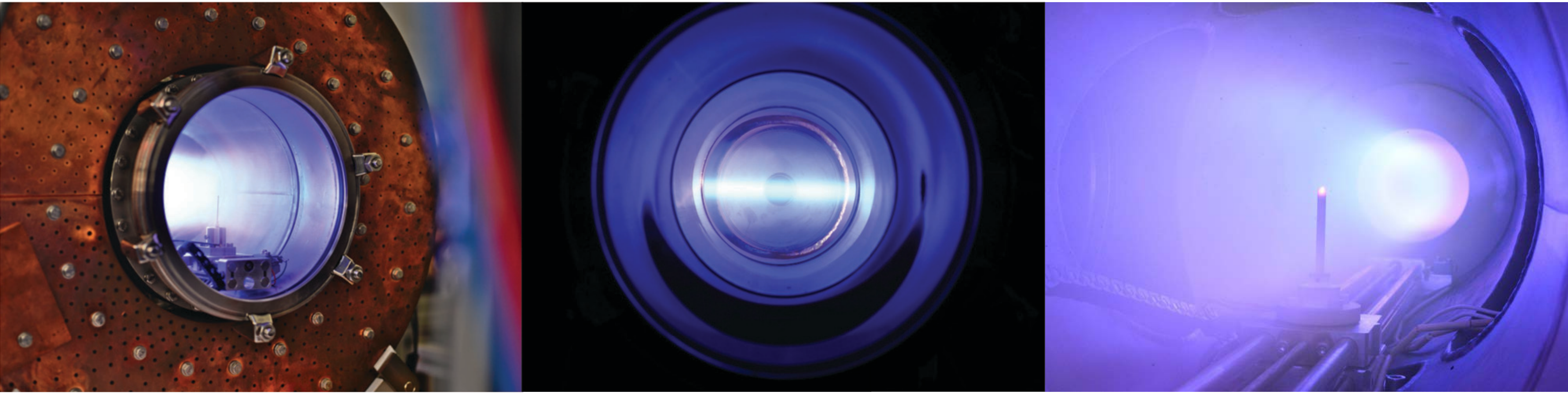
Plasma potential shaping using emissive electrodes: governed by sheaths



F. Pagaud, S. Vincent, V. Dolique, N. Plihon
B. Trotabas, R. Gueroult

Lab PHYS ENS de LYON
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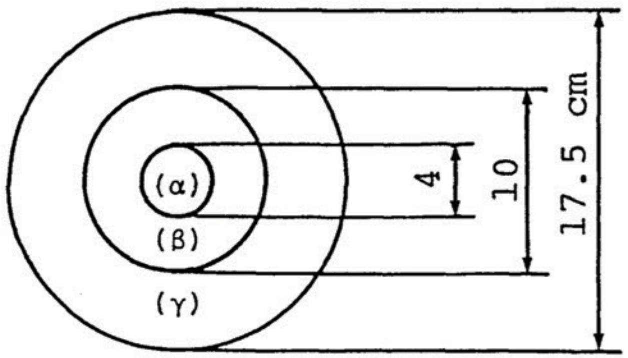
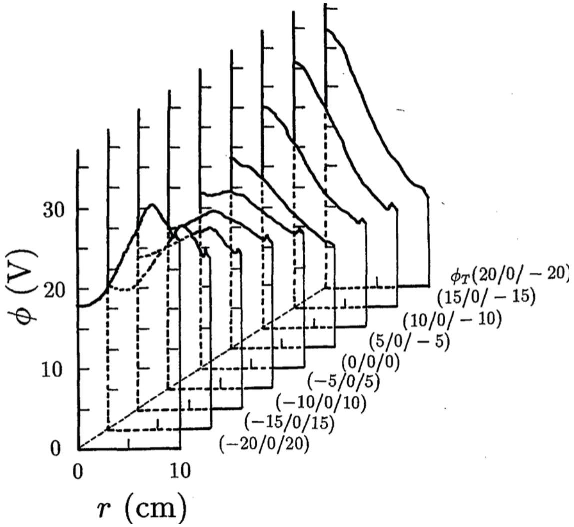
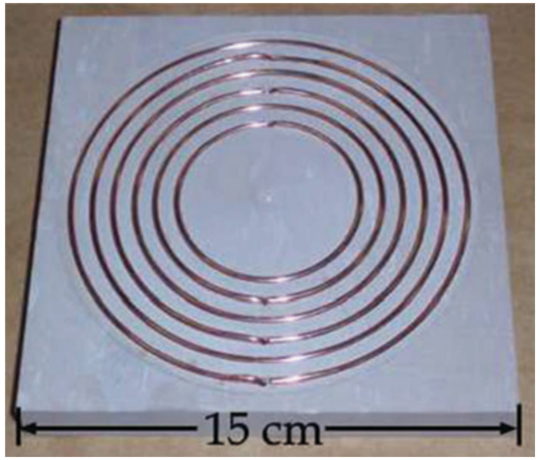
ENS DE LYON

Plasma potential shaping using cold electrodes

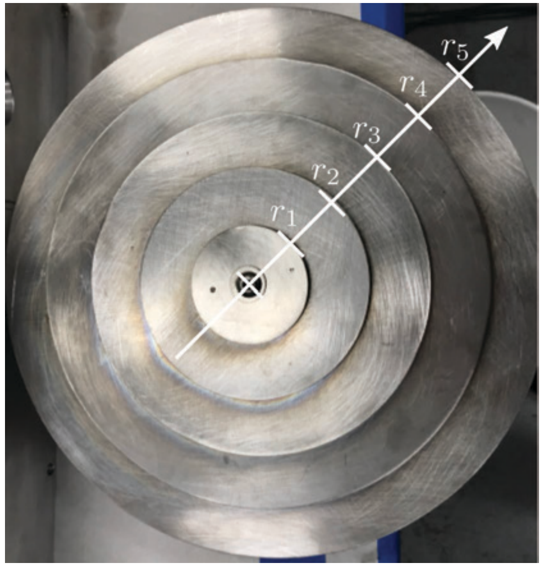




Tsushima, Sato
J. Phys. Soc. Japan (1991)

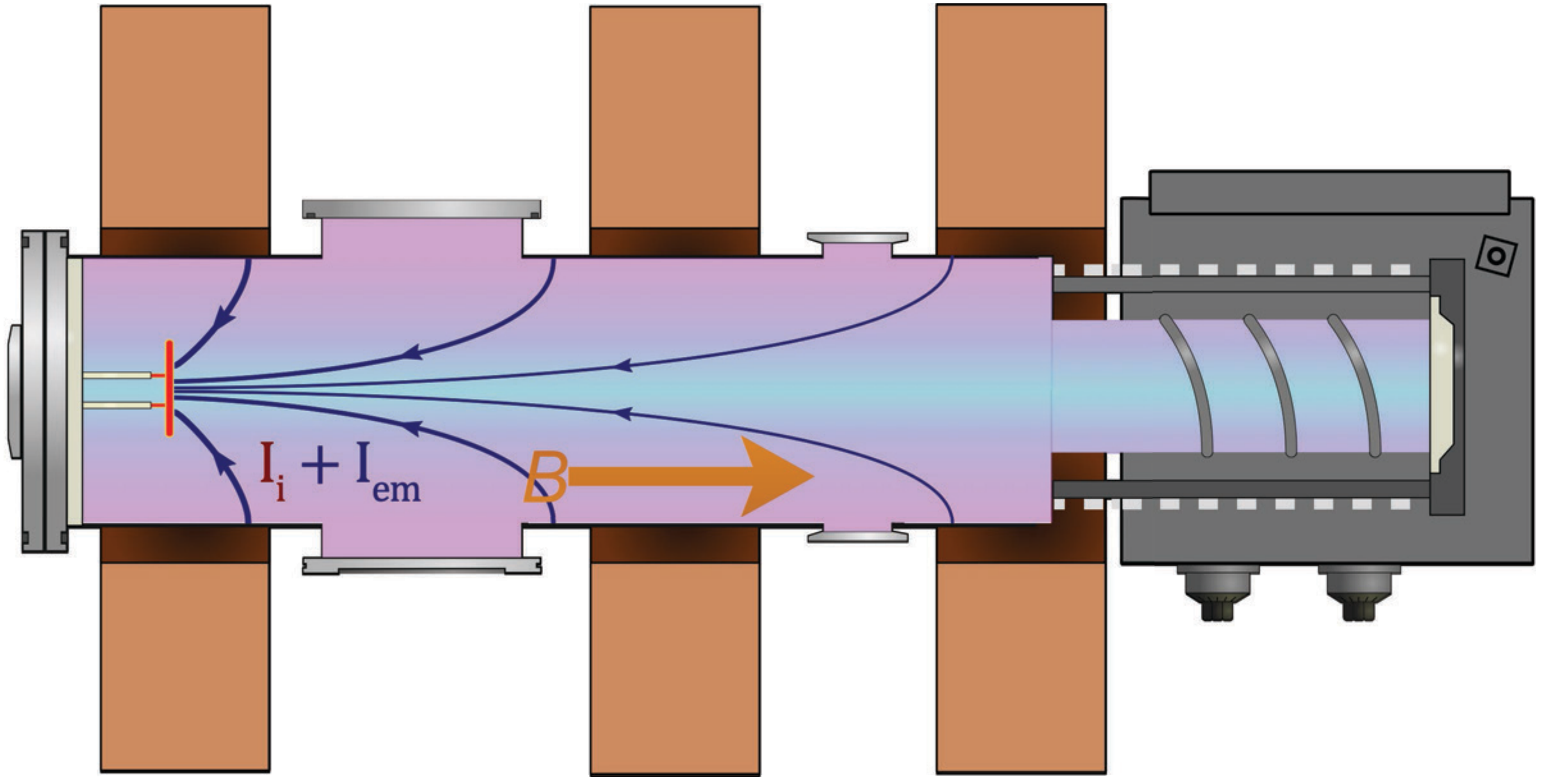


Desjardins, Gilmore
Phys. Plasmas (2018)



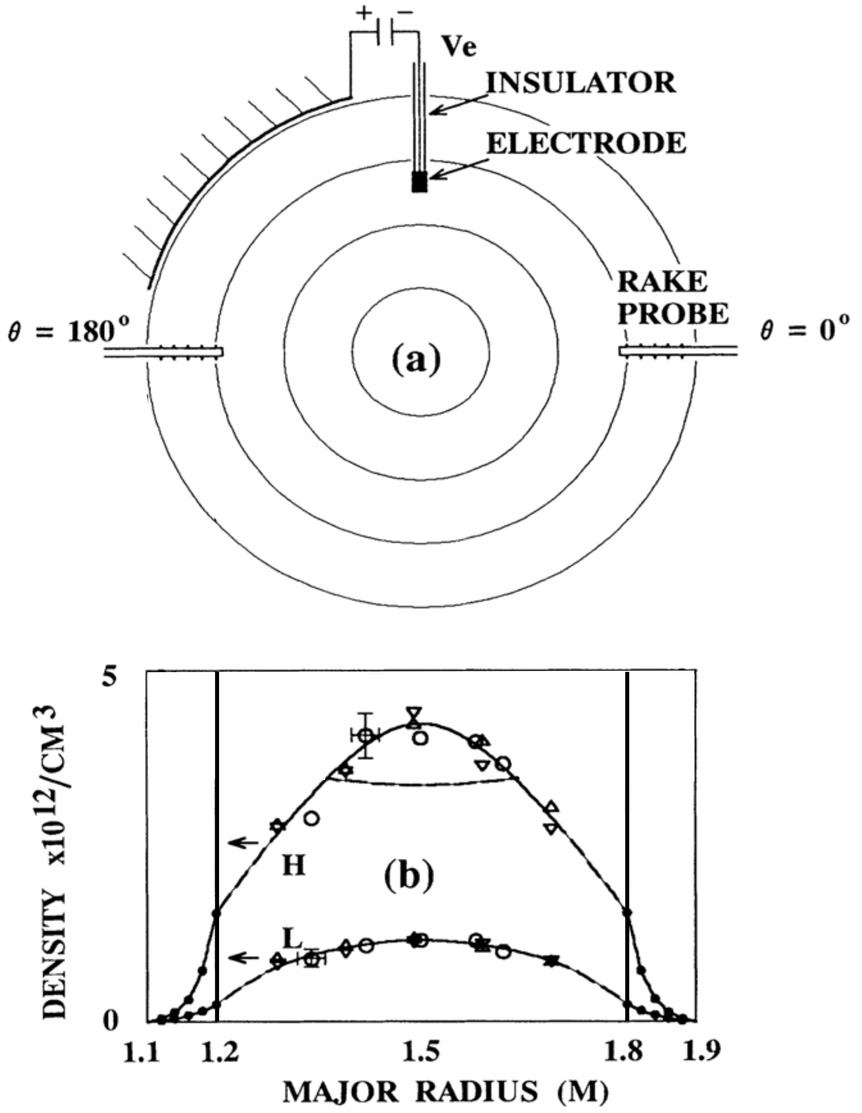
Gueroult *et al.*
ArXiv (2024)

Emissive cathodes: an additional control parameter

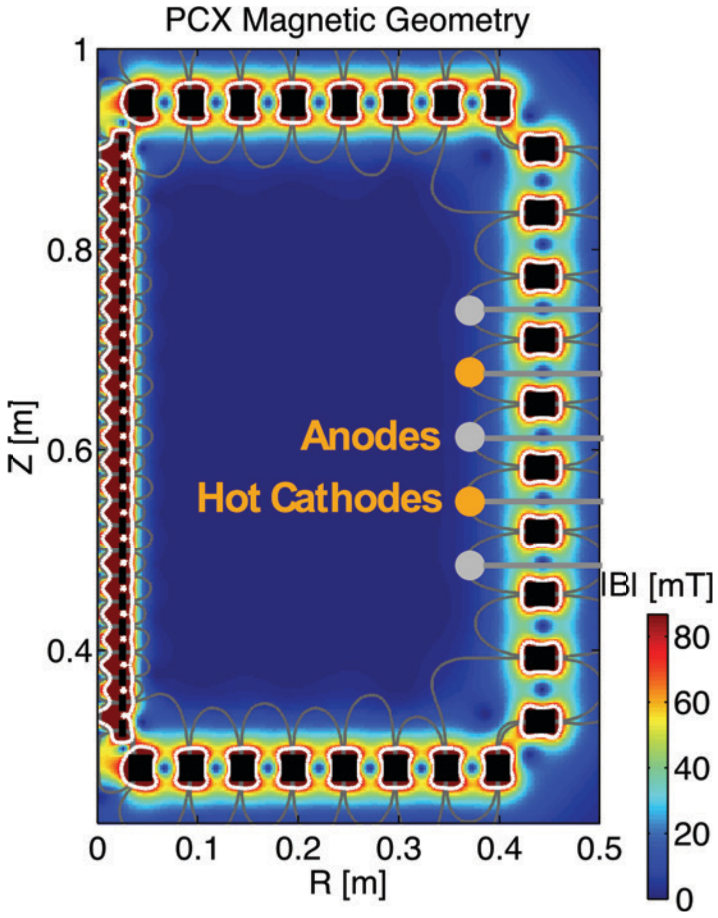


- Increase of the collected current
- Dimensionless control parameter : $\Xi = I_{em}/I_i \simeq 10$

