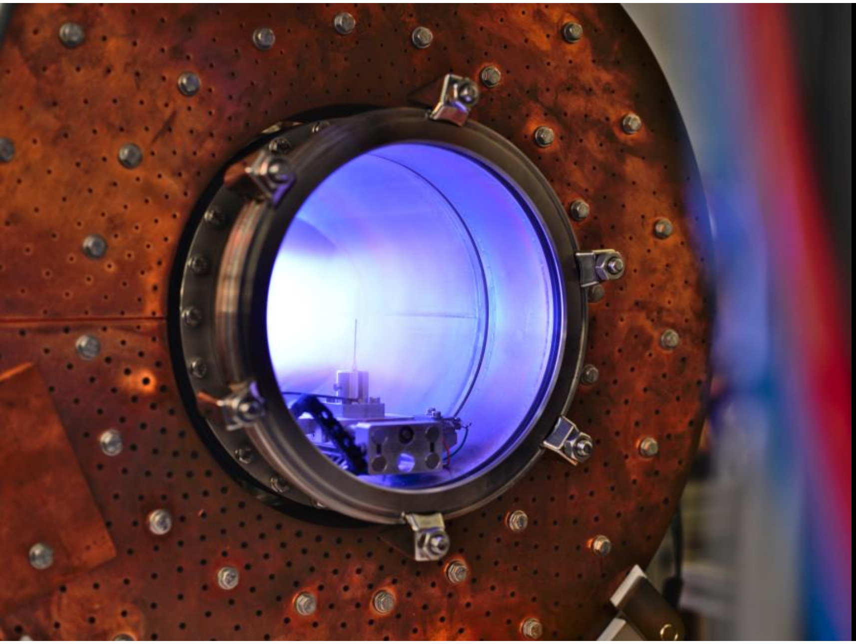
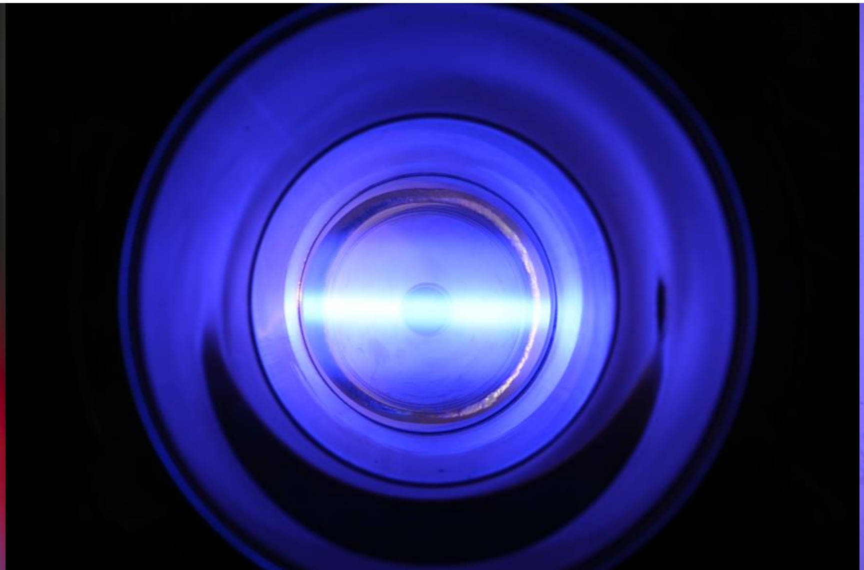
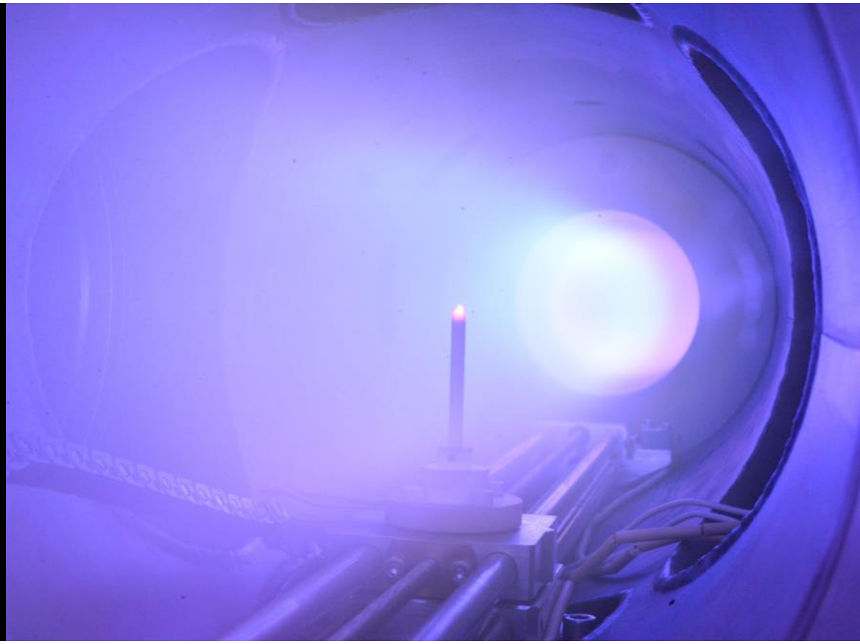
Potential and rotation control in magnetized plasma columns







Nicolas Plihon

CNRS & Ecole Normale Supérieure de Lyon

Lab PHYS ENS de LYON

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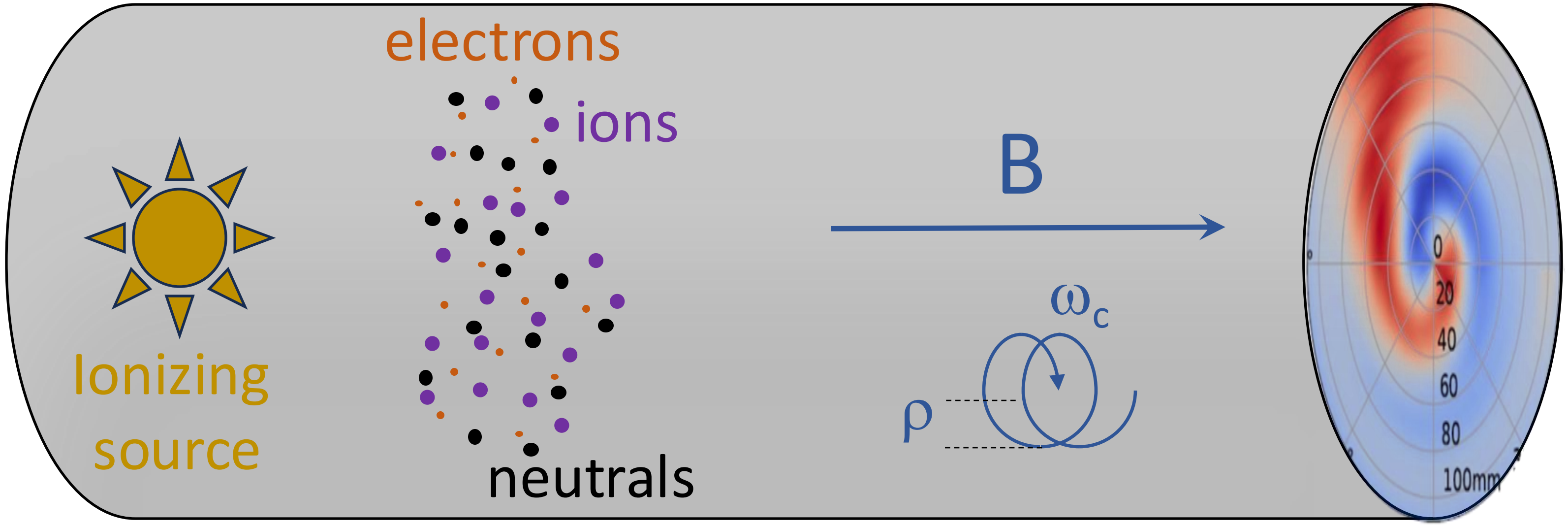
UNIVERSITÉ DE LYON

ENS DE LYON

Magnetized plasma columns



Outline

Outline

1 – Introduction

2 – Magnetized plasma columns

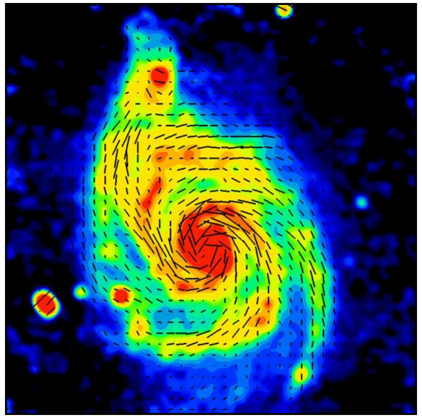
3 – Control of plasma potential and rotation using electrodes

4 – Control of plasma potential using current injection

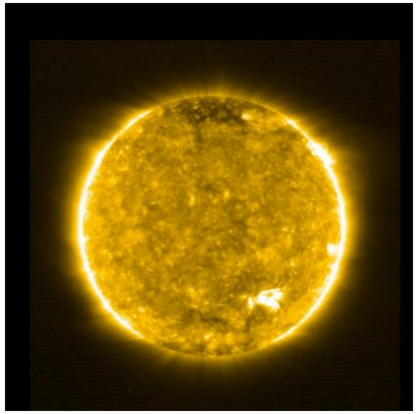
5 – Control of dynamics using current injection

Plasma flows are (nearly) everywhere

Astrophysical context



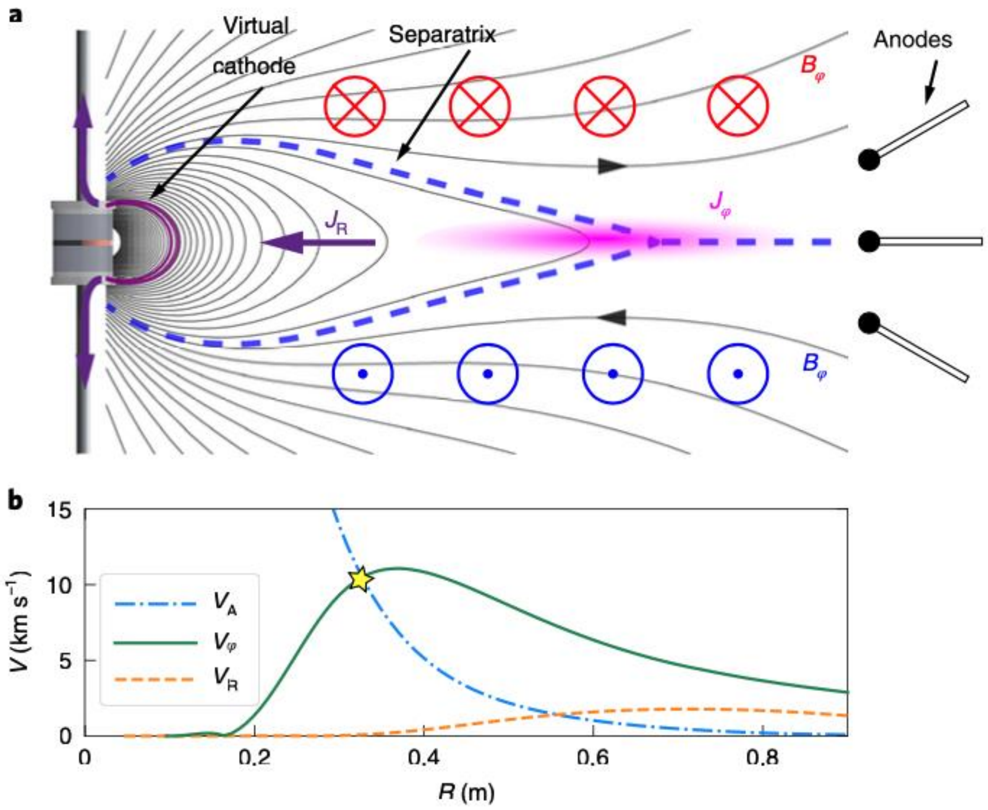
M 51 radio emission & B field lines

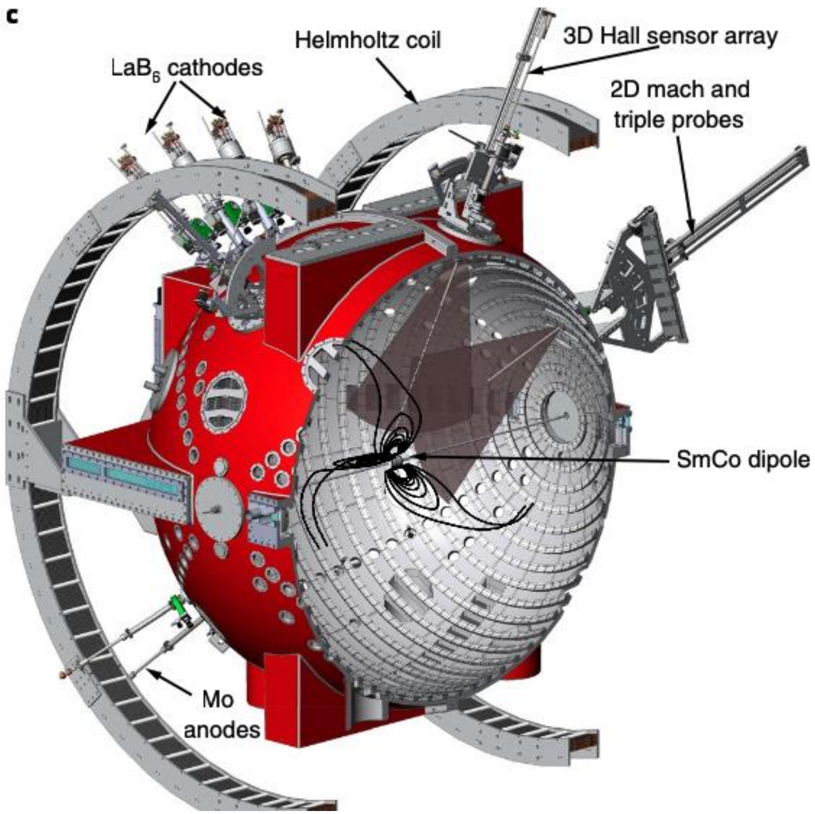


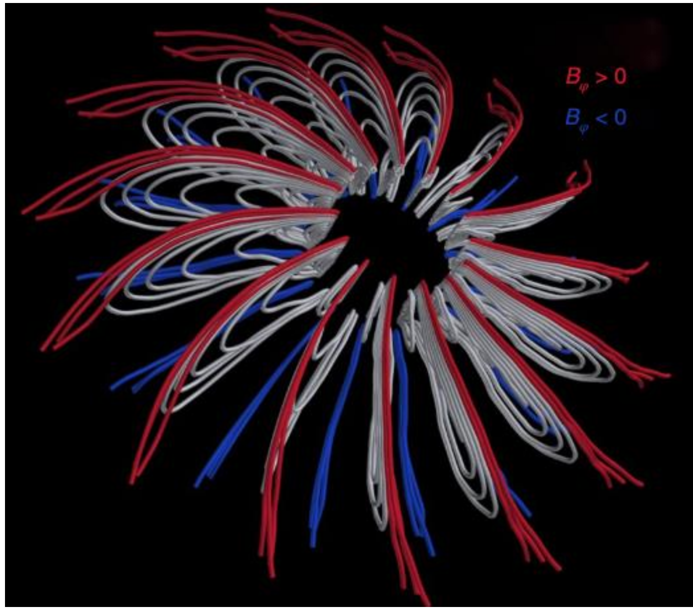
Solar Orbiter

Astrophysical plasma flows in the lab

Lab model for the Parker spiral



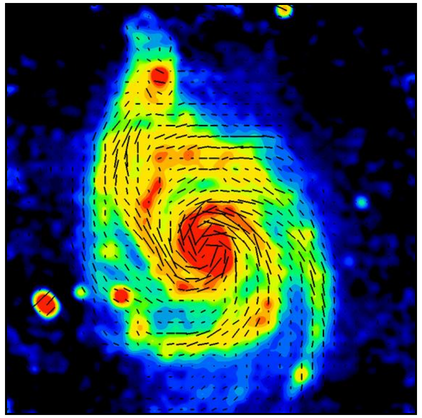




Peterson et al., Nat. Phys. 15, 1095–1100 (2019).

Plasma flows are (nearly) everywhere

Astrophysical context



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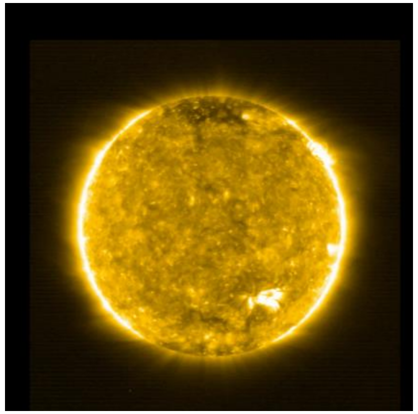
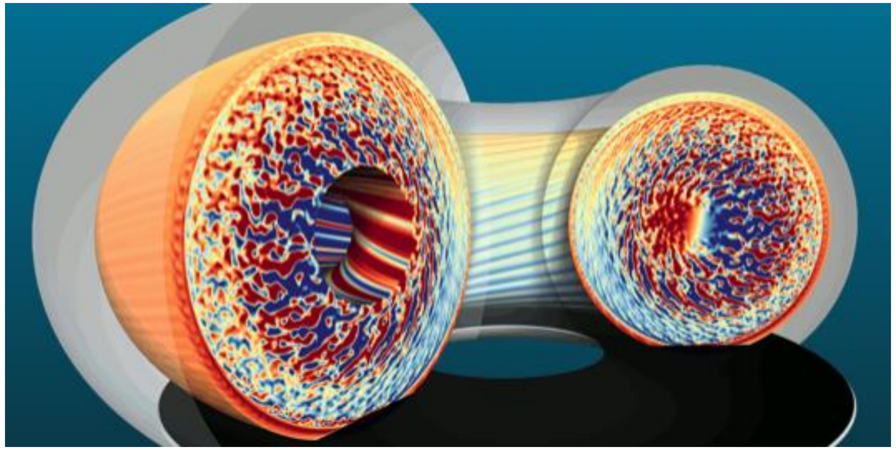
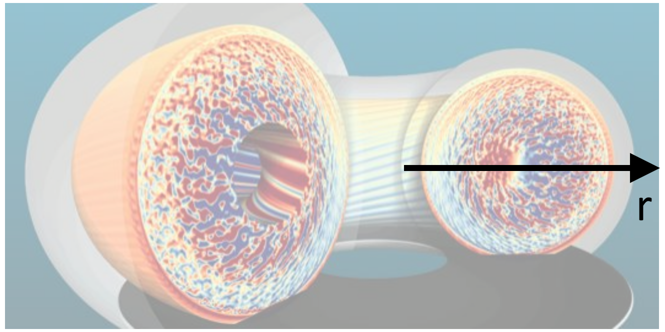


