Cylindrical Langmuir probe measurements in magnetized Helium plasma

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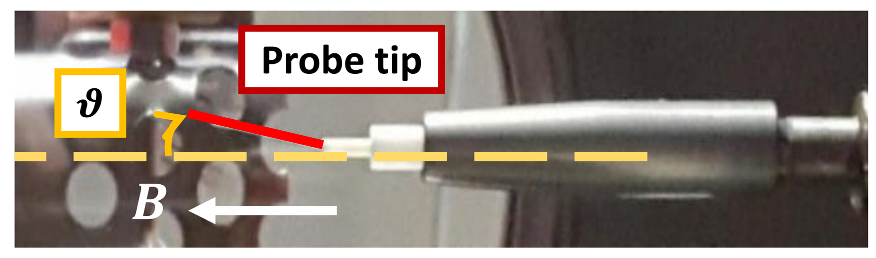
Introduction & experimental setup

■ Langmuir probe measurement is the most used technic to get access to plasma parameters :

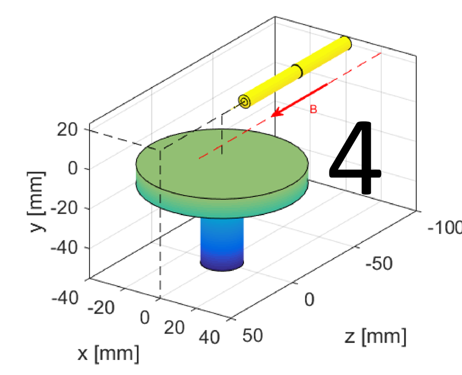
- Plasma temperature T_e
- Plasma density n_e
- Plasma potential ϕ_p

■ With external magnetic field : $I(V)$ characteristics difficult to interpret (anisotropy effects ⇔ asymmetric effects between ion and electron current).

■ Presented study on the role of RF-power, $\|\boldsymbol{B}\|$, and ϑ (angle between probe and $\boldsymbol{B}$ direction)



Range of parameters explored in the scope of this study		
RF power	Magnetic field magnitude	Angle ϑ (probe, $\boldsymbol{B}$)
From 20 to 200 W-RF	From 0 mT to 100 mT	From 0° to 90°
Gaz : Helium – **Pressure** : 1.2 Pa – **frequency** : 25 MHz – **Probe** : $r_p = 75$ µm, $L_p = 1$ cm		

