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► **To cite this version:**

J. Ledig, E. Faudot, N Lemoine, S. Heuraux, J. Moritz. Cylindrical Langmuir probe measurements in magnetized Helium plasma. 45th EPS Conference, Jul 2018, Prague, Czech Republic. hal-02880391

HAL Id: hal-02880391

<https://hal.science/hal-02880391>

Submitted on 24 Jun 2020

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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 :

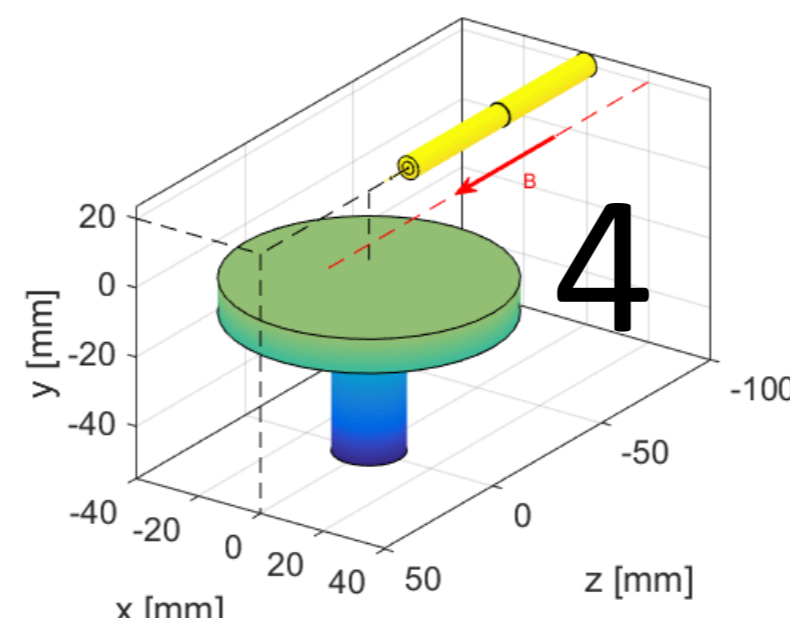
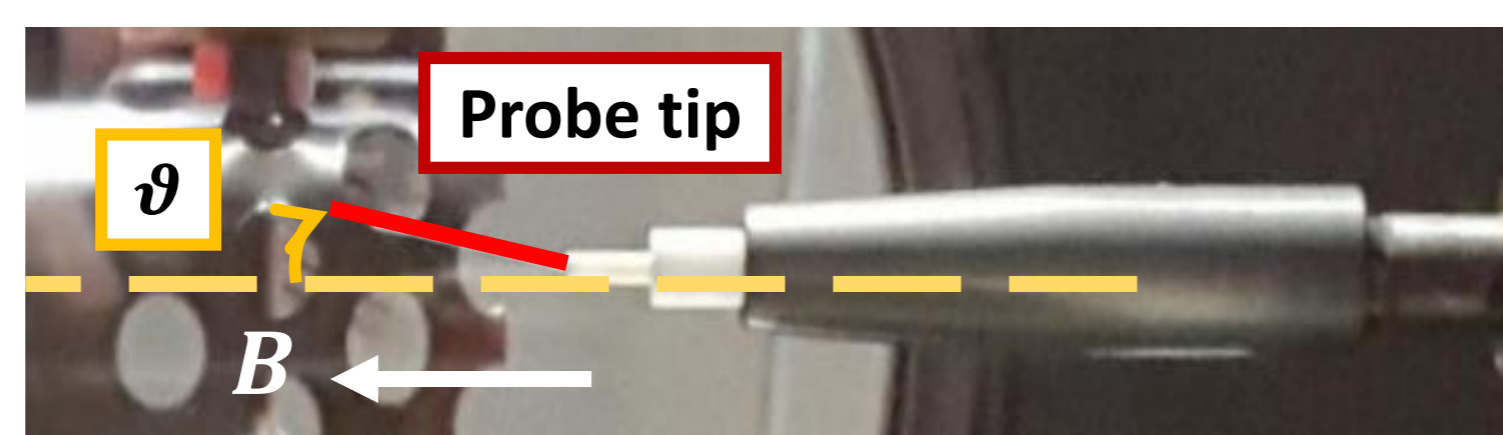
- Plasma temperature T_e
- Plasma density n_e
- Plasma potential ϕ_p

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

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

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.



