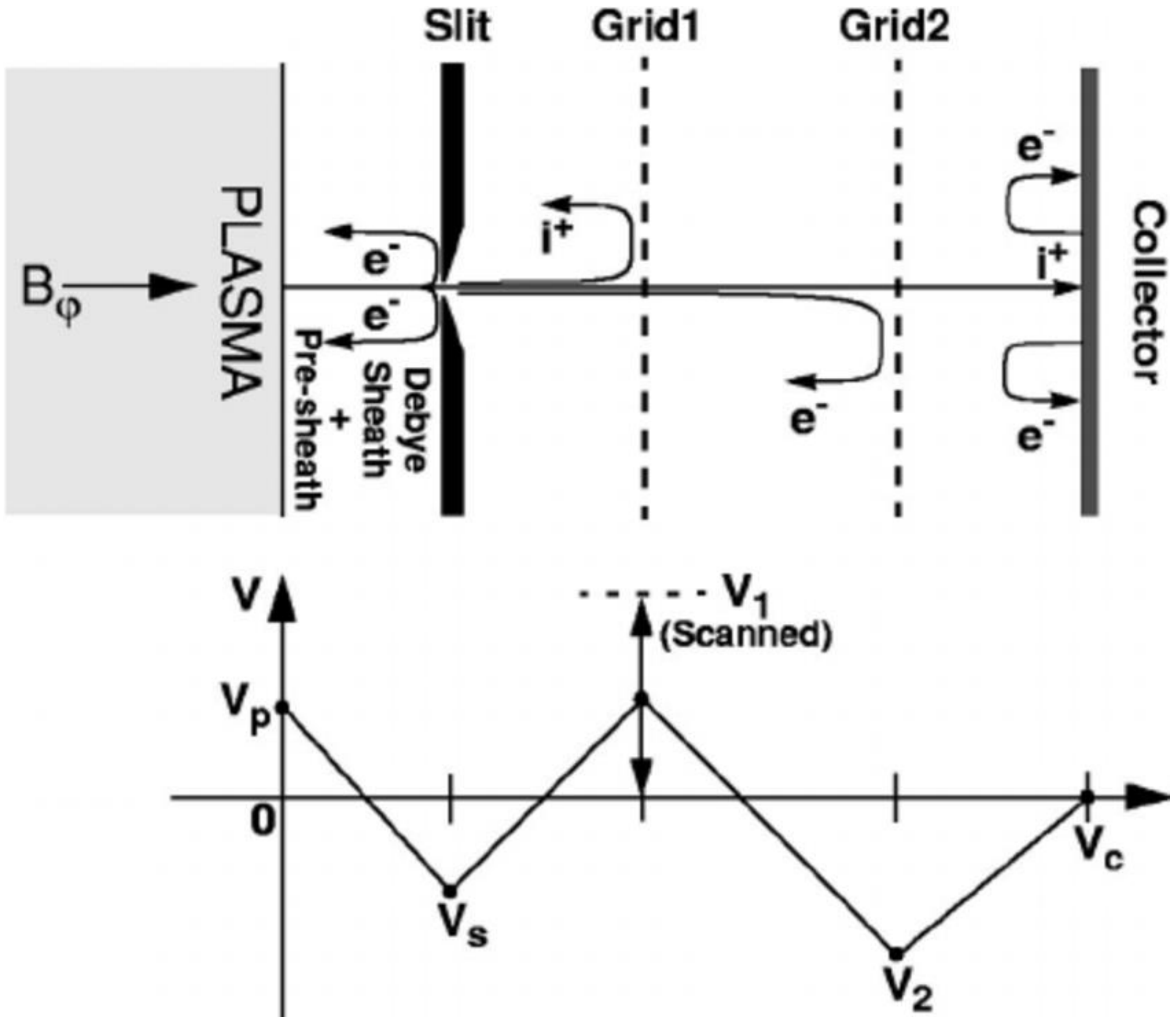


Figure 10.15 (a) A deflecting filter selects particles within a specific (narrow) range of energy; (b) a retarding filter passes particles with energy above a threshold level.

