Correction des effets de gaine pour la mesure de la densité des électrons par sonde micro-onde

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Presentation outline

1. Introduction and context
2. The correction algorithm
   a) The plasma-wall structure model
   b) Emitted EM field of the probe
3. Experimental assessment
   a) Unmagnetized ICP source
   b) Weakly-magnetized plasma thruster
4. Conclusion and discussion

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A sheath correction method for electron density measurements with the microwave resonant curling probe

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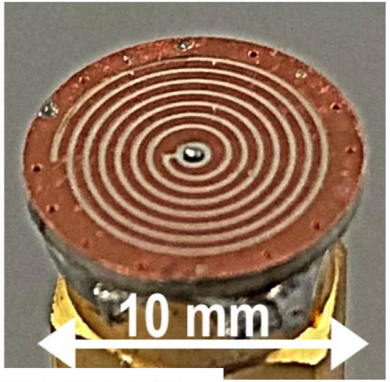
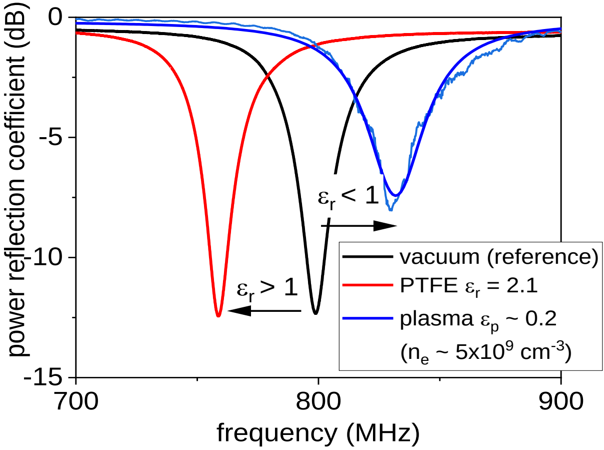
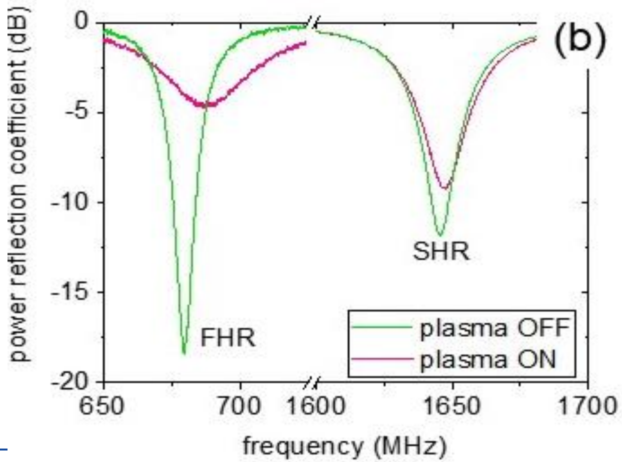
The microwave resonant curling probe

- Previous studies [Liang2011, Arshadi2017,Ogawa2020]
- **Principle**
  - Excitation with microwaves ~ GHz / ~mW
  - Resonance frequency f_r depends on ϵ_r of medium in contact with probe
  - Absolute calibration of the probe response $n_e \propto \Delta f$ (valid in collisionless and weakly-magnetized plasmas) [Boni2021, Boni2023]
  - Use of second harmonic (SHR) to extend the measurable density range

