The Open University

Sensing a plasma environment: electron density and ion flux

In effect ‘Plasma diagnostics’

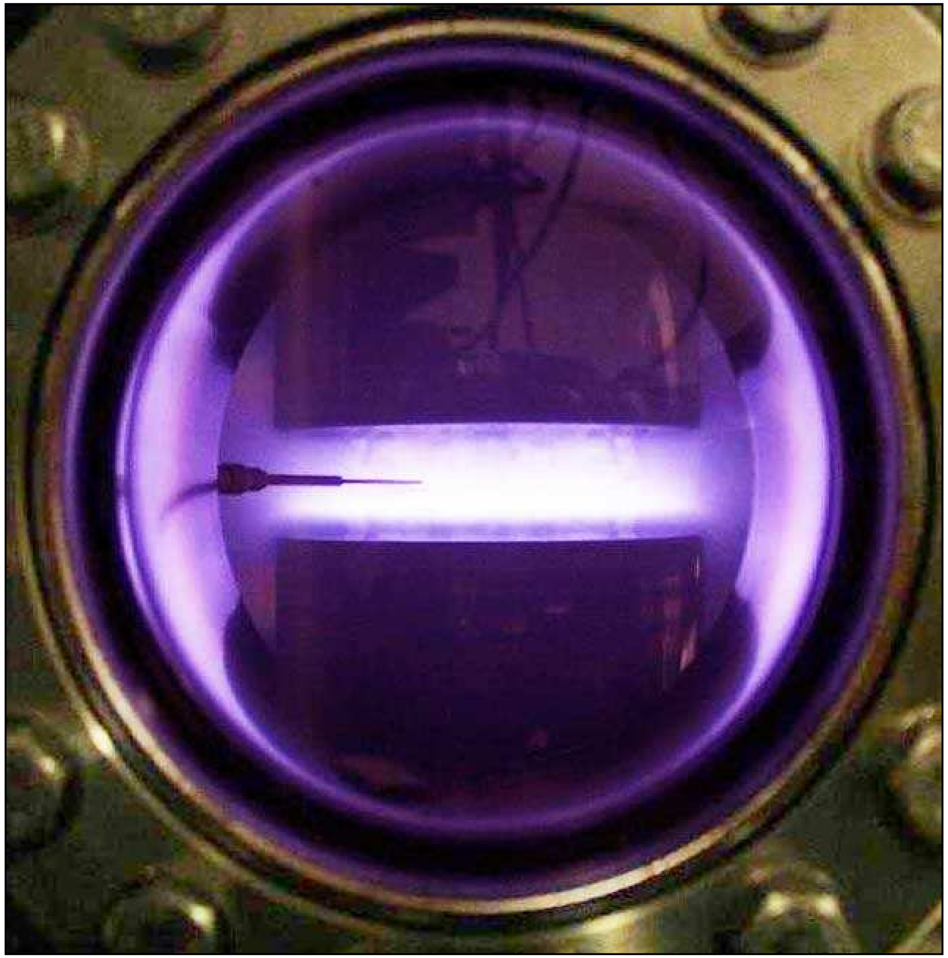
but without suggesting that the plasma is unwell

Nicholas Braithwaite, The Open University, UK

What will we discuss?

- Introduction: A range of plasmas…seeing is believing
- What do you want to measure?
- What can you measure?
  - currents & voltages
  - frequency spectra UV, visible, IR, microwave, RF
- What techniques?

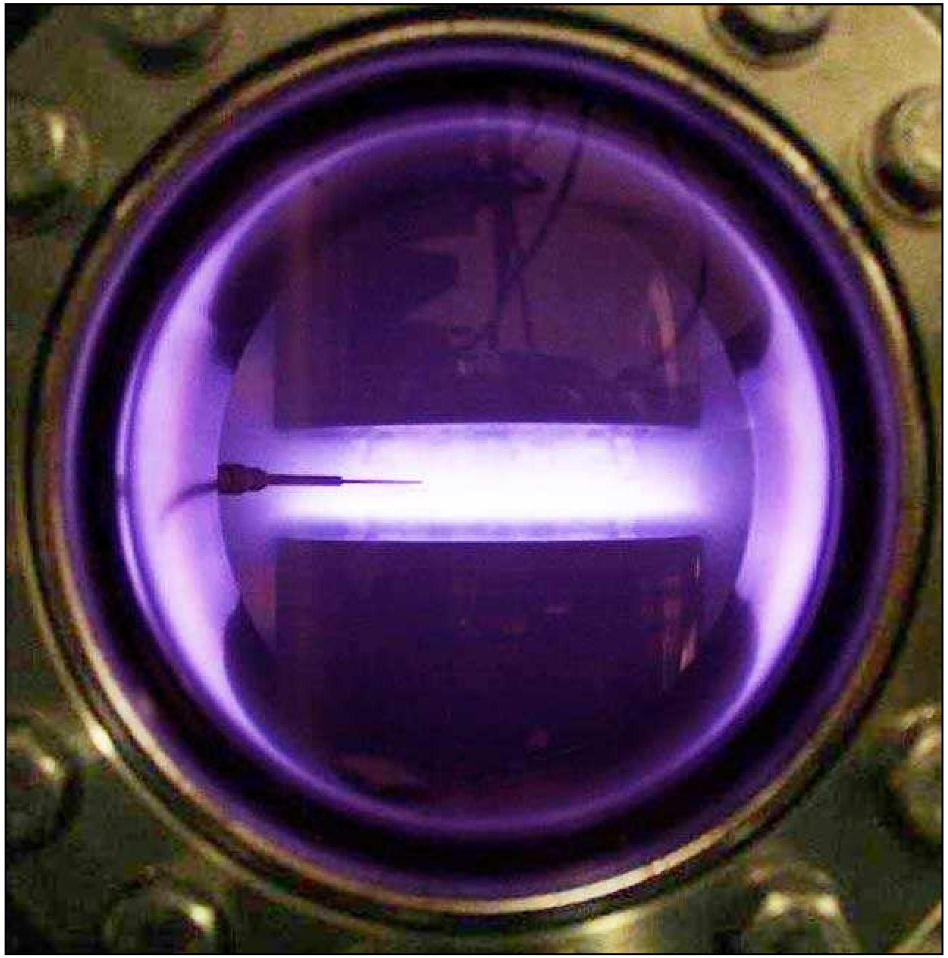
“seeing is believing…”

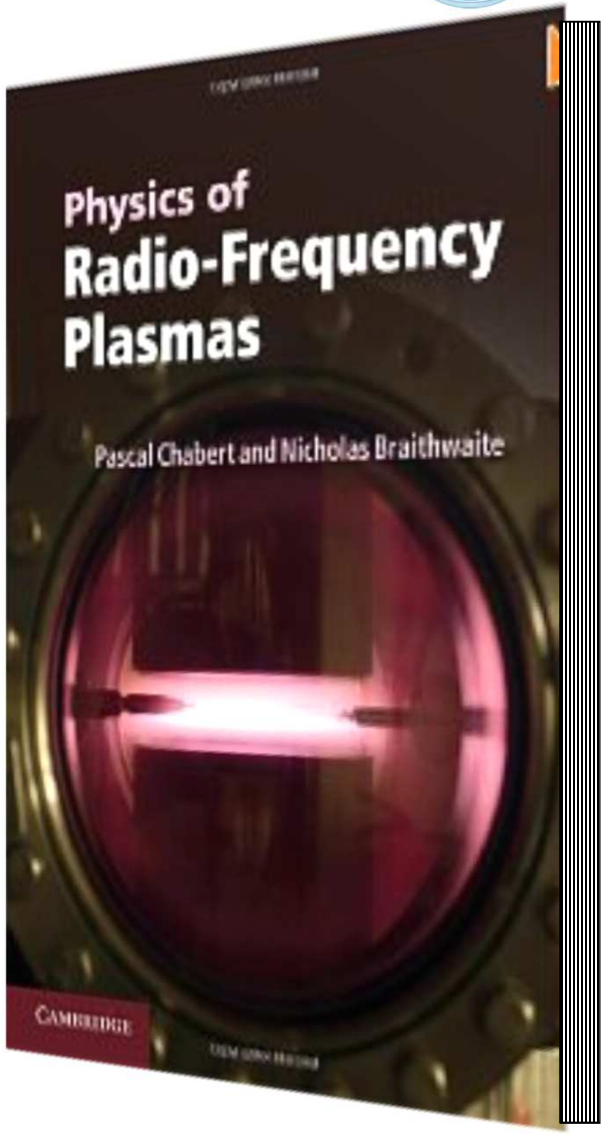


Introduction

Introduction

“seeing is believing…”

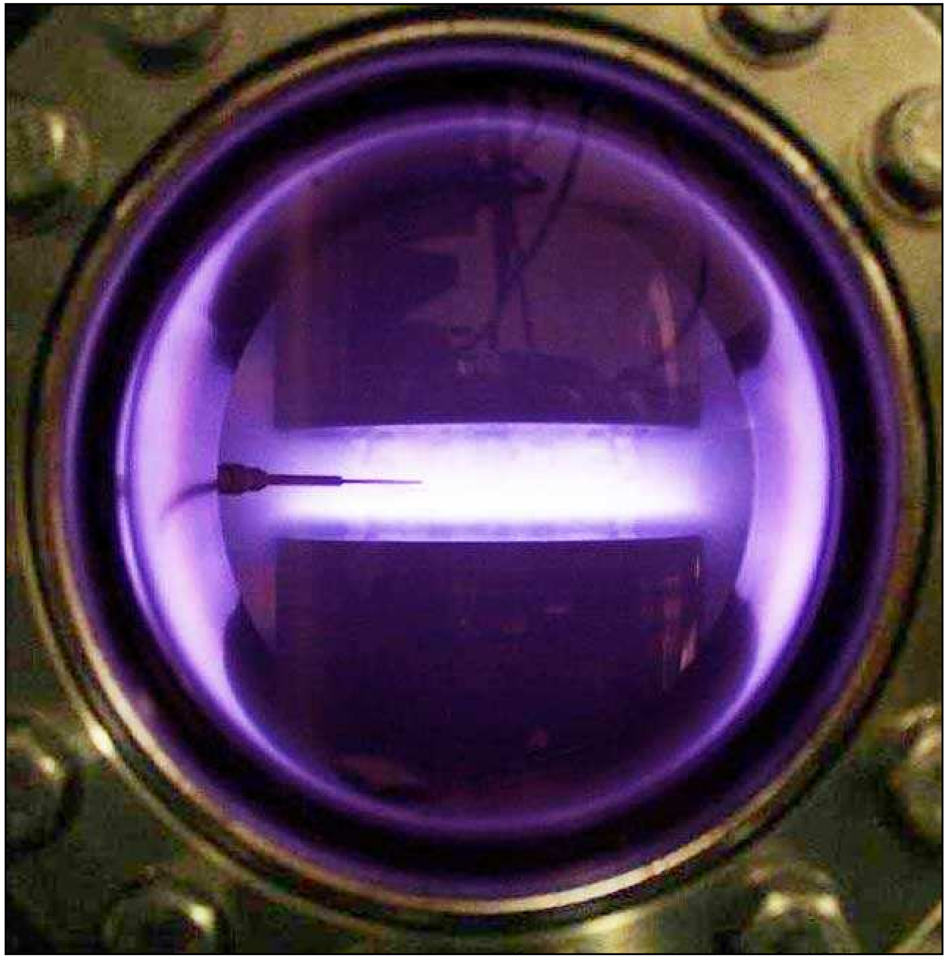




…beware of false colour

“seeing is believing…”

13.56 MHz
10 Pa, 50 W
Ar



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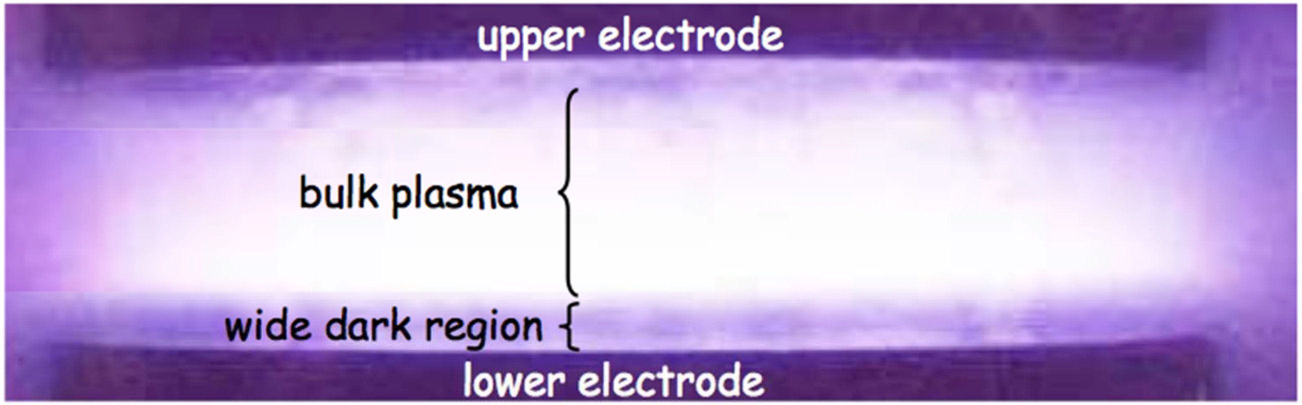

Side view of a plasma bounded by parallel plate electrodes, showing the dark space in front of the lower electrode - note that the camera is set to view exactly along the lower electrode and does not therefore capture a clear image of the dark space adjacent to the upper electrode

Introduction

“seeing is believing…”

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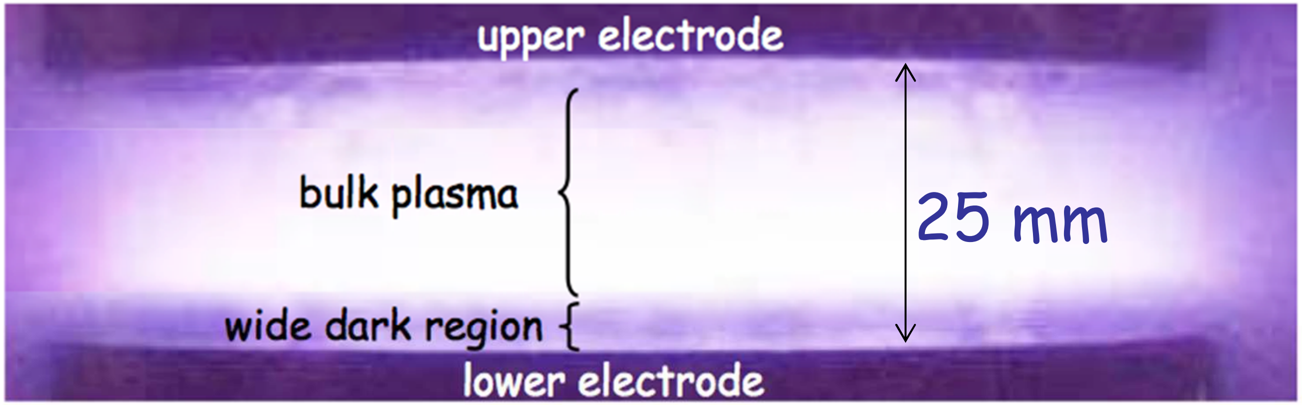

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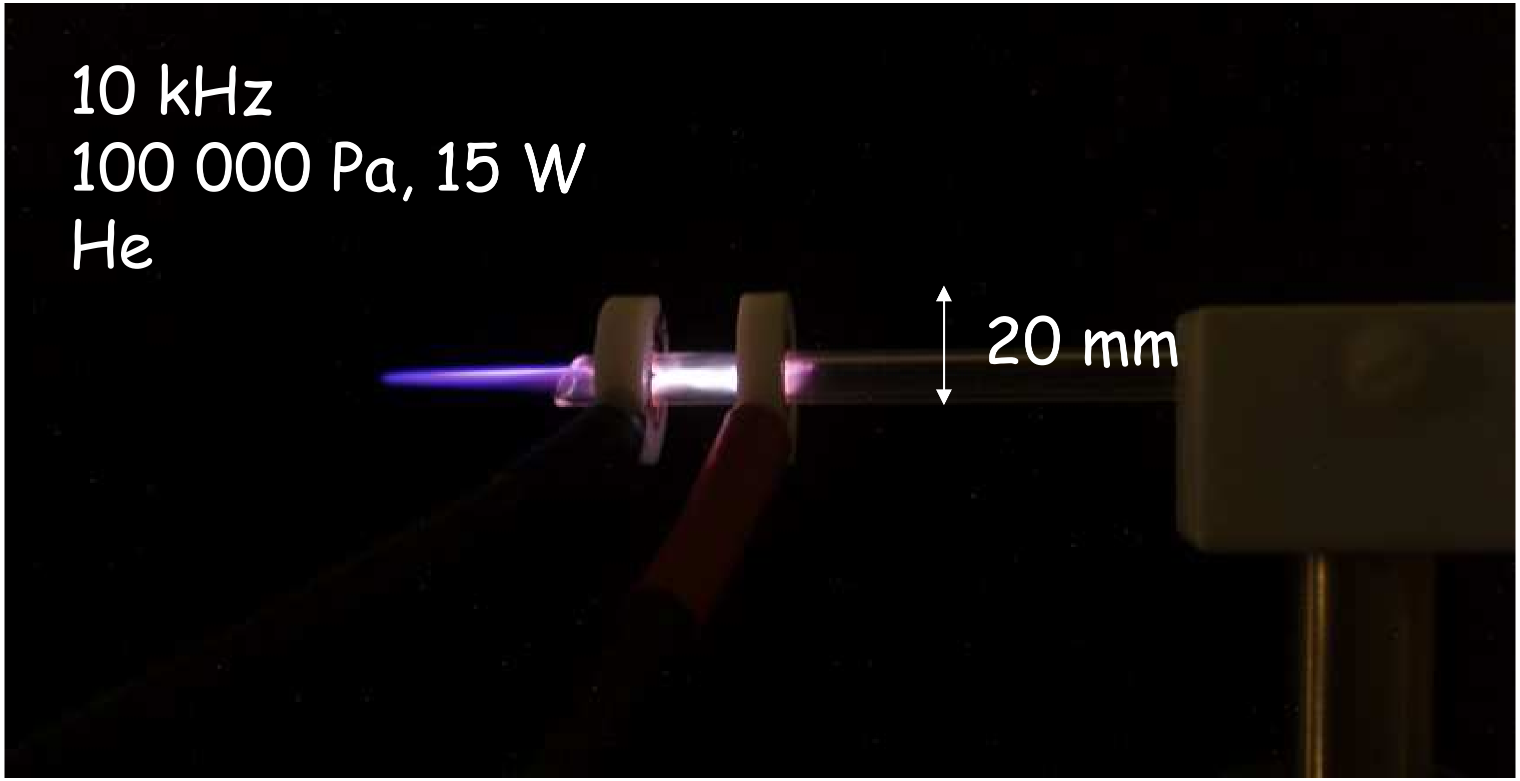
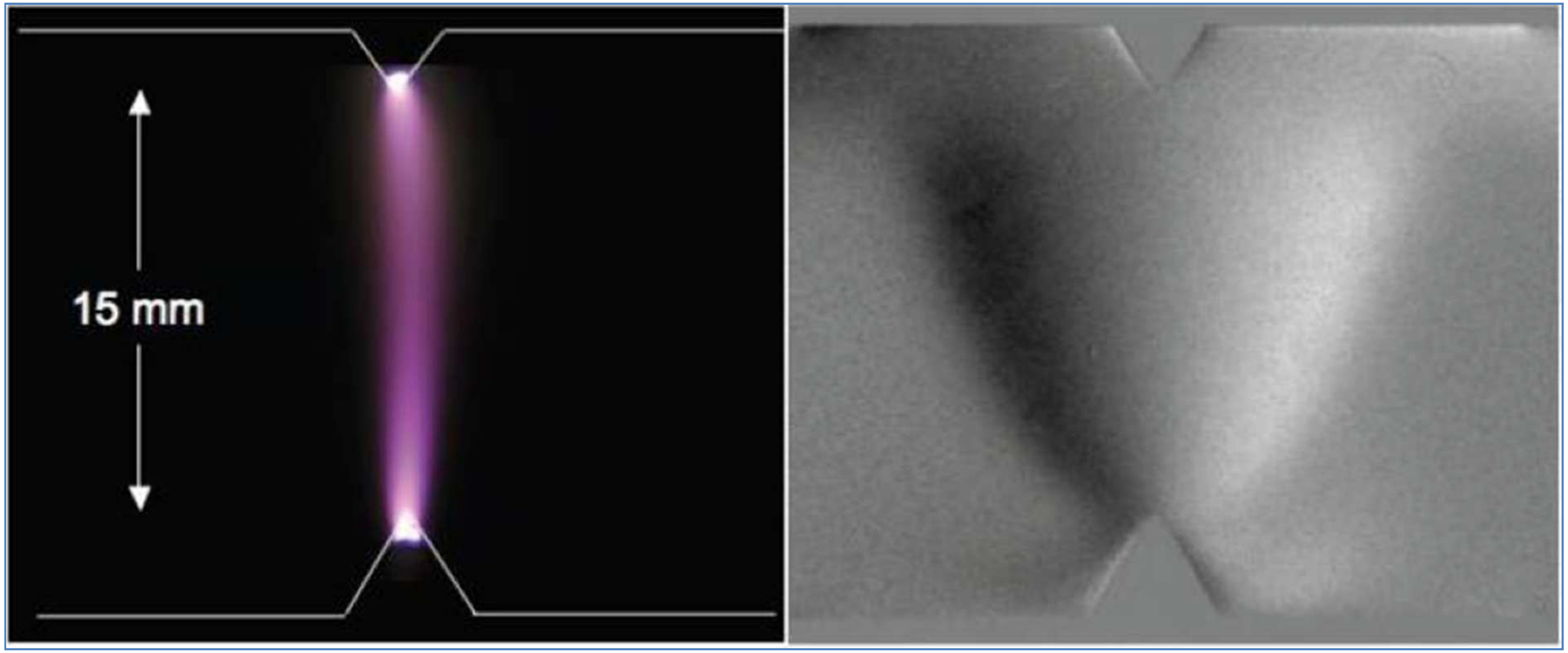
Introduction



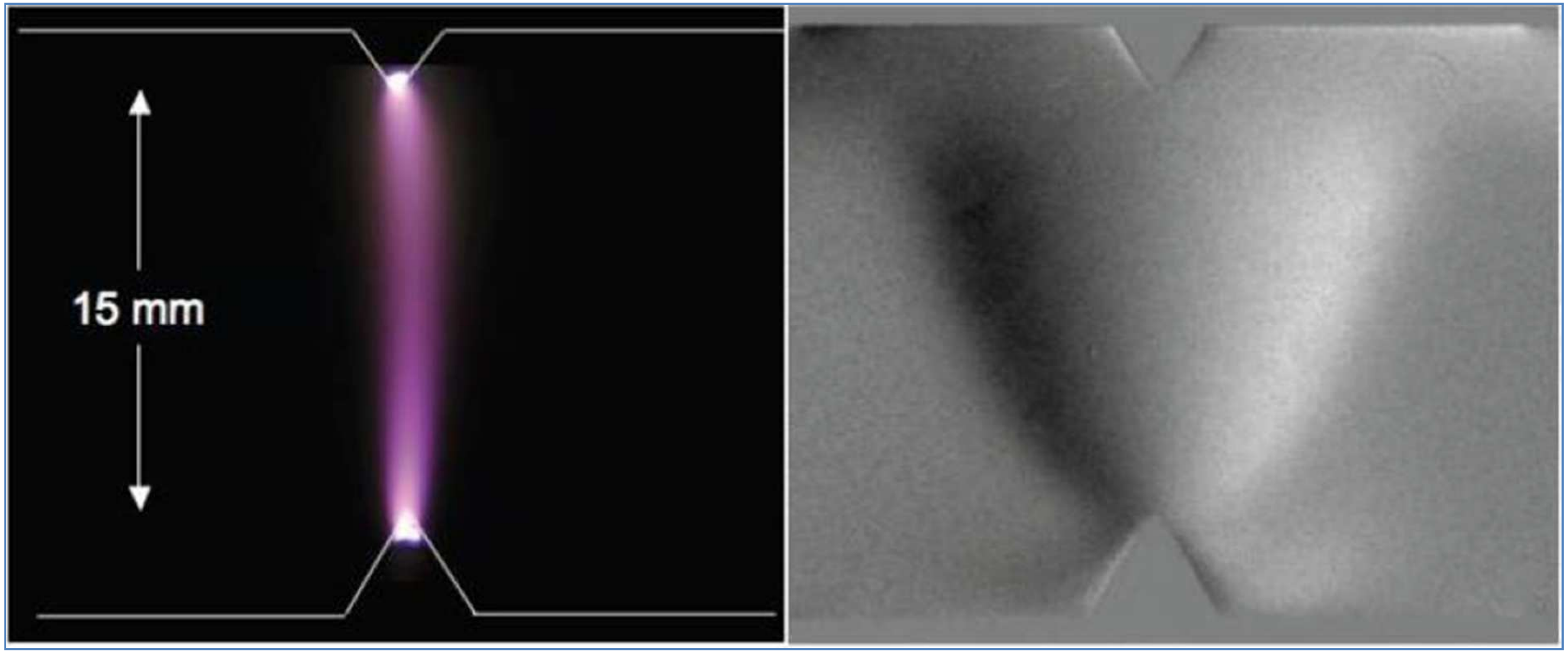
“seeing is believing…”

Introduction



“seeing is believing…”

Total light | Schlieren

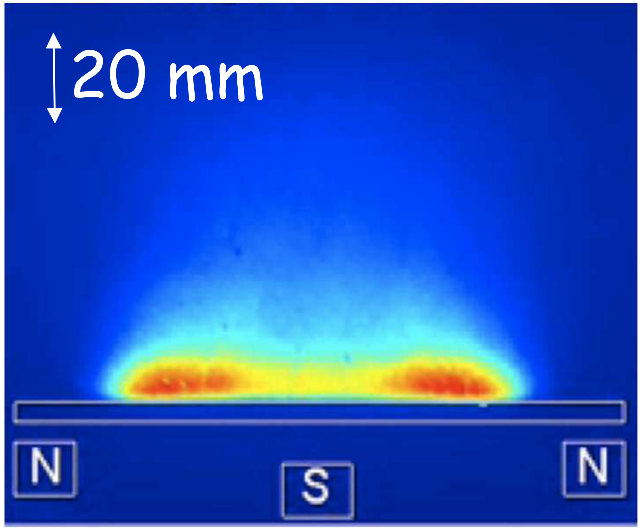


“seeing is believing…”

Introduction

Spectral line emission image

Pulsed
Argon
200 W 3 Pa



“seeing is believing…”

B. Liebig et al. / Thin Solid Films 519 (2010) 1699–1704

Spectral line emission image

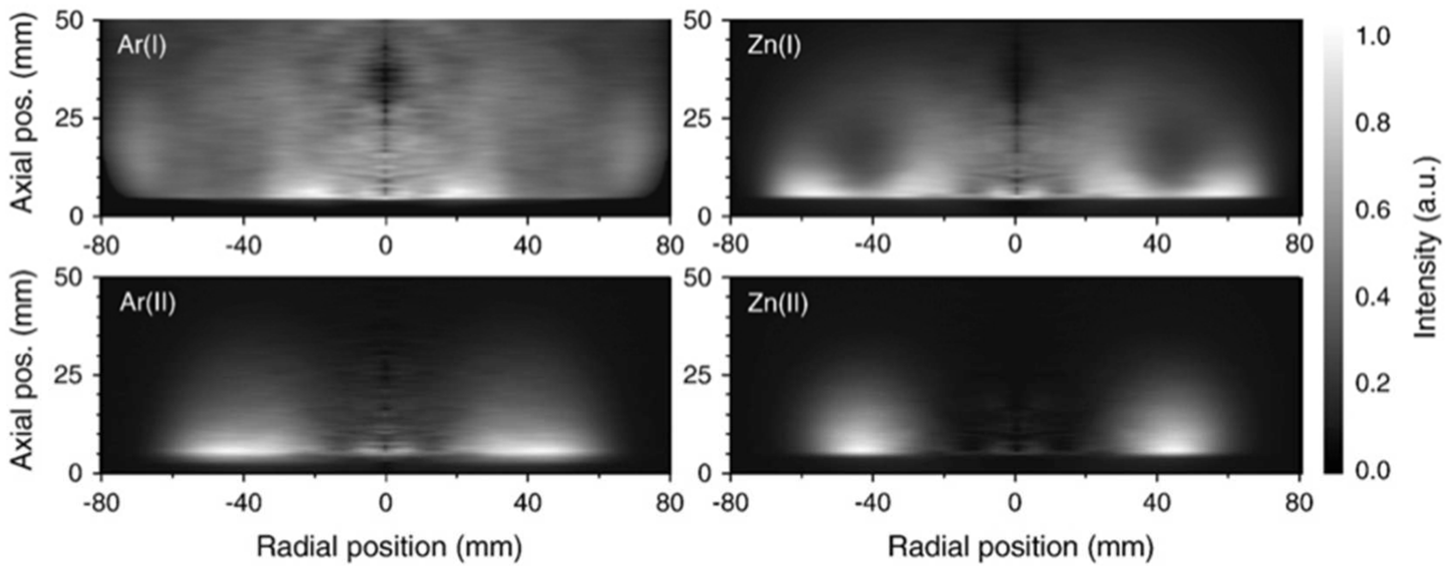
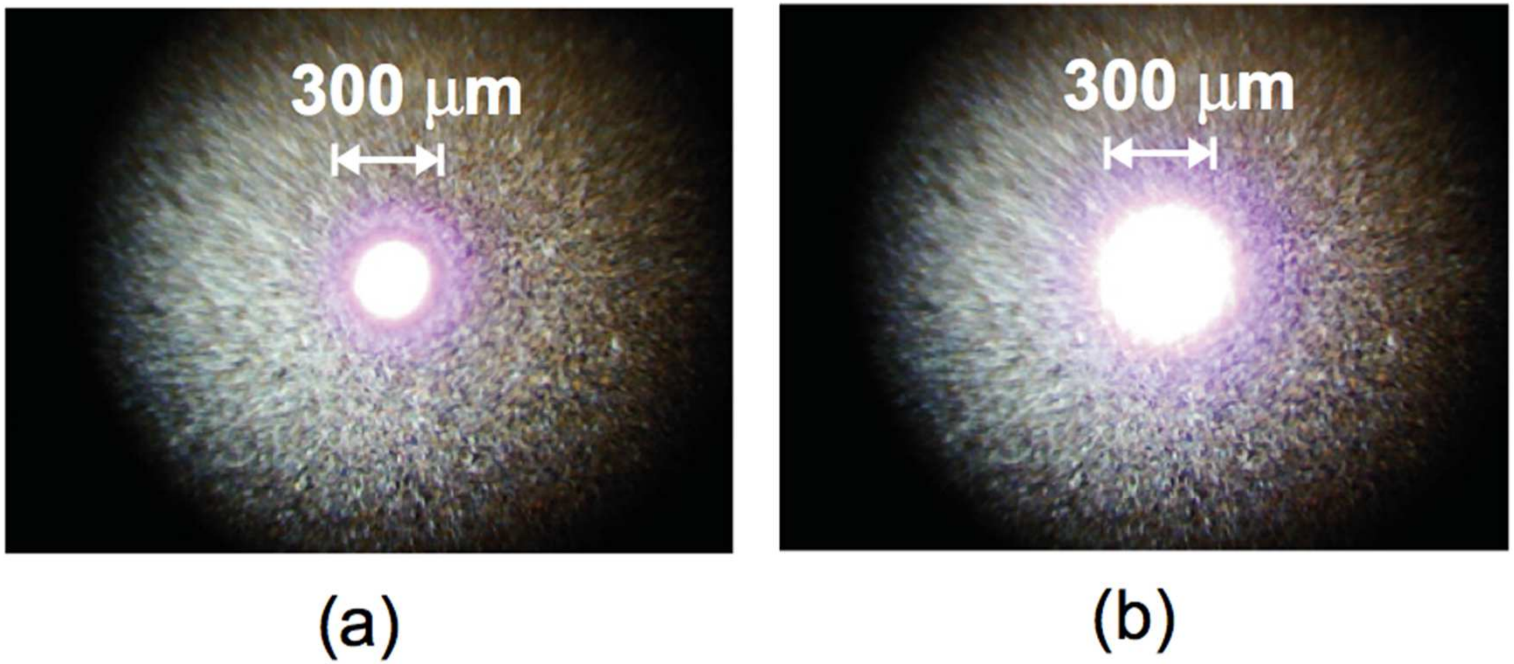


Fig. 3. Spatial distributions of the emission of argon and zinc neutrals and ions when sputtering an aluminium-doped zinc target. The images were obtained after analysing the measured data with Abel inversion. All images were recorded at the same temporal position 'B' 50 μs after pulse initiation when the discharge current peaks. The target was sputtered using an argon pressure of 1.33 Pa and an average power of 400 W.