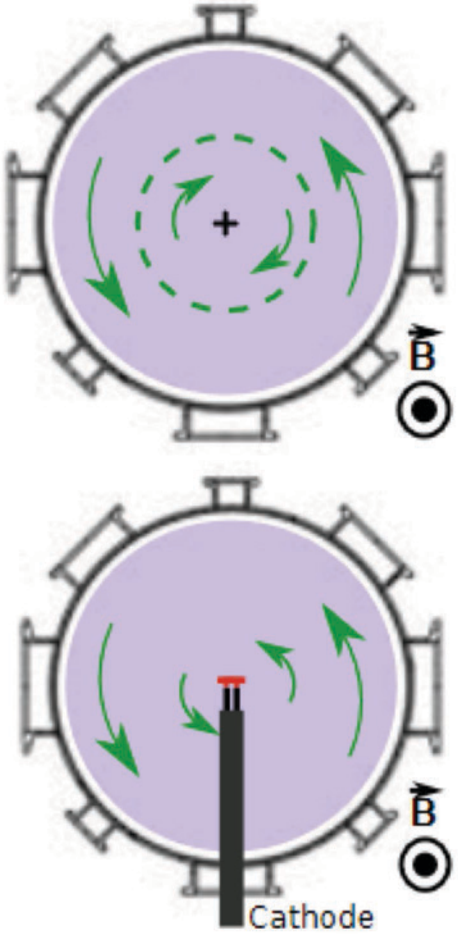
Influence of emissive cathode on potential and flows



Taylor *et al.*, Phys. Rev. Lett. (1989)



Collins *et al.*, Phys. Rev. Lett. (2012)
Flanagan *et al., Phys. Rev. Lett. (2020)*



Désangles *et al.*, J. Plasma Phys. (2021)

Experimental setup

Argon plasma

Inductive / helicon sources

$p_0 = 0.1 - 0.5 \text{ Pa}$

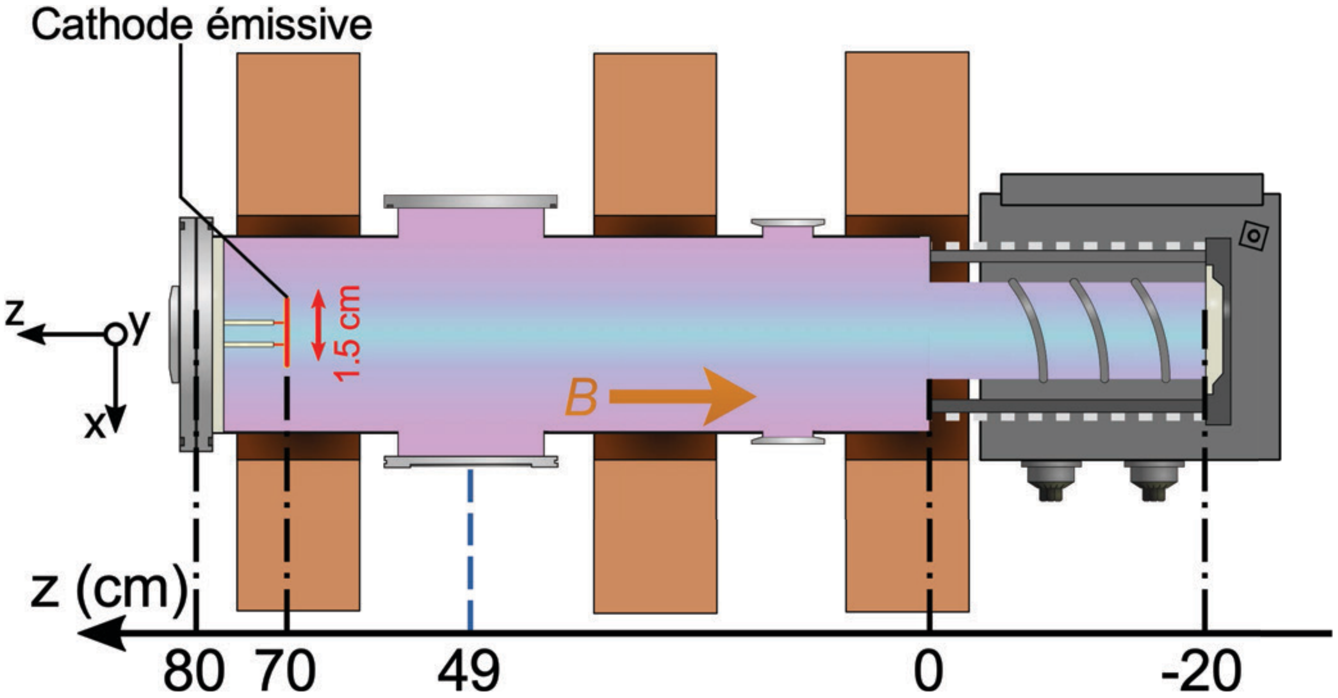
$P_w = 0.5 - 2 \text{ kW}$

$B = 100 - 1000 \text{ G}$

$n \sim 10^{18} \text{ m}^{-3}$

$T_e \sim 4 \text{ eV}$

$T_i \sim 0.2 \text{ eV}$



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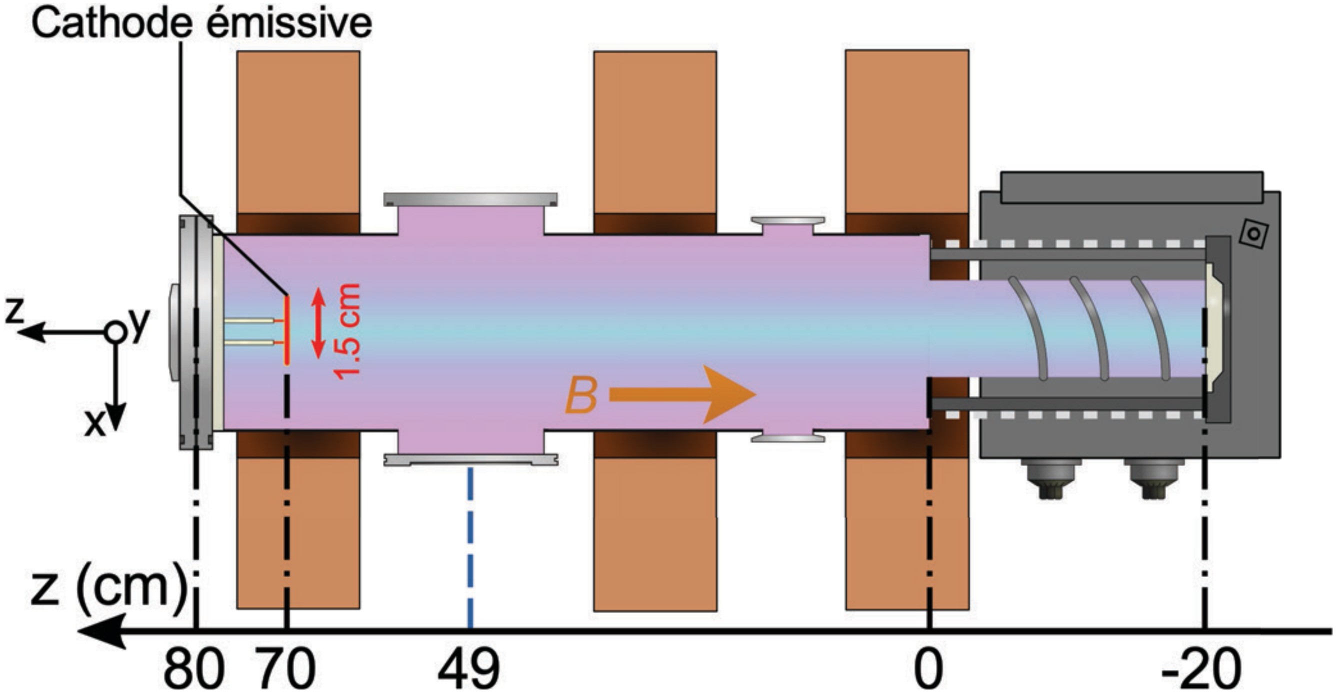
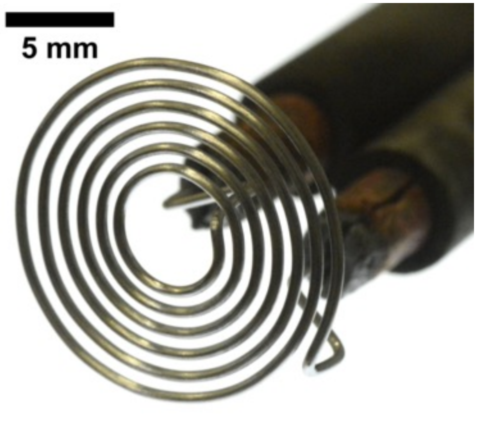
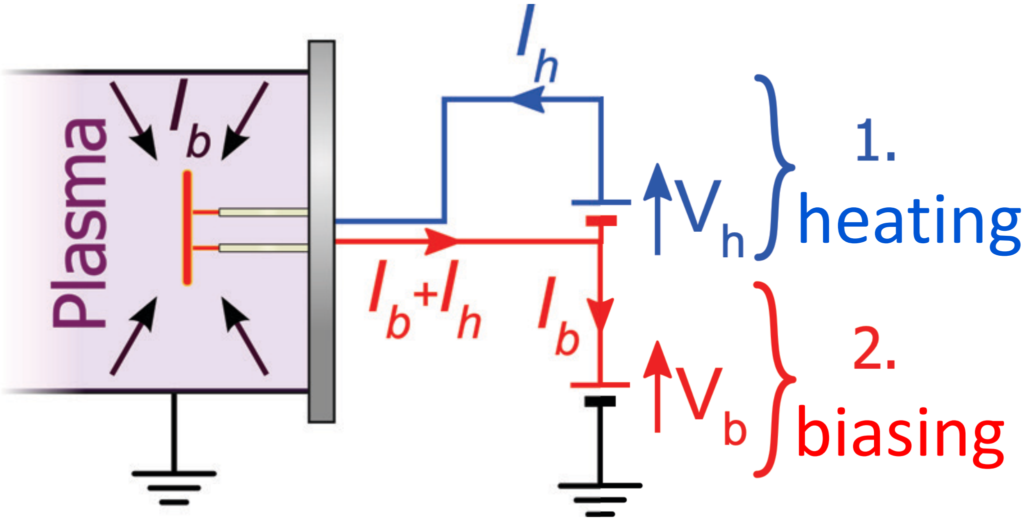
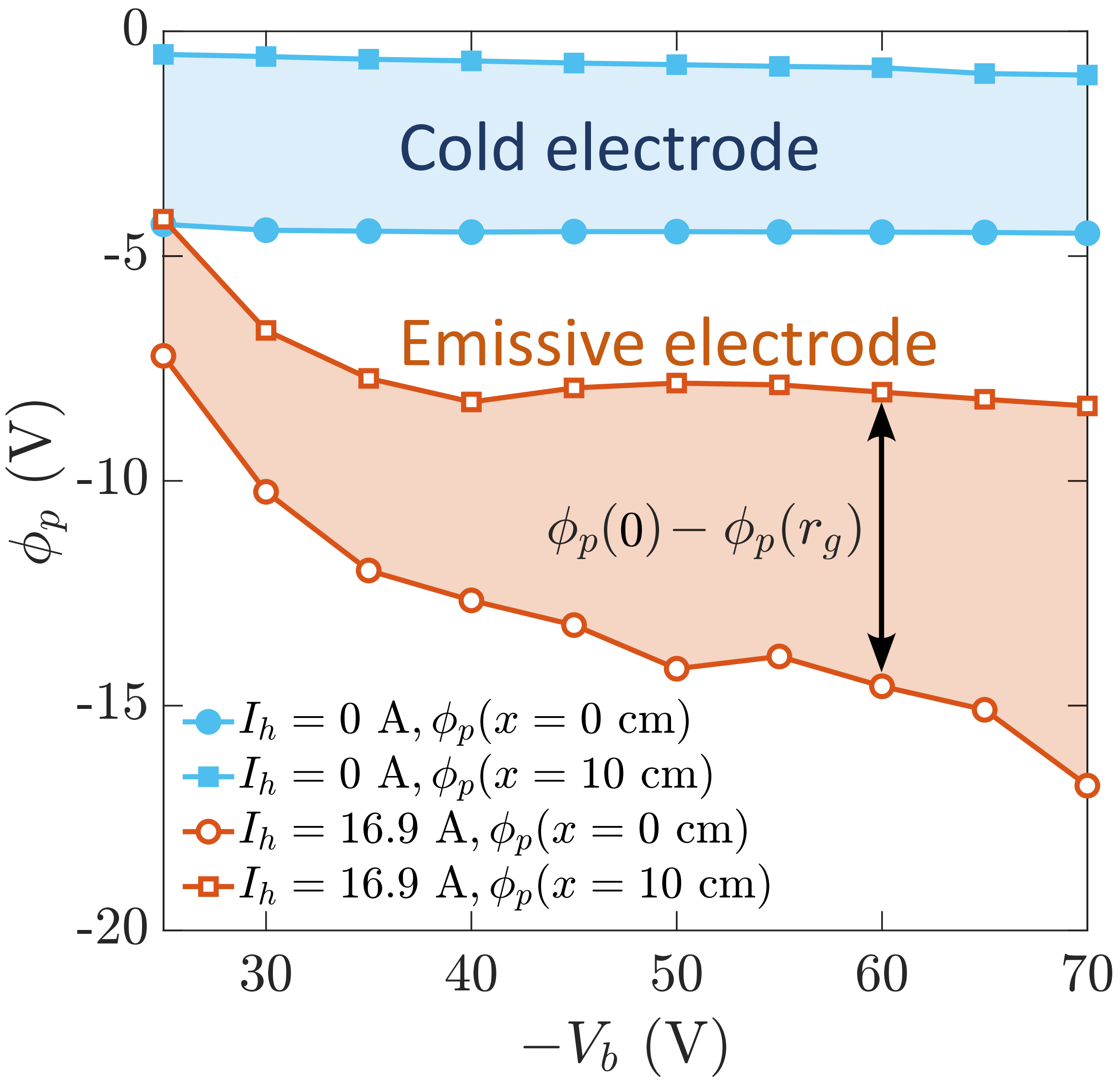
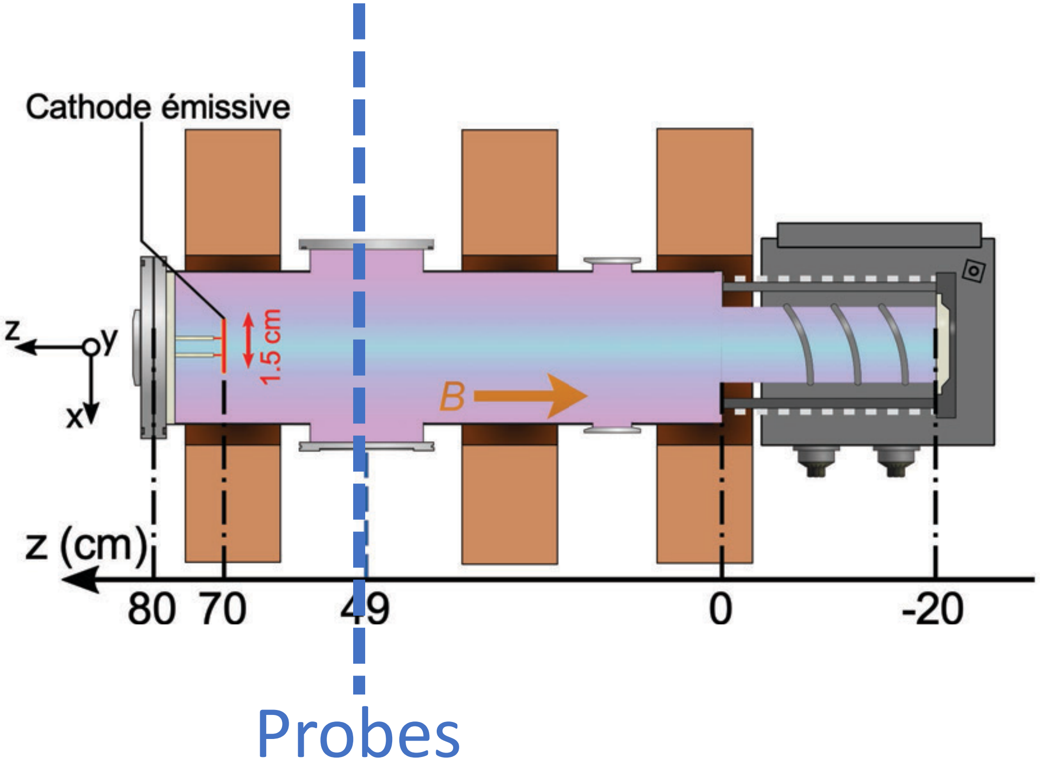




