Existe-t-il encore des questions fondamentales en physique des décharges ?

GDR EMILI 2023, Nancy, France

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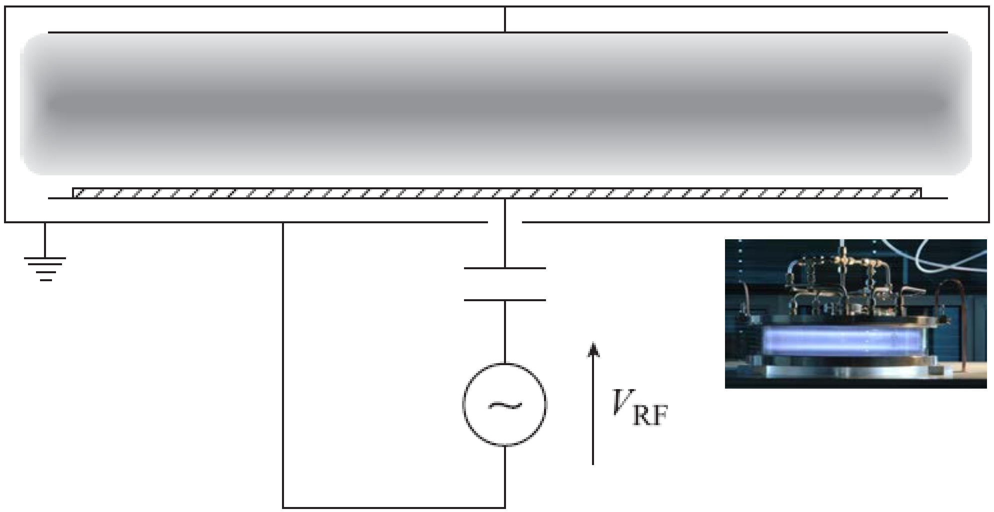
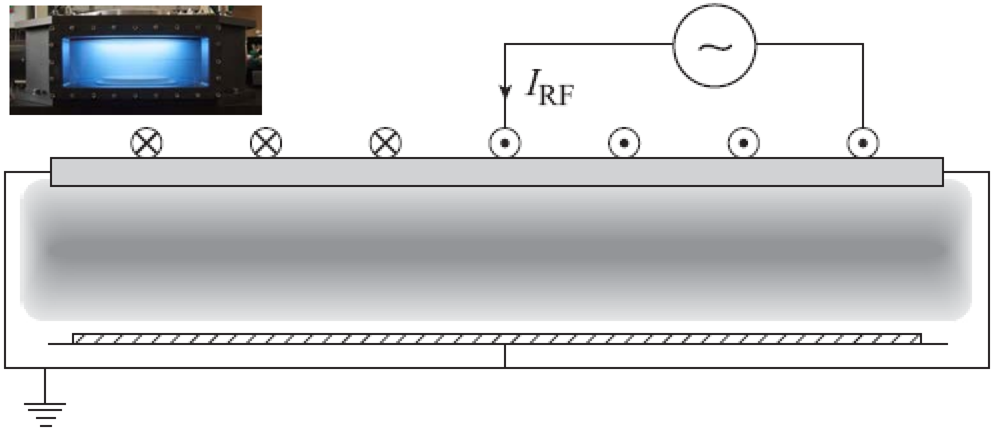
Le but de cette présentation est de donner envie à de jeunes chercheurs de faire de la recherche fondamentale en physique des décharges ; bref de la recherche qui ne sert à rien…

… ou presque.