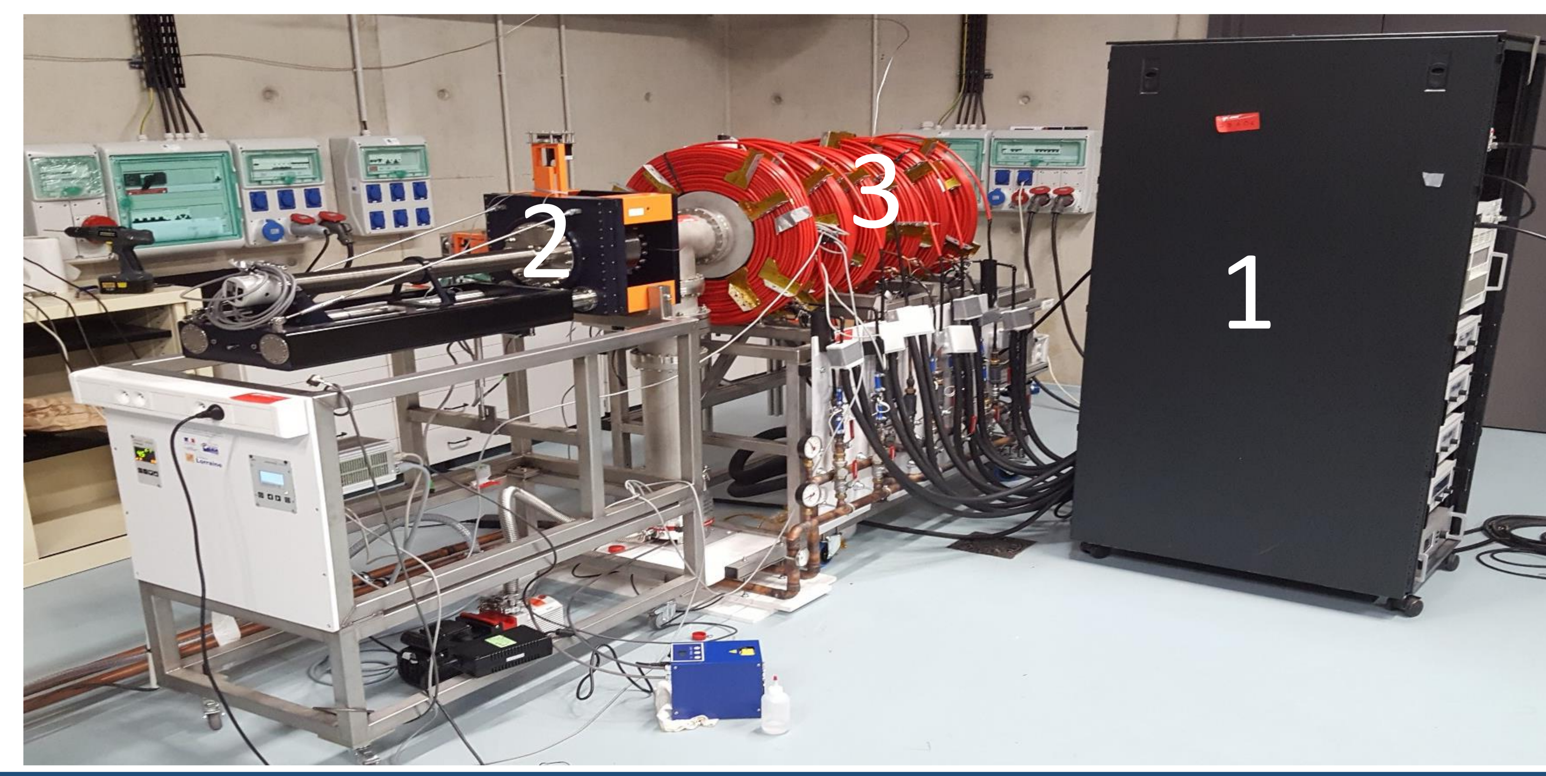


ALINE reactor : A LINEar plasma device $L = 1$ m, $R = 35$ cm. The axial magnetic field is created through 6 coils crossed by DC current from 0 to 220 A.

The cylindrical probe is RF-compensated to ensure reliable measurements. The antenna (or RF – cathode) generates a RF field of 25 MHz.

Note : RF – capacitive discharges were made in the frame of this work

E. Faudot, RSI **86**, 063502 (2015)



1. RF power supply
2. Arm of the Langmuir probe
3. Coils surrounding the vessel
4. Antenna and probe inside (3)

Probe measurements with $\boldsymbol{B}$

A bump appears on the characteristics between the electron saturation current and the exponential part of $I(V)$ in some conditions :