Solar Orbiter

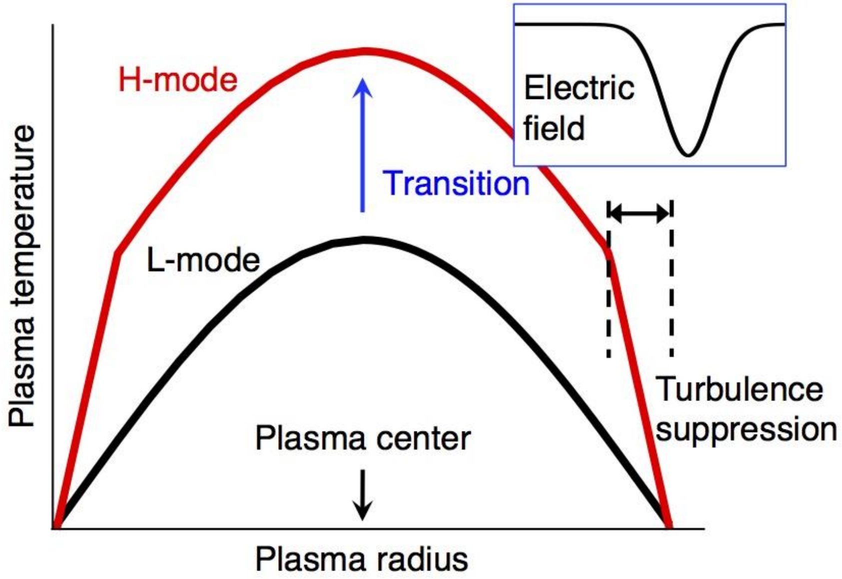
Magnetic fusion devices

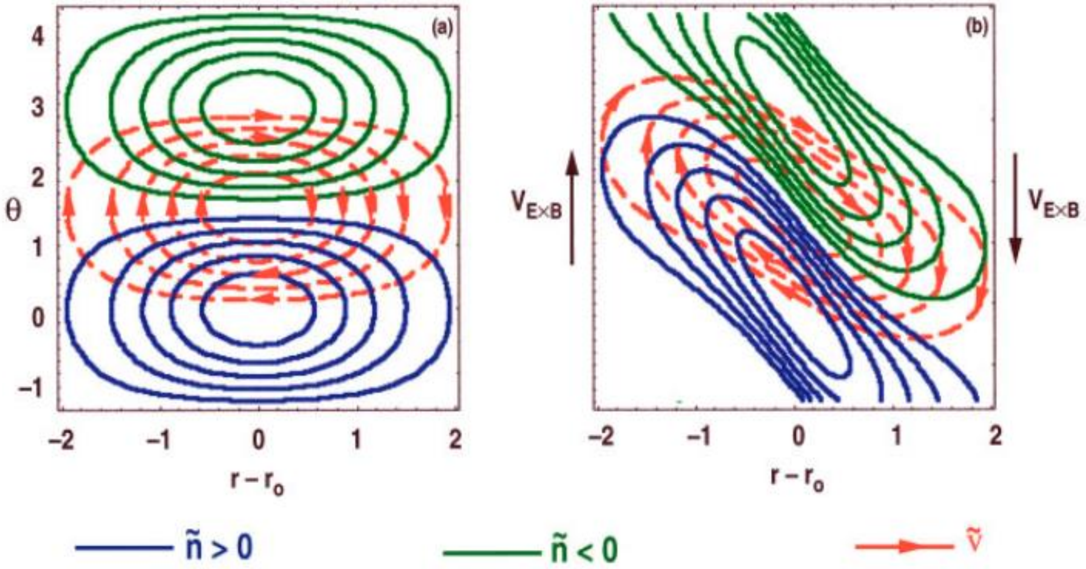


Toroidal rotation and H-mode



Sheared poloidal rotation
- leads to decorrolation between velocity and density perturbations
- reduces turbulent transport $\Gamma = \langle \tilde{n}\tilde{v} \rangle$

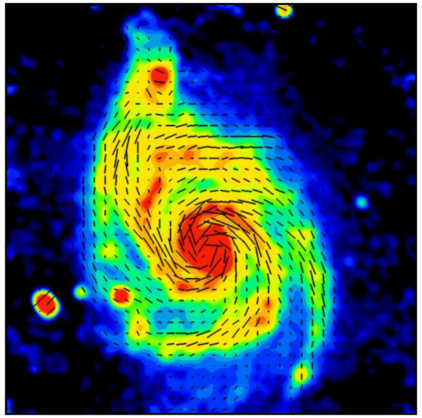




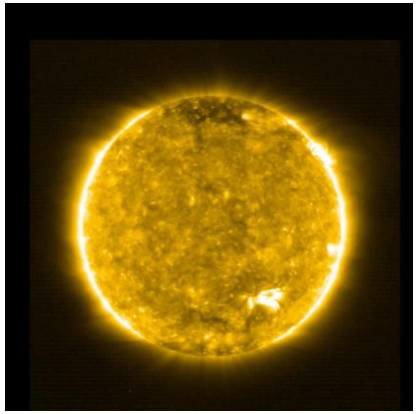
Burrell, Phys. Plasmas 4 1499 (1997)

Plasma flows are (nearly) everywhere

Astrophysical context

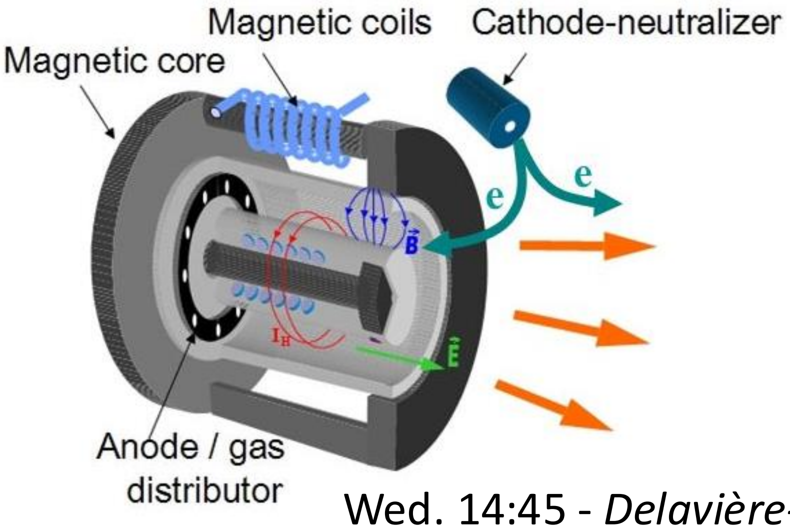


M 51 radio emission & B field lines



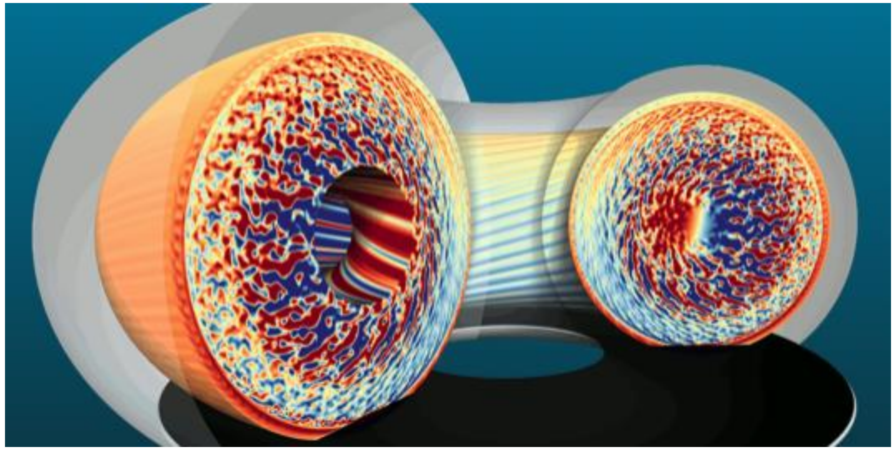
Solar Orbiter

Electric propulsion



Wed. 14:45 - *Delavière-Delion*

Magnetic fusion devices



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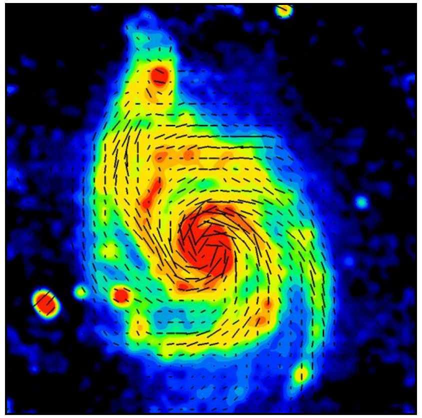

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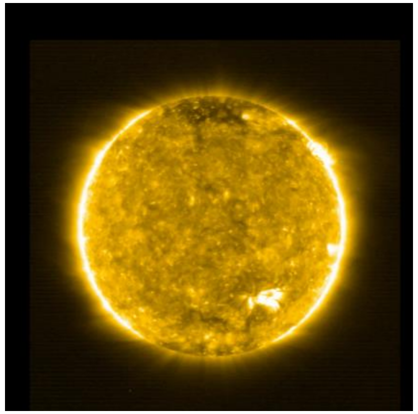

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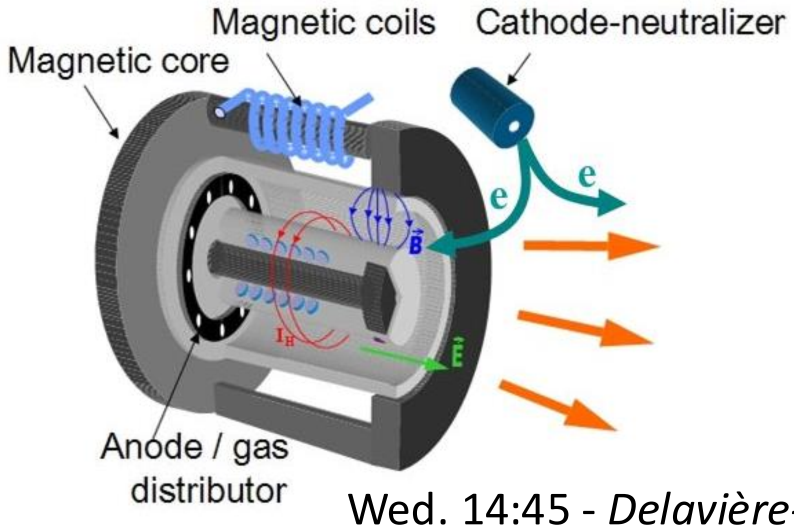

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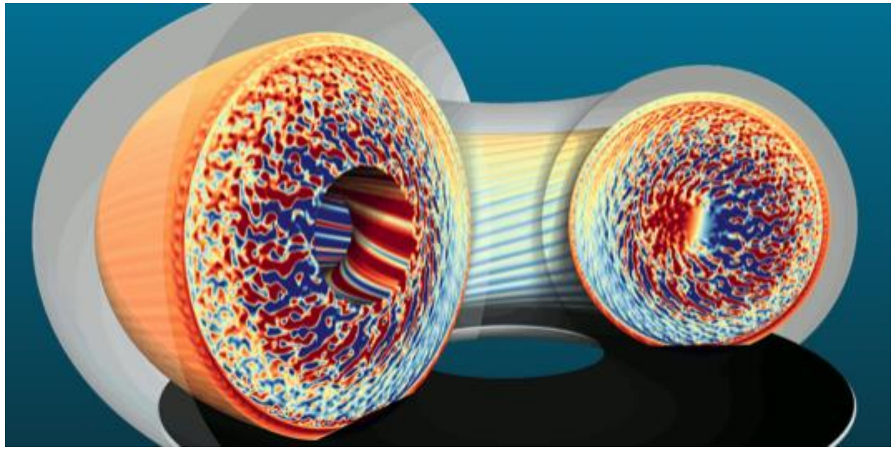
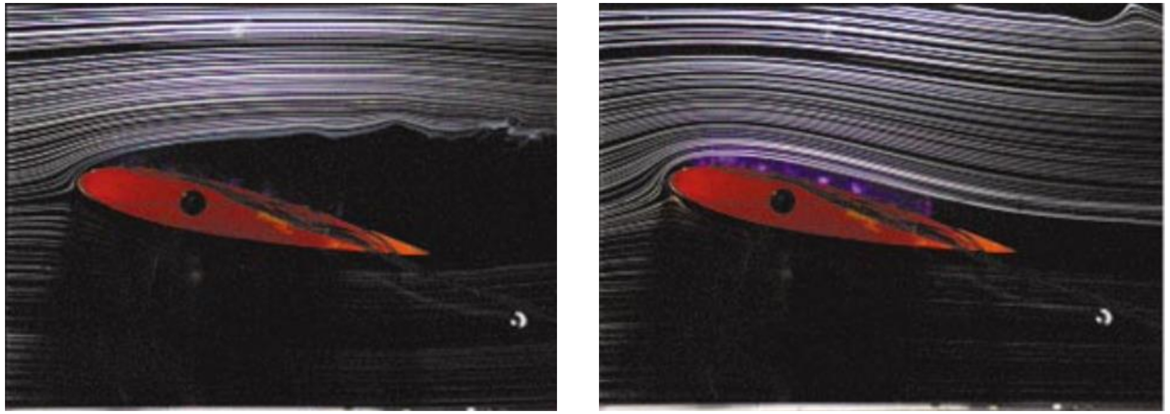
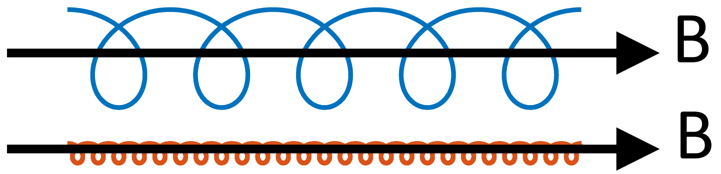


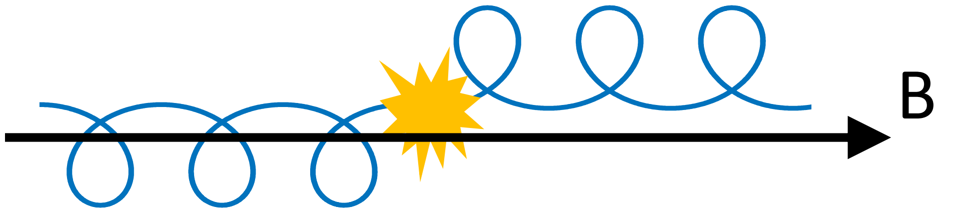
Airflow control by plasma actuator



Outline

Magnetized plasma columns





Cyclotron pulsation $\omega_c = |q|B/m$

Electrons @50 G	*140 MHz*
Argon ions @ 50 G	*2 kHz*

Elastic collisions

$$\nu_{m\,e}/s^{-1} \sim 1 \times 10^7 (p/\mathrm{Pa})$$
$$\nu_{m\,i}/s^{-1} \sim 1 \times 10^5 (p/\mathrm{Pa})$$

Electrons are magnetized when $\dfrac{\omega_{ce}}{\nu_{me}} \gg 1$ $\qquad p\ (\mathrm{Pa}) < 10^4 B(\mathrm{T})$ 1 atm requires 10 T !

Ions are magnetized when $\dfrac{\omega_{ci}}{\nu_{mi}} \gg 1$ $\qquad p\ (\mathrm{Pa}) < 10^3 \dfrac{m_p}{m_i} B(\mathrm{T})$ 1 atm requires 4000 T !

Larmor radii $r_L = mv_\perp/|q|B = v_\perp/\omega_c$

Electrons @50 G, 3eV	*1 mm*
Argon ions @50 G, 0.1 eV	*6 cm*

Ions are either weakly or not affected by magnetic fields in low temperature plasmas

Transport coefficients in magnetized plasmas

The magnetic field introduces a strong anisotropy

Slab geometry – static magnetic field along the *z*-direction (the parallel direction)

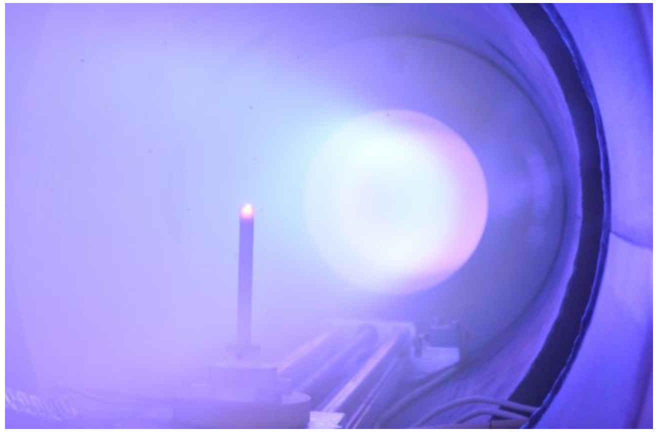
$$\hat{\mu} = \begin{pmatrix} \mu_\perp & -\mu_\times & 0 \\ \mu_\times & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix}$$

← The parallel components take values of the non-magnetized case

The perpendicular components are strongly reduced as compared to the parallel components

$$\mu_\perp = \frac{\mu_\parallel}{1+\Omega^2} = \frac{\mu_\parallel}{1+(\omega_c/\nu_m)^2}$$

$$D_\perp = \frac{D_\parallel}{1+\Omega^2} = \frac{D_\parallel}{1+(\omega_c/\nu_m)^2}.$$

