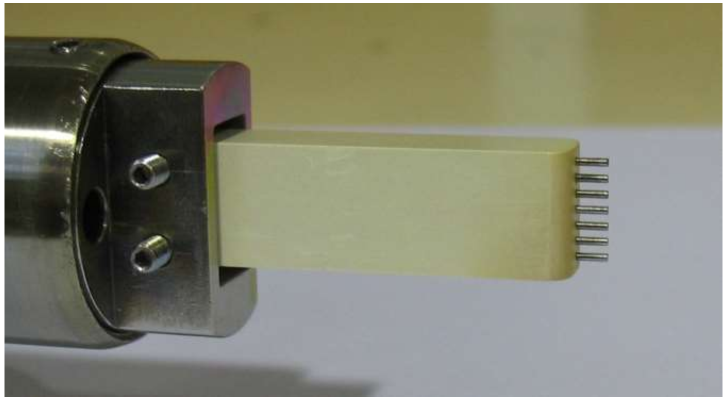
Diagnostics

➢ **Electric probes**

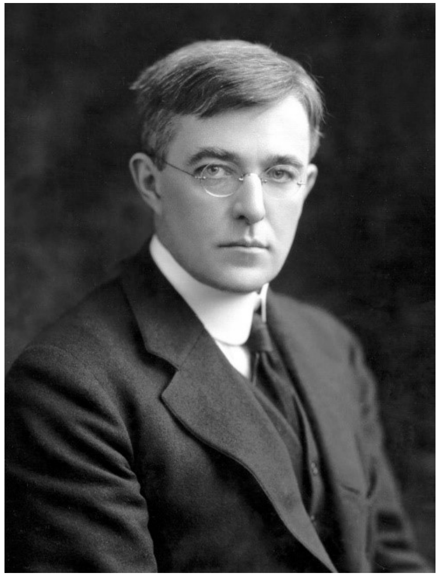
Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Lisbon, Portugal
http://www.ipfn.tecnico.ulisboa.pt

Langmuir probes

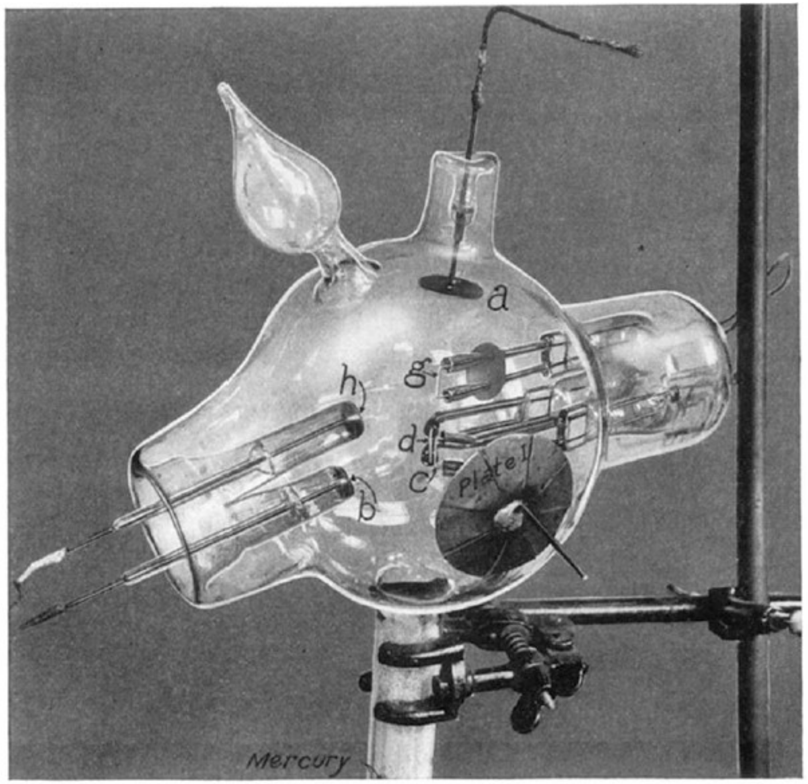
- Simplest diagnostic (inexpensive) – conductor immerse into the plasma
- Data interpretation complicated as probes perturb the plasma
- Limited to the plasma region were the probes can survive or do not perturb plasma
- Allows the determination of a large variety of plasma parameters (some of them only possible with probes)
- The most widely used diagnostic for low temperature plasmas, T_e < 100 eV



Irving Langmuir



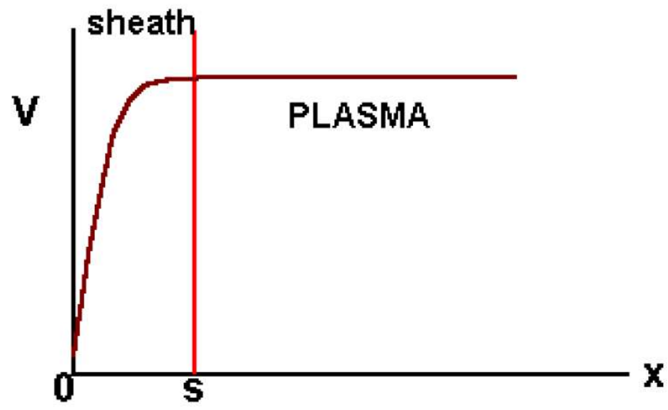
- Nobel Prize in Chemistry, 1932
- Pioneer of plasmas physics research
- Used electrical probes to characterize plasma
- Contributions include development of W incandescent light bulb



Mercury plasma device (or gas filled lamp) used to observe plasma oscillations

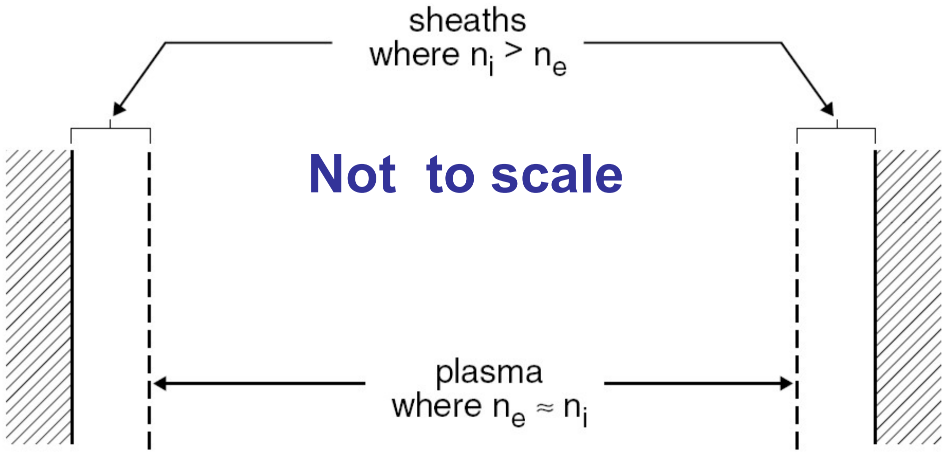
Debye shielding

- Physics of probes equivalent to that of plasma-wall interaction
- Electrostatic potentials are shielded within a short distance. Sheath keeps the plasma neutral
- Sheath dimension 10 λ_D ~ 0.1 mm, thin layer (λ_D~ 10^{-5} m for T_e = 20 eV, $n = 1 \times 10^{19}$ m^{-3})



$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}} \simeq 7.43 \times 10^6 \sqrt{\frac{T_e[eV]}{n_e[m^{-3}]}}$$

- Thin:
  $\lambda_D << d$ (probe dimension, ~mm)
- Collisionless:
  l (mean free path, cm - m) >> λ_D



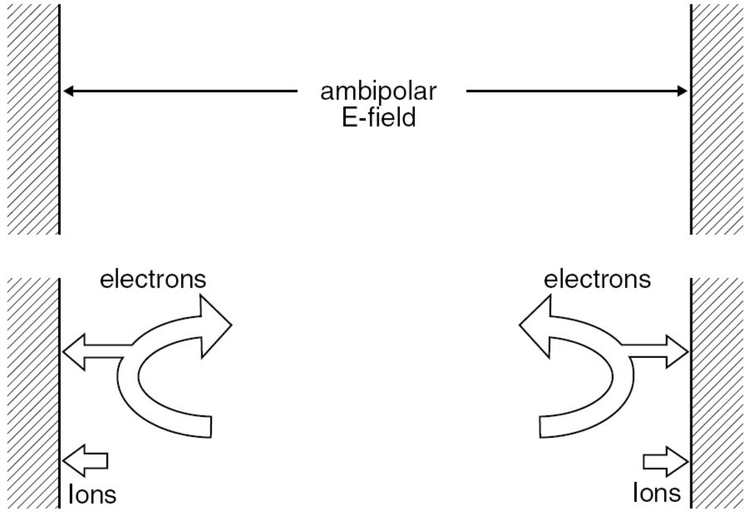
Debye shielding

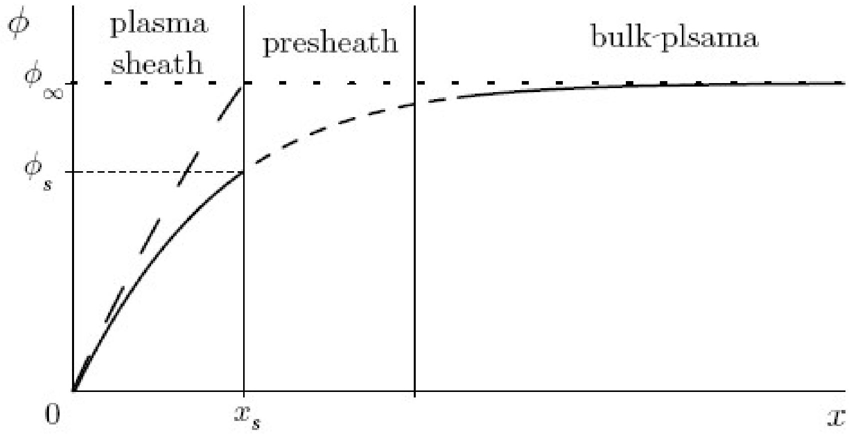
Typical values for the Debye length

Plasma	Density $n_e(\mathrm{m}^{-3})$	Electron temperature $T(\mathrm{K})$	Magnetic field $B(\mathrm{T})$	Debye length $\lambda_D(\mathrm{m})$
Solar core	10^{32}	10^{7}	--	10^{-11}
Tokamak	10^{20}	10^{8}	10	10^{-4}
Gas discharge	10^{16}	10^{4}	--	10^{-4}
Ionosphere	10^{12}	10^{3}	10^{-5}	10^{-3}
Magnetosphere	10^{7}	10^{7}	10^{-8}	10^{2}
Solar wind	10^{6}	10^{5}	10^{-9}	10
Interstellar medium	10^{5}	10^{4}	10^{-10}	10
Intergalactic medium	1	10^{6}	--	10^{5}

