Double probe measurements in nanodusty plasmas

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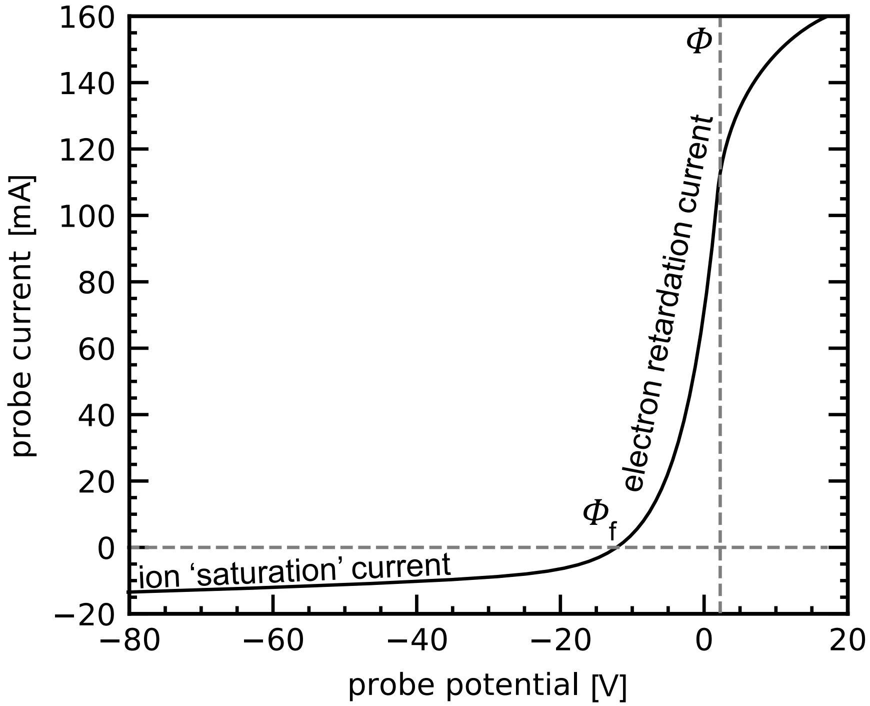
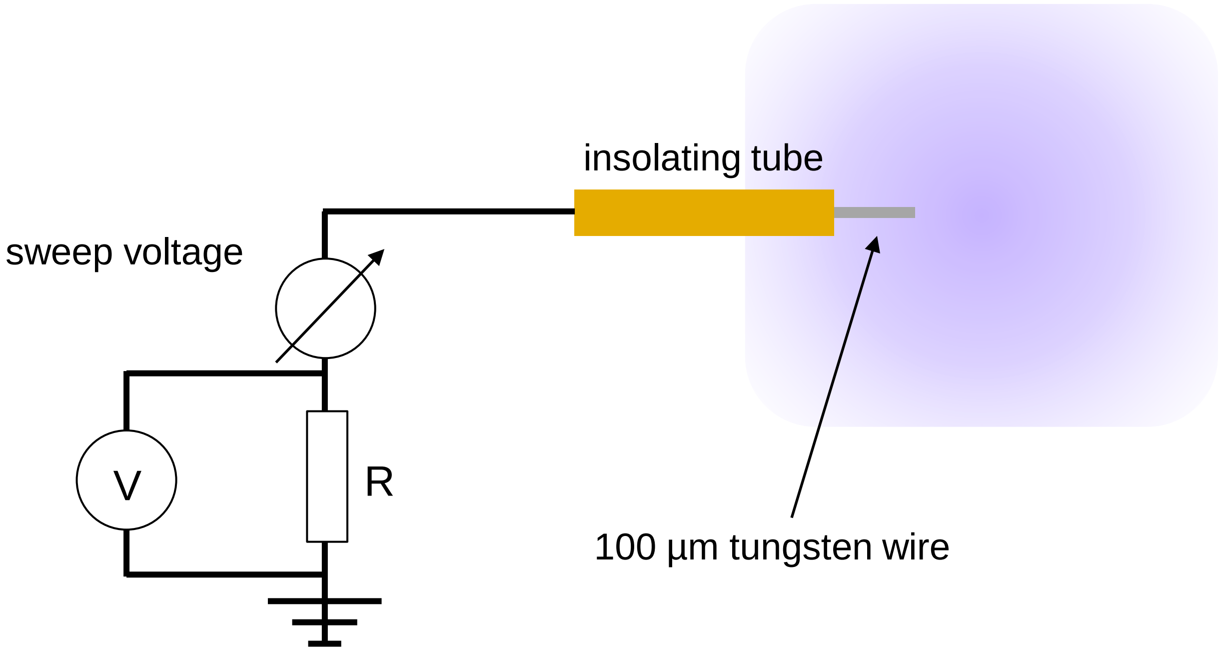
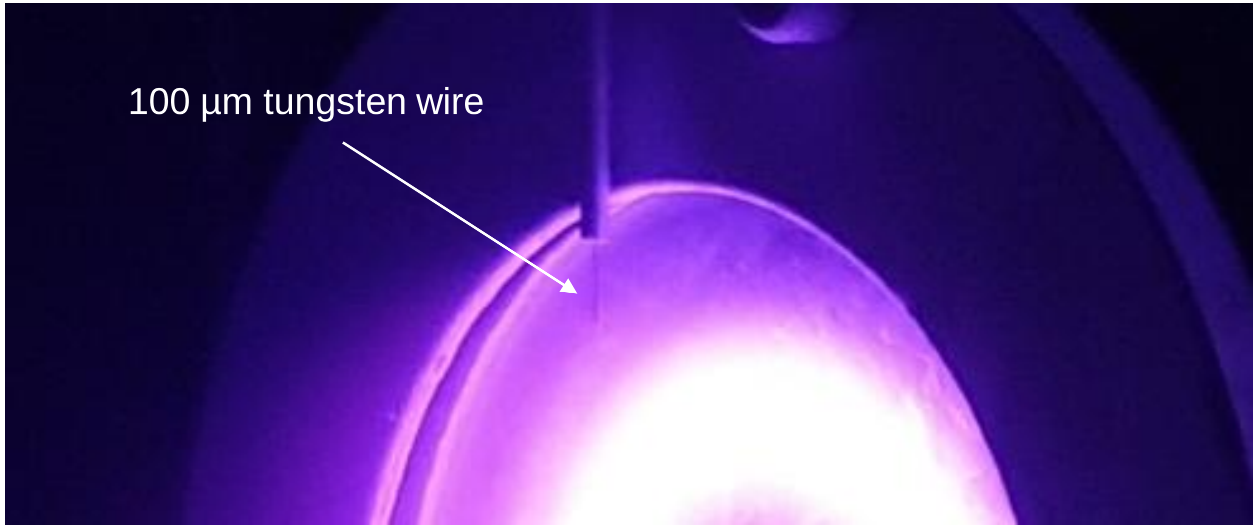
Introduction



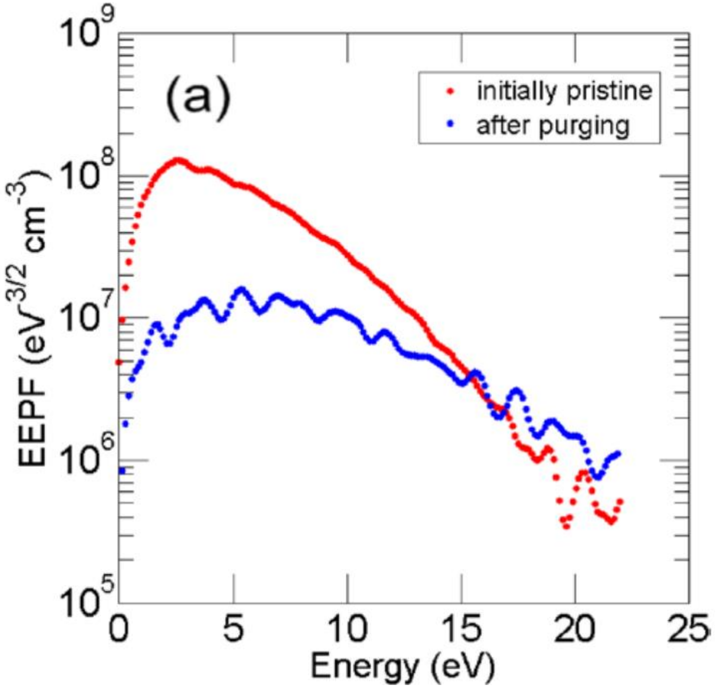




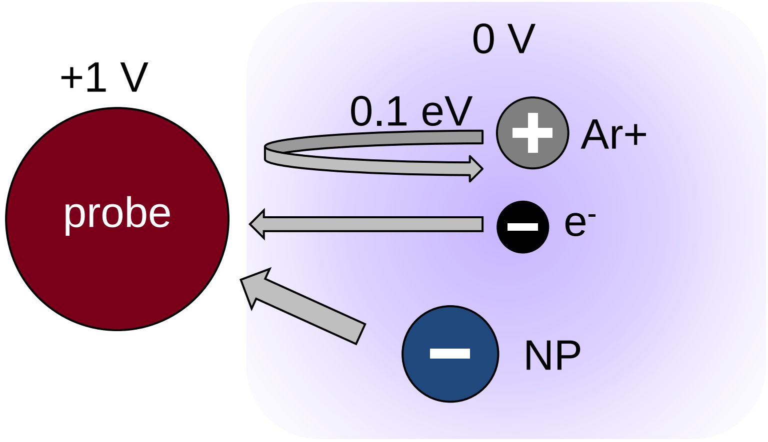
State-of-the-art single Langmuir probe analysis usually uses the Druyvesteyn equation to obtain the EEDF from the electron retardation current.