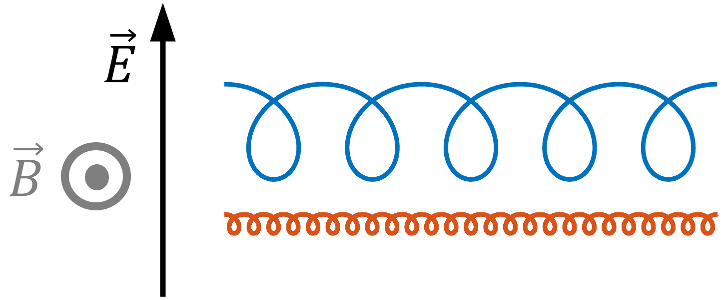


In strongly magnetized regimes, transition to the Bohm scaling

$$D_\perp = \frac{1}{16}\frac{kT_e}{eB_0} \propto \frac{1}{B_0}.$$

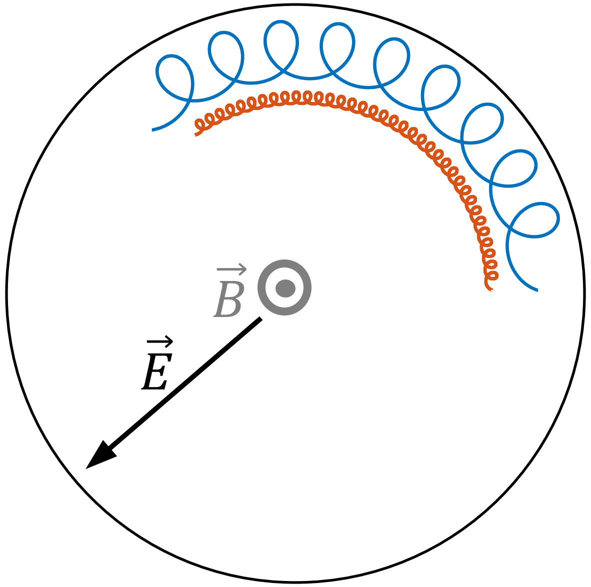
Plasma drifts

The particles experience strong drift due to crossed fields



$$\boldsymbol{v} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

In cylindrical geometry, a radial electric field will drive plasma rotation



$$\boldsymbol{v} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

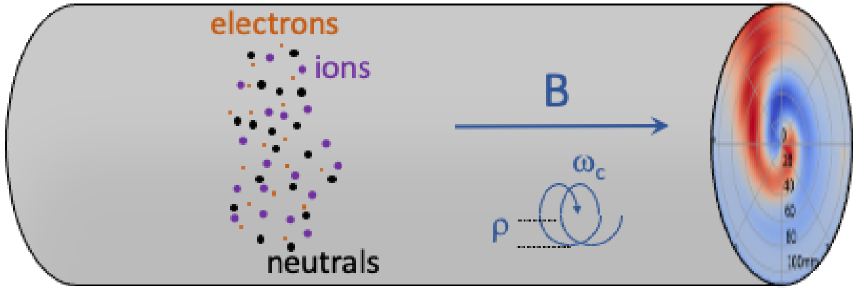
Pressure gradients lead to diamagnetic drift (collective effect, not a guiding center effect), opposite for electrons and ions

$$\boldsymbol{v_{Dia}} = q\frac{\nabla p \times \boldsymbol{B}}{q^2 n B^2}$$

In cylindrical geometry, radial pressure gradients lead to rotation

Outline

Electrical conductivity of magnetized columns



The parallel current is primarily carried by electrons

$$\sigma_{\parallel} \sim \frac{e^2 n}{m_e \nu_{en}}$$

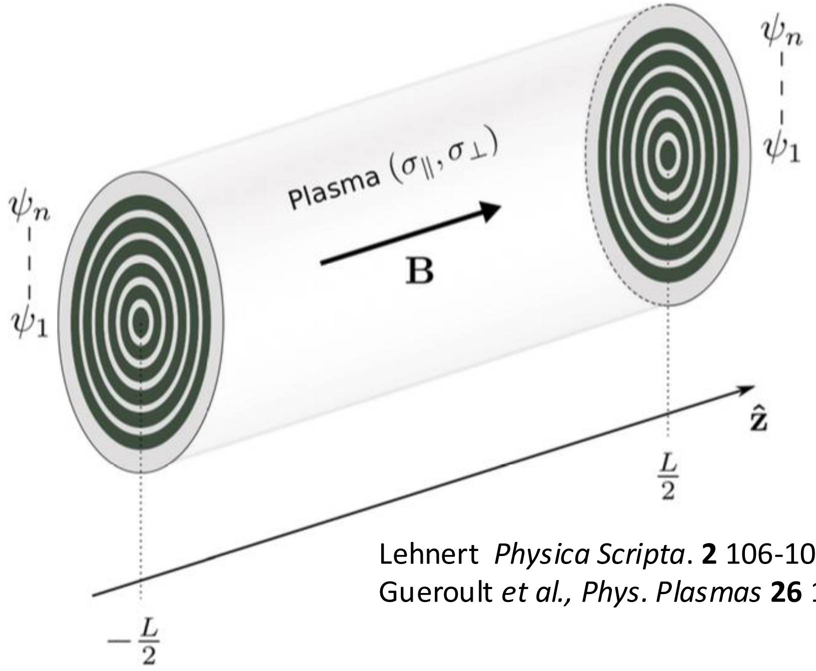
The perpendicular current is primarily carried by ions

$$\sigma_{\perp} \sim \sigma_p = \frac{e^2 n}{m_i} \frac{\nu_{in}}{\left[\Omega_{c,i}^2 + \nu_{in}^2\right]}$$

In most situations, the ratio $\boldsymbol{\mu = \frac{\sigma_{\perp}}{\sigma_{\parallel}} \ll 1}$

(i.e. the magnetic field lines are considered are isopotential)

Lehnert proposed the use of concentric rings as a way to control the radial electric potential (i.e. the electric drift).



Lehnert *Physica Scripta*. **2** 106-107 (1970)
Gueroult *et al., Phys. Plasmas* **26** 122106 (2019)

Since then,

many unsuccessful and
some successful attempts

A necessary condition for potential control

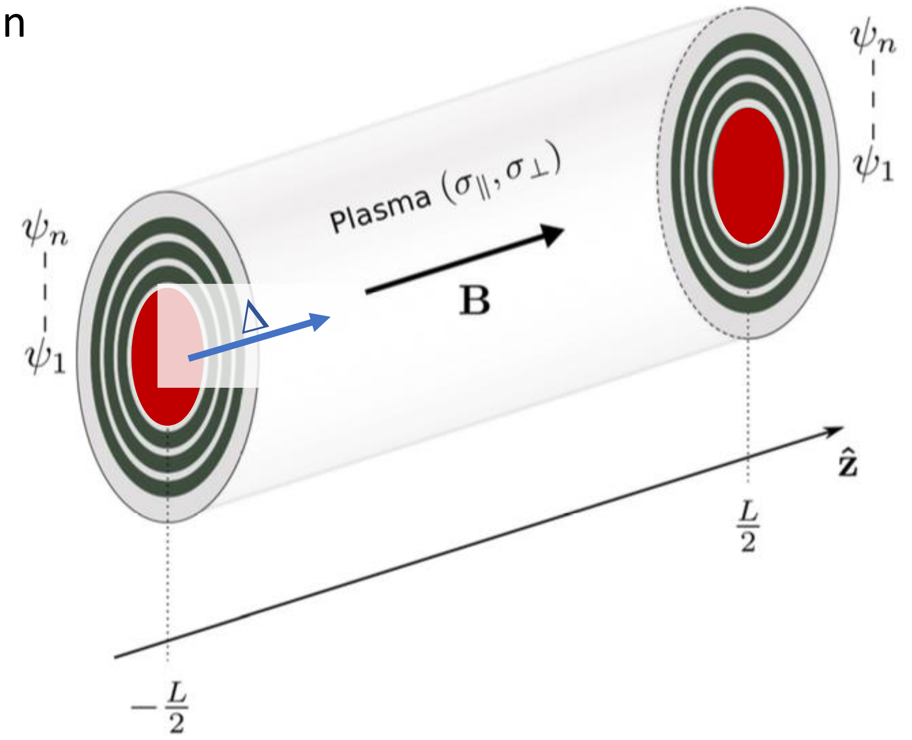
Gueroult and collaborators computed the axisymmetrical potential distribution

- column of length L
- one single electrode of size a
- strongly anistropic plasma $\mu = \frac{\sigma_\perp}{\sigma_\parallel} \ll 1$

The electric potential follows $\nabla_r^2 \phi + \frac{\sigma_\parallel}{\sigma_\perp} \nabla_z^2 \phi = 0.$

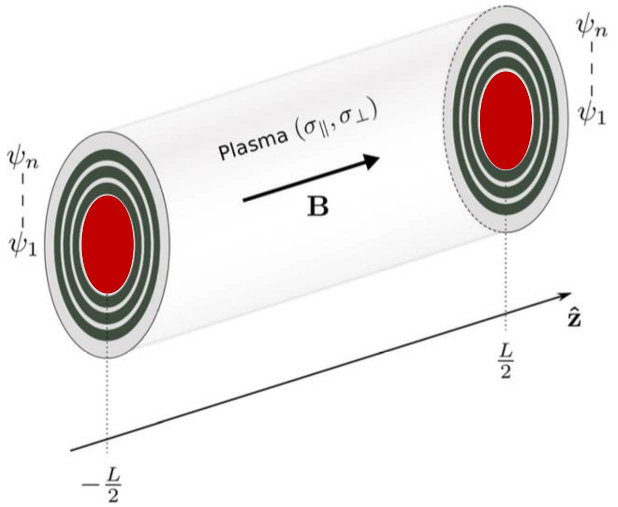
The potential perturbation is projected along B_0 with a scale $\Delta = \frac{a}{\sqrt{\mu}}$

The perturbation extends to the whole column if $\boldsymbol{\tau} = \frac{\boldsymbol{L}}{\boldsymbol{a}}\sqrt{\frac{\boldsymbol{\sigma_\perp}}{\boldsymbol{\sigma_\parallel}}} < \mathbf{1}$



Gueroult *et al.*, *Phys. Plasmas* **26** 122106 (2

A necessary condition for potential control



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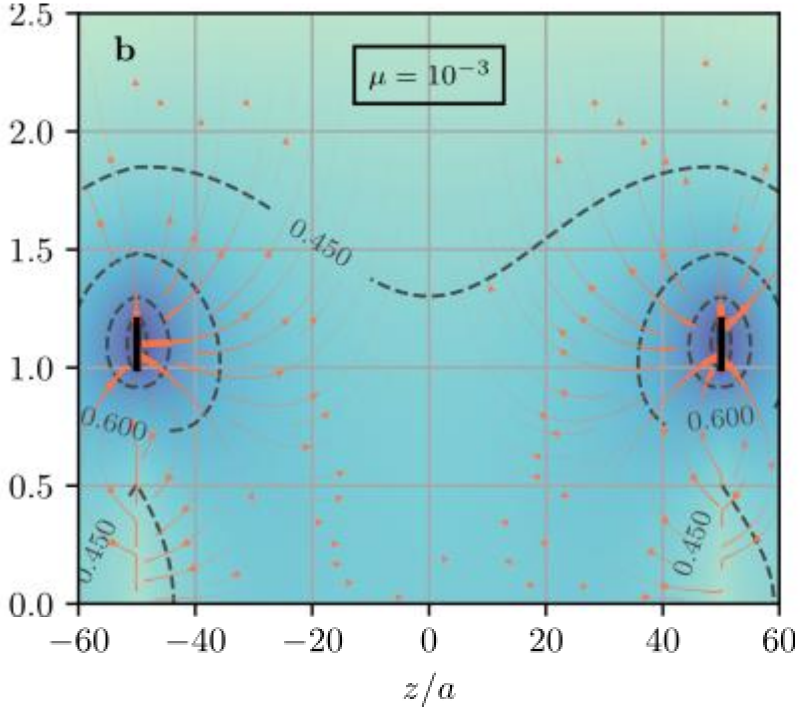
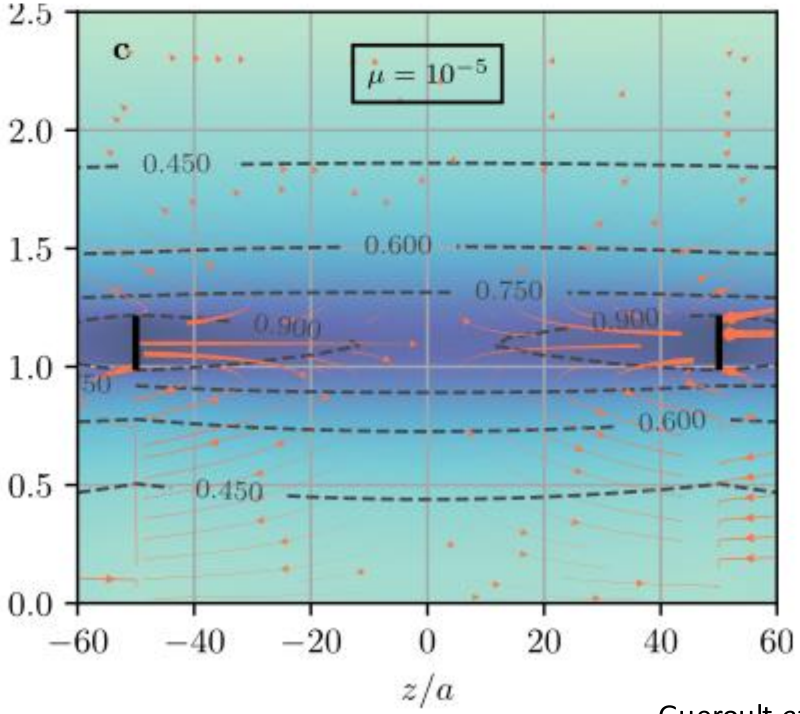
$\dfrac{L}{a} = 50$