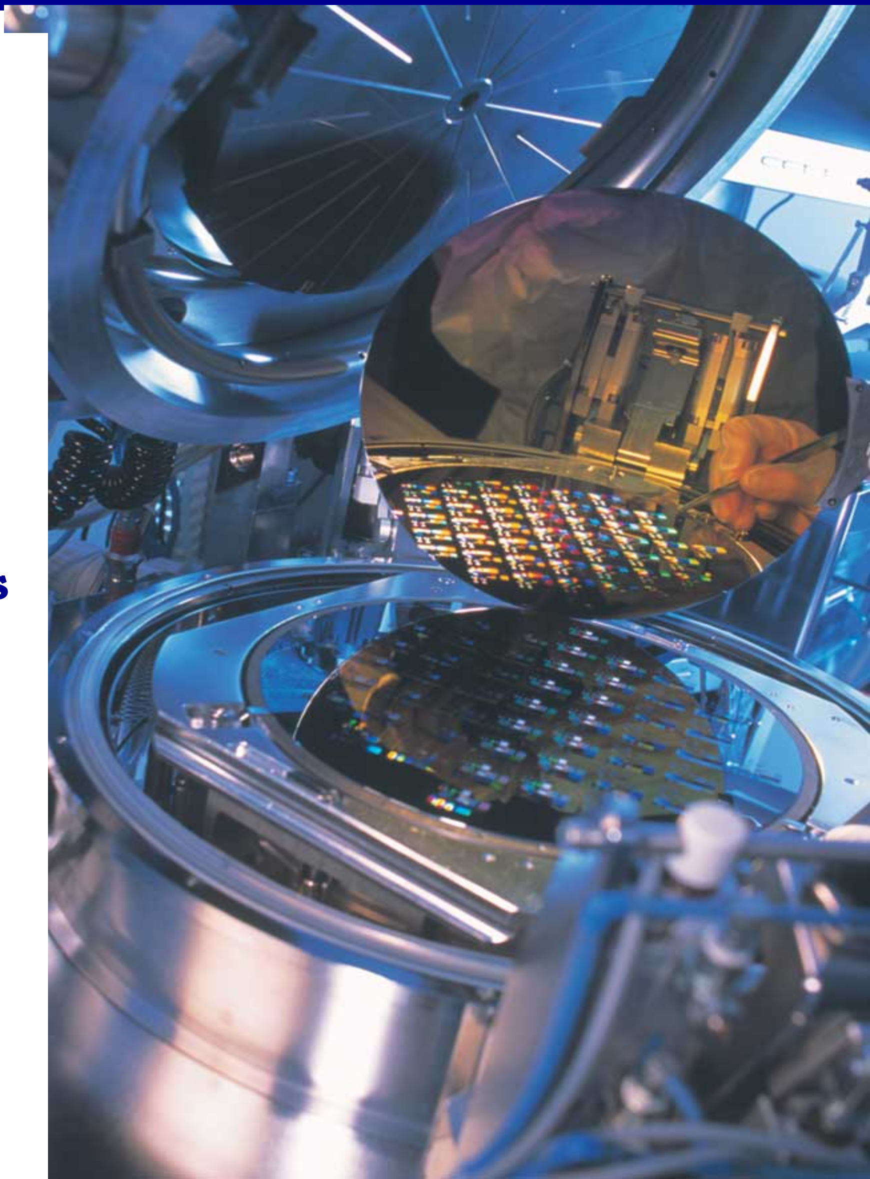
RF Plasmas in microelectronics



(a) **Radiofrequency Capacitive Discharges**



(b) **Radiofrequency Inductive Discharges**



Why would one study capacitive discharges after 1999 ?

- Capacitive discharges were very well understood in 1999 (People say) – The GEC cell reactor was introduced in 1991
- There were RF sheath models available (for sine waveform at least..)
- Complete experimental set (Voltage/current, power, electron density, eedf, etc..)
- Collisionless and ohmic heating models already existed (some debates about this but mostly "done")
- The benefit of VHF excitation (up to 200 MHz) was demonstrated
- Multiple frequency excitation had already been proposed
- The problems of non uniformity at high frequency were known

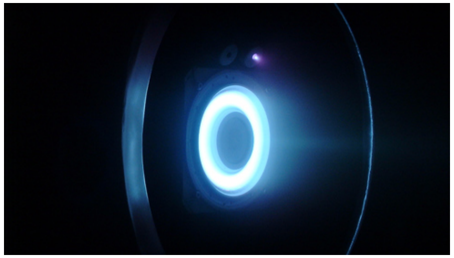
Shall I do research in this area?