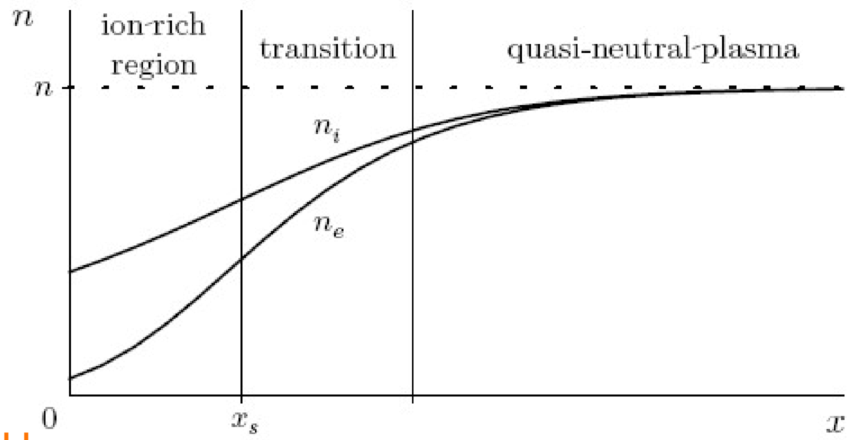
Sheath

- As electrons are more mobile a electric field arises in the sheath so that $\Gamma_i = \Gamma_e$.
- Probe/wall rapidly charges up negatively. Probe floats below the plasma potential: floating potential
- Sheath has a positive charge





electron-repelling potential difference, ~$3T_e/e$ for H



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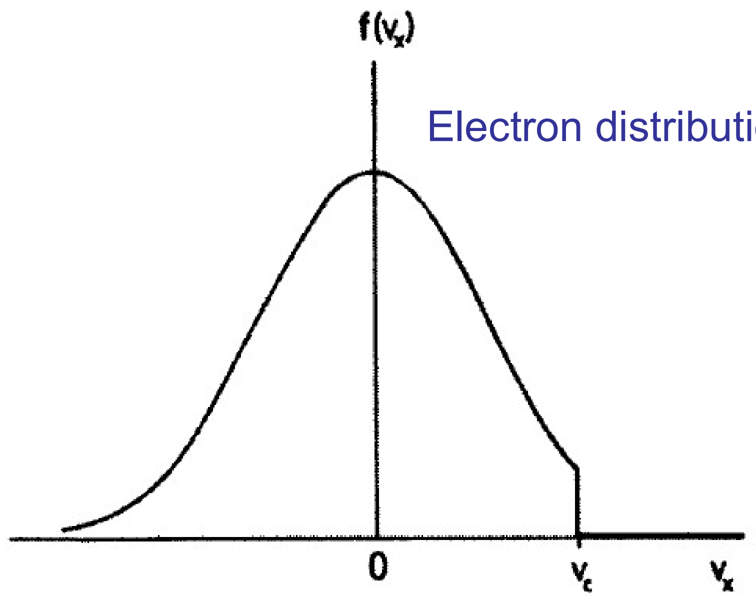
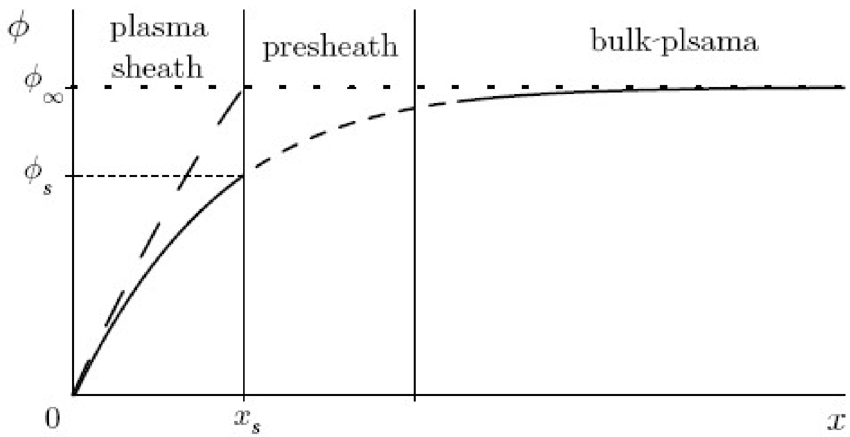
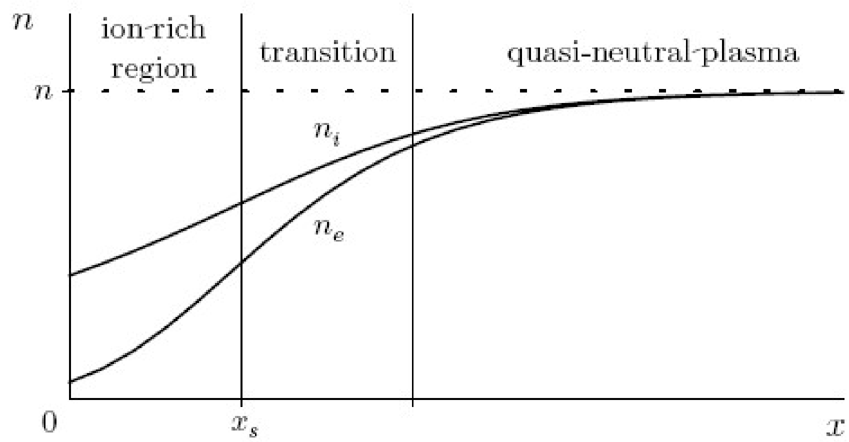
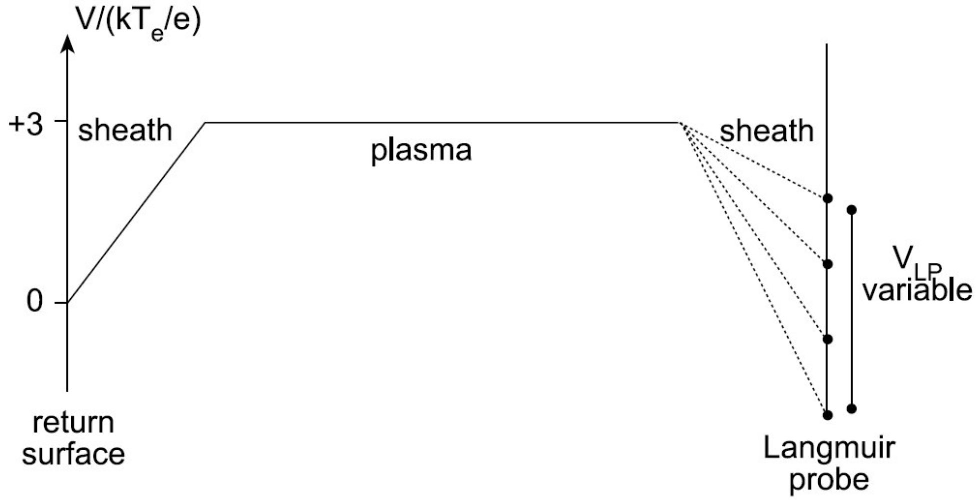


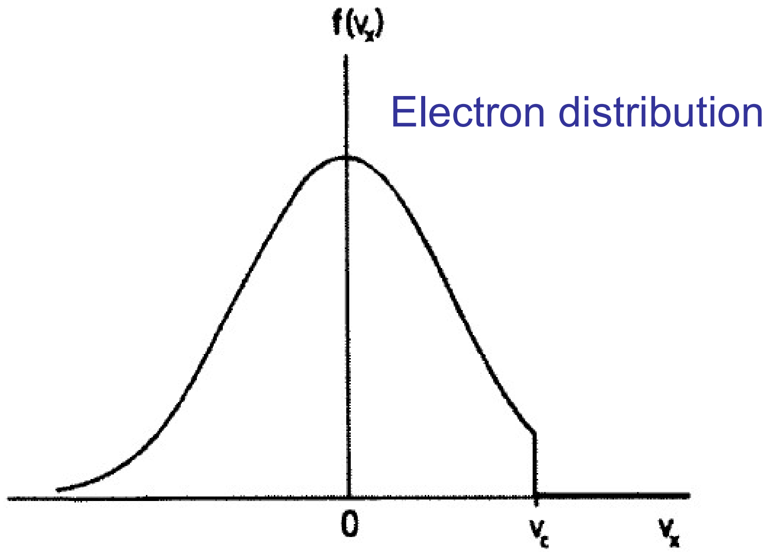




electron-repelling potential difference, ~3T_e/e for H

What if the surface is not floating, but electrically biased?

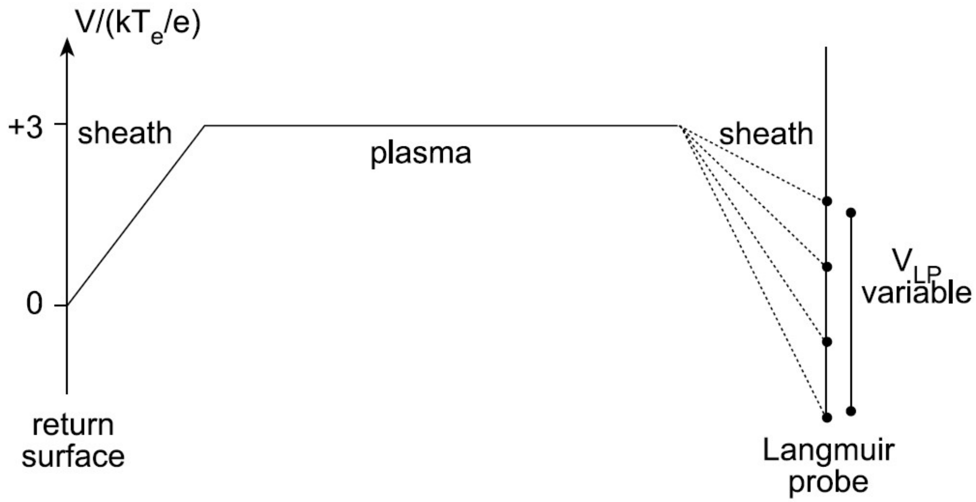


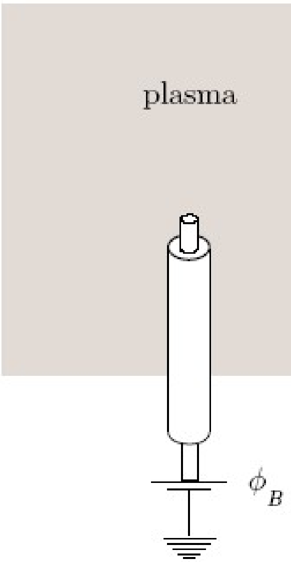


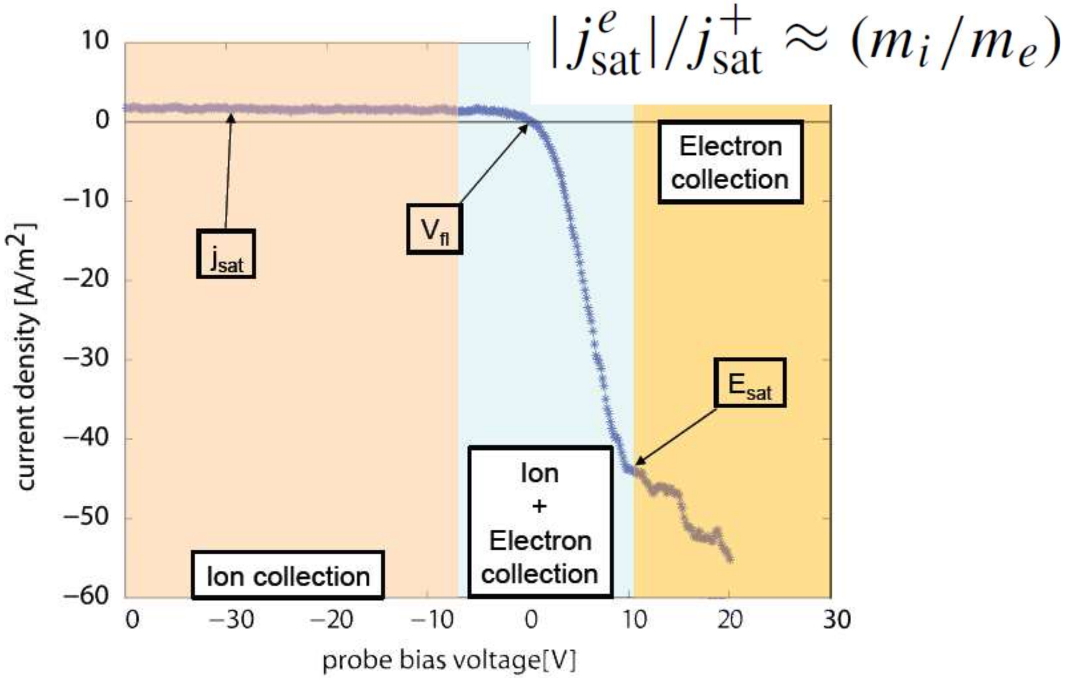
What if the potential drop is larger than V_f? Or smaller than V_f?