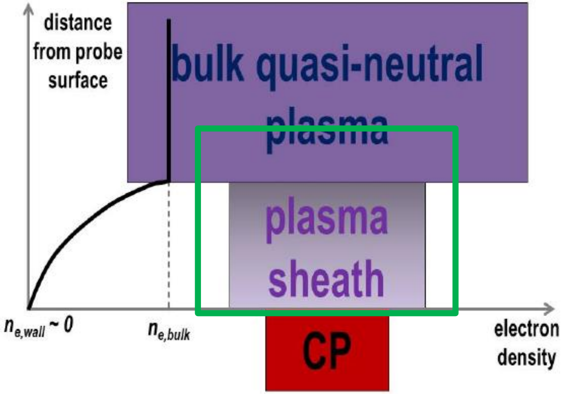


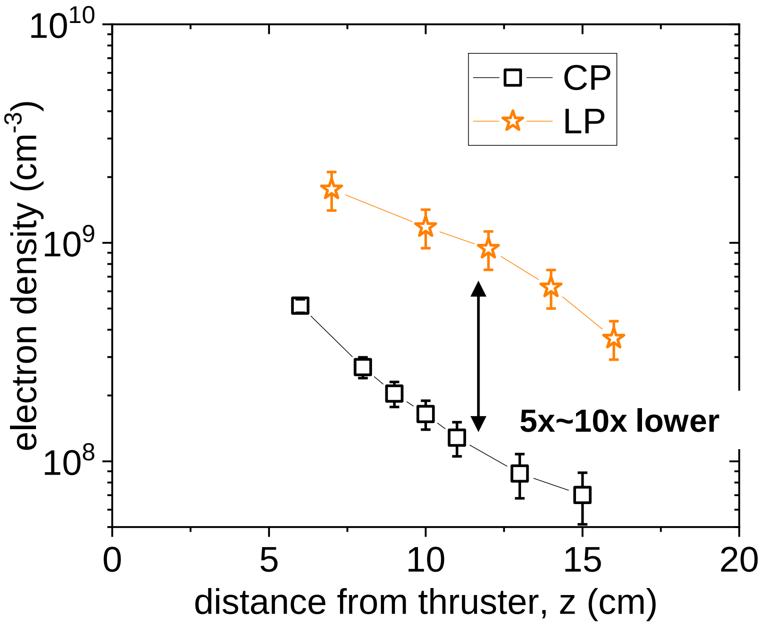




Problem statement

- *In-situ* measurement
- Probe electrically floating
- Formation of an (electron-depleted) sheath around the probe
- Underestimation of the measured electron density

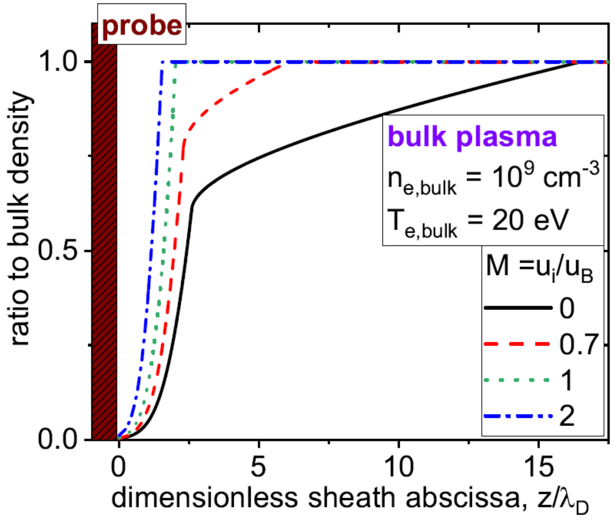




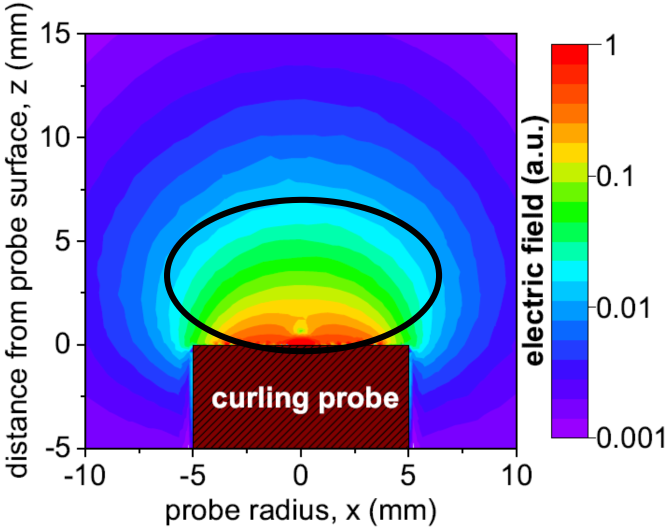
- **Sheath perturbation not negligible** when **sheaths** are **thick** compared to probed volume from CP
- **Underestimation** of raw measured density up to **90%** (worst case)

How to mitigate plasma sheath effects?

Electron density profile due to plasma-wall interaction



The characteristic decay length (~ mm) of the EM field emitted by the CP



Development of a plasma sheath correction method

The plasma-wall structure model

Main characteristics of the plasma-probe environment

- Electron densities 10^8-10^{11} cm^{-3}
- Electron temperatures 5-30 eV
- Possibility to account for subsonic or supersonic ions
- CP electrically floating