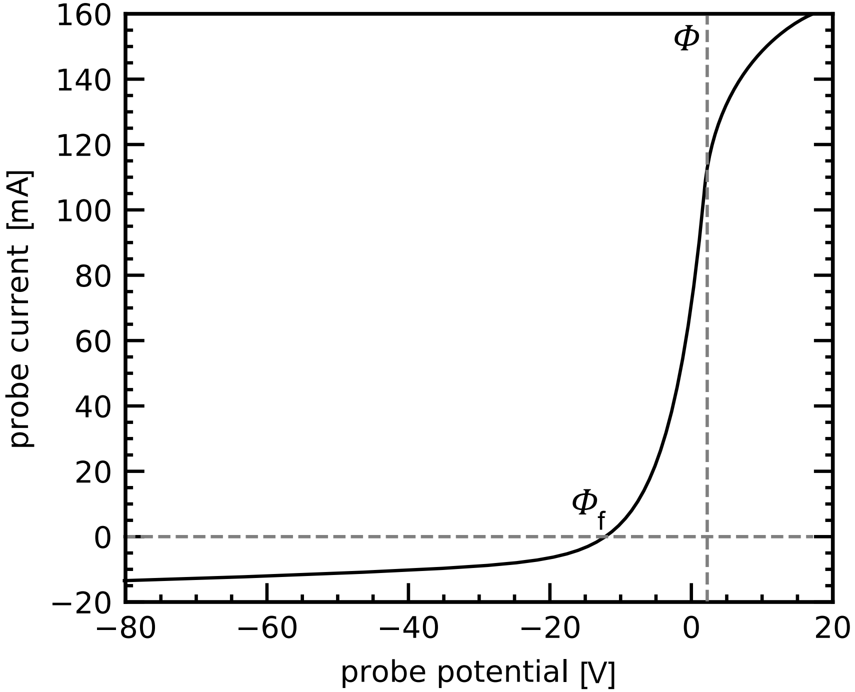
$$F_e(V) = \frac{2m_e}{e^2 A}\left(\frac{2eV}{m_e}\right)^{1/2}\frac{d^2 I_e}{dV^2}$$

Probes in dusty plasmas



Bilik et al, J. Phys. D: Appl. Phys. 48 (2015) 105204

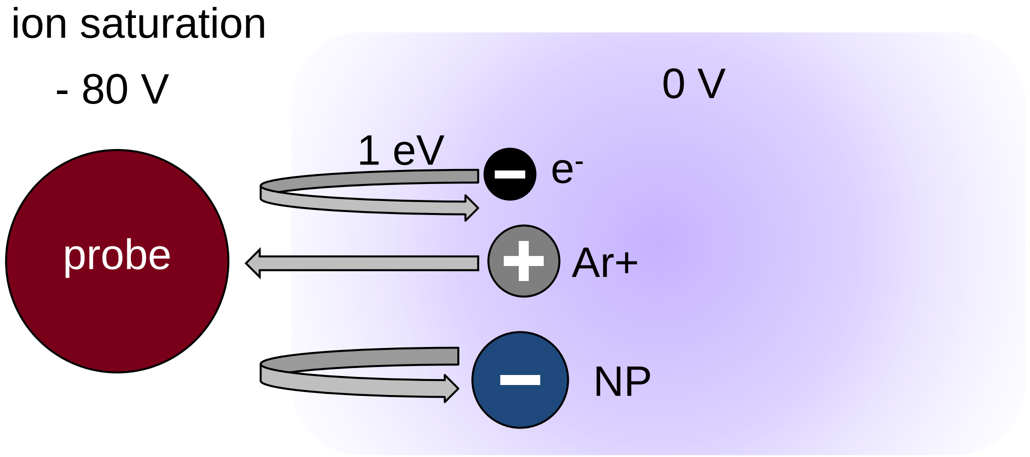


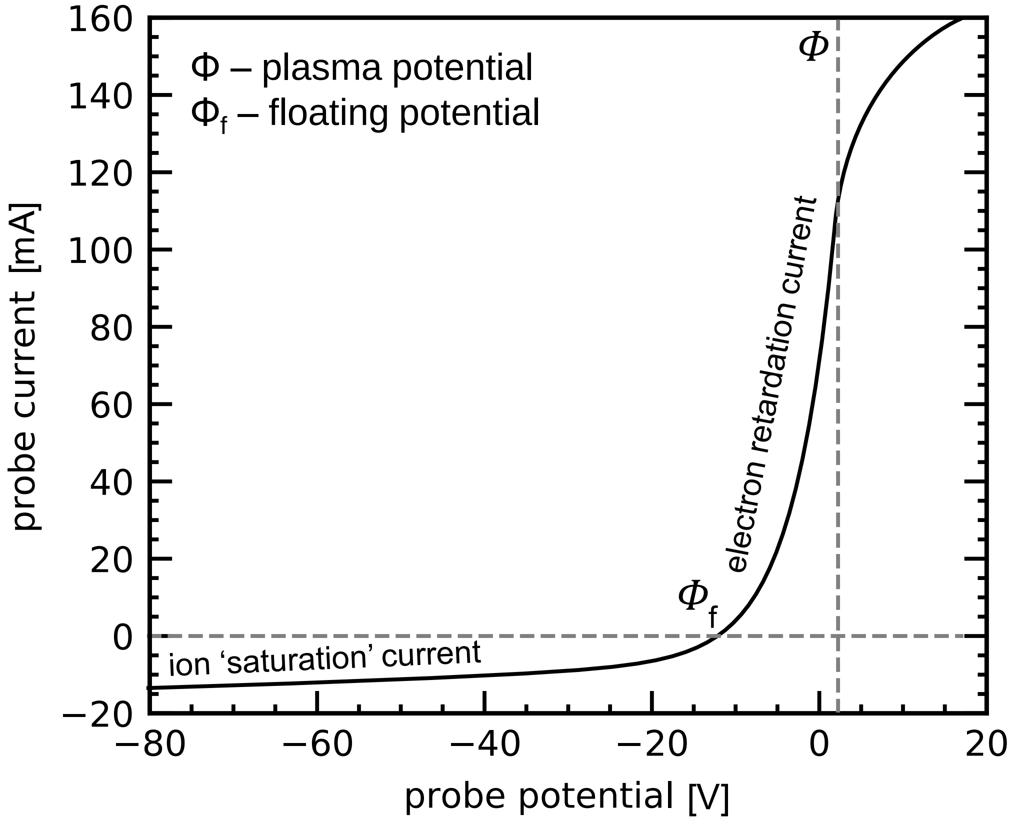


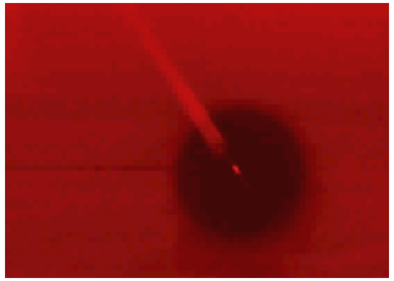
- Application of the Druyvesteyn equation requires voltage sweep across the plasma potential
- Voltages above the plasma potential attract NPs
- Exposure to dusty plasma contaminates the probe
- Probe becomes less conductive
  - less current, analysis impossible

Druyvesteyn approach not applicable to dusty plasmas.