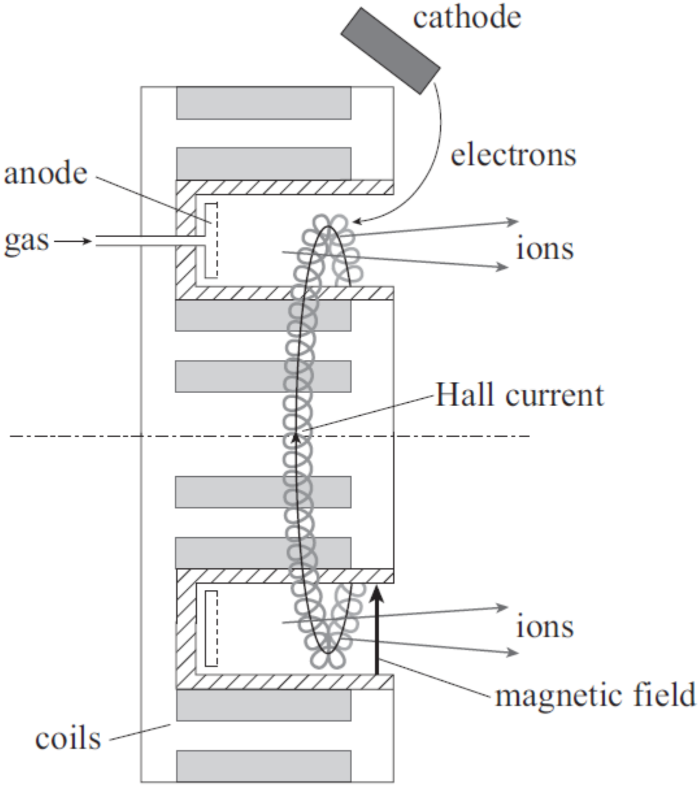
I asked a group of distinguished friends and scientists and as you can see, a consensus was not necessarily easy to find …

Yes !

After intense philosophical activity, the answer was clear … Yes!

Same applies for plasma Thrusters



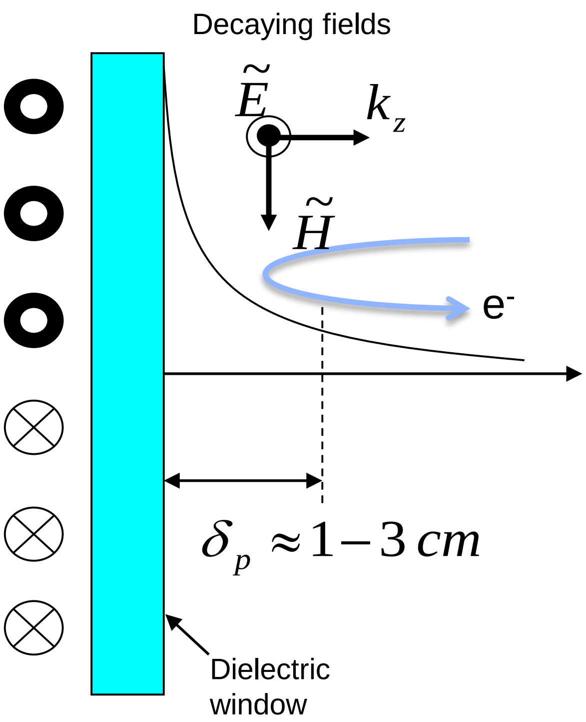


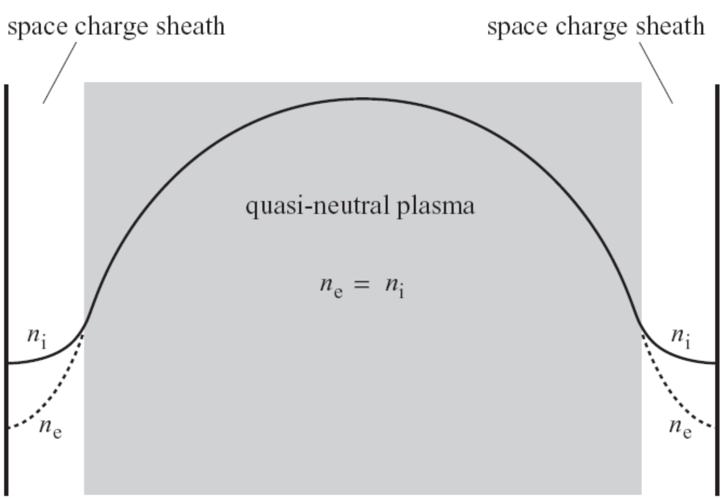
- Hall thrusters proposed in the 60's
- 2D fluid or hybrid codes in the late 90's (For instance at LAPLACE, Toulouse)
- PIC codes and theory of azimuthal instabilities in early 2000's (For instance at CPHT, Ecole Polytechnique)
- Effect of secondary electron emission in 2000's

Physics of low-pressure plasmas

- The physics of low-pressure (and low-temperature) plasmas may be decomposed in two main phenomena:

- Electron heating (wave-particle interaction)
- Plasma transport (or confinement)





- Both include the physics of collisions

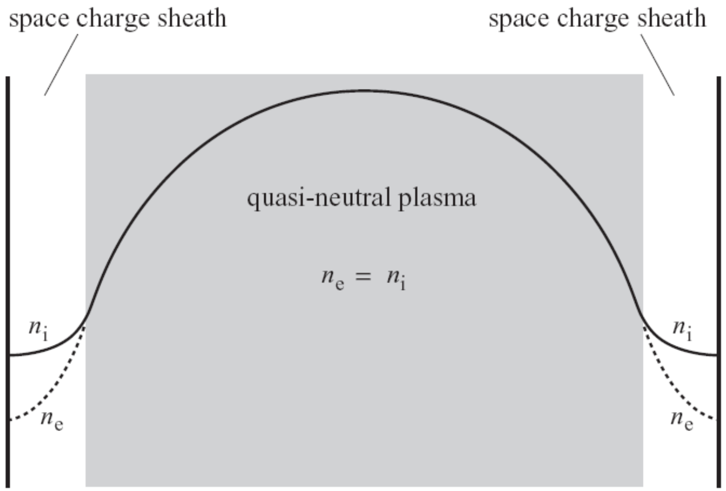
Let us focus on plasma transport

- First review the historical and “textbook” theories in the simple case: the plasma slab or plasma column

- Then challenge the assumptions: real discharges

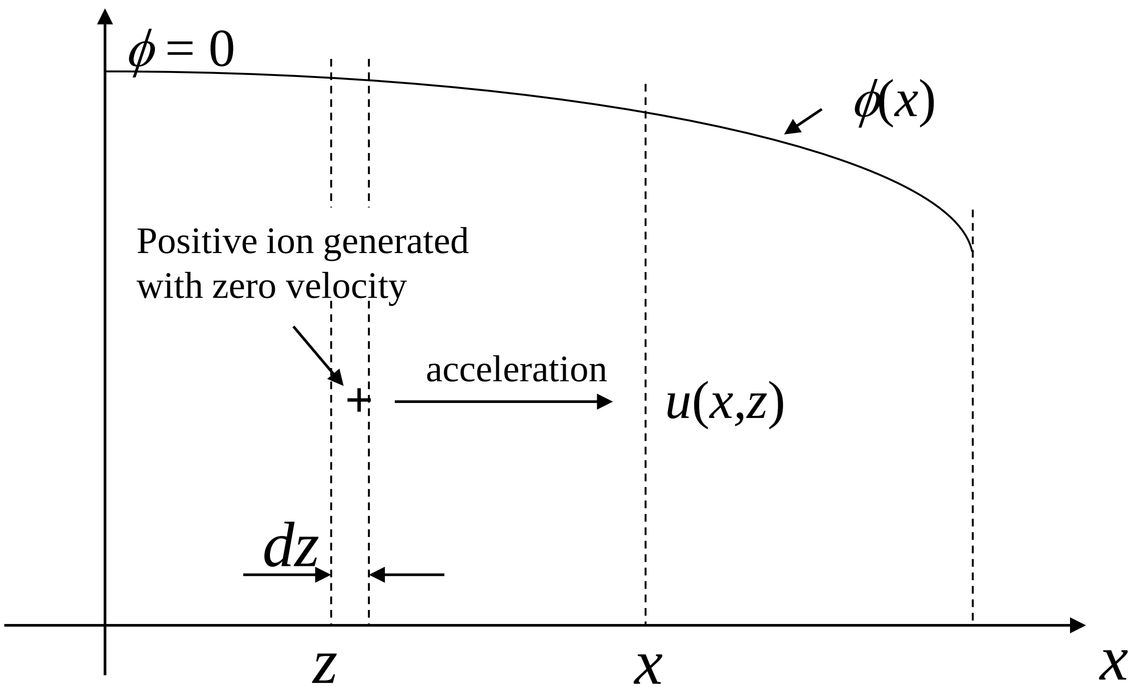
- Pressure effects
- Neutral gas dynamics
- Presence of negative ions
- Transport instabilities and patterns

- Magnetized plasma column



Transport in gas discharges

The low-pressure collisionless solution was studied by Tonks and Langmuir in the late1920's (L. Tonks and I. Langmuir. Physical Review, 1929)