"seeing is believing…"

B. Liebig et al. / Thin Solid Films 519 (2010) 1699–1704

DC
10 000 Pa, 160 mW
He



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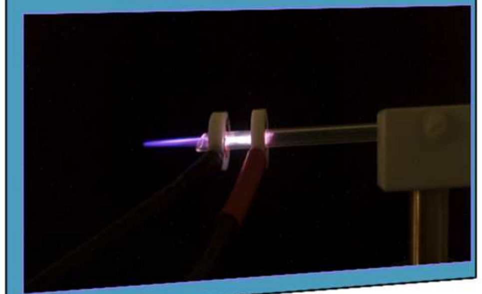
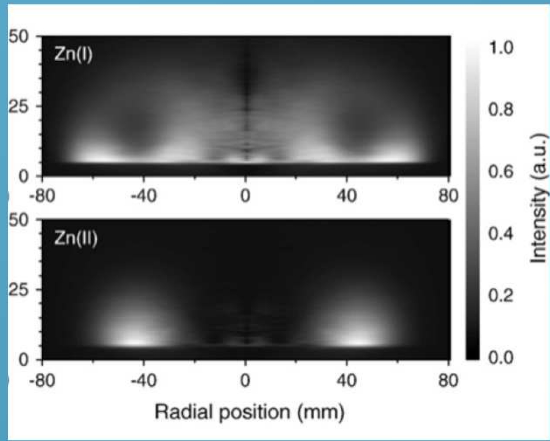
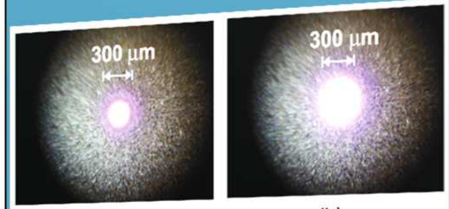
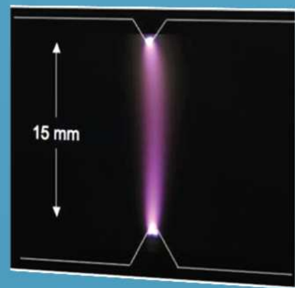






(a) (b)

Figure 4. (*a*) Anode view and (*b*) cathode view of a discharge generated by the device with semiconducting diamond electrodes, for the case of $V = 410\,\text{V}$, $I = 0.40\,\text{mA}$. The background gas was helium at a pressure of 10 kPa.



RF CCP
Atmospheric Cold-plasma Jet
Magnetron
Micro-Hollow-Cathode
RF atmospheric arc

Electron mean energy /eV	1 – 10
Charge density /m^{-3}	10^{16} – 10^{19} …10^{21}

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- What techniques?

What do you want to measure?

A semiconductor manufacturing engineer said to me …

"It would be useful to be able to monitor & control electron density, electron energy, ion flux, ion energy"

What do you want to measure?

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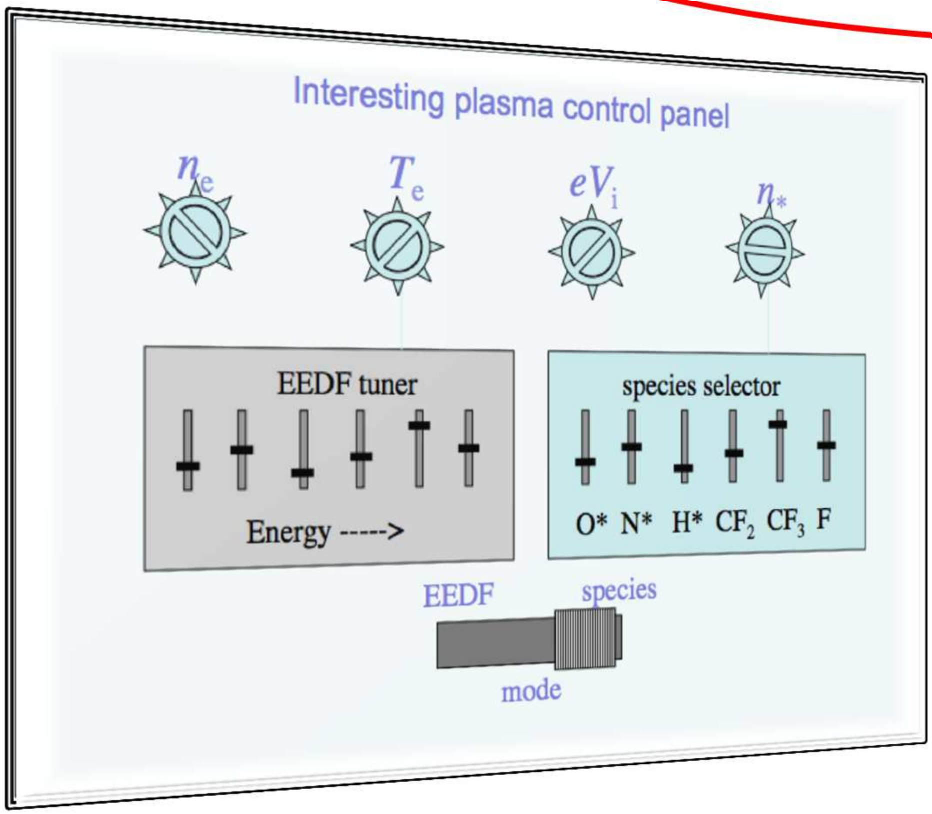
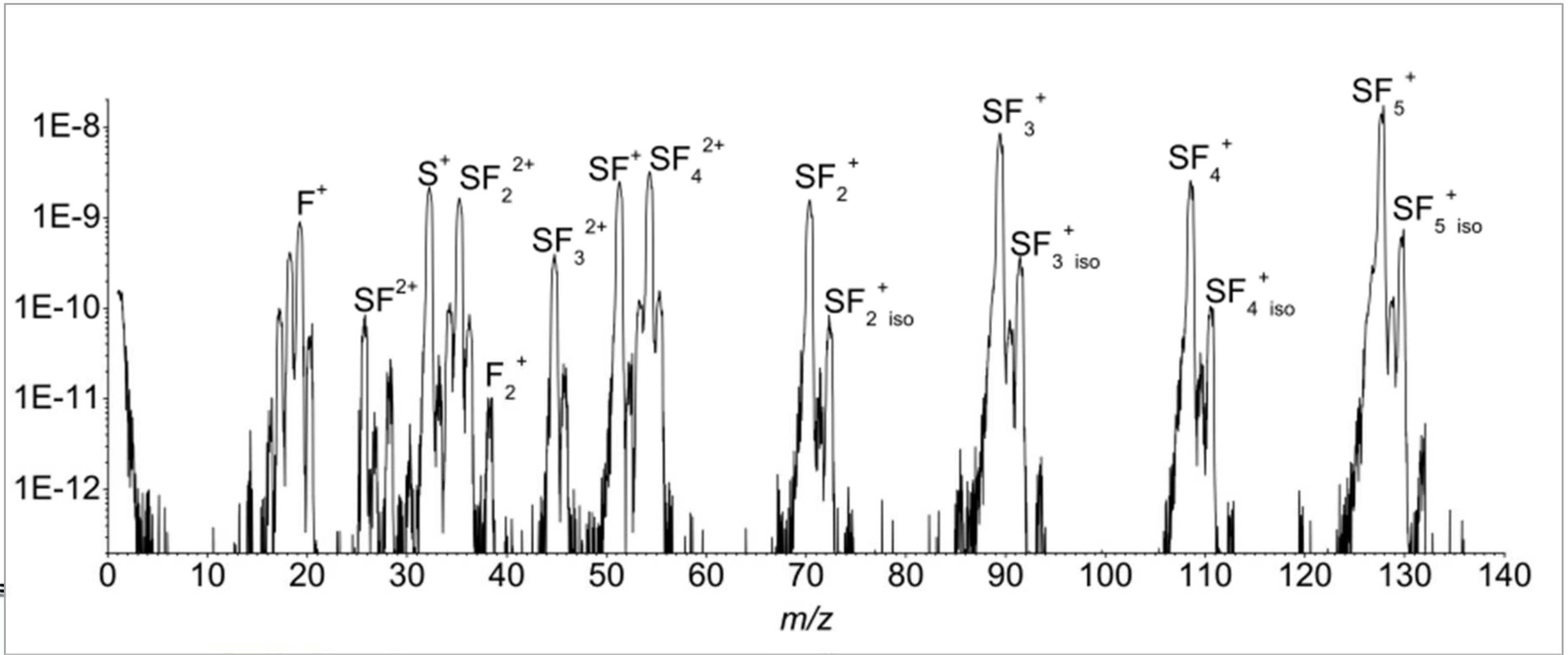
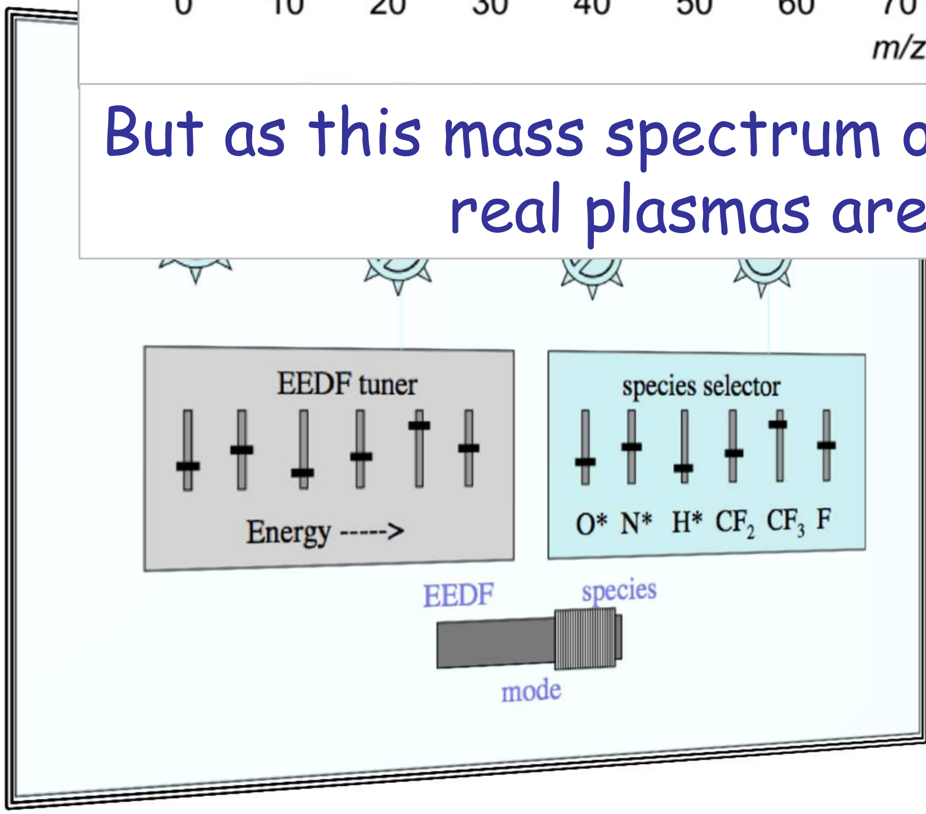


What do you want to measure?



But as this mass spectrum of an SF6 plasma shows…
real plasmas are complicated



What do you want to measure?

composition: atoms, radicals, molecules, dust
concentration: electrons, ± ions, neutral species
temperature/energy: various species
fluxes: various species
electric field…

What do you want to measure?

Gas composition

Density / m^{-3}
- ion (n_i)
- electron (n_e)
- neutrals (eg n_*)

Energy / eV
- ion ($\langle E_i \rangle$)
- electron ($\langle E_e \rangle$)
- neutrals (eg $\langle E_{vib} \rangle$)

Flux / $m^{-2}\ s^{-1}$
- ion (Γ_i)
- electron (Γ_e)
- neutrals (eg Γ_*)

Potential/V & E field / V m^{-1}
- $\Delta\phi$
- **E**

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  - frequencies UV, visible, IR microwave, RF
- What techniques do you have?

What can you measure ?

↑↑

What can you measure ?

temperature
current
↑↑ voltages
photons
spectra: mass, energy, wavelength

What electrical techniques do you have?

(Quadrupole) Mass Analyser

Langmuir Probe

Emissive Langmuir Probe

Retarding Field Analyser

Ion flux probe

Microwave interferometry

What optical techniques do you have?

Optical emission

Optical absorption (DLS, FTIR)

Laser Induced Fluorescence

Rayleigh scattering

Thomson scattering

What techniques do you have?

- (Quadrupole) Mass Analyser
- Langmuir Probe
- Emissive Langmuir Probe
- Retarding Field Analyser
- Ion flux probe
- Microwave interferometry
- RF probe spectroscopy
- Optical emission
- Optical absorption (DLS, FTIR)
- Laser Induced Fluorescence
- Rayleigh scattering
- Thomson scattering

What techniques do you have?

(Quadrupole) Mass Analyser

Langmuir Probe

Emissive Langmuir Probe

Retarding Field Analyser

Ion flux probe

Microwave interferometry

RF probe spectroscopy

Optical emission

Optical absorption (DLS, FTIR)

Laser Induced Fluorescence

Rayleigh scattering

Thomson scattering

Sensing a plasma environment

	Gas composition	Density / m^{-3}: ion (n_i)	electron (n_e)	neutrals (eg n_*)	Energy / eV: ion ($<E_i>$)	electron ($<E_e>$)	neutrals (eg $<E_{vib}>$)	Flux / m^{-2} s^{-1}: ion (Γ_i)	electron (Γ_e)	neutrals (eg Γ_*)	Potential/V & E field / V m^{-1}: $\Delta\phi$	**E**
(Quadrupole) Mass Analyser												
Langmuir Probe												
Emissive Langmuir Probe												
Retarding Field Analyser												
Ion flux probe												
Microwave interferometry												
RF probe spectroscopy												
Optical emission												
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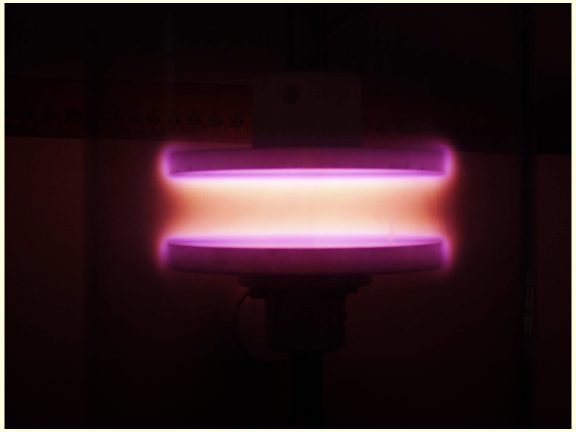
Laser Induced Fluorescence												
Rayleigh scattering												
Thomson scattering												

Sensing a plasma environment

SAQ What are typical parameters for 'low temperature plasmas'?



System size

Pressure /Pa

Power density /W m^{-2}

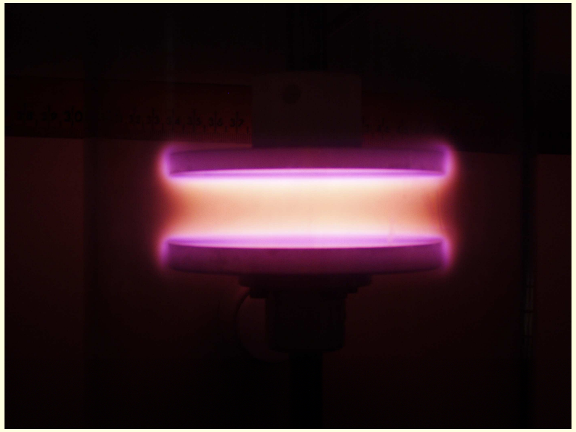
Plasma source

Electron mean energy /eV

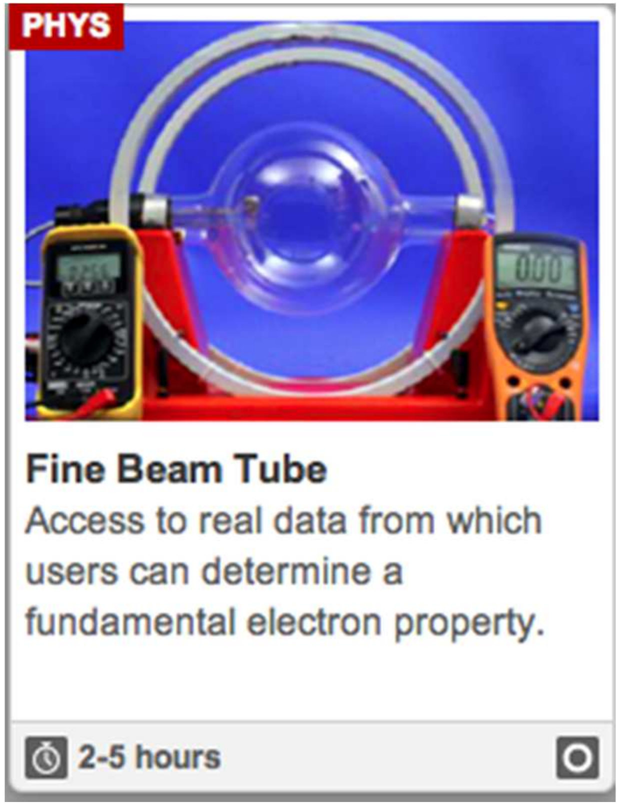
Charge density /m^{-3}

Gas density /m^{-3}

SAQ What are typical parameters for 'low temperature plasmas'?



System size	100s mm^3 …~100s µm^3
Pressure /Pa	0.3 – 30 … 10^5
Power density /W m^{-2}	100 - 10^4
Plasma source	CCP, ICP … DBD, micro
Electron mean energy /eV	1 – 10
Charge density /m^{-3}	10^{16} – 10^{19} … 10^{21}
Gas density /m^{-3}	10^{19} – 10^{21} … 10^{25}



Demonstration experiment from *The OpenScience Laboratory*
http://www.opensciencelab.ac.uk

What do you want to measure?

Fluxes onto surfaces

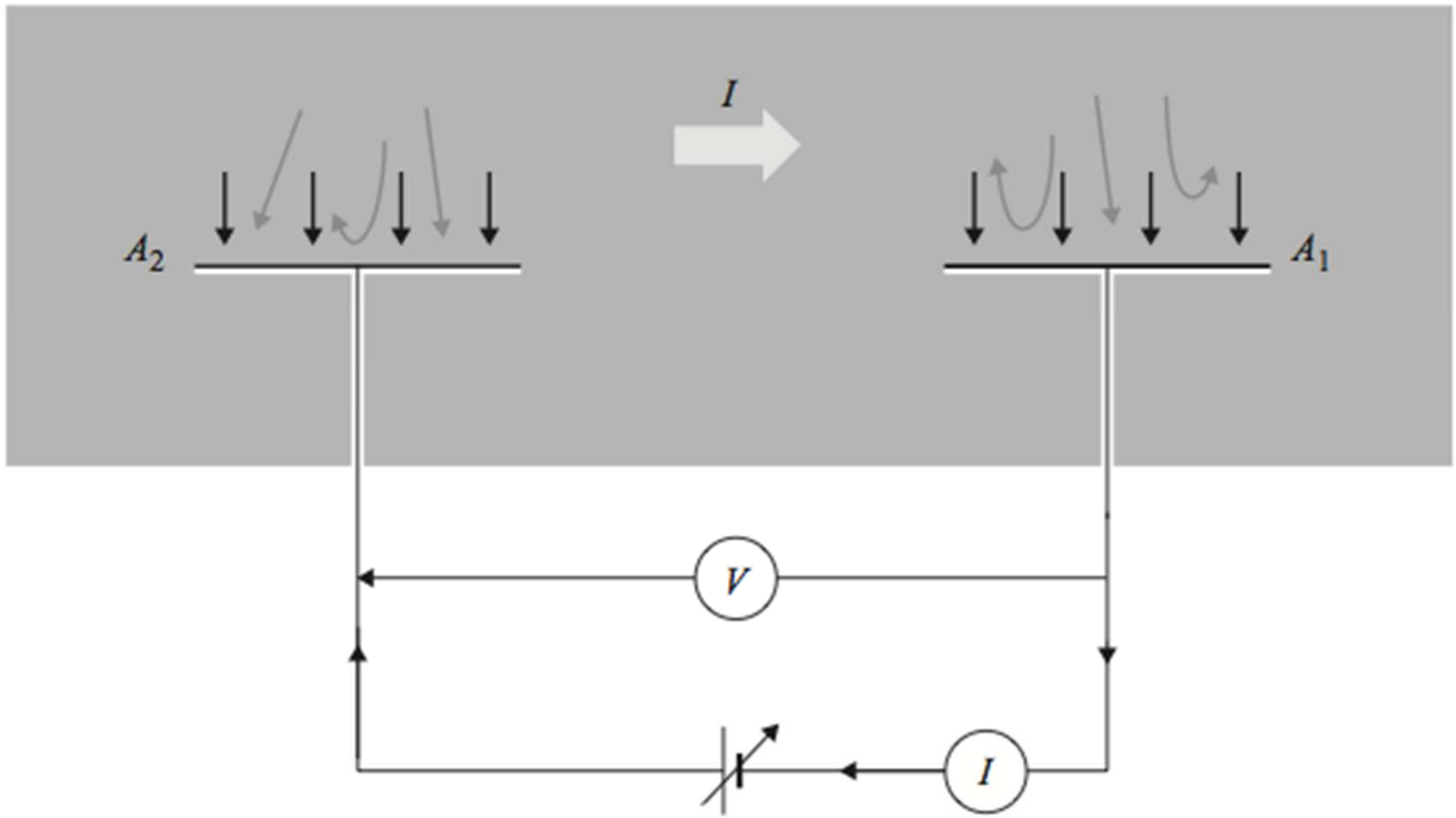
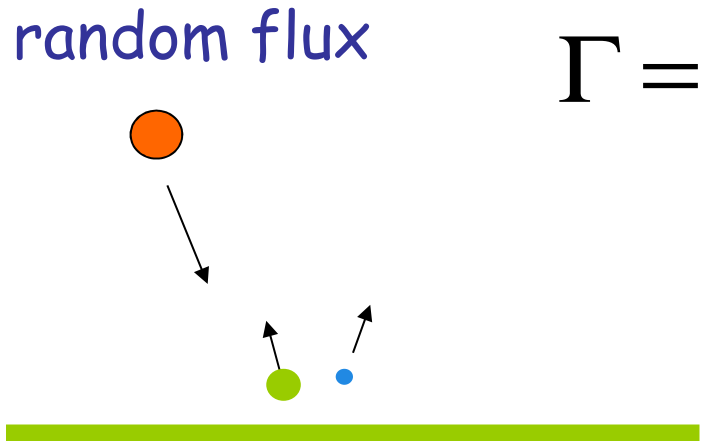


Figure 10.2 Two surfaces linked by a battery – the potential is distributed in order that the current is continuous. It is supposed that the lower surfaces are insulated from the plasma, so current is collected only on the upper surfaces. $I(V)$ is given by Eq. (10.2).

Fluxes onto surfaces

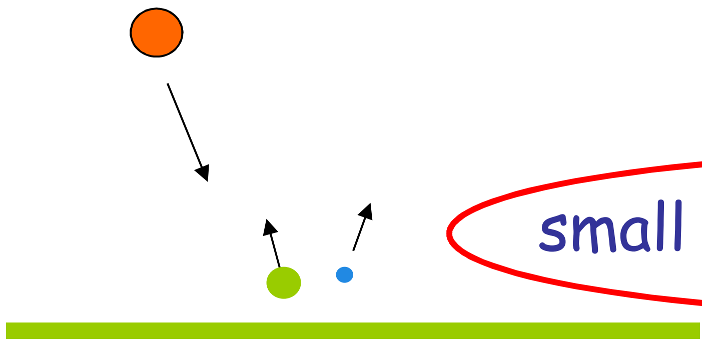


$$\Gamma = \frac{n\bar{c}}{4} = n\sqrt{\frac{kT_x}{2\pi M_x}}$$

What do you want to measure?

Fluxes onto surfaces

random flux



$$\Gamma = \frac{n\bar{c}}{4} = n\sqrt{\frac{kT_x}{2\pi M_x}}$$

small or non-absorbing surface

What do you want to measure?

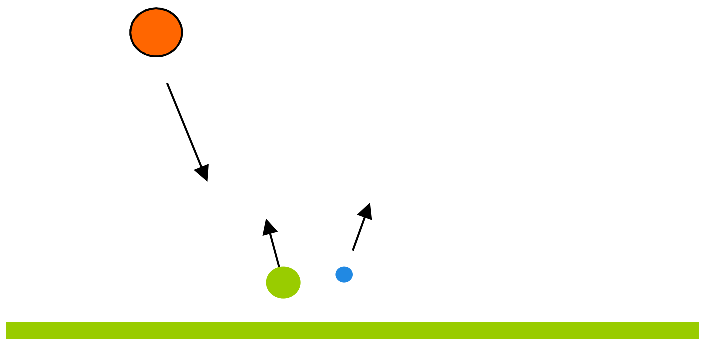
Fluxes onto surfaces

neutrals	charges
6.5 Pa, 50 amu, 300 K, 1% radicals	10^{16} m^{-3}, 3eV

Flux Γ

ground state

1.4×10^{23} m^{-2} s^{-1}



Fluxes onto surfaces

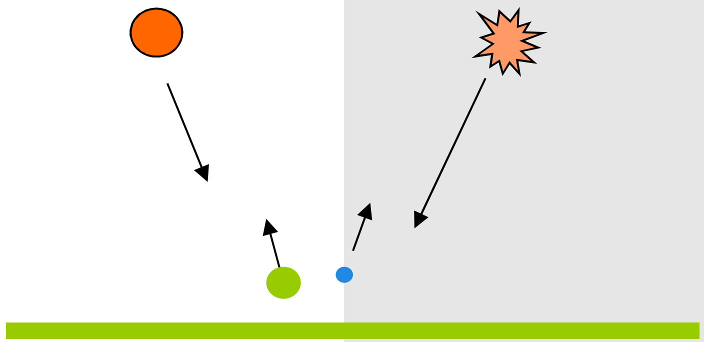
neutrals | charges

6.5 Pa, 50 amu, 300 K, 1% radicals | 10^{16} m^{-3}, 3eV

Flux Γ

ground state: 1.4 x 10^{23} m^{-2} s^{-1}

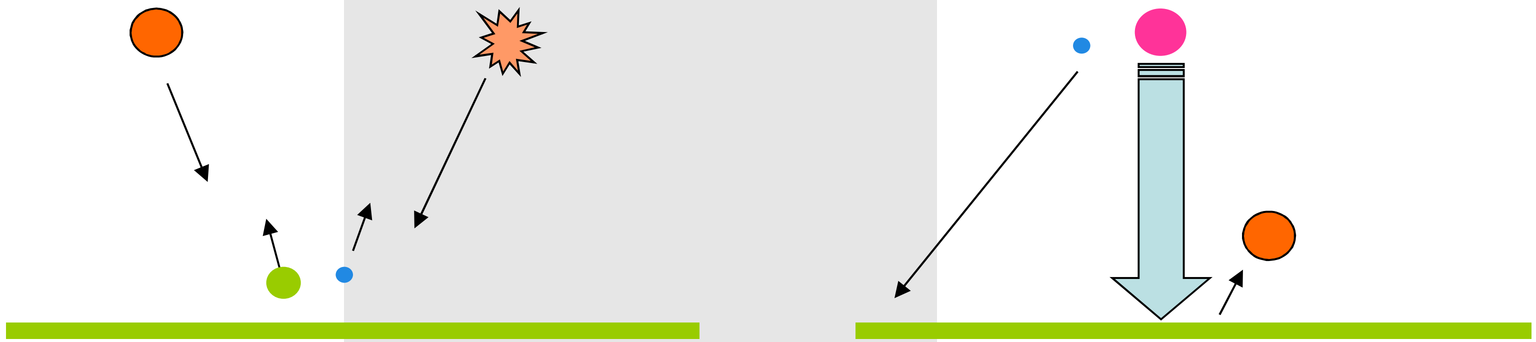
excited: 1.4 x 10^{21} m^{-2} s^{-1}



What do you want to measure?

Fluxes onto surfaces

	neutrals		charges
	6.5 Pa, 50 amu, 300 K, 1% radicals		10^{16} m^{-3}, 3eV
	ground state	excited	
Flux Γ	1.4 x 10^{23} m^{-2} s^{-1}	1.4 x 10^{21} m^{-2} s^{-1}	2 x 10^{19} m^{-2} s^{-1}



SAQ Electrical discharges through gases are used in the dry etching and deposition of thin films.

(a) Identify the role of electrons in these two applications.

SAQ Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(a) Identify the role of electrons in these two applications.

Electron-molecule collisions produce active species that combine with surface atoms to produce volatile products (etching) or to extend the surface (deposition)

SAQ Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(b) Explain how the uniformity of either process can be monitored in real-time.

What do you want to measure?

SAQ Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(b) Explain how the uniformity of either process can be monitored in real-time.

Monitor the electron density at various points in space in the region where active species are produced
or …

SAQ Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(c) Suggest how both processes could be speeded up.

What do you want to measure?

SAQ Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(c) Suggest how both processes could be speeded up.

Increase the density and/or energy of electrons to increase the production rate.

SAQ Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

(a) Identify the role of ions in this application.

SAQ Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

(a) Identify the role of ions in this application.

Sputtering.

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SAQ Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

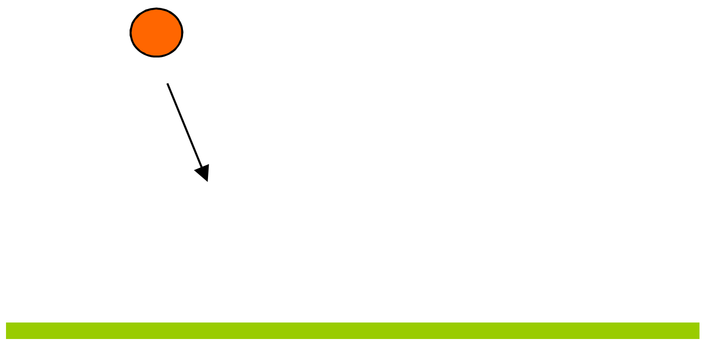
(b) Suggest how the process could be speeded up.

Increase ion flux and/or ion energy.

Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K



What can you measure?

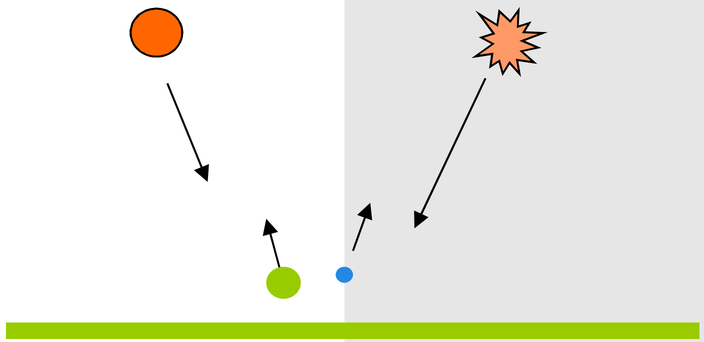
Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K, 1% radicals

ground state

excited



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Fluxes onto surfaces

neutrals

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excited

What can you measure?

Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K, 1% radicals

charges

10^{16} m^{-3}, 3eV

ground state

excited

Particle flux

1.4×10^{23} m^{-2} s^{-1}

1.4×10^{21} m^{-2} s^{-1}

2×10^{19} m^{-2} s^{-1}

What can you measure?

Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K, 1% radicals

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10^{16} m^{-3}, 3eV

ground state

excited

Particle flux

1.4×10^{23} m^{-2} s^{-1}

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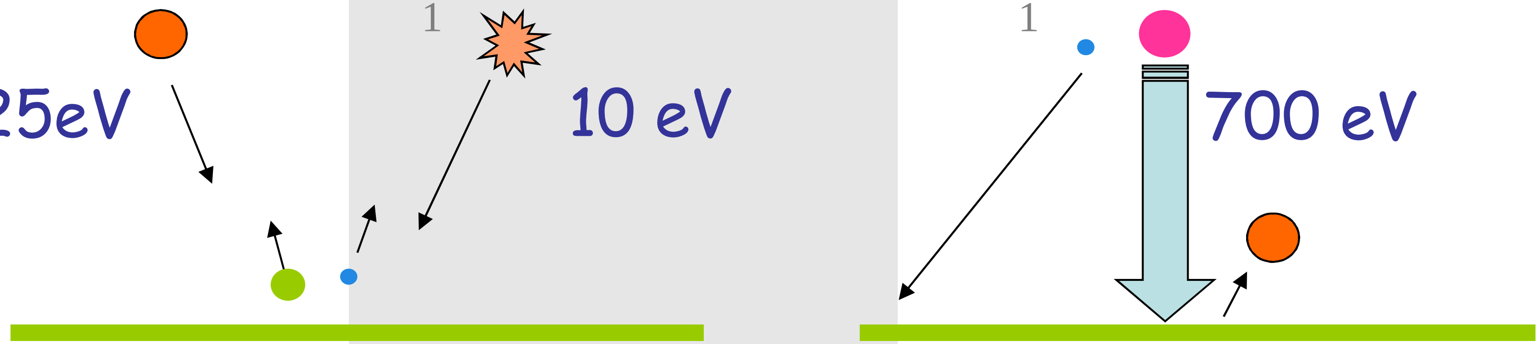
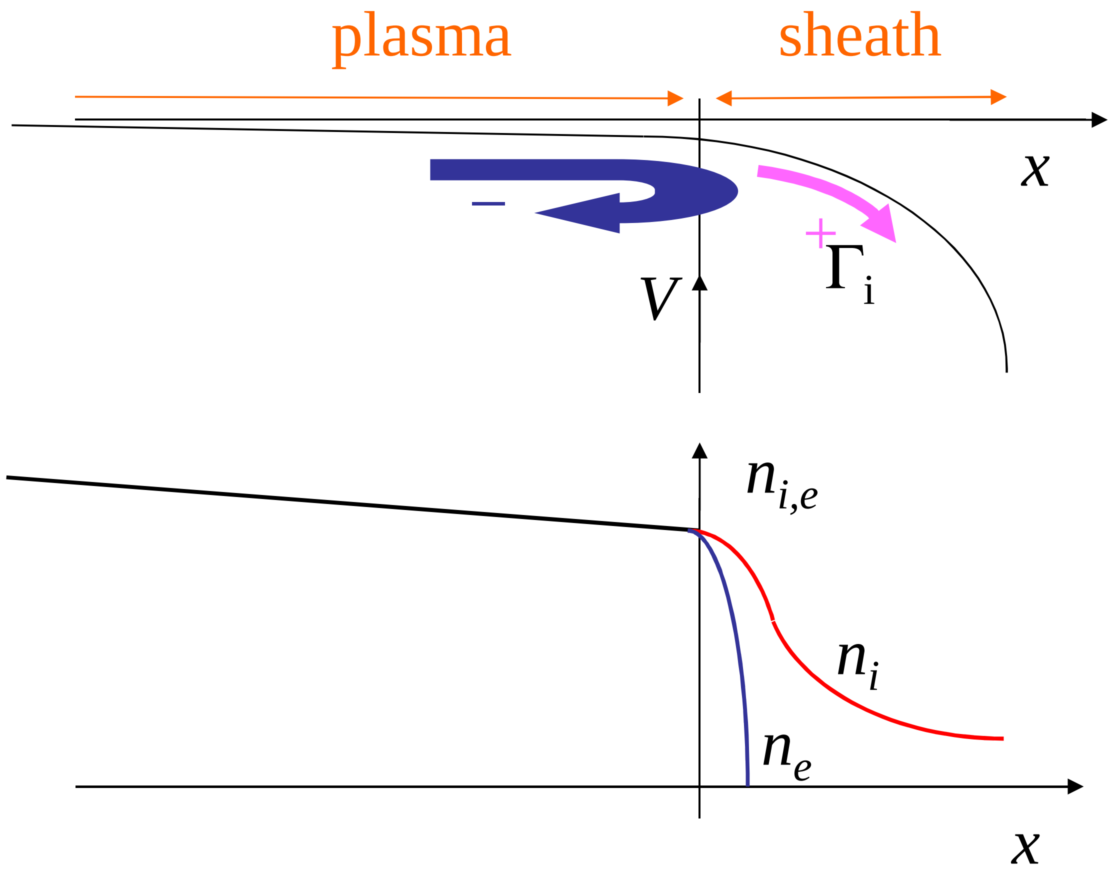
What can you measure?

Fluxes onto surfaces

	neutrals		charges
	6.5 Pa, 50 amu, 300 K, 1% radicals		10^{16} m^{-3}, 3eV
	ground state	excited	
Particle flux	1.4×10^{23} m^{-2} s^{-1}	1.4×10^{21} m^{-2} s^{-1}	2×10^{19} m^{-2} s^{-1}
	0.025eV	10 eV	700 eV
Energy flux	~500 W m^{-2}	~2000 W m^{-2}	~2000 W m^{-2}

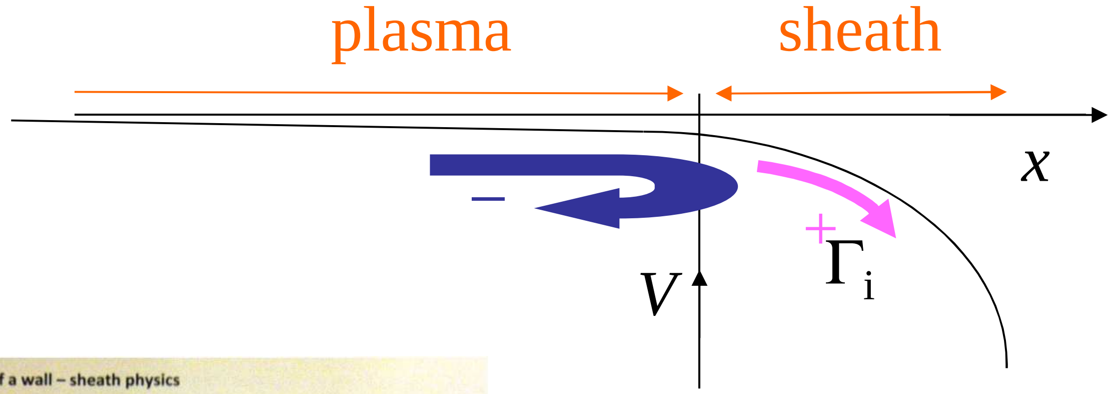


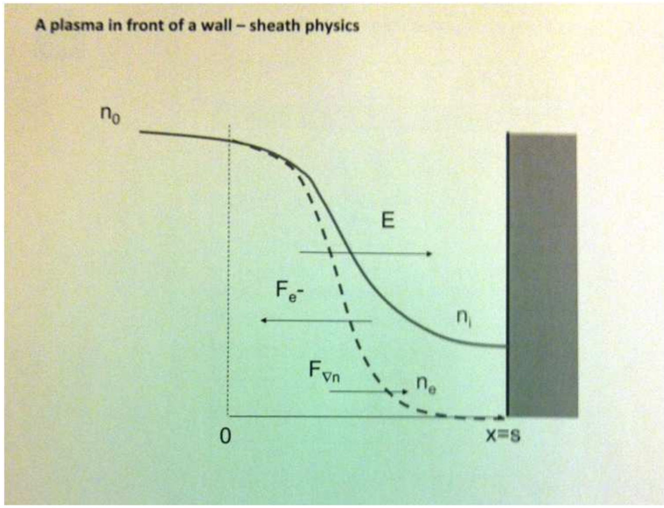
Electrical models for plasma boundaries

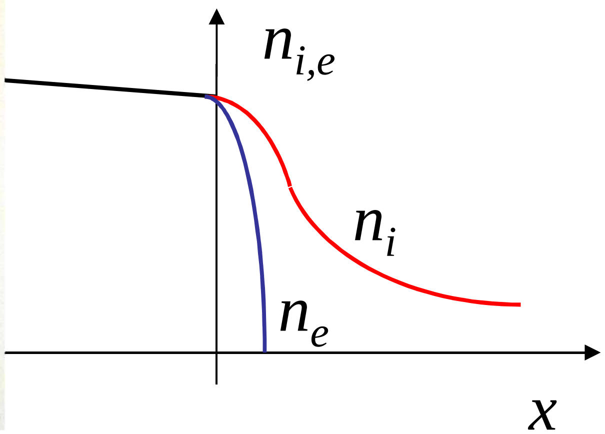


What can you measure?

Electrical models for plasma boundaries







From A von Keudell's lecture

This is how ions approach a sheath…

Niagara Falls

Electrical models for plasma boundaries

Boltzmann

Boltzmann relation

$$n_e(x) = n_s \exp\left(\frac{e\phi(x)}{kT_e}\right) .$$

For the cold ions, the low pressure continuity and momentum equations,

$$\begin{aligned} n_i(x)u(x) &= n_s u_s \\ \frac{1}{2}Mu(x)^2 + e\phi(x) &= \frac{1}{2}Mu_s^2 , \end{aligned}$$

where u_s is the positive ion fluid speed at the plasma/sheath transition,

positive ion density as a function of the potential,

$$n_i(x) = n_s\left(1 - \frac{2e\phi(x)}{Mu_s^2}\right)^{-1/2} .$$

Electrical models for plasma boundaries

The net space-charge in the sheath is therefore

$$\rho = en_s \left[\left(1 - \frac{2e\phi}{Mu_s^2} \right)^{-1/2} - \exp\left(\frac{e\phi}{kT_e} \right) \right] \quad (3.29)$$

$$\frac{d\rho}{d\phi} < 0\,.$$

Differentiating Eq. (3.29) with respect to ϕ leads to a requirement that

$$\frac{e^2 n_s}{Mu_s} \left(1 - \frac{2e\phi}{Mu_s} \right)^{-3/2} < \frac{e^2 n_s}{kT_e} \exp\left(\frac{e\phi}{kT_e} \right)\,.$$

Expanding this for small ϕ the development of positive space-charge requires that

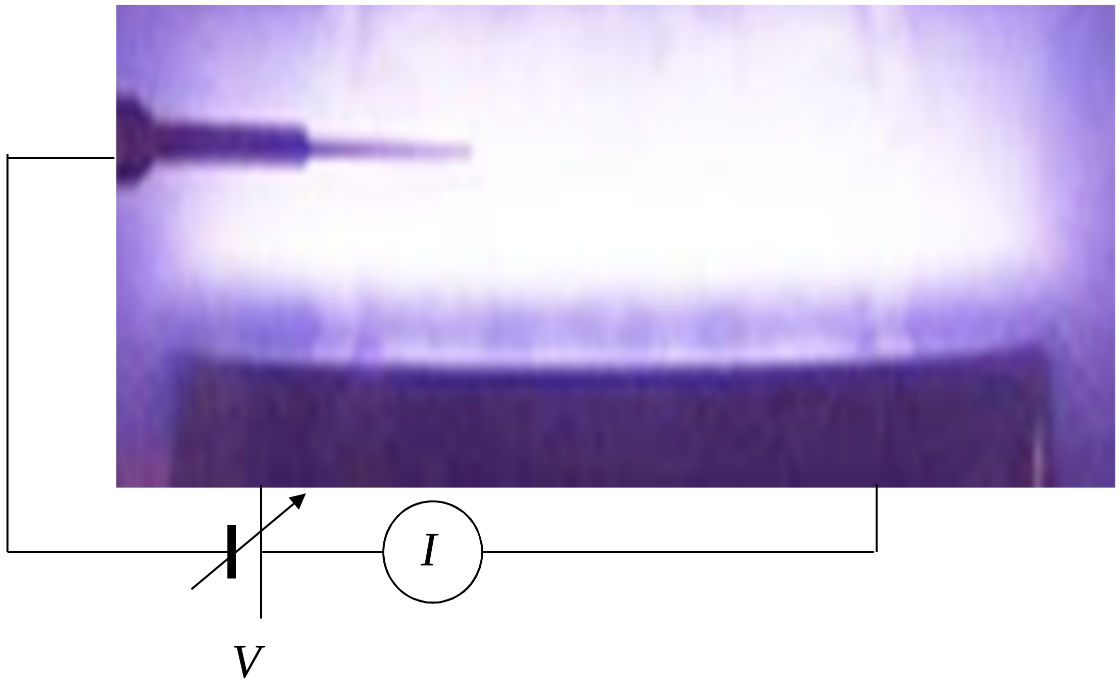
$$\frac{e^2 n_s}{Mu_s} \left(1 + \frac{3e\phi}{Mu_s} \ldots \right) < \frac{e^2 n_s}{kT_e} \left(1 + \frac{e\phi}{kT_e} \ldots \right)$$

and for $\phi < 0$ this inequality is satisfied if at the boundary the ion speed is such that

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

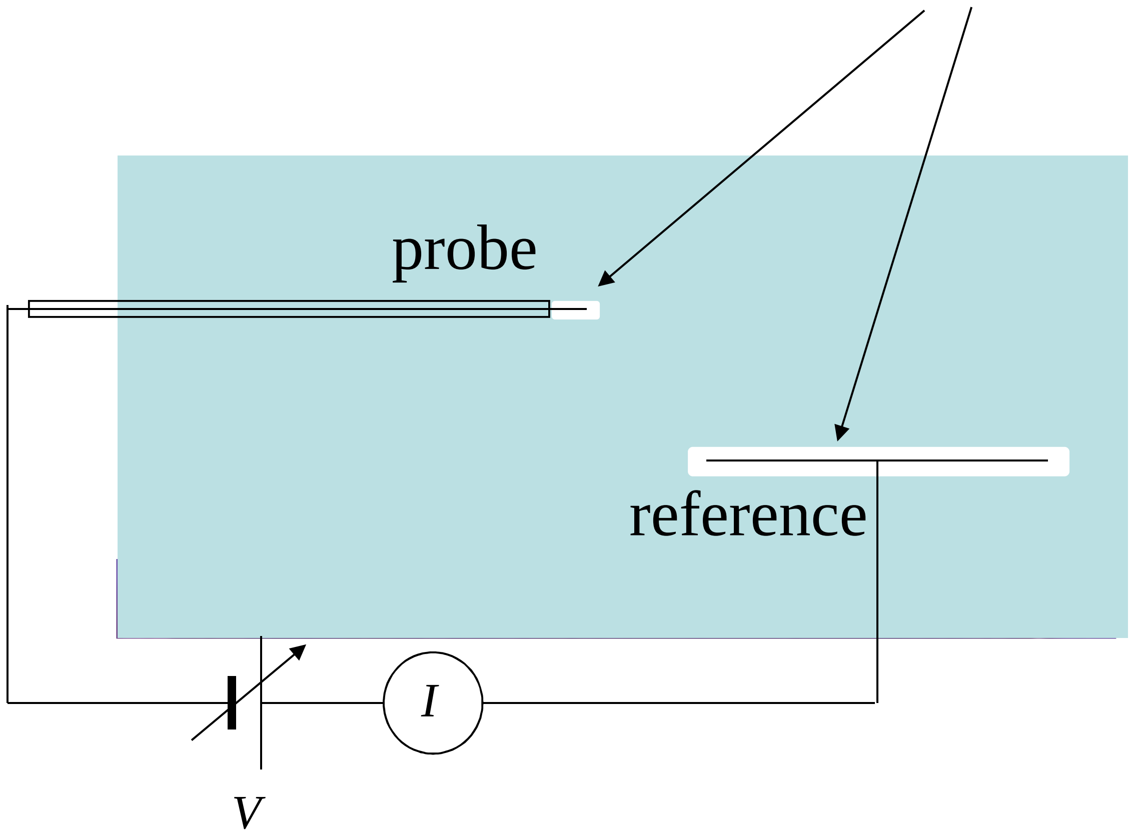
Bohm

Electrical models for plasma boundaries

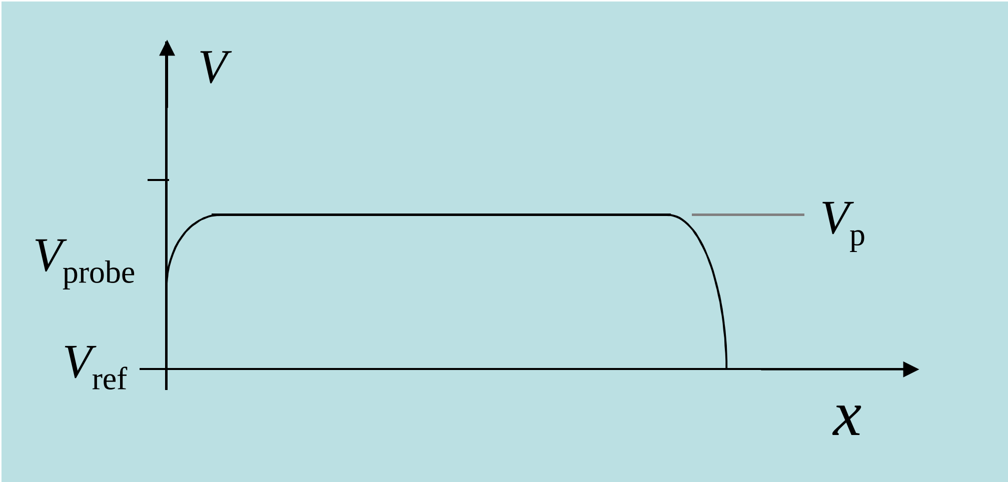


What can you measure?

Electrical models for plasma boundaries

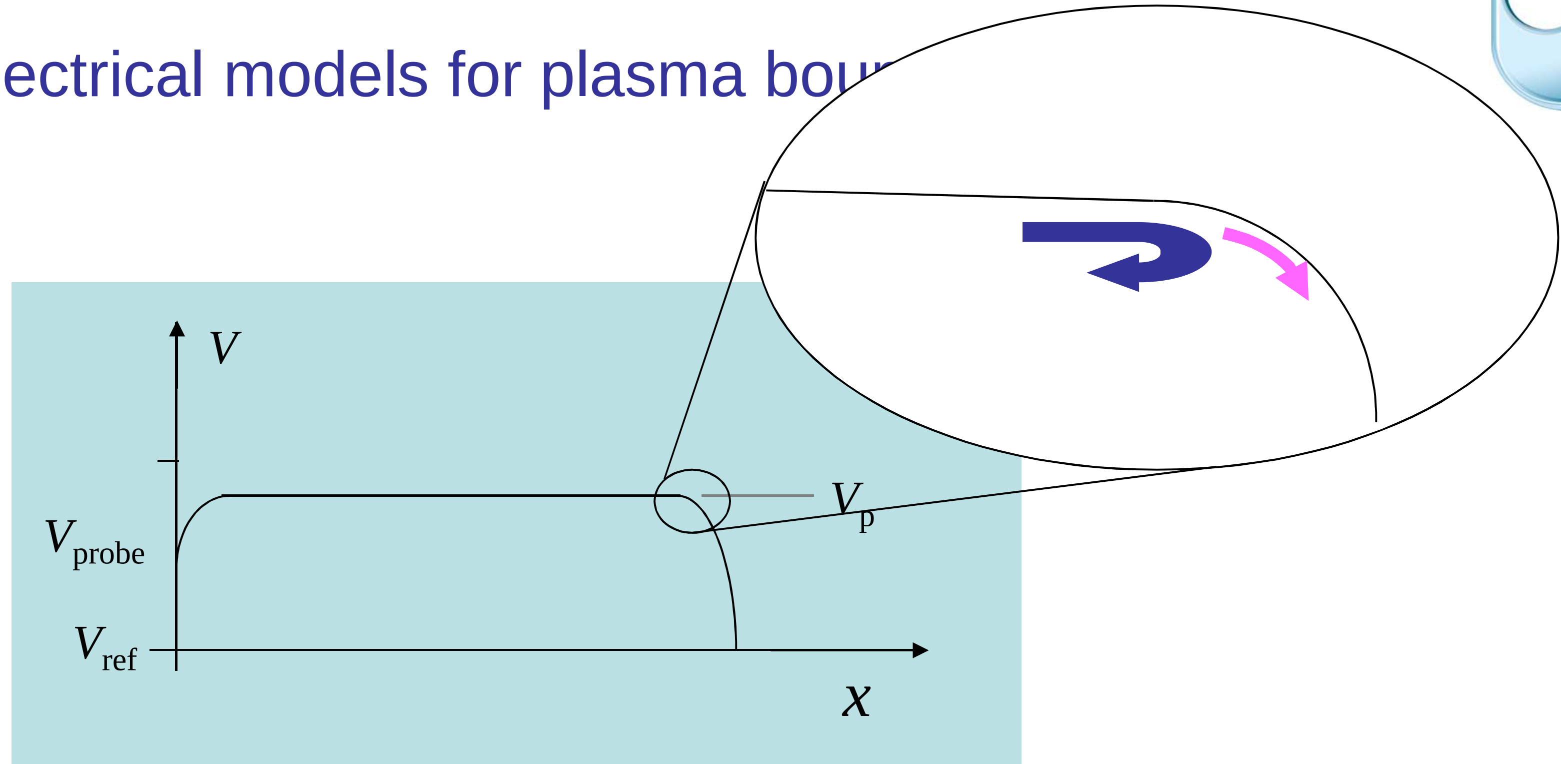


Electrical models for plasma boundaries



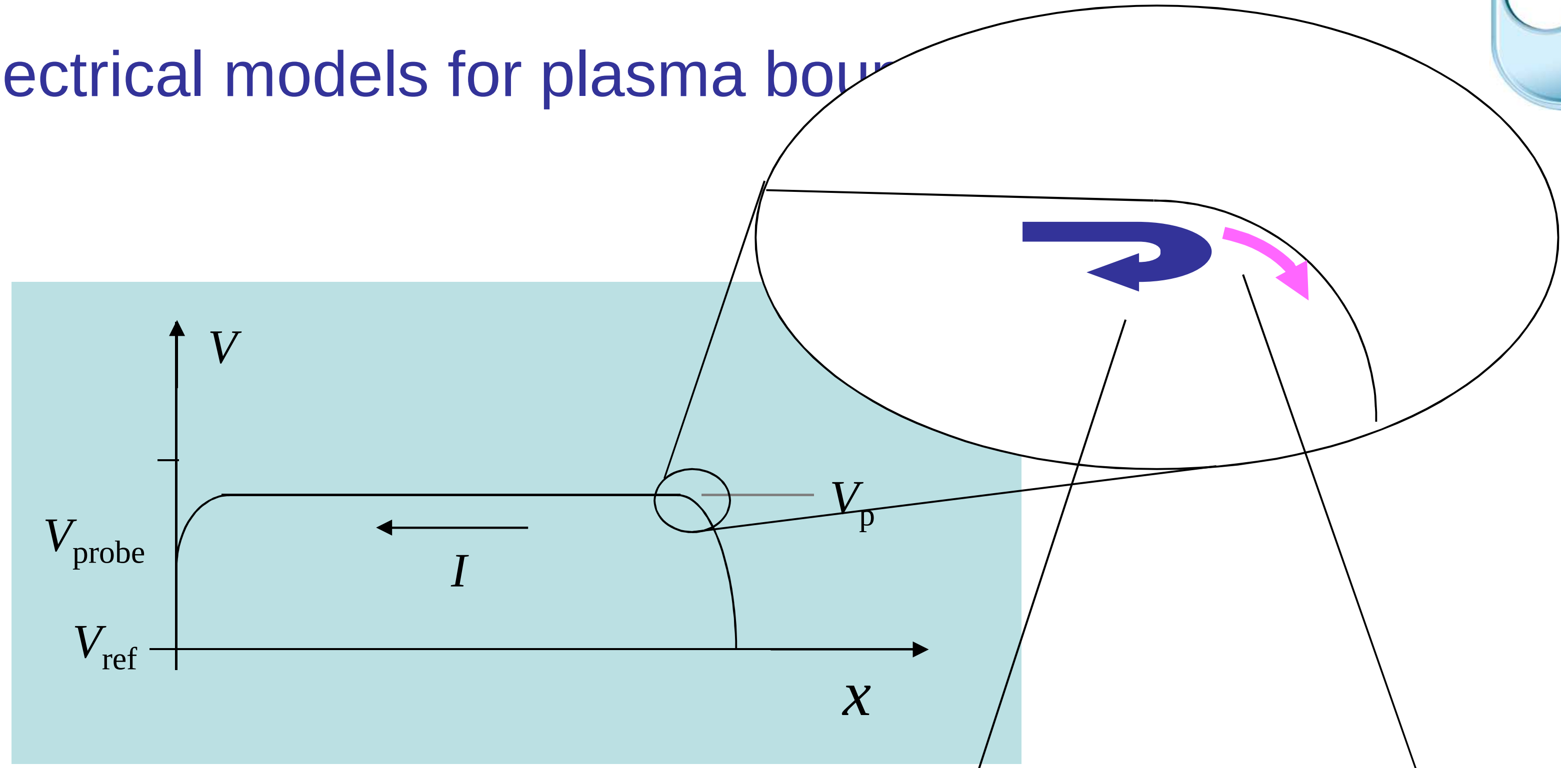
What can you measure?

Electrical models for plasma bou



What can you measure?

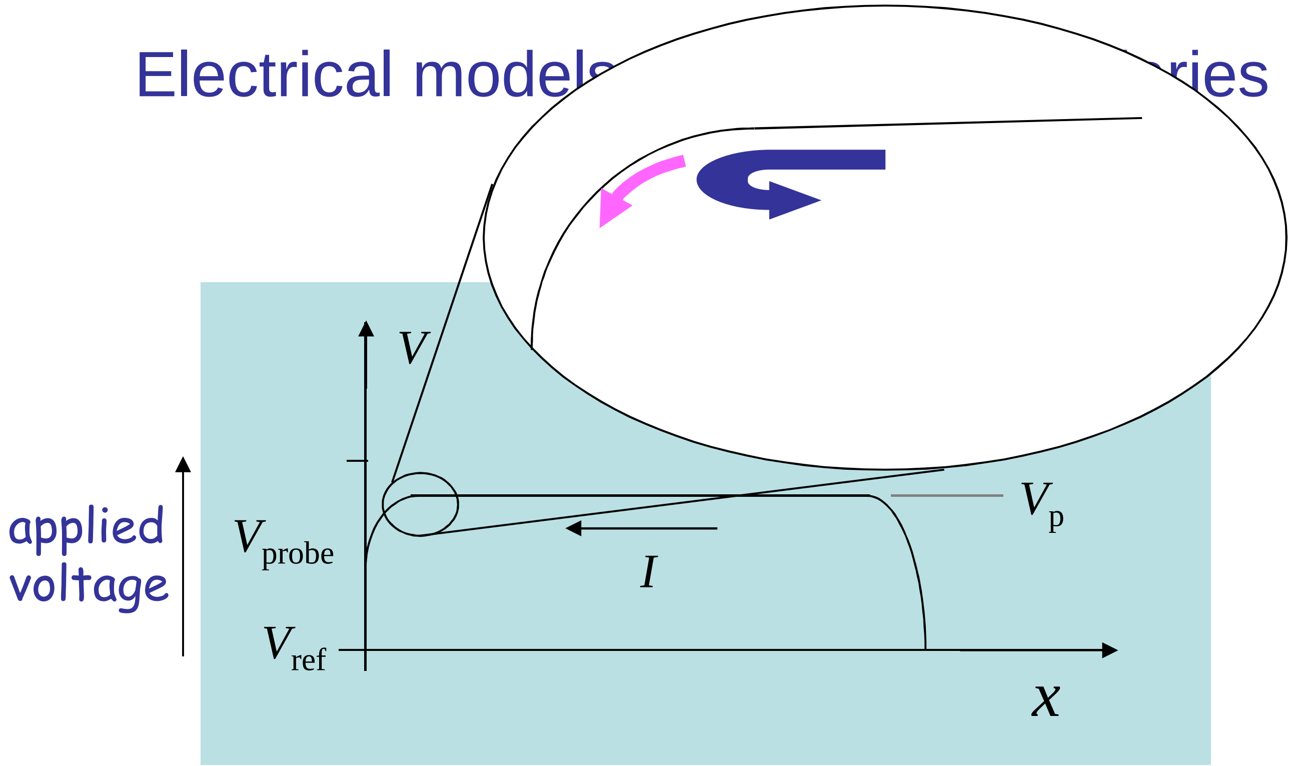
Electrical models for plasma bou…



$$I = -j_{\mathrm{ref}} A_{\mathrm{ref}} = eA_{\mathrm{ref}} \left\{ n_{\mathrm{s,ref}} \frac{c_{\mathrm{e}}}{4} \exp(e(V_{\mathrm{ref}} - V_{\mathrm{p}}) / kT_{\mathrm{e}}) - n_{\mathrm{s,ref}} c_{\mathrm{s}} \right\}$$

What can you measure?

Electrical models … ries

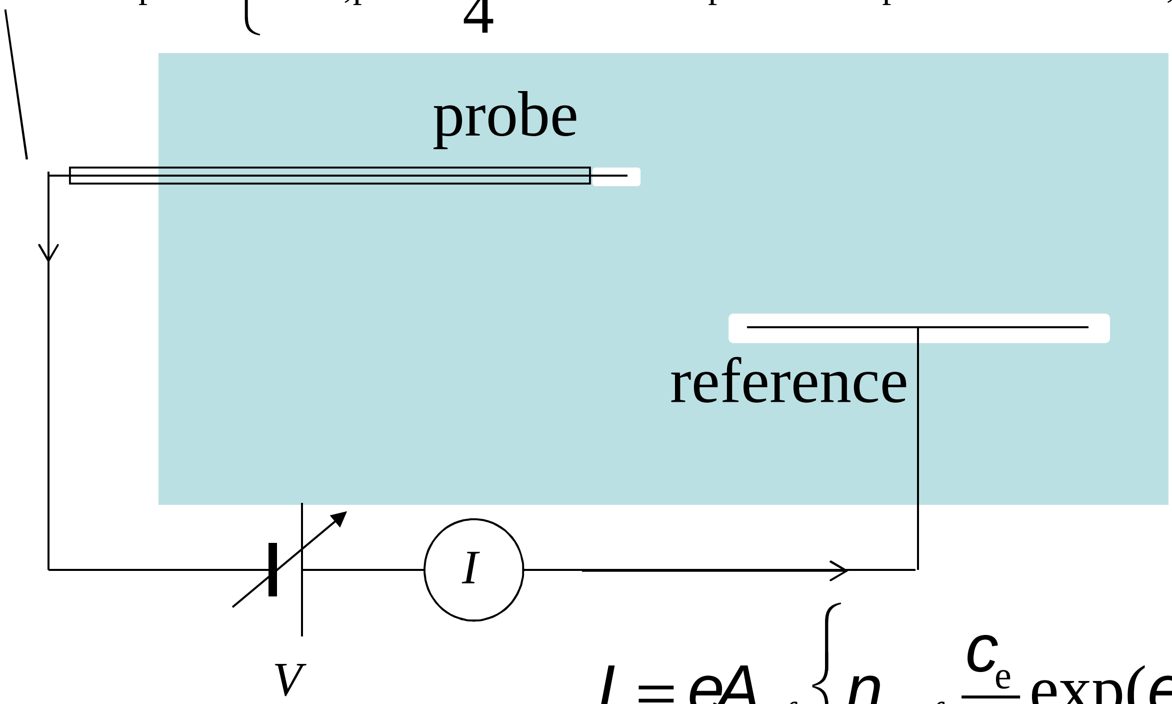


$$I = j_{\mathrm{probe}} A_{\mathrm{probe}} = eA_{\mathrm{probe}} \left\{ -n_{\mathrm{s,probe}} \frac{c_{\mathrm{e}}}{4} \exp\left(e(V_{\mathrm{probe}} - V_{\mathrm{p}}) / kT_{\mathrm{e}}\right) + n_{\mathrm{s,probe}} c_{\mathrm{s}} \right\}$$

What can you measure?

Electrical models for plasma boundaries

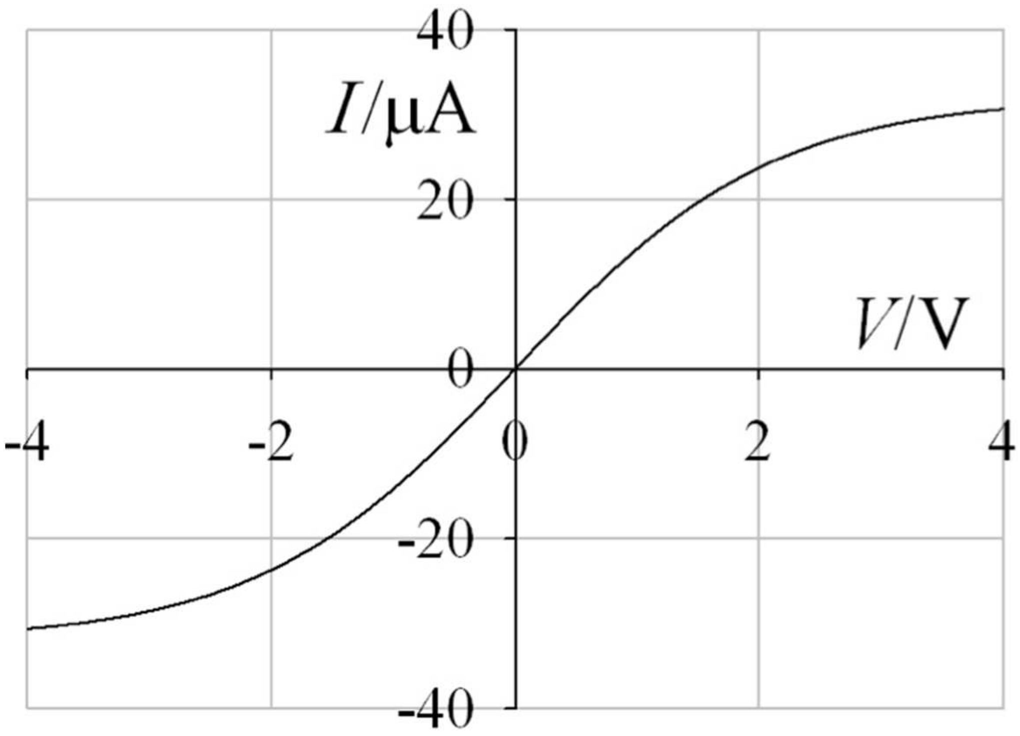
$$I = eA_{\text{probe}}\left\{ -n_{\text{s,probe}}\frac{c_{\text{e}}}{4}\exp(e(V_{\text{probe}} - V_{\text{p}})/kT_{\text{e}}) + n_{\text{s,probe}}c_{\text{s}} \right\}$$



$$I = eA_{\text{ref}}\left\{ n_{\text{s,ref}}\frac{c_{\text{e}}}{4}\exp(e(V_{\text{ref}} - V_{\text{p}})/kT_{\text{e}}) - n_{\text{s,ref}}c_{\text{s}} \right\}$$

What can you measure?