Ion saturation current



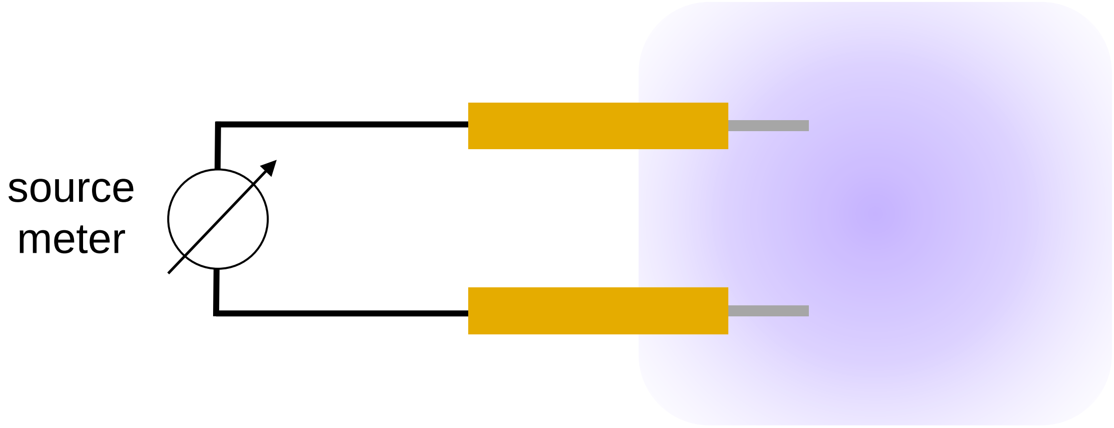


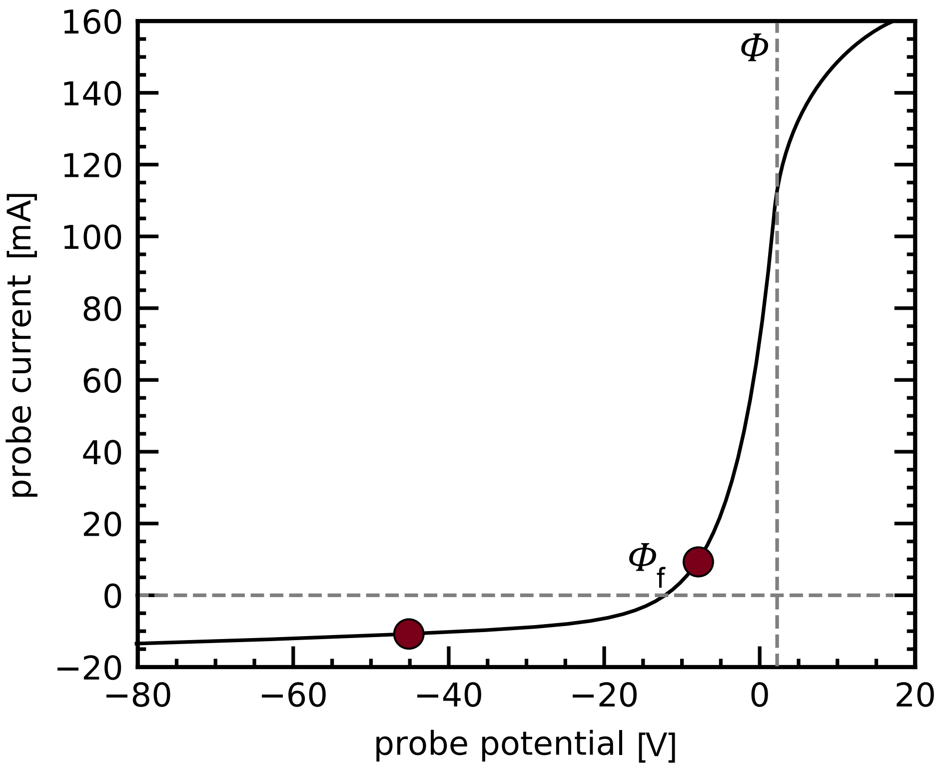


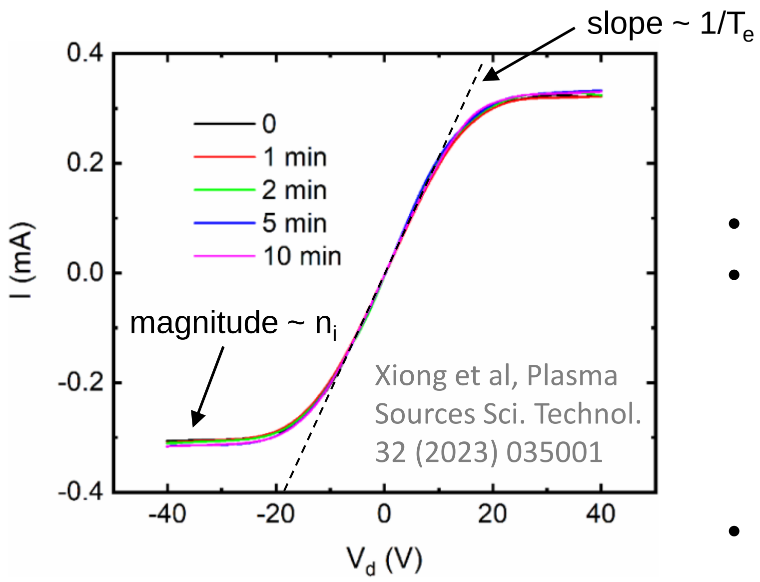
- If the probe remains negative compared to the plasma, nanoparticles are repelled
- Creates a void around the probe

Ion saturation part of the I-V characteristic suitable for dusty plasmas.

Double probe







- Two probes with voltage between them
- No net current from plasma:
  - $I_1 + I_2 = 0$
  - One probe draws ion current
  - The other electron current of same magnitude
- No need for RF compensation (arguably)

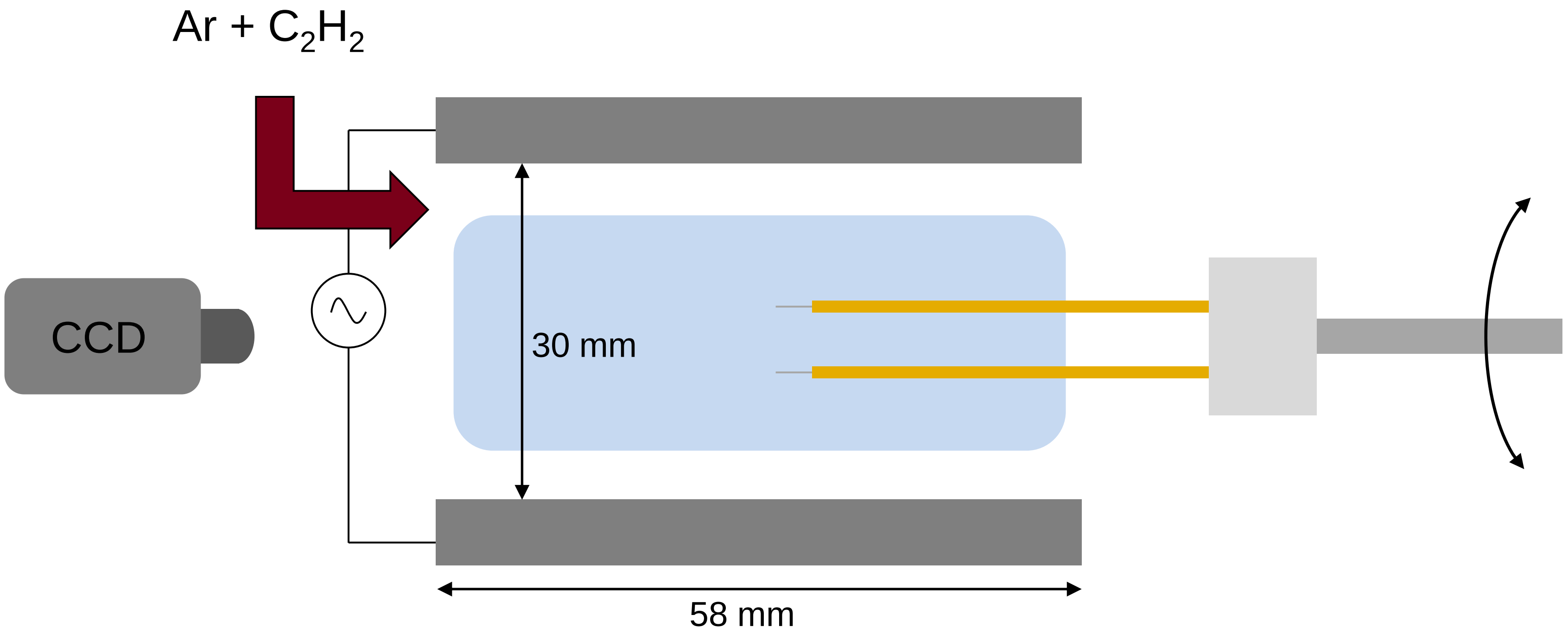
One probe will adjust slightly above the floating potential, the other is much more negative ➔ probes ion saturation current.

Are double probe measurements suitable for dusty plasmas?