Range of parameters explored in the scope of this study		
RF power	Magnetic field magnitude	Angle ϑ (probe, 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 : $r_p = 75 \mu\text{m}$, $L_p = 1$ cm		



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

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

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

Probe measurements with B

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

- \rightarrow magnetic field must be strong enough
- \rightarrow probe must not be tilted

Hypothesis:

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

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

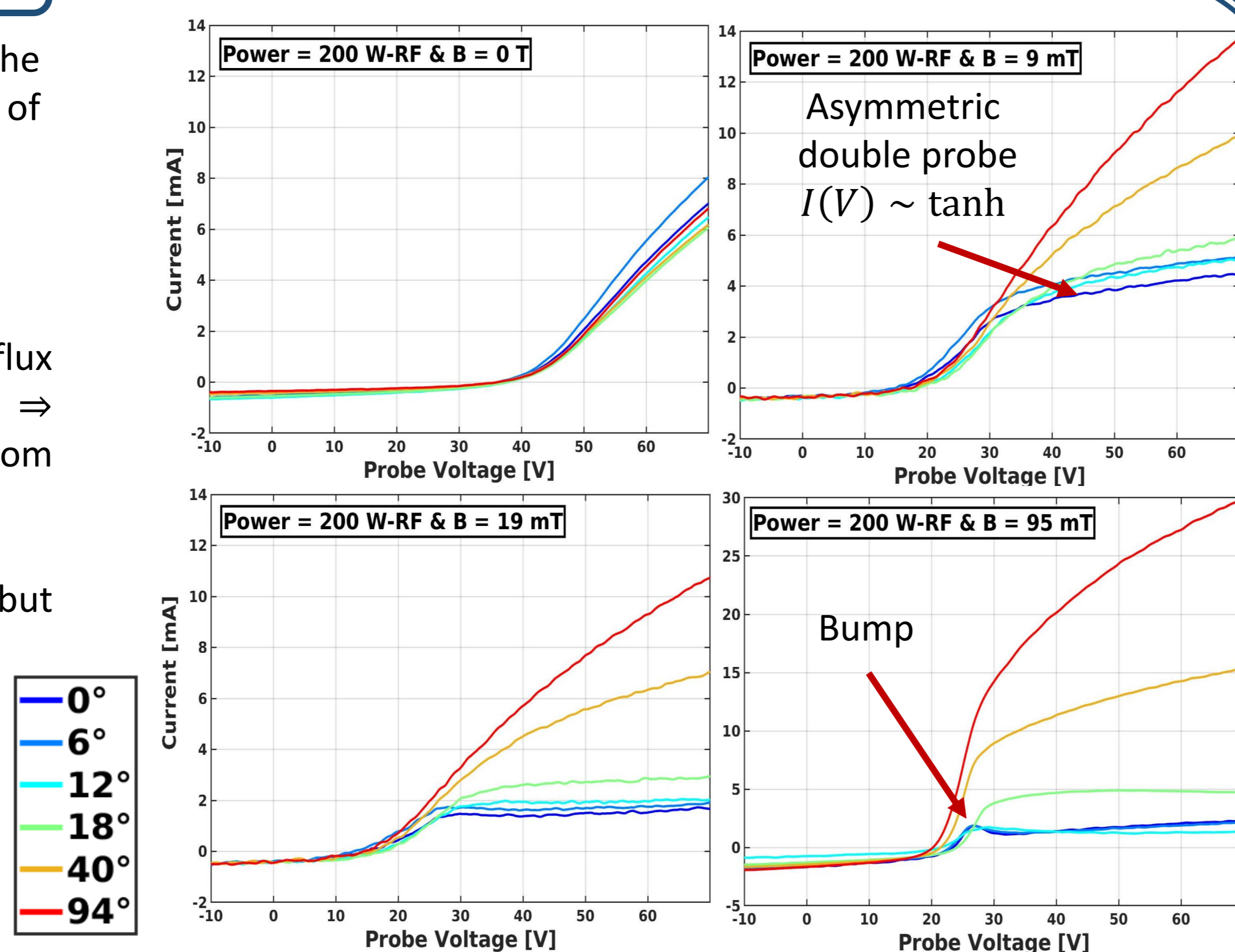
$$S_{\text{coll}} \propto \pi r_p^2 \cos \vartheta + 2\pi r_p L_p \sin \vartheta$$