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

$$e\Phi = \frac{1}{2}mv^2$$

$$ed\Phi = mvdv$$

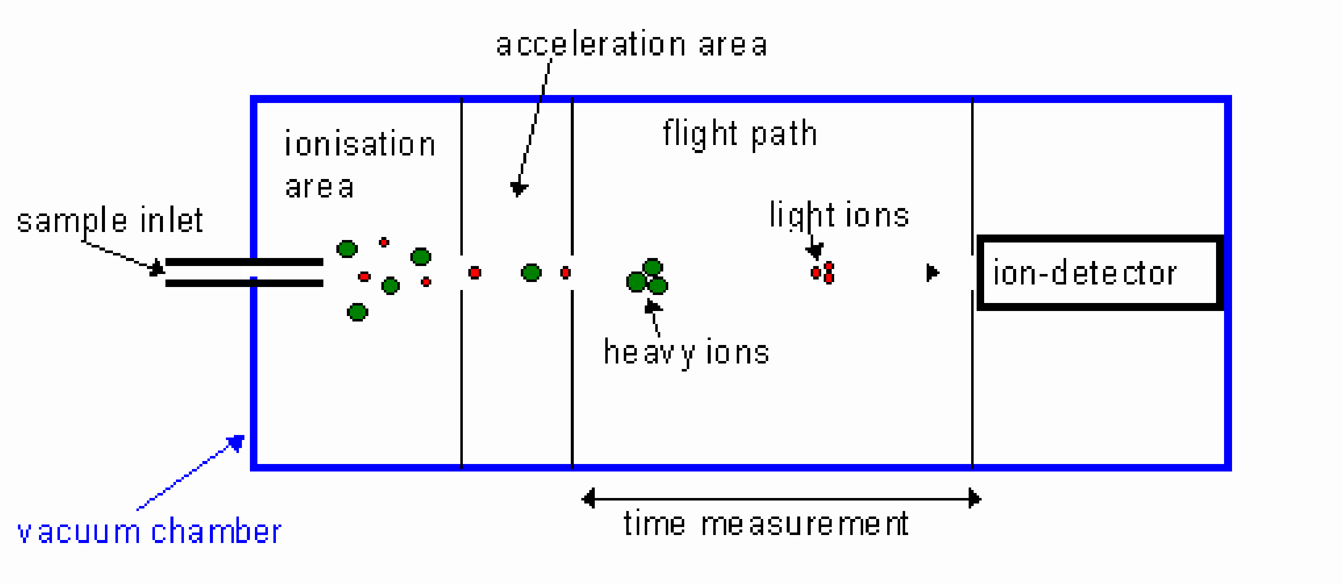
$$\frac{dv}{d\Phi} = \frac{e}{mv}$$

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

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

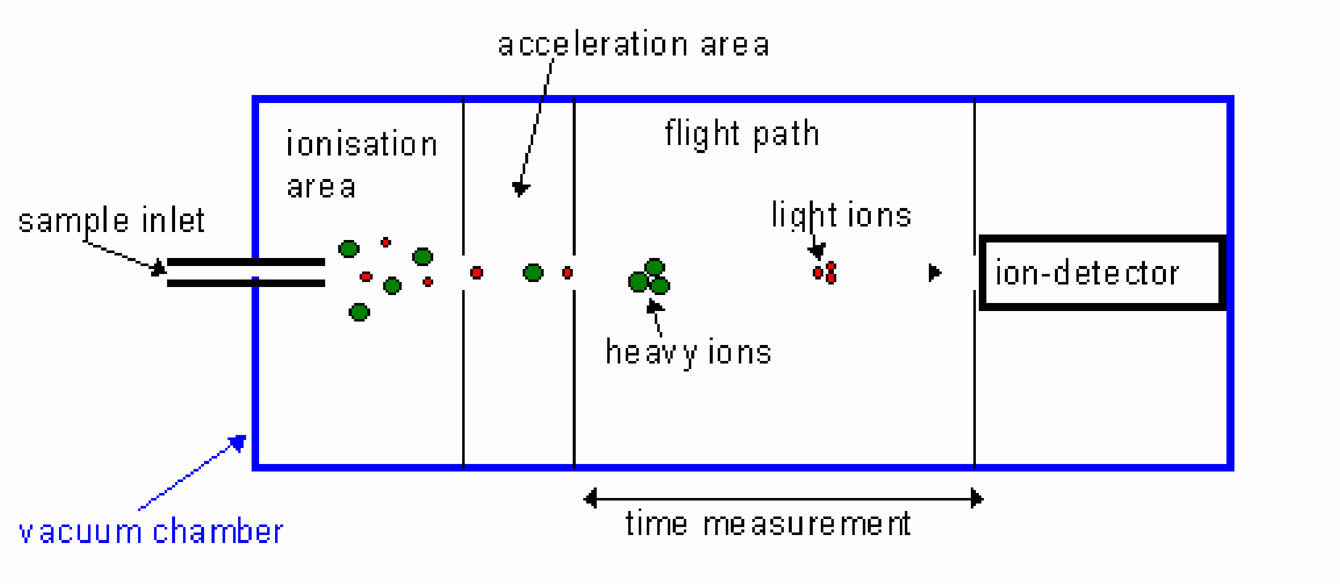
$$\frac{dI}{d\Phi} = A\frac{e^2}{m}f(v)$$