PART I

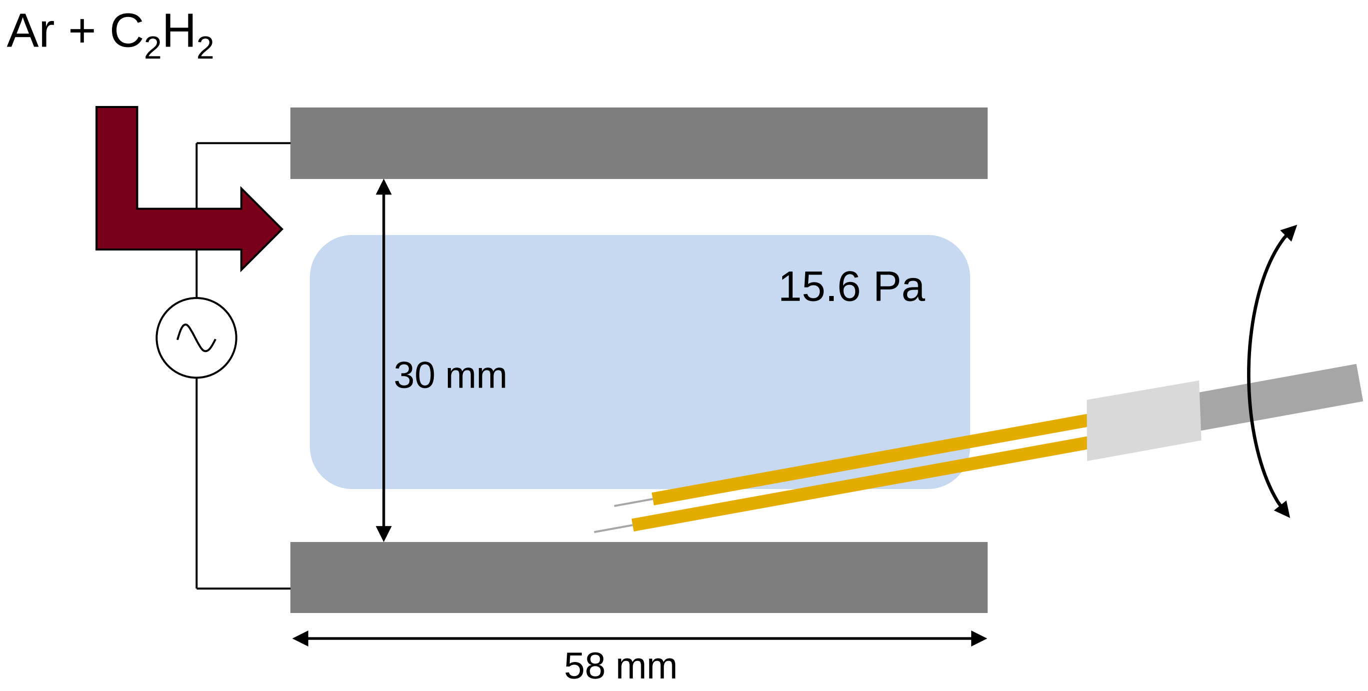
Practical Challenges

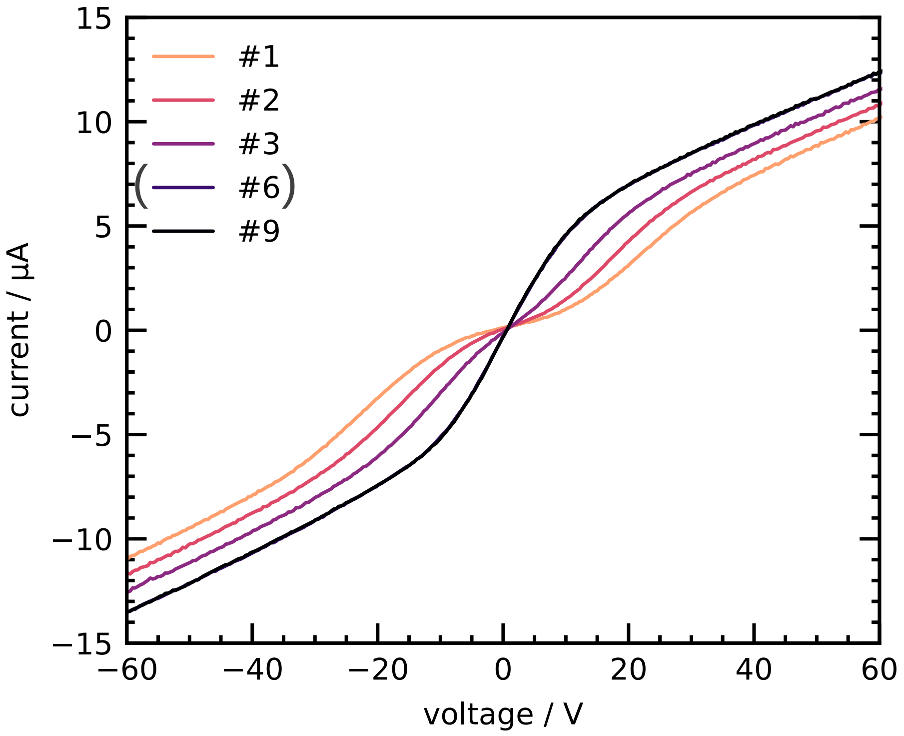
Experimental setup



- Particle growth from Ar-C_2H_2 mixture to 200 nm diameter particles
- Then: C_2H_2 switched off for measurements
- Probe: 50 µm diameter, 4.2 mm length, 7 mm distance

Probe contamination



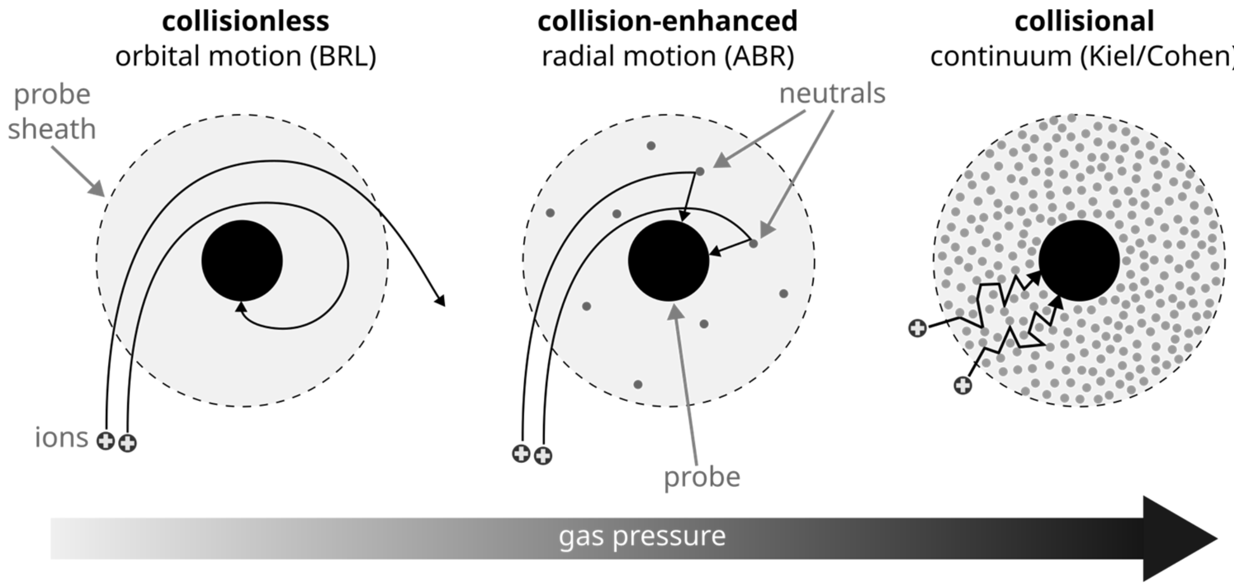


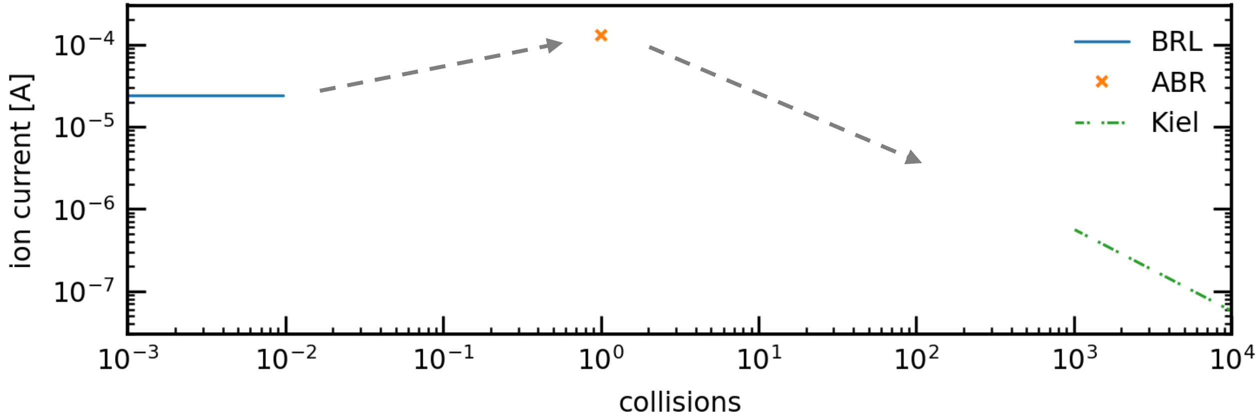
- Need to prevent probe contamination during nucleation/coagulation phase
- Here: ‘hiding’ the probe in the sheath