$\tau = \sqrt{10}$



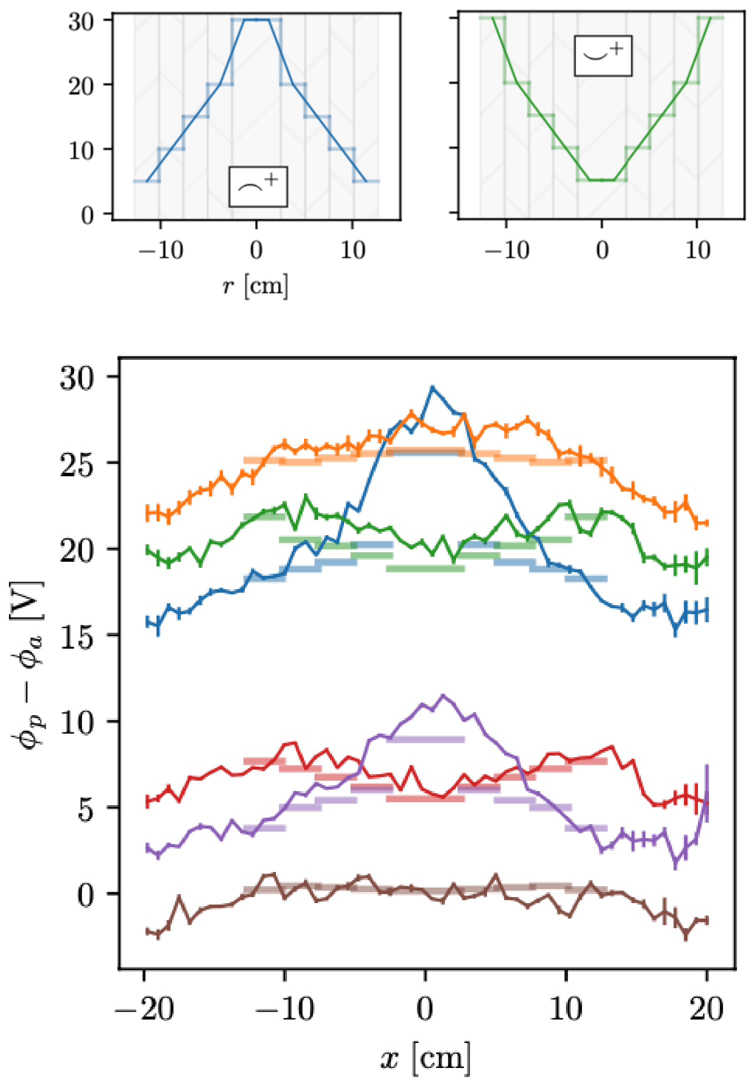
$\tau = 1/\sqrt{10}$

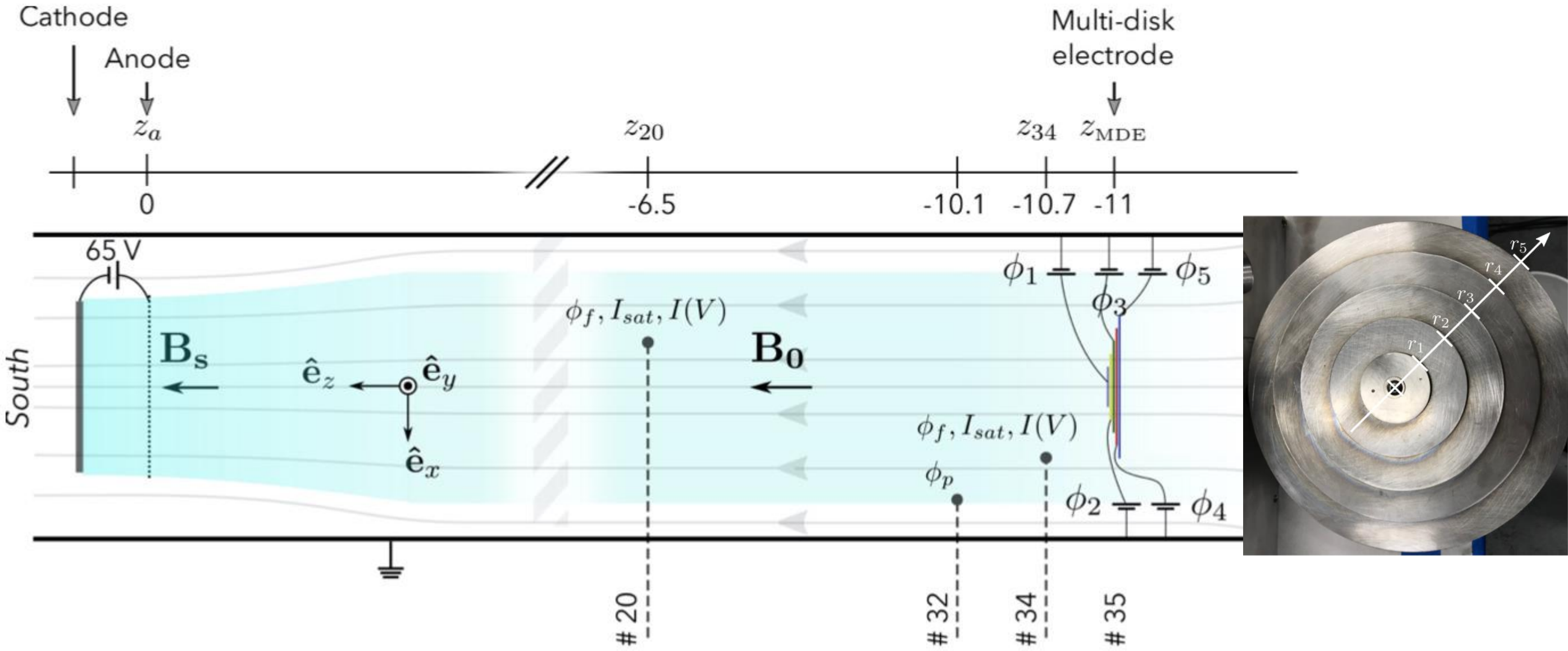


Gueroult *et al., Phys. Plasmas* **26** 122106 (2

Successful experiments

Multidisk biasing at LAPD





Gueroult *et al.*, *J. Plasma Phys.* ***90*** 905900603 (20

Successful experiments

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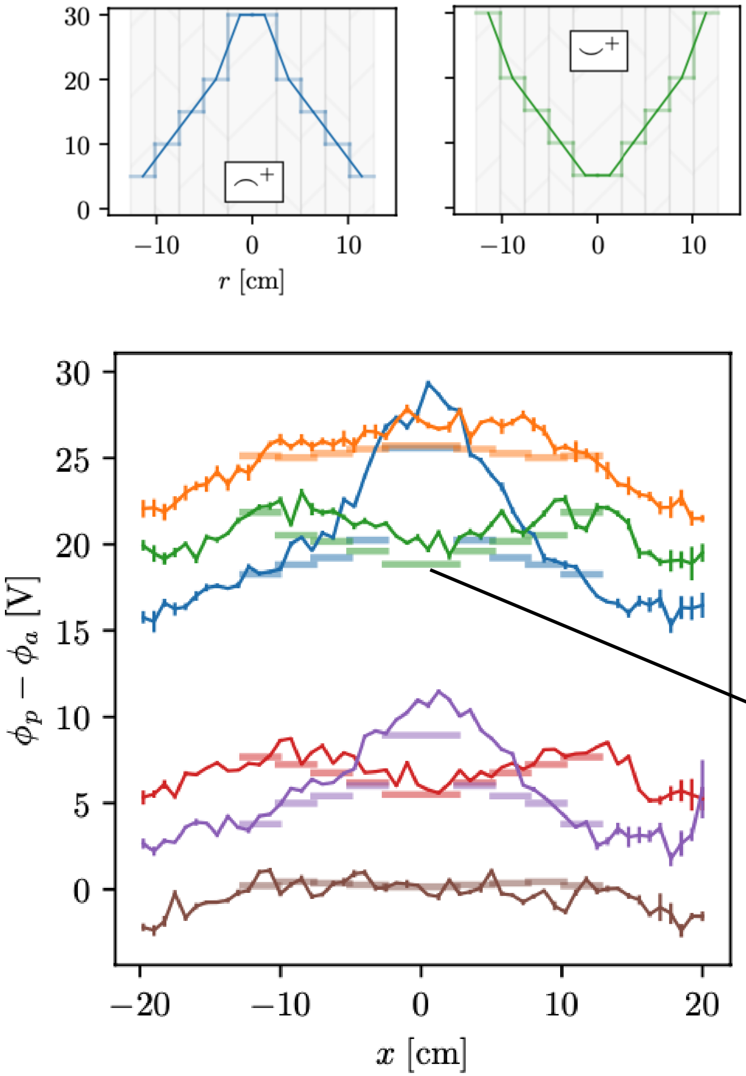
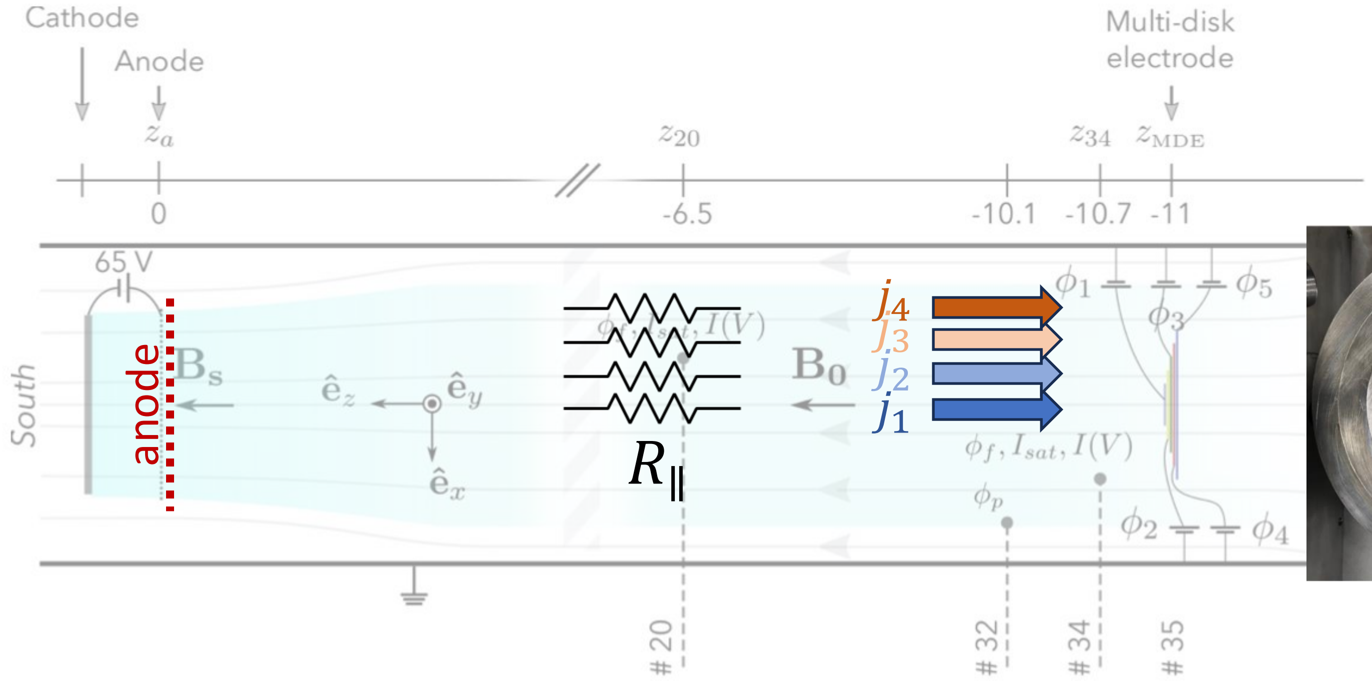
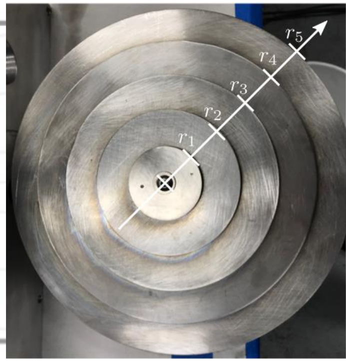






The plasma potential is indeed controlled by the current drawn at each disk

$$\phi_p(r,z) = \phi_a + \eta_\parallel j_i (z_a - z) + \varphi$$

Gueroult *et al.*, *J. Plasma Phys.* **90** 905900603 (20

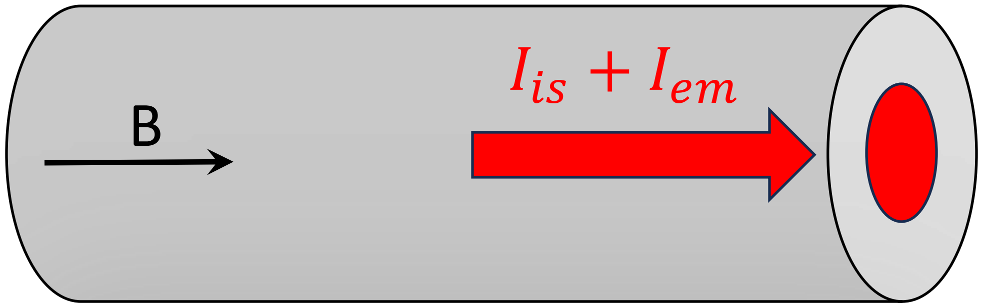
Outline

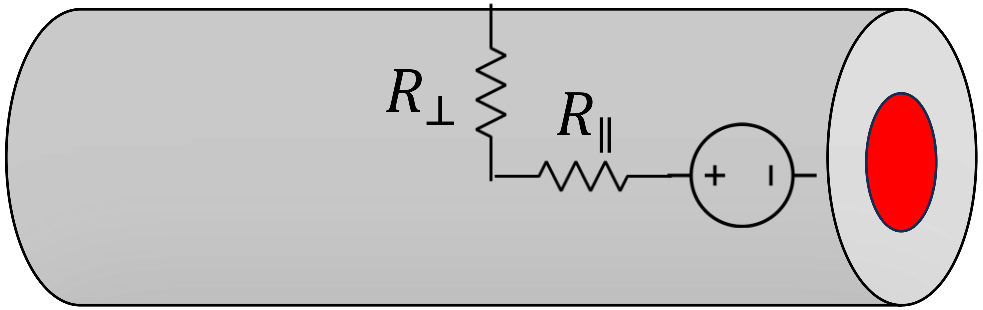
Plasma potential control using current injection

The perturbation extends to the whole column if $\tau = \frac{L}{a}\sqrt{\frac{\sigma_\perp}{\sigma_\parallel}} < 1$,

however the current collected at the electrode cannot be ignored

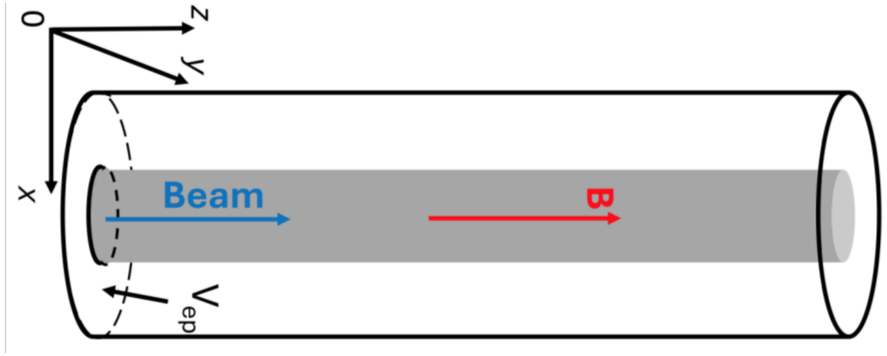
Current injection form a cathode allows increased current densities and provides an additional control parameter

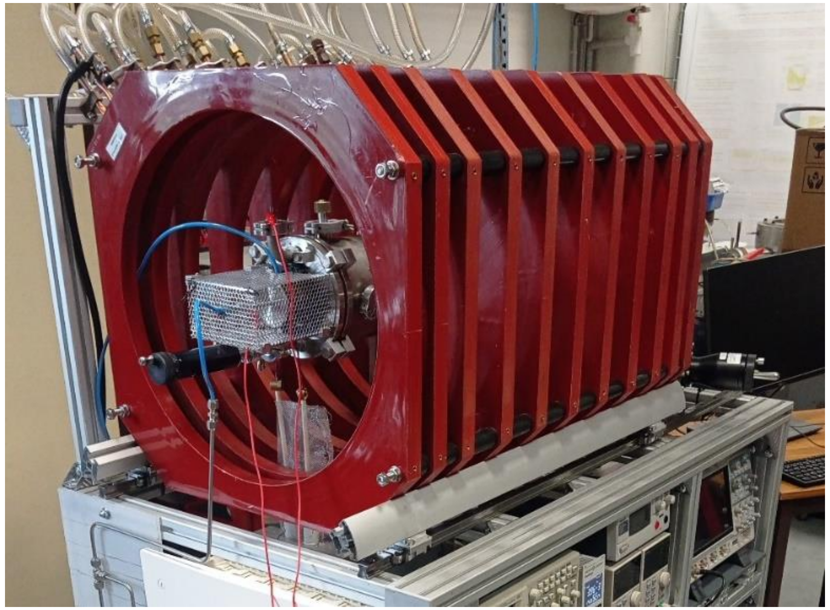




Penning discharges and current injection

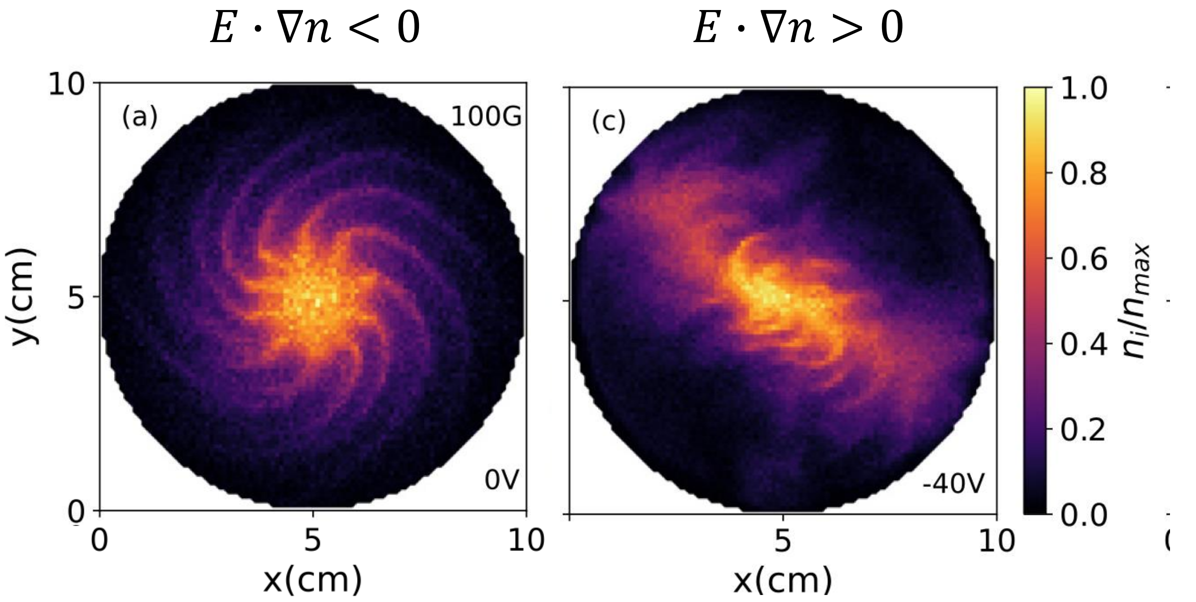
Penning discharges are canonical magnetized plasma columns.





IRENE, talk by L. Garrigues, Wed. 10 am

Radial electric field controls the dynamics



V_{ep} = 0 V, I_b =40 mA

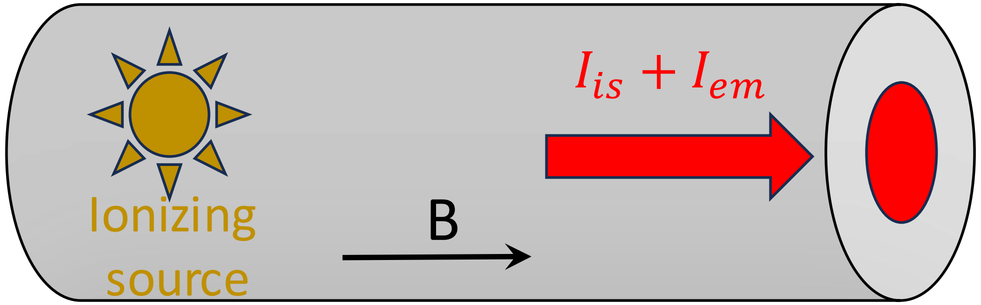
V_{ep} = -40 V, I_b =5 mA

However, the beam energy and the beam intensity do not independently control the plasma density and the radial electric field.

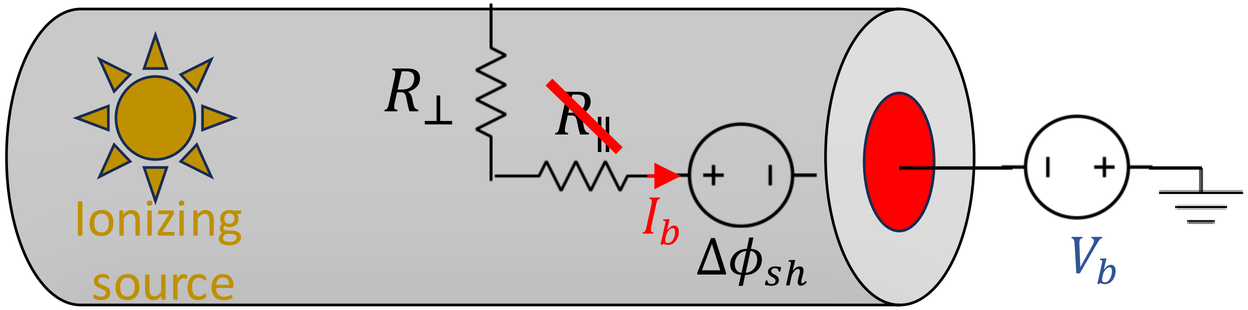
Powis *et al.*, *Phys.Plasmas* **25**, 072110 (2018)
Fubiani *et al.*, *Phys.Plasmas* **32**, 080704 (2025), and mar

Current injection on a background plasma column

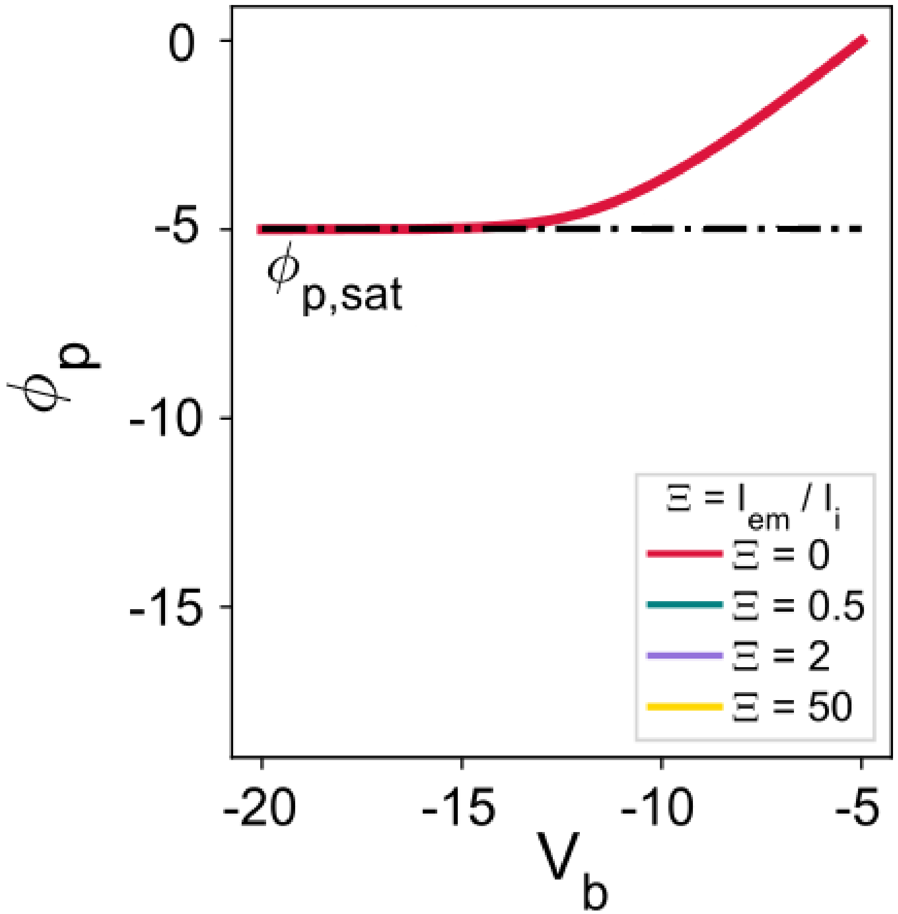
Independent control of background plasma parameters
current injection



$$\Xi = I_{em}/I_{is}$$



$$I_b = I_{em} + I_{is} = (1 + \Xi)I_{is}$$



Trotabas & Gueroult, *PSST* **31**, 025001 (2022)

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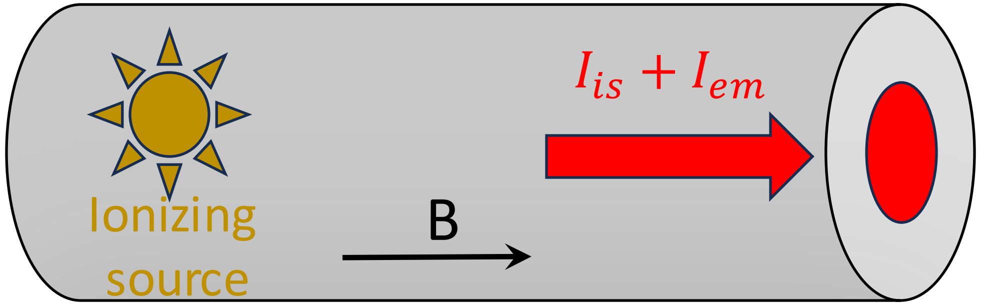

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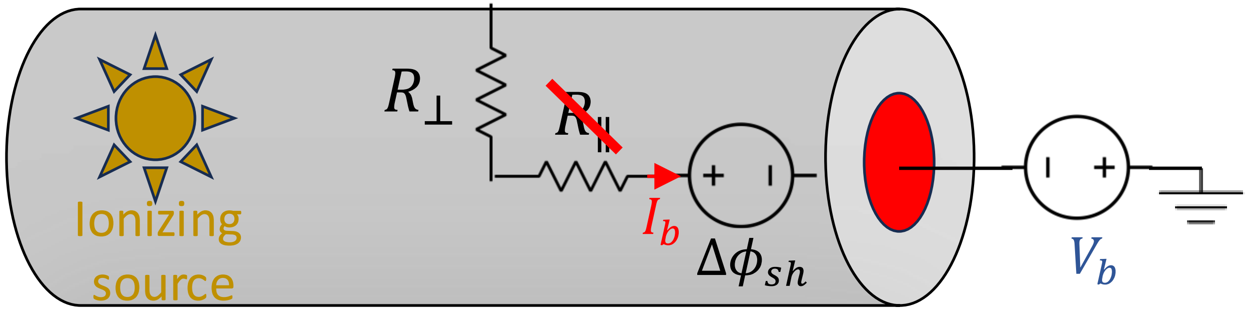