I-V characteristic

- What if the surface is not floating, but electrically biased?

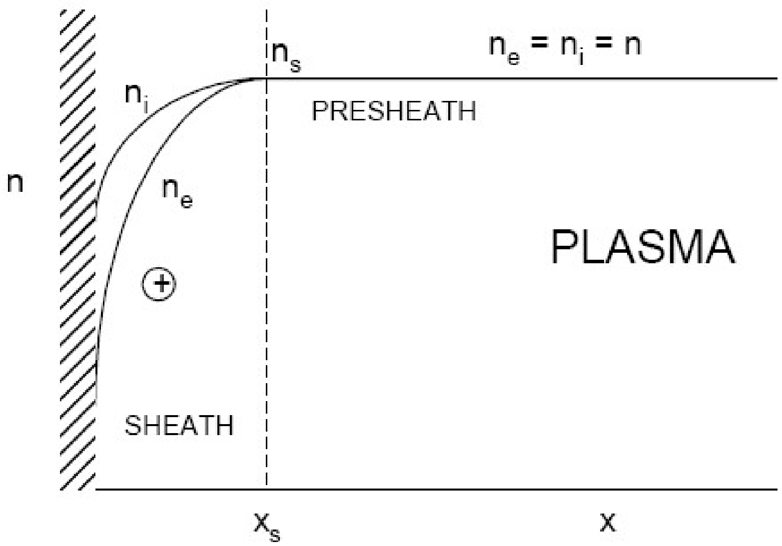




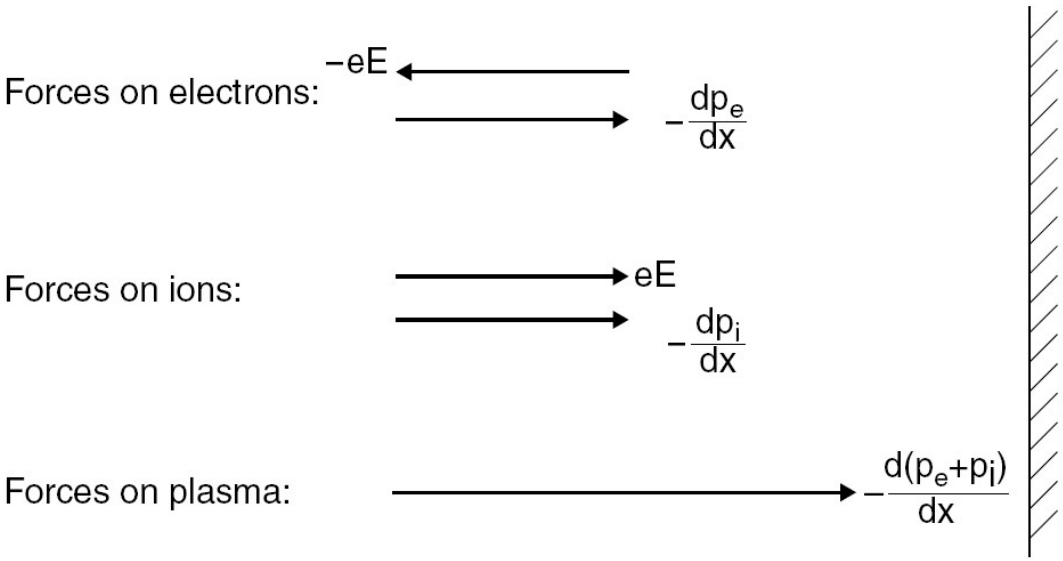


Sheath analysis

- **Sheath complex:** Strong E, $n_{e,i}$ determined by Poisson's eq + motion particles + probe geometry $\Rightarrow$ numerical solution
- **Analytic solution only simplest possible case:** *B = 0, Z = 1, T_i = 0*, collisionless, plane probe, 1D, all particles absorbed by the probe
- **Aim:** estimate parameters at sheath edge
- Relation density and potential follows Boltzmann factor (Maxwellian)



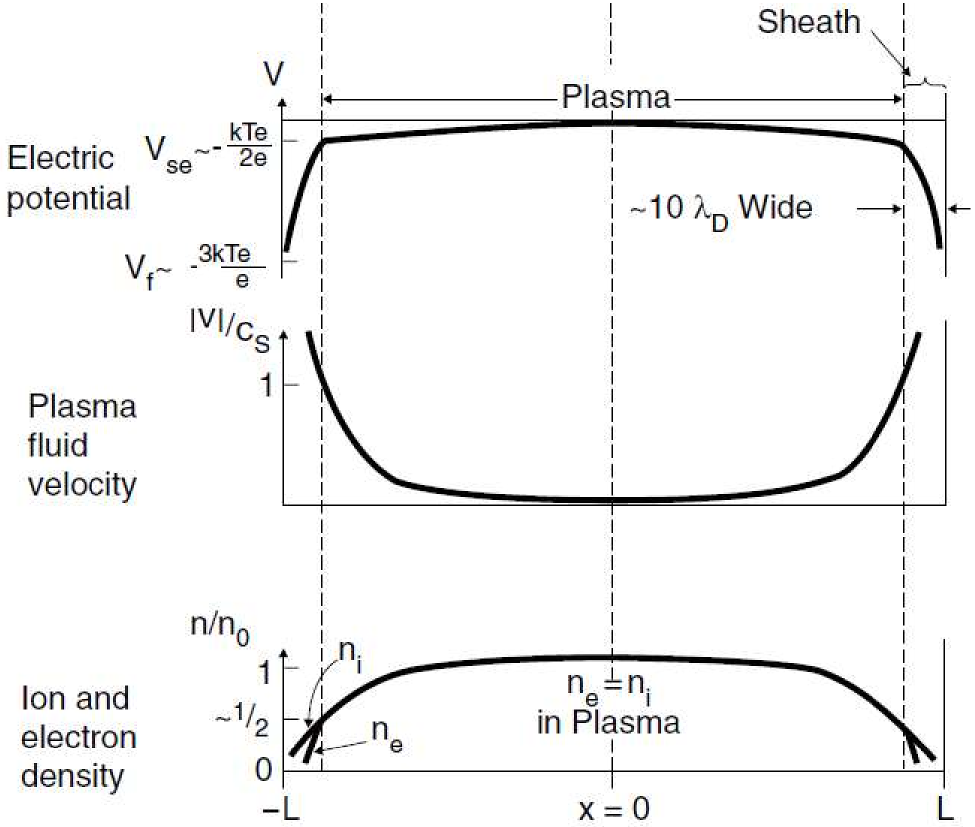
$$n_e(x) = n_{se} \exp[e(V - V_{se})/kT_e]$$



Bohm criterion

- V_{se} has to be different from V_p
- A plasma can coexist with a material boundary only if a thin sheath forms
- Ions have to enter the sheath edge with (Bohm, 1949):
  - $|V_{se}| = kT_e/2e \;\Rightarrow$
  - $v_{se} = (kT_e/m_i)^{1/2} = c_s$, sound speed
  - $n_{se} = n_0 e^{-\frac{1}{2}} \approx 0.6 n_0$
  - $\Gamma_{se} = n_{se} v_{se} = 0.6 n_0 c_s$
  - $\Gamma_{se} = \Gamma_w$

  Expression almost always used in practice



For $\Gamma_i = \Gamma_e \Rightarrow V_f \approx 3\, kT_e/e$
for $T_e \approx T_i$, H plasma