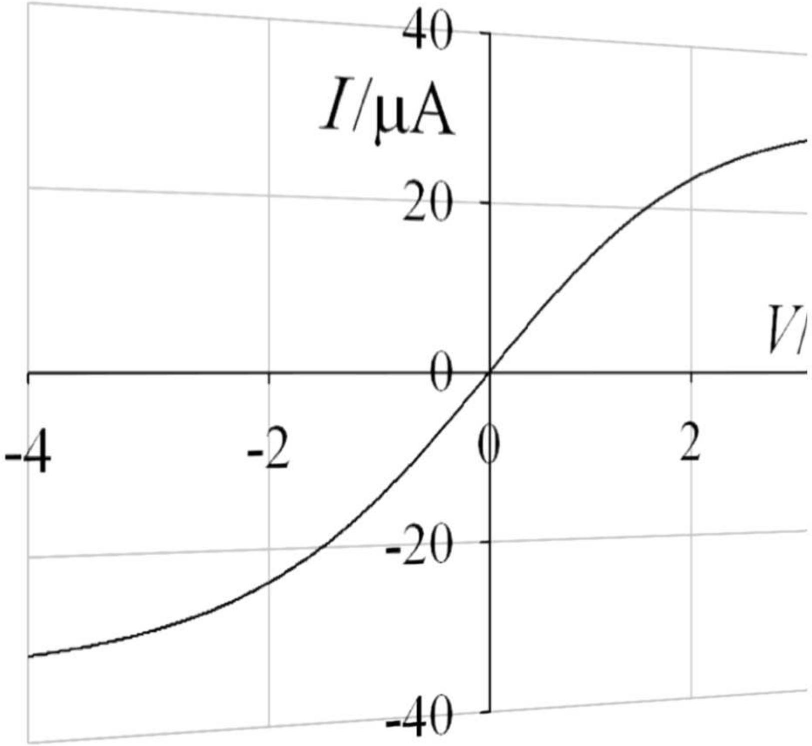
If $A_{ref} = A_{probe}$

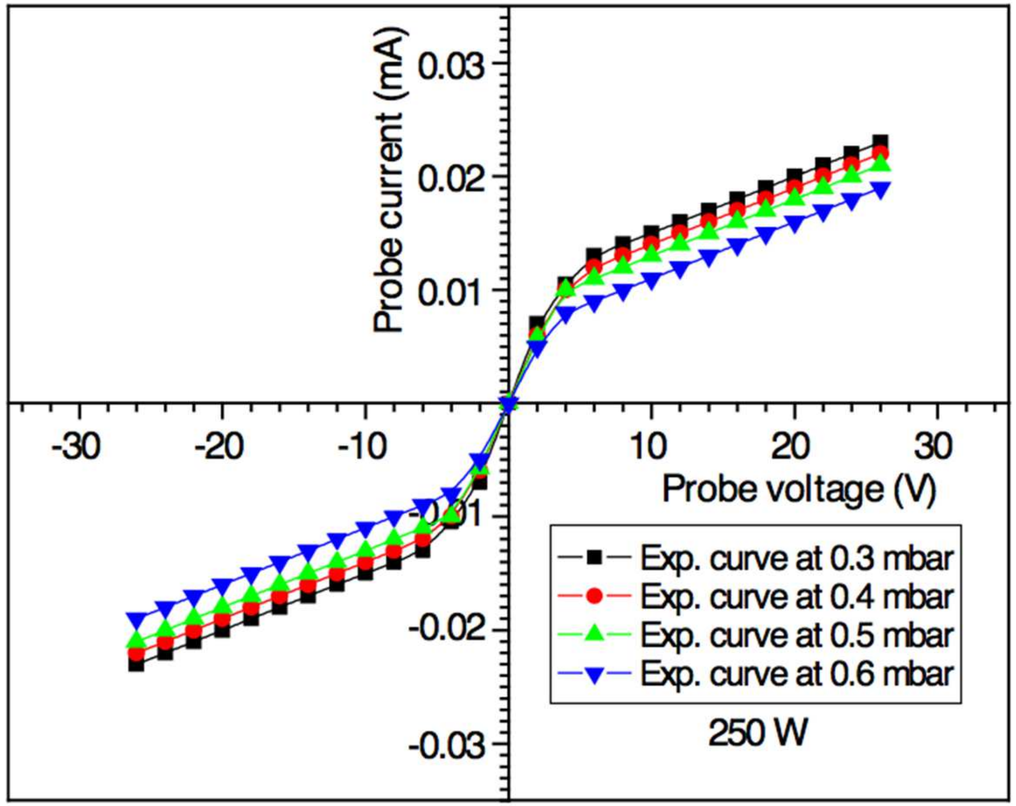


"Double probe"

$$I = I_o(n_e, kT, A_{ref})\tanh\left(\frac{eV_{applied}}{kT}\right)$$

What can you measure?

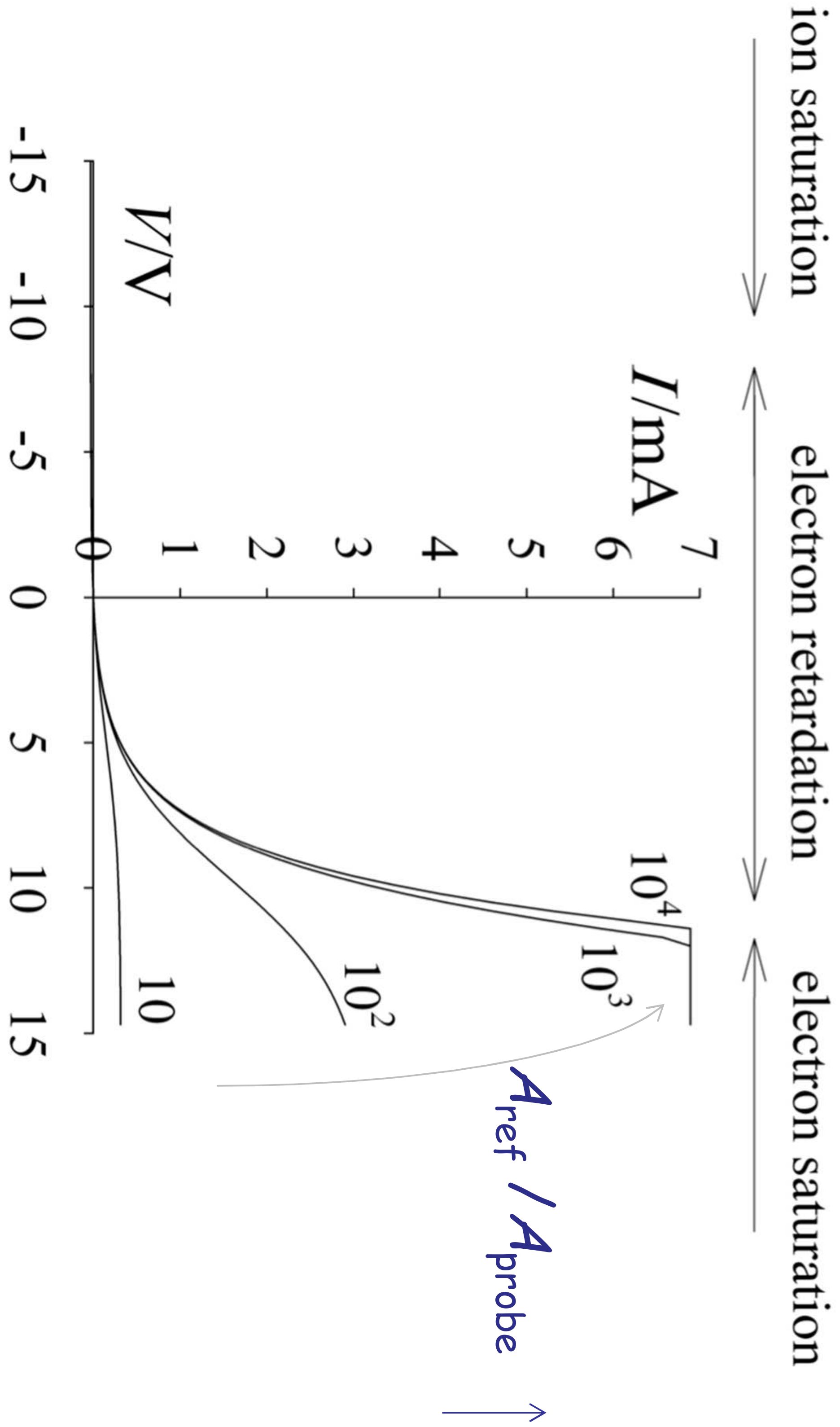




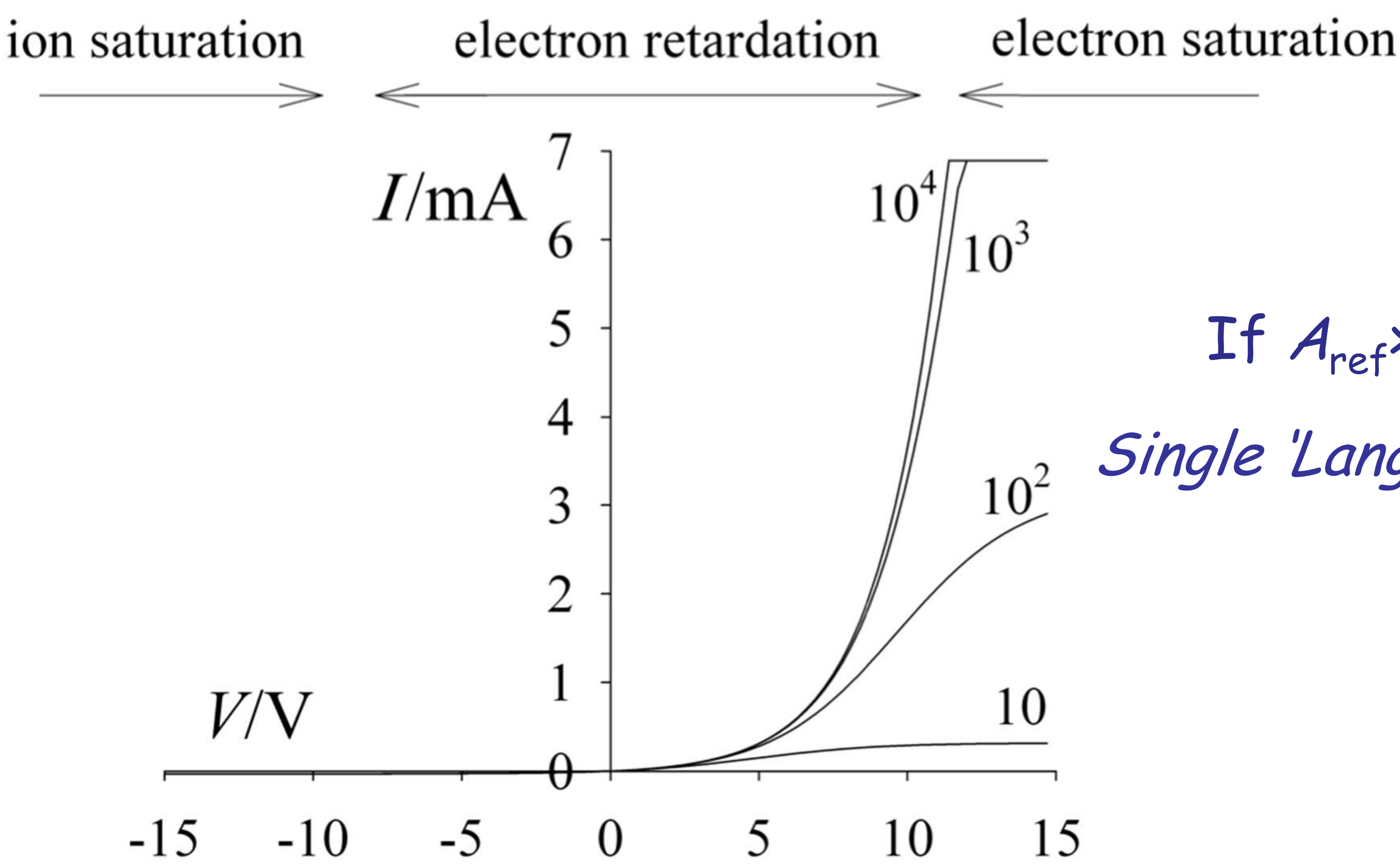
Nitrogen, inductively coupled plasma, 250 W

Double And Triple Langmuir Probes Measurements In Inductively Coupled Nitrogen Plasma, Naz et al. 2011
Prog. Electromagnetics Research **114** 113-128 **DOI:** 10.2528 PIER10110309

What can you measure?



What can you measure?

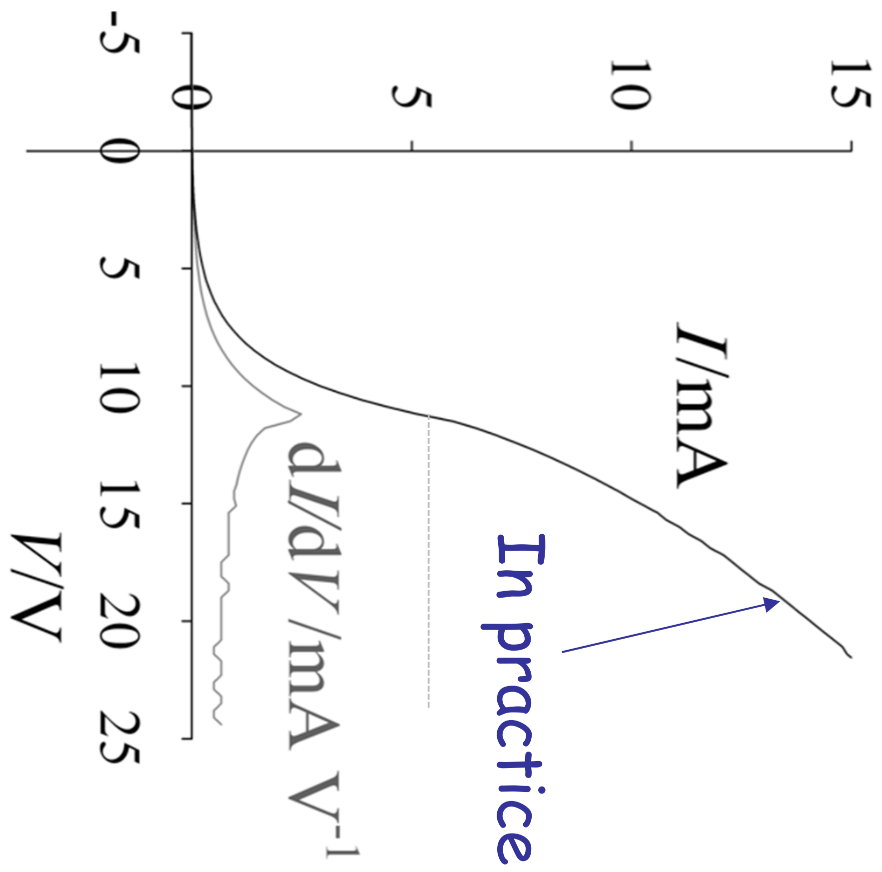


If $A_{ref} >> A_{probe}$

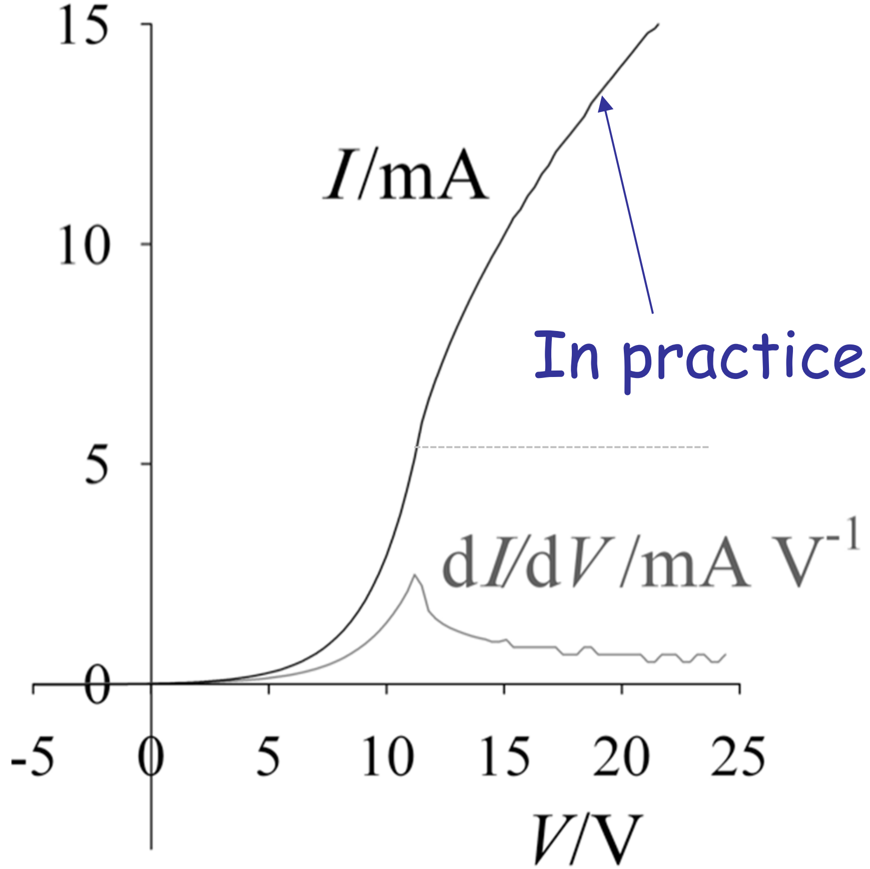
Single 'Langmuir' probe

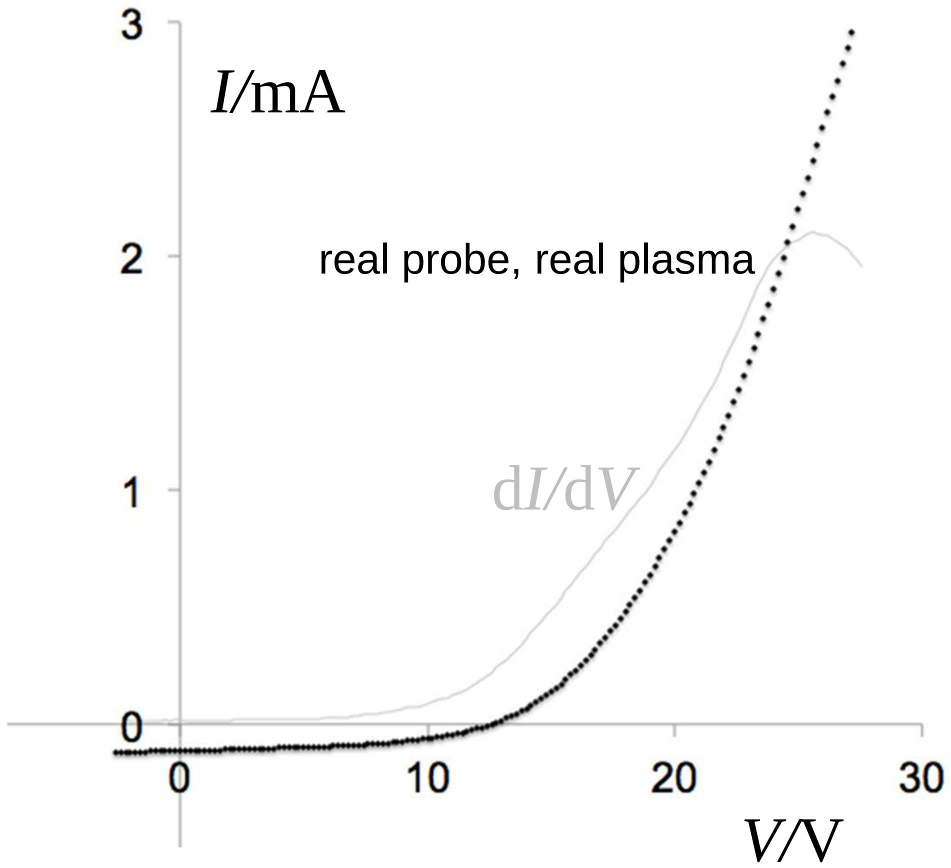
$$I = I_i(V_{applied}) - I_o(n_e, kT, A_{probe}) \exp(eV_{applied} / kT)$$

What can you measure?



What can you measure?





What can you measure?

SAQ Identify

(a) Plasma potential V_p

(b) Floating potential V_f

(c) Where to measure n_e

From Plasma Sources Science & Technology

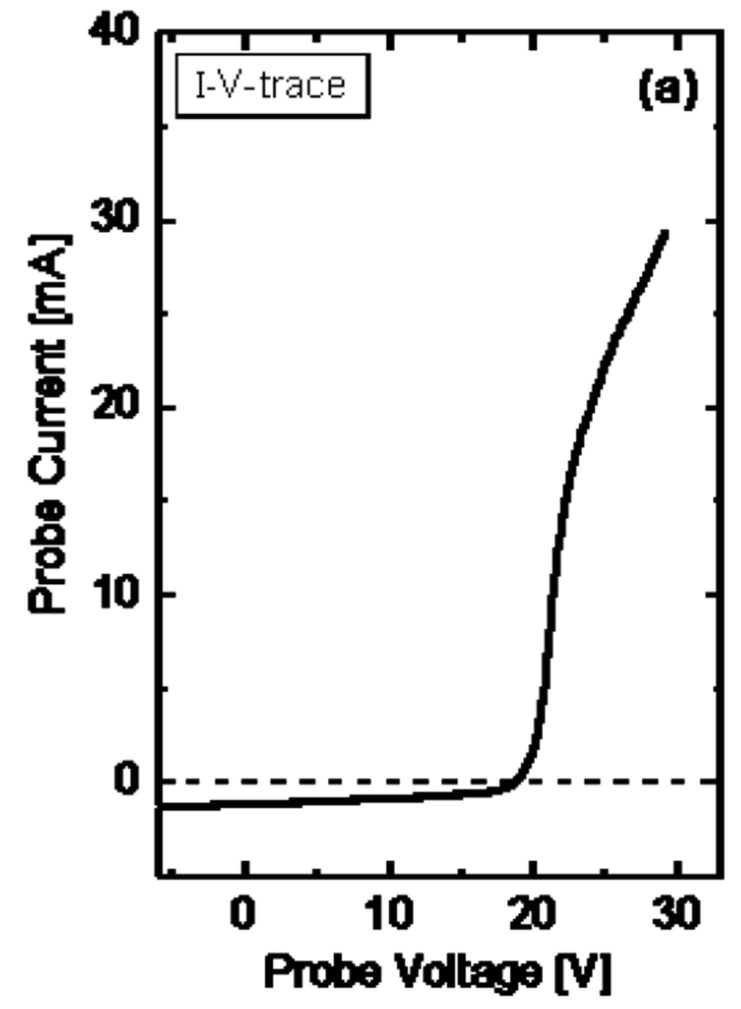
Special issuse: 80 yrs of 'Plasma'

A Langmuir probe system for high power RF-driven negative ion sources on high potential

P McNeely[1,3], SV Dudin[2], S Christ-Koch[1], U Fantz[1] and NNBI Team[1]

[1]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-84748 Garching, Germany*

[2]*V.N. Karazin Kharkov National University, 4 Svobody Sq., Kharkov-61007, Ukraine*



What can you measure?

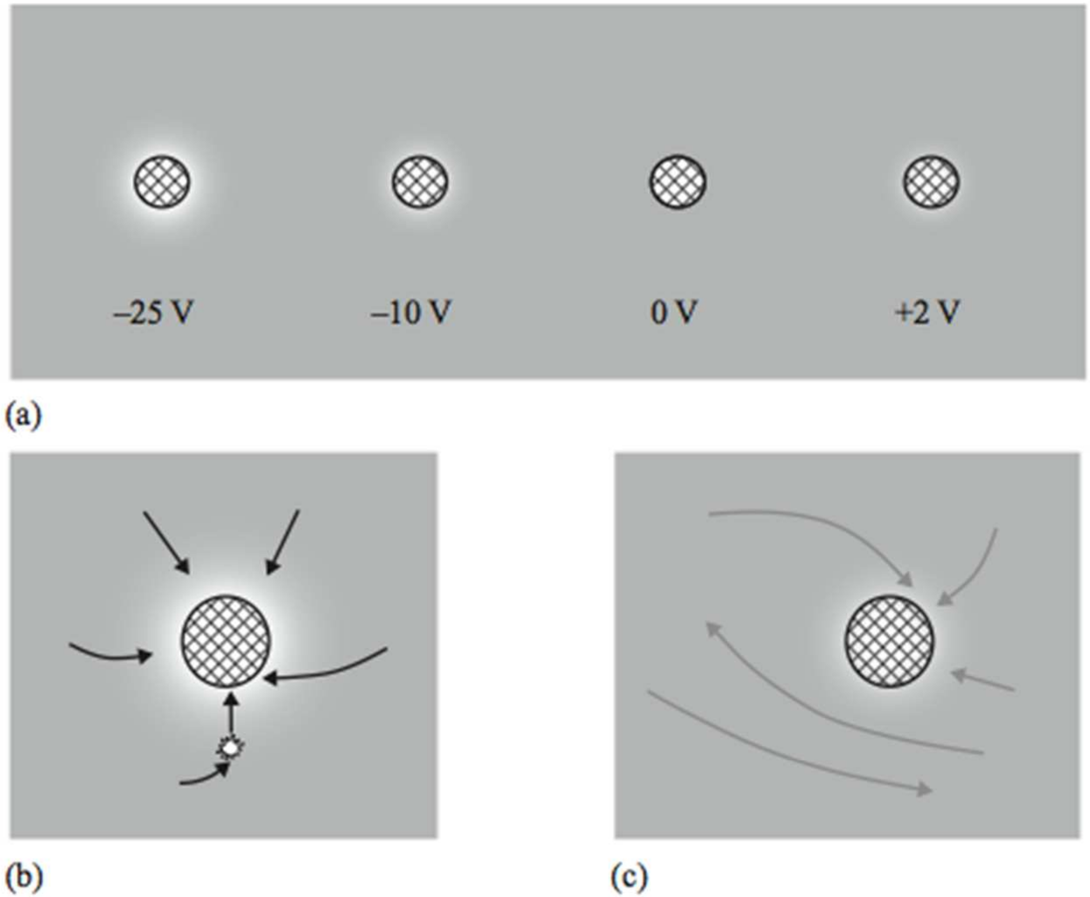


Figure 10.7 Schematics of a cylindrical (or spherical) probe. (a) Sheath development around a biased probe – the potential indicated is referenced to the plasma (ϕ_p); (b) example ion trajectories ($\phi < \phi_p$); (c) example electron trajectories in electron saturation ($\phi > \phi_p$). The lighter regions represent net space charge: positive if $\phi_p < 0$ and negative if $\phi > \phi_p$.

What can you measure?

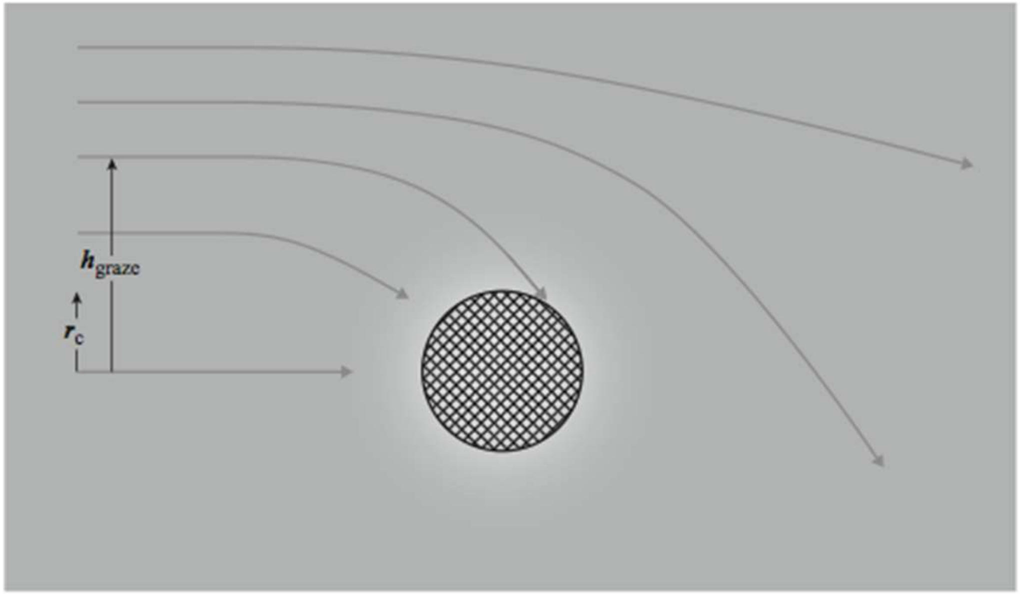


Figure 10.8 Trajectories of particles with the same energy, starting with different impact parameters. Those with $h \leq h_{graze}$ are collected by the probe; those with $h > h_{graze}$ miss the probe.

will be conserved, so that for an electron that is accelerated to just graze the probe at the surface,

Orbital Motion Limited electron collection

$$\frac{1}{2}mv^2 = \frac{1}{2}mv_c^2 - e(V_c - \phi_p).$$

energy

At the same time angular momentum must be conserved, so that for a particle that is going to graze the probe,

$$mvh_{graze} = mv_c r_c.$$

angular momentum

These two expressions can be combined to give the impact parameter for grazing incidence as a function of the initial speed:

$$h_{graze} = r_c \left(1 + \frac{2e(V_c - \phi_p)}{mv^2}\right)^{1/2}. \qquad (10.9)$$

What can you measure?

$$dI_e = 2el \times r_c \left(1 + \frac{2e(V_c - \phi_p)}{mv^2}\right)^{1/2} v\,dn.$$

current from v to $v + dv$

$$f_{s-cyl} = \frac{dn}{dv} = n_0 \left(\frac{m}{2\pi kT_e}\right) 2\pi v \exp\left(-\frac{mv^2}{2kT_e}\right)$$

$$I_e = e\,2\pi r_c l \frac{n_0 \bar{v}}{4} 2\sqrt{\frac{1 + e(V_c - \phi_p)/kT_e}{\pi}};$$

electron current $\propto \sim V^{1/2}$

Orbital Motion Limited
electron collection

What can you measure?