λ_D = 50 µm – 4 mm

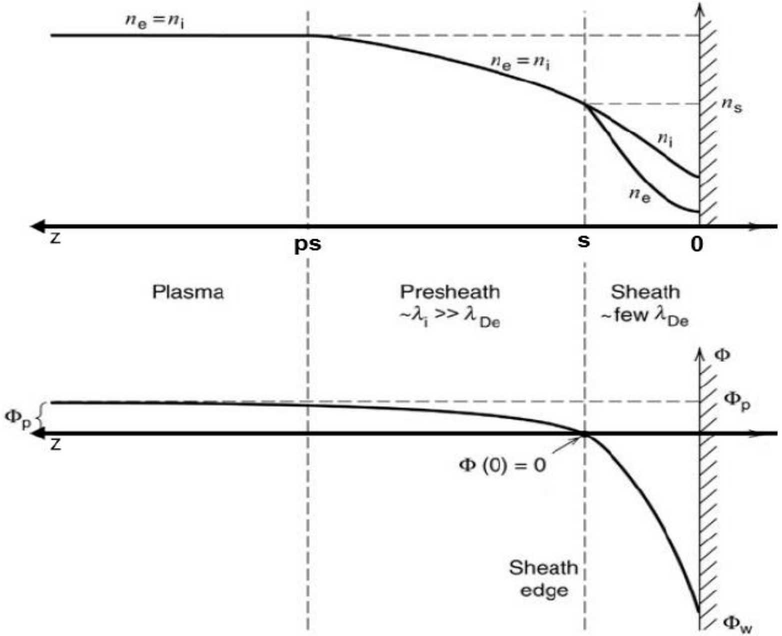
Hypothesis of the model

- 1D
- Collisionless and weakly-magnetized
- Maxwellian electrons (bulk+sheath = $T_{e,bulk}$)
- Singly charged ions with T_i=0
- Ion velocity drives sheath formation
- SEE neglected
- Bohm criterion respected [Bohm1949]

$\rightarrow \boldsymbol{M_i = u_i/c_s < 1}$**: bulk plasma – presheath + sheath – wall**

$\rightarrow \boldsymbol{M_i = u_i/c_s > 1}$**: bulk plasma – sheath – wall**

$$\boldsymbol{c_s = \sqrt{\frac{eT_e}{M_i}}}$$



[Lieberman2005]

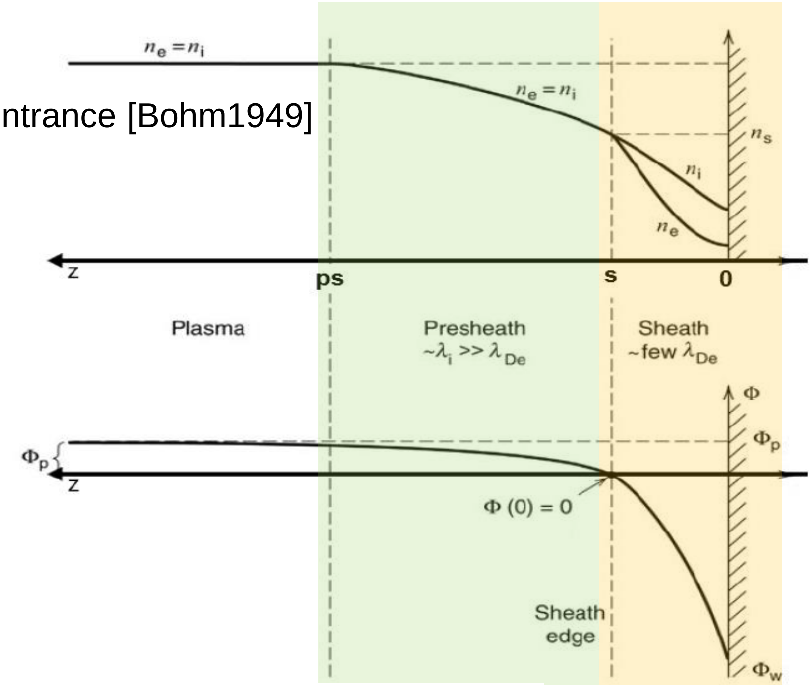
The presheath region

When $\mathbf{M_i} = \boldsymbol{u_i/c_s}$ <1 in the bulk plasma → presheath

Acceleration region in which ions reach sound speed at the sheath entrance [Bohm1949]

- Quasi-neutral region, modeled according to [Riemann1991] scales with ion-neutral mean free path → $\lambda_i \propto 1/p$
- Potential drop → $\boldsymbol{\frac{\Delta\phi_{ps}}{T_e} = -\frac{1}{2}\left(1 - M^2\right)}$
- Density drop → $\boldsymbol{\alpha_{ps} = \frac{n_s}{n_b} = e^{\left[-\frac{1}{2}\left(1-M^2\right)\right]}}$
- If M$_i$=0 → $\Delta\phi_{ps} = T_e/2$ and $\alpha_{ps} = 0{,}61$ [Lieberman2005]

Presheath effect accounted for through presheath/sheath density drop $\boldsymbol{\alpha_{ps}}$



Presheath [Riemann1991]

Sheath [Lieberman2005]

The sheath region

- Electrostatic potential equation (Poisson + Maxwellian electrons + conservation of ion flux [Lieberman2005])
- E field at sheath edge is non-zero [Godyak1990]
- $d\phi/dz$ numerically integrated to obtain $\phi(z)$
- **Solved for $n_b = 10^8 - 10^{11}$ cm^{-3}, $T_e = 1 - 50$ eV, $E_{ki} = 5 - 300$ eV → $0 \le M_i \le 10$**

$$\frac{d\Phi}{dz}(z) = -\sqrt{\frac{2en_s}{\epsilon_0}\left\{k_B T_e\left(\exp\left(\frac{e\Phi(z)}{k_B T_e}\right)-1\right)+2E_{ki}\left(\sqrt{1-\frac{e\Phi(z)}{E_{ki}}}-1\right)\right\}} - \frac{k_B T_e}{e\lambda_D}$$