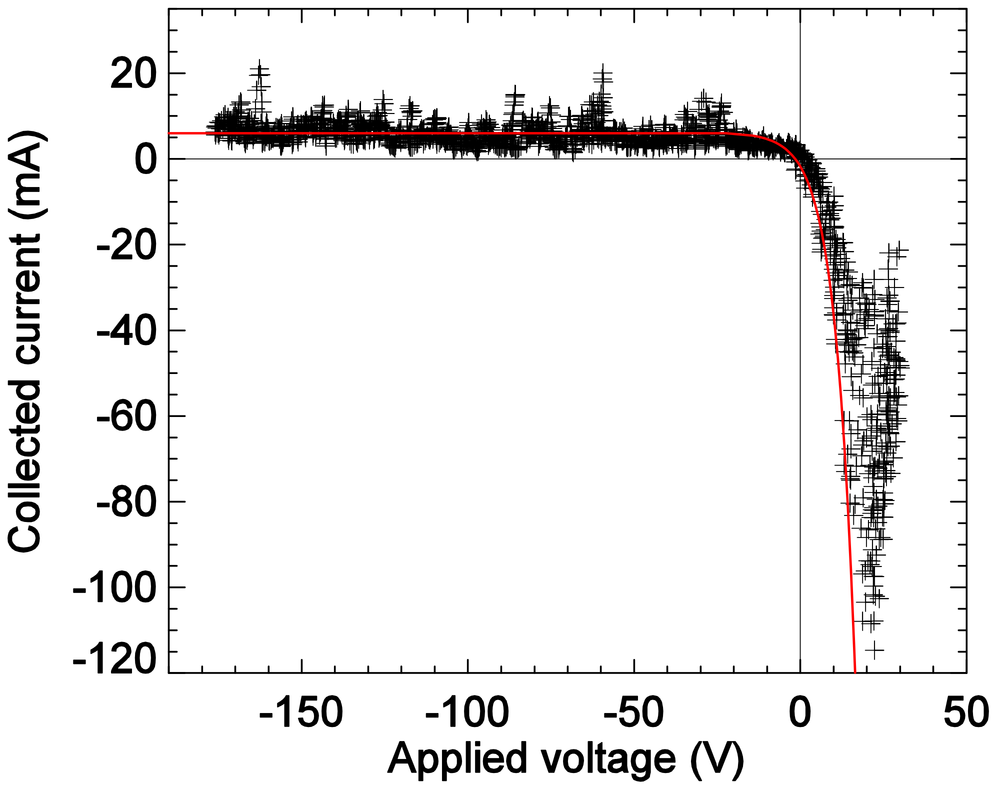
I - V characteristic

$$I = I_{sat}\left(1 - e^{\frac{e(V_{bias} - V_f)}{kT_e}}\right)$$

$$I_{sat} = 0.5eAnc_s$$

$$c_s = \sqrt{\frac{k(T_e + T_i)}{m_i}}$$

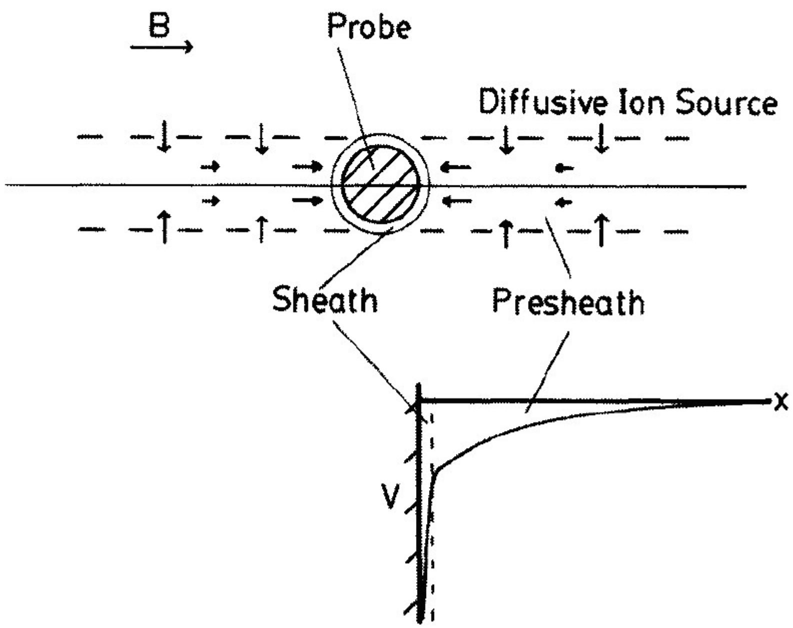
$$V_p = V_f + 3kT_e/e$$

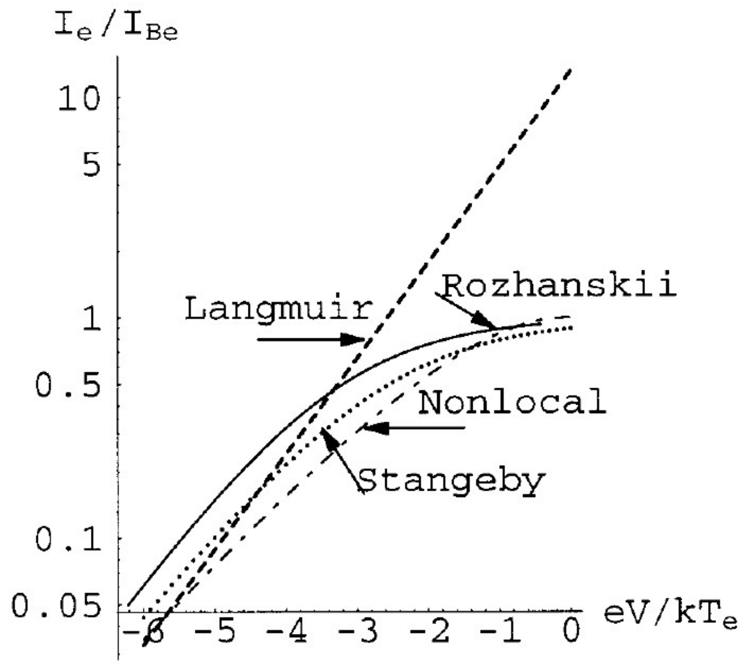


- T_e, V_f and I_{sat} obtained from the I-V, then derive n, V_p

Effect of the magnetic field

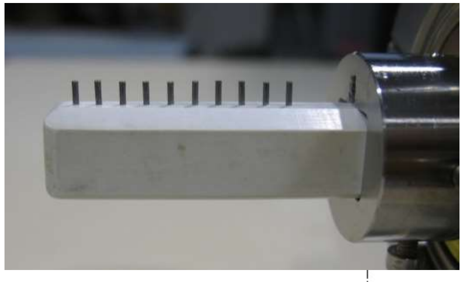
- Motion across B limited (Larmor radius): particles collected over larger distances
- Plasma resistance influences the analysis
- Despite theoretical difficulties, Bohm formula is valid and information may be extracted assuming for the area $A_\perp$, limiting the analysis to V_{bias} ~< V_f