E. Faudot, PoP **22**, 083506 (2015)

I. Mihaila, Contrib. of Plasma Physics **53**, 1 (2012)

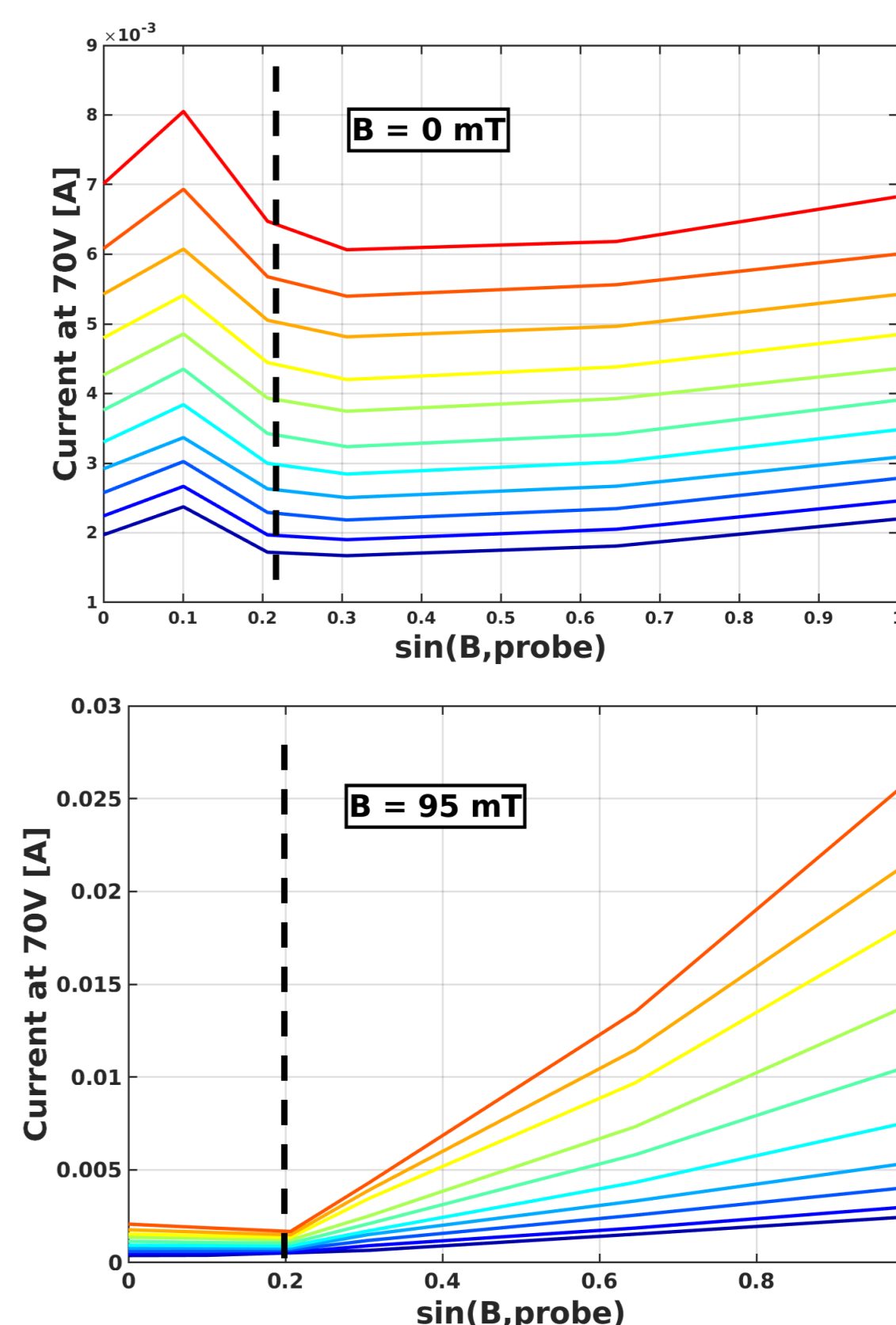
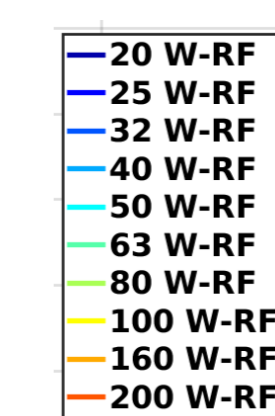
M. Usoltceva, PoP (2018)