Sheath thickness is defined as the length over which a potential drop of modified ϕ_{wall} occurs

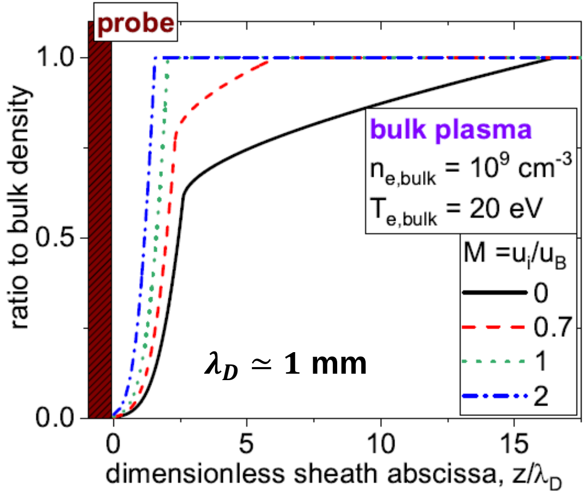
$$\phi_{wall} = k_B T_e \ln\frac{4u_s}{u_{el}}$$

Ion velocity at sheath edge $M_i \ge 0$

The dimensionless sheath thickness

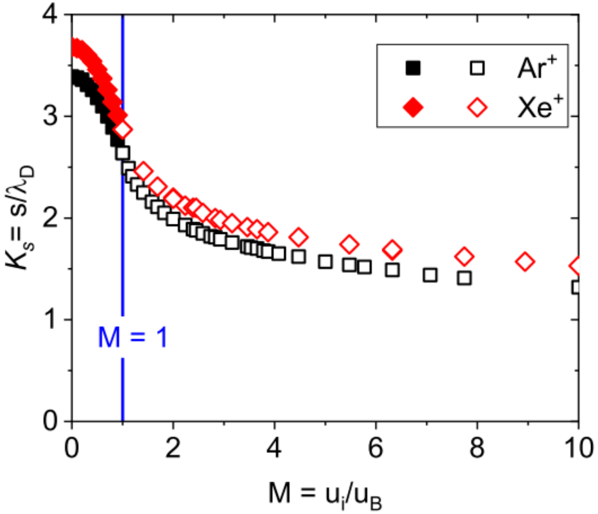
Dimensional sheath thickness (s)

- dependent upon bulk conditions (n_b, T_e, M_i) and gas
- For $M_i = 0$, thickness = $16\lambda_D$
- For $M_i = 2$, thickness = $1{,}6\lambda_D$



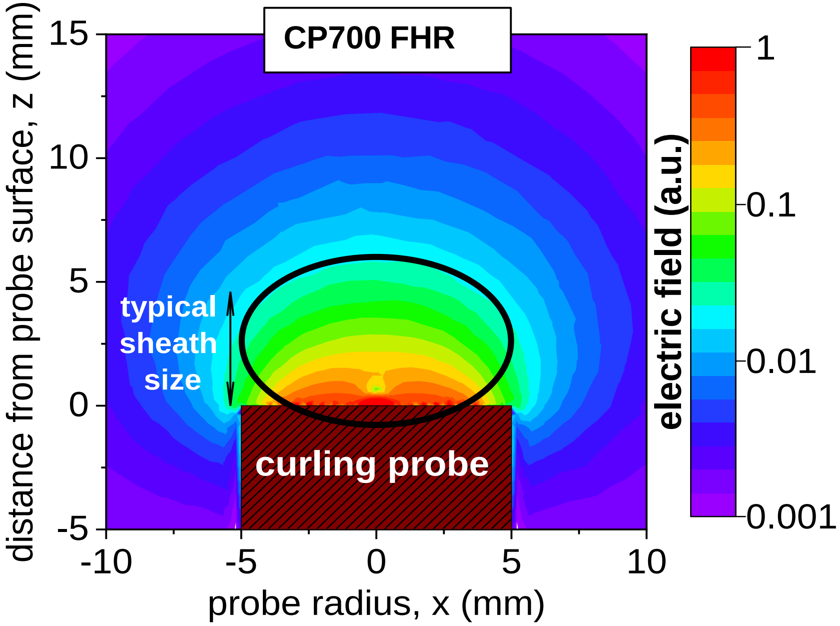
Dimensionless sheath thickness $K_s = \frac{s}{\lambda_D}$

- Only dependent upon M_i and gas
- Simpler use in the algorithm
- Does not include presheath width