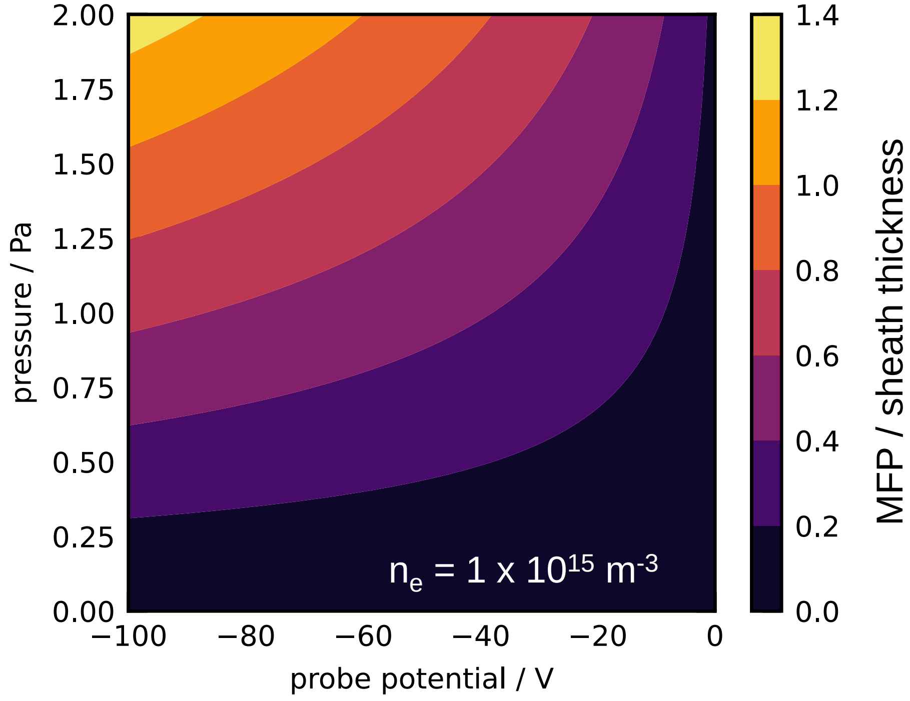
- Repeated measurements can clean remaining contamination
- Measurements are *very* easy (experimentally)

PART II
Analysis

Ion current and collisions

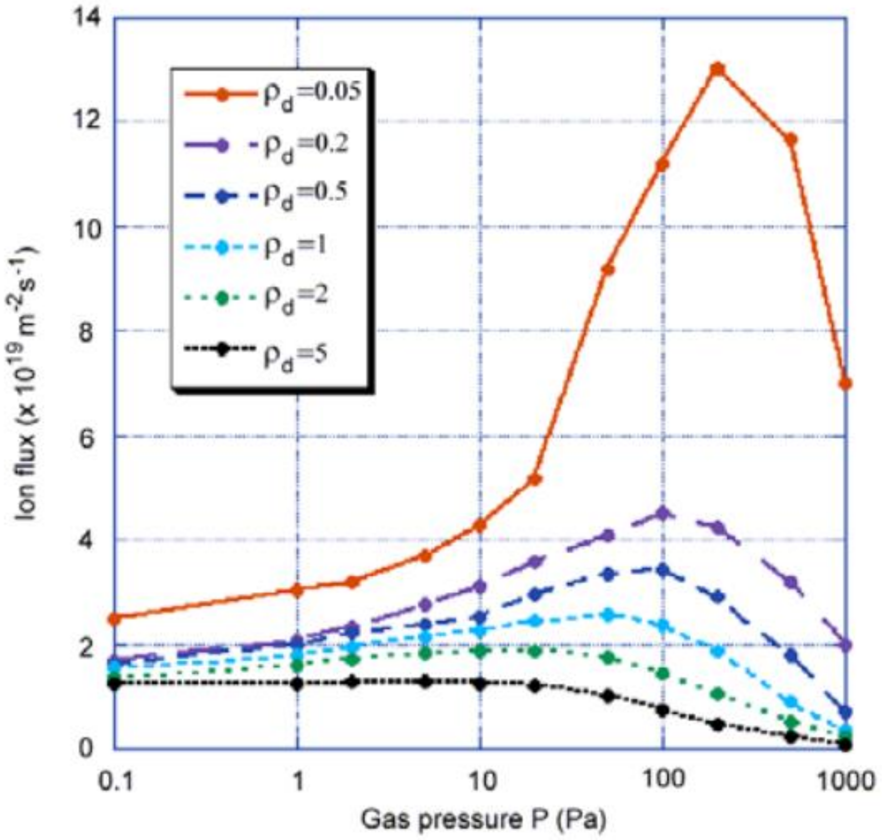




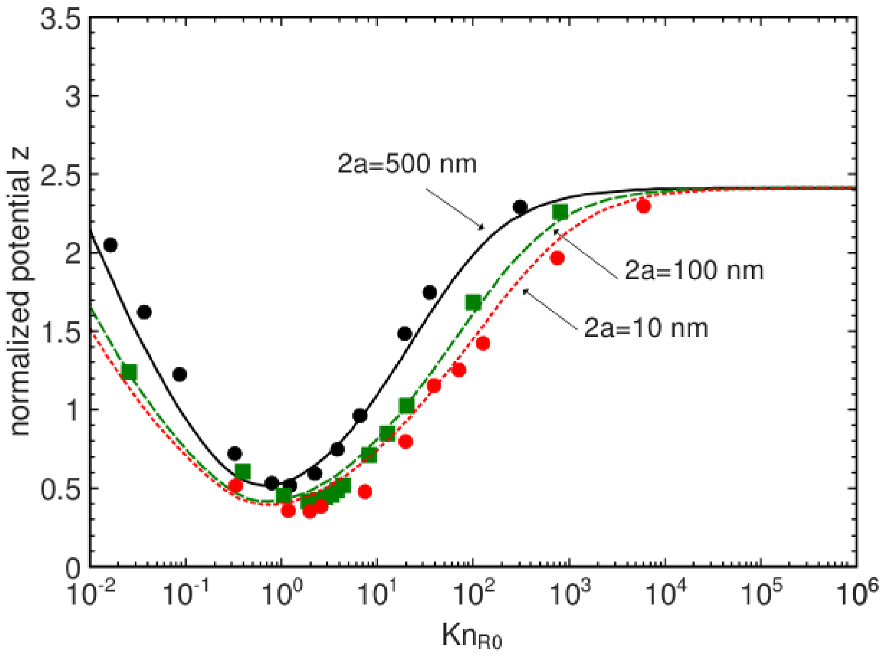


- Ion collection by probes is a complex and depends on the collision frequency.
- The collisionless case is very well described by theory, but almost never applicable.
- At intermediate pressure, the angular momentum of ions is destroyed by collisions and the current *increases*.
- At high pressure, ion mobility is lowered and the current *decreases*.

Dust charging



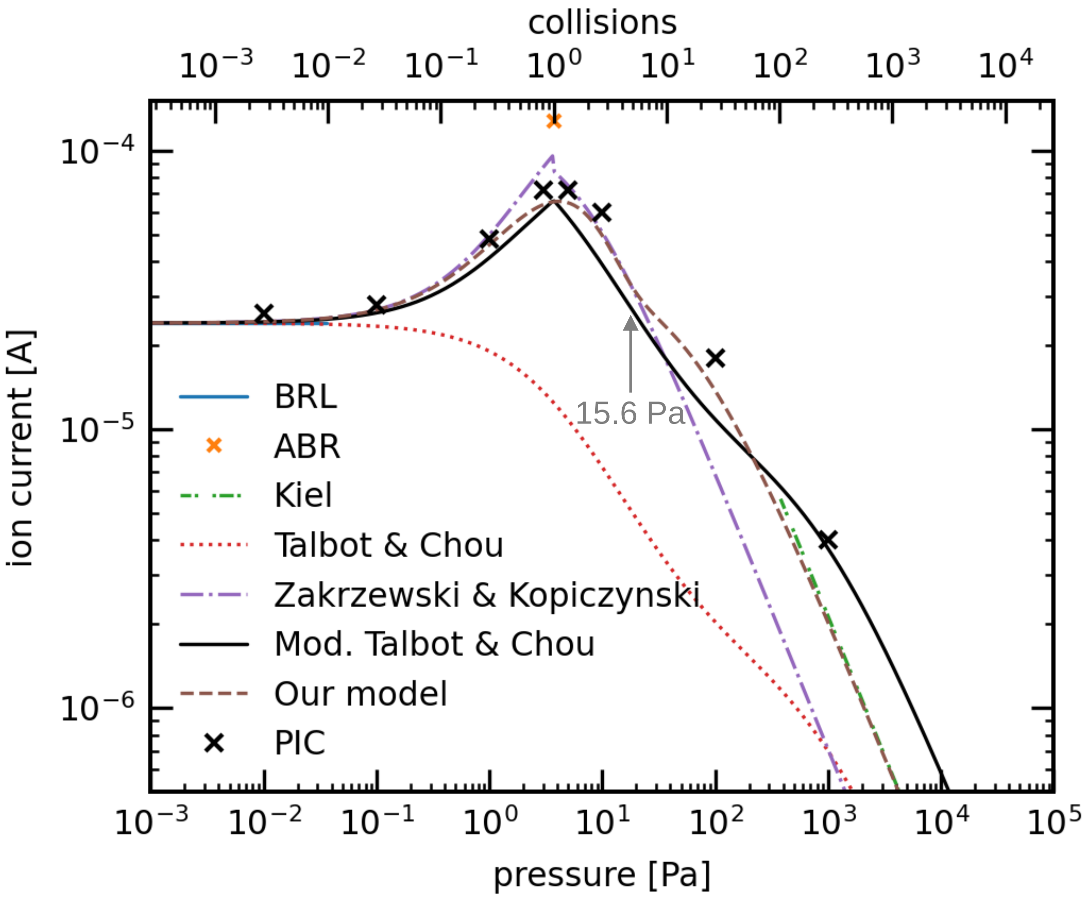
Taccogna: Contrib. Plasma Phys. 52 (2012) 744