T. Dote, Journal of Phys. Soc. Of Japan **19**, 10 (1964)



Influence of ϑ

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

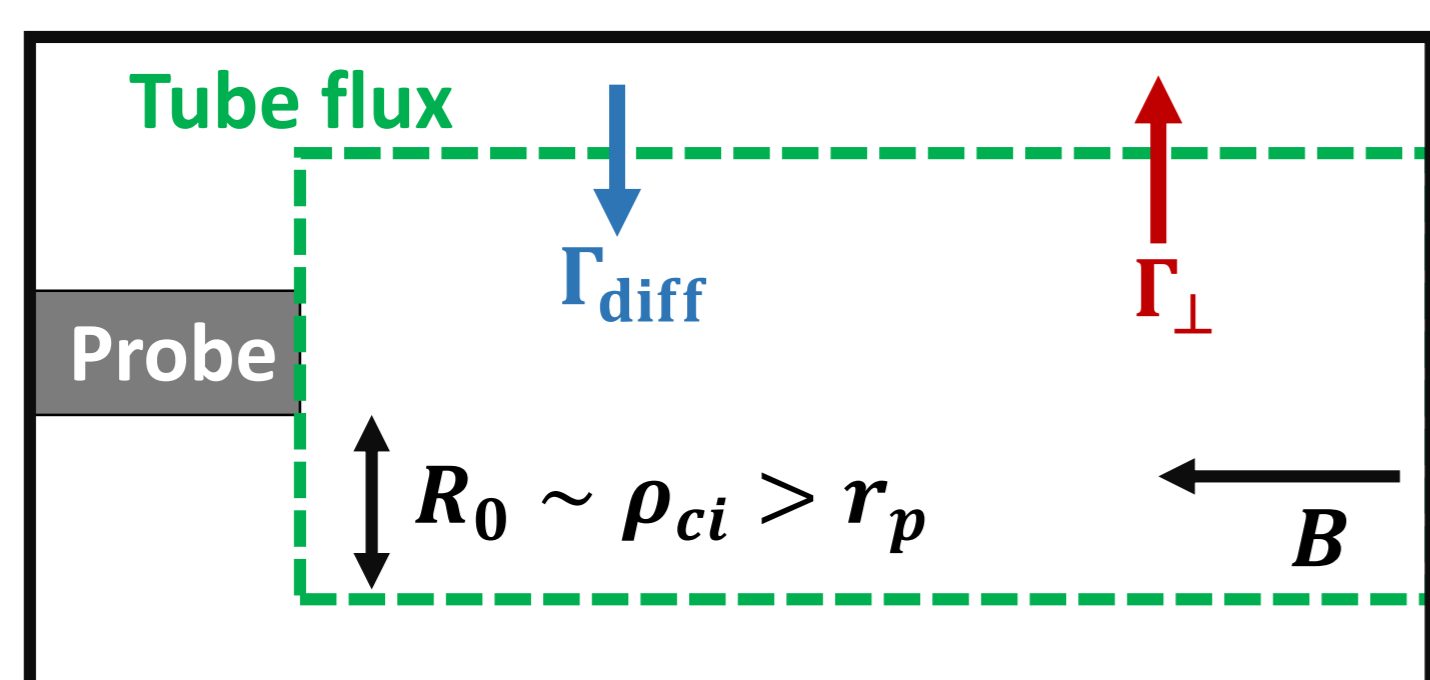


In presence of magnetic field dependence of collected current $\propto \sin \vartheta$ is clear above 10°

Construction of an analytical model

Hypothesis :