Mass Spectrometer



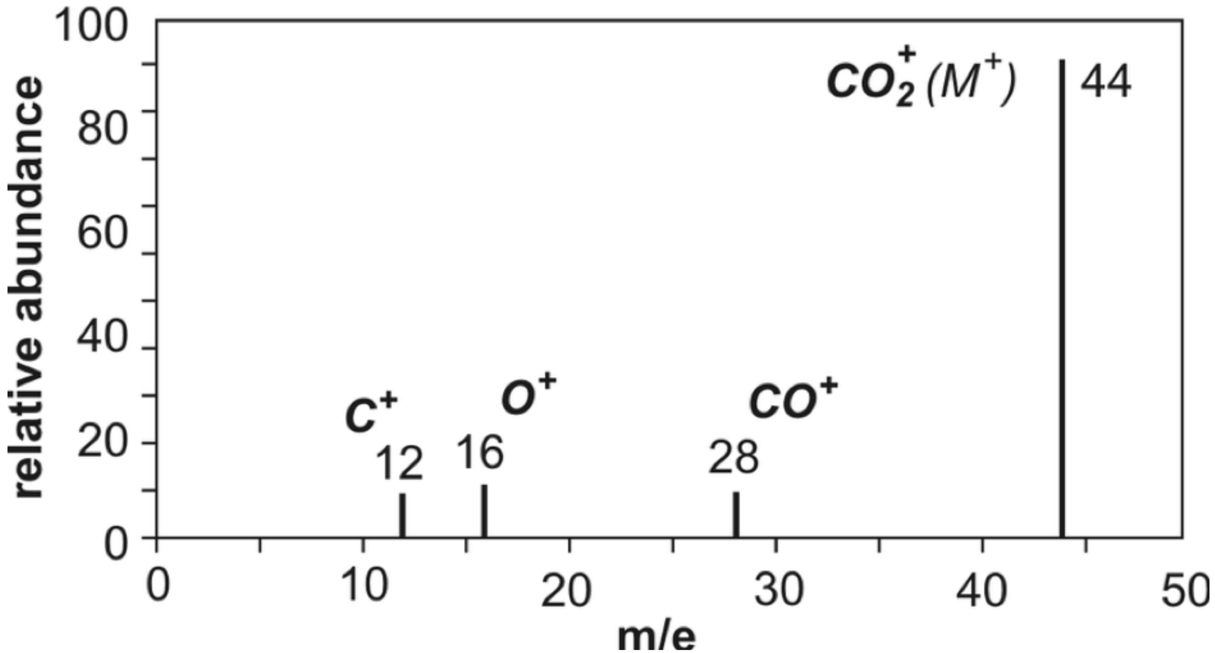
A **Time-of-Flight Mass Spectrometer** works by **accelerating** an **ionised** sample and calculating **mass per charge** based on how long each 'object' is in **flight** for. Since every 'object' receives equal force, according to Newton's Second Law, the acceleration of each 'object' will be inversely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