A GENERAL THEORY OF THE PLASMA OF AN ARC

BY LEWI TONKS AND IRVING LANGMUIR
RESEARCH LABORATORY, GENERAL ELECTRIC CO., SCHENECTADY

(Received August 3, 1929)

Transport in gas discharges

- The fully collisional solution was studied by Walter Schottky, also in the 1920's

$$n(x) = n_0 \cos \beta x \qquad \beta = \left(\frac{n_g K_{iz}}{D_a}\right)^{1/2} \approx \frac{\pi}{l}$$

$$\Gamma(x) = -D_a n'(x) = D_a n_0 \beta \sin \beta x \qquad D_a = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}$$

- A drift-diffusion theory that assumes that the plasma density is zero at the wall and ignore sheaths

W. Schottky. *Phys. Z.*, 25:635, 1924

The plasma-sheath transition

Problem identified by Langmuir: the plasma equations are singular near the edge

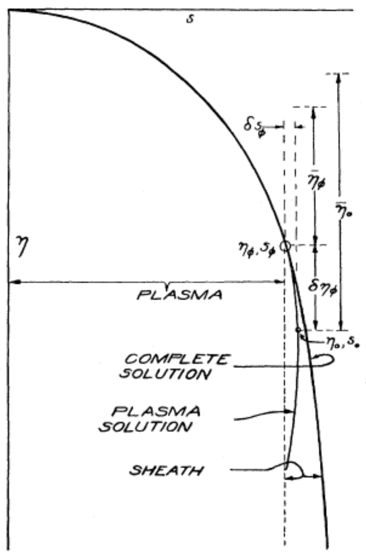
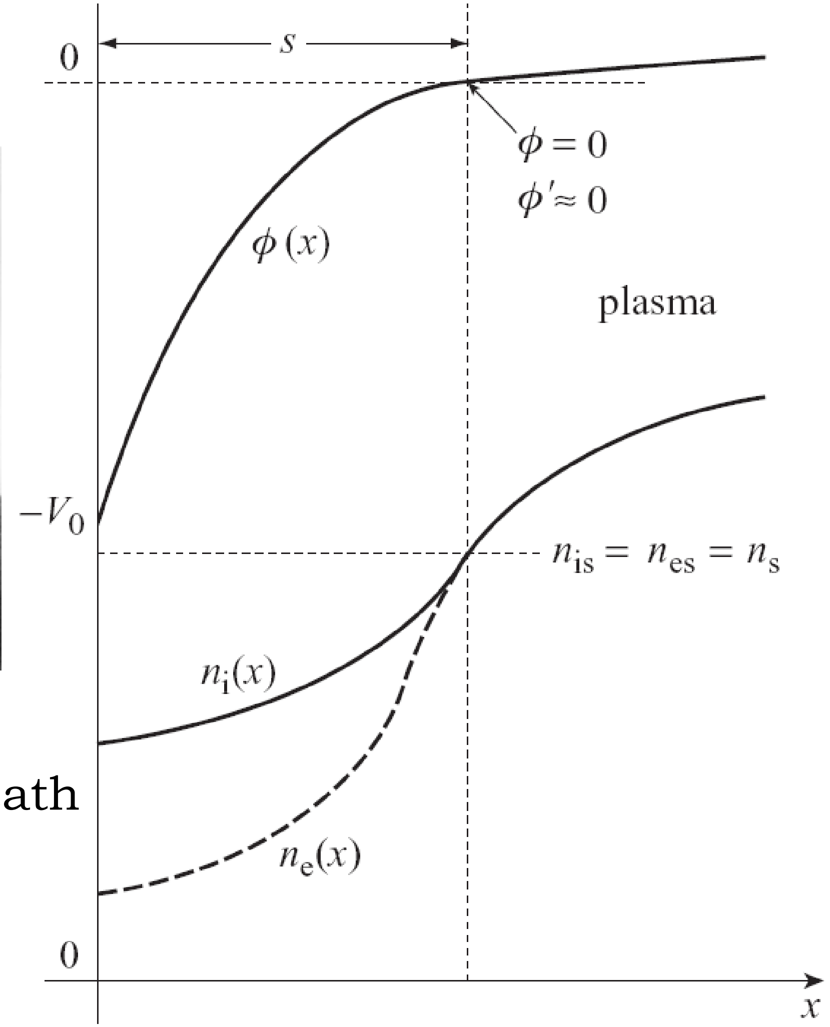


Fig. 6. The relation of the plasma and complete solutions of the plasma-sheath integral equation.