→ magnetic field must be strong enough

→ probe must not be to tilted

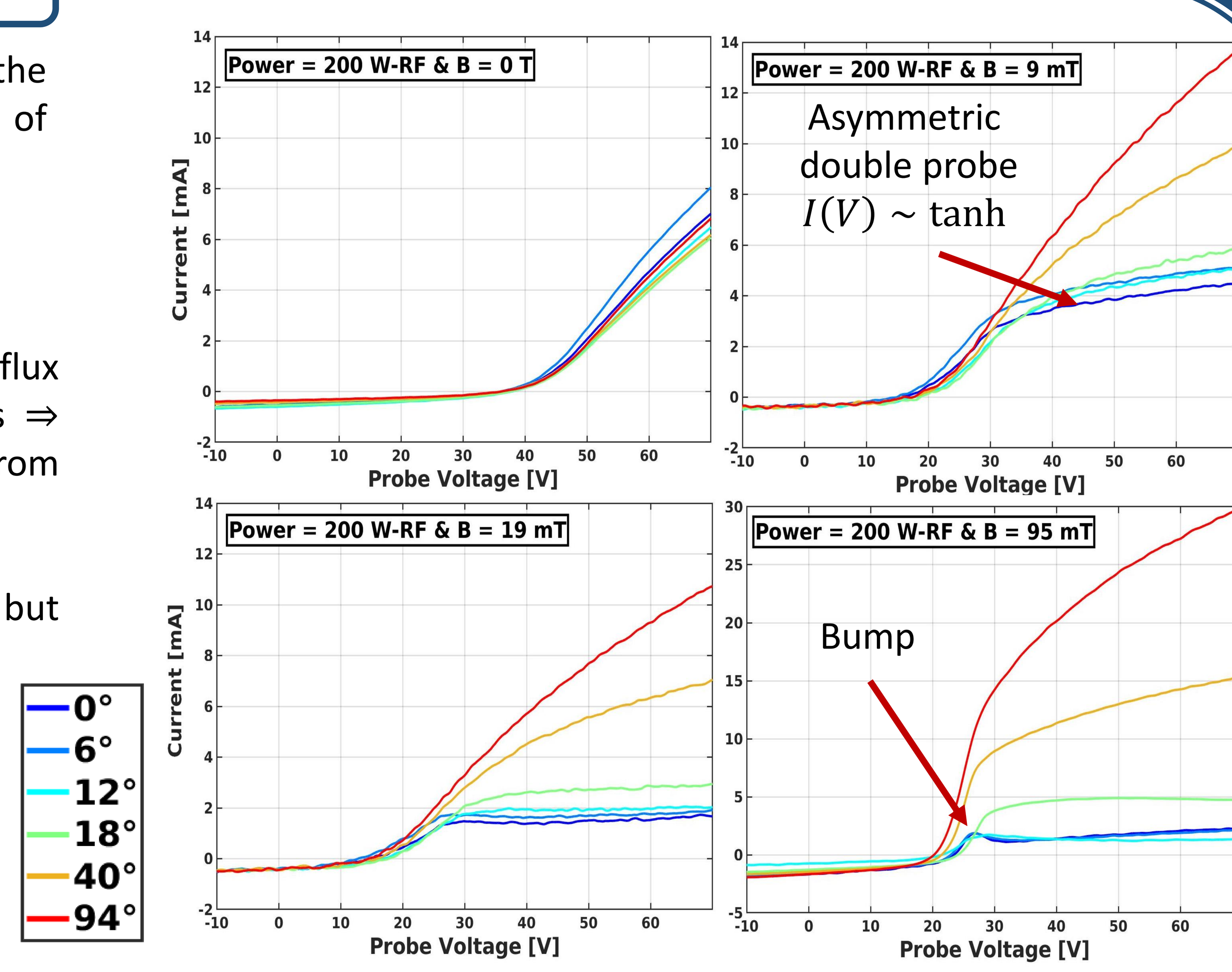
Hypothesis:

- $\boldsymbol{B}$ confines the electrons ($\rho_{ce} < \rho_{ci}$) ⇒ the tube flux linked to the probe becomes narrow as $\boldsymbol{B}$ increases ⇒ asymmetric double probe behavior = only the plasma from the tube is probed.

- Collecting surface if $\boldsymbol{B} \neq \boldsymbol{0}$ is not the whole probe but only a projection of it ⇒ linked flux tube wider if $\vartheta > 0$.