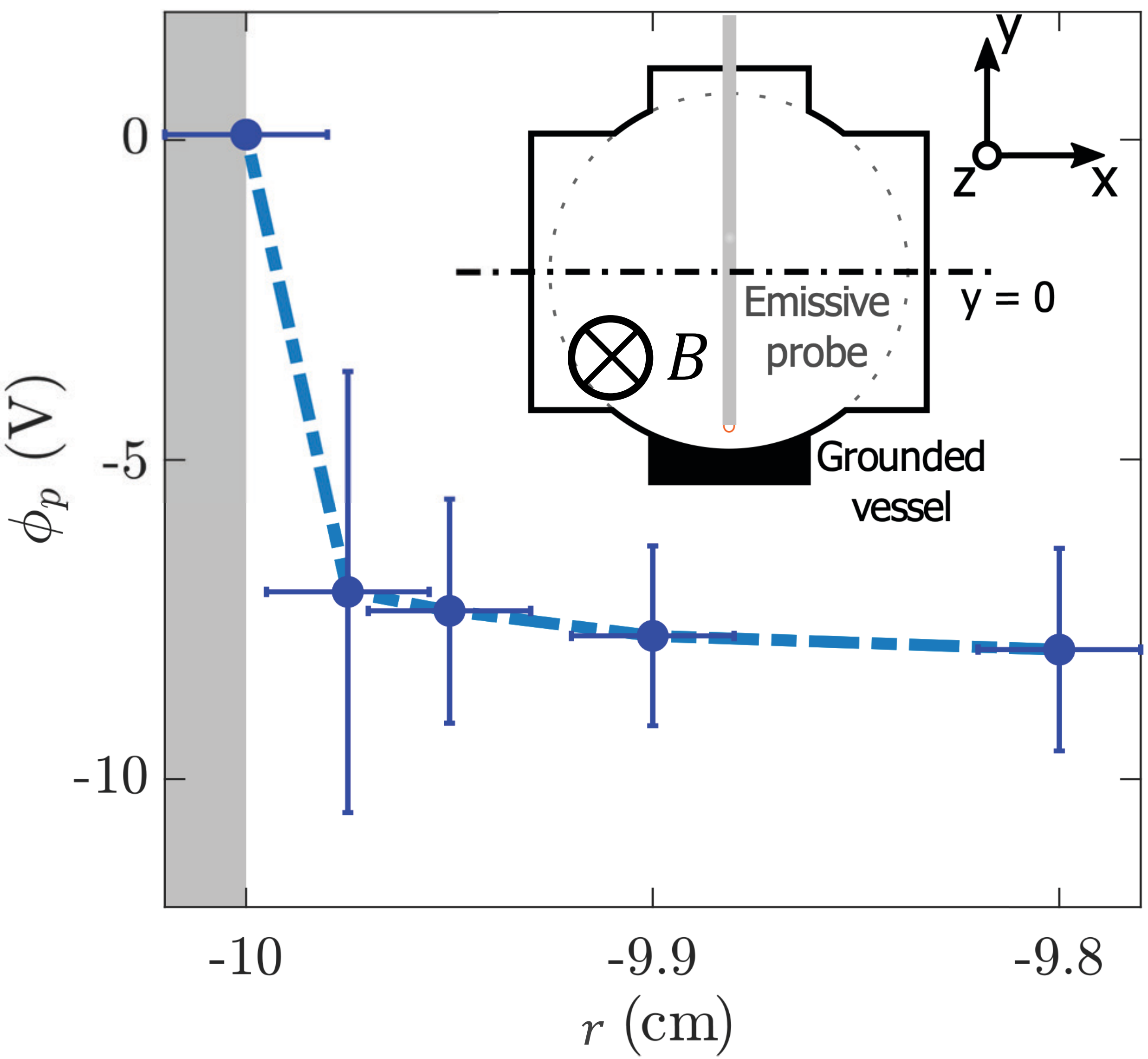


Plasma potential drive





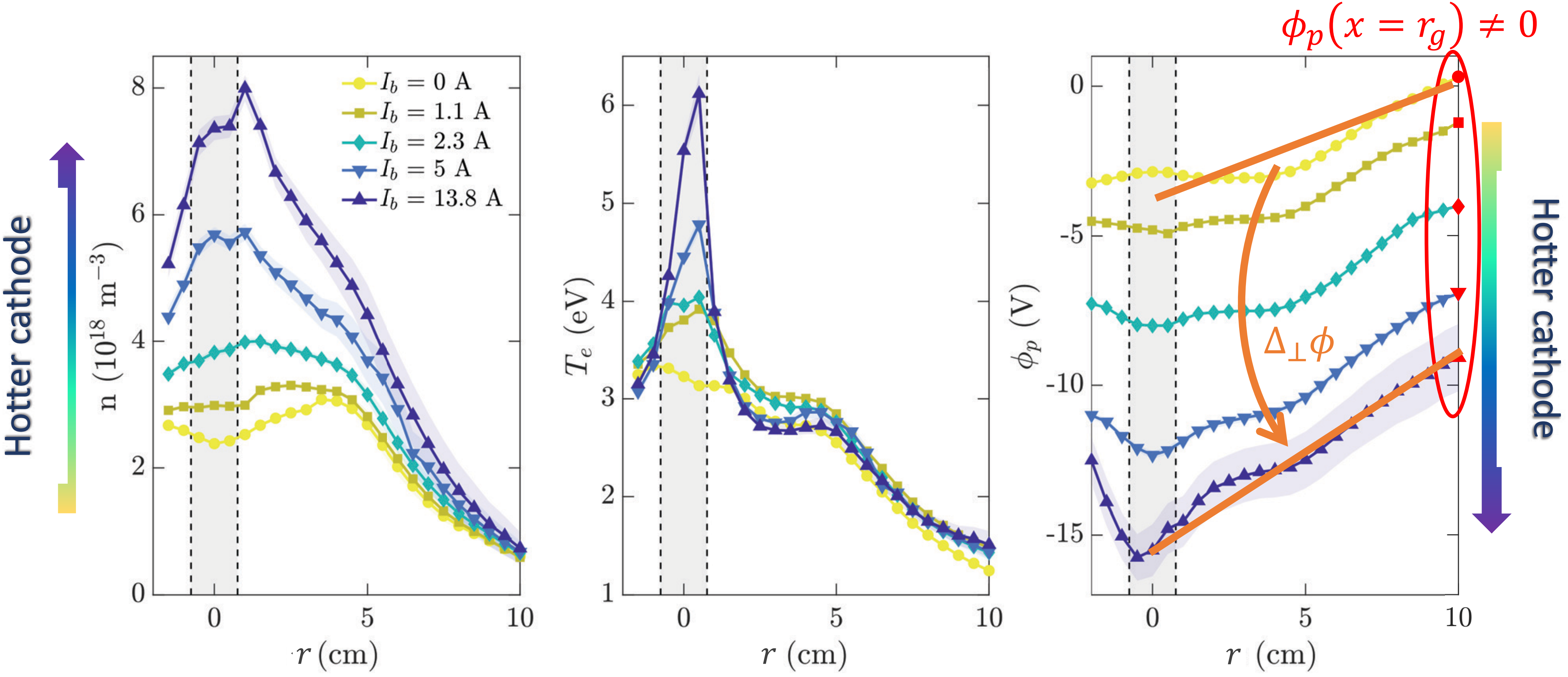
Large anode sheath



- Large anode sheath when $\Xi > 1$
- Electron extraction
- Grazing incidence

Radial scan of plasma parameters

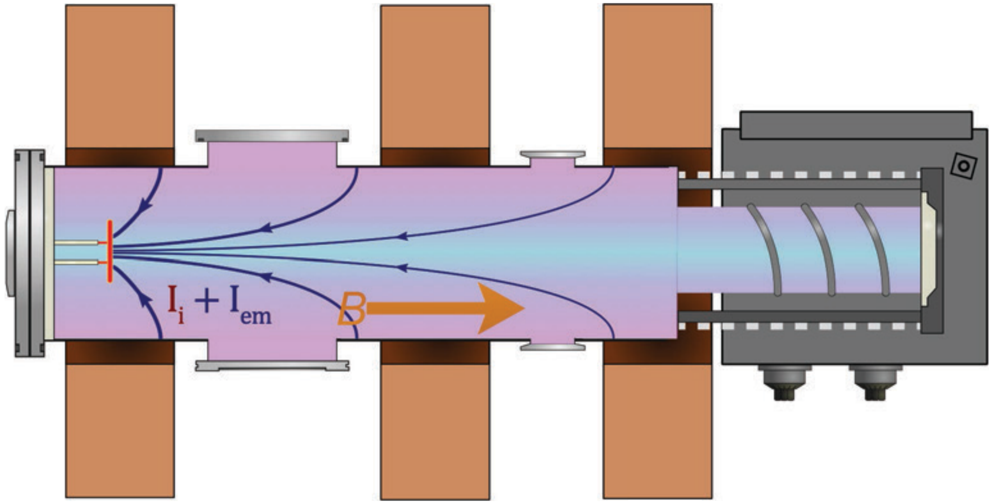
240 G, 0.27 Pa, 1 kW, V_b = -60 V

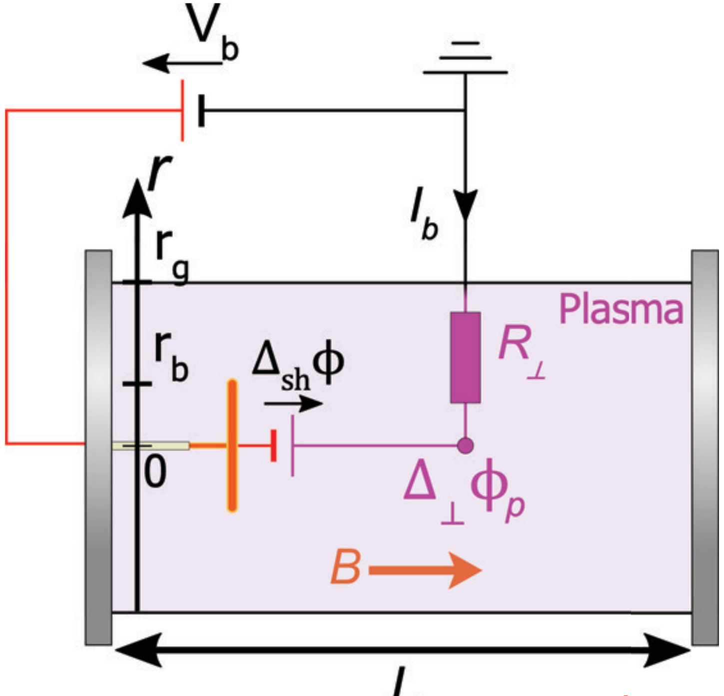


- Anode sheath $\phi_p(x = r_g)$, radial potential drop $\Delta_\perp \phi_p$

Plasma potential drive

Anisotropic conductivity : $\Delta_{\perp}\phi_p \gg \Delta_{||}\phi_p$





Collisions $(\omega_{c,i}, \nu_{in})$

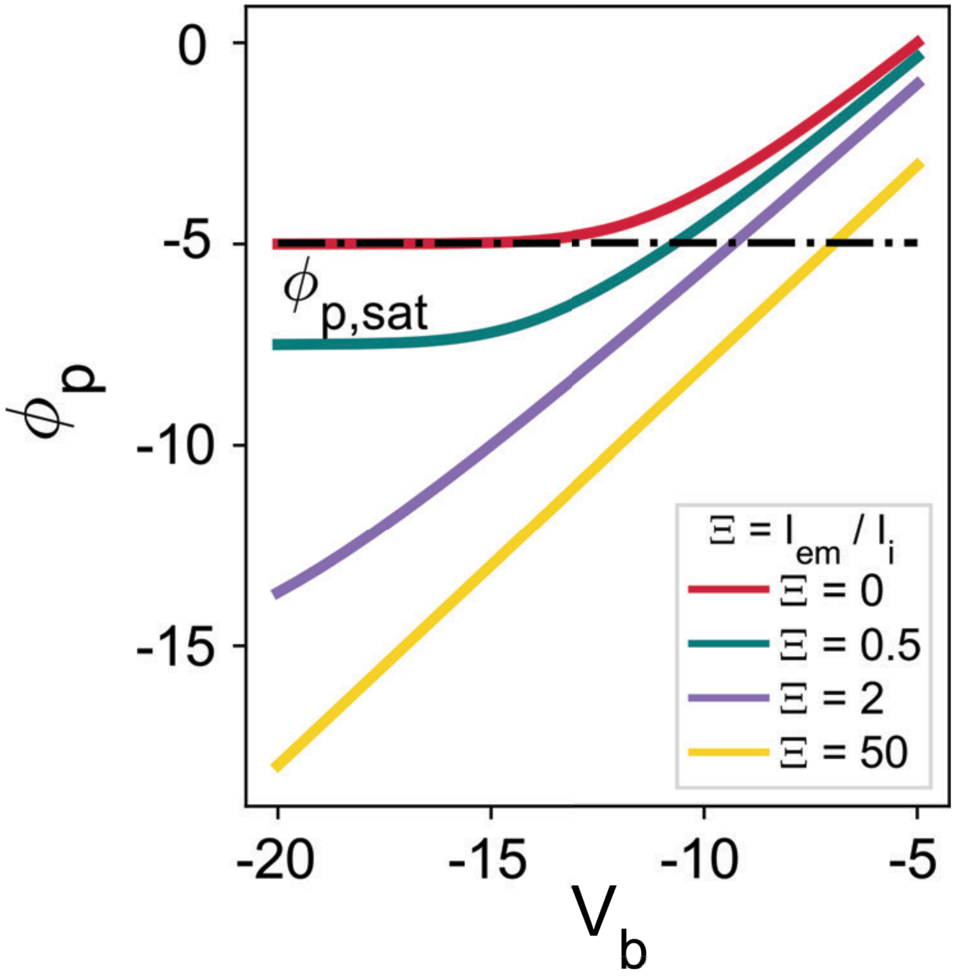
$$R_{\perp} = \int_{r_b}^{r_g} \frac{\eta_{\perp}(r)}{2\pi r L}\,\mathrm{d}r$$