Gatti & Kortshagen: Phys. Rev. E 78, 046402 (2008)

- Same situation as for the charging of dust particles
- Probes are more difficult:
  - Cylindrical system
  - Larger size

Models for collisional ion currents



Mod. Talbot & Chou:
Tichy et al: Contrib. Plasma Phys. 34 (1994), 59-68

Models for pressure-dependent ion currents are available, but:

- Difficult to use, especially with double probes
- Unknown accuracy
- Do not consider dust

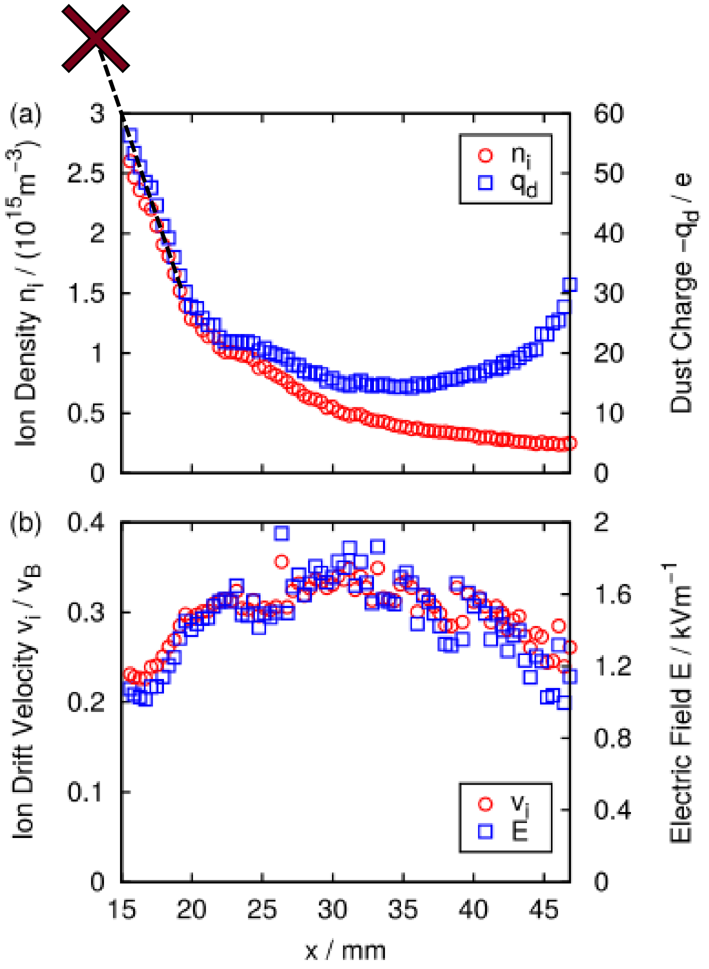
Here: modified Talbot & Chou theory (Contrib. Plasma Phys. 34 (1994), 59-68)

$$\left.\begin{aligned} &I_1 + I_2 = 0 \quad V_1 + V_2 = V_D \\ &I_1 = -I_2 = I \\ &I_1 = I_{e,1}(V_1, n_e, T_e) - I_{i,1}(V_1, n_i, T_e) \\ &I_2 = I_{e,2}(V_2, n_e, T_e) - I_{i,2}(V_2, n_i, T_e) \end{aligned}\right\}$$

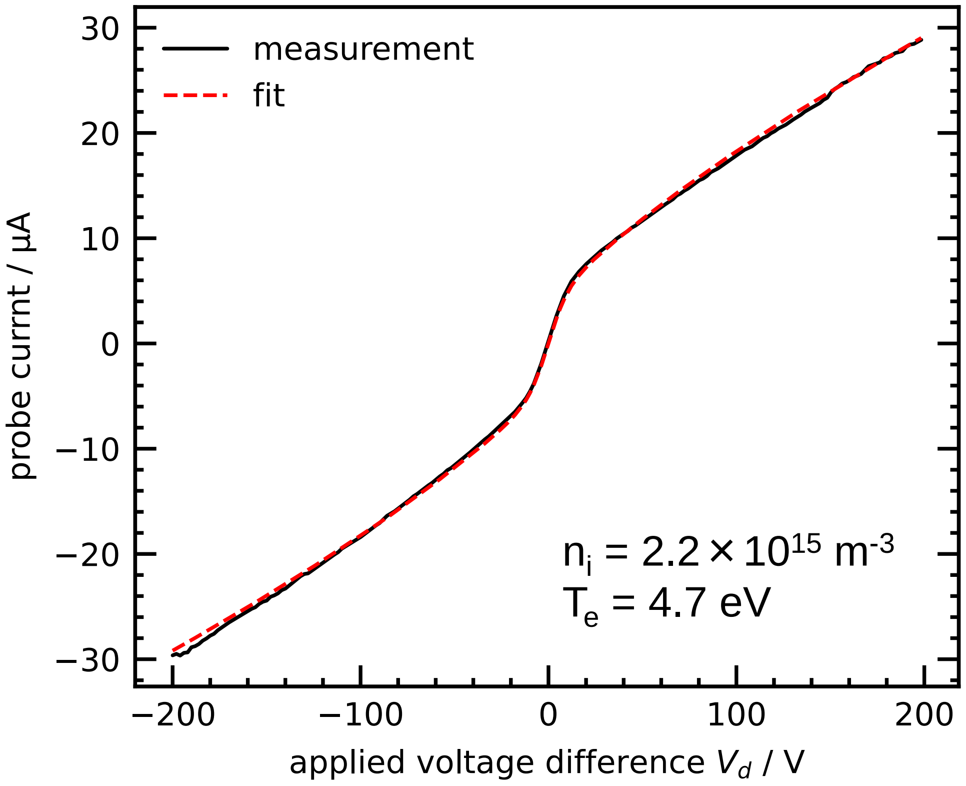
solved numerically and fit to the data

Will this produce at least approximate results?

Results



Tadsen et al, Physics of Plasmas, 22, 113701 (2015)



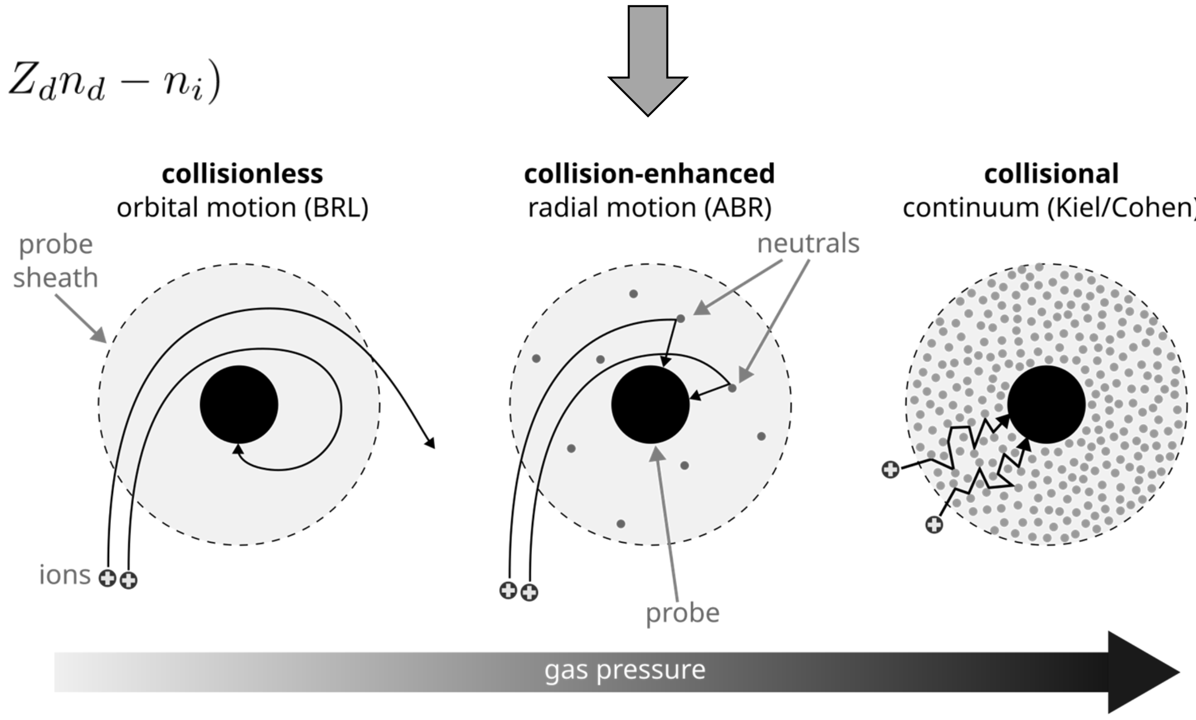
- Fairly good agreement.
- Probe underestimates density by about a factor of 2.

Measurements (seemingly) produce approximate results without considering dust in the probe analysis.