$$S_{\text{coll}} \propto \pi r_p^2 \cos\vartheta + 2\pi r_p L_p \sin\vartheta$$

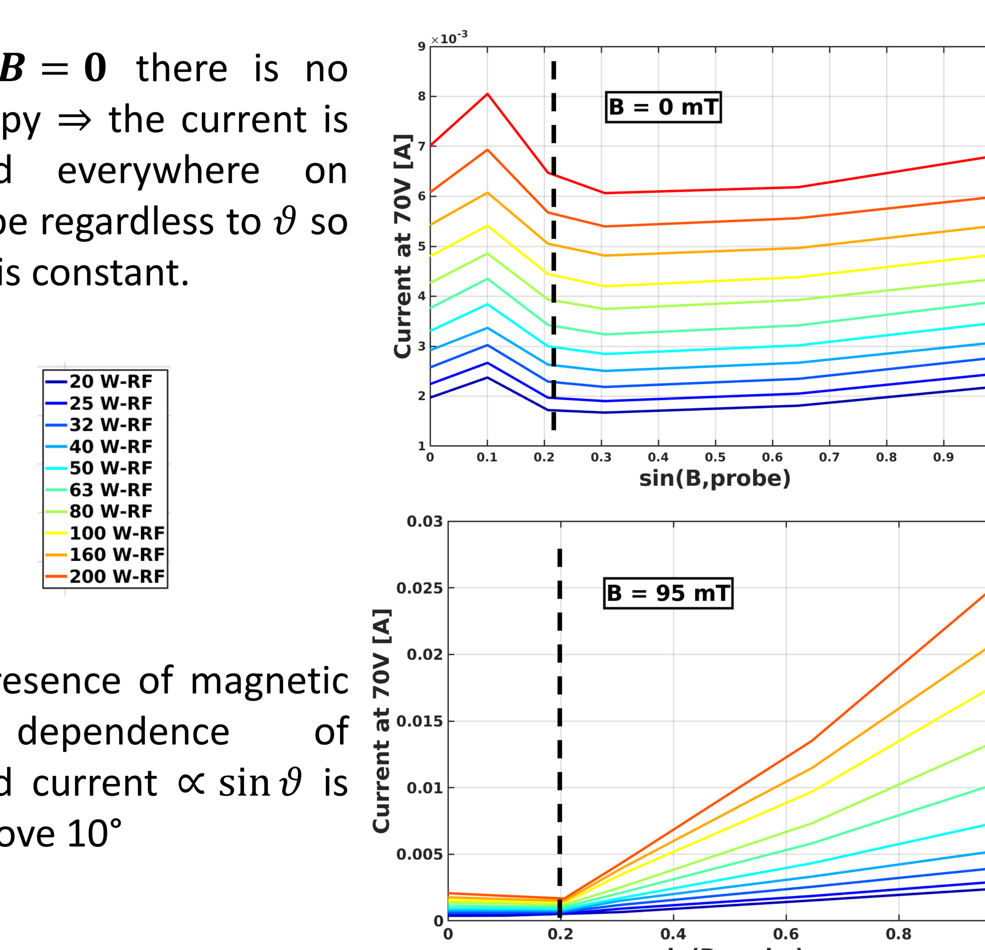
E. Faudot, PoP **22**, 083506 (2015)
I. Mihaila, Contrib. of Plasma Physics **53**, 1 (2012)
M. Usoltceva, PoP (2018)
T. Dote, Journal of Phys. Soc. Of Japan **19**, 10 (1964)



Influence of ϑ

For $\boldsymbol{B} = \boldsymbol{0}$ there is no anisotropy ⇒ the current is collected everywhere on the probe regardless to ϑ so $I(70V)$ is constant.

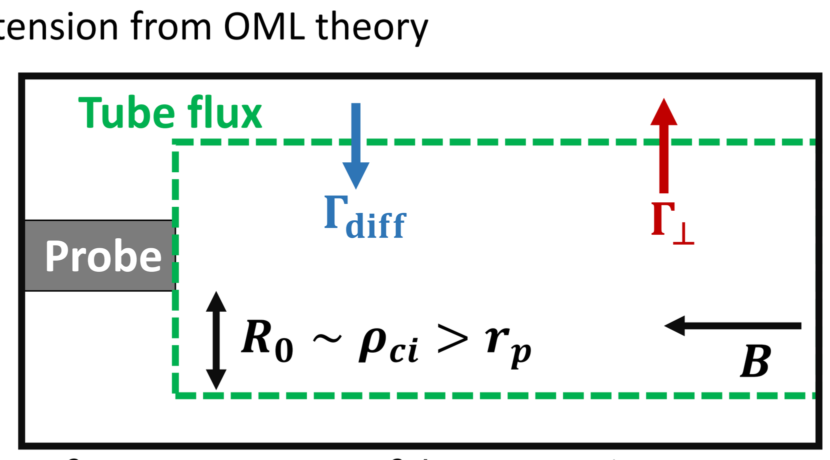
In presence of magnetic field dependence of collected current $\propto \sin\vartheta$ is clear above 10°



Construction of an analytical model

Hypothesis :