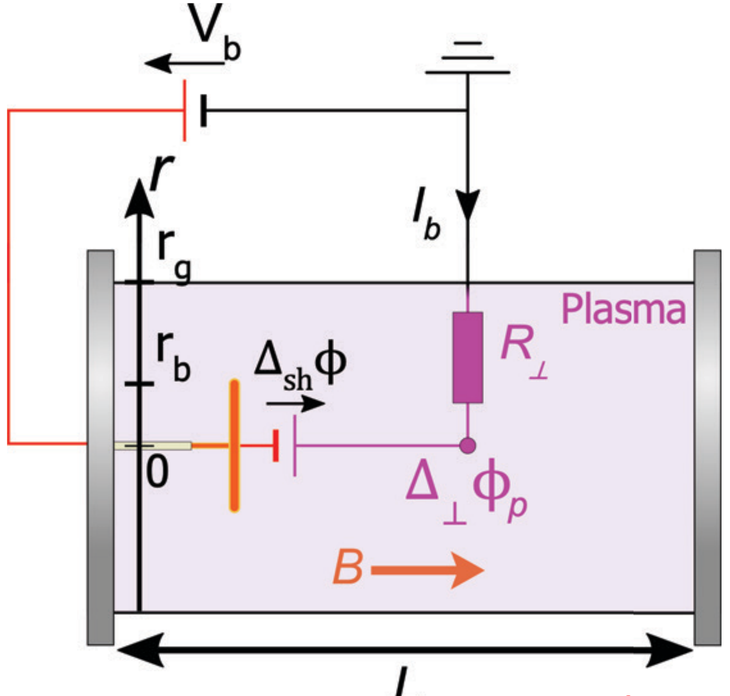
$$\boxed{\Delta_{\perp}\phi_p = R_{\perp} I_b}$$

Trotabas & Gueroult, PSST 2022

Plasma potential drive

Anisotropic conductivity : $\Delta_{\perp}\phi_p \gg \Delta_{||}\phi_p$





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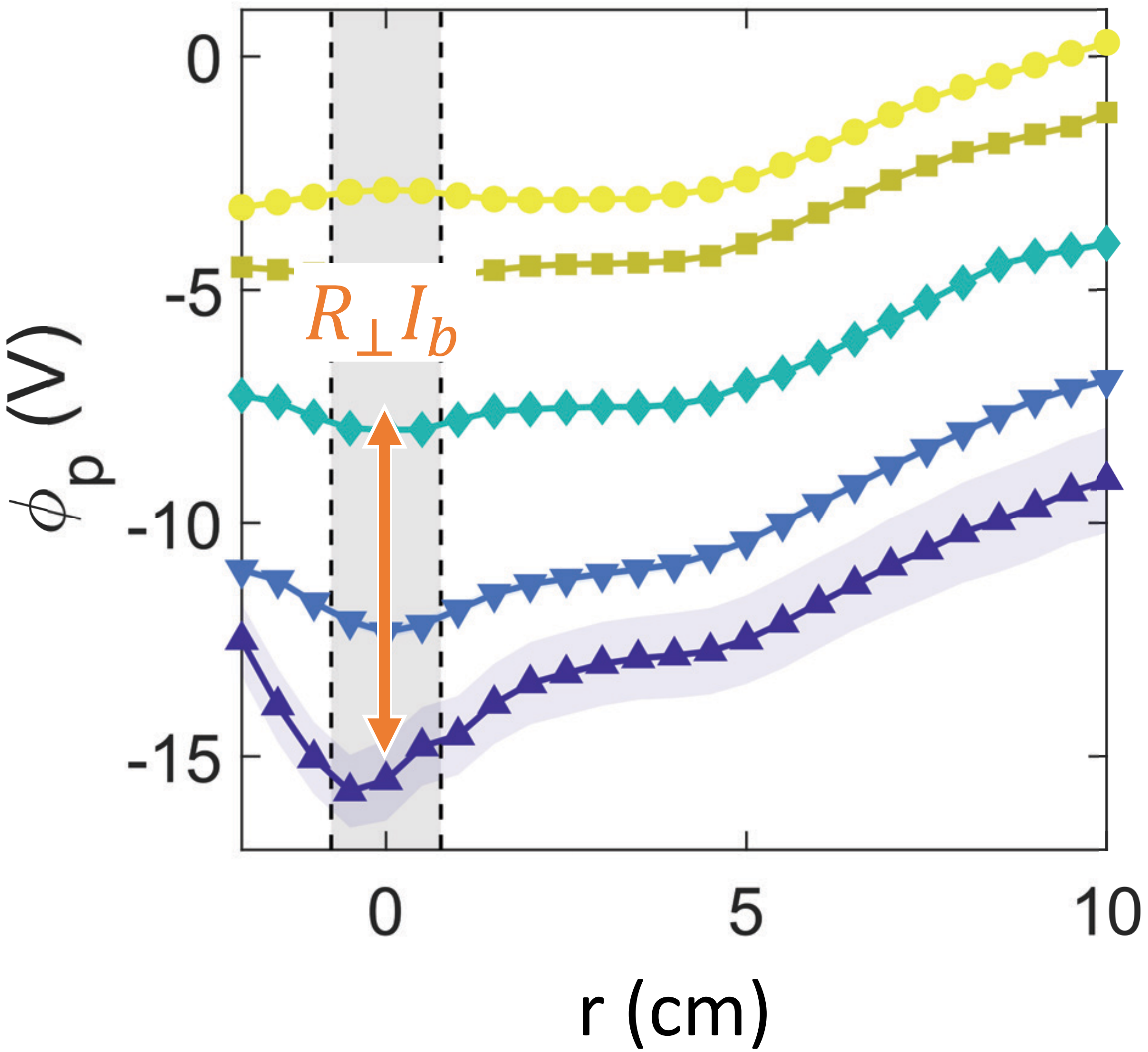
Trotabas & Gueroult, PSST 2022

Radial potential drop



- Model $$R_\perp = \int_{r_b}^{r_g} \frac{\eta_\perp(r)}{2\pi r L}\,\mathrm{d}r$$

- Parametric evolution

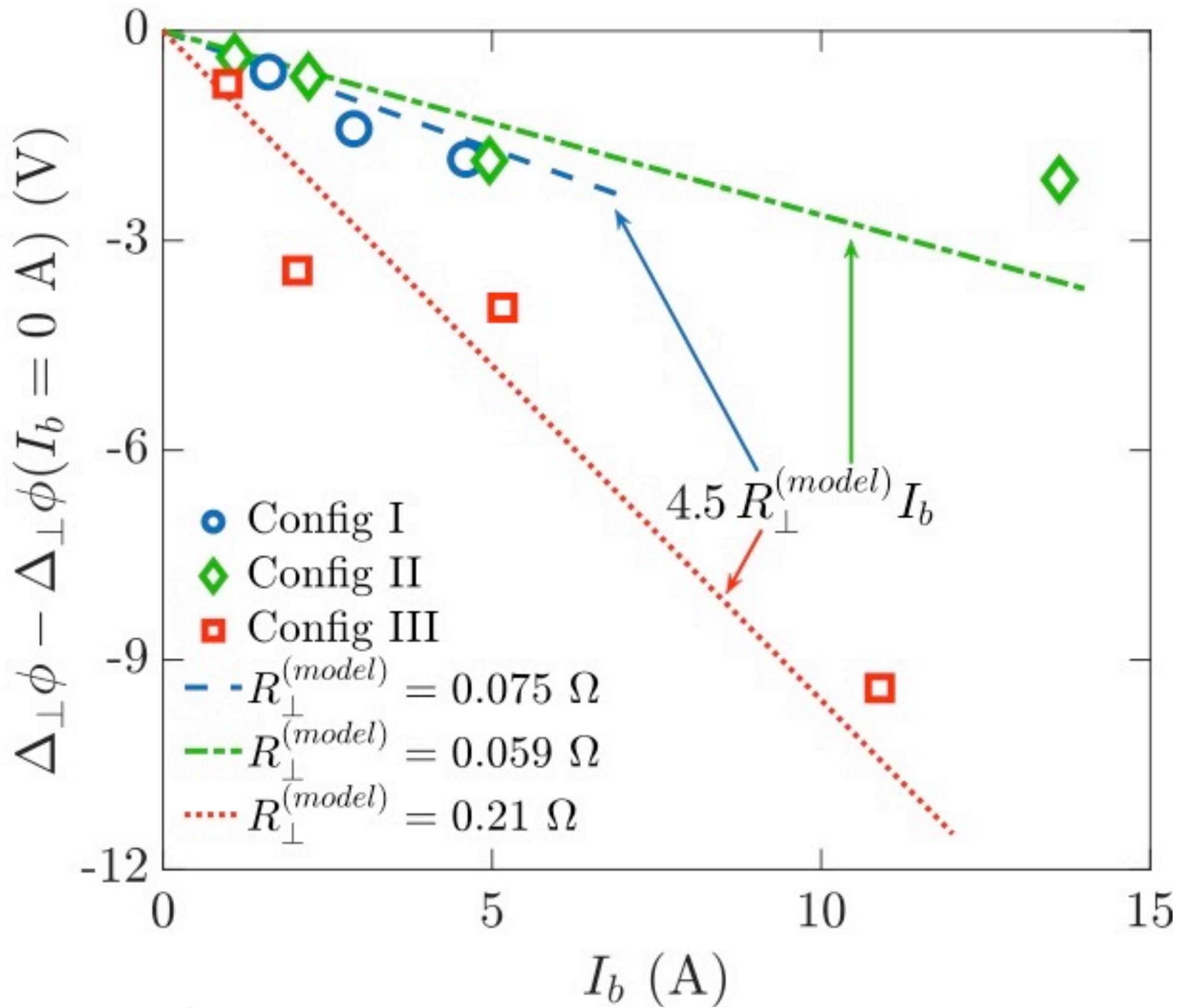
$$\eta_\perp \propto \frac{B^2}{p_0}\frac{1}{n(r)}$$

Control parameters

Measur.

Trotabas et Gueroult, Plasma Sources Sci. Technol. (2022)