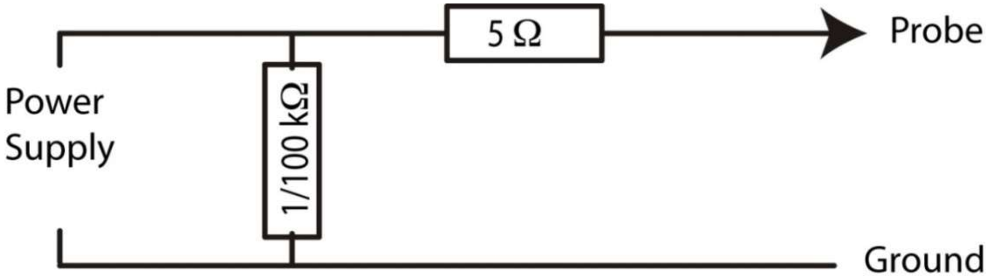




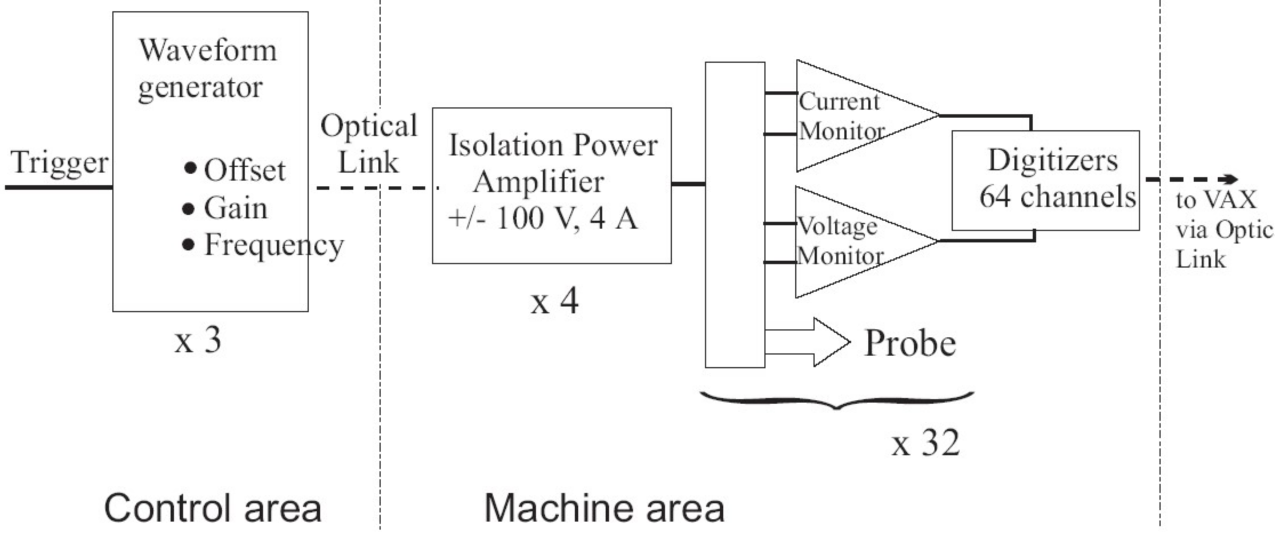
Typical applications

Typical circuit

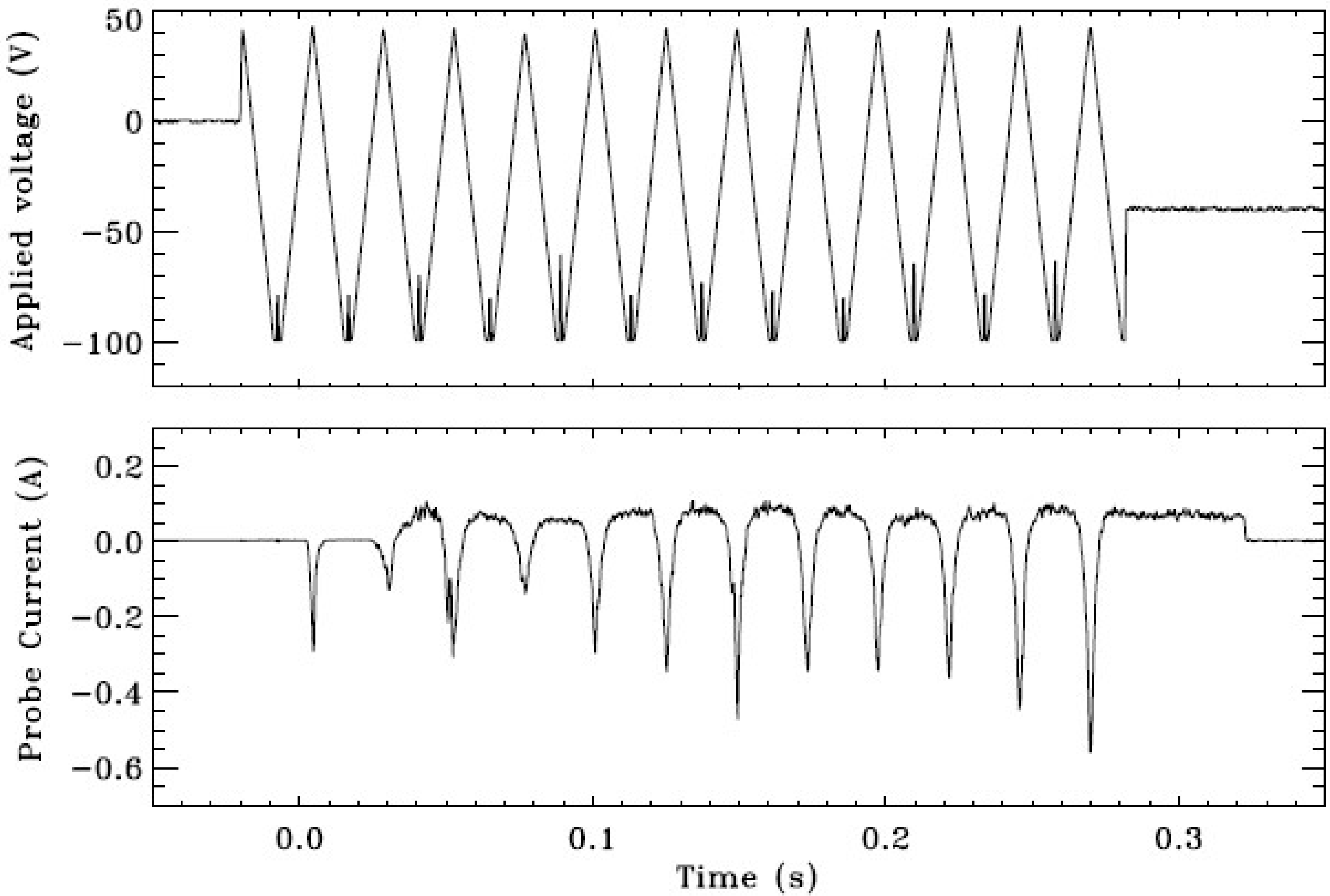




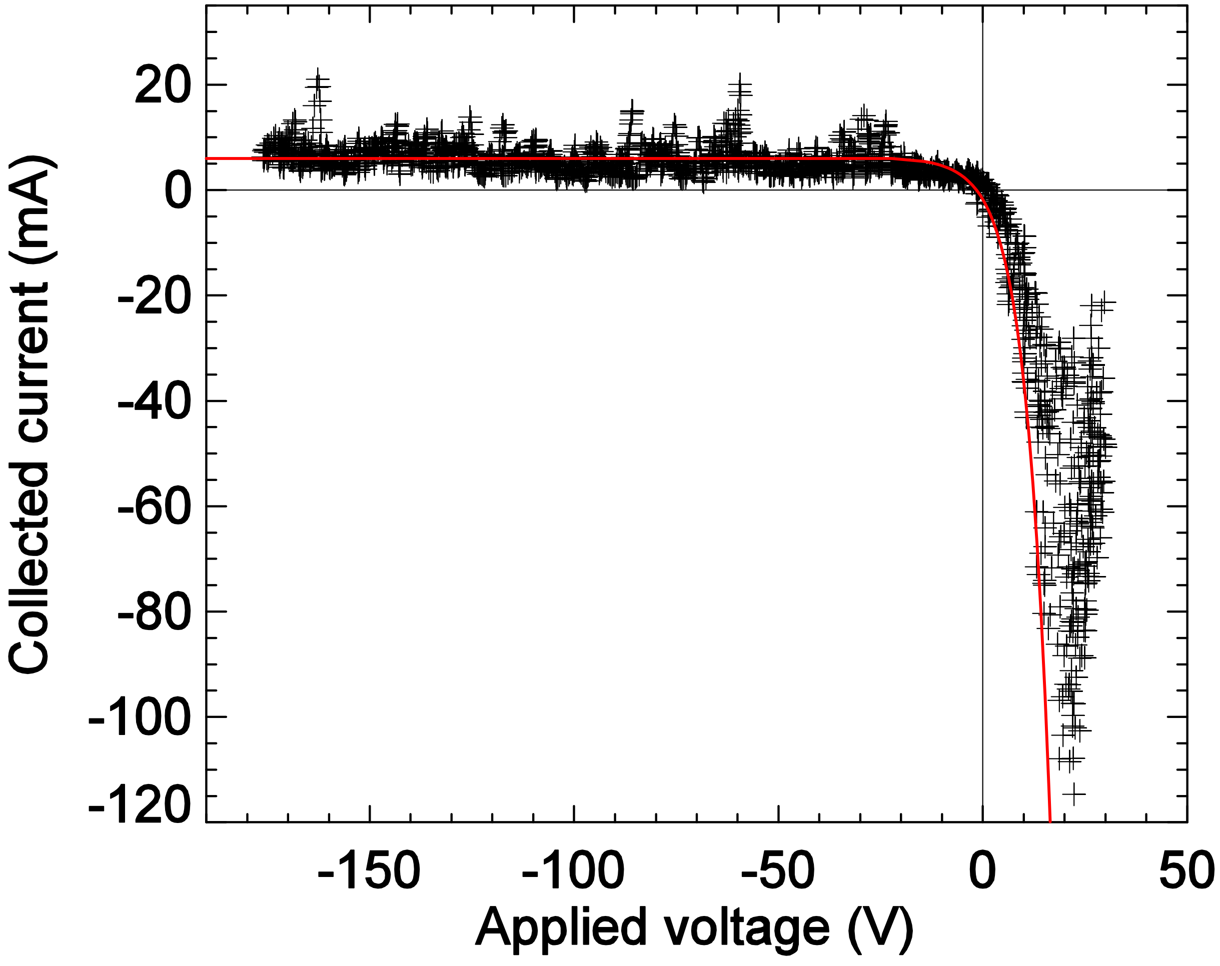
Experimental set-up basic apart from the need for galvanic isolation



Typical I, V signals

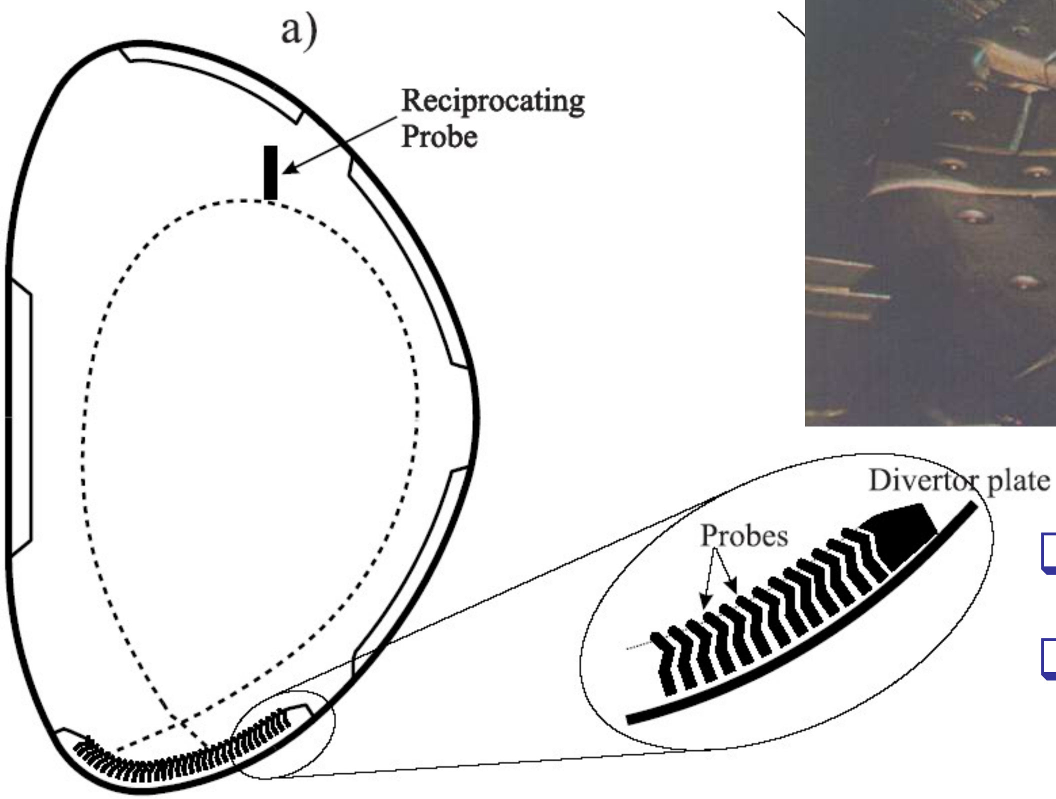


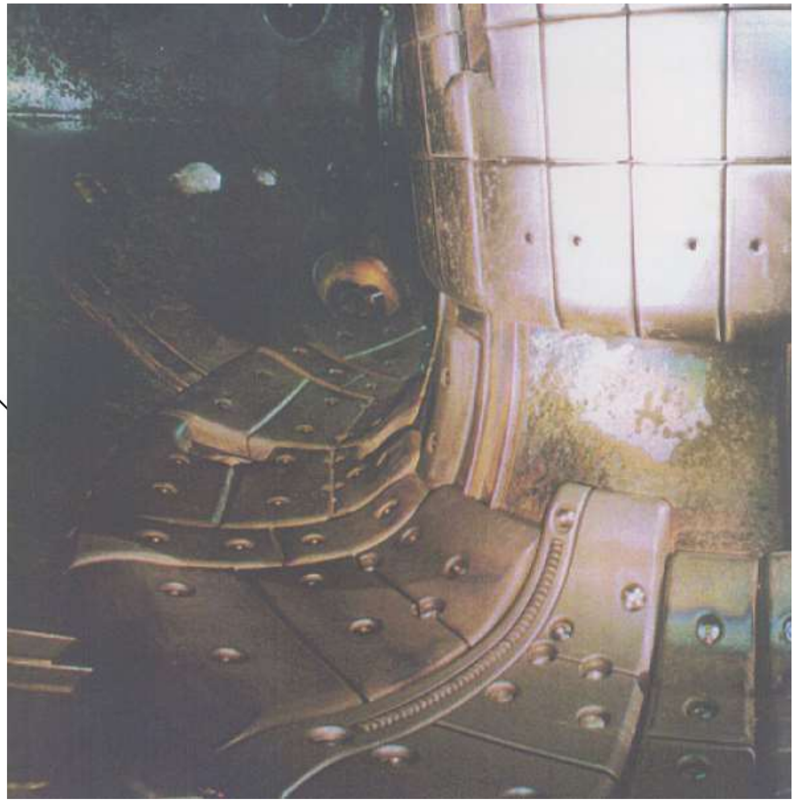
I - V characteristic



Fixed probes

- ❑ Probes fixed in the plasma facing components (same material as PFCs): do not perturb the plasma
- ❑ Study plasma-wall interaction
- ❑ Materials: Graphite, Tungsten

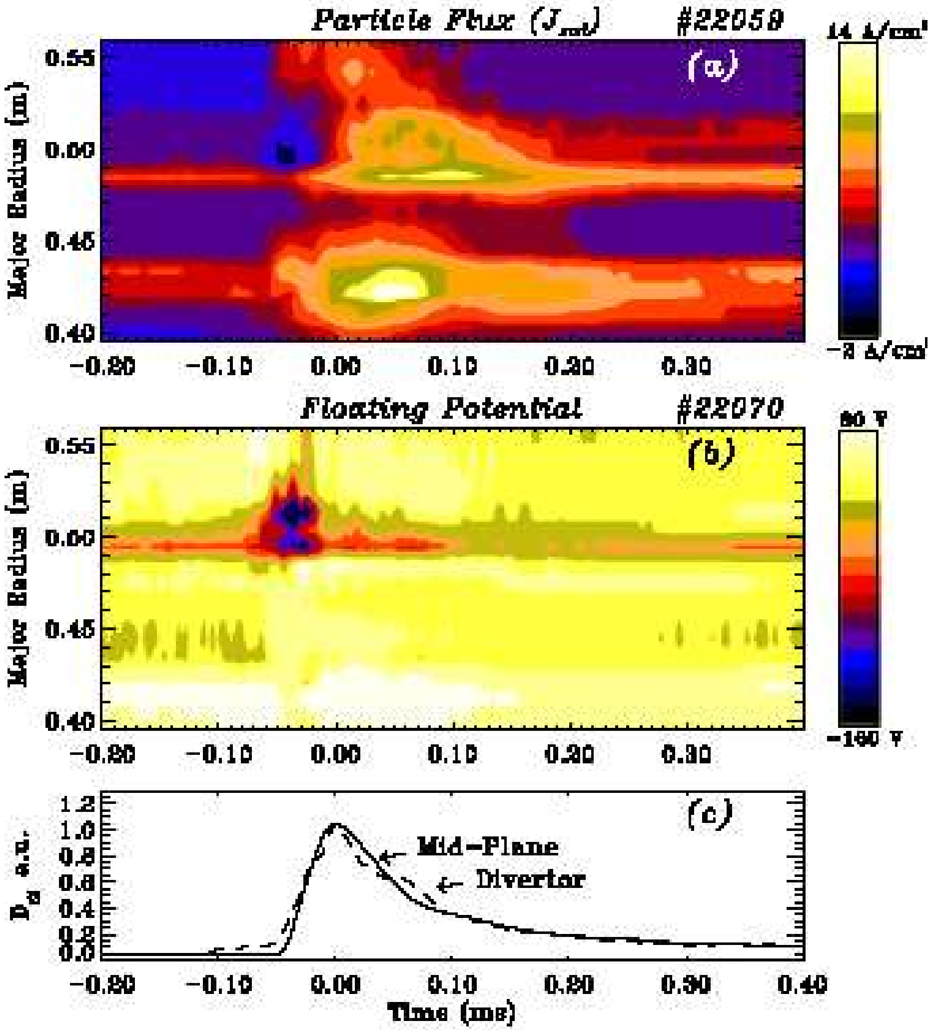




- ❑ $\Gamma_{wall} = I^{+}_{sat}/eA_p$ [$m^{-2}s^{-1}$]
- ❑ $q_{wall} = \gamma T_e \Gamma_{wall}$ [Wm^{-2}]