Mass Spectrometer



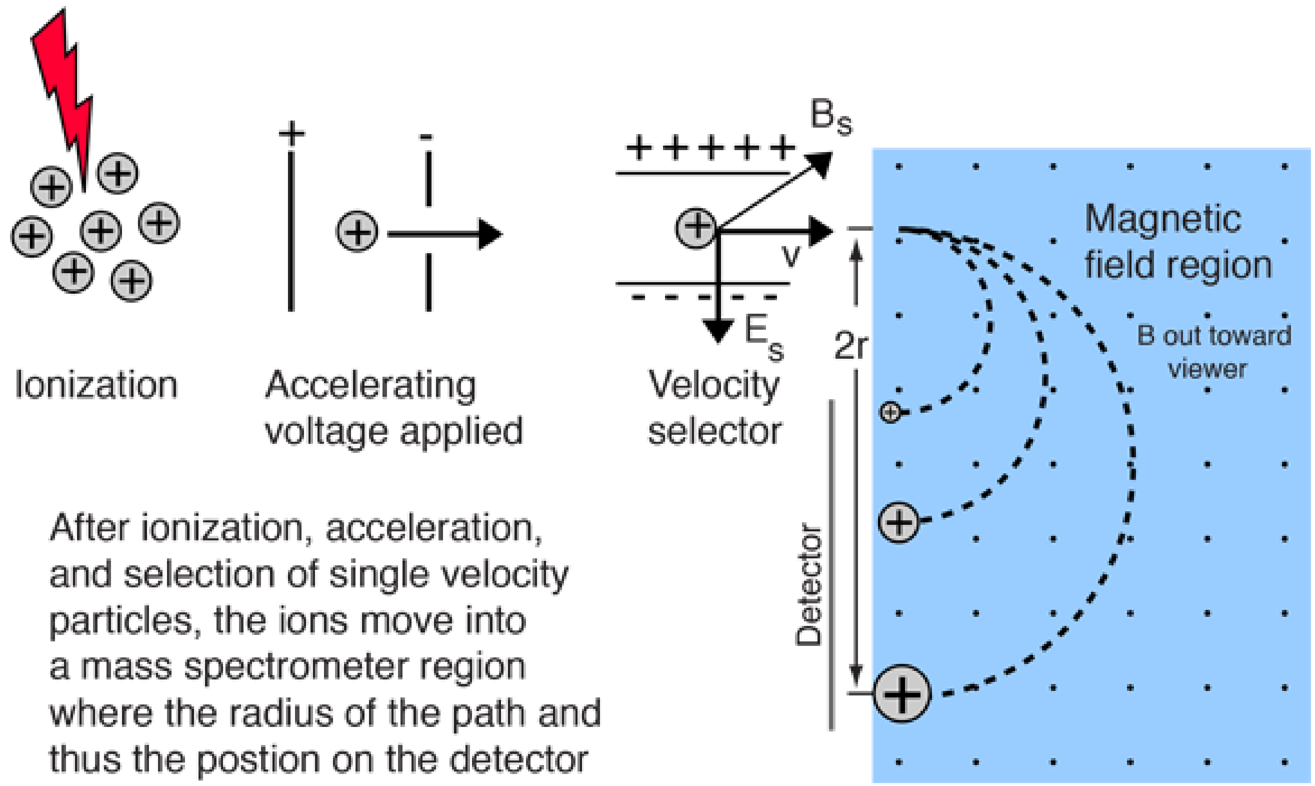
The sample is first **ionised** by **bombarding it with electrons**, which also causes **fragmentation** to form smaller groups of atoms. Ions tend to have **+1 charge**, since a bombarding electron will knock an electron out of an atom's shell, so 'mass per charge' can generally be taken as simply '**mass**'.

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



After ionization, acceleration, and selection of single velocity particles, the ions move into a mass spectrometer region where the radius of the path and thus the postion on the detector is a function of the mass.