Emitted EM field of the curling probe

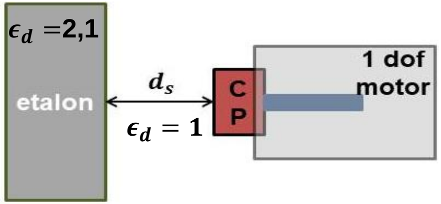
- 3D numerical simulations (COMSOL): frequency sweep studies
- EM field emitted by the CP extends for several mm above the probe surface
- A change in permittivity in the probed volume affects the resonance frequency



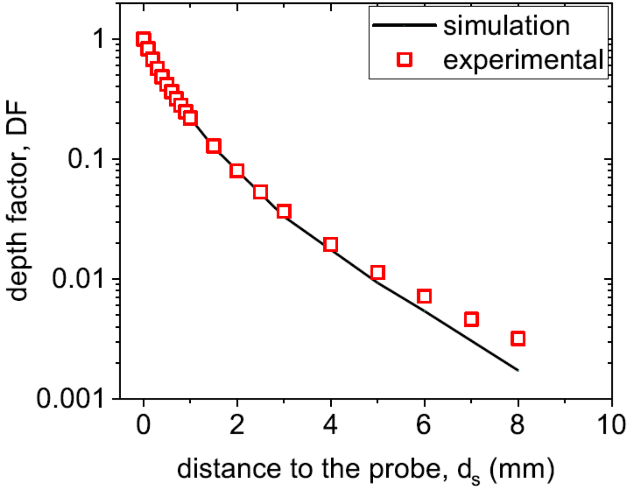
- **E field decreases by 10x times at z~5 mm**
- **Spatial distribution is harmonic/probe dependent**

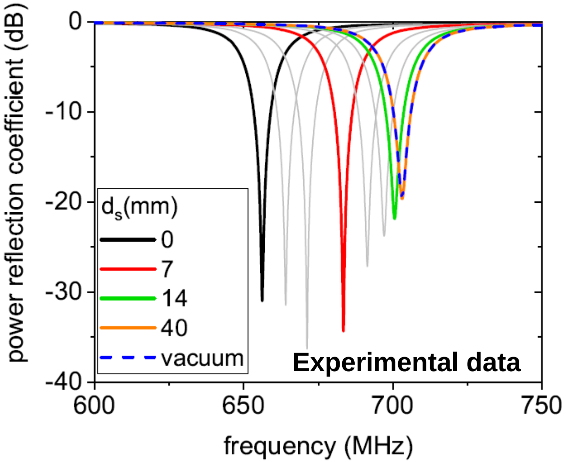
Definition of the dielectric depth factor of a CP

- This case can be reproduced numerically and experimentally
- Thickness of etalon >> characteristic decay length of emitted EM field



$$DF(d_s) = \frac{\Delta f(d_s)}{\Delta f(d_s = 0)} = \frac{f_r(d_s) - f_0}{f_r(d_s = 0) - f_0},$$





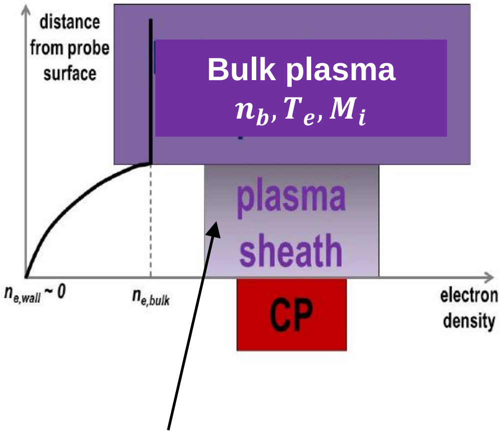
- Direct relation btw Δf (freq shift) and d_s (dist etalon-probe)
- Excellent agreement simulations / experiments
- **3D numerical simulations are considered representative of CP behavior in the presence of non-homogenous permittivity profile**

Definition of the plasma depth factor of a CP

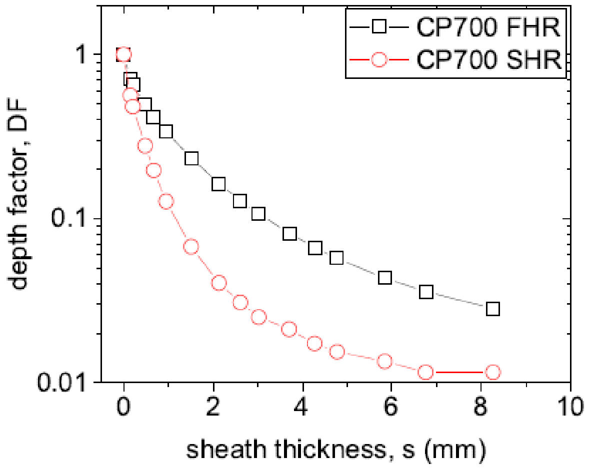
$n_b = 10^8 - 10^{11}$ cm^{-3}, $T_e = 1 - 50$ eV, $E_{ki} = 5 - 300$ eV
→ $\mathbf{20\ \mu m \leq \lambda_D \leq 5\ mm}$ **and** $\mathbf{100\ \mu m \leq s \leq 8\ mm}$