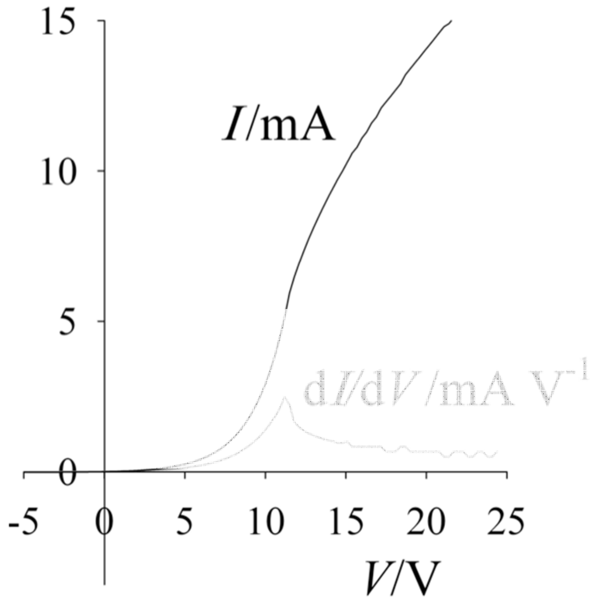
$$dI_e = 2el \times r_c \left(1 + \frac{2e(V_c - \phi_p)}{mv^2}\right)^{1/2} v\, dn.$$

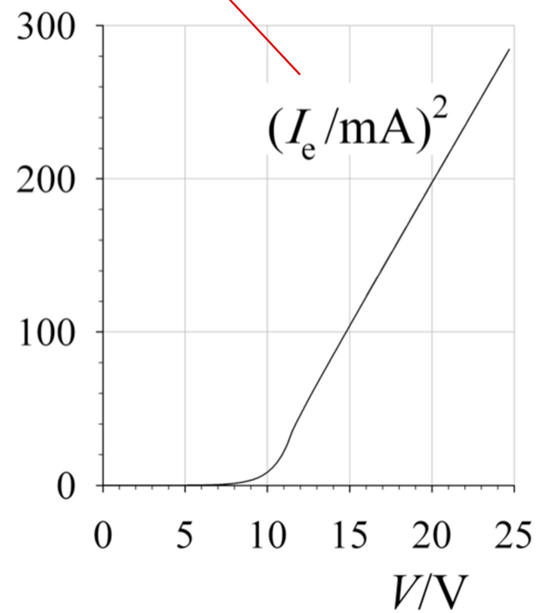
$$f_{s-cyl} = \frac{dn}{dv} = n_0 \left(\frac{m}{2\pi k T_e}\right) 2\pi v \exp\left(-\frac{mv^2}{2kT_e}\right)$$

$$I_e = e\, 2\pi r_c l \frac{n_0 \bar{v}}{4} 2\sqrt{\frac{1 + e(V_c - \phi_p)/kT_e}{\pi}};$$

$I^2 \propto V$

Orbital Motion Limited electron collection

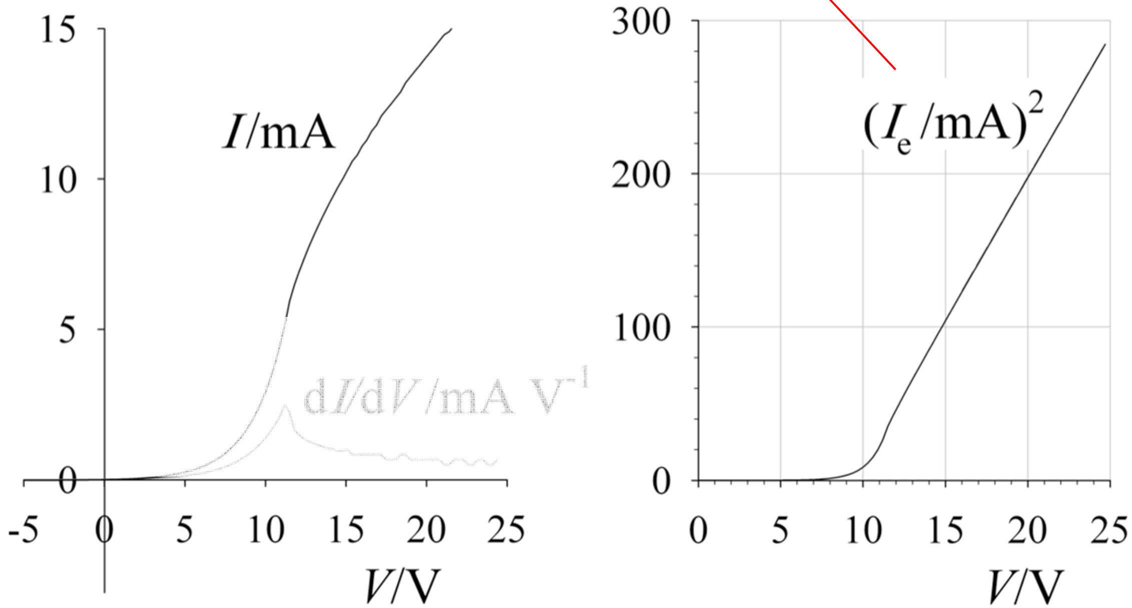




What can you measure?

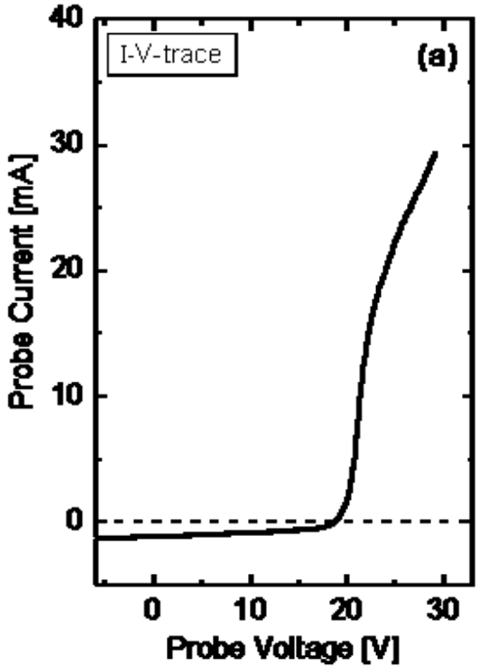
Orbital Motion Limited collection doesn't work so well for ions...

$I^2 \propto V$



SAQ Some say that Orbital Motion Limited collection doesn't work so well for ions…why not?

Techniques



Single (Langmuir) probe

From Plasma Sources Science & Technology
Special issuse: 80 yrs of 'Plasma'

A Langmuir probe system for high power RF-driven negative ion sources on high potential

P McNeely[1,3], SV Dudin[2], S Christ-Koch[1], U Fantz[1] and NNBI Team[1]

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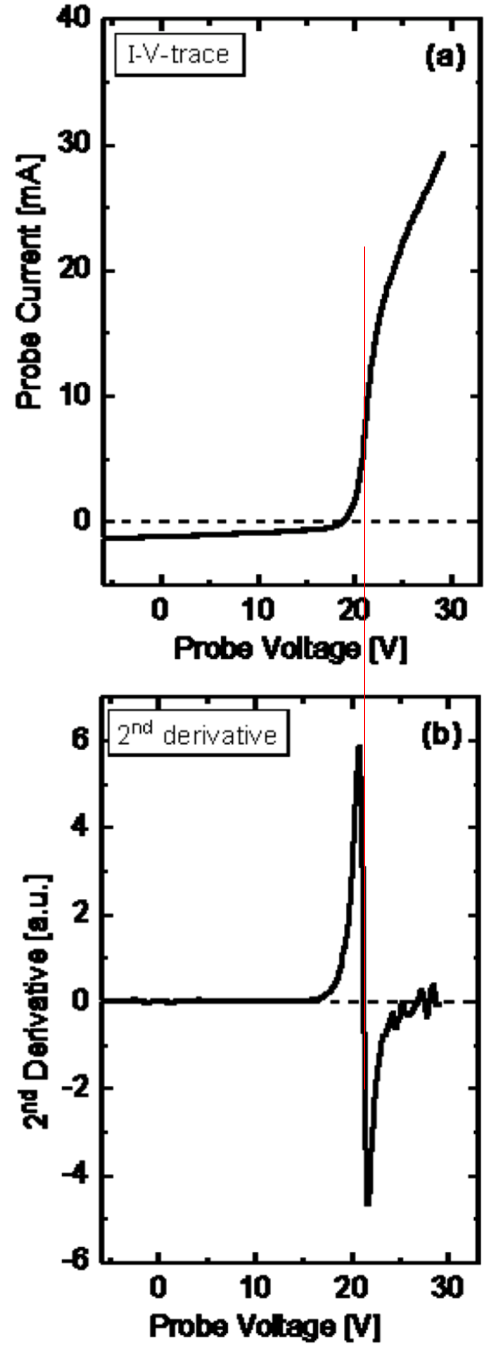
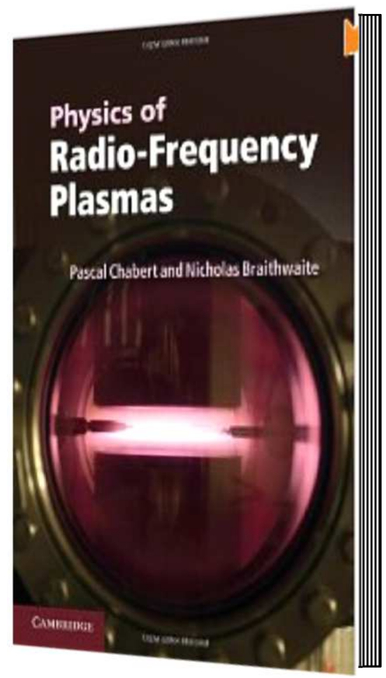
Techniques

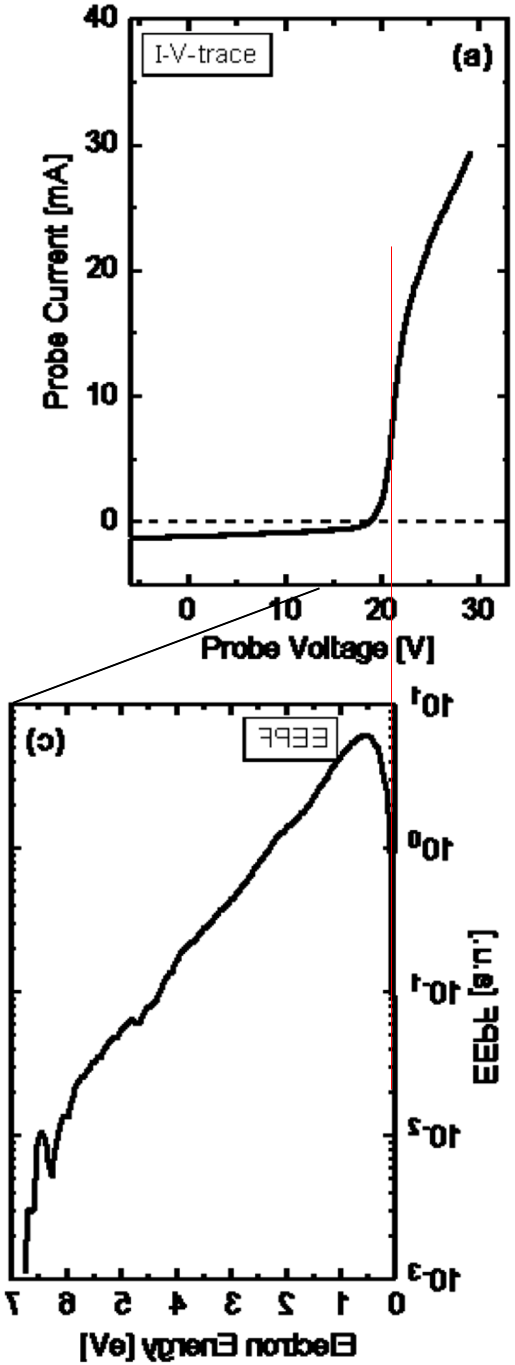


$V<V_p$

$$\frac{d^2 I_e}{dV^2} = -\frac{1}{4}e^2 A\left(\frac{2}{m}\right)^{1/2}(-e)\varepsilon_{\min}^{-1/2} f_\varepsilon(\varepsilon_{\min}) = \frac{1}{4}e^3 A\left(\frac{2}{m}\right)^{1/2}\left[\frac{f_\varepsilon(\varepsilon_{\min})}{\varepsilon_{\min}^{1/2}}\right],$$

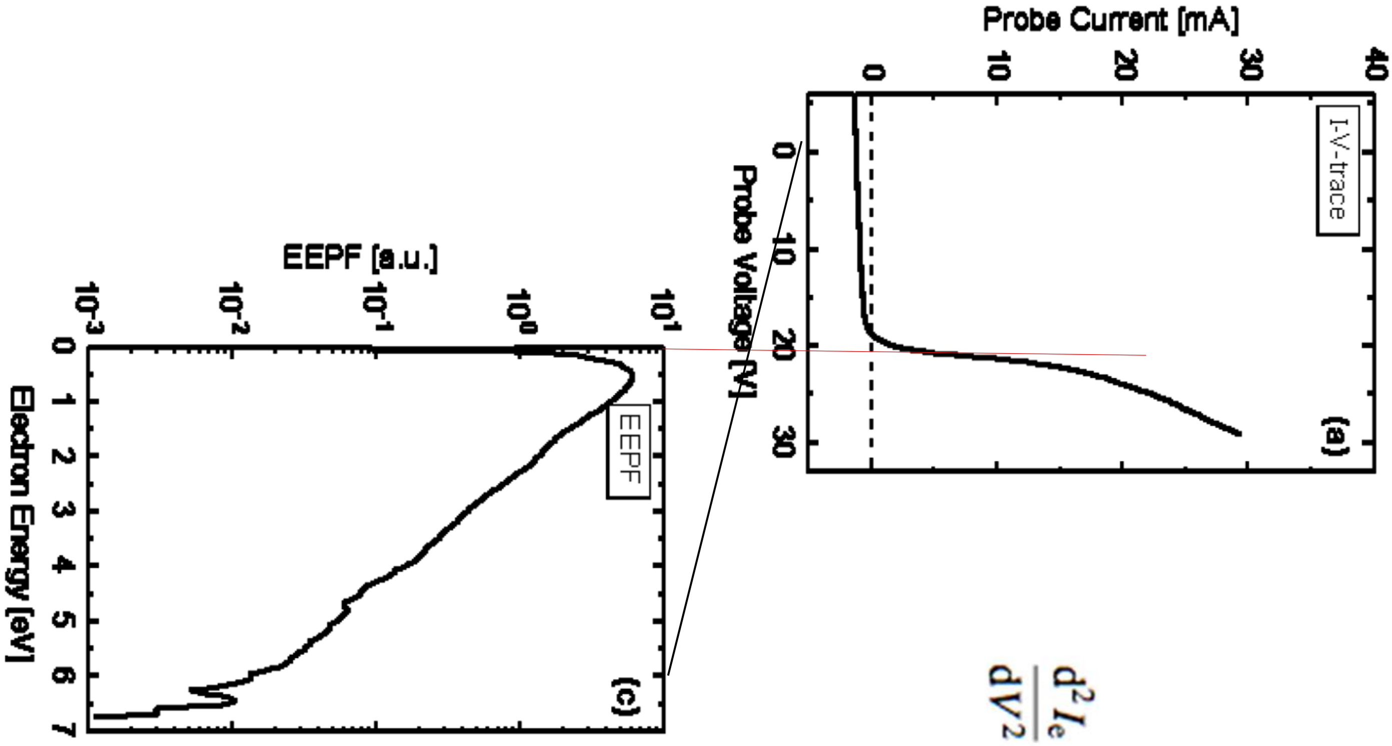


Techniques



$$\frac{d^2 I_e}{dV^2} = -\frac{1}{4}e^2 A \left(\frac{2}{m}\right)^{1/2} (-e)\varepsilon_{\min}^{-1/2} f_\varepsilon(\varepsilon_{\min})$$
$$= \frac{1}{4}e^3 A \left(\frac{2}{m}\right)^{1/2} \left[\frac{f_\varepsilon(\varepsilon_{\min})}{\varepsilon_{\min}^{1/2}}\right],$$

Techniques



$$\frac{d^2 I_e}{dV^2} = -\frac{1}{4} e^2 A \left(\frac{2}{m}\right)^{1/2} (-e)\varepsilon_{\min}^{-1/2} f_\varepsilon(\varepsilon_{\min})$$
$$= \frac{1}{4} e^3 A \left(\frac{2}{m}\right)^{1/2} \left[\frac{f_\varepsilon(\varepsilon_{\min})}{\varepsilon_{\min}^{1/2}}\right],$$

What can you measure?

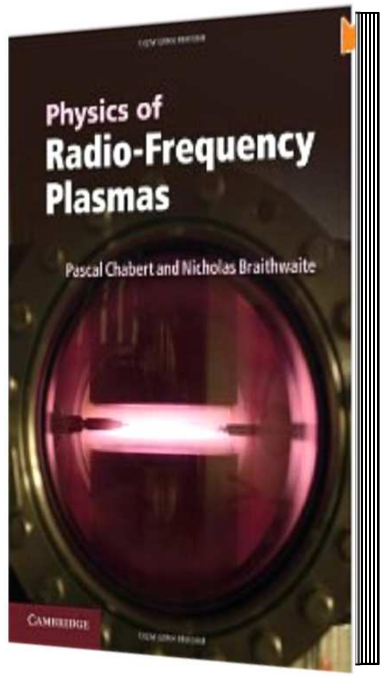
	Gas composition	Density / m^{-3}: ion (n_i)	Density: electron (n_e)	Density: neutrals (eg $n_\cdot$)	Energy / eV: ion ($<E_i>$)	Energy: electron ($<E_e>$)	Energy: neutrals (eg $<E_{vib}>$)	Flux / m^{-2} s^{-1}: ion (Γ_i)	Flux: electron (Γ_e)	Flux: neutrals (eg $\Gamma_\cdot$)	Potential/V & E field / V m^{-1}: $\Delta\phi$	**E**
(Quadrupole) Mass Analyser												
Langmuir Probe												
Emissive Langmuir Probe												
Retarding Field Analyser												
Ion flux probe												
Microwave interferometry												
RF probe spectroscopy												
Optical emission												
Optical absorption (DLS, FTIR)												
Laser Induced Fluorescence												
Rayleigh scattering												
Thomson scattering												

What do you want to measure?

But what effect do the following have?

- collisions
- geometry - planar/cylindrical/hemispherical
- RF potentials in the plasma
- secondary emission and reflection from surfaces
- non-thermal electrons
- magnetic fields
- negative ions

Precise models for *I*(*V*)...book by Swift & Schwar and reviews by Chen...Chabert & B.



What can you measure?

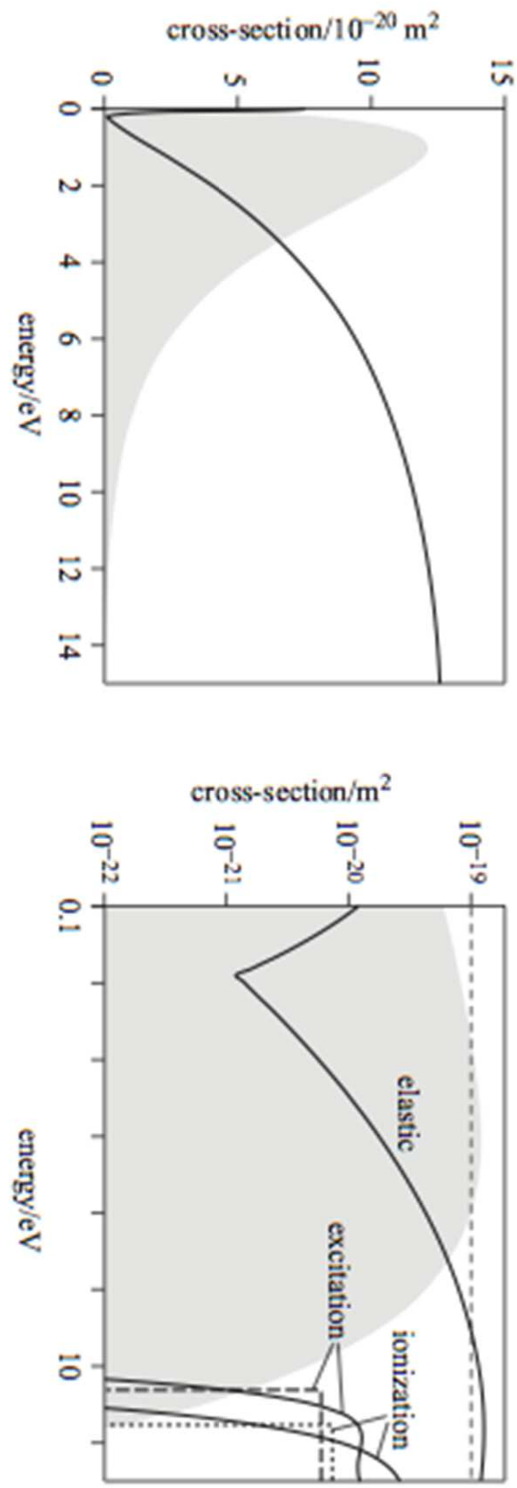
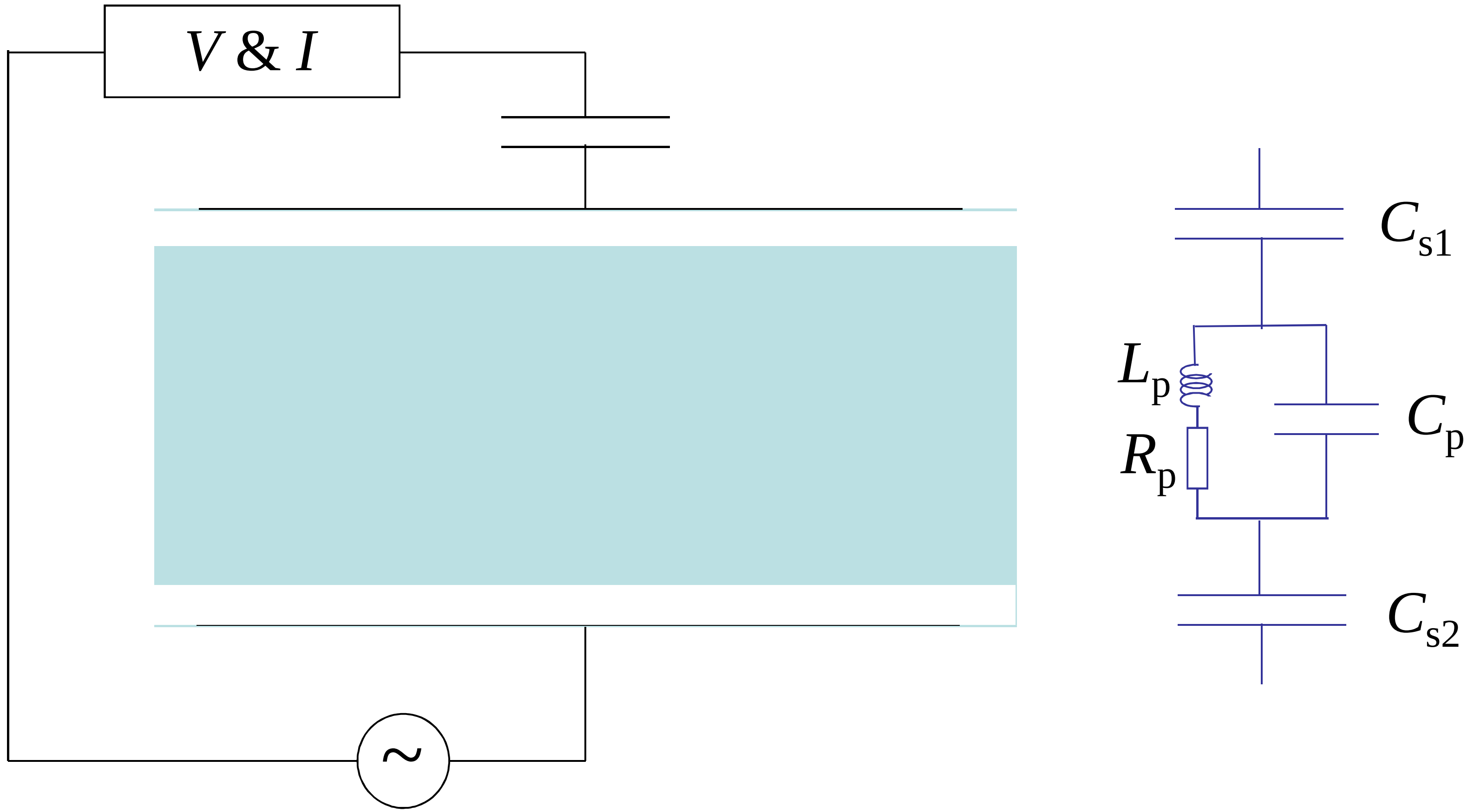


Figure 2.4 Elastic and inelastic cross-sections in argon – schematic. Broken lines indicate useful approximations.

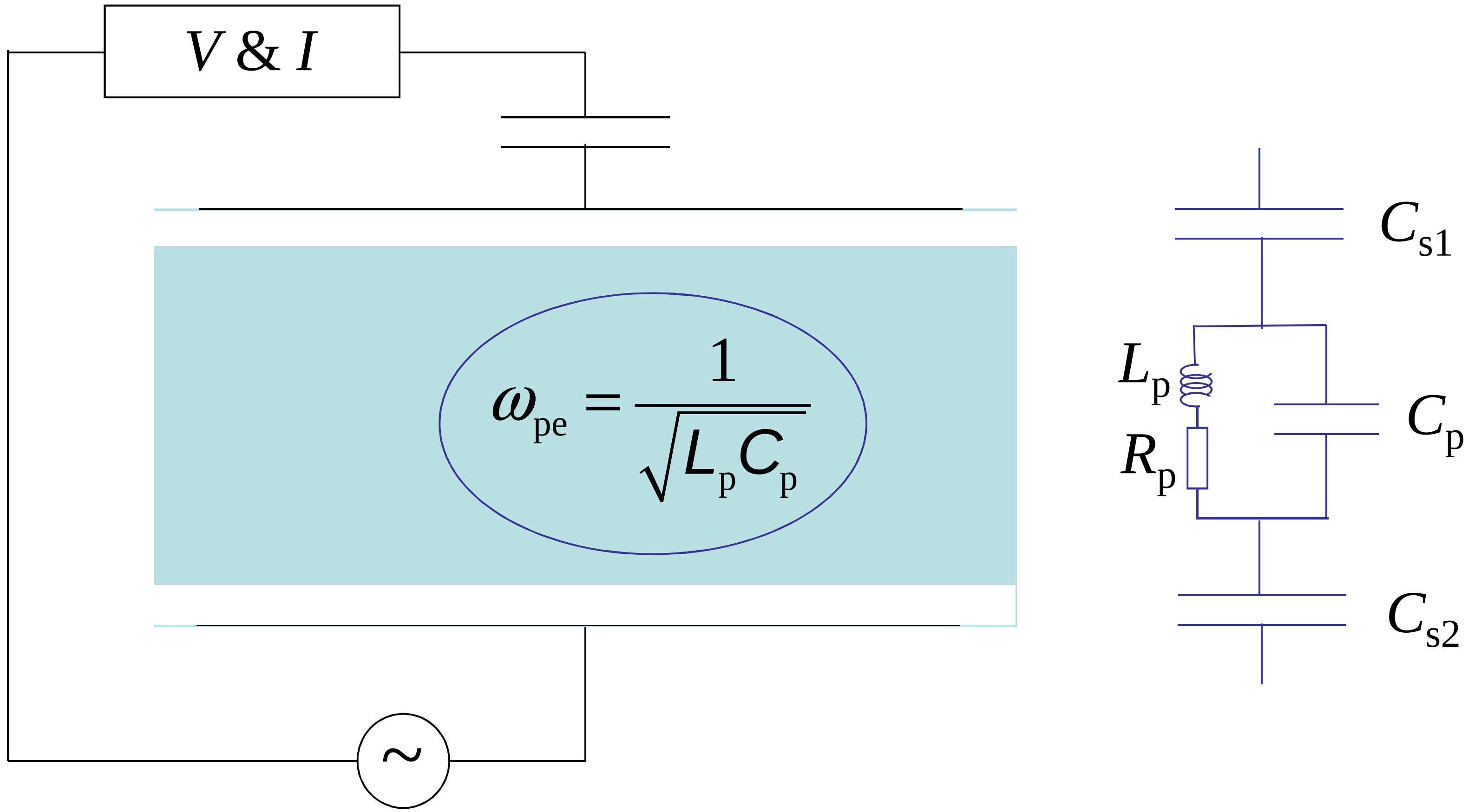
What can you measure?

	Gas composition	Density / m^{-3}			Energy / eV			Flux / $m^{-2}\ s^{-1}$			Potential/V & E field / V m^{-1}	
`		ion (n_i)	electron (n_e)	neutrals (eg $n_\bullet$)	ion ($<E_i>$)	electron ($<E_e>$)	neutrals (eg $<E_{vib}>$)	ion (Γ_i)	electron (Γ_e)	neutrals (eg $\Gamma_\bullet$)	$\Delta\phi$	**E**
(Quadrupole) Mass Analyser												
Langmuir Probe												
Emissive Langmuir Probe												
Retarding Field Analyser												
Ion flux probe												
Microwave interferometry												
RF probe spectroscopy												
Optical emission												
Optical absorption (DLS, FTIR)												
Laser Induced Fluorescence												
Rayleigh scattering												
Thomson scattering												

Resonances in plasma-sheath systems



Resonances in plasma-sheath systems



Resonances in plasma-sheath systems

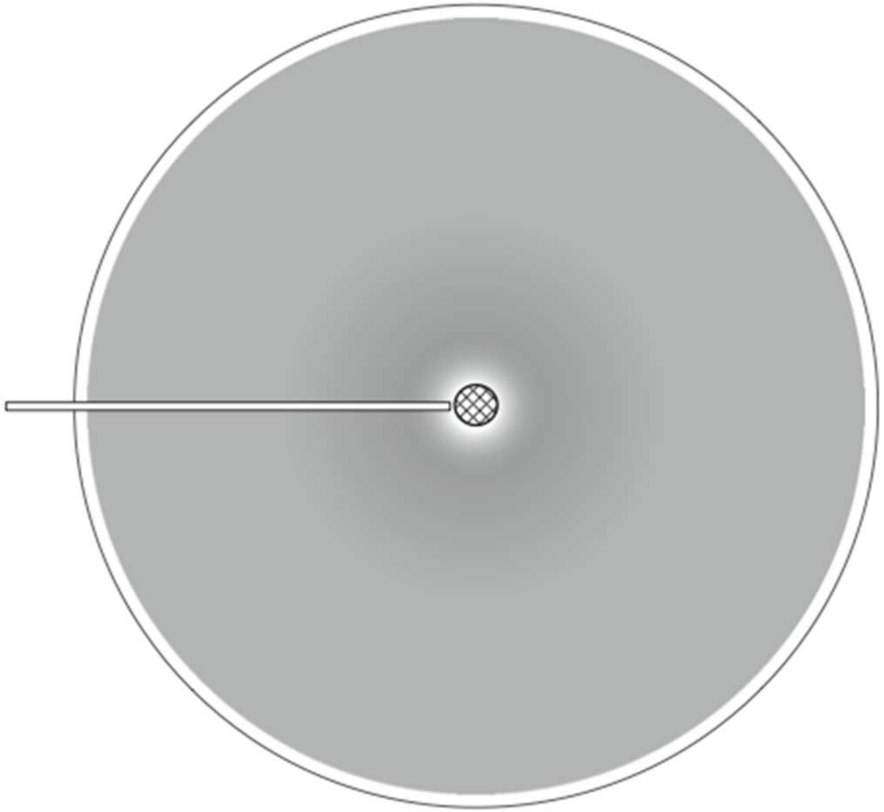
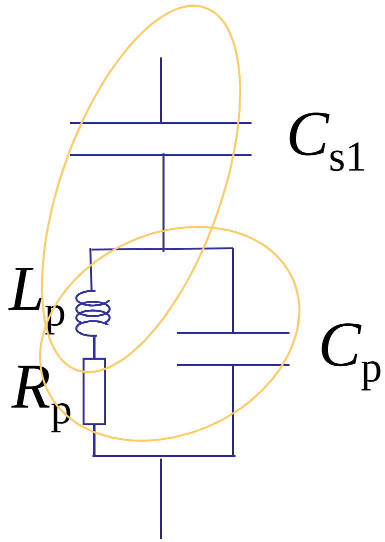


Figure 10.19 A spherical probe coupling a coaxial cable to a large volume of plasma.