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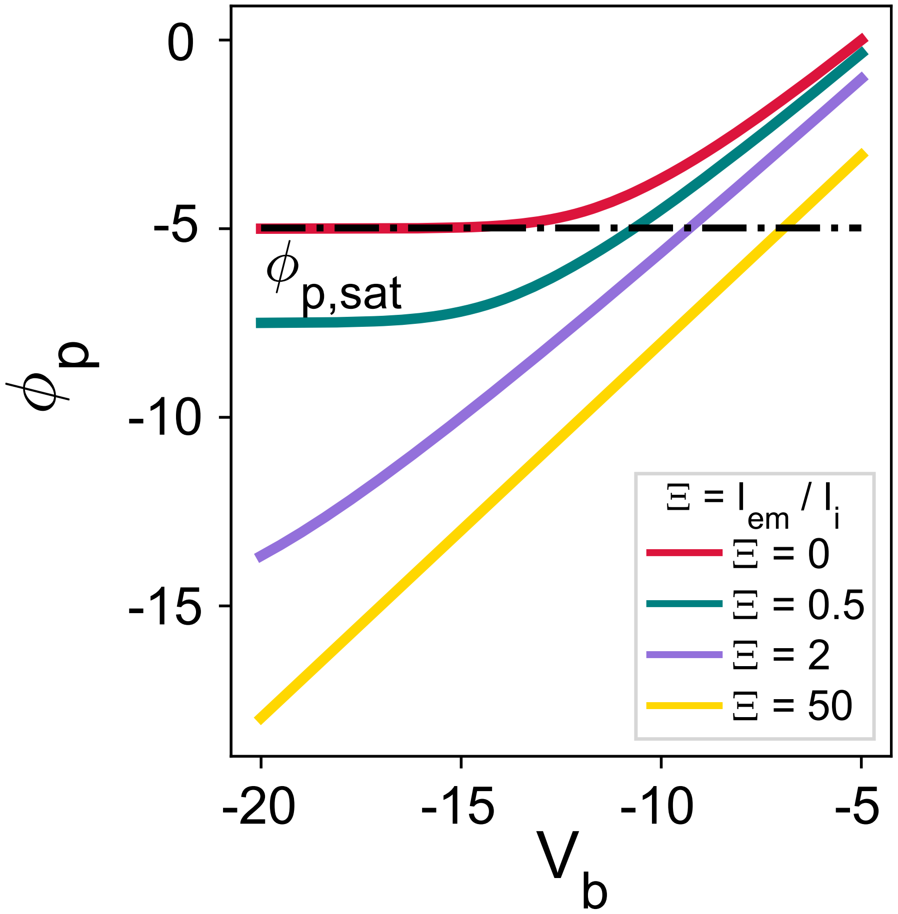
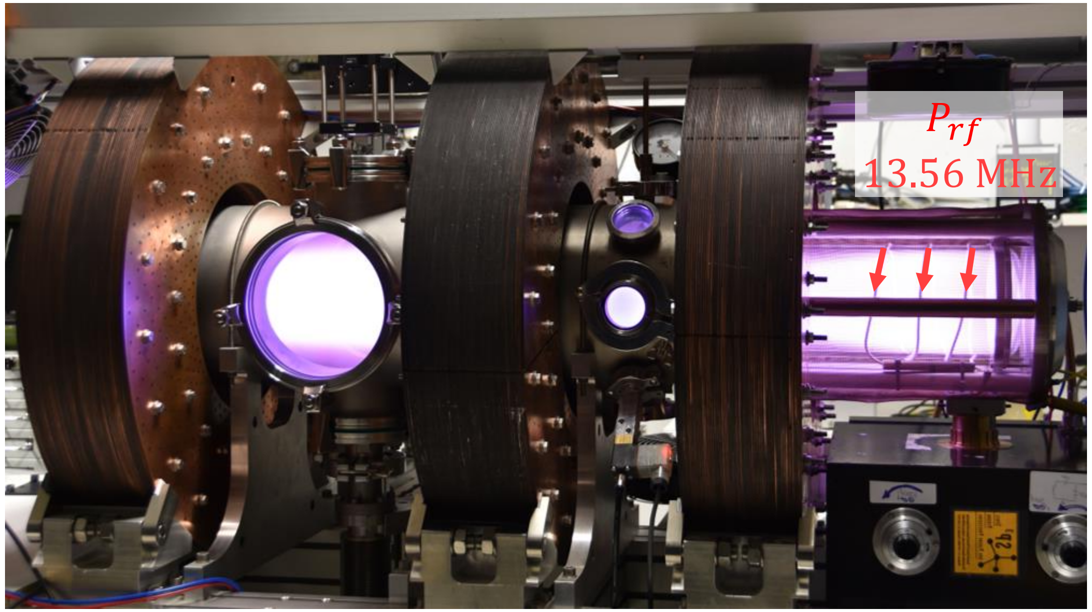


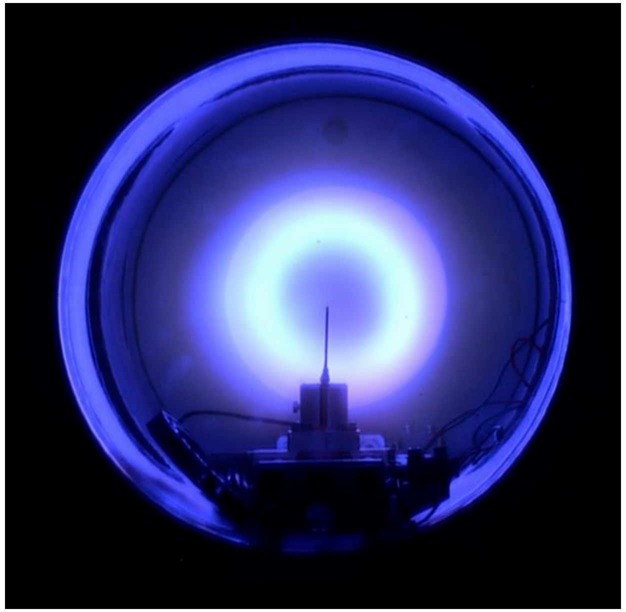
Trotabas & Gueroult, *PSST* **31**, 025001 (2022)

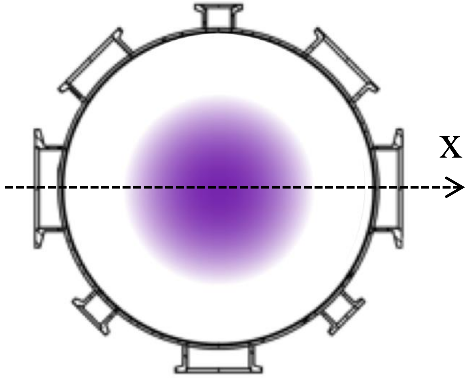
Implementation at ENS de Lyon

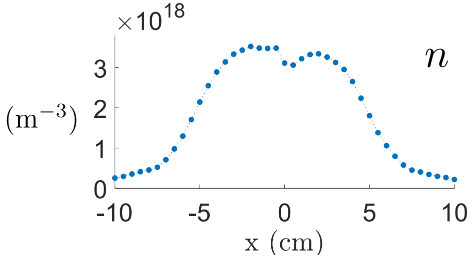
13.56 MHz inductive / helicon source – Ar plasma

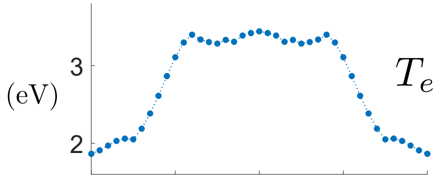
$p_0 \sim 1$ mTorr $(10^{-6}$ atm$)$
$P_W \sim 1$ kW

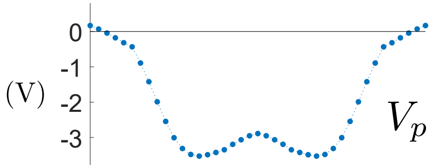










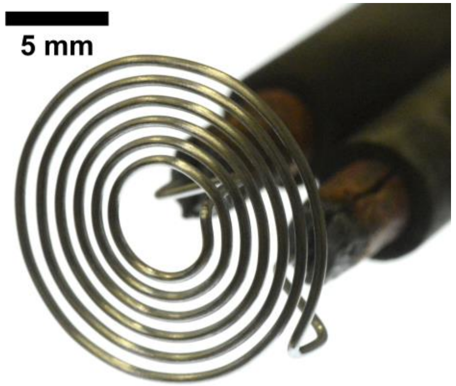


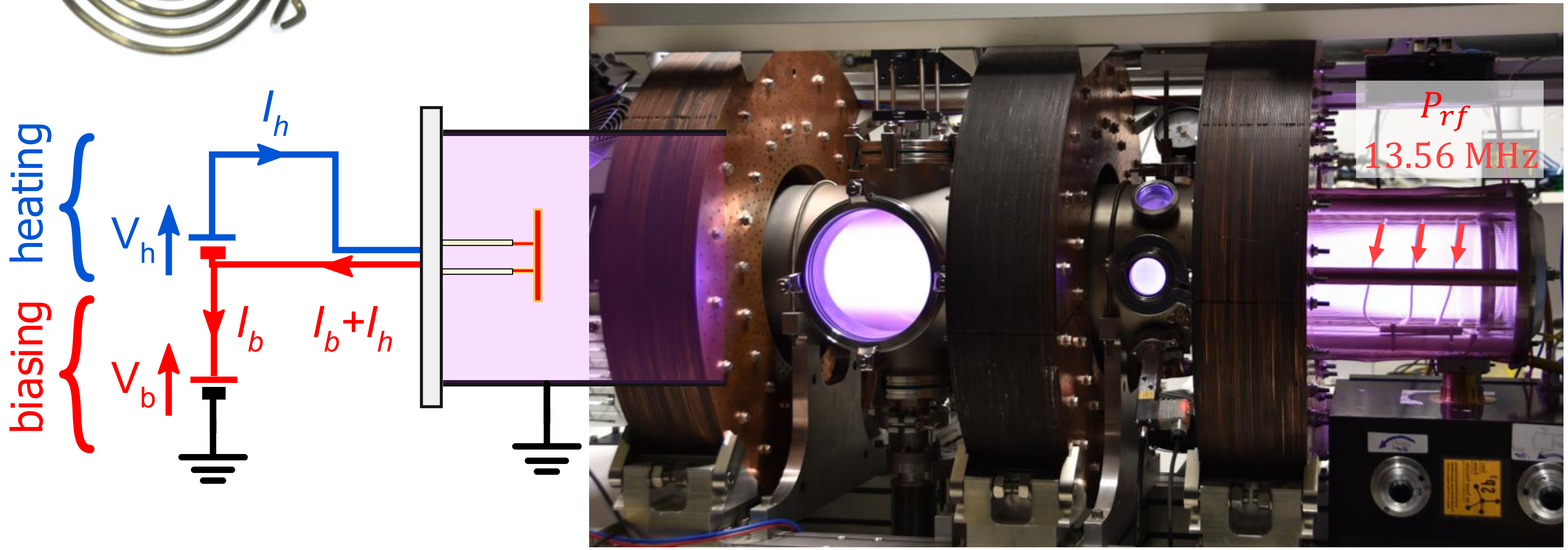
$n \sim 10^{18}$ m^{-3}
$T_e \sim 4$ eV $(5.10^4$ K$)$
$T_i \sim 0.2$ eV $(10^3$ K$)$

Plihon *et al.*, *Journal of Plasma Physics*, **81**, 345810102 (2015)
Vincent *et al. Phys. Plasmas* **29**, 032306 (2022)

Current injection from an emissive cathode

Negatively biased Joule heated tungsten coil. Emission up to 15 A

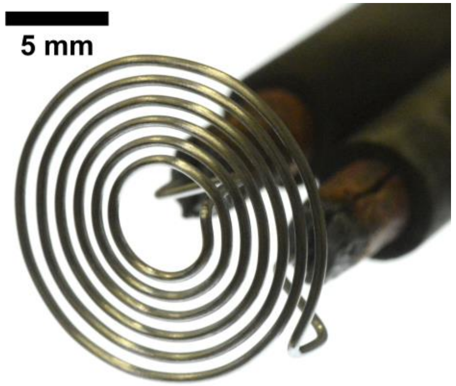


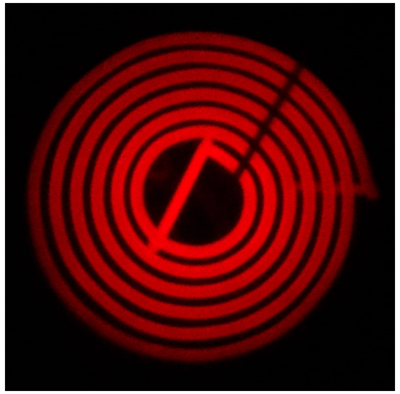


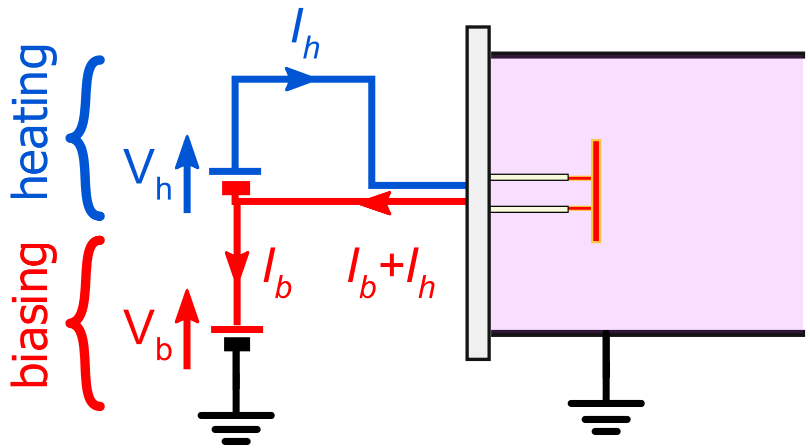
Pagaud *et al.*, *Plasma Sources Sci. Technol* **32**, 115019 (2023)

Current injection from an emissive cathode

Negatively biased Joule heated tungstene coil. Emission up to 15 A







$$I_b = \cancel{I_i} + \cancel{I_{is}} + I_{em}$$

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

$$I_{em} = A_G S T_w^2 e^{-eW/k_B T_W}$$

Joule heating balanced by radiative losses

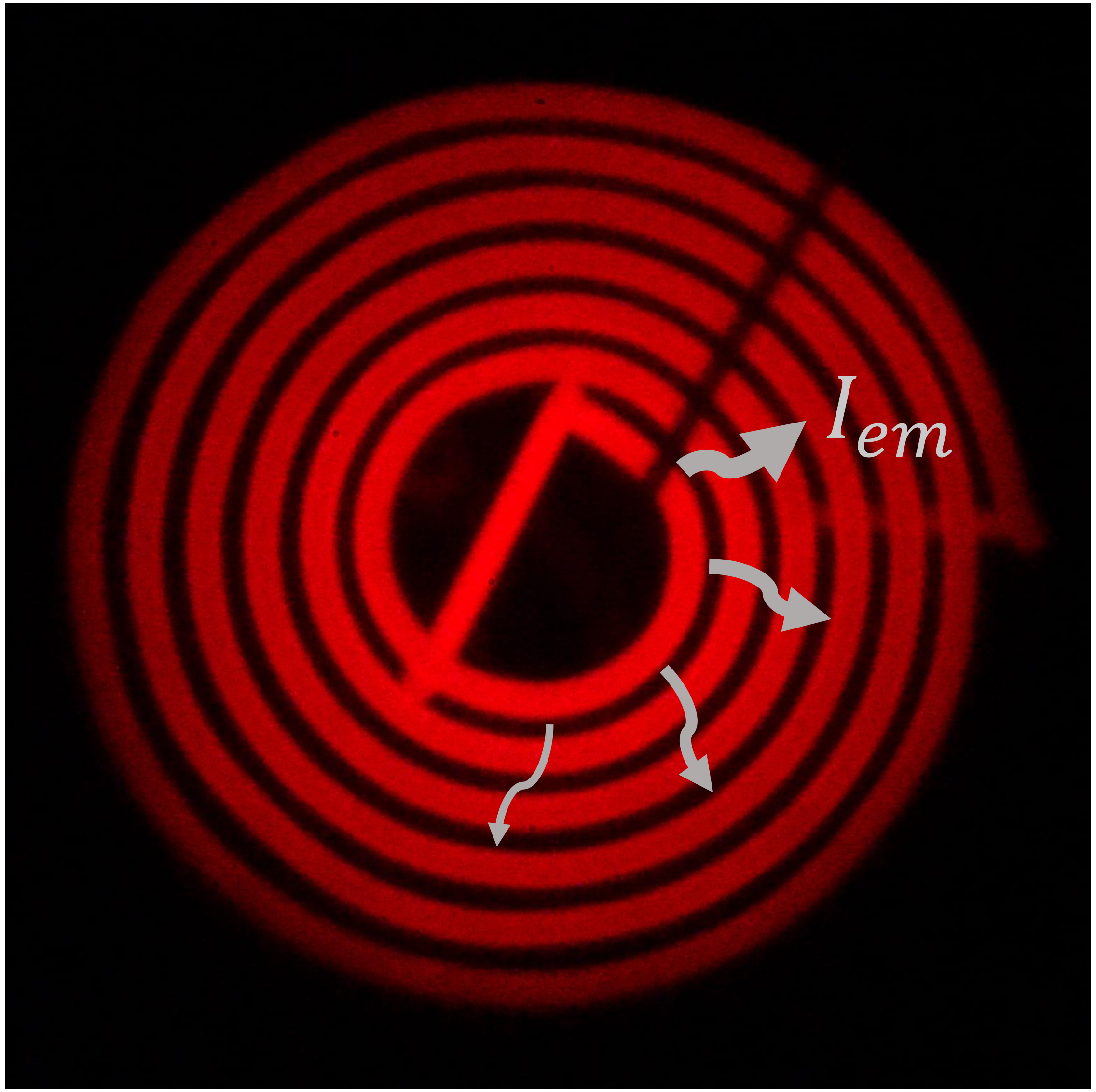
$$R I_h^2 = \sigma \varepsilon S T_w^4$$

$$T_w \propto \sqrt{I_h}$$

However T_W evolves during a plasma shot, and I_b strongly depend on plasma-surface interactions

Pagaud *et al., Plasma Sources Sci. Technol* **32**, 115019 (2023)

Spatially and temporally resolved thermal model



Pagaud *et al., Plasma Sources Sci. Technol* **32**, 115019 (2023)

Joule heating:

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

- heterogeneous heating

Ion bombardment:

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

Kersten *et al.*, Appl. Phys. Lett. (19

- Influence of biasing V_b+ coupling with plasma
- 5% of the power

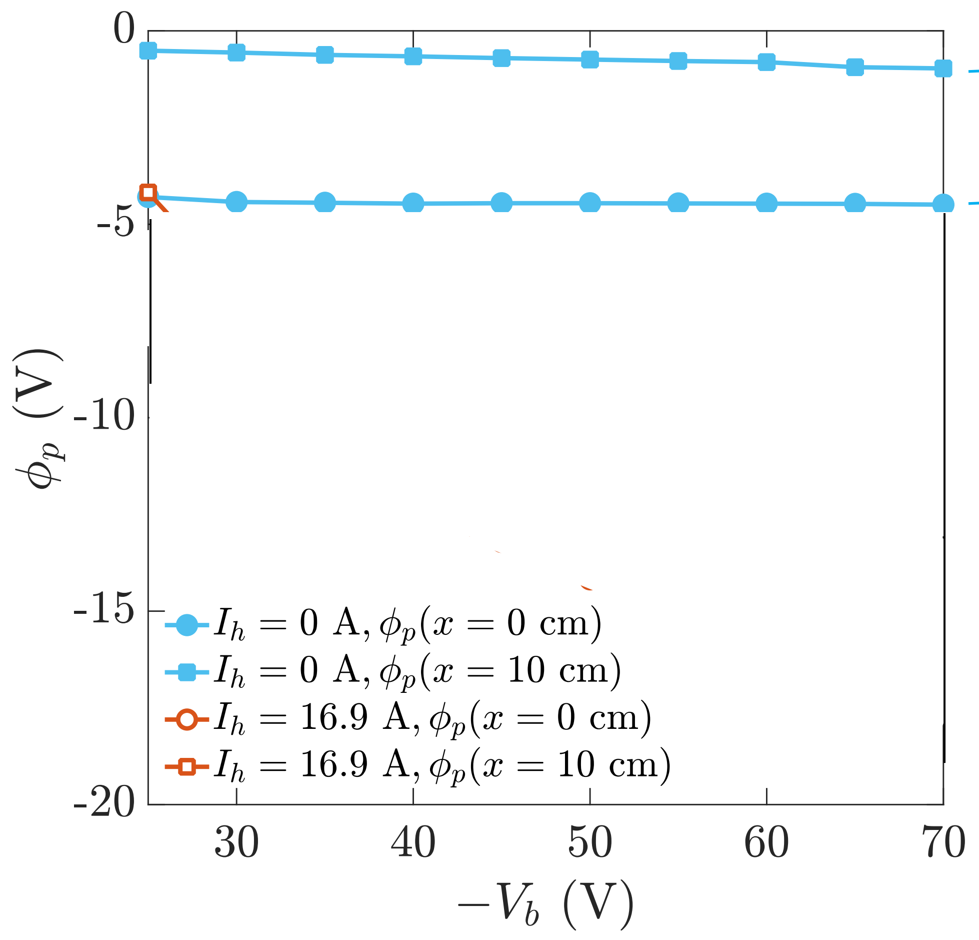
Transpiration cooling (from electron emission)

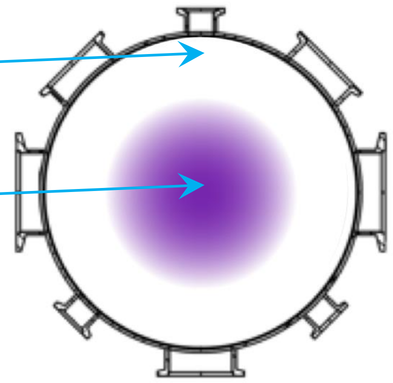
$$\dot{Q}_e = \frac{I_{em}}{e}(eW + 2k_B T_W)$$

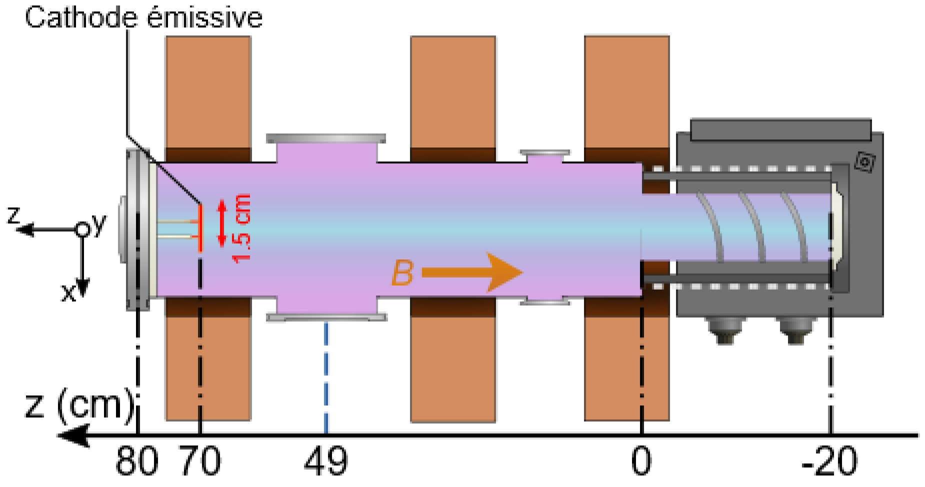
Hanquist *et al.*, J..Appl. Phys. (2

Plasma potential drive

Cold, negatively biased electrode are inefficient to drive plasma potential



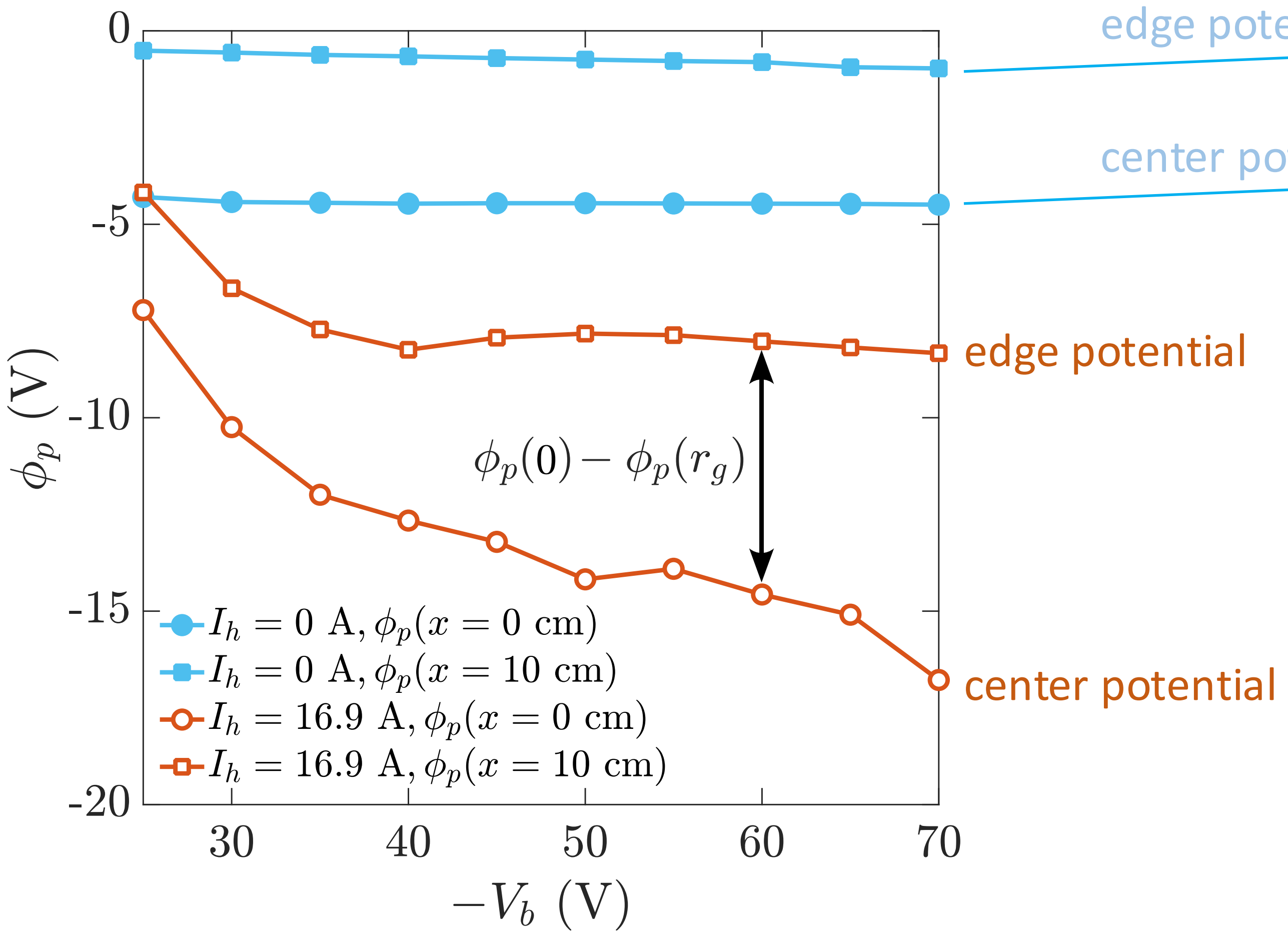


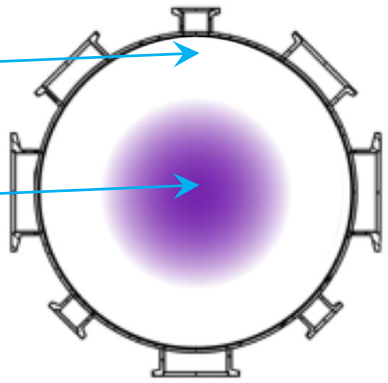


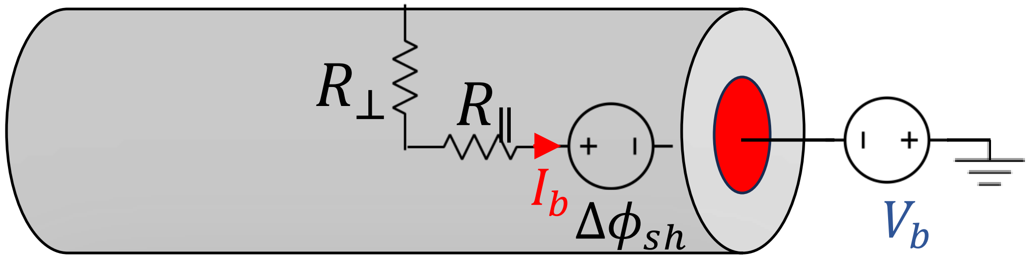
Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

Plasma potential drive

Cold, negatively biased electrode are inefficient to drive plasma potential
Emissive cathode offers an efficient to drive plasma potential