Radial potential drop



● $B^2/p_0 = 1$ B = 170 G

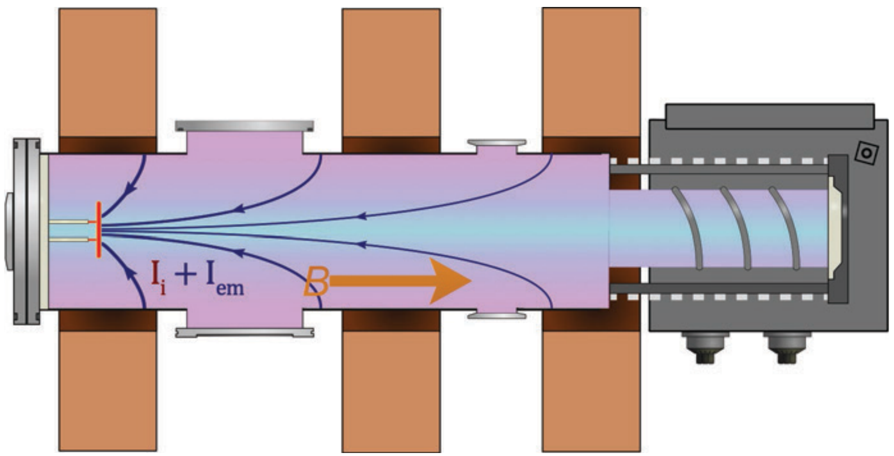
◆ $B^2/p_0 = 1$ B = 240 G

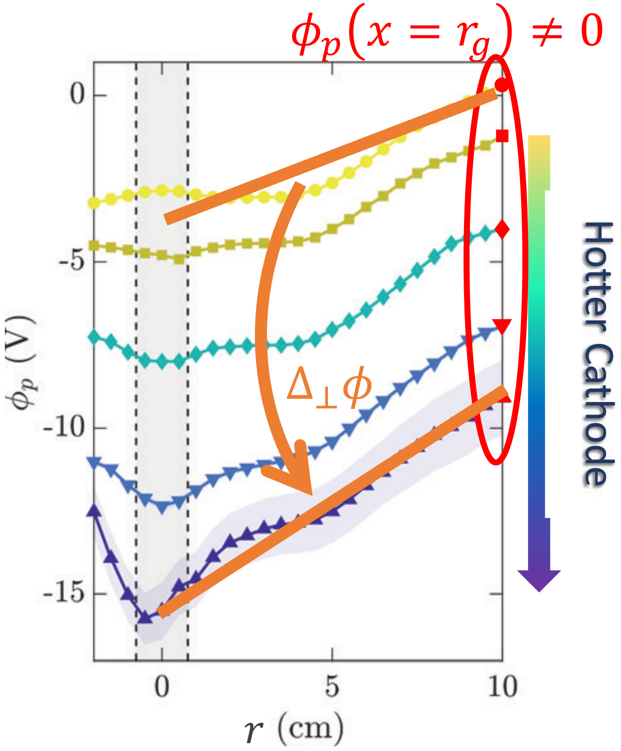
■ $B^2/p_0 = 2$ B = 340 G

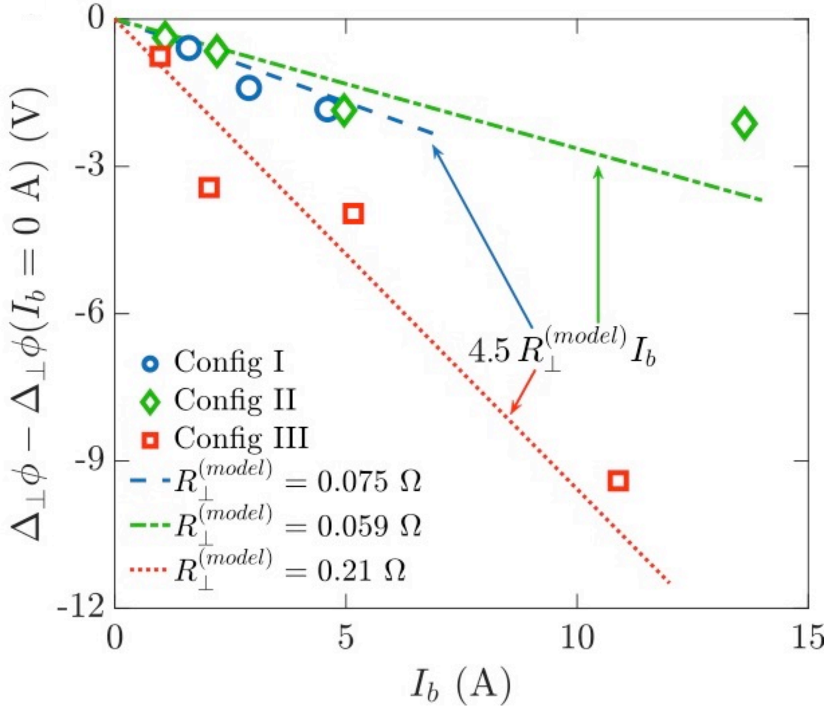
Qualitative agreement : $R_\perp \propto B^2/p_0$

Needs refinement for collisions modeling (neutral density, ion temperature)

Summary



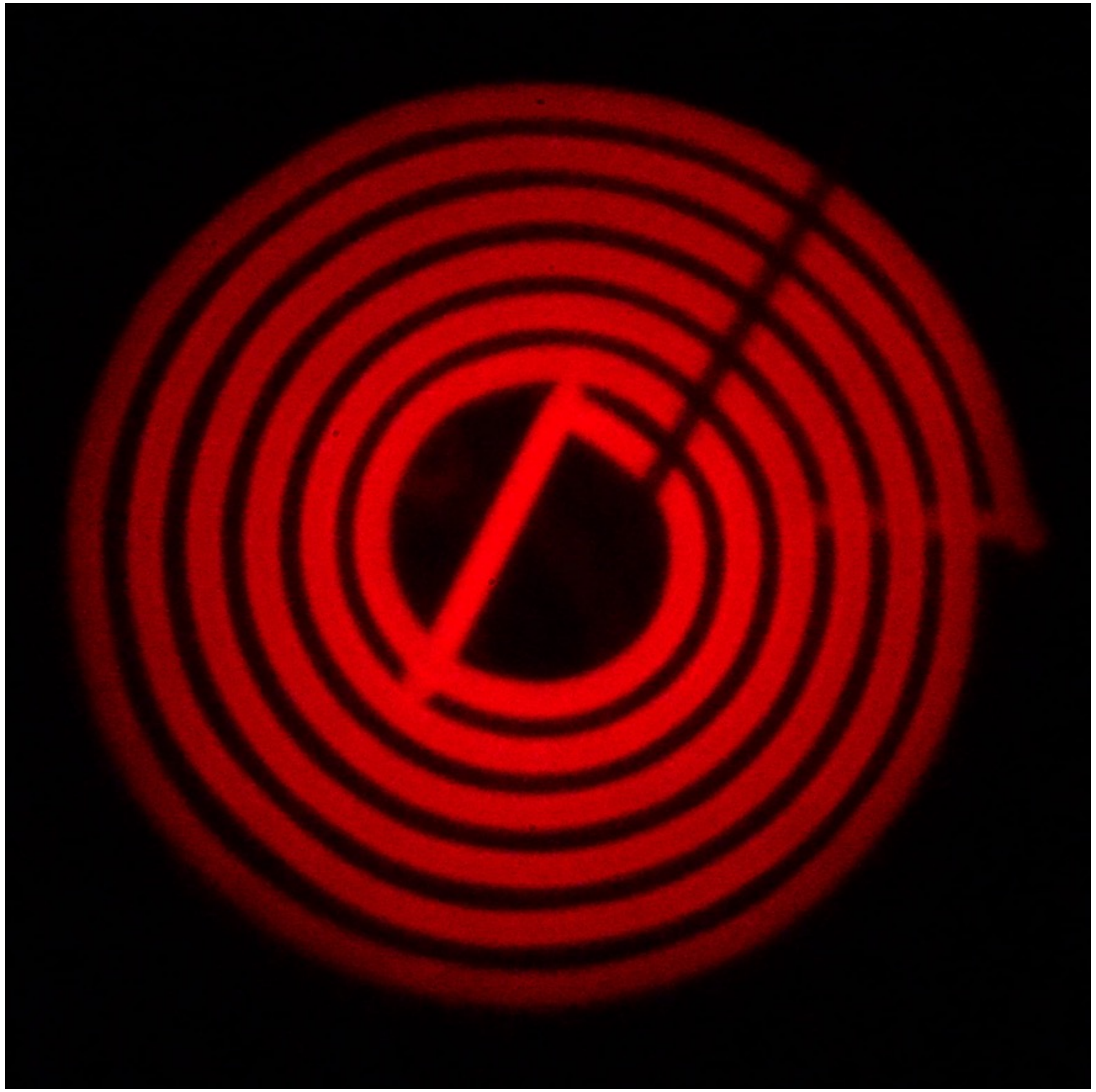




Large (a few Te) anode sheath

Bulk potential drop in qualitative agreement : $R_\perp \propto B^2/p_0$

Plasma-cathode interactions



Computation of I_{em} requires the knowledge of the cathode temperature

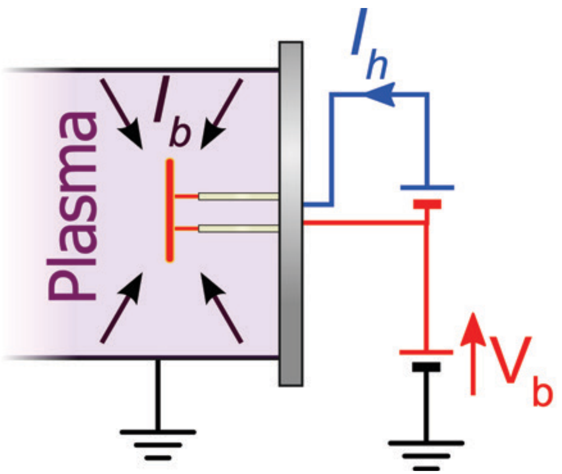
Pagaud *et al.* PSST (2023)
https://doi.org/10.1088/1361-6595/ad0b2f

Current emission control (naïve interpretation)

$$I_b = I_{em} + \cancel{I_i} - \cancel{I_e}$$

$$\Xi = I_{em}/I_i \gg 1$$

Richardson law $$I_{em} = A_G S \boxed{T_W^2} \exp\left(-\frac{eW}{k_B \boxed{T_W}}\right)$$



Power balance sets T_W

Joule heating

$$RI_h^2$$

Radiative cooling

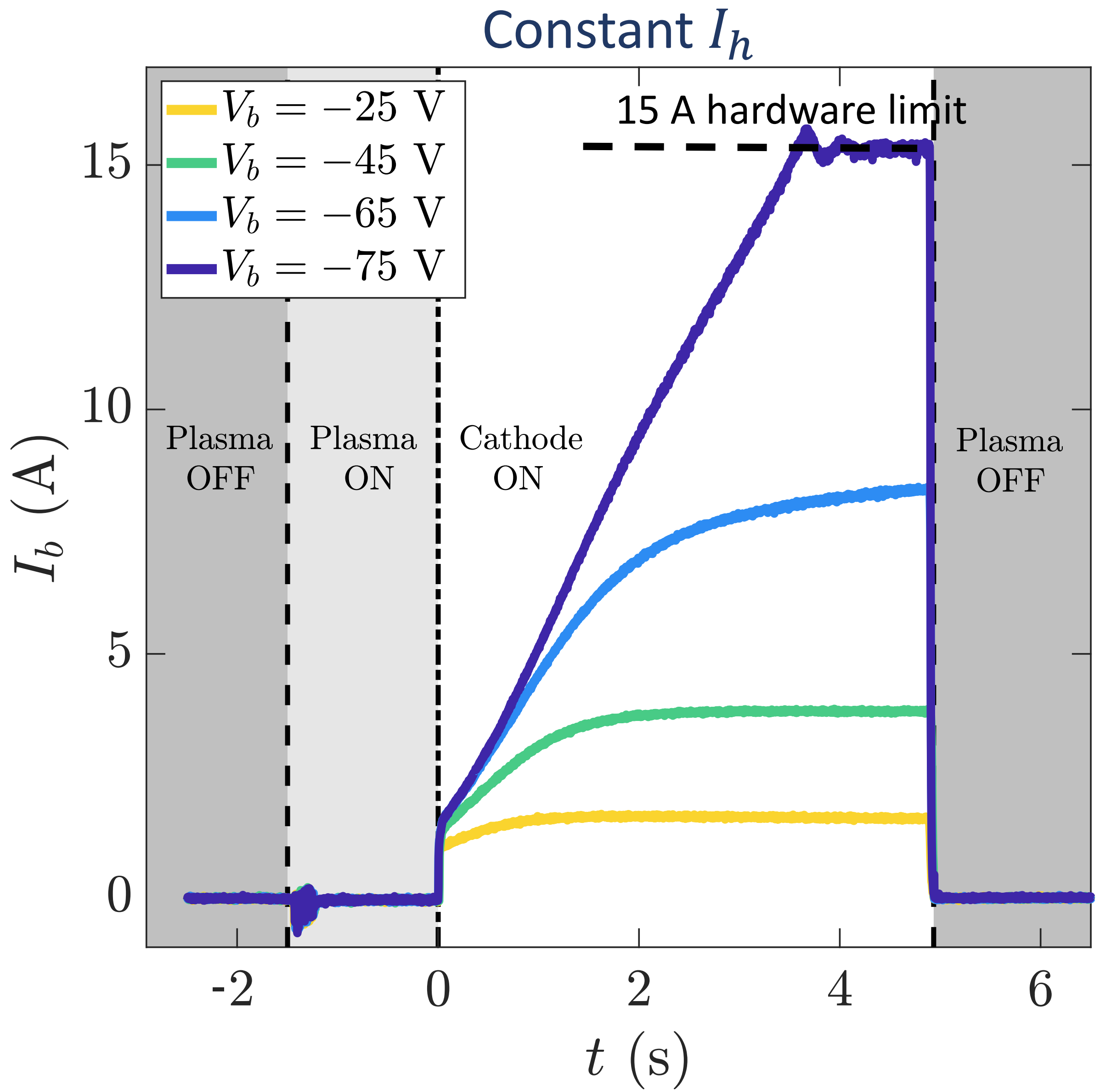
$$\sigma S \epsilon T_W^4$$

$$T_W \propto \sqrt{I_h}$$

$$I_b \propto I_h \exp\left(-1/\sqrt{I_h}\right)$$

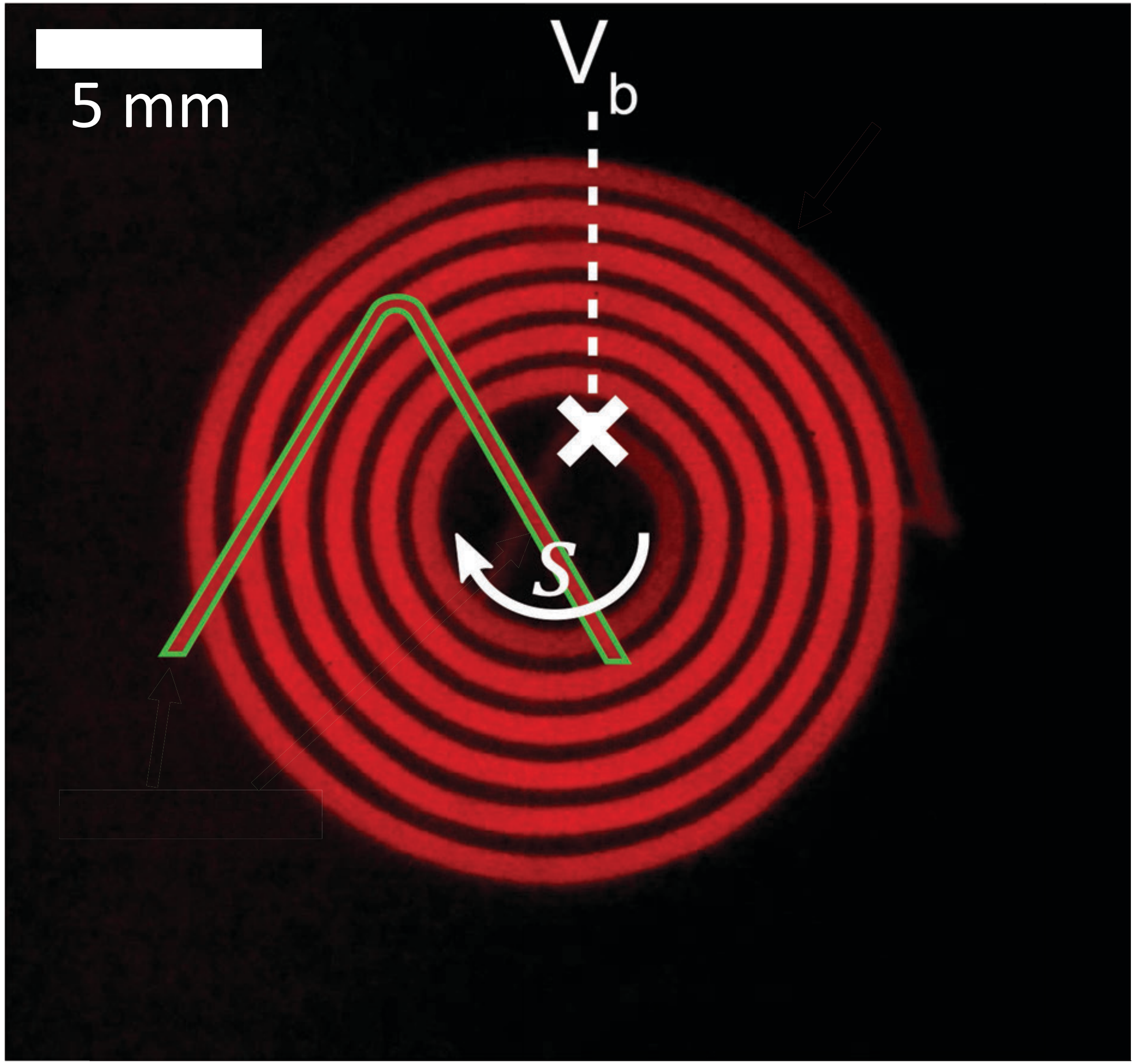
The heating power supply controls cathode current