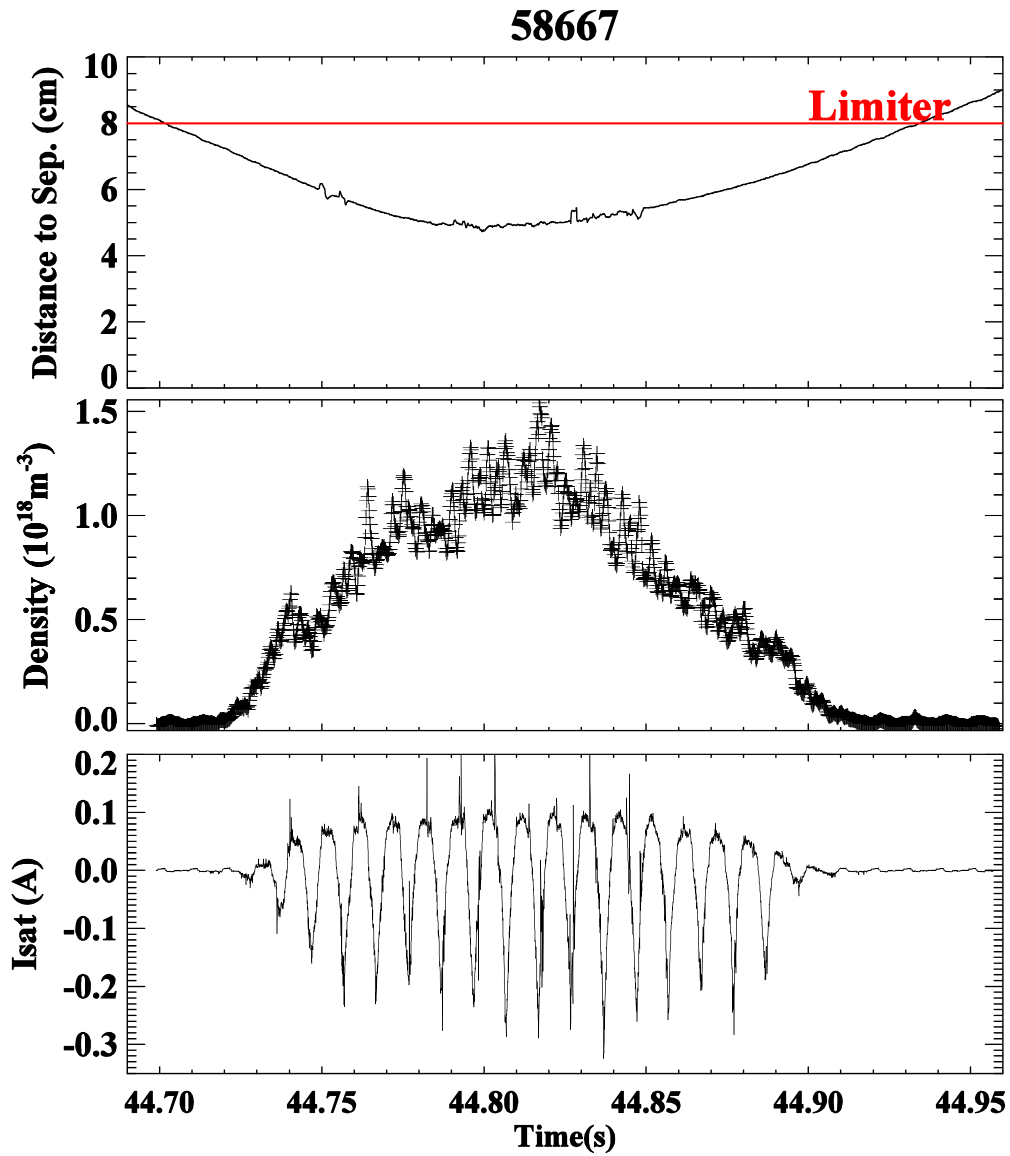
Particle flux to plasma facing components

- Temporal evolution of the particle flux to the PFCs
- High temporal resolution, local measurement



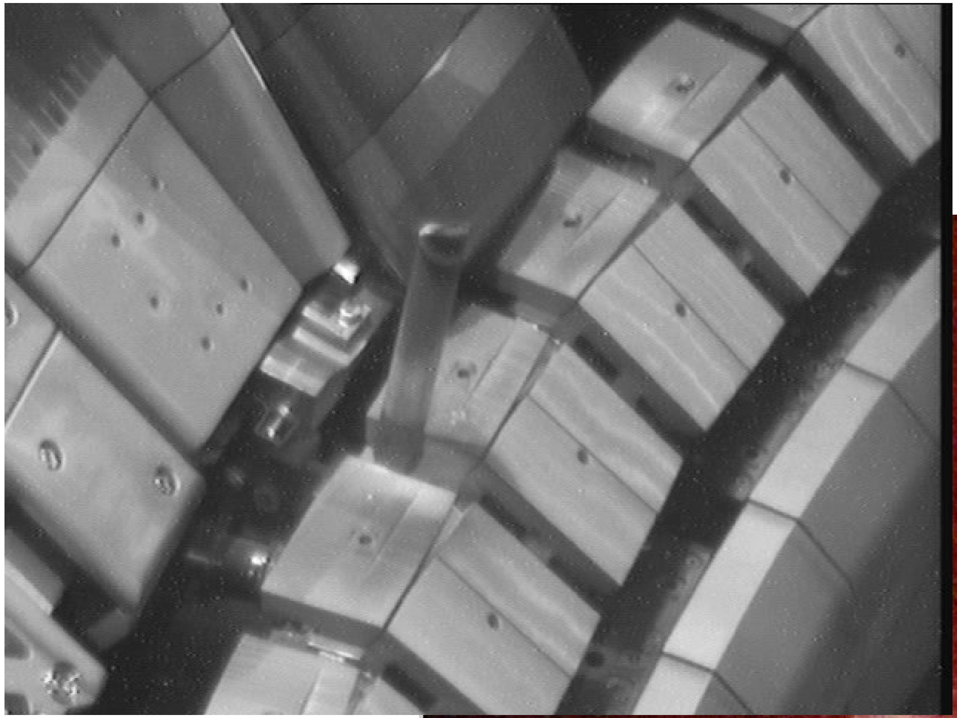
Reciprocating probes

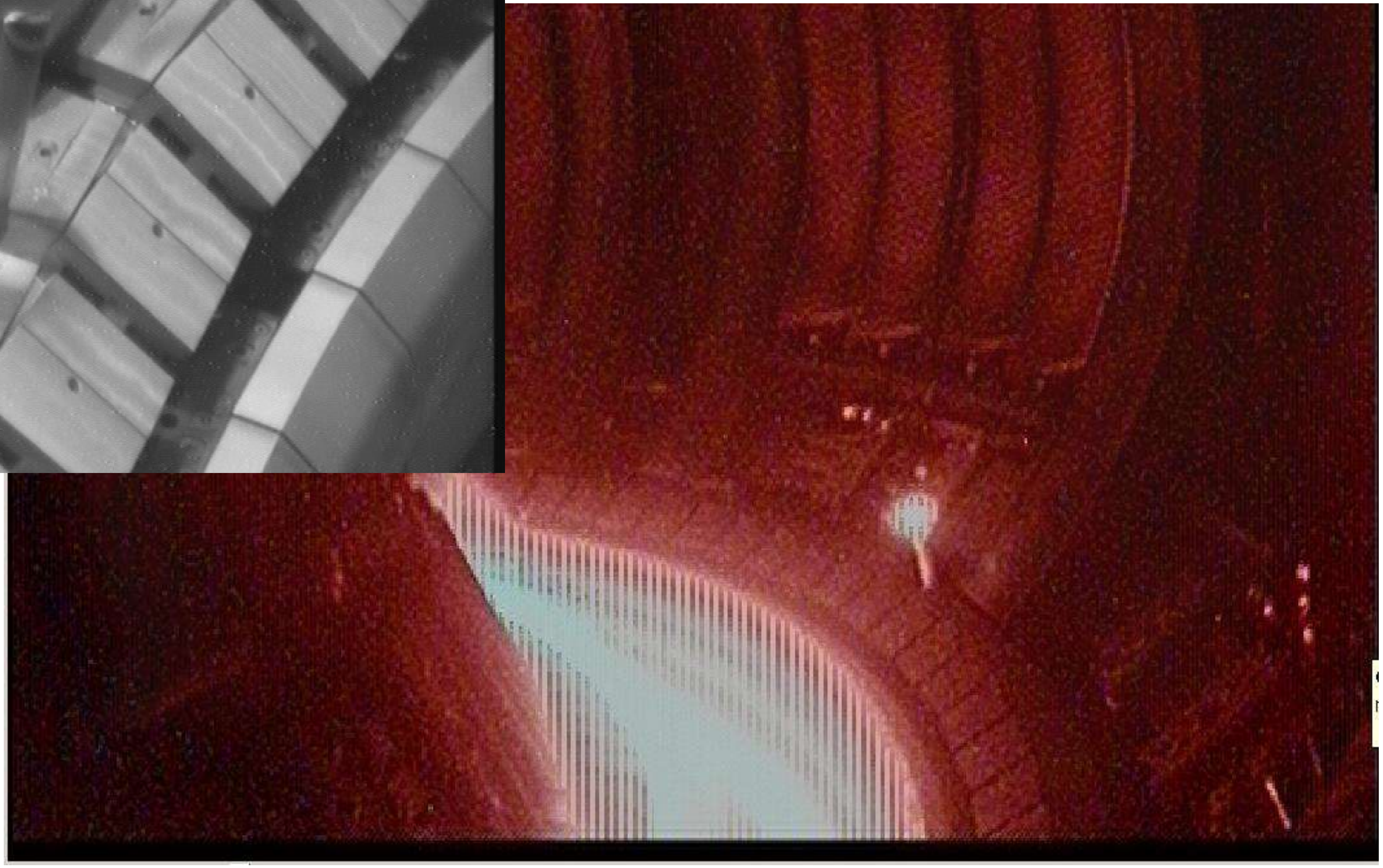
- ❑ Reduce the probe heat loads (few 100 ms)
- ❑ Pneumatic systems
- ❑ Typical velocity 1 m/s