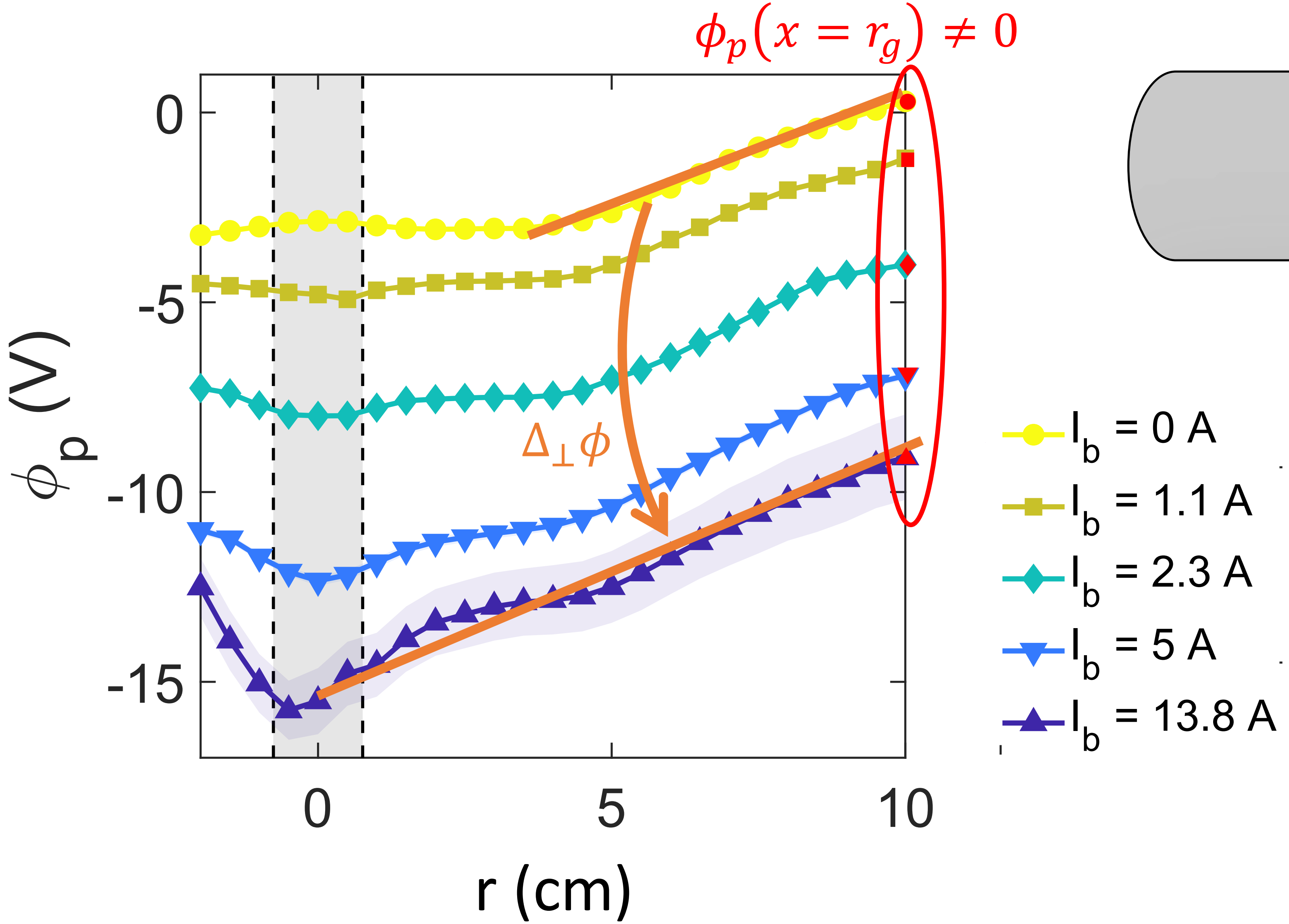


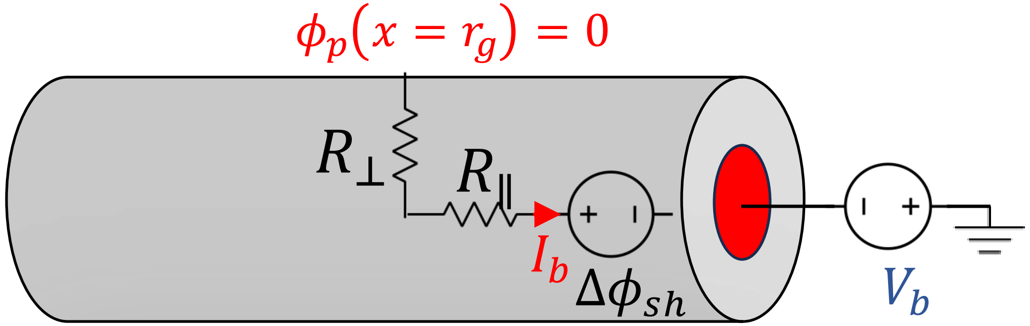




Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

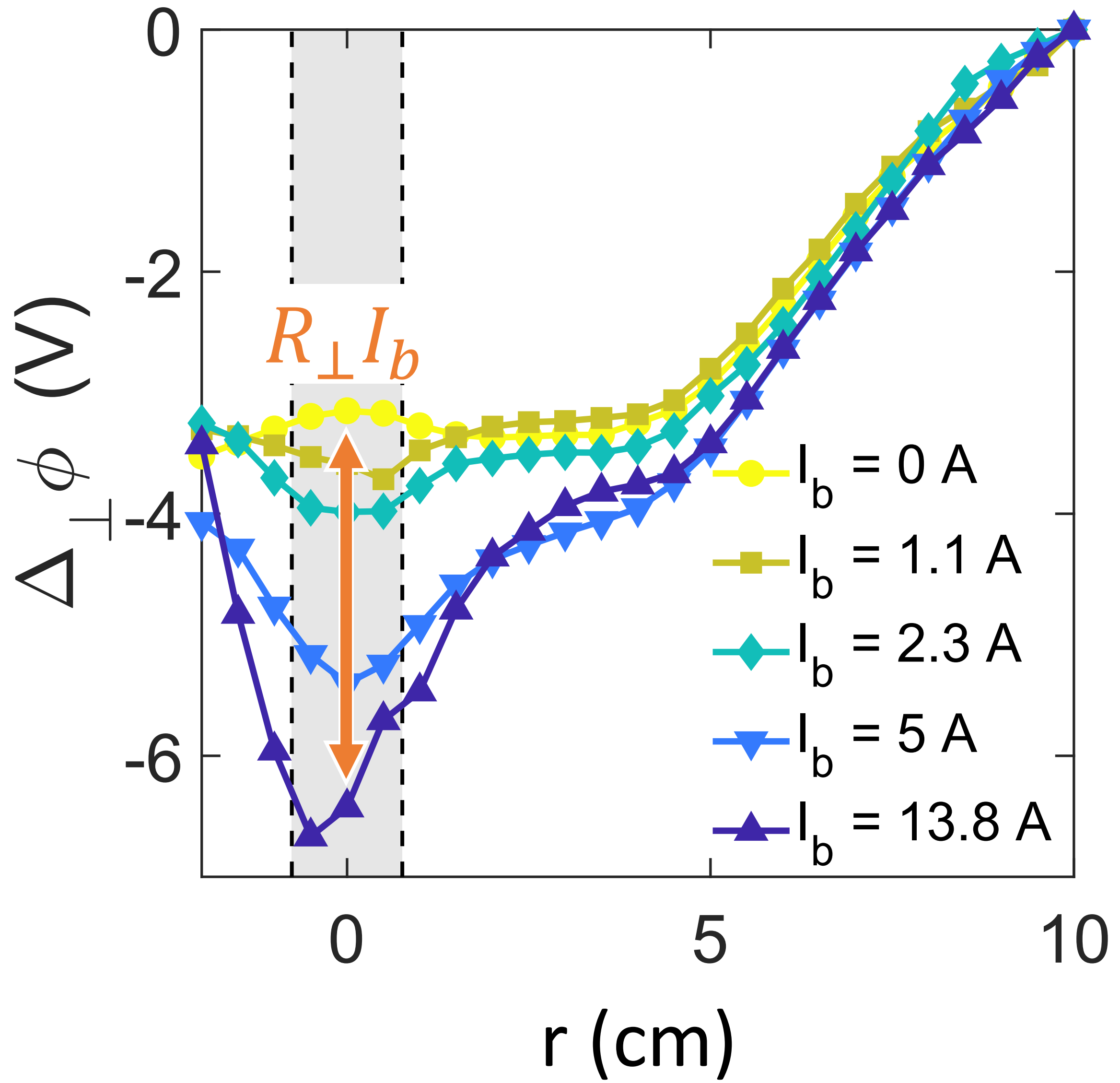
Radial potential drop

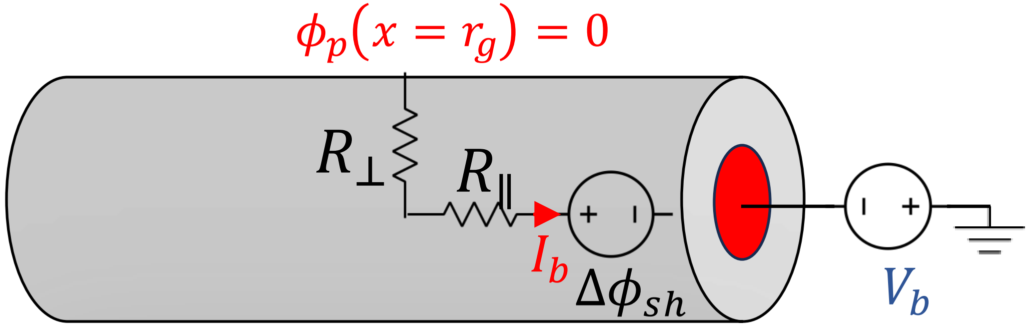




Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

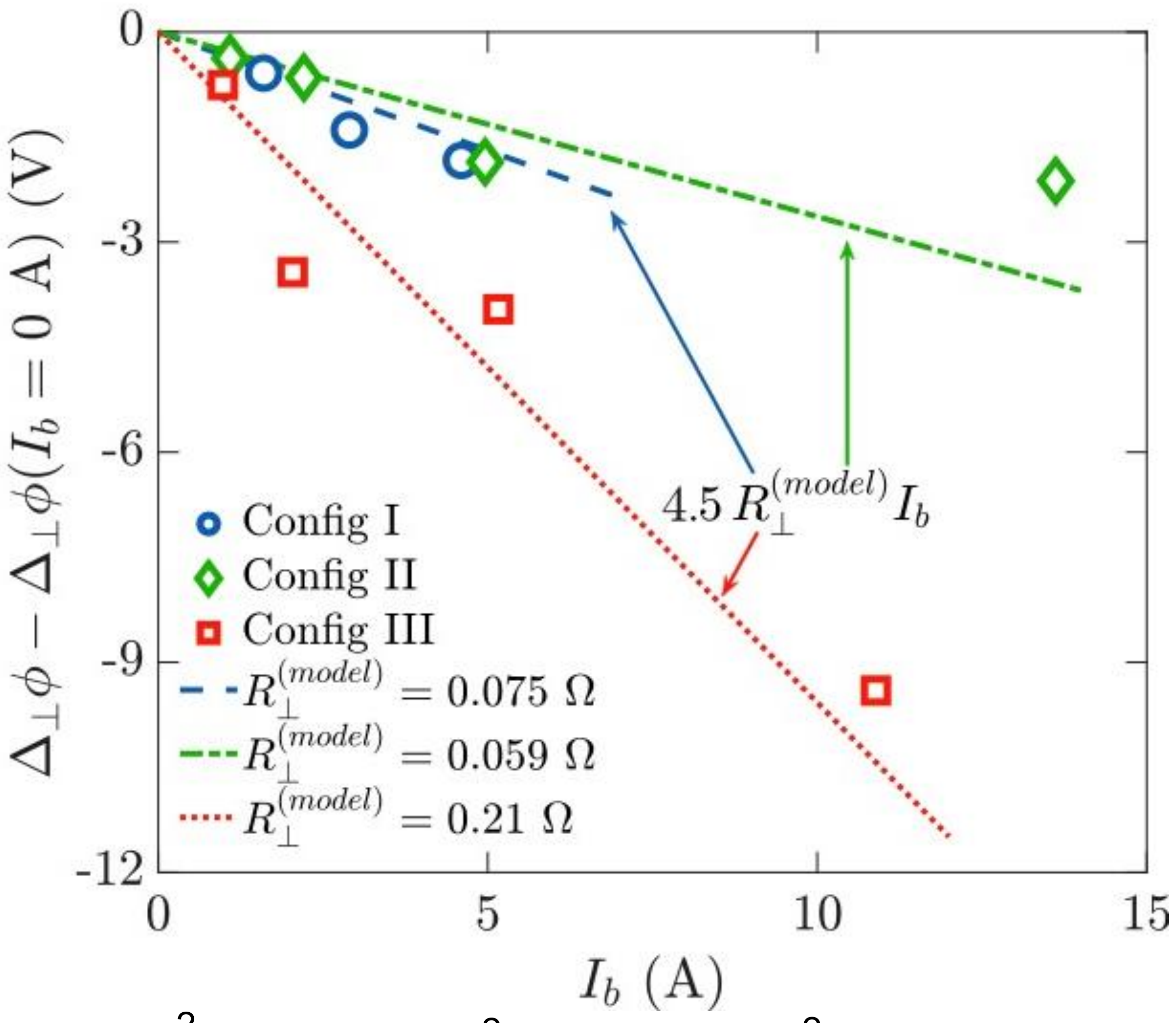
Radial potential drop





Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

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

- Model

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

- Parametric evolution

$$\sigma_\perp \sim \sigma_p = \frac{e^2 n}{m_i} \frac{\nu_{in}}{\left[\Omega_{c,i}^2 + \nu_{in}^2\right]}$$

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

Control parameters

Measur.

Trotabas & Gueroult, *Plasma Sources Sci. Technol .* **31**, 02500 (2022)

Qualitative agreement

Needs refinement for collisions modeling

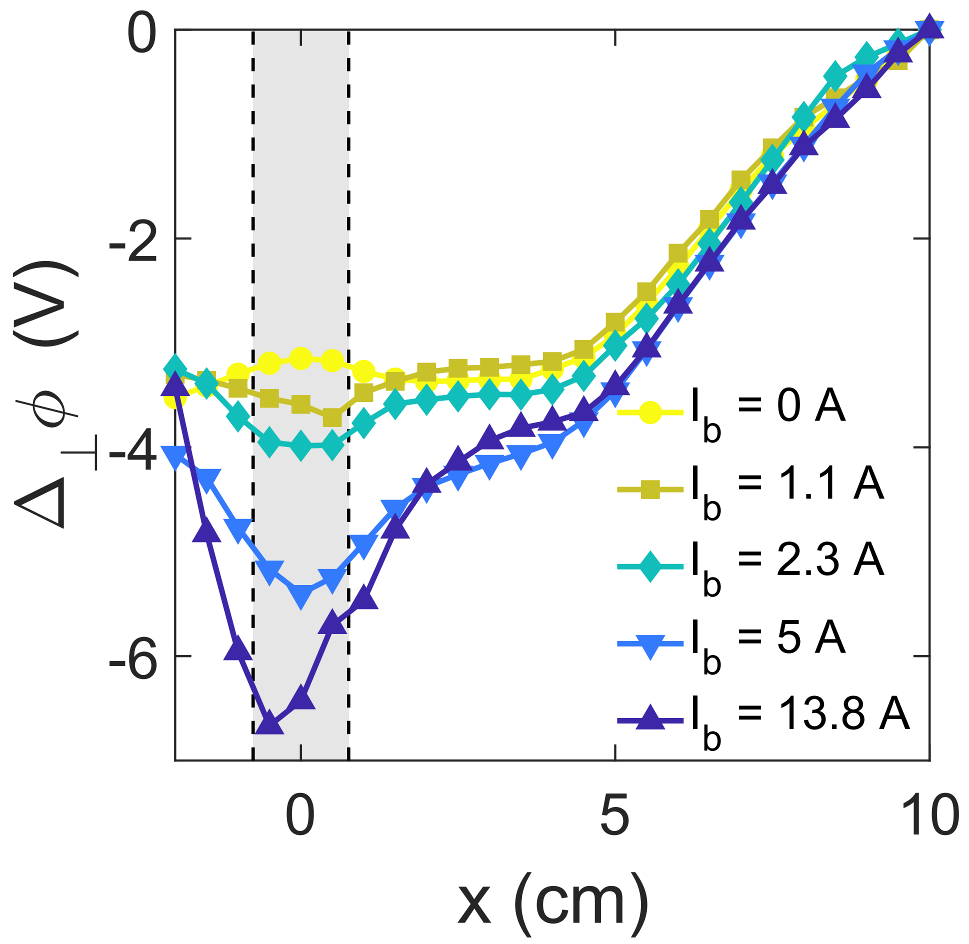
(neutral density, ion temperature)

Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

- Emissive cathodes offer an additional control parameter for plasma potential drive
- The radial potential drop is set by the perpendicular (ionic) resistivity as $R_{\perp} I_b$
- Existence of a strong electron sheath at the anode

Control of plasma rotation

Current injection modifies the concavity of the potential profile at the center

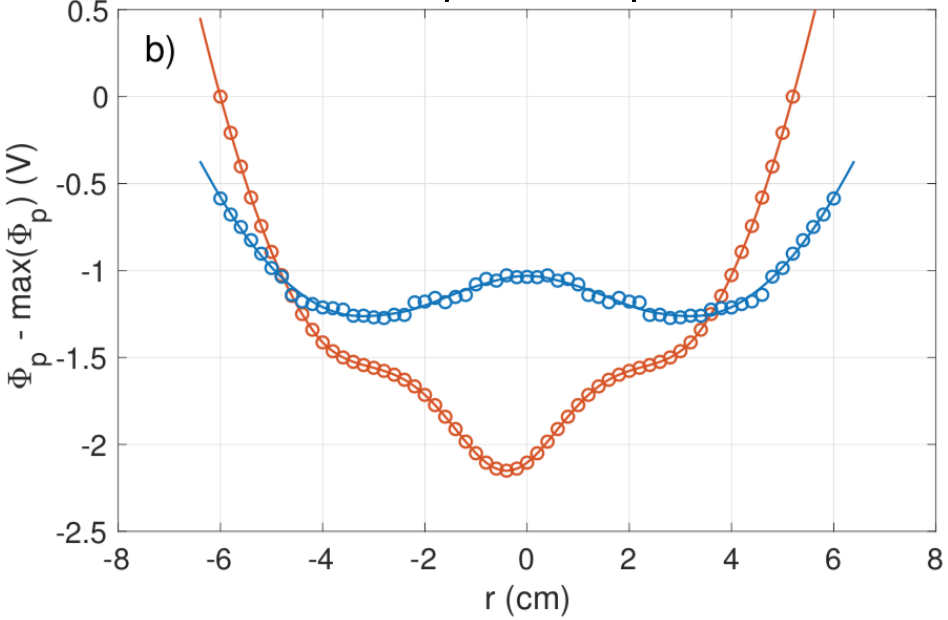


Désangles *et al.*, *J. Plasma Phys* (2021)

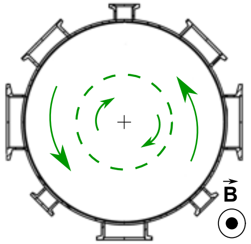
Control of plasma rotation

Current injection modifies the concavity of the potential profile at the center

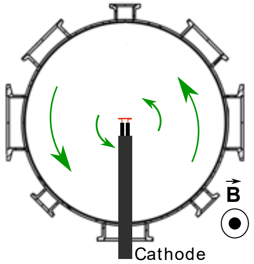
Plasma potential profile



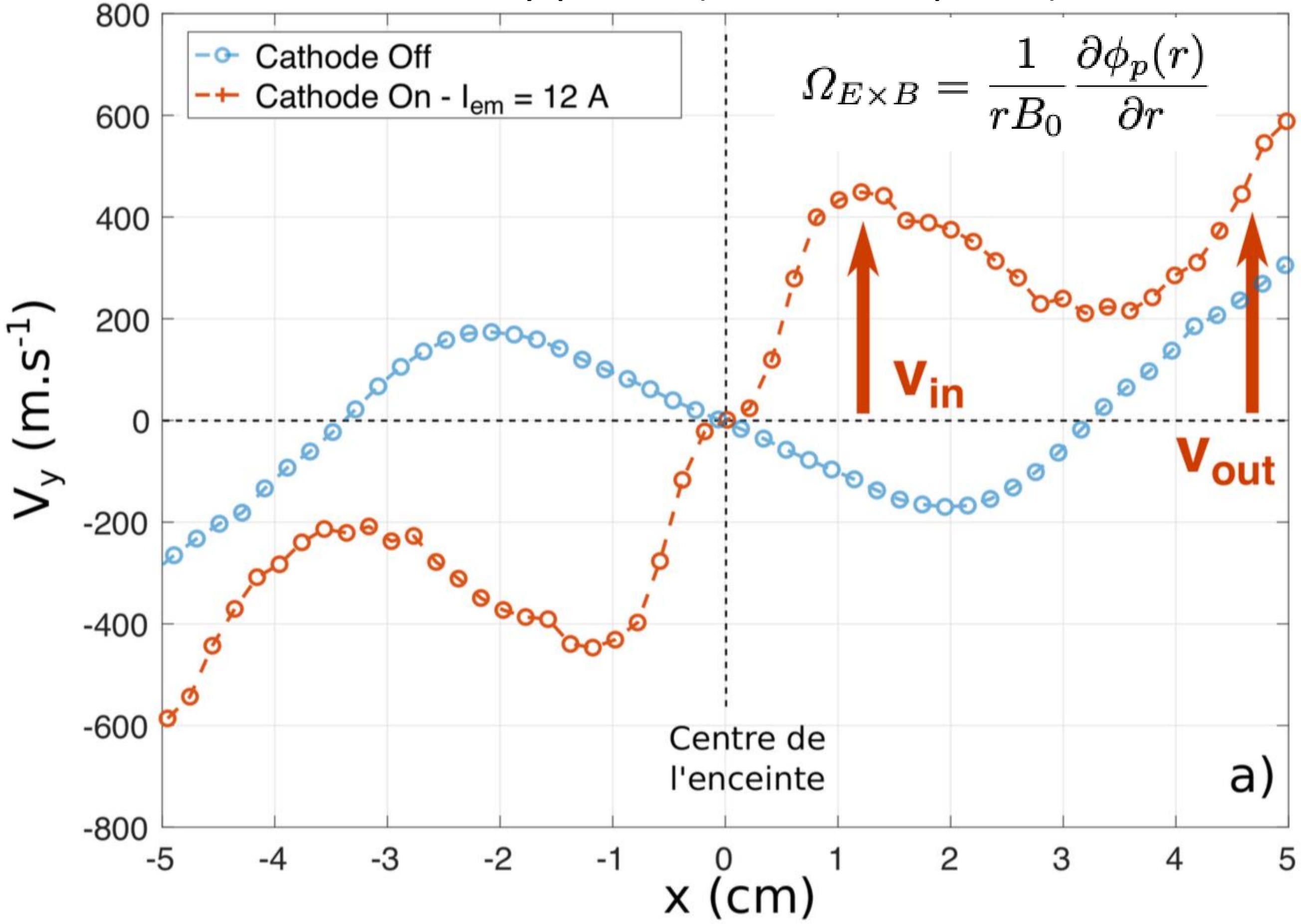
Cathode Off



Cathode On



Velocity profile (from Mach probe)



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

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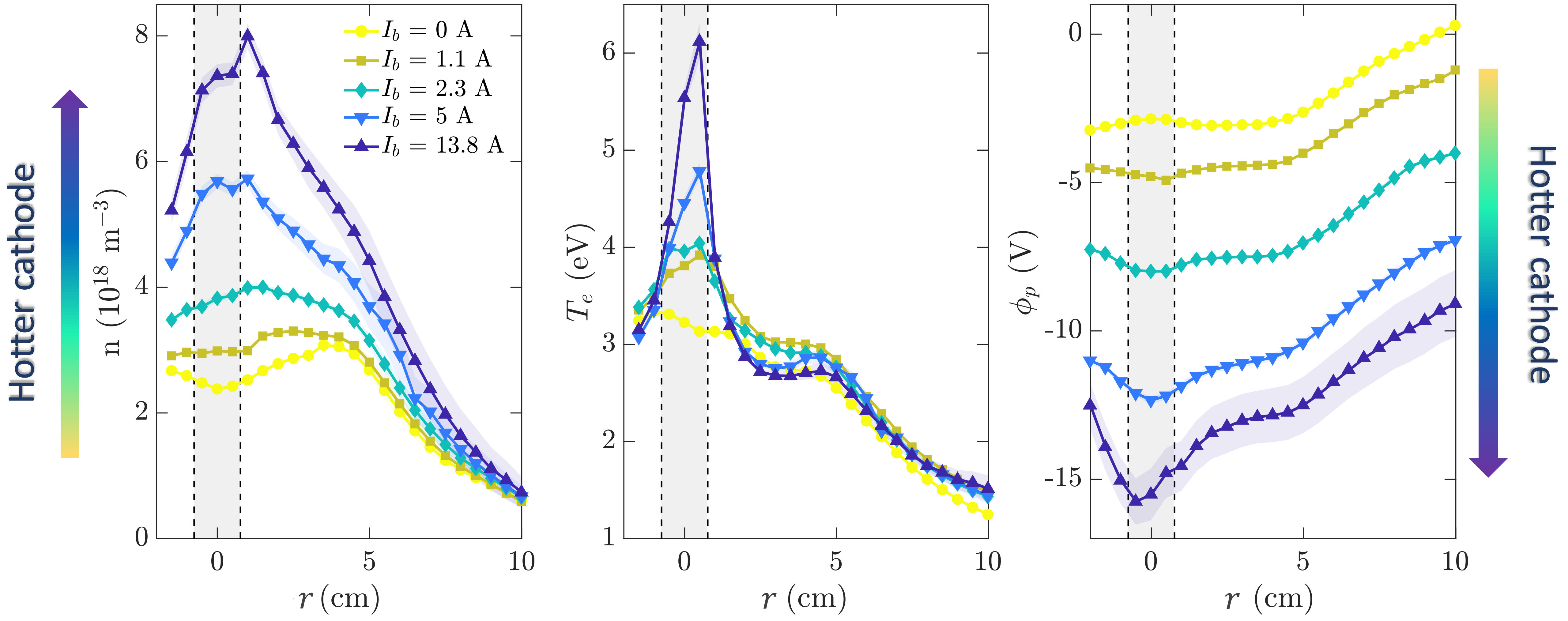
- The rotation of the plasma column is set by the electric drift
- Rotation control can be achieved using current injection

Current injection affects background plasma



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

Pagaud *et al.*, *Plasma Sources Sci. Technol* **34**, 065012

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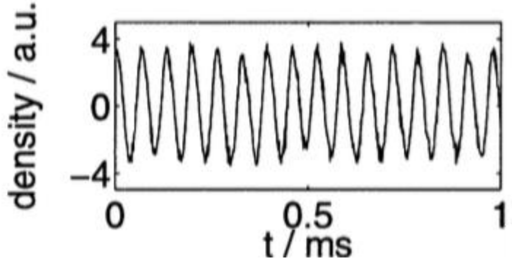
- Current injection has a dramatic effect on the equilibrium plasma parameters

Outline

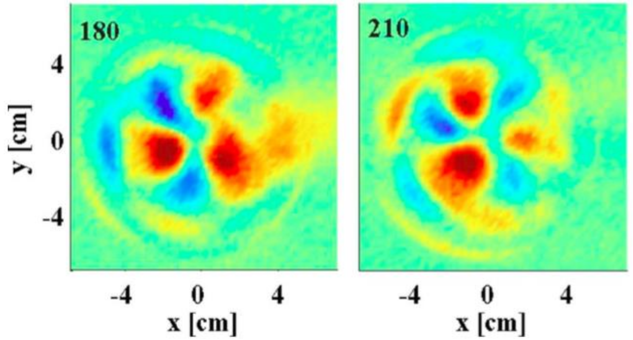
Instabilities in plasma columns

Probe measurements



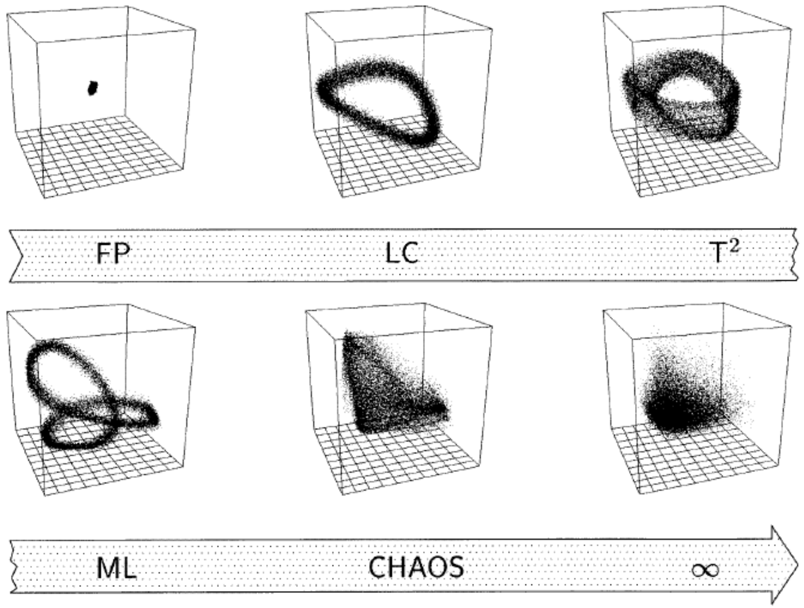
Grulke *et al., Physics of Plasmas, 6, 788 (1999)*