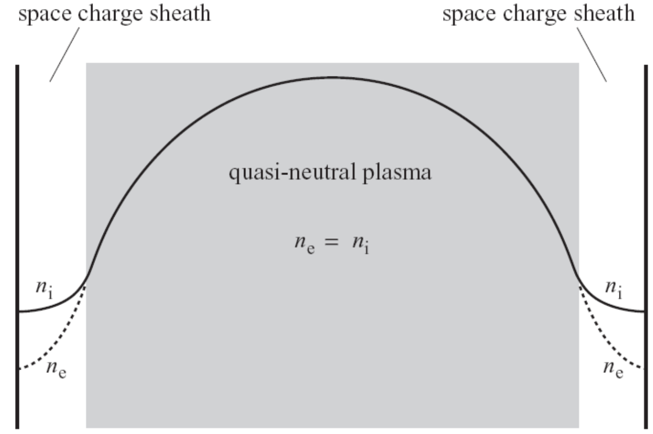
Bohm in 1949 proposed that the plasma-sheath transition occurs when the ion speed u_s is :

$$u_s = \left(\frac{kT_e}{M}\right)^{1/2}$$

Fluid equations for plasma transport

Particle conservation equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = S - L$$



Momentum conservation equation

$$nm\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = nq\mathbf{E} - \nabla p - m\mathbf{u}\left[n\nu_{\mathrm{m}} + S - L\right]$$

$$p = nkT$$

Commonly for a simple electropositive plasma:

$$S = n_e n_g K_{\mathrm{iz}}$$

$$L = 0$$

Isothermal approximation

$$\nabla p = kT\nabla n$$

Momentum conservation
The two limits in the pressure range

For electrons:

$$nm\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = nq\mathbf{E} - \nabla p - m\mathbf{u}\left[n\nu_{\mathrm{m}} + S - L\right]$$

For ions in the steady-state collisionless (Tonks and Langmuir) limit:

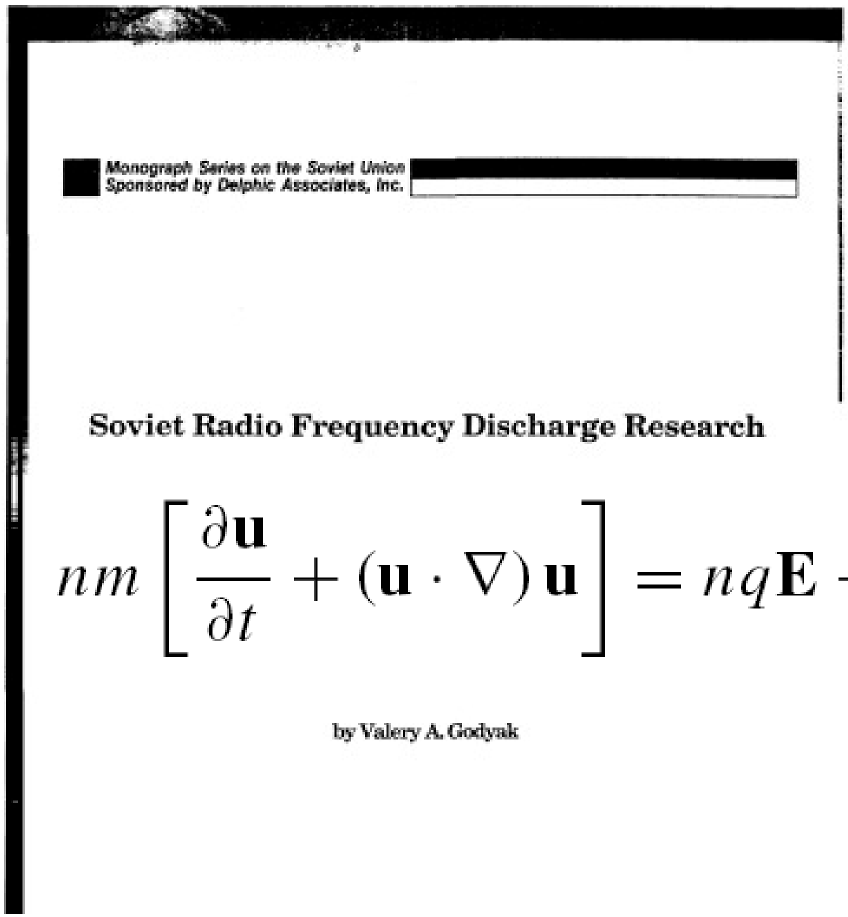
$$nm\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = nq\mathbf{E} - \nabla p - m\mathbf{u}\left[n\nu_{\mathrm{m}} + S - L\right]$$