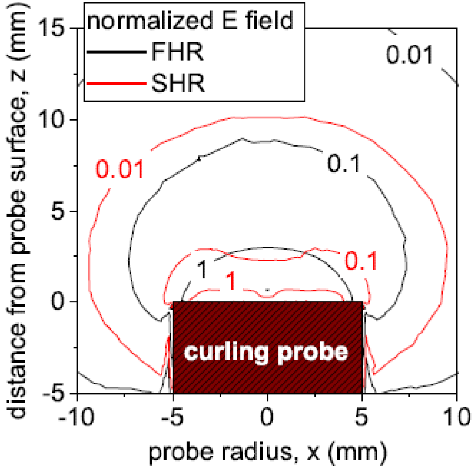
$$\boxed{DF(s) = \frac{\Delta f(s)}{\Delta f(s=0)} = \frac{n_e(s)}{n_e(s=0)} = \frac{n_{e,\mathrm{raw}}}{n_{e,\mathrm{bulk}}},}$$

Simulation setup



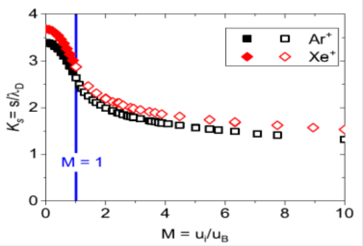
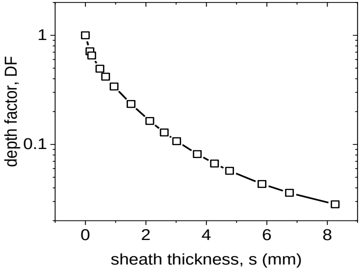
Sheath with $n_e(z)$ obtained with model presented before (no presheath)





- **DF is the probe sensitivity to the plasma sheath (equivalency btw Δf and n_e^{MEAS})**
  DF uniquely depends upon sheath thickness and is harmonic/probe dependent

The correction algorithm

Inputs	n_{meas}^{RAW}, T_e (estimation), M_i (estimation)
Computation	$K_s = function(M_i, gas)$ 
Iterations	$n_{bulk}^{i+1} = DF\left(s\left(n_{bulk}^{i}, T_e, M_i\right)\right) \cdot n_{meas}^{RAW}$ $s\left(n_{bulk}^{i}, T_e, M_i\right) = K_s(M_i) \cdot \lambda_D\left(n_{bulk}^{i}, T_e\right)$ 
Final step	**If $M_i < 1$ → presheath→ α_{ps} correction**
Output	n_{bulk}

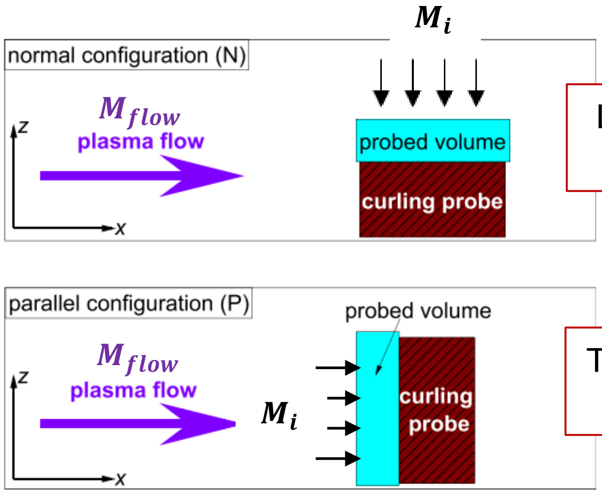
Experimental assessment of the method

Two plasma sources

- **ICP source (4 MHz)**
  - No B field
  - Maxwellian electrons [Esteves2022]
  - Subsonic-to-sonic ions
- **ECR thruster plume**
  - weakly-magnetized (B = 500-10 G)
    → minor role of B [Chodura1982]
  - Possible deviations from Maxwellian [Correyero2017]
  - Supersonic ions

Three comparisons

1. Curling probe *vs* Langmuir probe
2. FHR *vs* SHR of CP700
   → same sheath thickness, different DF
3. Change of CP orientation wrt ion beam
   → same DF, different sheath thickness