Camera imaging



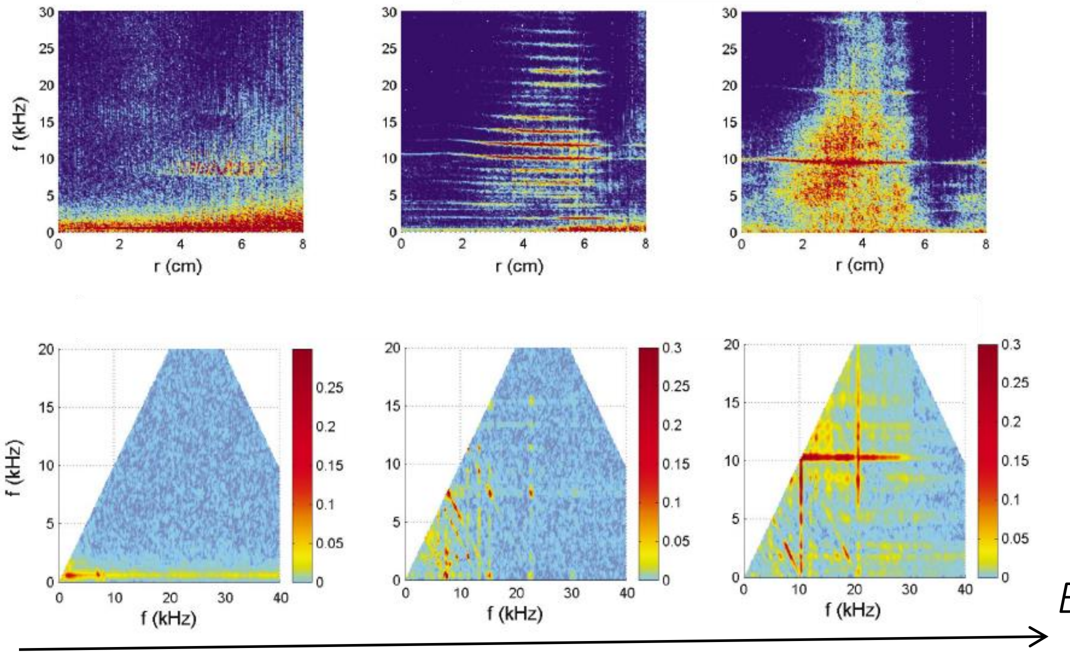
Antar et al., *Physics of Plasmas, 14, 022301 (2007)*

Transition to chaos



Klinger *et al., Plasma Phys. Control. Fusion, 39, B145 (1997)*

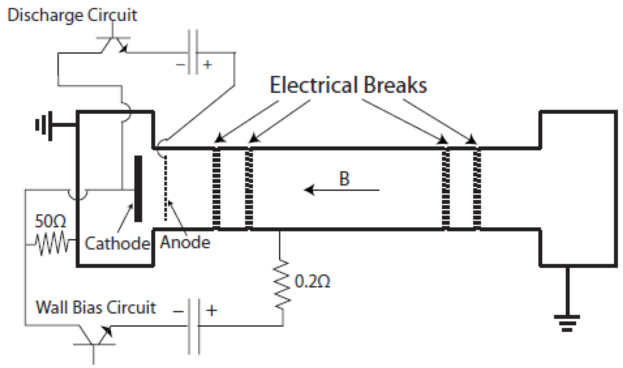
Wave-turbulence transition

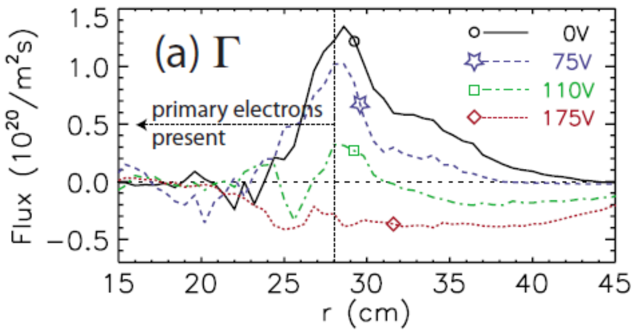


Burin *et al., Physics of Plasmas, 12, 052320 (2*

Instabilities in plasma columns

Static control

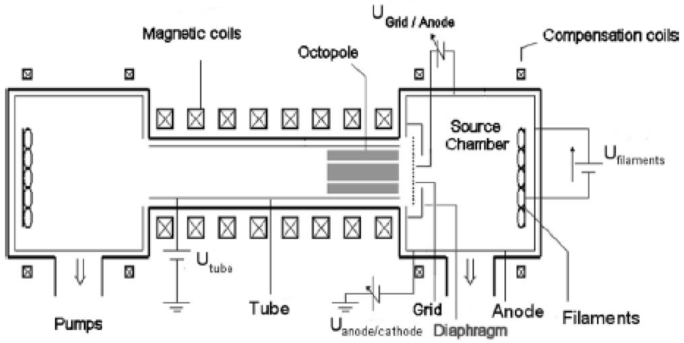


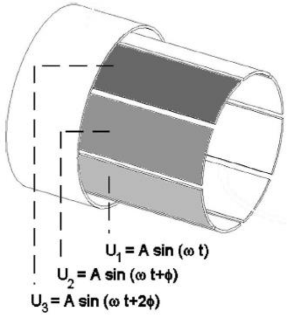


Carter and Maggs., *Phys. Plasmas, 16, 012304 (2009)*

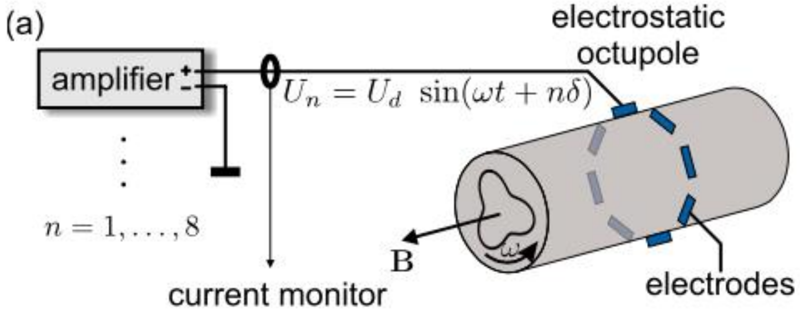
Reduction of turbulent transport

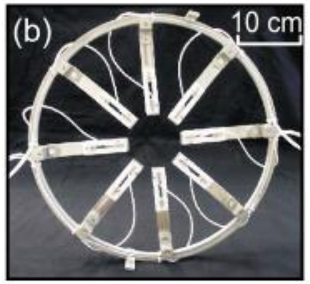
Dynamic control





Brochard et al., *Phys. Plasmas, 13, 052509 (2006)*



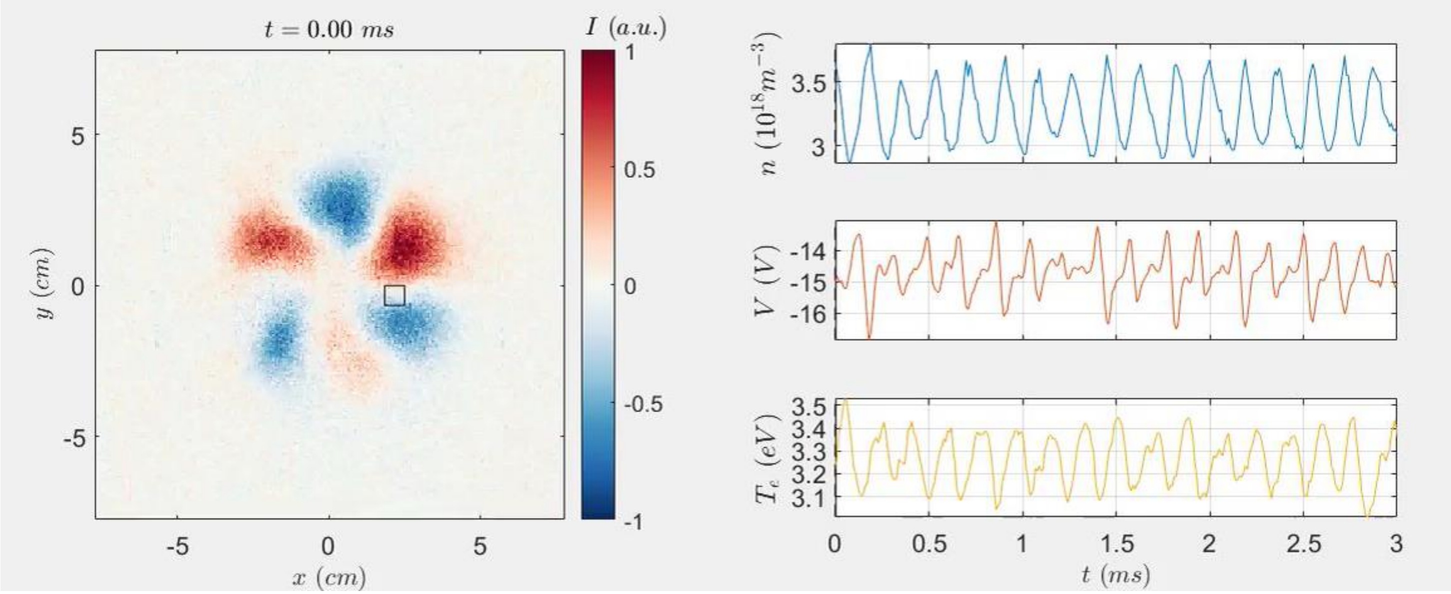


Brandt et al., *Phys. Plasmas, 17, 032403 (2010)*

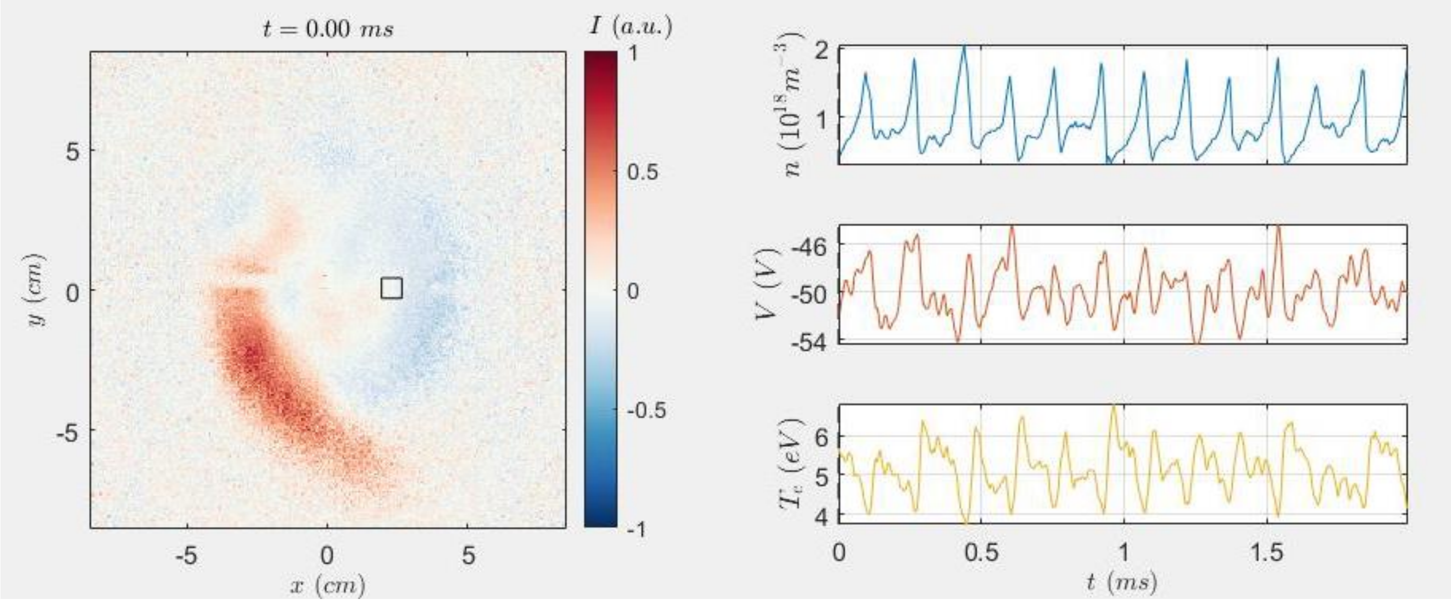
Wave synchronization

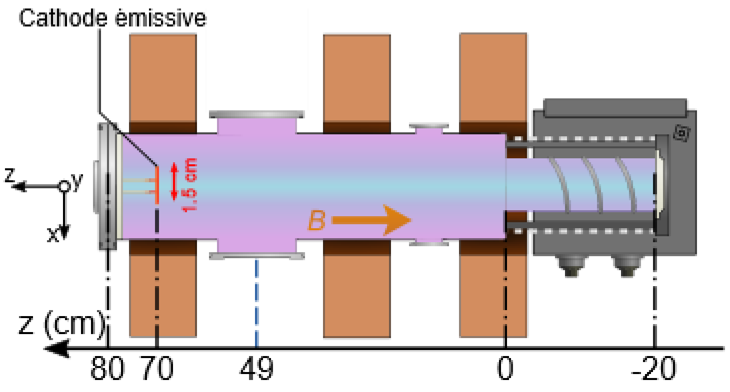
Influence of current injection on dynamics

No Cathode

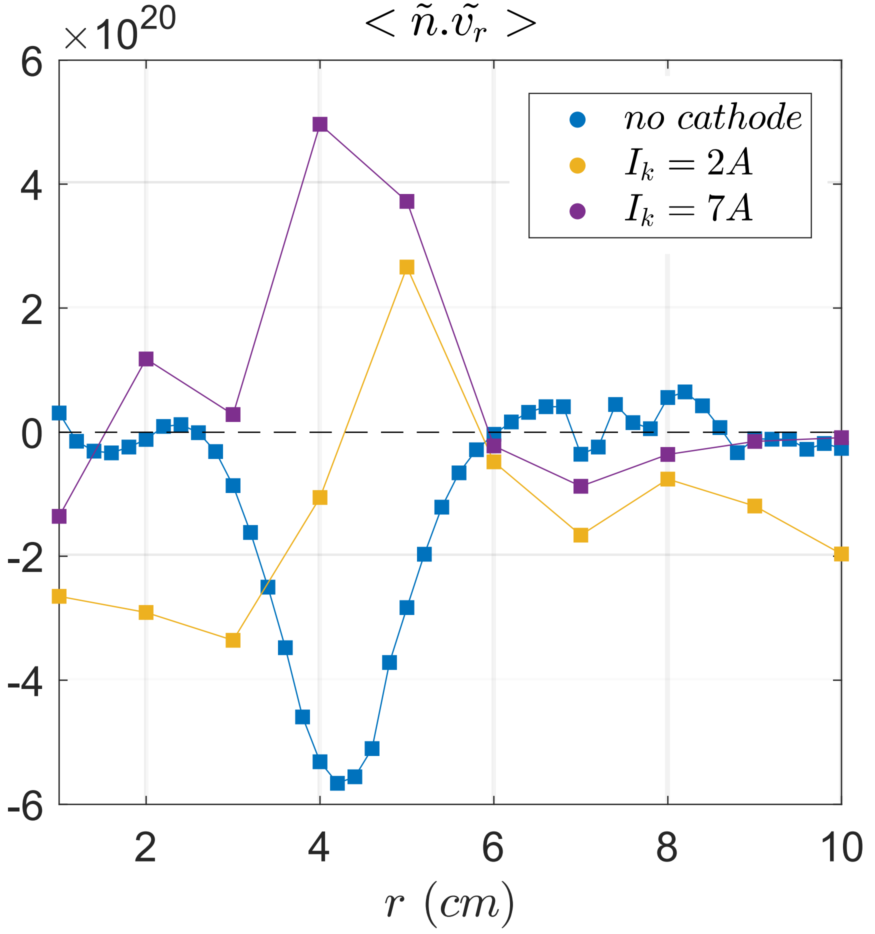


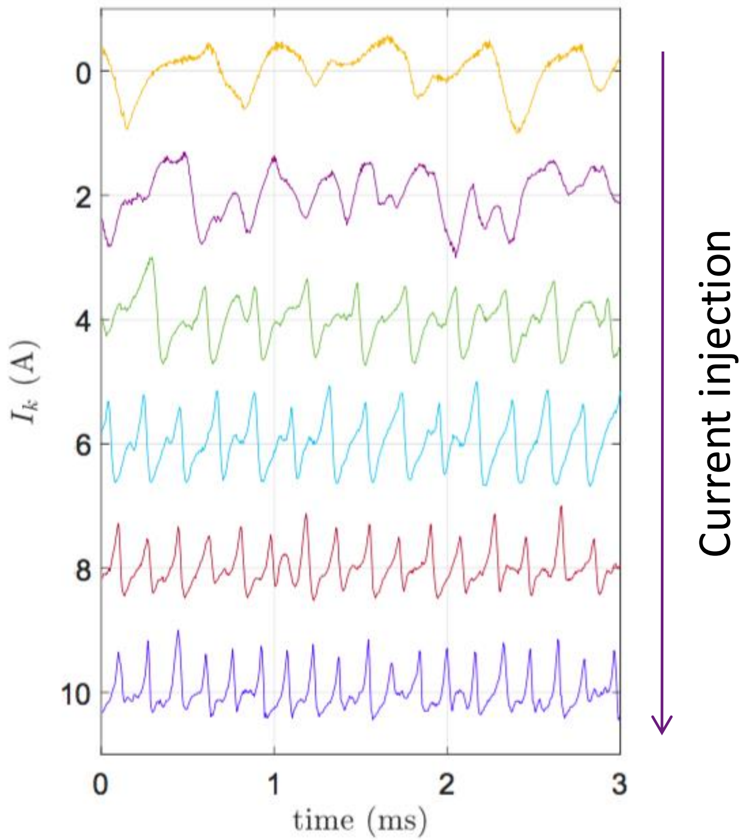
I_k = 10 A





Influence of current injection on transport





Outward transport, convective & intermittent

Summary

- Emissive cathodes offer an additional control parameter for plasma potential drive
- The radial potential drop is set by the perpendicular (ionic) resistivity as $R_{\perp} I_b$
- Existence of a strong electron sheath at the anode

- The rotation of the plasma column is set by the electric drift
- Rotation control can be achieved using current injection

- Current injection has a dramatic effect on the equilibrium plasma parameters

- Current injection allows to control the dynamics of large amplitude rotating structures and the associated turbulent transport

A collaborative framework


R. Gueroult


B. Trotabas


F. Pagaud


S. Vincent


V. Désangles


G. Bousselin


A. Poyé


V. Dolique

Laplace

Lab PHYS
ENS de LYON

Thank your for your attention