Resonances in plasma-sheath systems

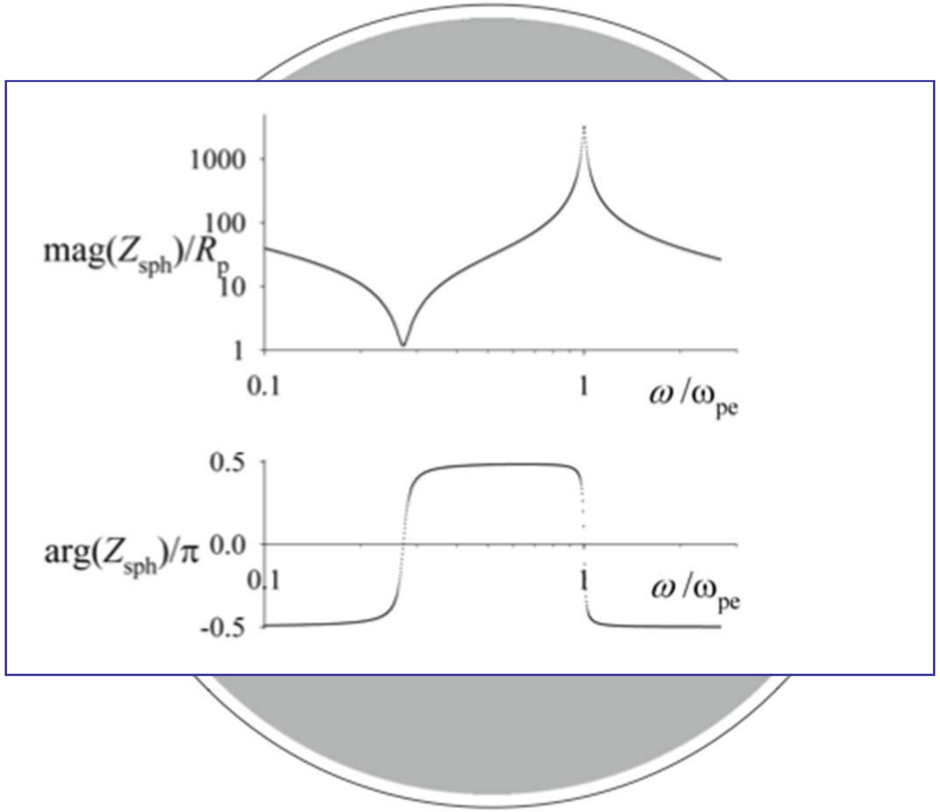
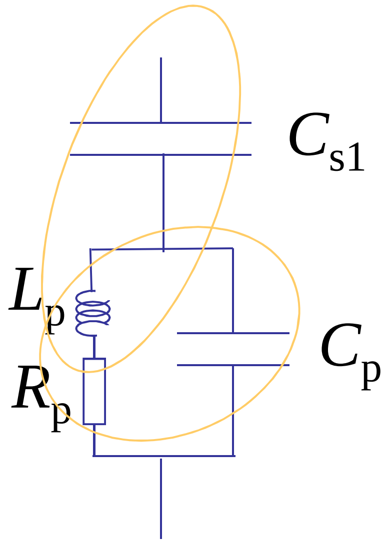
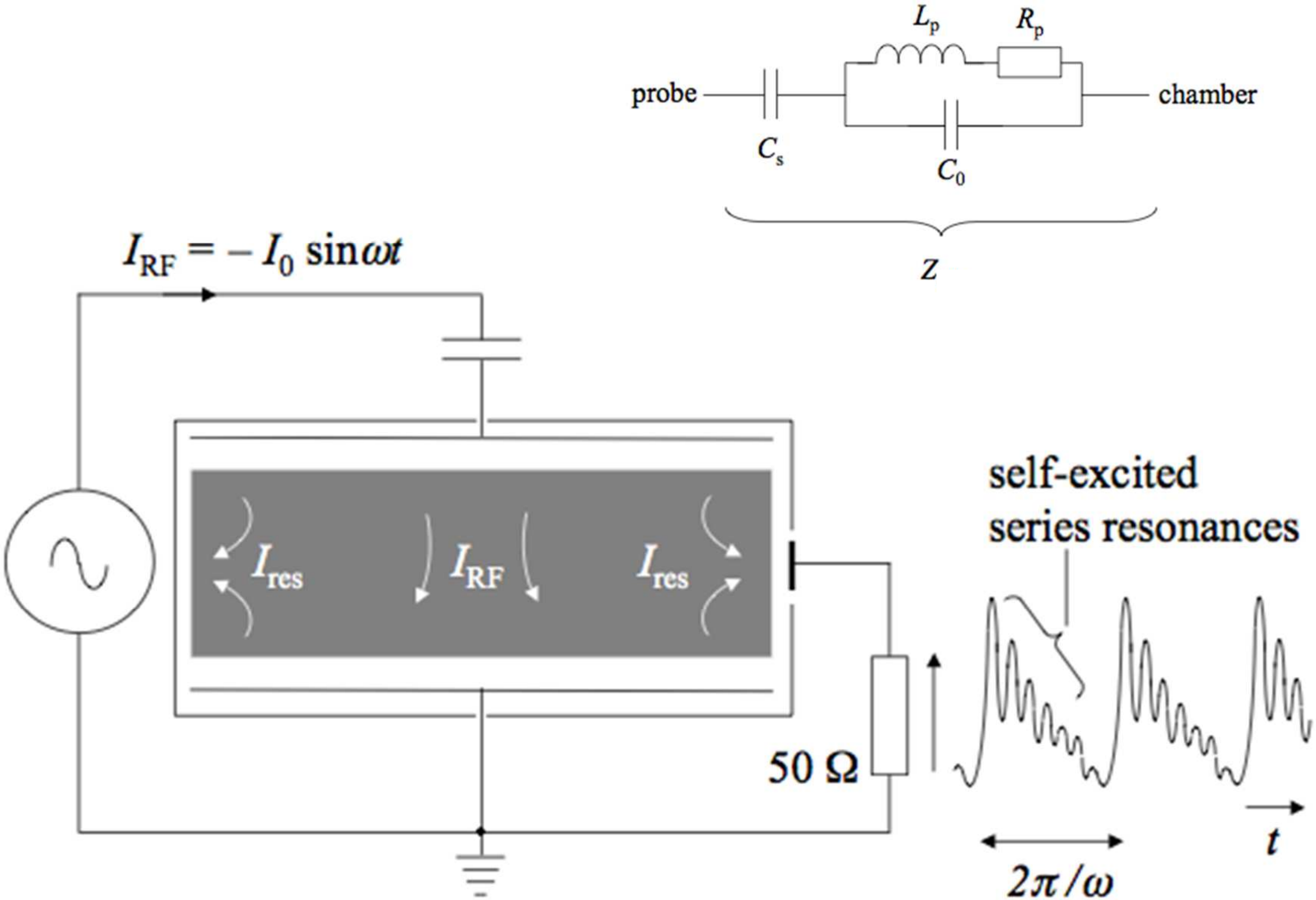


Figure 10.19 A spherical probe coupling a coaxial cable to a large volume of plasma.



Resonances in plasma-sheath systems



Not-Langmuir probes

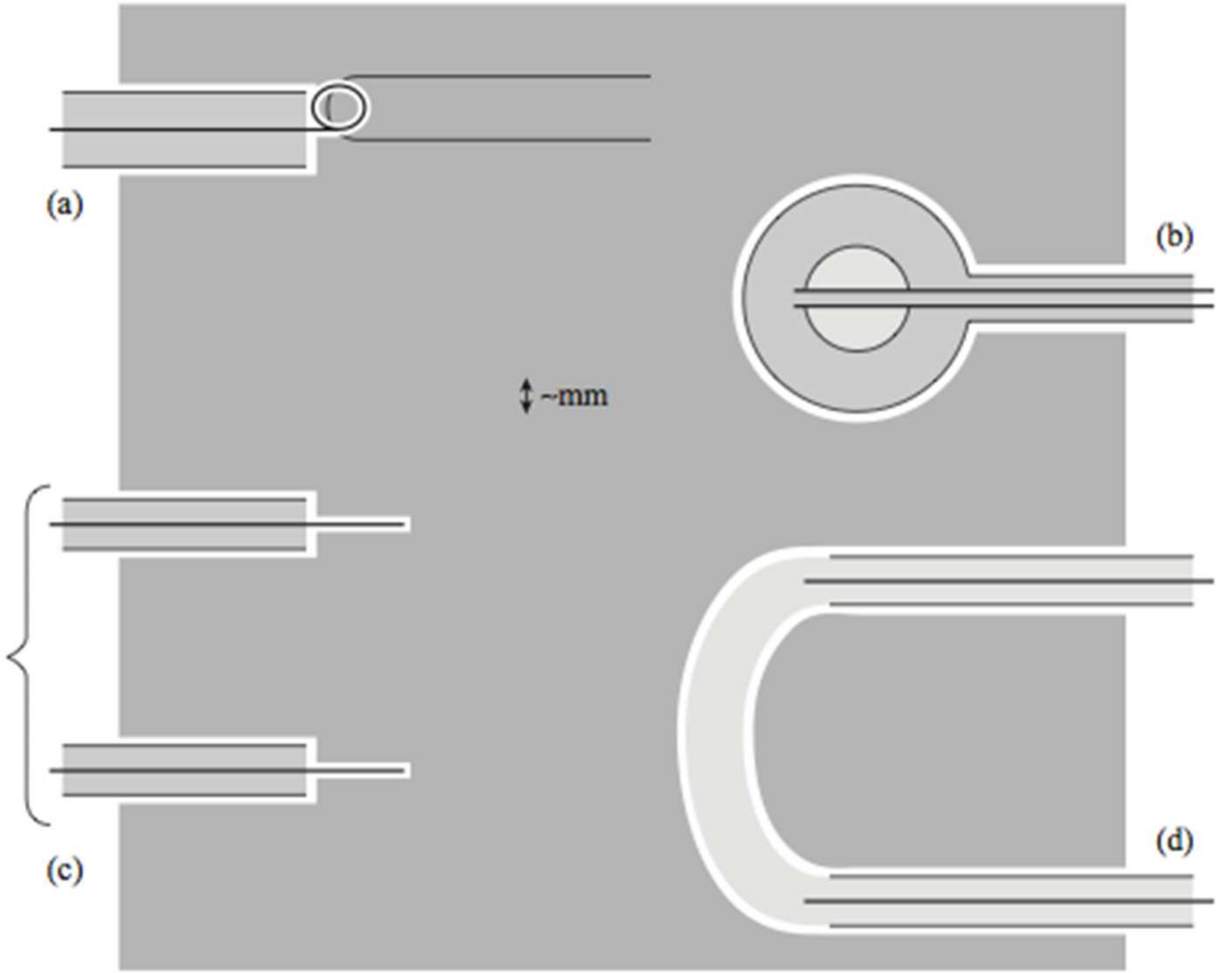
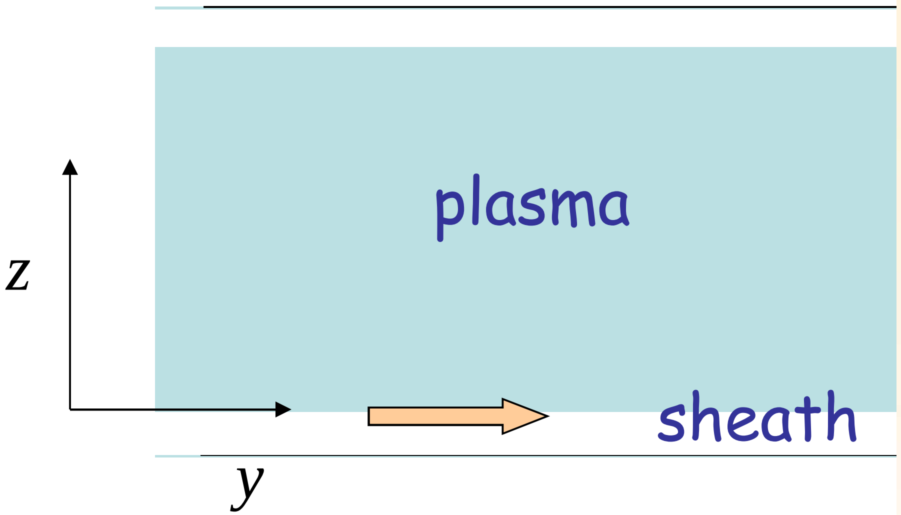
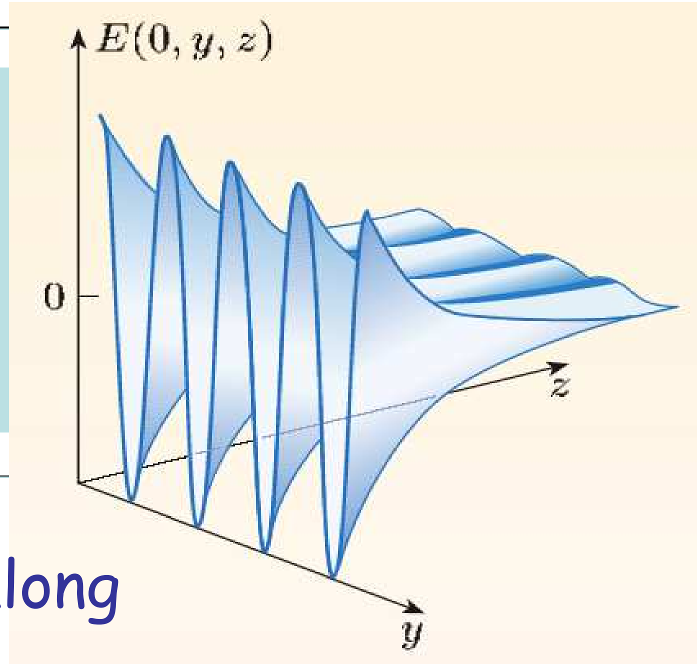


Figure 10.18 Various types of microwave probes in cross-section: (a) hairpin resonator (the hairpin is supported in a plane slightly behind that of the loop, from which it is DC-isolated); (b) multipole resonator; (c) transmission cut-off; (d) surface waveguide.

Techniques

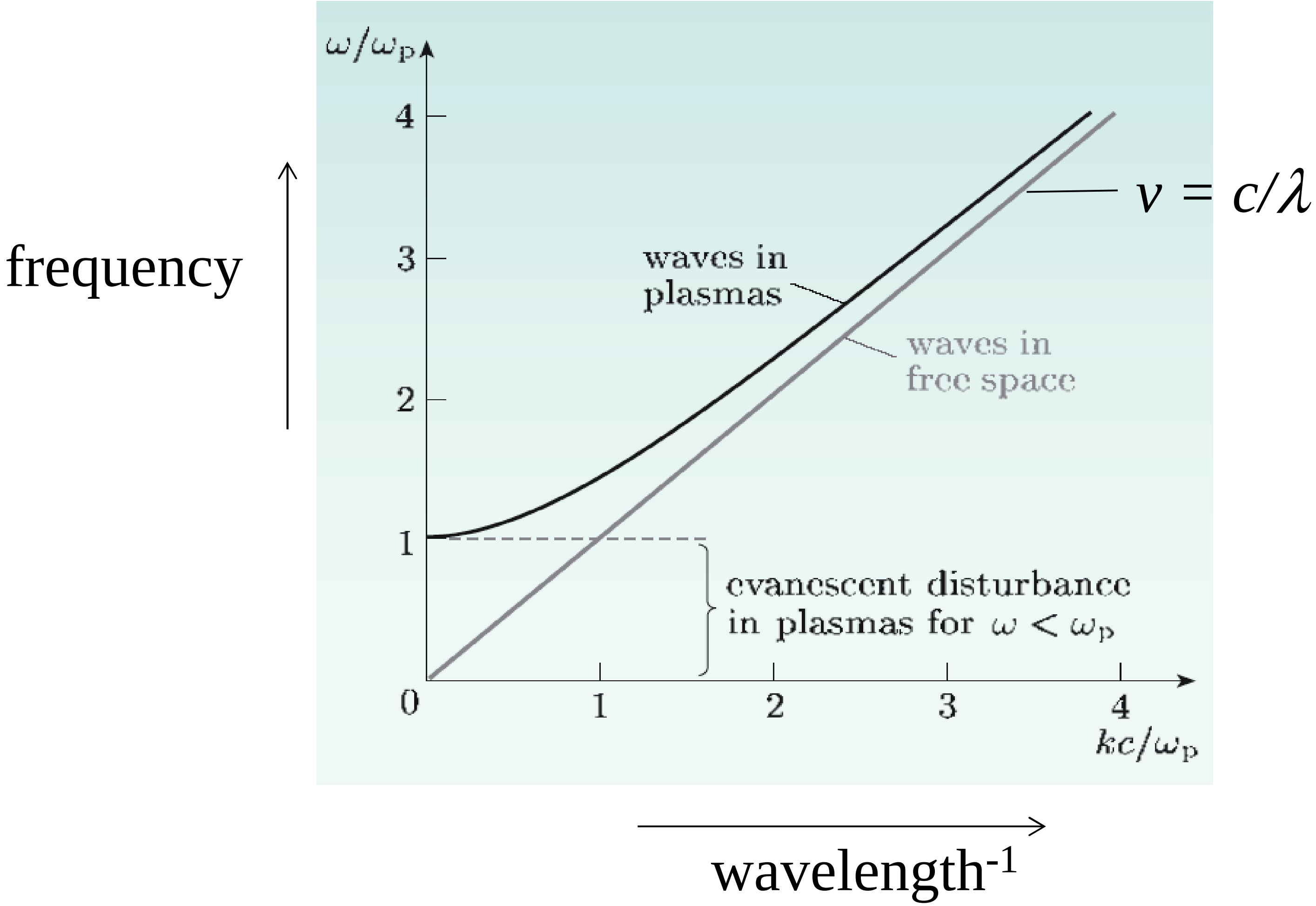
Electromagnetic modes in plasmas





E-M waves are guided along interfaces:
vacuum/dielectric
dieletric/dielectric
dielectric/conductor

Electromagnetic waves in *unmagnetized*, collisionless, unbounded plasma



What do you want to measure?

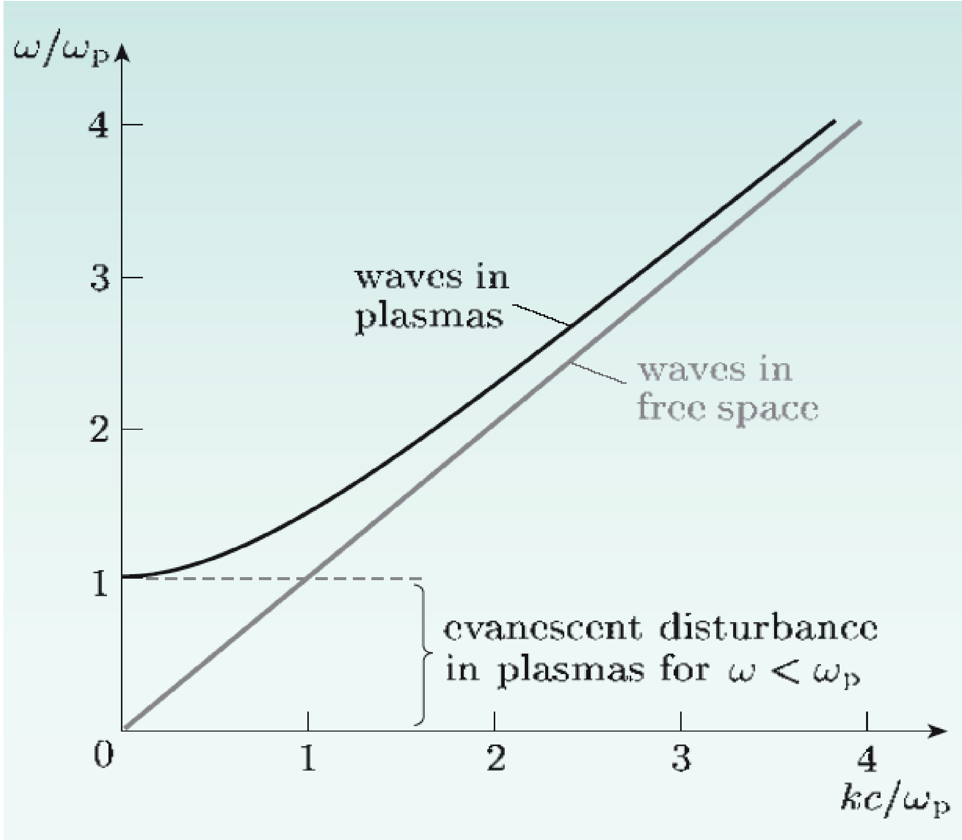
Electromagnetic waves in *unmagnetized*, collisionless, unbounded plasma

$$\varepsilon_{\text{eff}}(\omega) = 1 - \frac{\omega_{\text{p}}^2}{\omega^2}.$$

$$k = \frac{n\omega}{c} = \frac{\sqrt{\varepsilon_{\text{eff}}}\,\omega}{c}.$$

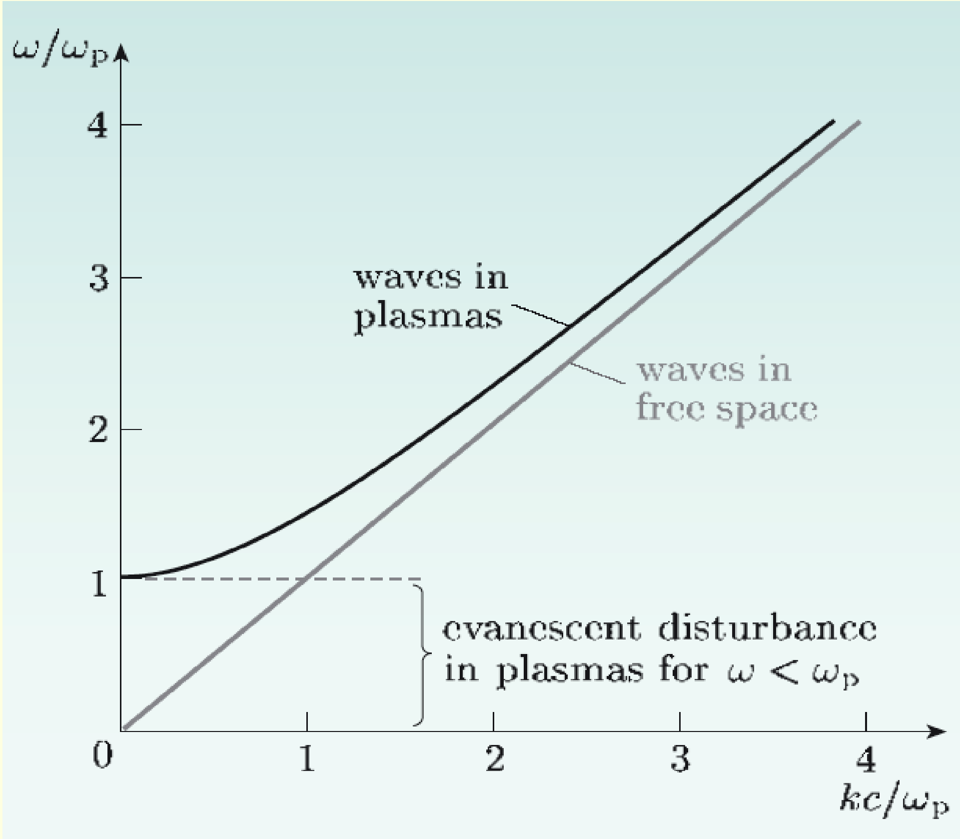
refractive index

$$\omega = \sqrt{\omega_{\text{p}}^2 + k^2c^2},$$



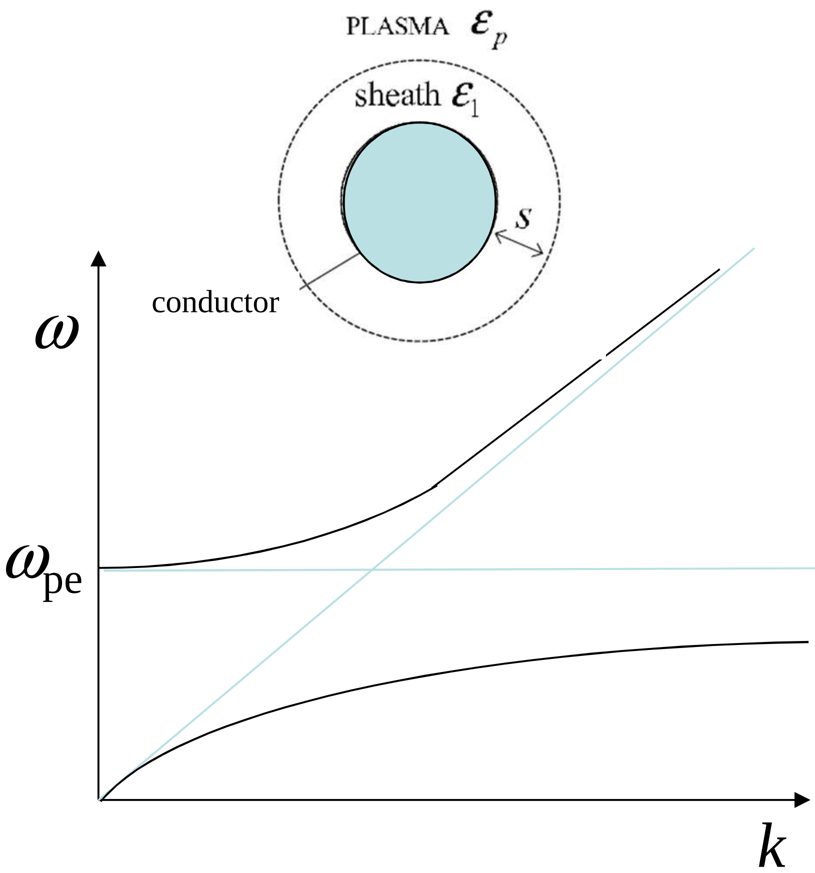
SAQ Suggest a microwave 'cut-off' experiment for measuring n_e

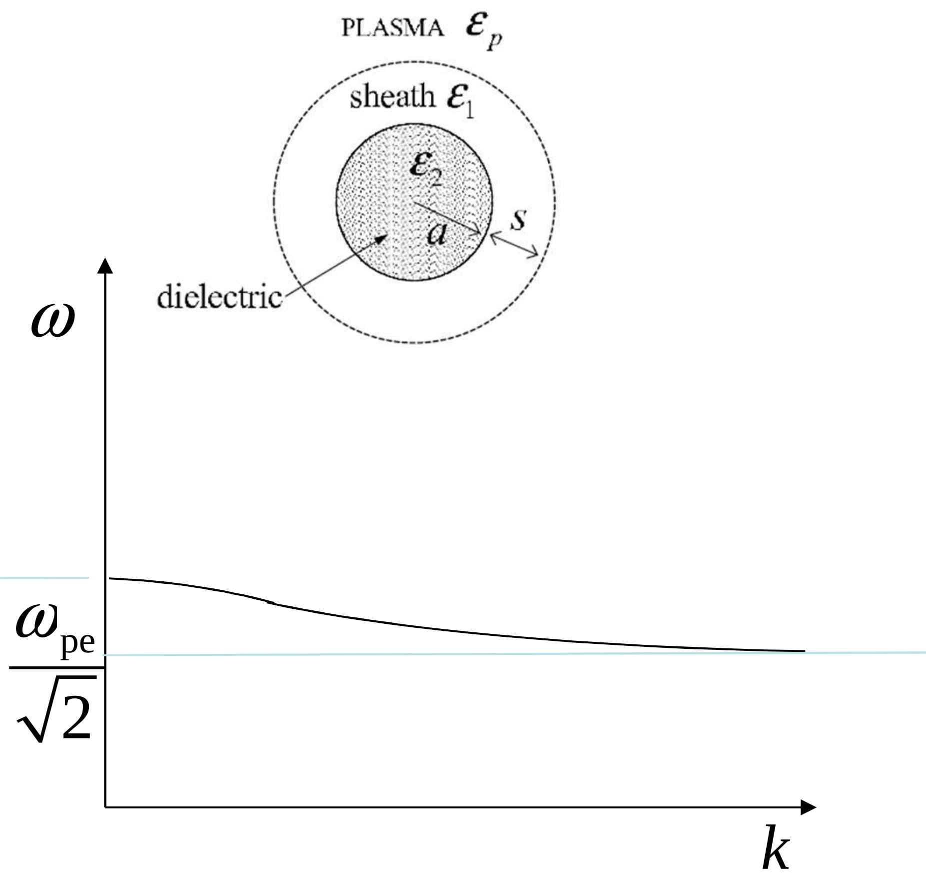
SAQ Suggest a microwave interferometer experiment for measuring n_e



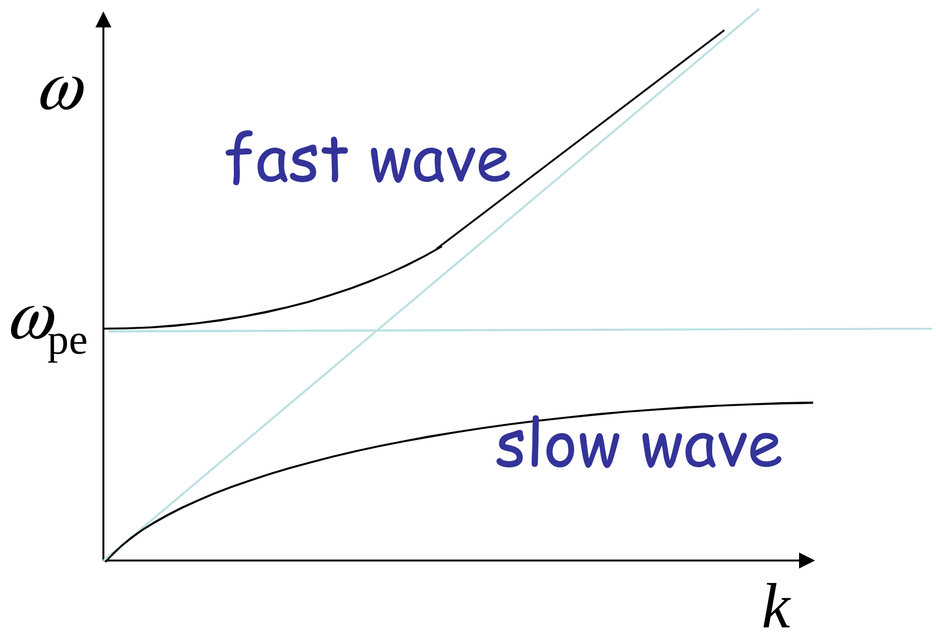
What can you measure?

Electromagnetic waves in *unmagnetized*, collisionless, plasma around a cylinder



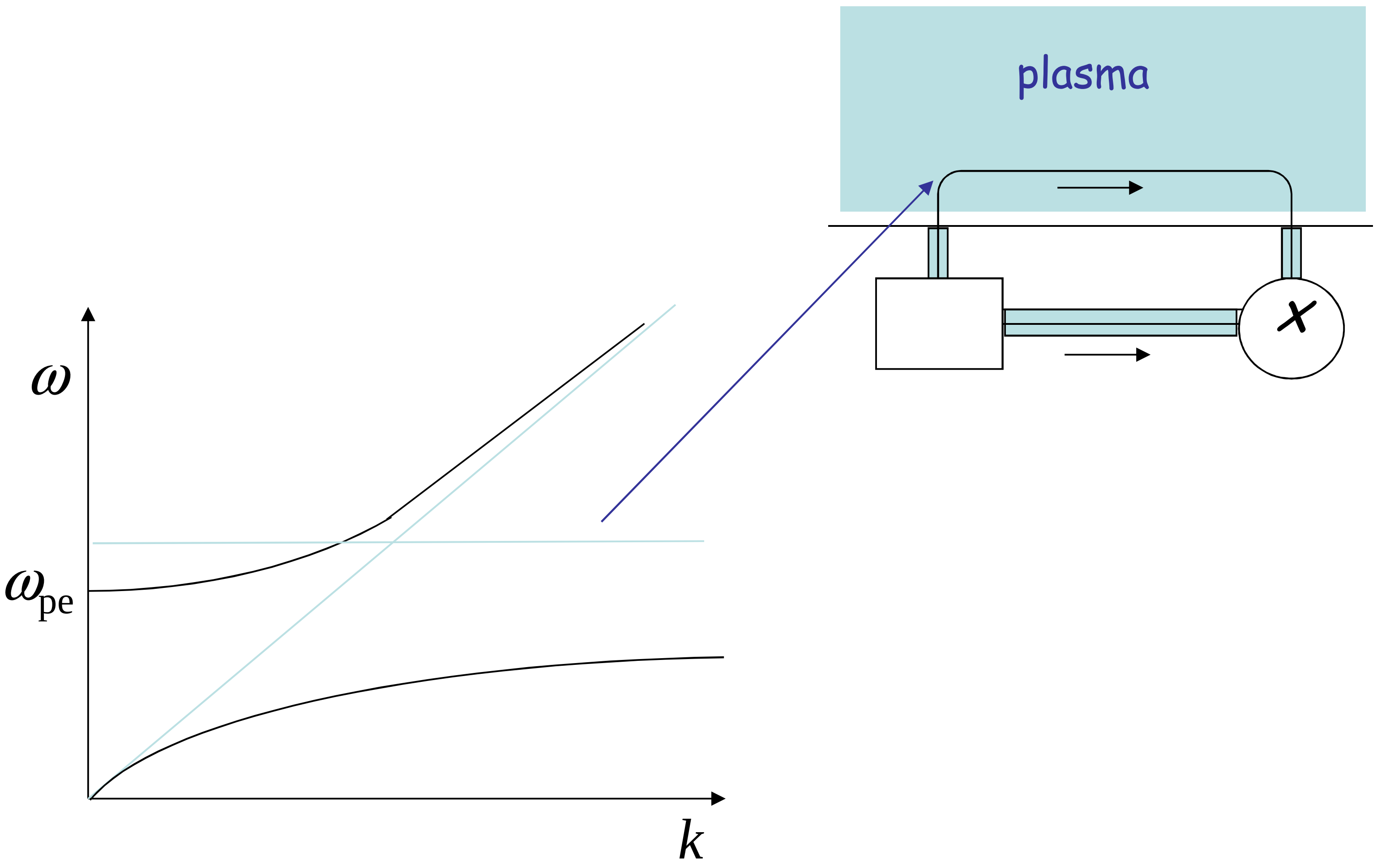


What can you measure?



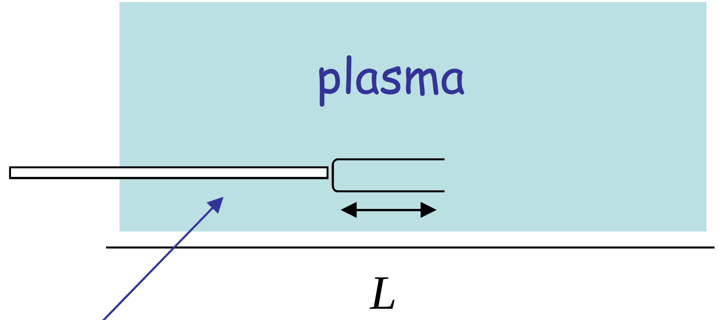
What can you measure?