Dusty ABR

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \Phi}{\partial r}\right) = \frac{e}{\epsilon_0}(n_e - n_i) \quad \Rightarrow \quad \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \Phi}{\partial r}\right) = \frac{e}{\epsilon_0}(n_e + Z_d n_d - n_i)$$

$$\boxed{n_e = n_0 \exp\left(\frac{e\Phi}{k_B T_e}\right)} \qquad \boxed{n_i = \frac{I}{2\pi r}\left(-\frac{2e\Phi}{m_i}\right)^{-1/2}}$$



Dust density

$$m_d n_d \left(\frac{\partial v_x}{\partial t} + (v \cdot \nabla) v_x\right) = e n_d E_x - \frac{\partial p}{\partial x}$$

$$\boxed{\frac{\partial p}{\partial r} = e Z_d n_d \frac{\partial \Phi}{\partial r}}$$

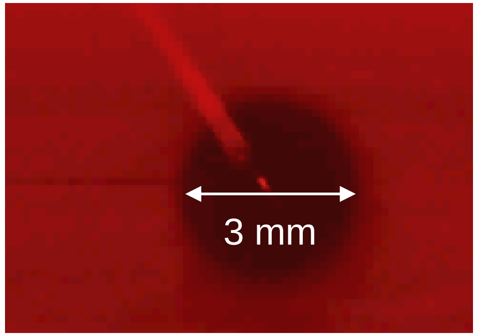
$$p_d = n_d k_B T_d + n_d k_B \left(\frac{T_e T_i}{T_e + T_i}\right)\left(\frac{Z_d^2 n_d}{n_e + n_i}\right)$$

Fisher et al: Phys. Rev. E 88, 031101(R) (2013)

$$\boxed{n_d = -k_B T_d \alpha + \alpha\sqrt{(k_B T_d)^2 + 2p_d/\alpha}} \qquad \alpha = \frac{1}{2}\left(\frac{T_e + T_i}{T_e T_i}\right)\left(\frac{n_e + n_i}{Z_d^2}\right)$$

This allows us to calculate the dust density as an additional species in the sheath model.

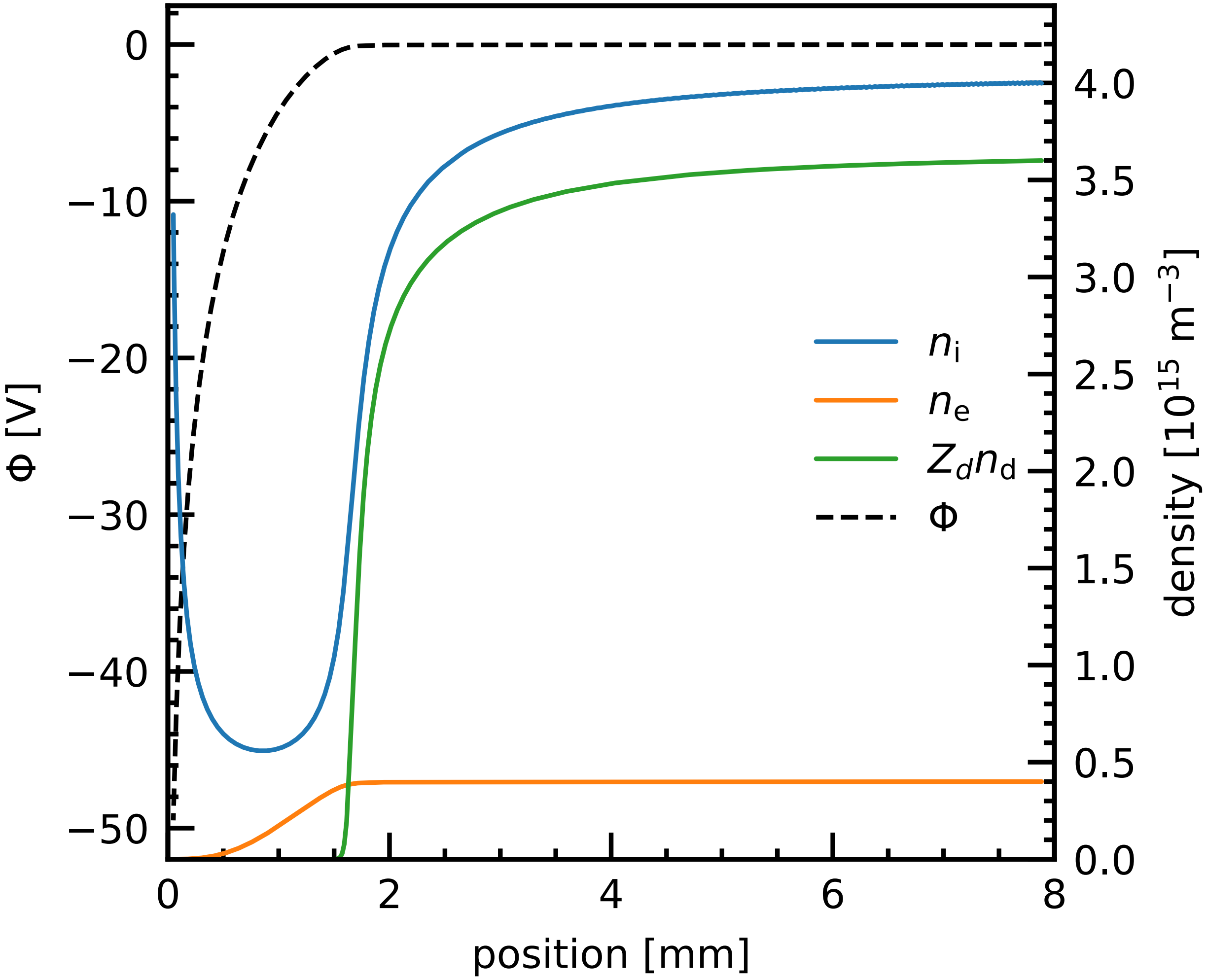
Dusty ABR



n_0 = 4x10^{15} m^{-3}
T_e = 5 eV

n_d = 6x10^{13} m^{-3}
Z_d = 60
T_d = 3 eV
T_i = 0.05 eV

$Z_d\, n_d / n_0 = 0.9$



Reproducing the small void radius observed in the experiment (~1.5 mm @ 50 V) requires high dust temperature (T_d = 3 eV).

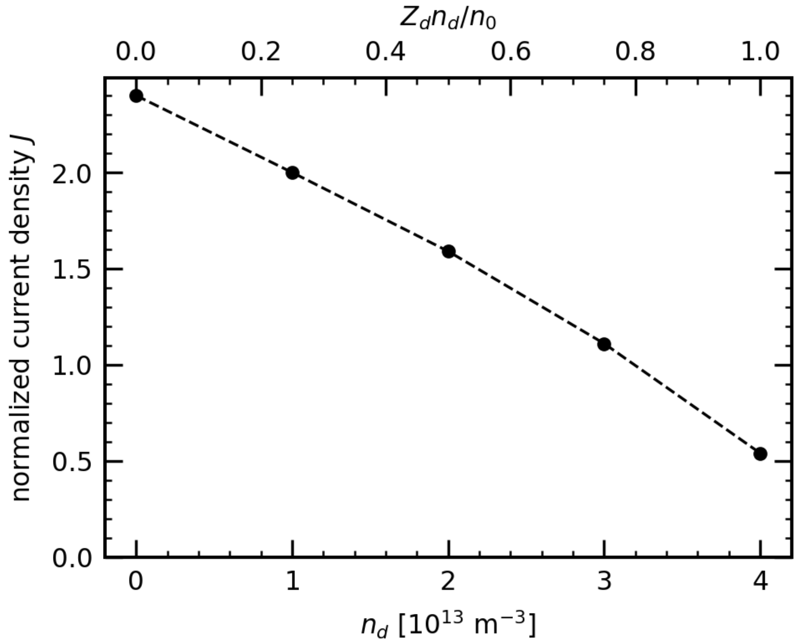
- Might be missing influence of ion drag force.
- *This might not even matter.*

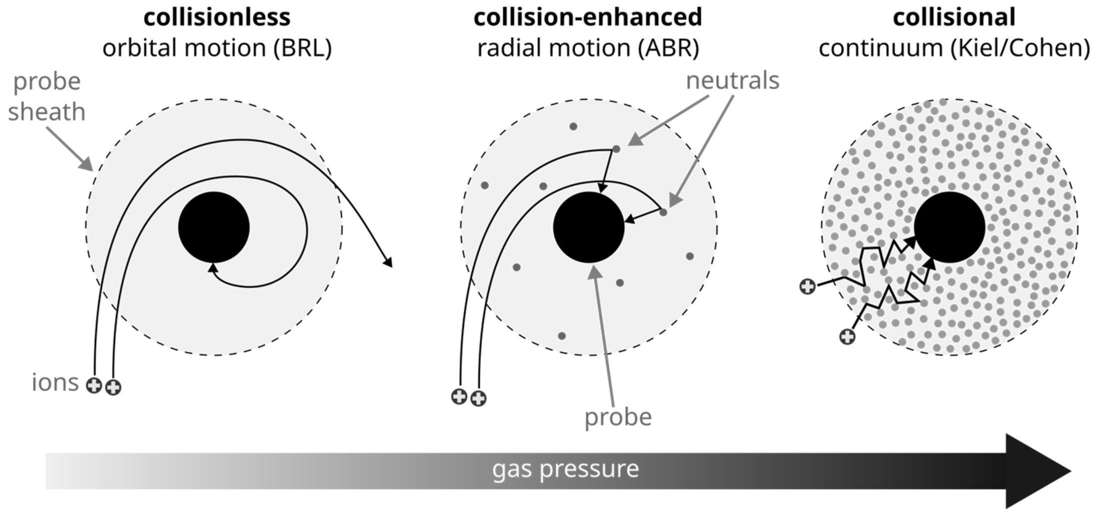
Dusty ABR

- Impact of the dust on the collected current is significant, but not huge.
- Dust leads to density *underestimation* up to a factor of 4 *for ABR*.
- Uncertainty of ion collecting probes is already similar, we still hit the right order of magnitude.
- This is the reason why the measurements *appear* to work!