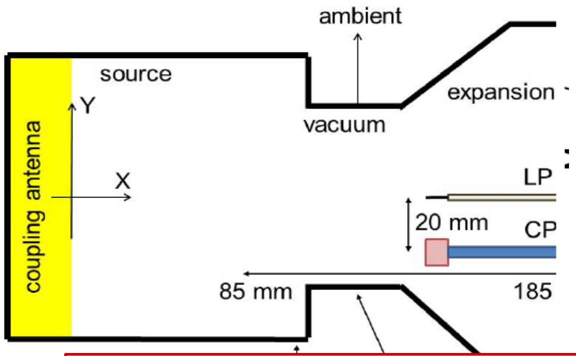


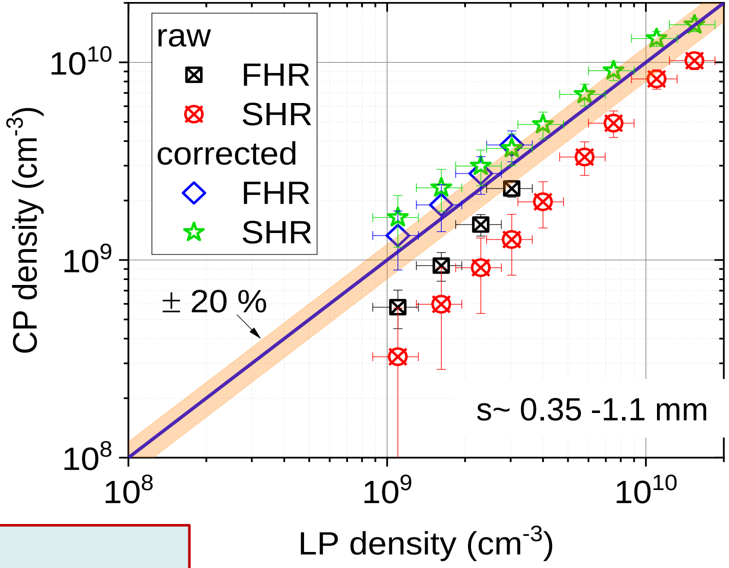
Larger sheath
$M_i < M_{flow}$

Thinner sheath
$M_i \sim M_{flow}$

ICP source: FHR and SHR vs LP

- Pressure between 10^{-2}-10^{-3} mbar, power between 50-100 W, argon gas
- Measurements taken far downstream the antenna (low coll. and ioniz.)
- LP post-processed using [Druyvesteyn1940]
- CP used in P configuration
- M_i = 0,7-1,3 & T_e~2-4 eV → $\boldsymbol{M_{corr} = 1, T_{corr} = 3\ \mathrm{eV}}$



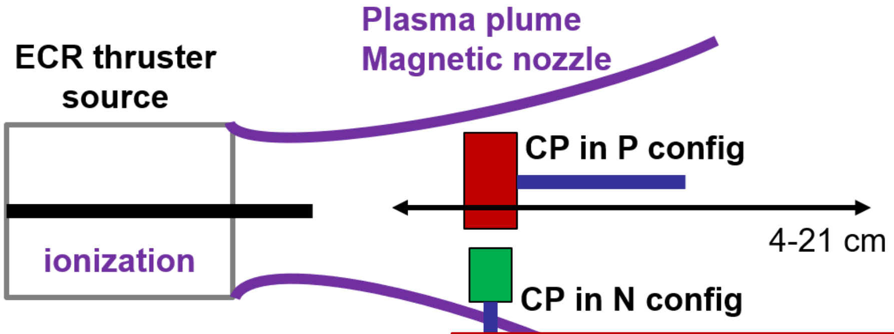


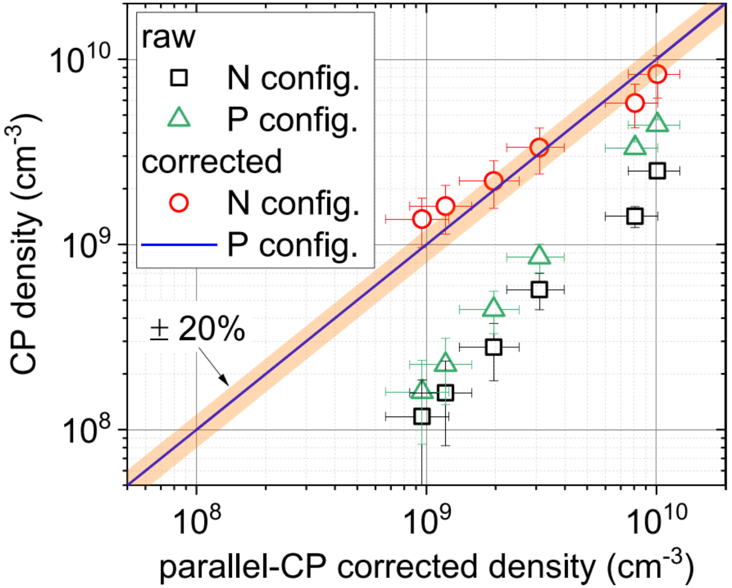
- $n_{raw}^{SHR} < n_{raw}^{FHR}$ → consistent with their DFs
- Corrected CP data in agreement with LP (20% discrepancy)
- Discrepancy btw FHR and SHR reduced from 40% to 10%

Validation of depth factor approach
(same plasma sheath and bulk, different harmonic)