Reciprocation at JET

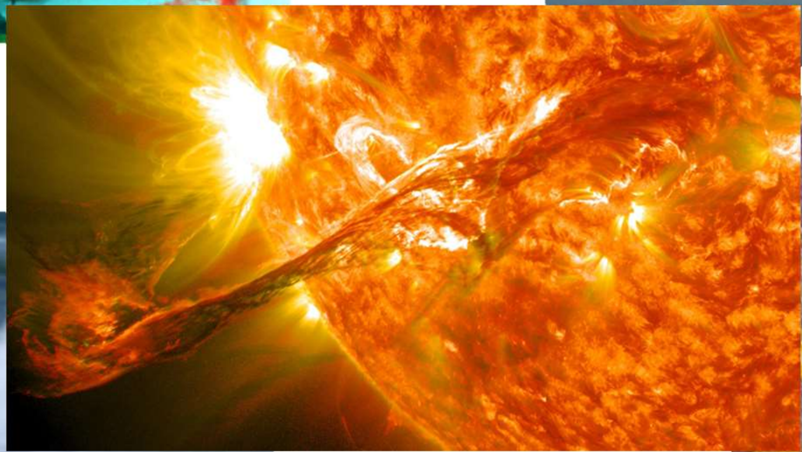
Reciprocation at JET





Turbulence is ubiquitous…

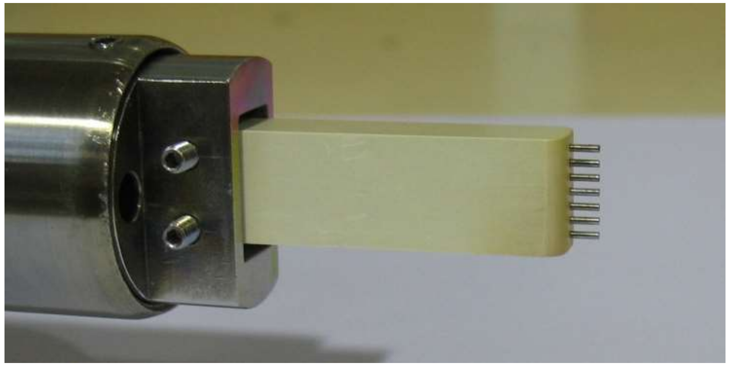




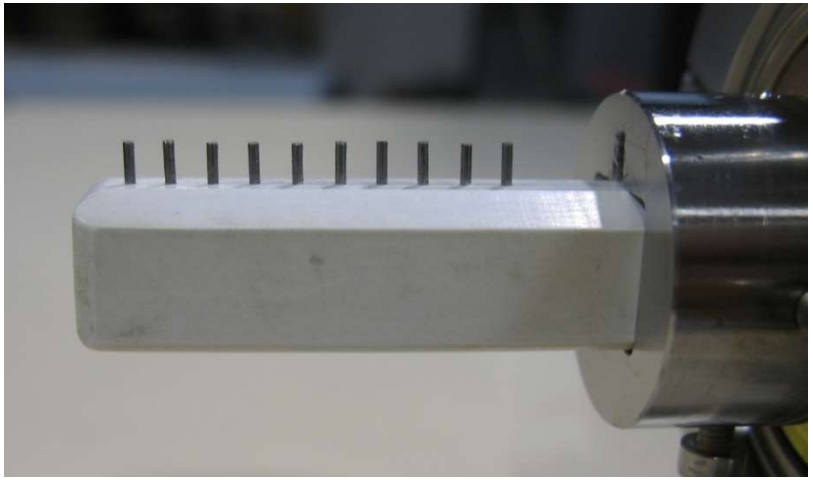
as well as an important unsolved physics problem

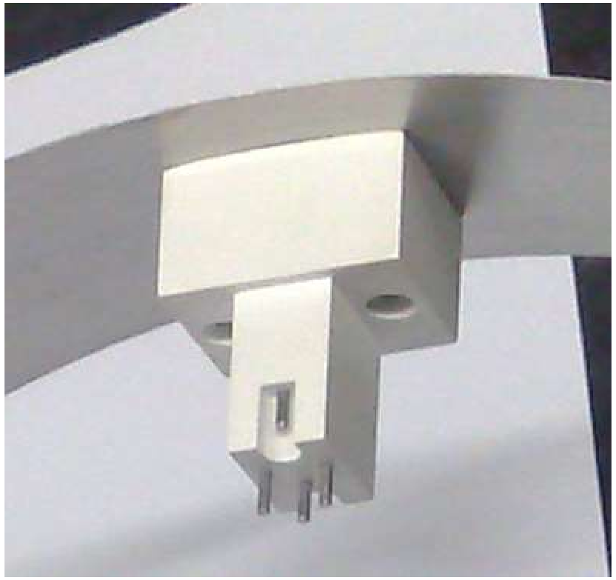
ISTTOK probe arrays

Poloidal array



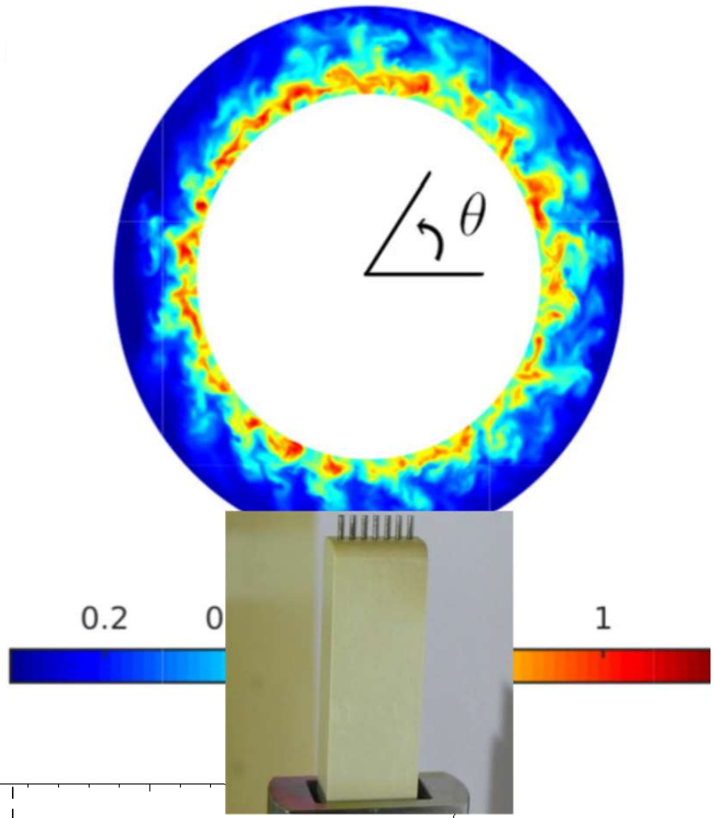
Radial array

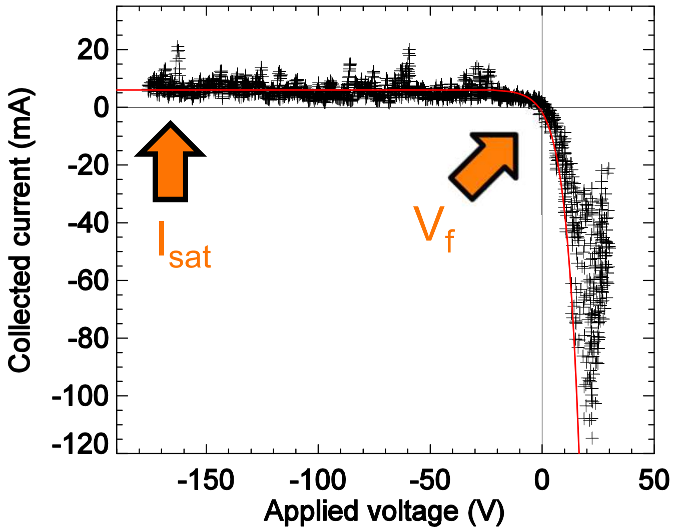


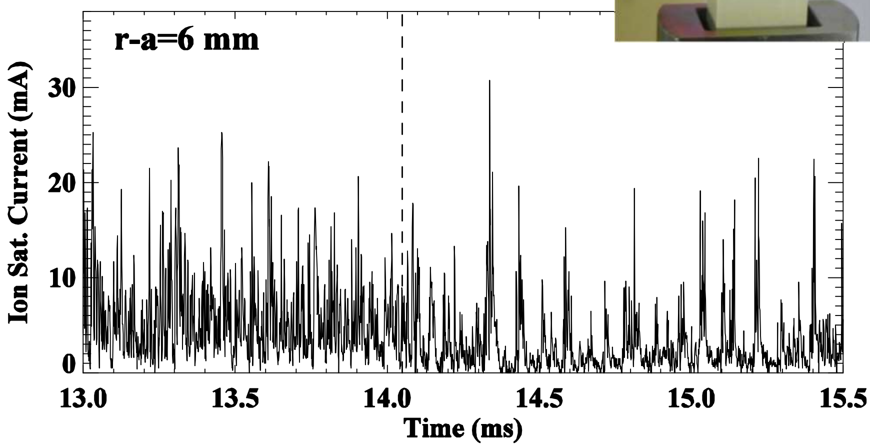


Turbulence characterization

- ❑ Plasma losses dominated by turbulence
- ❑ Probes allows the determination of a large variety of parameters
- ❑ Local measurements: limited pin size
- ❑ High temporal resolution: limited by the data acquisition system
- ❑ Ideal for turbulence studies







Space plasmas

- One of two Langmuir probes on board ESA's space vehicle Rosetta (intended to study the comet 67P/Churyumov-Gerasimenko) in 2016
- Spherical titanium probe, 50 mm in diameter. Probe biased with respect to spacecraft body.
- Aimed at studying the plasma around the comet

- Langmuir probe also used to characterize the ionosphere using instrumented rockets (up to ~500 km)

“Industrial plasmas”

- Characterisation of plasmas for deposition experiments
- RF and DC arc plasma sources used at low gas pressure ($10^{-4} - 10^{-2}$ mbar)

Commercial systems

Home / Products / Langmuir / Langmuir Probe

Langmuir Probe

The Langmuir Probe is one of the most common and widely used plasma diagnostics and plasma characterisation instruments to measure parameters in the bulk of the plasma.

The Langmuir Probe measures plasma parameters such as floating potential, plasma potential, plasma density, ion current density, electron energy distribution function and electron temperature. Our system uses the most up to date probe theory available, drawing on Orbital Motion Limited and as the pressure regimes change, moving on to Allen Boyd Reynolds to account for collisions.

The Langmuir Probe is by far the best commercial Langmuir Probe on the market, with its ultra fast repeatable measurements. The inclusion of both a Single and Double Langmuir Probe in each system is evidence of Impedans commitment to its customers.