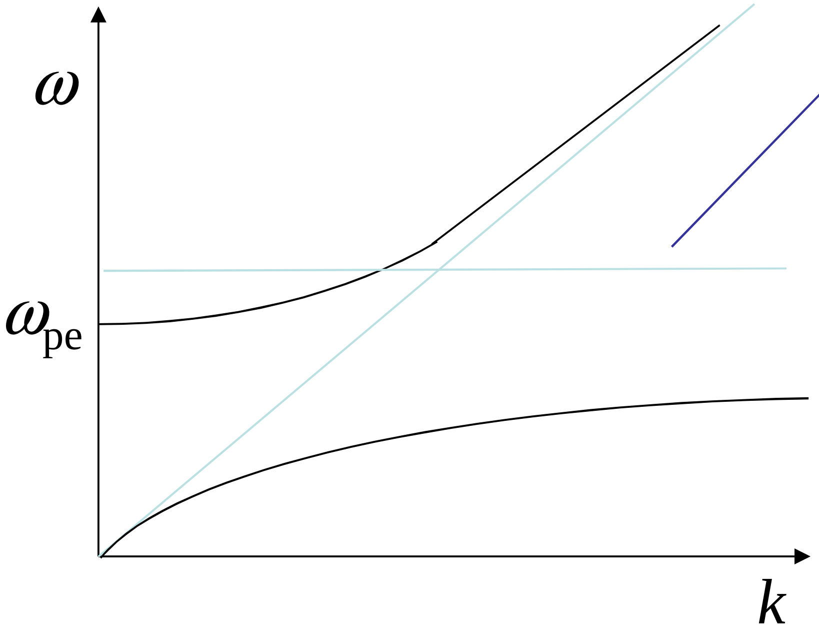
Transmission line interferometer



Techniques

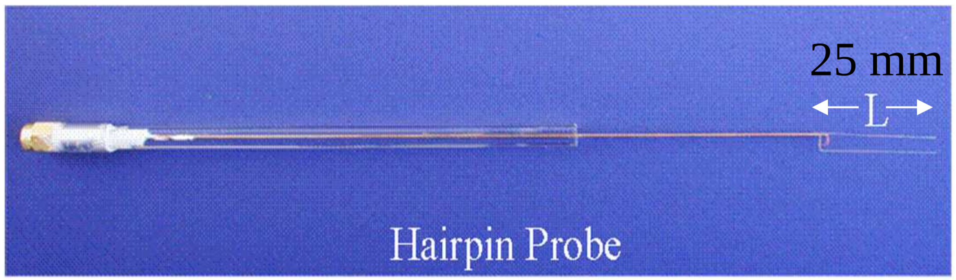
Hairpin resonator





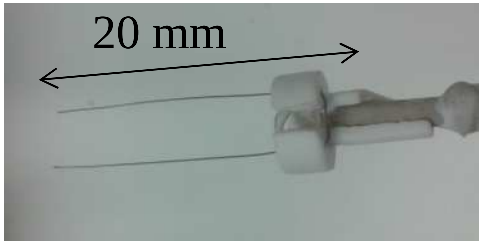
$$f_{\mathrm{vac}} = \frac{c}{4L}$$

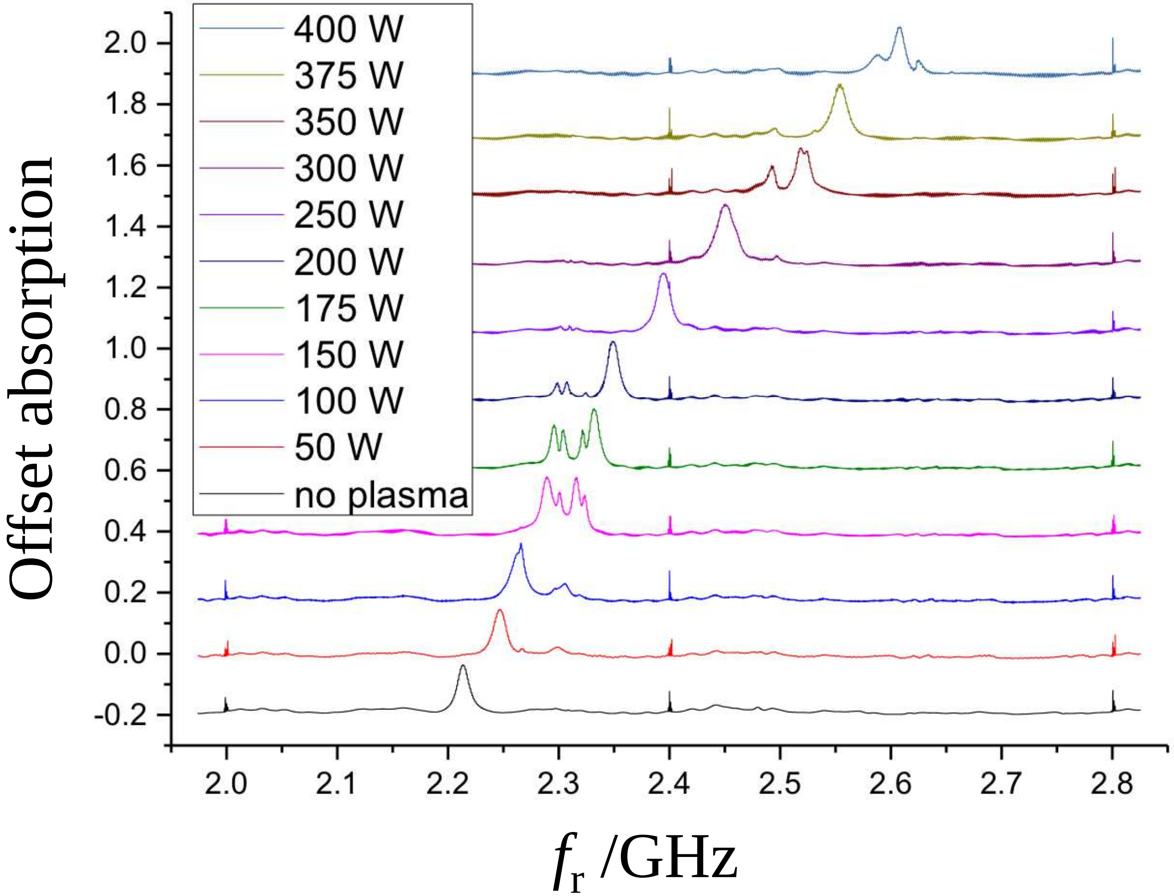
$$f_{\mathrm{plasma}} = \frac{c/\sqrt{\varepsilon}}{4L} = \frac{c/\sqrt{1-\omega_p^{\,2}/\omega^2}}{4L}$$



Techniques

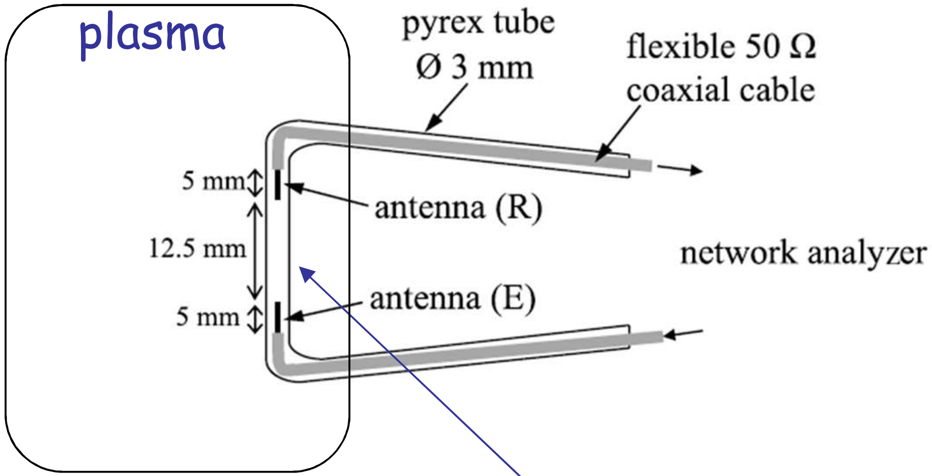
Hairpin resonator

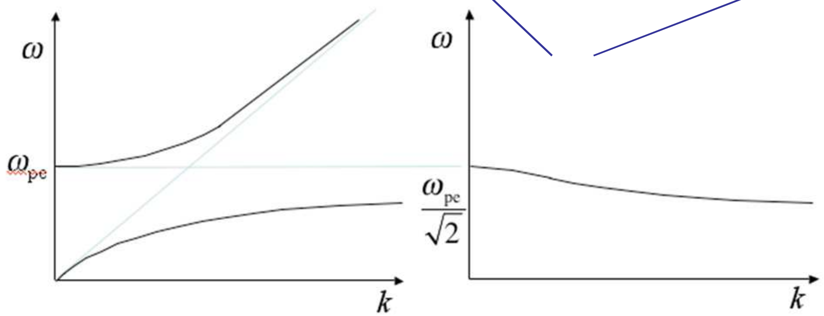




ICP
Argon

Plasma transmission probe





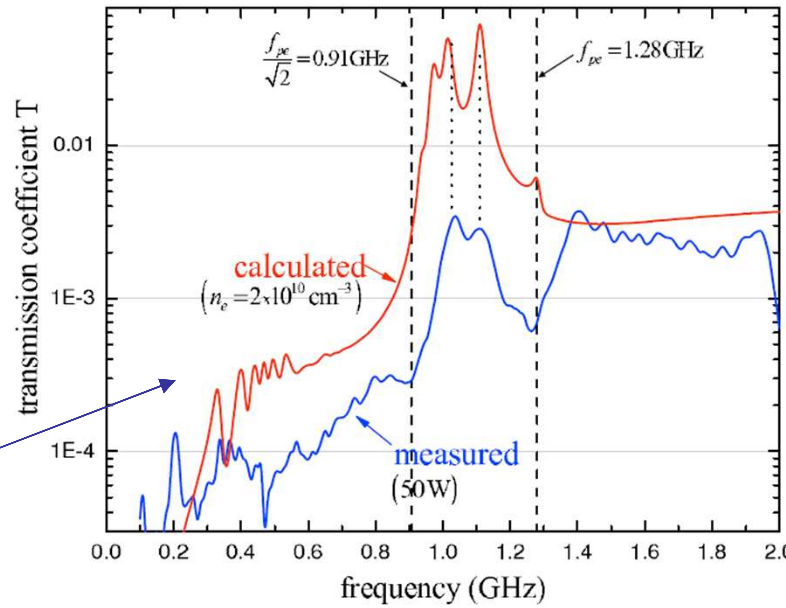


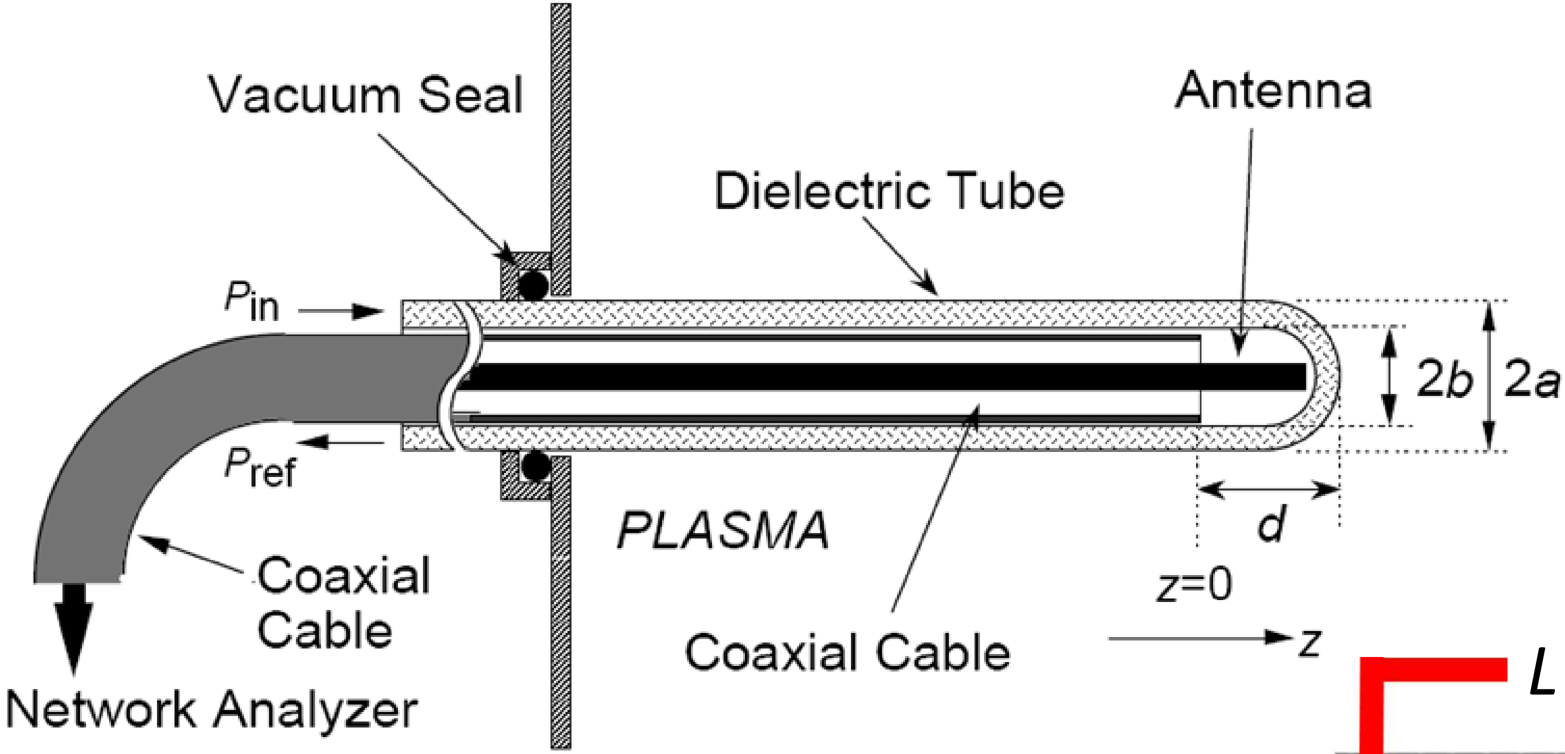
Figure 10. Comparison between the measured transmitted coefficient spectrum (50 W) and the calculated one ($n_e \simeq 2 \times 10^{10}$ cm^{-3}) at 40 mTorr in argon.

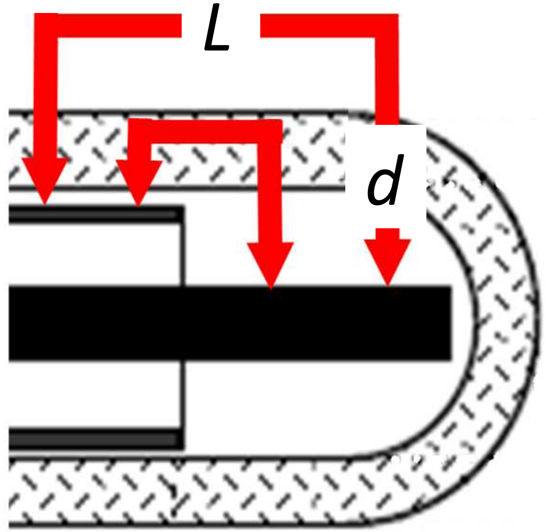
S Dine, J-P Booth[1], G A Curley, C S Corr, J Jolly and J Guillon

Plasma Sources Sci. Technol. **14** (2005) 777–786

Techniques

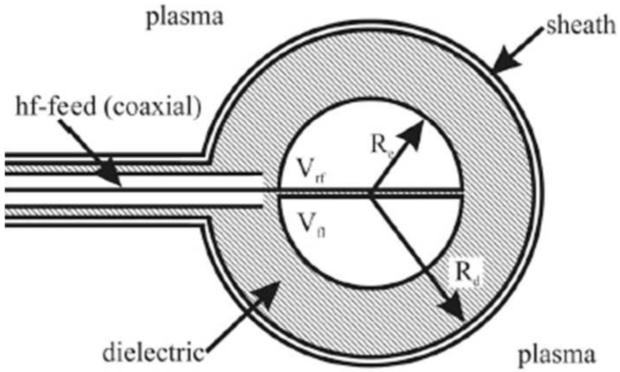
Plasma absorption probe





Techniques

Plasma absorption probe/Multipole Resonance Probe



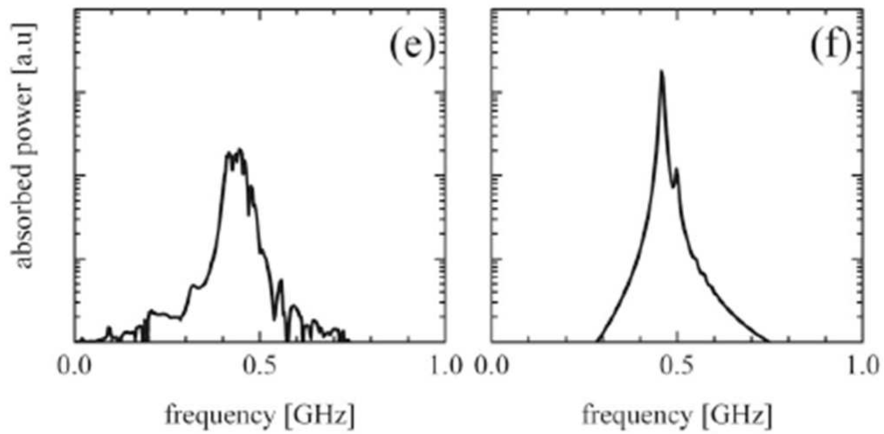


FIG. 3. Comparison of experiment (left) and simulation (right) with increasing thickness *d* of the surrounding dielectric (top down).

Scharwitz *et al.* Appl. Phys. Lett. **94**, 011502 (2009)

Plasma absorption probe/Multipole Resonance Probe

Techniques

T Styrnoll *et al*

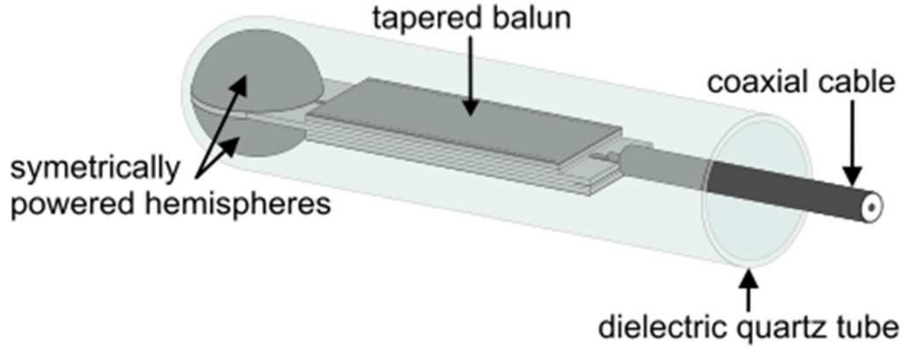


Figure 5. Schematic of the MRP. Two metallic hemispheres are mounted on a multilayer printed circuit board (tapered balun), that also a serves as a holder for the hemispheres. The holder also serves as a balancing unit for an unbalanced signal from the NWA.

Plasma Sources Sci. Technol. **23** (2014) 025013

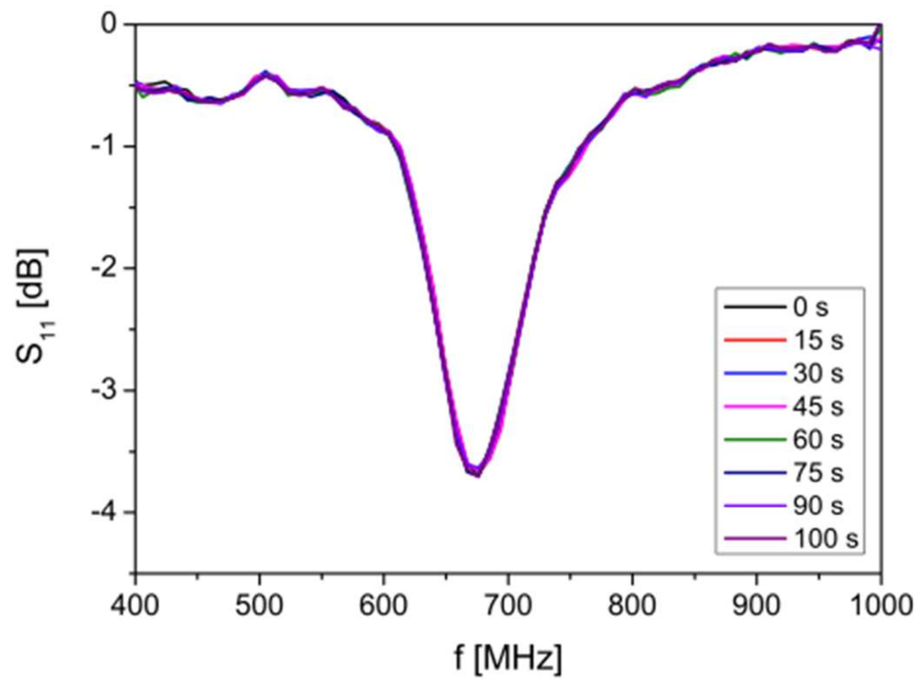


Figure 11. Absorption spectra taken with the MRP obtained in a dielectric deposition process.

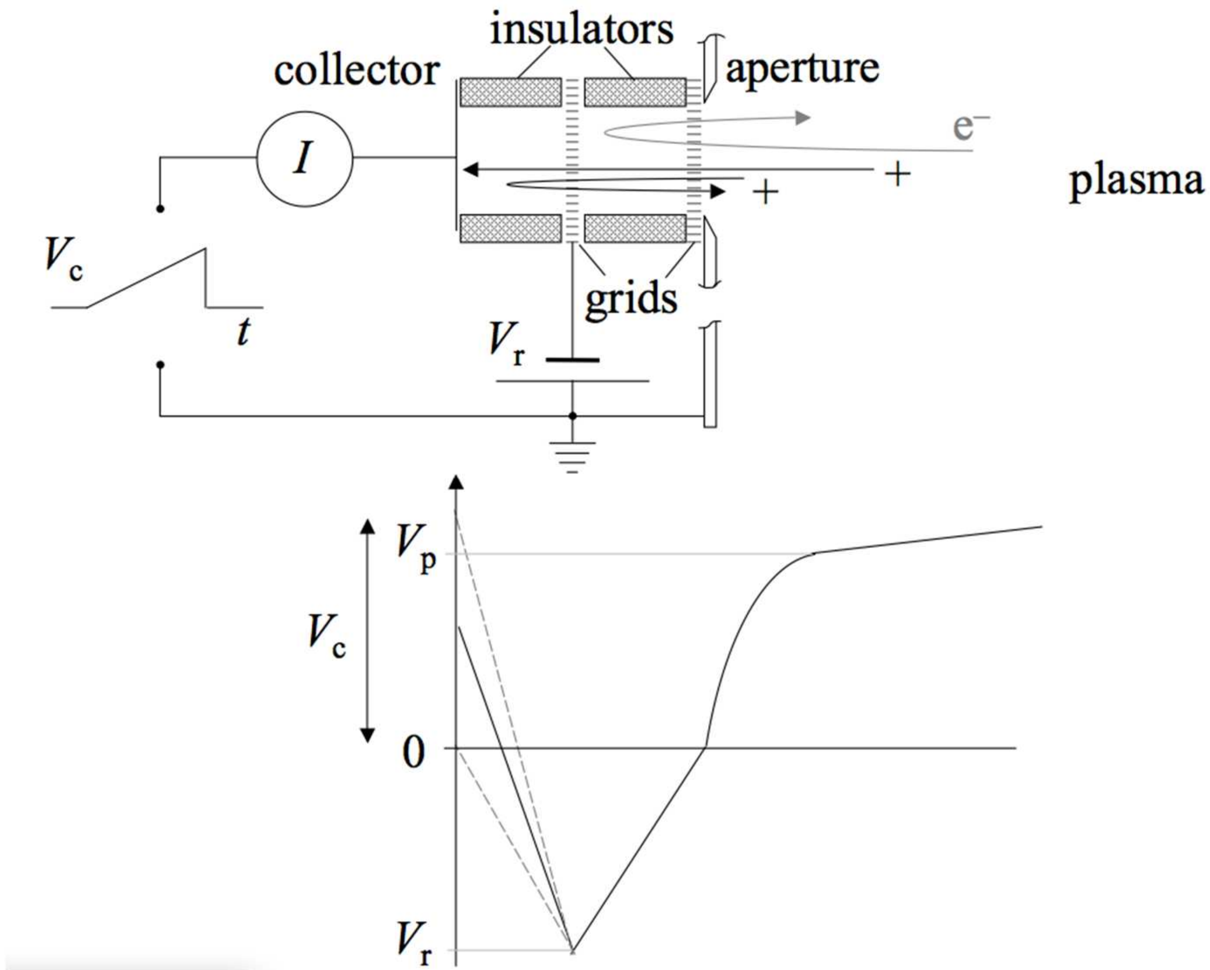
Techniques

`	Gas composition	Density / m^{-3} ion (n_i) electron (n_e) neutrals (eg $n_\cdot$)	Energy / eV ion ($\langle E_i \rangle$) electron ($\langle E_e \rangle$) neutrals (eg $\langle E_{vib} \rangle$)	Flux / m^{-2} s^{-1} ion (Γ_i) electron (Γ_e) neutrals (eg $\Gamma_\cdot$)	Potential/V & E field / V m^{-1} $\Delta\phi$ **E**
(Quadrupole) Mass Analyser					
Langmuir Probe					
Emissive Langmuir Probe					
Retarding Field Analyser					
Ion flux probe					
Microwave interferometry					
RF probe spectroscopy					
Optical emission					
Optical absorption (DLS, FTIR)					
Laser Induced Fluorescence					
Rayleigh scattering					
Thomson scattering					

SAQ How will the presence of negative ions affect the measurement of electron density with a hairpin resonator ?

SAQ What is required for a satisfactory measurement of charged particle density ?

Retarding Field Analyzer



J. Phys. D: Appl. Phys. **21** (1988) 1496–1503.

Techniques

Retarding Field Analyzer

$$I_+ = Ae \int_{v_{min}}^{v_{max}} v f(v)\, \mathrm{d}v \qquad v_{min} = \sqrt{2e\varphi/M}$$

$$\frac{\mathrm{d}I}{\mathrm{d}\phi} \propto f(v)$$

$$f(\sqrt{2e\phi/M})$$

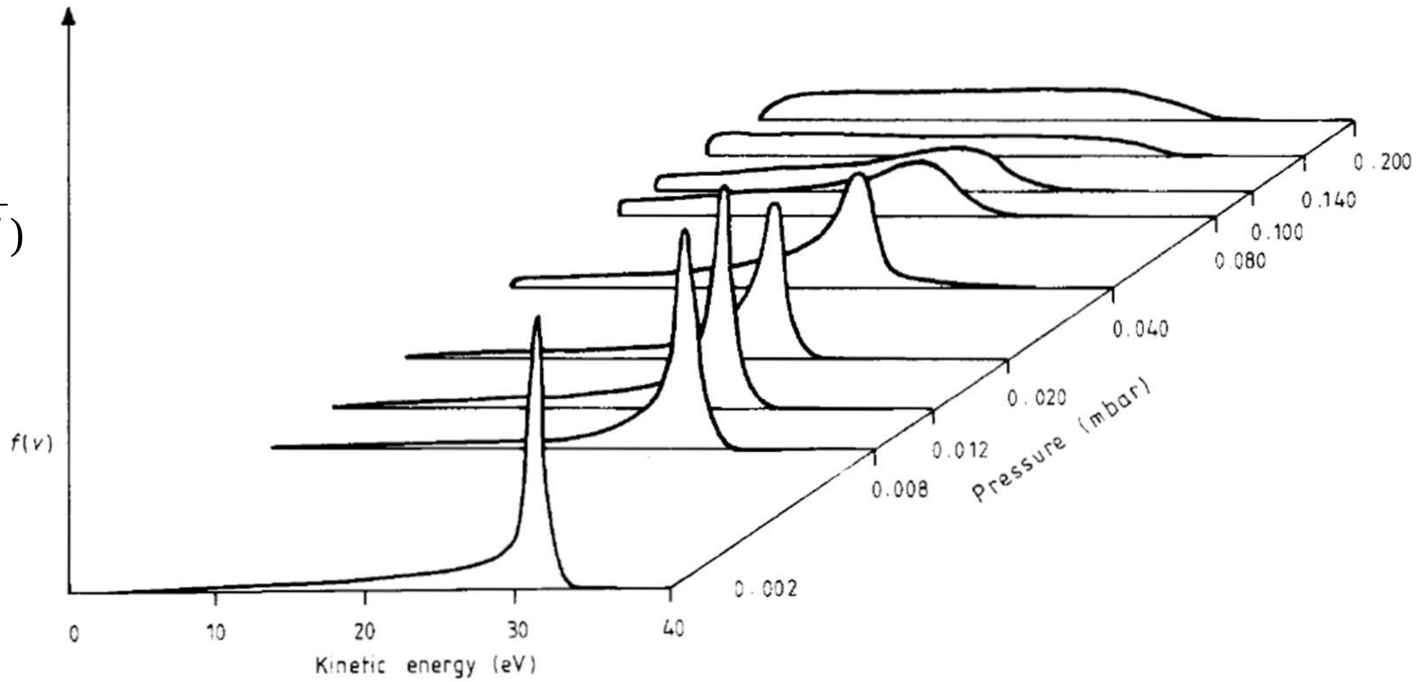
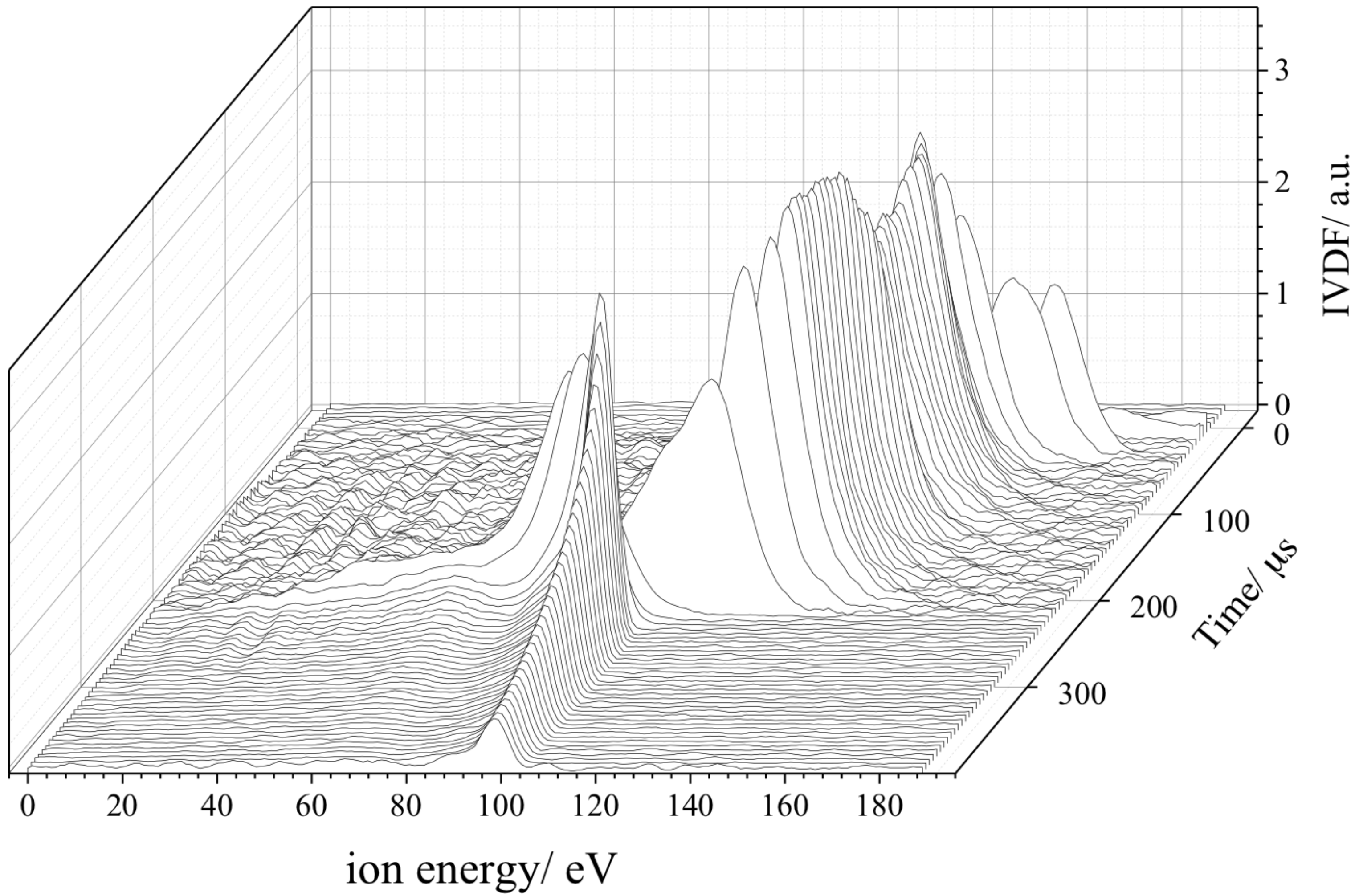
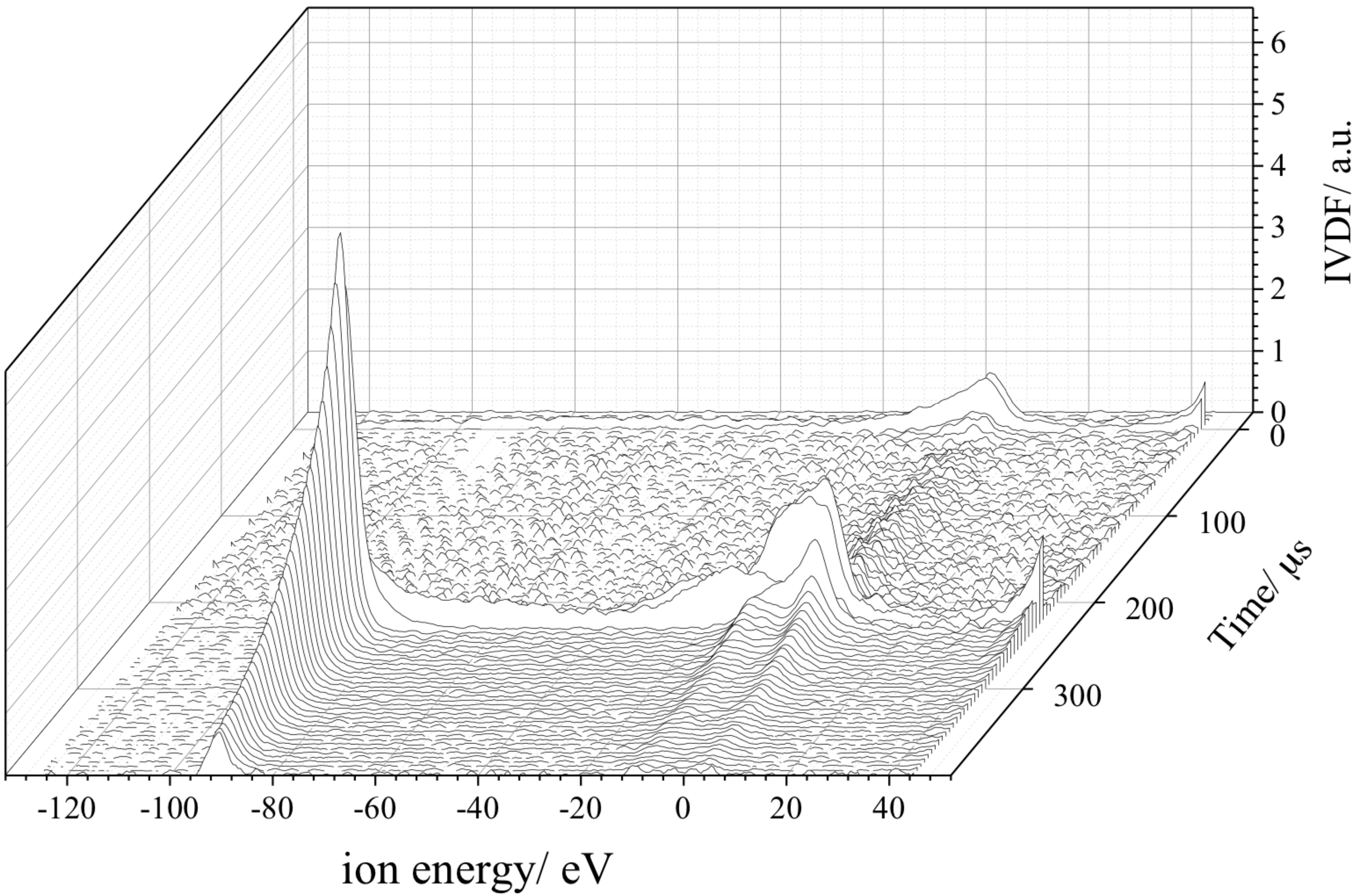


Figure 3. Ion velocity distributions for a range of pressures. N.B. The horizontal axis is kinetic energy ($\frac{1}{2}Mv^2/e$).