$$r = \frac{mv}{qB} = \frac{mE_s}{qBB_s}$$

The emission Spectrum

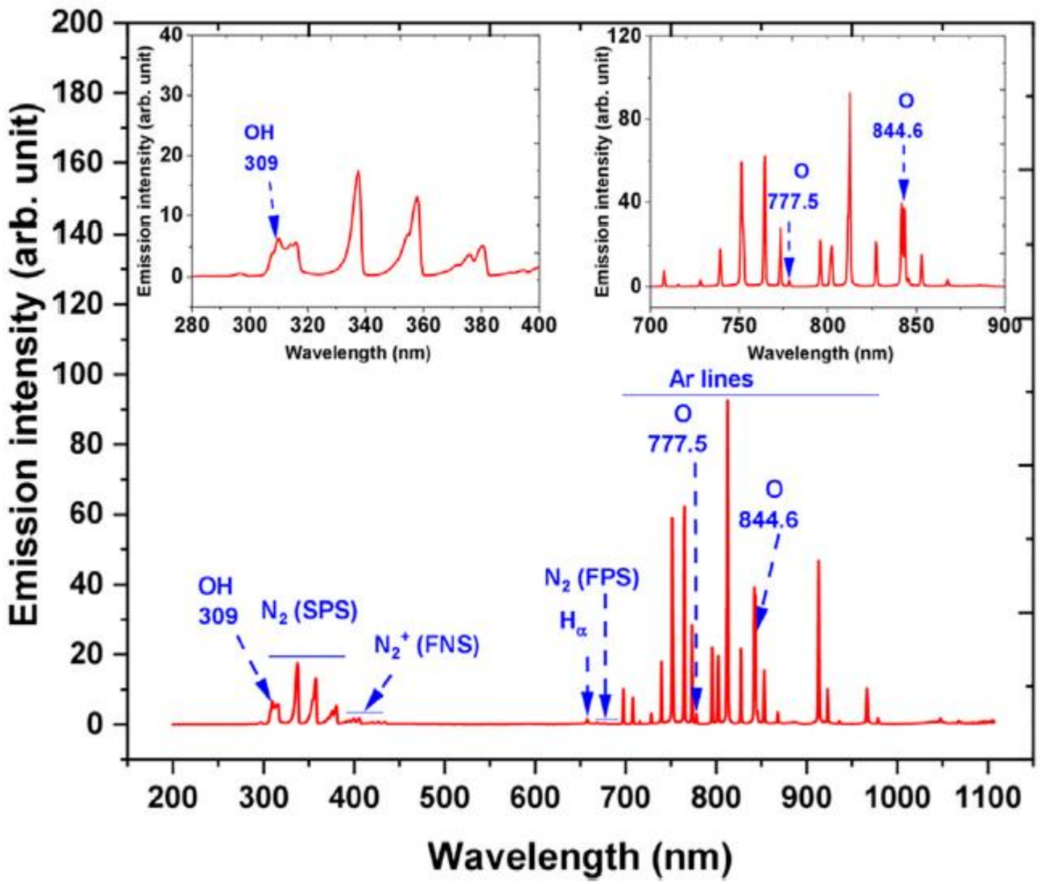
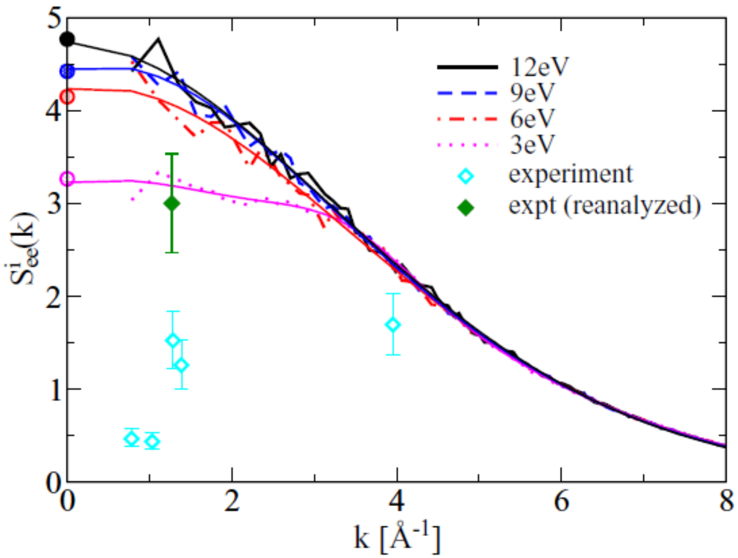
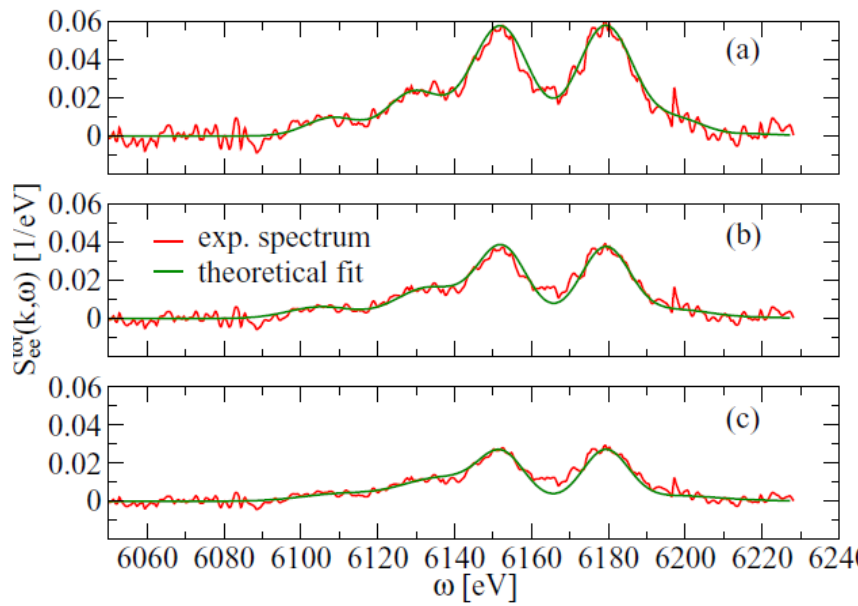