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



$$\Gamma_{\text{diff}} = -D \frac{\partial n}{\partial r} ; \Gamma_{\perp} = -\frac{an}{e} \frac{\partial \phi}{\partial r} ; I = \frac{1}{2} en_{\text{tube}} (v_{\text{THE}}) S_{\text{OML}}$$

with collecting surface given by r_p plus some electron gyroradii,

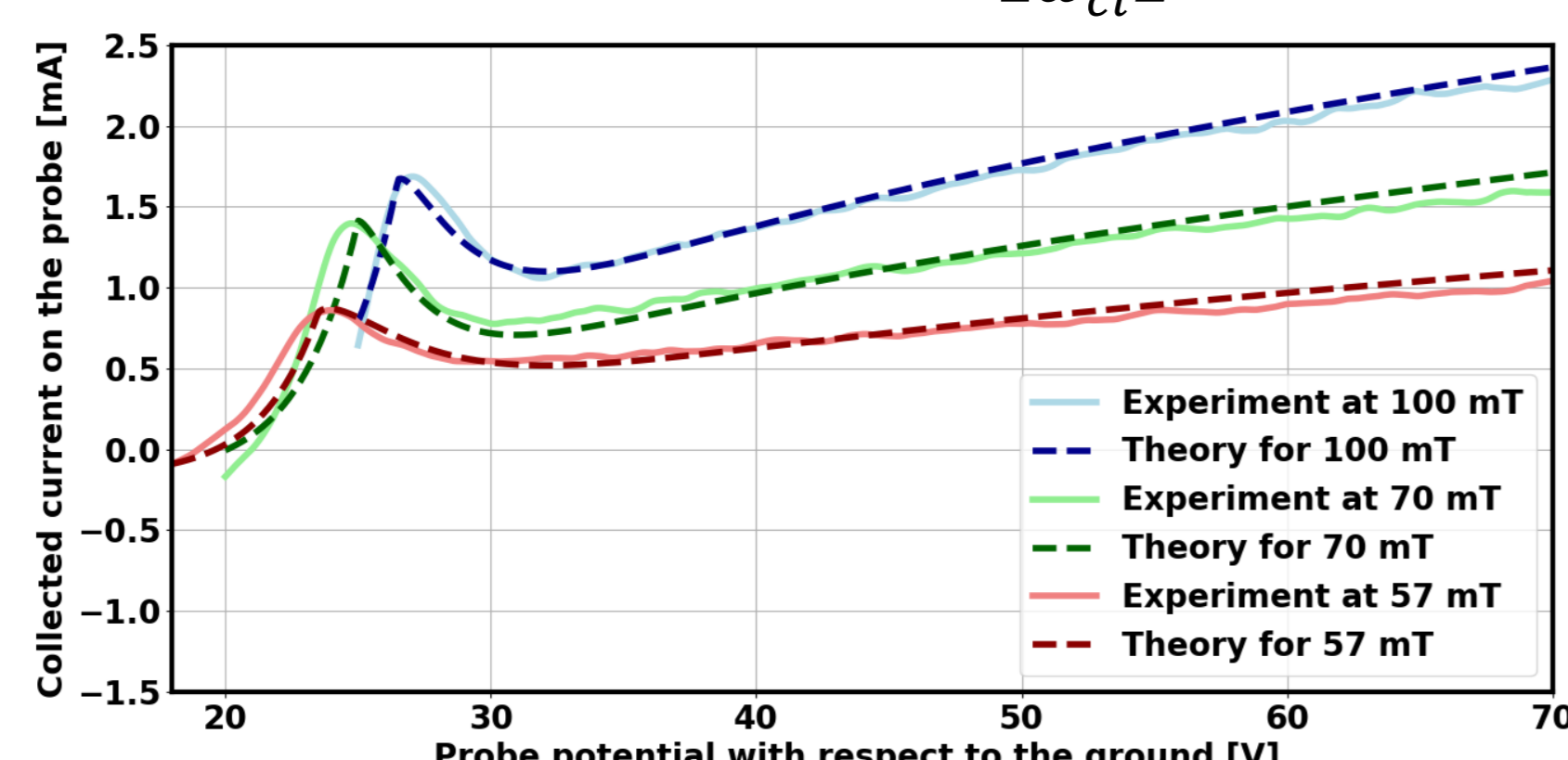
$$S_{\text{OML}} = \pi (r_p + N\rho_{ce})^2 \times \left(2\sqrt{\frac{\chi}{\pi}} + e^{\chi} \cdot \text{erfc} \sqrt{\chi} \right)$$