- Electronegative sheath (no ion flux in the parallel direction)
- Stationary model (no RF currents)
- Perpendicular currents $\boldsymbol{J}_\perp = \sigma_\perp \boldsymbol{E} = -\sigma_\perp \nabla\phi = -\alpha n \nabla\phi$
- Sheath extension from OML theory



$$\Gamma_{\text{diff}} = -D\frac{\partial n}{\partial r} \quad ; \quad \Gamma_\perp = -\frac{\alpha n}{e}\frac{\partial\phi}{\partial r} \quad ; \quad I = \frac{1}{2} e n_{\text{tube}} \langle v_{\text{THe}} \rangle S_{\text{OML}}$$

with collecting surface given by r_p plus some electron gyroradii,

$$S_{\text{OML}} = \pi\left(r_p + N\rho_{ce}\right)^2 \times \left(2\sqrt{\frac{\chi}{\pi}} + e^{\chi}\cdot \operatorname{erfc}\sqrt{\chi}\right)$$

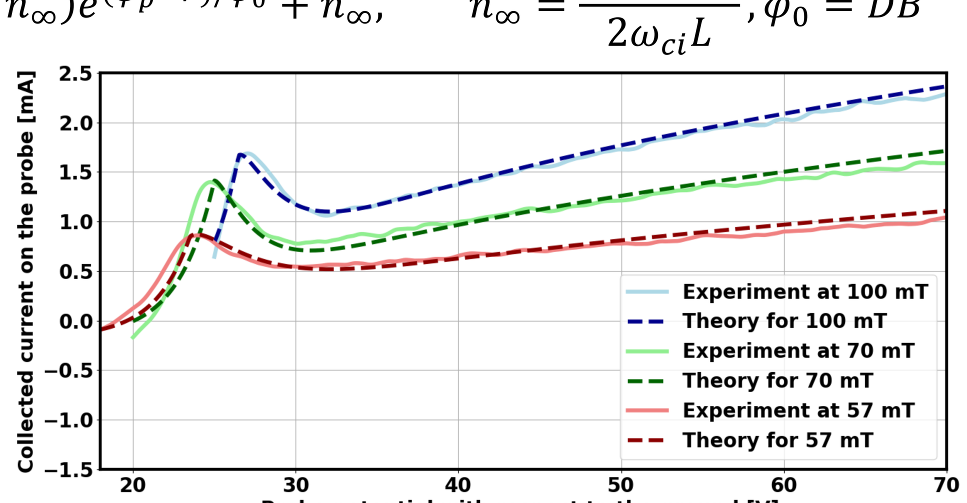
Ion flux continuity:

$$\operatorname{div}(\Gamma_i) = S_0 \Rightarrow \oiint_{\text{tube}} \boldsymbol{\Gamma}_{\text{i}} \cdot \mathrm{d}\boldsymbol{S} = \underbrace{\Gamma_{\parallel i} \cdot S_\perp}_{=0} + \Gamma_{\perp i} \cdot S_\parallel = \pi\rho_{ci}^2 \times \frac{1}{2} e n_0 \langle v_{\text{THe}} \rangle$$

Taking $\rho_{ci} = v_{\perp i}/\omega_c \approx |\boldsymbol{E} \times \boldsymbol{B}|/\omega_c B^2 = -\partial_r \phi/\omega_c B^2$ gives density:

$$n_{\text{tube}}(V) = (n_0 - n_\infty)e^{(\phi_p - V)/\varphi_0} + n_\infty, \qquad n_\infty = \frac{n_0 \langle v_{\text{THe}} \rangle}{2\omega_{ci} L}, \varphi_0 = DB$$