J. Phys. D: Appl. Phys. **21** (1988) 1496–1503.


IVDF/ a.u.
0
1
2
3
Time/ μs
0
100
200
300
0
20
40
60
80
100
120
140
160
180
ion energy/ eV



IVDF/ a.u.
0
1
2
3
4
5
6
Time/ μs
0
100
200
300
-120
-100
-80
-60
-40
-20
0
20
40
ion energy/ eV

Techniques

Retarding Field Analyzer

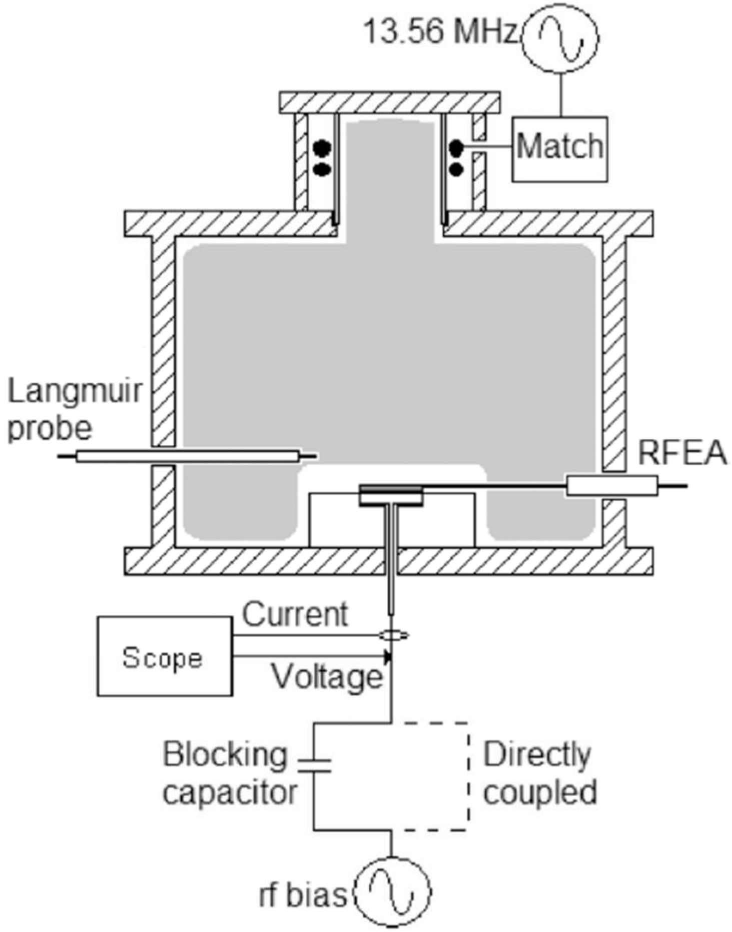


Figure 1. The experimental reactor with the RFEA mounte remote (independently biased) electrode.

C Hayden *et al*

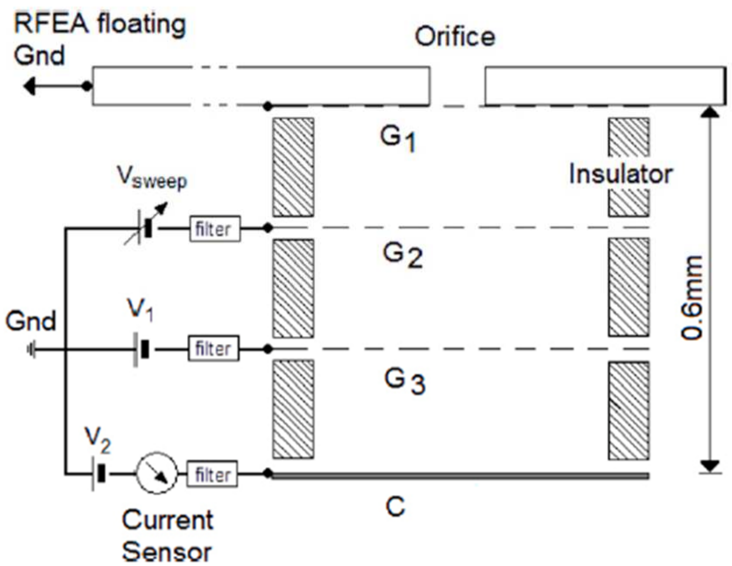


Figure 2. Cross section of the RFEA.

Plasma Sources Sci. Technol. **18** (2009) 025018

Retarding Field Analyzer

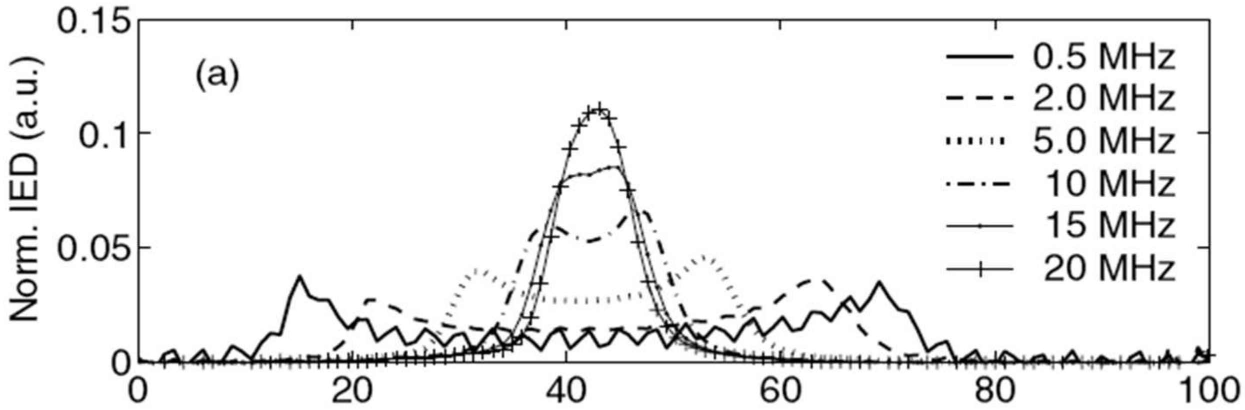


Figure 14. Ar IED plots as a function of frequency: (*a*) capacitively coupled; at a fixed bias of 37.5 V_{pk} at 300 W and pressure of 0.2 Pa.

Plasma Sources Sci. Technol. **18** (2009) 025018

Techniques

`	Gas composition	Density / m^{-3} ion (n_i)	Density electron (n_e)	Density neutrals (eg $n_\bullet$)	Energy / eV ion ($<E_i>$)	Energy electron ($<E_e>$)	Energy neutrals (eg $<E_{vib}>$)	Flux / m^{-2} s^{-1} ion (Γ_i)	Flux electron (Γ_e)	Flux neutrals (eg $\Gamma_\bullet$)	Potential/V & E field / V m^{-1} $\Delta\phi$	**E**
(Quadrupole) Mass Analyser												
Langmuir Probe												
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Ion flux probe												
Microwave interferometry												
RF probe spectroscopy												
Optical emission												
Optical absorption (DLS, FTIR)												
Laser Induced Fluorescence												
Rayleigh scattering												
Thomson scattering												

What will we discuss?

- Introduction: A range of plasmas…seeing is believing
- What do you want to measure?
- What can you measure?

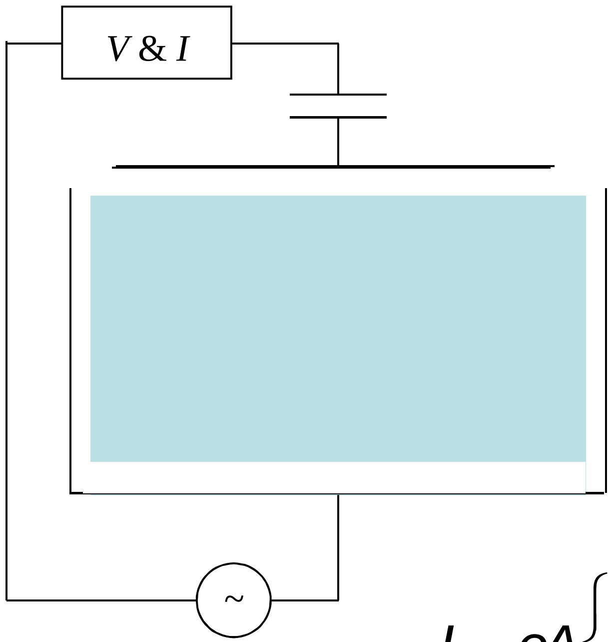
    - currents & voltages

    - frequency spectra UV, visible, IR, microwave, RF
- What techniques?

Appendix (slides not used in 2013 presentation)

What can you measure?

Self bias in RF driven plasma sheaths



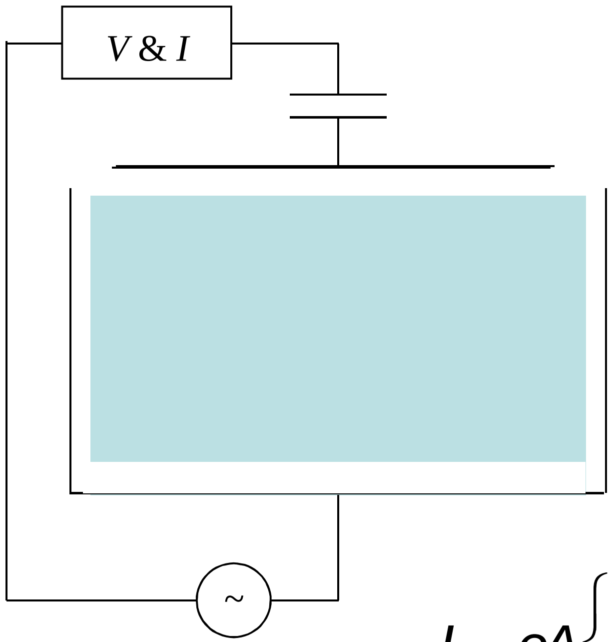
1. RF applied voltage
2. No dc current

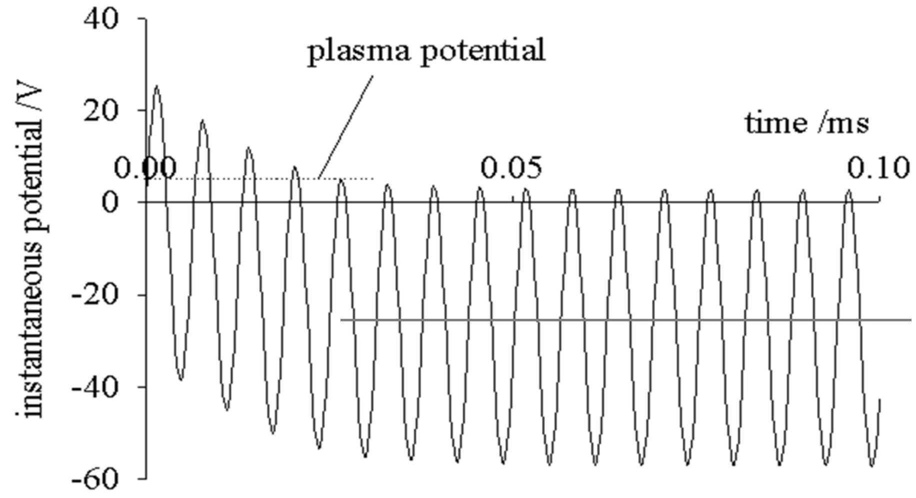
$$I = eA\left\{-n_s \frac{c_e}{4}\exp[e(\tilde{V}_s \cos(\omega_{RF} t) - \bar{V}_s]/kT_e) + n_s c_s\right\}$$

$$\langle I \rangle = 0$$

$$\Rightarrow \frac{e\bar{V}_s}{kT} = \ln\sqrt{\frac{2\pi m}{M}} - \ln \mathrm{I}_0\left(\frac{\epsilon \tilde{V}_s}{kT}\right)$$

Self bias in RF driven plasma sheaths





$$I = eA\left\{ -n_s \frac{c_e}{4} \exp[e\tilde{V}_s \cos(\omega_{RF} t) - \bar{V}_s]/kT_e) + n_s c_s \right\}$$

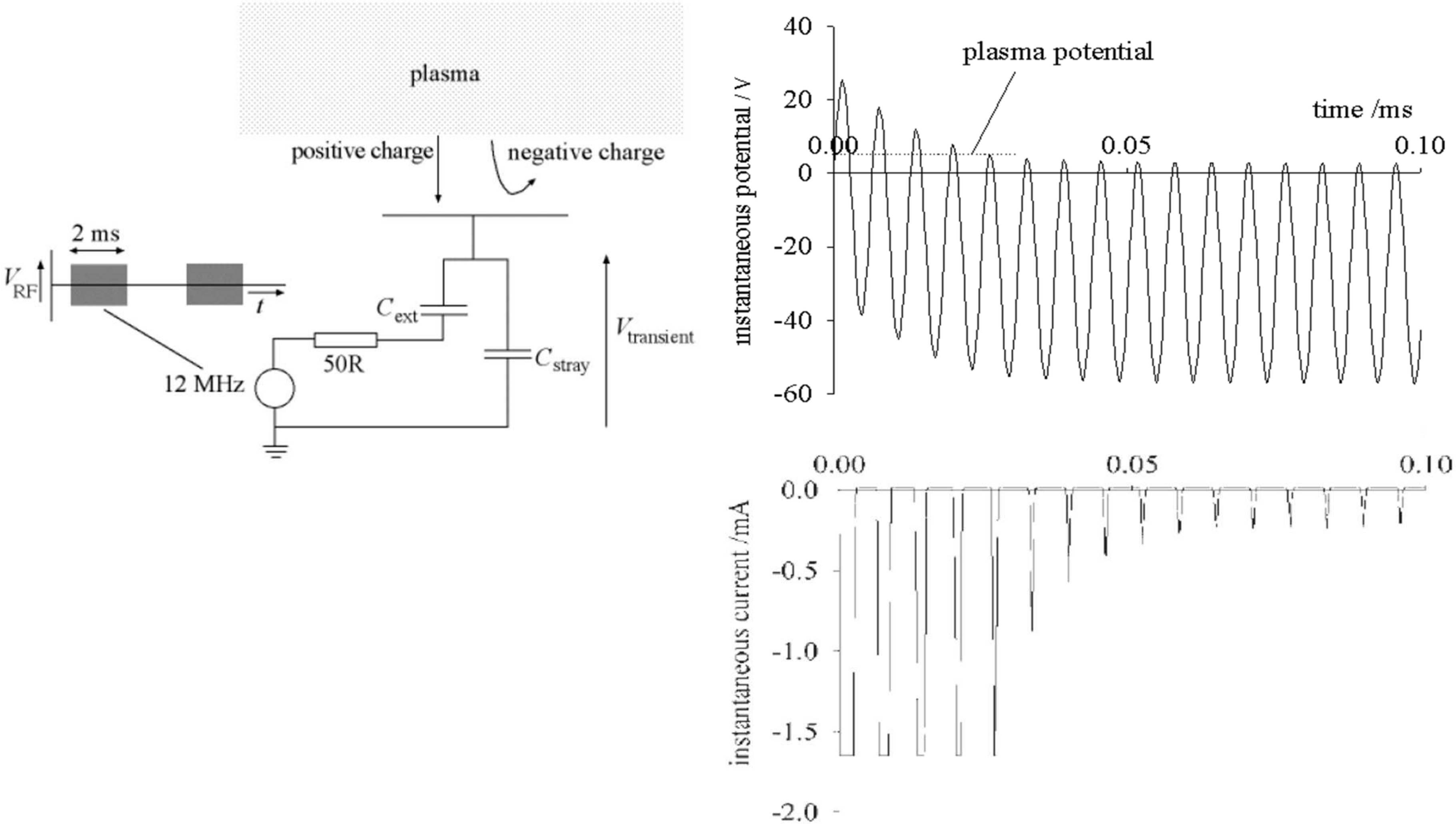
$$\langle I \rangle = 0$$

$$\Rightarrow \frac{e\bar{V}_s}{kT} = \ln\sqrt{\frac{2\pi m}{M}} - \ln \mathrm{I}_0\left(\frac{e\tilde{V}_s}{kT}\right)$$

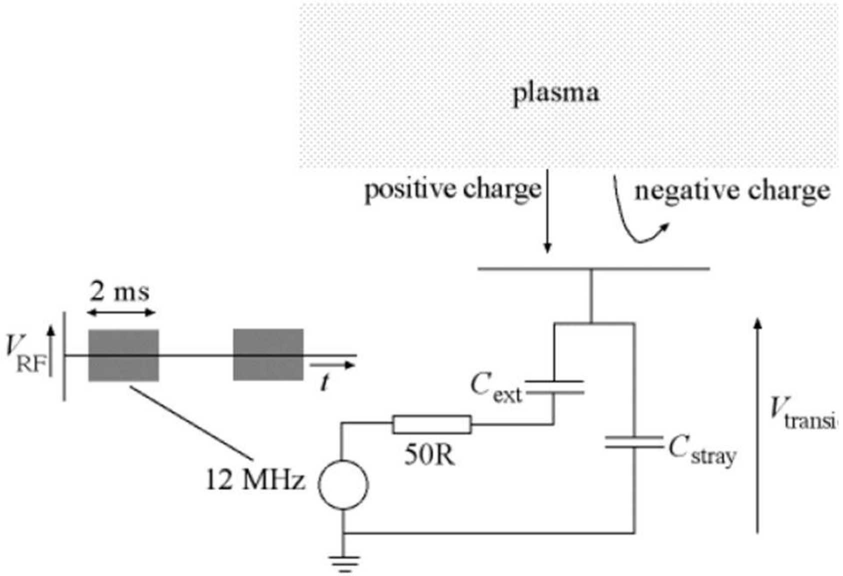
modified Bessel function

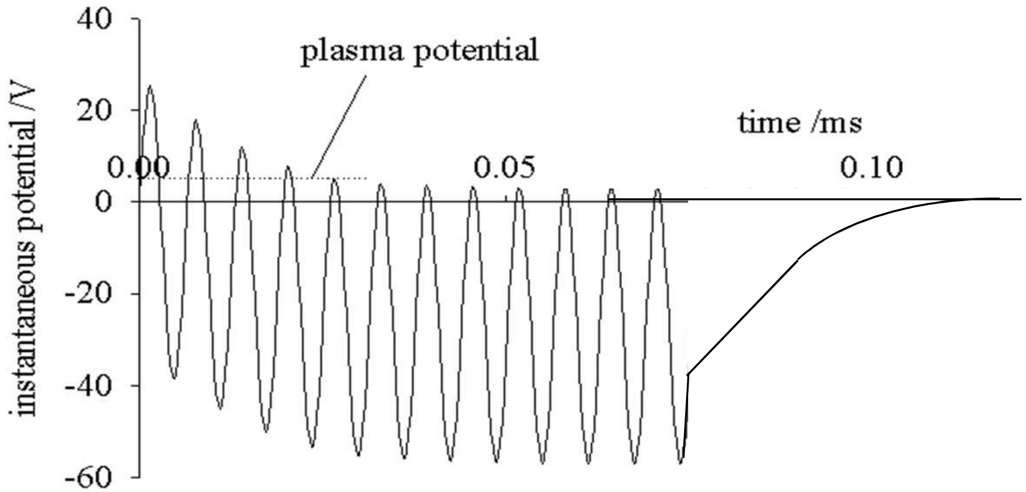
What can you measure?

Self bias in RF driven plasma sheaths



Self bias in RF driven plasma sheaths

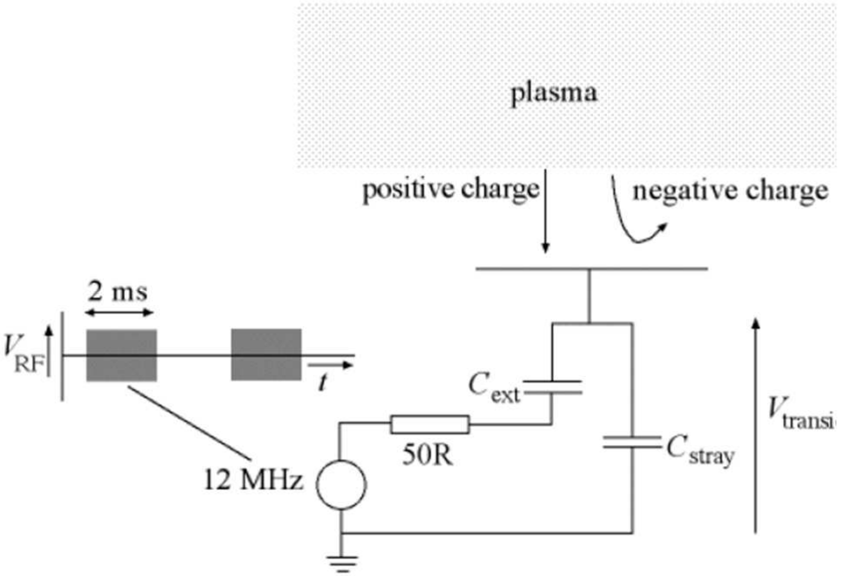


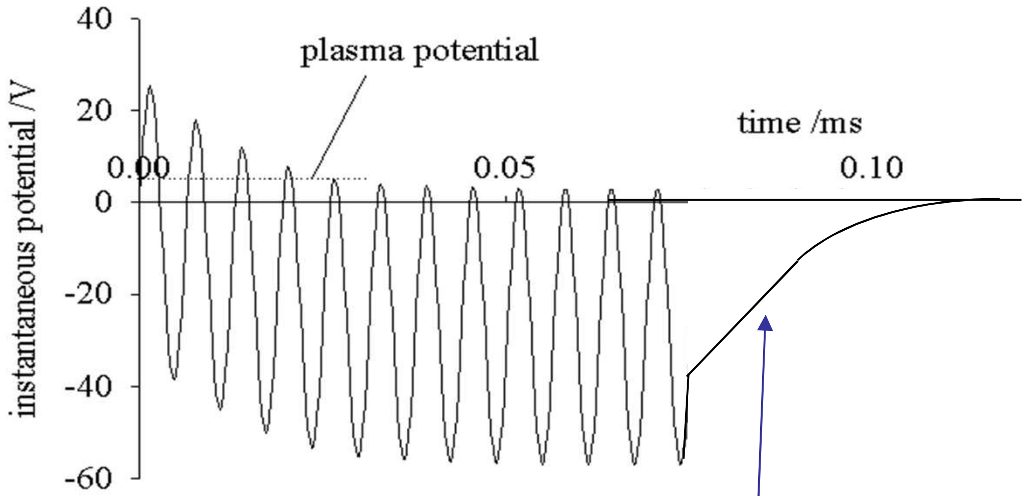


Techniques

Techniques

Self bias in RF driven plasma sheaths





$$C\frac{dV_0}{dt} = \left[\Gamma_+ - \Gamma_0 \exp\left(\frac{eV_0}{kT}\right) I_0\left(\frac{eV_{RF}}{kT}\right)\right] eA$$

=1

Electromagnetism in plasmas

Maxwell

$$\mathrm{div}\,\mathbf{D} = \rho$$

$$\mathrm{div}\,\mathbf{B} = 0$$

$$\mathrm{curl}\,\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathrm{curl}\,\mathbf{H} = \mathbf{J}_\mathrm{f} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\mathbf{D} = \varepsilon\varepsilon_0\mathbf{E}$$

$$\mathbf{B} = \mu\mu_0\mathbf{H}$$

ε = ?

μ =1

Dielectric function (permittivity) for a plasma

$$\operatorname{curl}\mathbf{H} = \mathbf{J}_\mathrm{f} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\mathbf{J}_\mathrm{f} = \sigma\mathbf{E}$$

$$\operatorname{curl}\mathbf{H} = \sigma\mathbf{E} + \varepsilon\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}.$$

E, **H** ~ exp –iωt

$$\operatorname{curl}\mathbf{H} = \underbrace{\sigma\mathbf{E} - \mathrm{i}\omega\varepsilon\varepsilon_0\mathbf{E}}.$$

$$\operatorname{curl}\mathbf{H} = -\mathrm{i}\omega\,\varepsilon_\mathrm{eff}(\omega)\,\varepsilon_0\mathbf{E},$$

where $\varepsilon_\mathrm{eff}(\omega) = \varepsilon - \sigma/\mathrm{i}\omega\varepsilon_0$

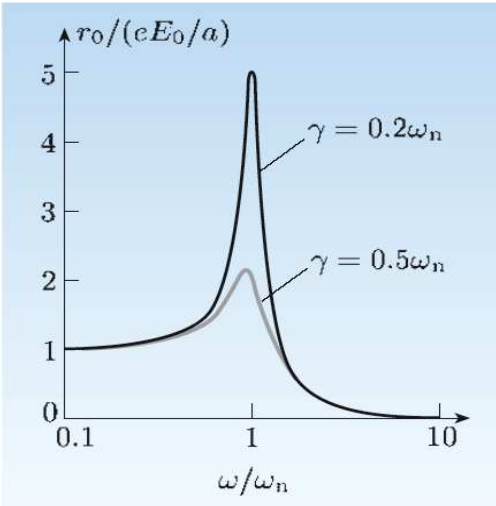
Define a complex dielectric function

Dielectric function (permittivity) for an insulator

Dielectric model: Motion of a bound electron in an E-M field

$$m\,\frac{\mathrm{d}^2\mathbf{r}(t)}{\mathrm{d}t^2} + a\,\mathbf{r}(t) + b\,\frac{\mathrm{d}\mathbf{r}(t)}{\mathrm{d}t} = -e\,\mathbf{E}_0\exp[-\mathrm{i}\omega t]$$

$$[-m\omega^2 + a - \mathrm{i}\omega b]\mathbf{r}_0 = -e\,\mathbf{E}_0$$



$$\mathbf{r}_0 = -\frac{e\mathbf{E}_0}{m}\,\frac{1}{(\omega_\mathrm{n}^2 - \omega^2) - \mathrm{i}\omega\gamma}$$

resonances

losses

Dielectric function (permittivity) for an insulator

Polarization:

$$\begin{aligned}\mathbf{P}(t) &= n_e(-e)\,\mathbf{r}(t)\\ &= -n_e e \mathbf{r}_0 \exp[-\mathrm{i}\omega t]\\ &= \frac{n_e e^2}{m}\frac{1}{(\omega_n^2-\omega^2)-\mathrm{i}\omega\gamma}\mathbf{E}_0\exp[-\mathrm{i}\omega t]\\ &= \omega_p^2\frac{1}{(\omega_n^2-\omega^2)-\mathrm{i}\omega\gamma}\varepsilon_0\mathbf{E}_0\exp[-\mathrm{i}\omega t].\end{aligned}$$

$$\mathbf{P} = (\varepsilon - 1)\mathbf{E}$$

Dielectric function:

$$\varepsilon(\omega) = 1 + \omega_p^2\frac{1}{(\omega_n^2-\omega^2)-\mathrm{i}\omega\gamma}.$$

Dielectric function (permittivity) for a plasma

Dielectric model: free electron in an E-M field

$$\varepsilon(\omega) = 1 + \omega_p^2 \frac{1}{(\omega_n^2 - \omega^2) - i\omega\gamma}.$$

= 0 for free electron

= 0 for low collisionless

$$\varepsilon_{\text{eff}}(\omega) = 1 - \frac{\omega_p^2}{\omega^2}.$$

$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}.$$

	(Quadrupole) Mass Analyser	Langmuir Probe	Emissive Langmuir Probe	Retarding Field Analyser	Ion flux probe	Microwave interferometry	RF probe spectroscopy	Optical emission	Optical absorption (DLS, FTIR)	Laser Induced Fluorescence	Rayleigh scattering	Thomson scattering
Gas composition	x	x						x	x	[x]		
Density / m^{-3}												
ion (n_i)		x			[x]	[x]				x		
electron (n_e)		x			[x]	x	x				[x]	x
neutrals (eg n_*)	x							x	x	x		
Energy / eV												
iIon ($<E_i>$)	x	[x]		x						x		
electron ($<E_e>$)		x		x	x							x
neutrals (eg $<E_{vib}>$)								x		x	x	
Flux / m^{-2} s^{-1}												
ion (Γ_i)		x		[x]	x					x		
electron (Γ_e)		x		[x]	x							
neutrals (eg Γ_*)										x		
Potential/V & E field / V m^{-1}												
$\Delta\phi$		x			x							
E			x							x		