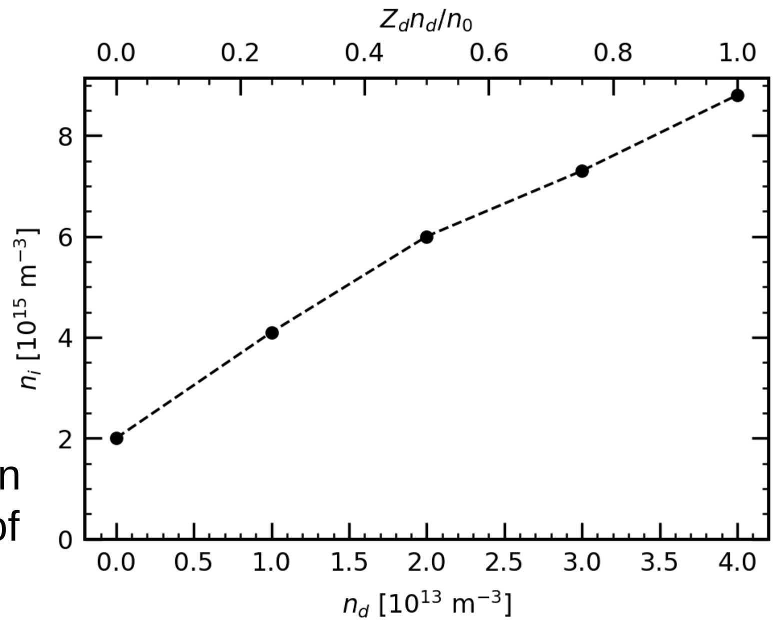
n_0 = 2x10^{15} m^{-3}
T_e = 3 eV

Z_d = 50
T_d = 1.00 eV
T_i = 0.03 eV



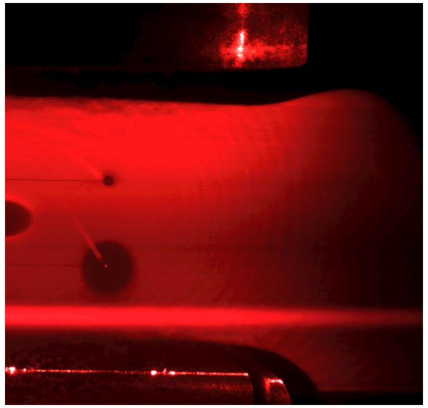


Real density, for an *apparent density* of n_0 = 2x10^{15} m^{-3}

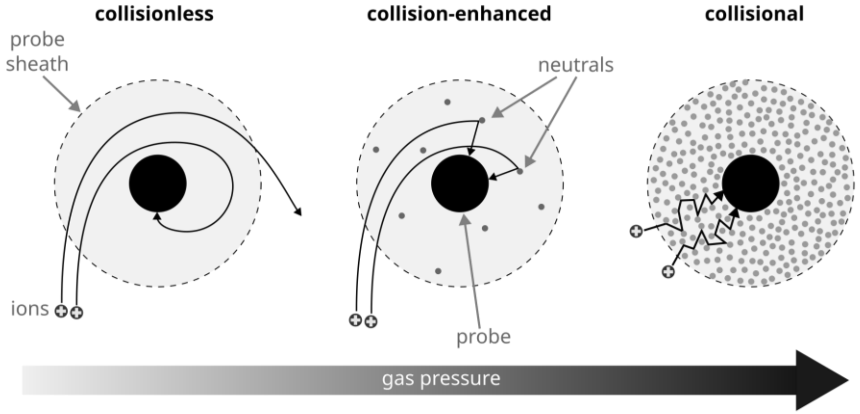


Conclusion

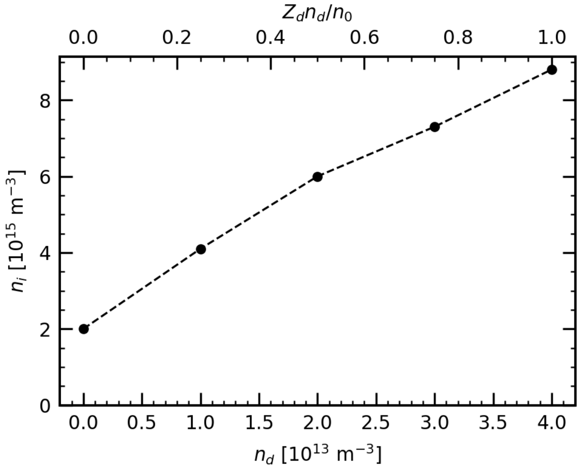
Supported by the DOE directly (DE-SC0024479, DE-SC0022242) and via the PCRF (Contract No. DE AC02-09CH11466).



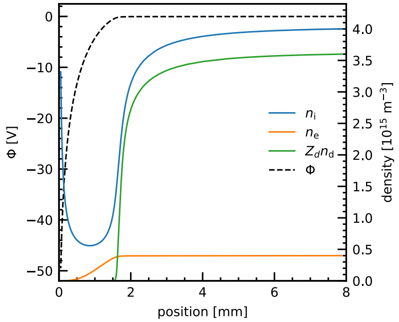
Probe measurements in dusty plasmas are experimentally easy but require us to rely on the ion current part of the probe characteristic.



Under basically all relevant pressure conditions, collisional probe theory has to be employed. However, available theories are not very good.



The presence of dust leads to an underestimation of the ion density.



Using modified probe theory and images of the void size around the probe, reliable double probe measurements should be possible.

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Thank you for listening!

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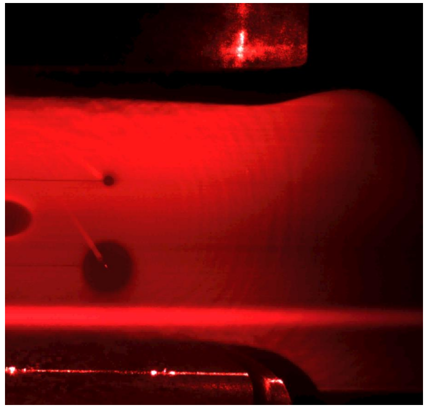

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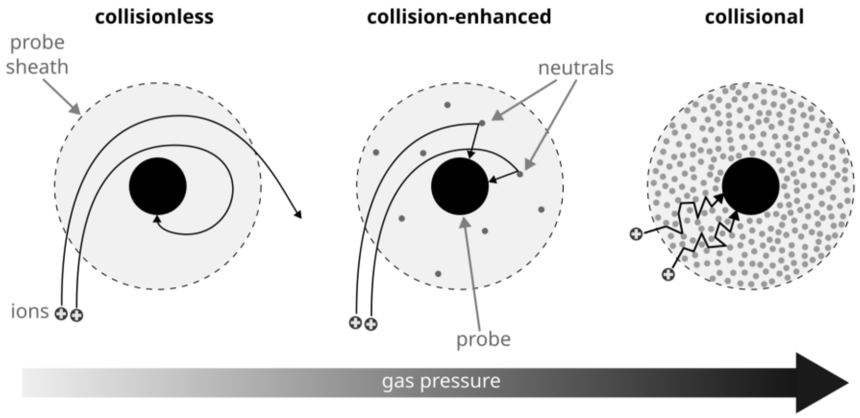

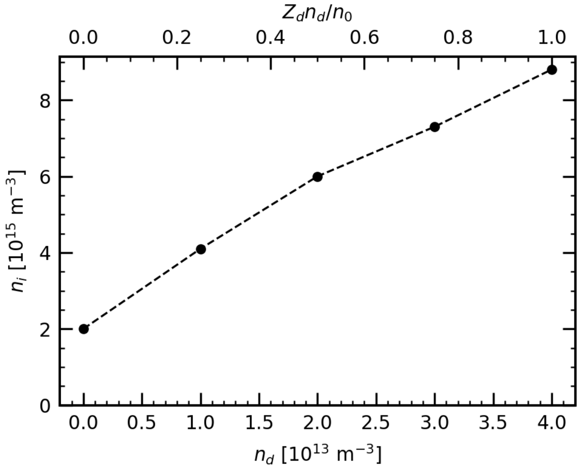

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