For ions in the high-pressure (Schottky) limit:

$$nm\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = nq\mathbf{E} - \nabla p - m\mathbf{u}\left[n\nu_{\mathrm{m}} + S - L\right]$$

Momentum conservation intermediate pressure regime

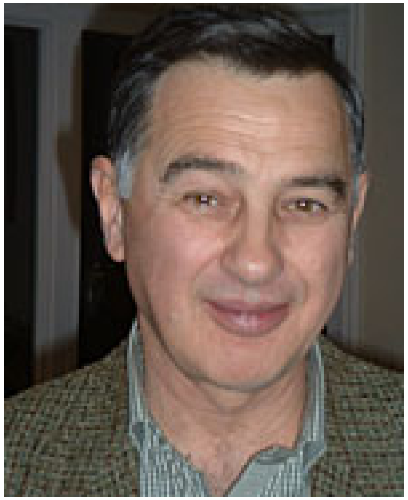
Valery Godyak showed in the 1980's that a non linear friction force should be used for ions in the intermediate pressure range:



Monograph Series on the Soviet Union
Sponsored by Delphic Associates, Inc.

Soviet Radio Frequency Discharge Research

by Valery A. Godyak



$$nm\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\mathbf{u}\right] = nq\mathbf{E} - \nabla p - m\mathbf{u}\left[n\nu_{\mathrm{m}} + S - L\right]$$

$$\nu_m(u_i) = \frac{\pi u_i}{2\lambda_i}$$

Particle conservation

Particle conservation equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = S - L$$

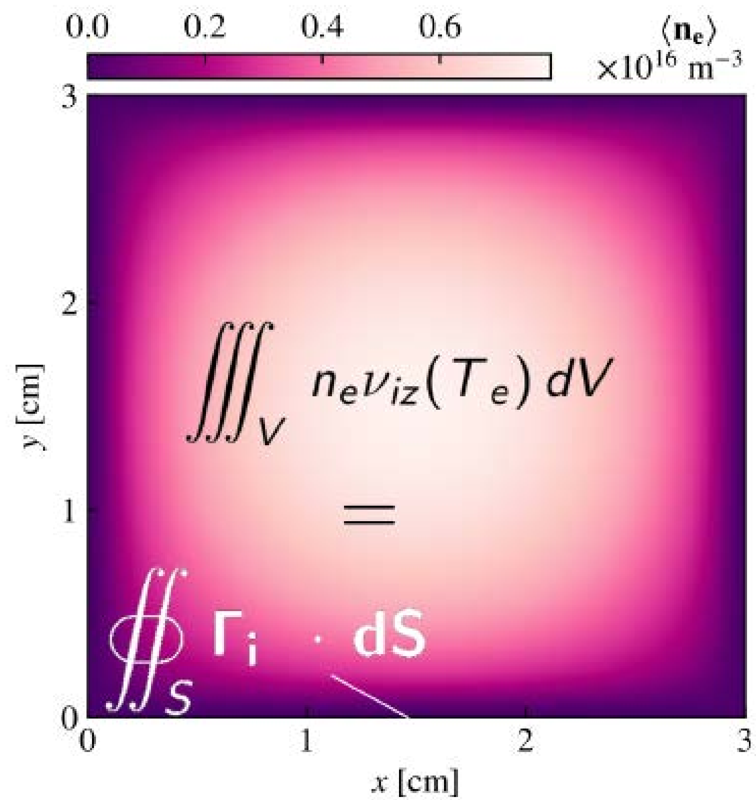
Integrated over the discharge volume

$$n_0 n_g K_{\rm iz} V = \oint\!\!\!\oint_S \mathbf{\Gamma}_i \cdot \mathbf{dS}$$