FIGURE 6 | The emission spectrum of Ar—APPJ in contact with ambient air and over a liquid surface. During the diagnostics, AB25 was placed under APPJ, $V_o = 5$ ml, Ar 1 slm, P_{mean} at the sample 11 W. Inset plots show parts of the spectrum zoomed.

There is no experiment, theory free!!!



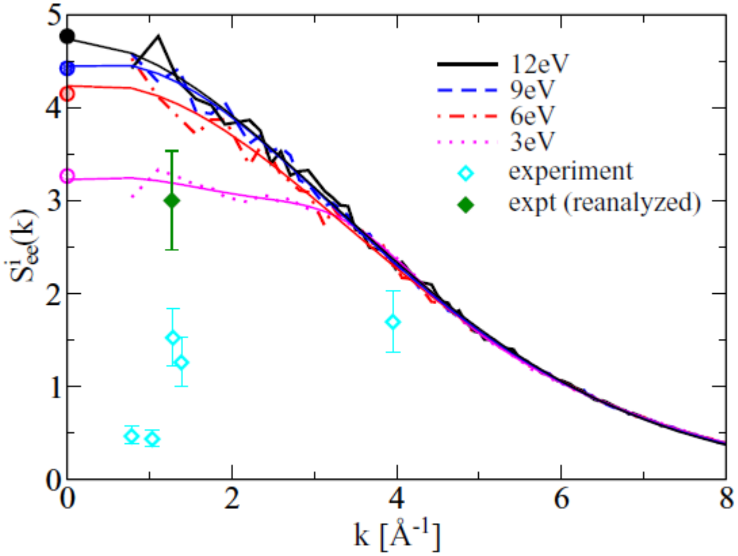


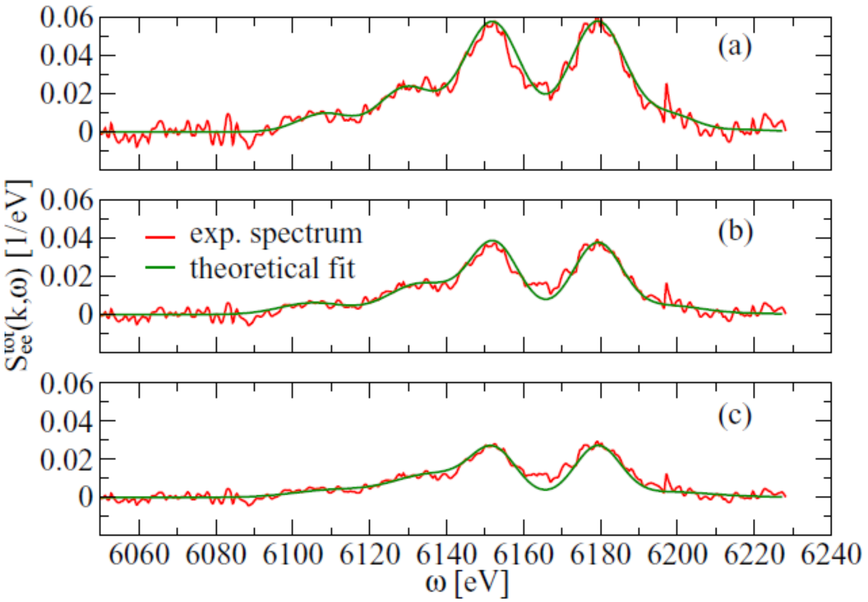
PHYSICAL REVIEW E **92**, 013103 (2015)

Ab initio calculation of the ion feature in x-ray Thomson scattering

Kai-Uwe Plagemann,[1,*] Hannes R. Rüter,[1] Thomas Bornath,[1] Mohammed Shihab,[1,2] Michael P. Desjarlais,[3] Carsten Fortmann,[4] Siegfried H. Glenzer,[5] and Ronald Redmer[1]