Influence of biasing voltage on current emission



Precise current estimate requires
the knowledge of T_W
thus a refined power balance

Temperature measurements

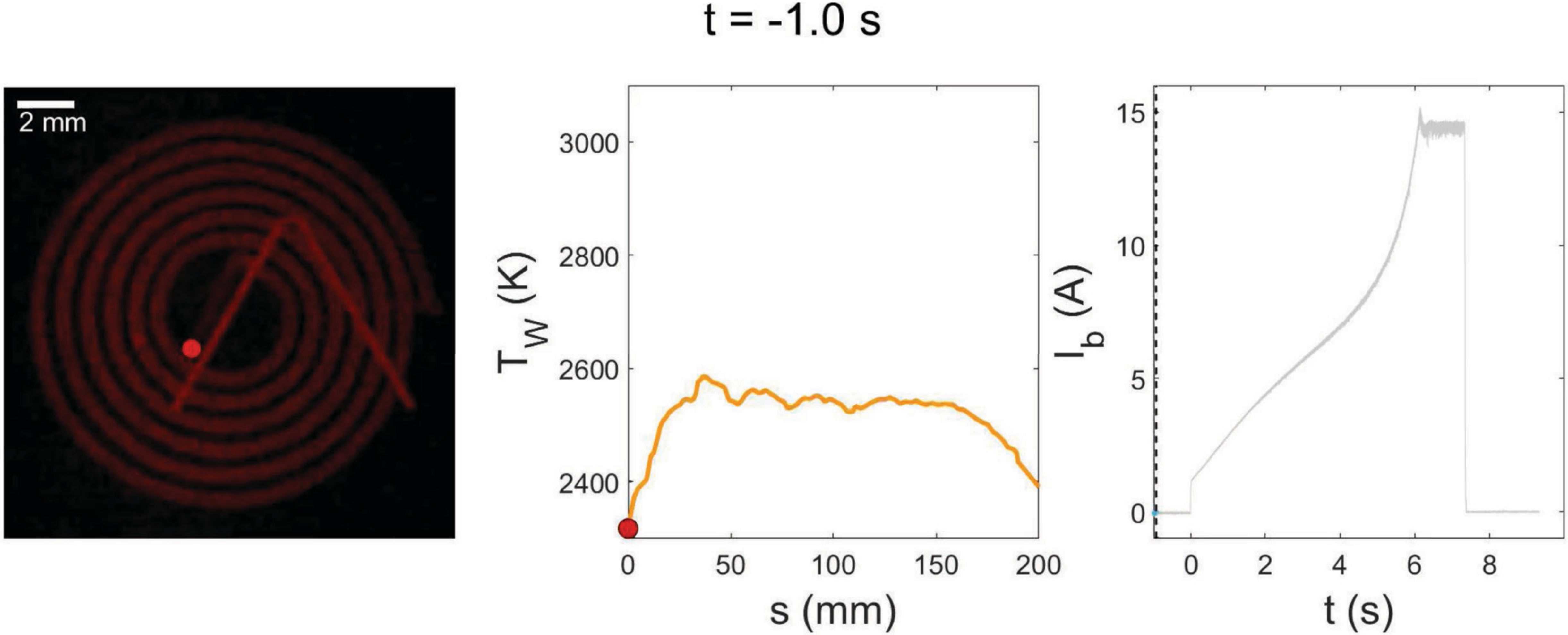


Pyrometry from light intensity measurement at 650 nm.

Spatially and temporally resolved

Collaboration : Nicolas Claire, PIIM (Aix-Marseille)

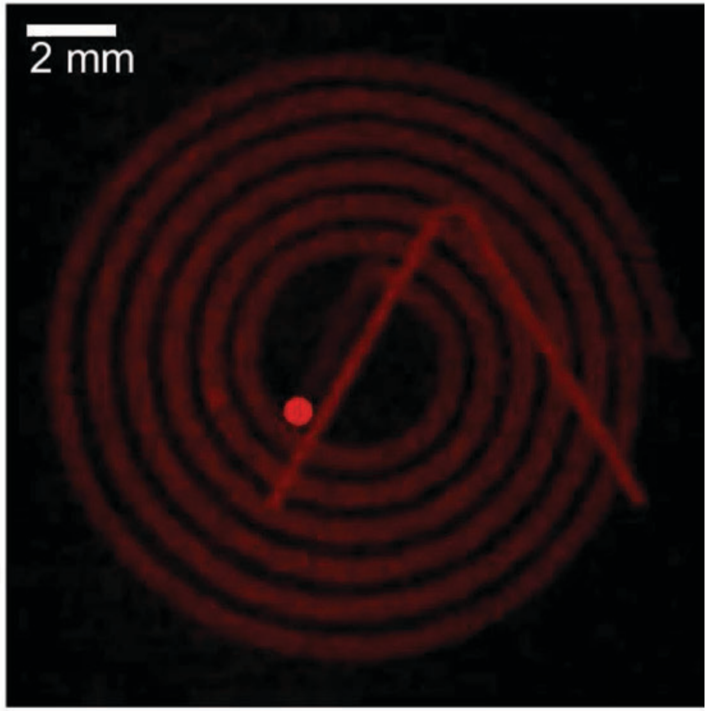
Highly inheomogeneous temperature profile

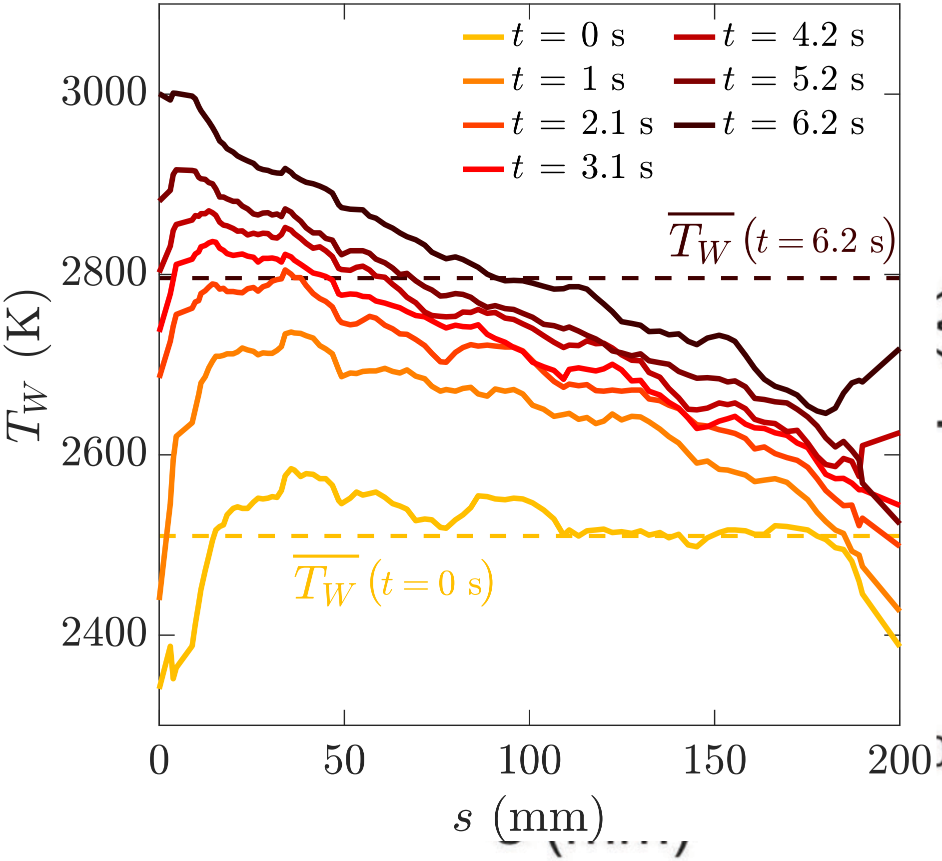


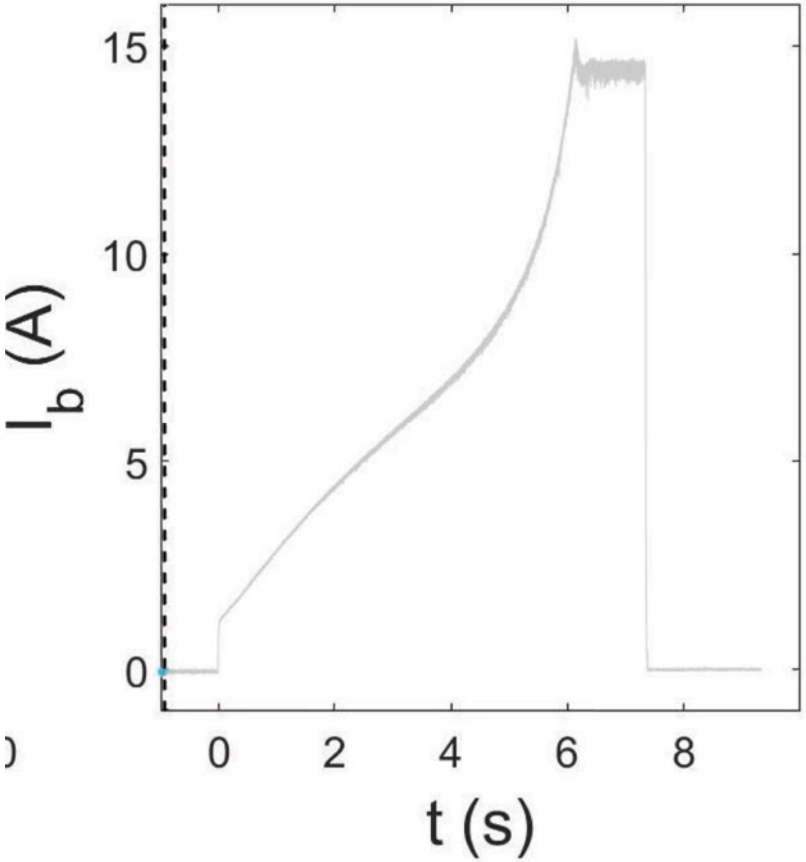
- Inhomogeneous heating due to electron emission
    - Current divergence when T_W reaches 3000 K

Highly inheomogeneous temperature profile

t = -1.0 s







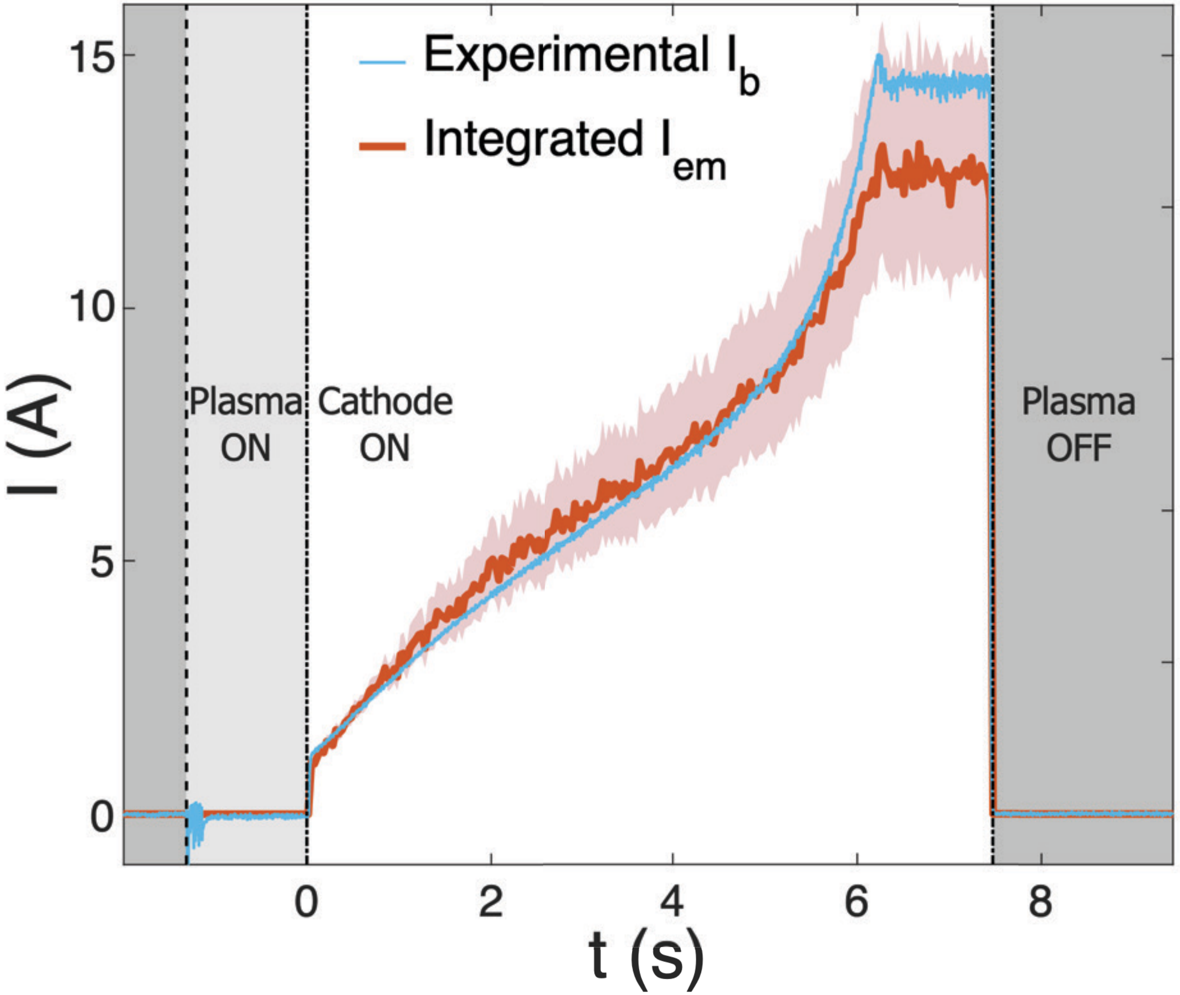
- Inhomogeneous heating due to electron emission
  - Current divergence when T_W reaches 3000 K