References

- Principles of Plasma Diagnostics, Hutchinson, Cambridge
- The Plasma Boundary of Magnetic Fusion Devices, Stangeby, IoP

Assignment

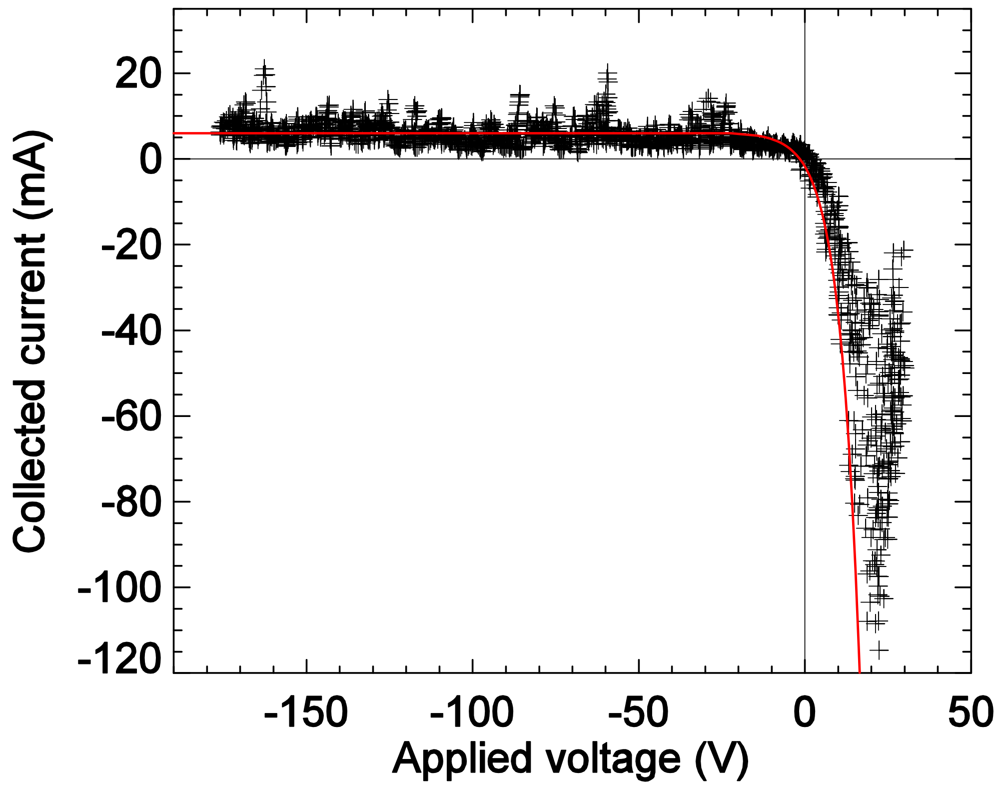
I - V characteristic

$$I = I_{sat}\left(1 - e^{\frac{e(V_{bias}-V_f)}{kT_e}}\right)$$

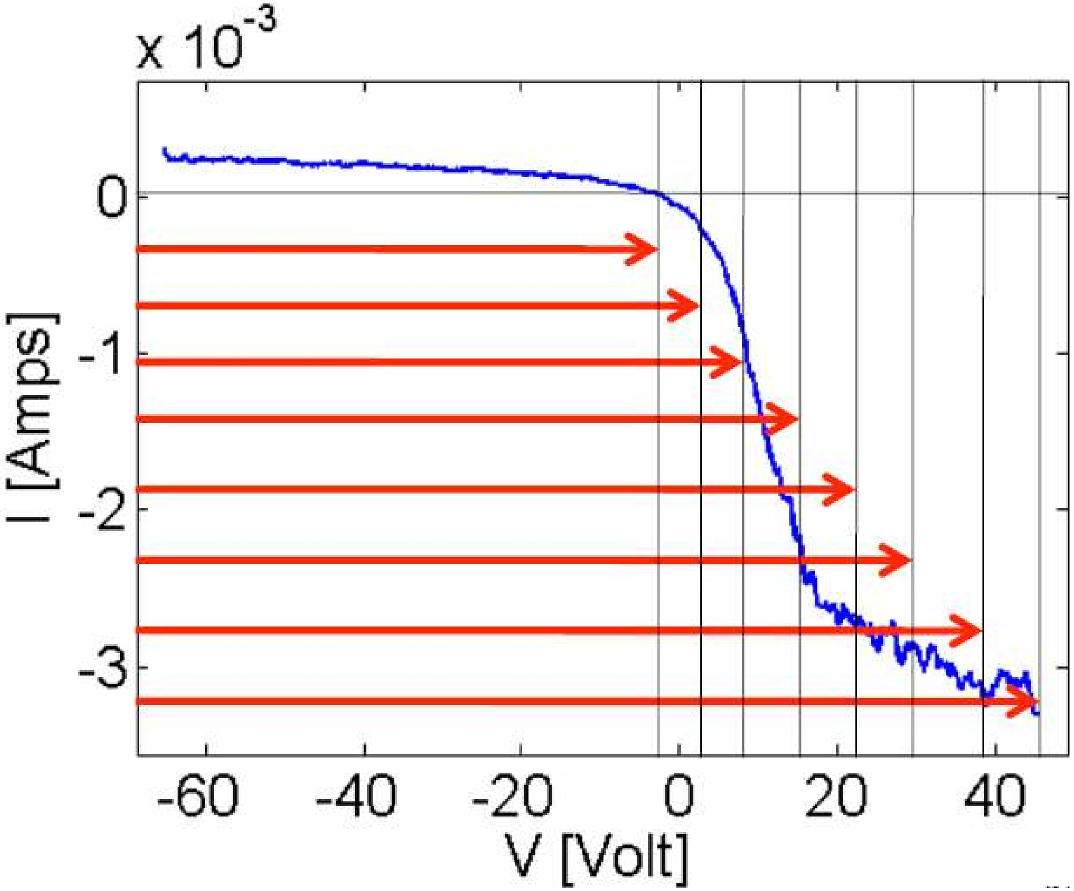
$$I_{sat} = 0.5eAnc_s$$

$$c_s = \sqrt{\frac{k(T_e + T_i)}{m_i}}$$

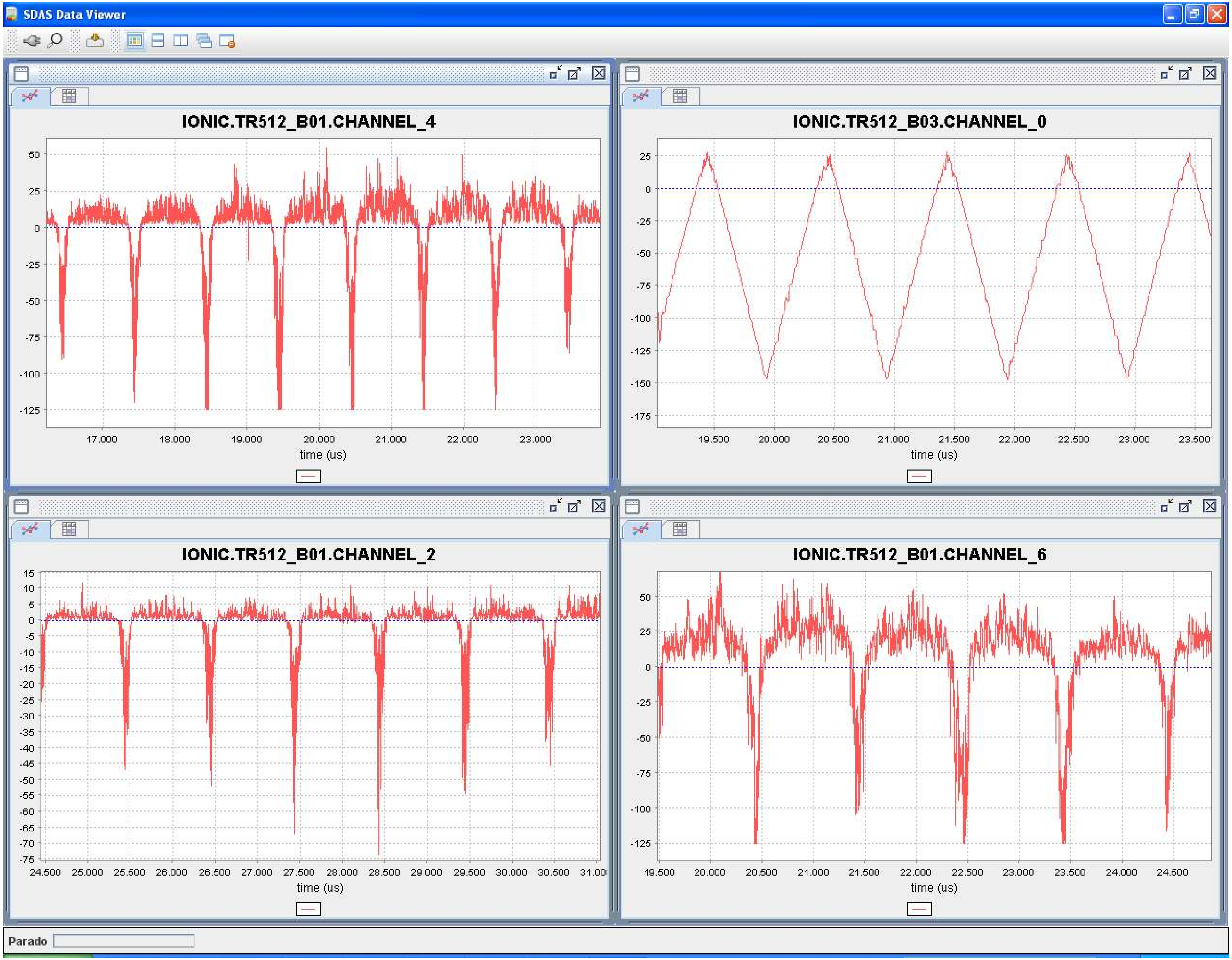
$$V_p = V_f + 3kT_e/e$$



- T_e, V_f and I_{sat} obtained from the I-V characteristic using a curve fit routine, then derive n, V_p
- Small uncertainties in I_{sat} but large for T_e (20%)



- Use different values for the cut-off voltage and study the variation in the fitted parameters
- Often real temperature corresponds to the minimum of T_e vs V_c



SDAS Data Viewer
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17.000 18.000 19.000 20.000 21.000 22.000 23.000
time (us)
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time (us)
Parado

Method

1. Study the effect of the cut-off voltage. Select 1-4 'clean' sweeps in a stable discharge period (statistics vs stationary). Number of data points not an issue, main problems related with plasma fluctuations (time scale ~0.1 - 1 ms)

2. Study the temporal evolution of the plasma parameters. Some I-V characteristics may not be valid

- ❑ Note signal saturation at ~250 mA
- ❑ No need to include the codes

Report

- 4 pages should be enough, no need for long theoretical introduction
- Justify different analysis steps and decisions
- Indicate analysis details (shot number, time interval, input parameters of the function used, …)
- Figures: Temporal evolution I, V; a few representative I-V characteristics with the respective fit; dependence on the cut-off voltage; temporal evolution of the plasma parameters
- Discuss uncertainties and fit quality
- Discussion between students most welcome but reports are individual! Different datasets available

- Should progress with the home work asap
- Additional lecture to follow the home work (clarifications) on Tuesdays 16:00 - 18:00
- Room V1.10 (October 11, 18 and 25)
- Clarifications, not a lecture
- Deadline, 12 October