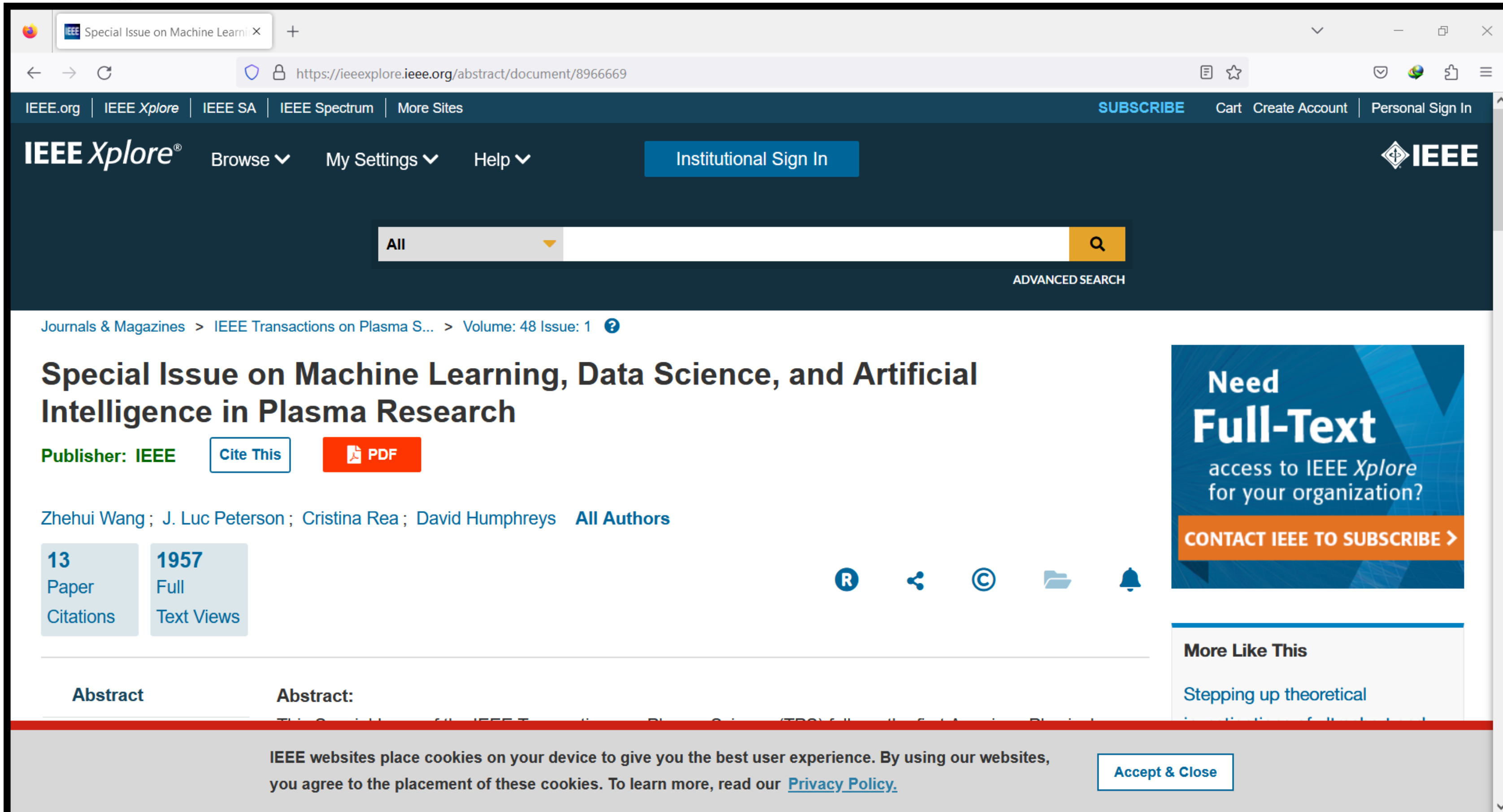
There is no experiment, theory free!!!





Fit	C	Ion feature	Variance of the fit
(a)	5.46	2.15 ± 0.26	3.6×10^{-3}
(b)	8.42	1.20 ± 0.19	4.6×10^{-3}
(c)	11.28	0.75 ± 0.17	7.3×10^{-3}
Ref. [3]		0.78	7.2×10^{-3}

Machine Learning



Errors analysis and Artificial Intelligence

- True error
- Relative true error
- Approximate error
- Relative approximate error

Good and fast Start

- **References:**

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Thanks!