Cathode current in agreement with Richardson law

$$I_b = I_{em} + \cancel{I_i} - \cancel{I_e}$$

$$\Xi = I_{em}/I_i \gg 1$$

$$I_{em} = \int_0^s A_G \boxed{T_W^2} \exp\left(-\frac{eW}{k_B \boxed{T_W}}\right) 2\pi r\, dx$$



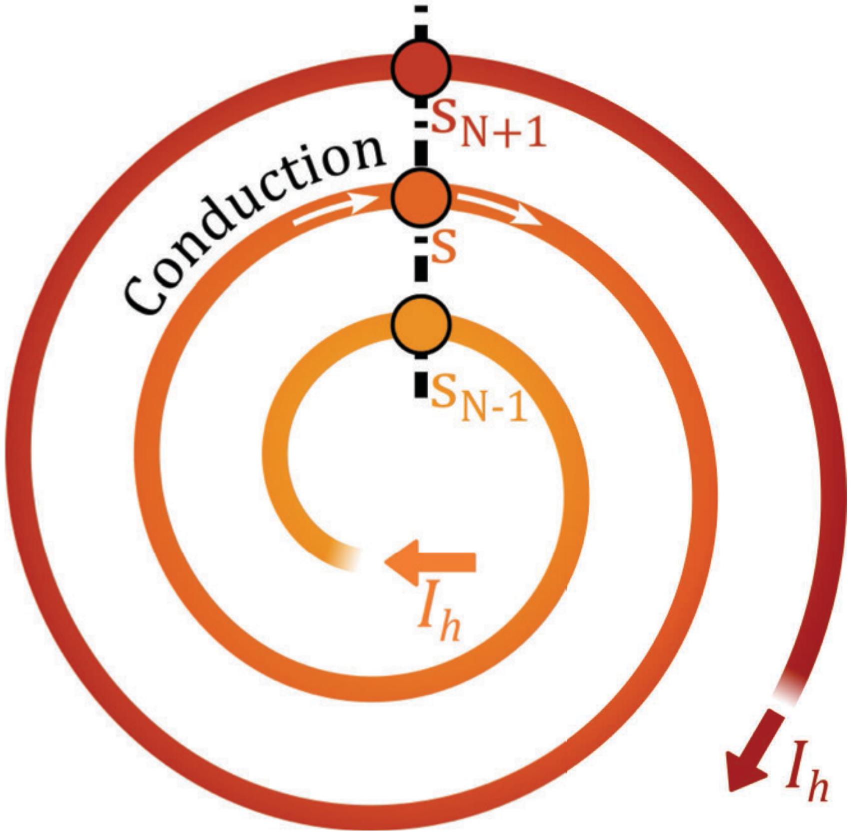
I_b in agreement with Richardson law when inserting measured T_W profiles.

Predicting T_W requires thermal modeling

Thermal model

In absence of plasma-cathode interactions

$$\dot{H} = \dot{Q}_\Omega + \dot{Q}_c$$



Thermal Inertia : $\dot{H} = C_p \rho V \frac{\partial T_W}{\partial t}$

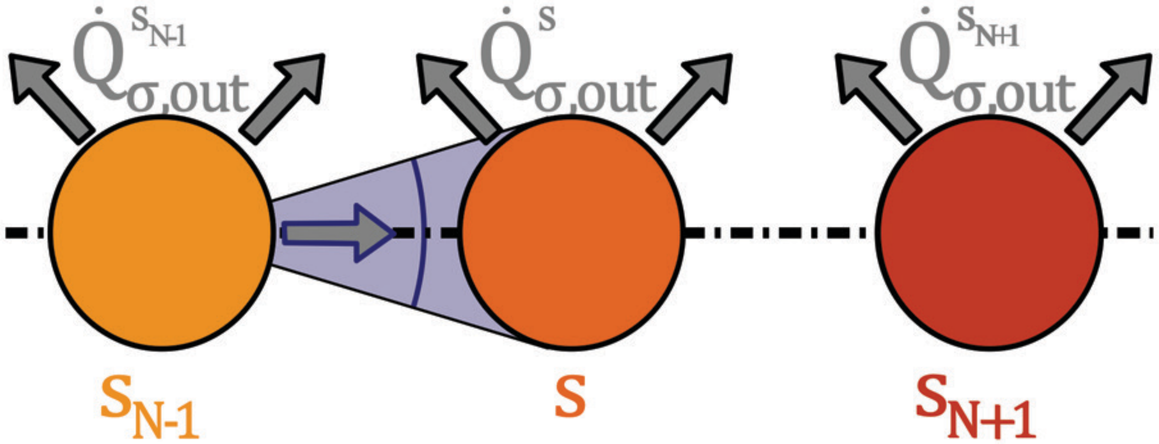
Joule heating : $\dot{Q}_\Omega = R(I_h + I_b)^2$

Thermal conduction : $\dot{Q}_c = \lambda \pi r^2 \frac{\partial^2 T_W}{\partial s^2}$

Thermal model

In absence of plasma-cathode interactions

$$\dot{H} = \dot{Q}_\Omega + \dot{Q}_c - \dot{Q}_{\sigma,out} + \dot{Q}_{\sigma,in}$$



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Thermal conduction : $\dot{Q}_c = \lambda \pi r^2 \frac{\partial^2 T_W}{\partial s^2}$

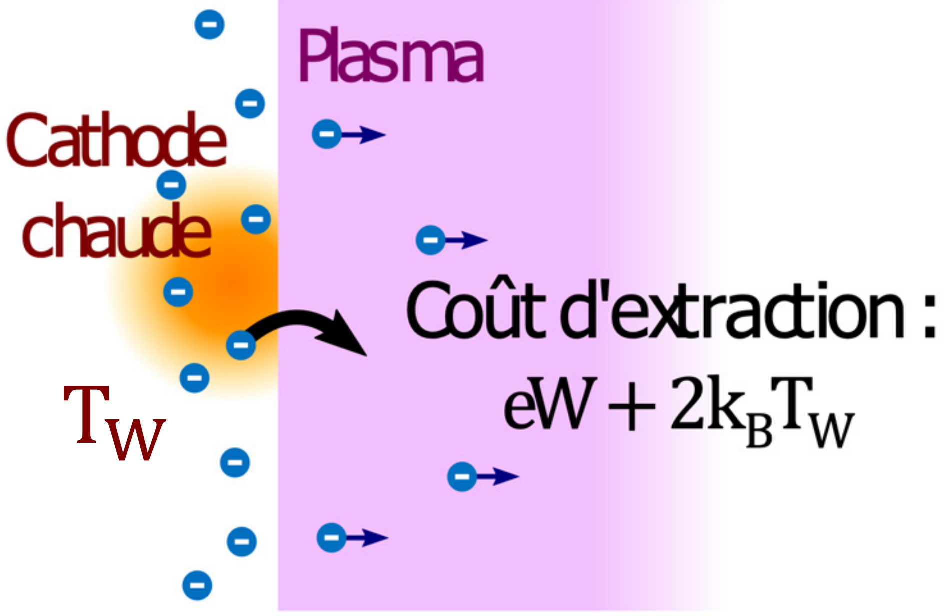
Radiative cooling : $\dot{Q}_{\sigma,out} = \sigma S \epsilon T_W^4$

Spiral geometry : $\dot{Q}_{\sigma,in} = C_1 \left(Q^{N-1}_{\sigma,out} + Q^{N+1}_{\sigma,out}\right)$

Geometry : $C_1 \approx 0.15$

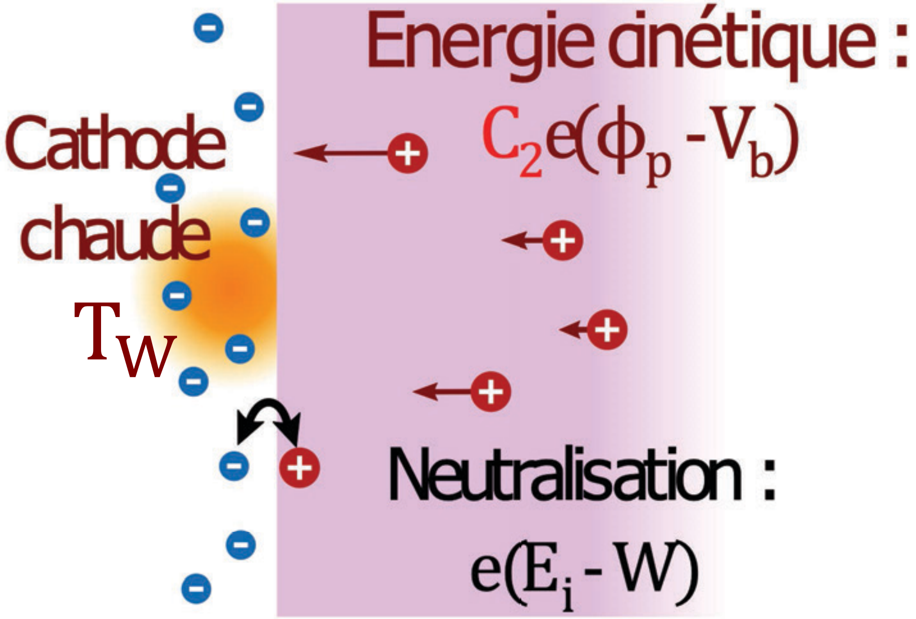
Plasma cathode interactions

Cooling from electron emission



$$\dot{Q}_e = \frac{I_{em}}{e}(eW + 2k_B T_W)$$

Heating from ion bombardment



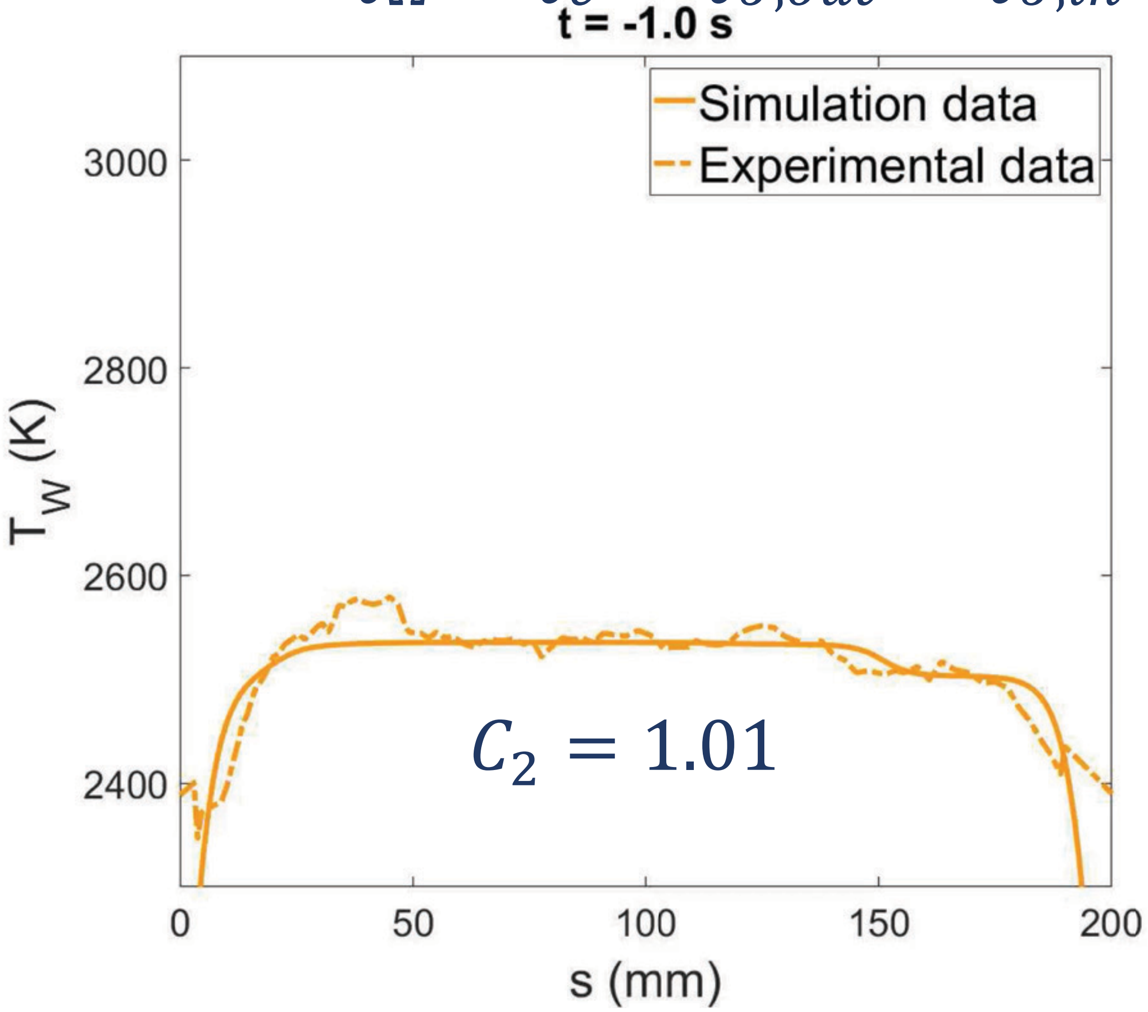
$$\dot{Q}_i = \frac{I_i}{e} e[E_i - W + C_2(\phi_p - V_b)]$$