Comparison for 200 W-RF and $\vartheta = 0°$ theory vs experiment



V. Rozhansky, Nuclear Fusion **39**, 5 (1999)

Influence of power & sheath extension

Position of ϕ_p unsure ⇒ normalization to $I(V = 70V)$

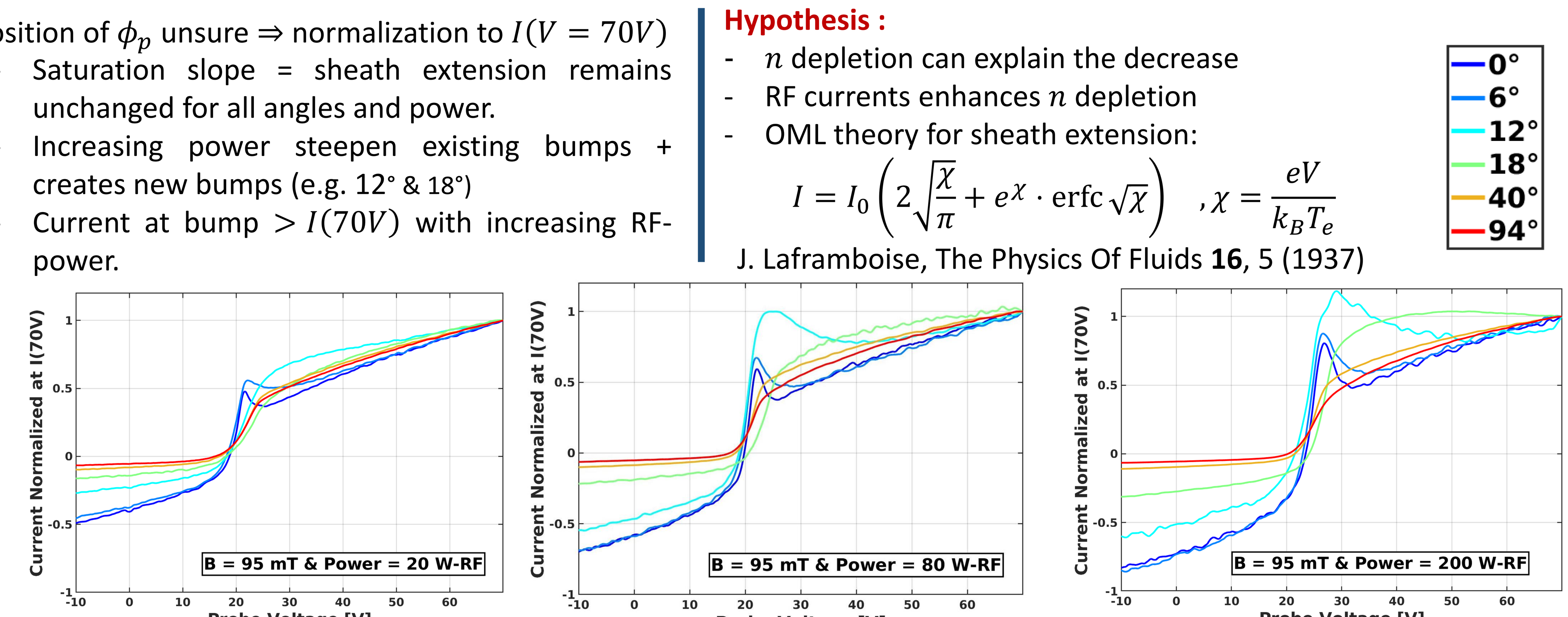
- Saturation slope = sheath extension remains unchanged for all angles and power.
- Increasing power steepen existing bumps + creates new bumps (e.g. 12° & 18°)
- Current at bump $> I(70V)$ with increasing RF-power.

Hypothesis :

- n depletion can explain the decrease
- RF currents enhances n depletion
- OML theory for sheath extension:

$$I = I_0\left(2\sqrt{\frac{\chi}{\pi}} + e^{\chi}\cdot \operatorname{erfc}\sqrt{\chi}\right) \quad , \chi = \frac{eV}{k_B T_e}$$

J. Laframboise, The Physics Of Fluids **16**, 5 (1937)



Conclusions

→ Use of cylindrical Langmuir probe imposes to be careful in magnetized plasmas : deformation of "classical" characteristics and apparition of a bump.

→ Bump occurs if $B \geq B_{\text{lim}}$ and,

- B_{lim} increases if incidence angle ϑ increases.
- B_{lim} decreases if RF – Power increases ⇔ n_e increases in plasma.

$$\Big\} \Rightarrow B_{\text{lim}} = f\left(\frac{\vartheta}{n_e}\right)$$

→ Our stationary model displays an electron pumping mechanism.

→ Bumps lead to bad evaluation of n_e, T_e and ϕ_p.

→ Model suggests that ϕ_p is on the top of the bump.

→ Current and collecting surface dependence in $\sin\vartheta$.

⇒ Further studies are needed to get access to plasma parameters

- Model taking into account "real" RF-currents for $\Gamma_\perp$
- Numerical model to find plasma parameters