Ion flux continuity:

$$\text{div}(\Gamma_i) = S_0 \Rightarrow \oint_{\text{tube}} \Gamma_i \cdot dS = \Gamma_{\parallel i} \cdot S_{\perp} + \Gamma_{\perp i} \cdot S_{\parallel} = \pi \rho_{ci}^2 \times \frac{1}{2} en_0 (v_{\text{THE}})$$

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

$$n_{\text{tube}}(V) = (n_0 - n_{\infty}) e^{(\phi_p - V)/\phi_0} + n_{\infty}, \quad n_{\infty} = \frac{n_0 (v_{\text{THE}})}{2\omega_{ci} L}, \quad \phi_0 = DB$$



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

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

Influence of power & sheath extension

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

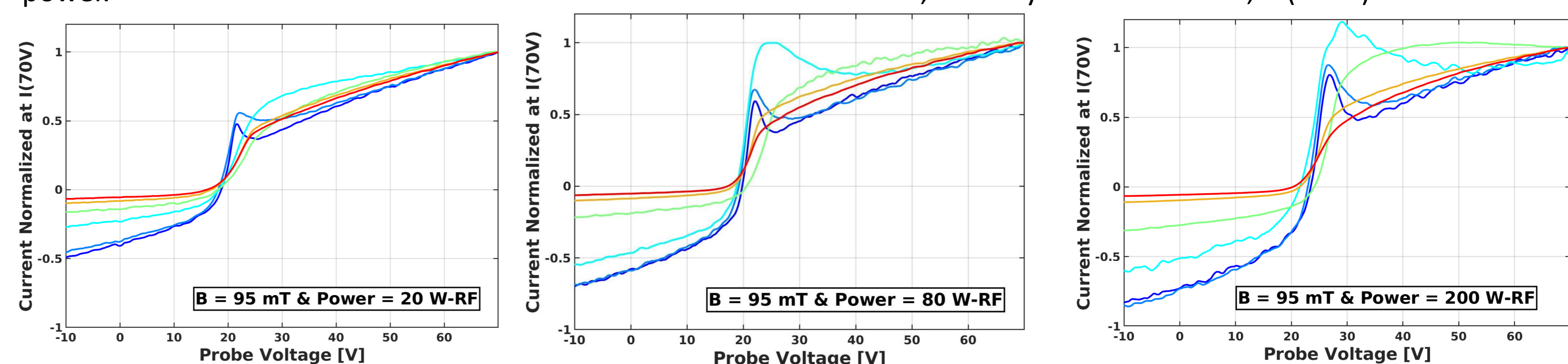
- Saturation slope = sheath extension remains unchanged for all angles and power.
- Increasing power steepen existing bumps + creates new bumps (e.g. 12° & 18°)
- Current at bump $> I(70V)$ with increasing RF-power.

Hypothesis :

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

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

J. Laframboise, The Physics Of Fluids **16**, 5 (1973)



Conclusions

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

- \rightarrow Bump occurs if $B \geq B_{\text{lim}}$ and,
- B_{lim} increases if incidence angle ϑ increases.
- B_{lim} decreases if RF – Power increases $\Leftrightarrow n_e$ increases in plasma. $\left. \begin{matrix} \rightarrow \\ \rightarrow \end{matrix} \right\} B_{\text{lim}} = f\left(\frac{\vartheta}{n_e}\right)$

- \rightarrow Our stationary model displays an electron pumping mechanism.
- \rightarrow Bumps lead to bad evaluation of n_e , T_e and ϕ_p .
- \rightarrow Model suggests that ϕ_p is on the top of the bump.
- \rightarrow Current and collecting surface dependence in $\sin \vartheta$.

- \Rightarrow Further studies are needed to get access to plasma parameters
- Model taking into account "real" RF-currents for Γ_{\perp}
- Numerical model to find plasma parameters