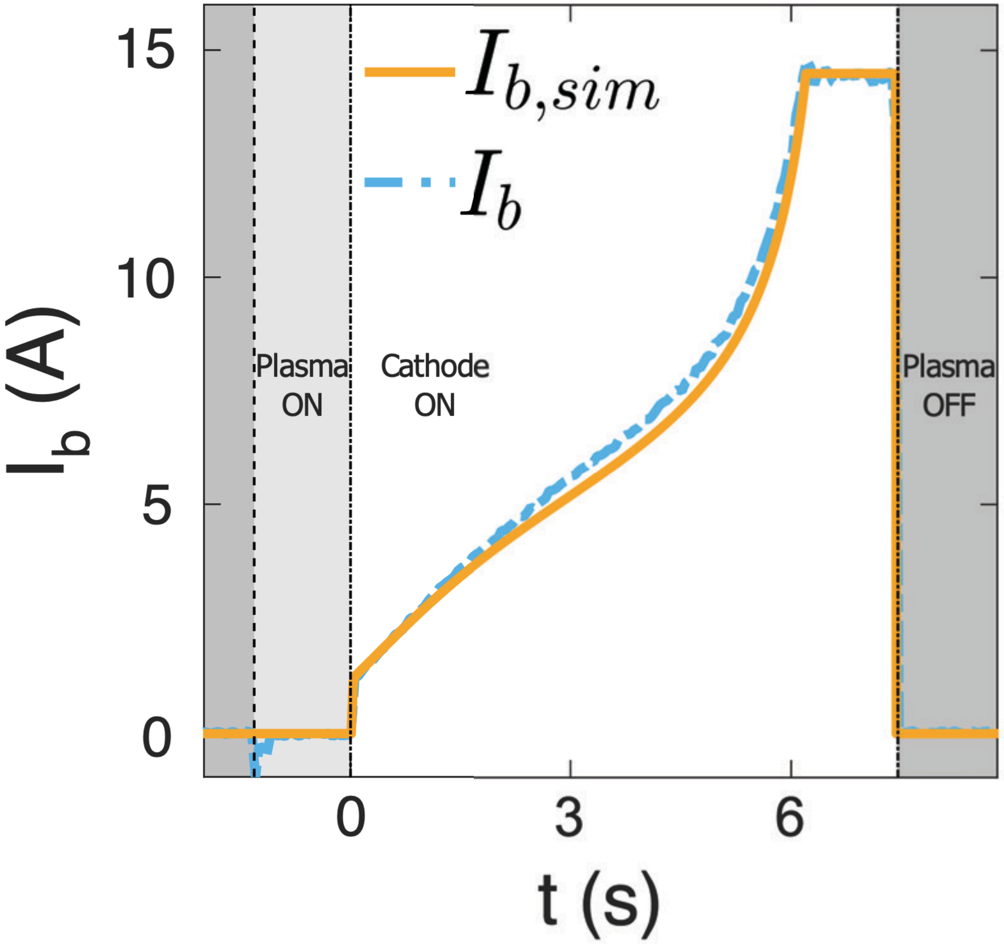
Hanquist *et al.*, Journ. Appl. Phys. (2017)

Kersten *et al.*, Appl. Phys. Lett. (1993)

Thermal model simulations

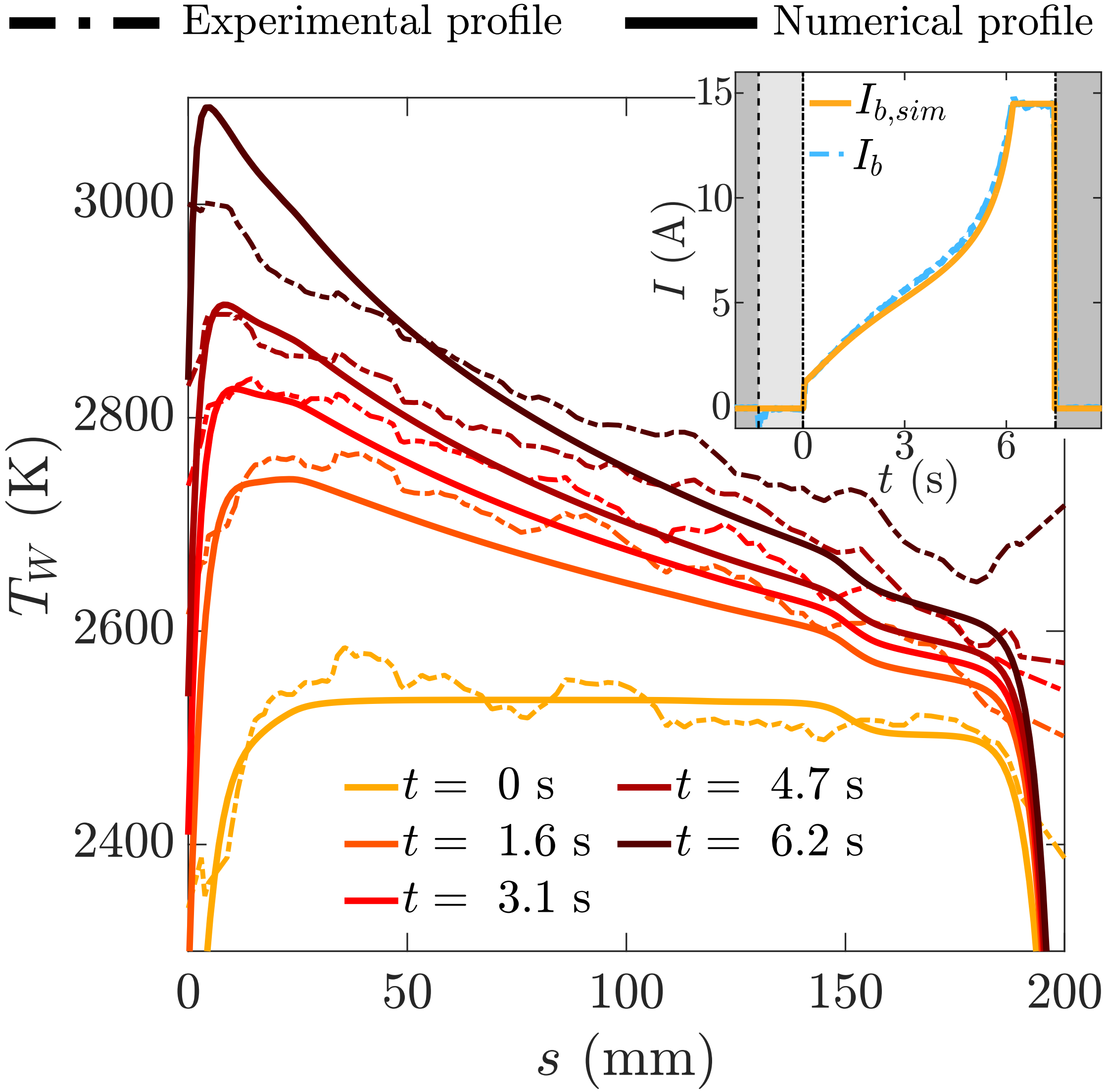
$$\dot{H} = \dot{Q}_\Omega + \dot{Q}_c - \dot{Q}_{\sigma,out} + \dot{Q}_{\sigma,in} + \dot{Q}_i - \dot{Q}_e$$

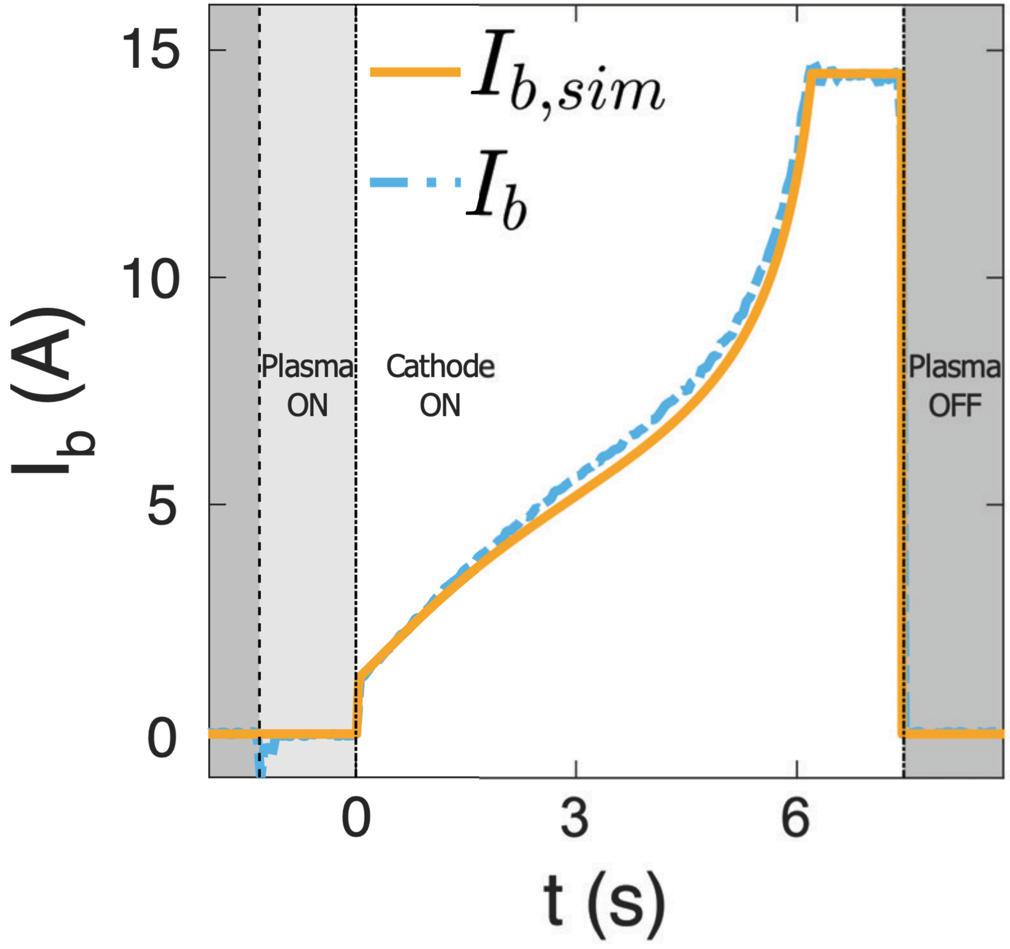




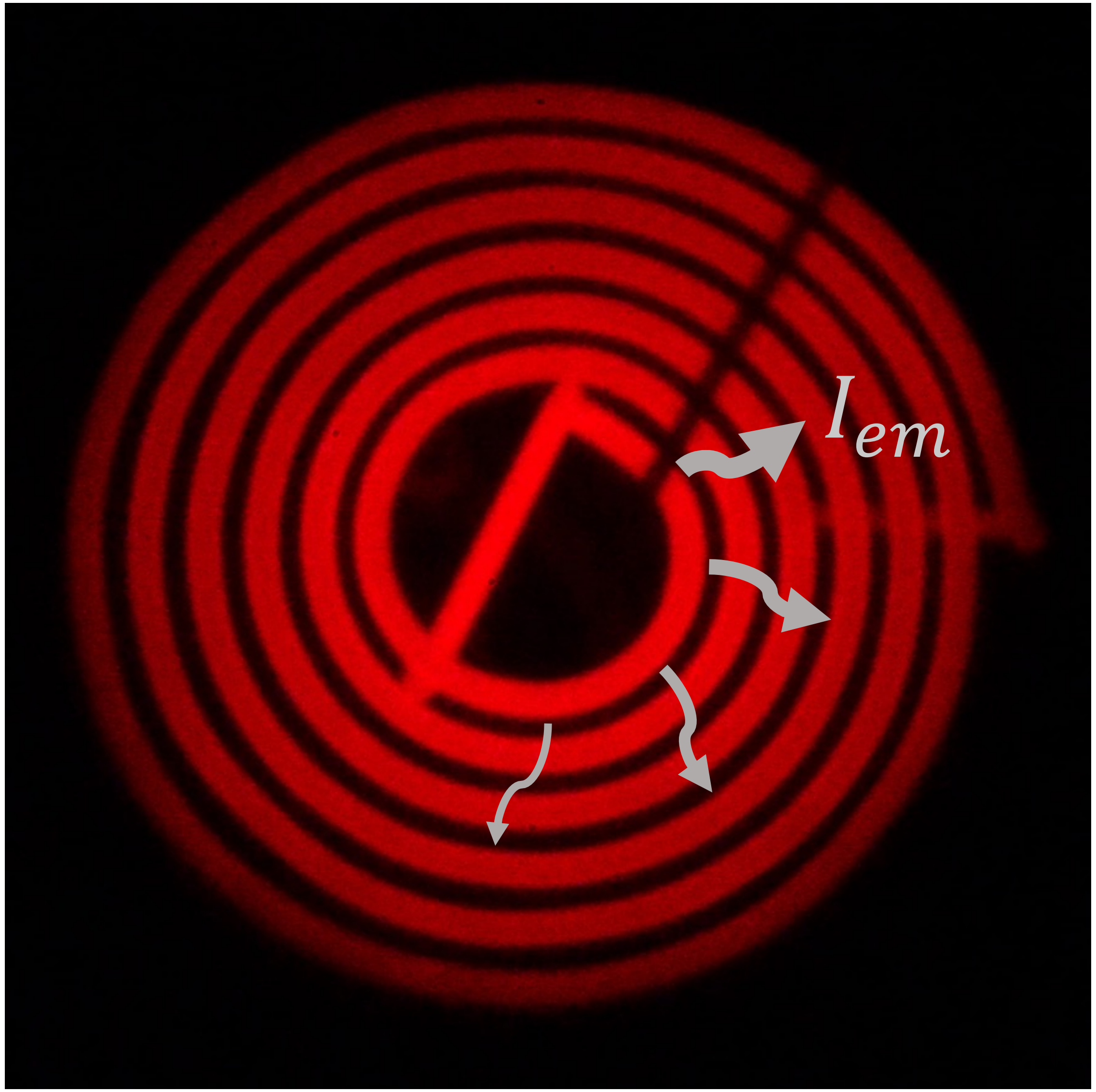
Thermal model simulations

$$\dot{H} = \dot{Q}_{\Omega} + \dot{Q}_c - \dot{Q}_{\sigma,out} + \dot{Q}_{\sigma,in} + \dot{Q}_i - \dot{Q}_e$$





Inhomogeneous heating



Joule heating

$$\dot{Q}_{\Omega} = R\left(I_h + \int_{s}^{L_W} i_{em}(u)\,\mathrm{d}u\right)^2$$

Highly inhomogeneous (and non linear)

Ion bombardment

$$\dot{Q}_i = I_i\left[E_i - W + C_2(\phi_p - V_b)\right]$$

Accounts for 5% of heating power, key factor for the time evolution

CONCLUSION

- Current injection as an additional control parameter for plasma potential control
- Existence of a large anode sheath
- Bulk voltage drop scales as $\Delta_{\perp}\phi_p = R_{\perp} I_b$
- Thermal modeling (plasma cathode interactions) allows to predict cathode current