ECR thruster plume: N and P configurations

- Pressure ~ 10^{-6} mbar, power ~ 30 W, 1 SCCM xenon
- $M_i = 1 - 3, T_e = 20$ eV
- CP700 FHR
  - P configuration → $\boldsymbol{M_{corr} = M_i = 2, T_{corr} = 20}$ **eV**
  - N configuration → $\boldsymbol{M_{corr} = 0.3, T_{corr} = 20}$ **eV**





- $n_{Nconfig}^{RAW} < n_{Pconfig}^{RAW}$ due to larger sheath (discrepancy 38%)
- s~0,7-2 mm in P config *vs* s~1-4 mm in the N config
- Corrected parallel and normal CP data in good agreement (discrepancy <15%)

Validation of the effect of Mi on the sheath formation
(same harmonic=same DF, same bulk plasma, different sheath)

General remarks and conclusion

- K_s depends only on M_i and gas
- **DF property is <u>directly</u> correlated to $\boldsymbol{n_e}$ decrease due to presence of sheath**
- Semi-analytical 1D and DC model used is appropriate in the cases studied here
  - Density 10^8 – 10^{11} cm^{-3}
  - Temperature 5-30 eV
  - Ion beams up to 200 eV (~17 km/s for xenon)
  - Weakly-magnetized (< 400 G, f_{ce}~1 GHz with CP at 1700 MHz)
  - Collisionless or weakly-collisional (f_c up to ~100 MHz with CP at 700 MHz)
- Experimental observations
  - $n_{CP}^{RAW} < n_{LP}$ due to sheath effects forming around the CP
  - n_{CP}^{CORR} in agreement with n_{LP}
  - $n_{Nconfig}^{CORR}$ in agreement with $n_{Pconfig}^{CORR}$ → **ion velocity drives sheath thickness**
  - n_{FHR}^{CORR} in agreement with n_{SHR}^{CORR} → **DF property related to density decrease in sheath**

✓ **Method globally validated**

Limitations of the presented model

- In the **sonic-to-supersonic regime** ($M \gtrsim 1$), method **not too sensitive to $\boldsymbol{M_{corr}}$, $\boldsymbol{T_{corr}}$** (discrepancies ~20-30%)
- In the **subsonic regime** ($M < 1$), method is much **more sensitive to input parameters** (discrepancies ~40-60%) (due to presence of presheath → additional correction due to α_{ps} that is absent in the supersonic case)
- Uncertainties on T_{corr} affect more the output accuracy compared to E_{ki} → see example below

$n_b = 10^{10}$ **cm^{-3}**, $T_e = 20$ **eV**, $M_i = 0{,}7$ **(E_{ki}=5 eV)**, $n_{raw} = 3{,}3 \times 10^9$ **cm^{-3}**

Input						
T_e (eV)	E_{ki} (eV)	M	α_{ps}	s (mm)	DF (s)	Estimated bulk density ($\times 10^{10}$ cm^{-3})
20	5	0.7	0.77	1.08	0.43	0.99
40	5	0.5	0.69	1.63	0.32	1.48
20	2.5	0.5	0.69	1.15	0.41	1.17

- T_e and E_{ki} affects M_i
  → same effect on α_{ps}
- T_e affects sheath thickness more than E_{ki}
  → it changes the scale length (λ_D)

- Magnetized models should be used if $f_p < f$ and $f_{ce} \to f$ (B field effects cannot be neglected on ϵ_p)
- P configuration → B field and ion velocity are always aligned → sheath is governed by velocity magnitude
- N configuration → according to [Ahedo1997], B effects should be weak
  Considering good accordance btw N and P corrected data → B effects in sheath formation in N config can be neglected here

What can be improved

- **Inclusion of collisions and ionization** in presheath/sheath models
- **More representative IEDF** (not a Dirac as here)
  → may help reduce uncertainties in the sonic transition region (where high uncertainties are now obtained)
- Computation of **DF with presheath** (now computed with sheath n_e drop)
  Acceptable in cases where density gradient in the sheath >> than that presheath AND sheath ~10x times thinner than presheath → this could enable **more precise** determination of **CP sensitivity** to plasma sheath in **subsonic** case and **thin sheaths**
- Effect of **strong B field** at grazing incidence on **sheath formation** → magnetic presheath?
- **Non-Maxwellian electrons / non-uniform T_e** across the plasma-wall structure
  → Maxwellian + uniform T_e could currently overestimate sheath potential drop [Kushner1985]
- Increase representativity of sheath potential drop by considering ion beam velocity and EEDF [Schroder2015]

s_{80} is thickness value for which DF=80%
→ if $s = s_{80}$ then sheath effects could be neglected, since underestimations <20%

- $\lambda_D > s_{80}$ in our case → underestimations are always non-negligible
  → application of this method ↑ accuracy of results
- If $\lambda_D \leq s_{80}$→ underestimations <20% and the application of method could potentially ↓ accuracy of n^{CORR}

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Thank you for your attention !