Generalized h factor

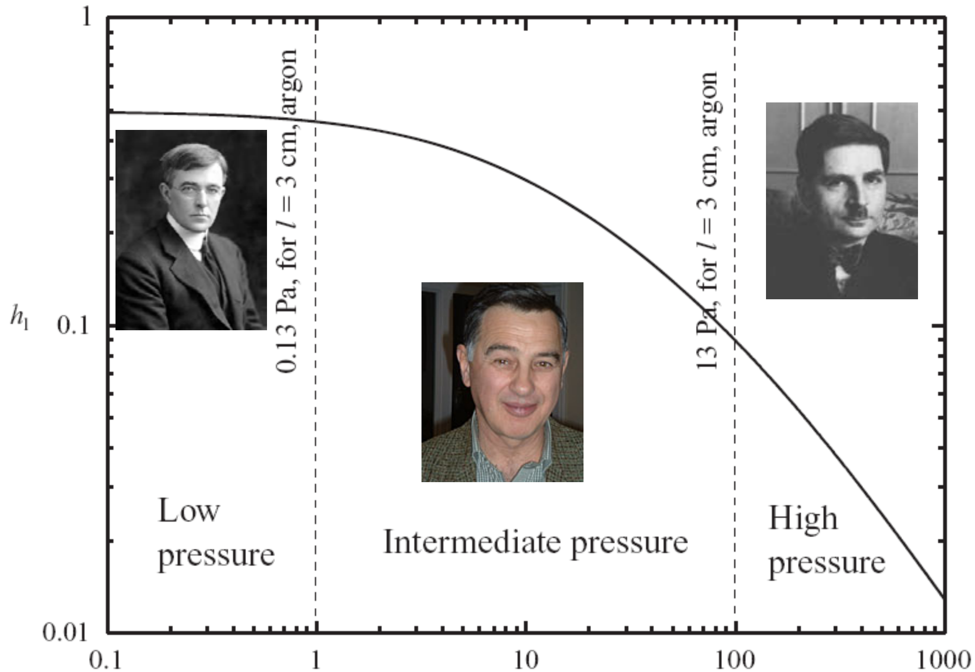
$$h = \frac{\oint\!\!\!\oint_S \mathbf{\Gamma}_i \cdot \mathbf{dS}}{n_0 u_{\rm B} S}$$

In 1 D: $\Gamma = n_s u_B$ $\quad h_1 = \frac{n_{\rm s}}{n_0}$



The h factor in 1D

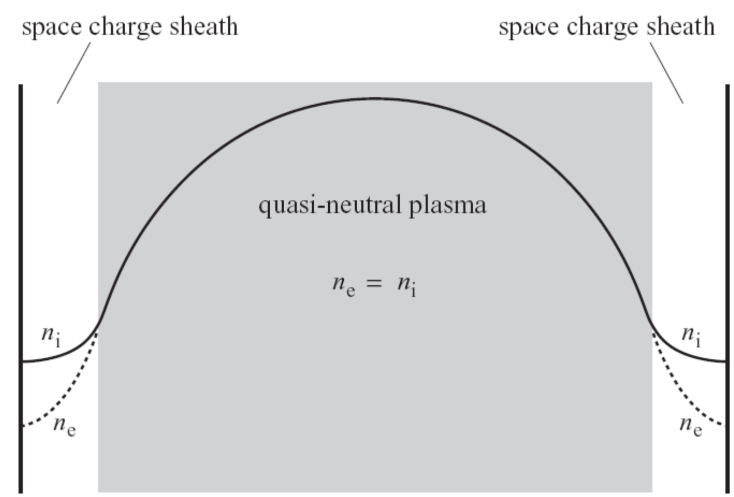
P. Chabert and N. Braithwaite, *Physics of Radio-Frequency Plasmas* (Cambridge University Press, 2011).



$$\Gamma = h_l n_0 u_B$$

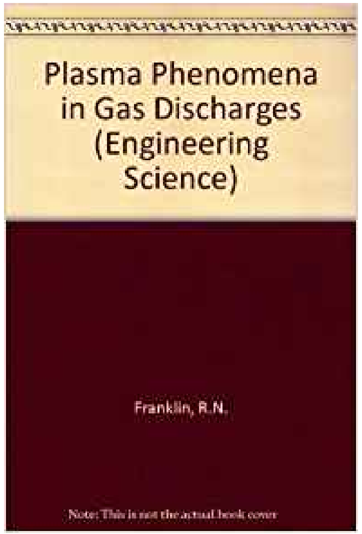
$$h_l = \frac{n_s}{n_0}$$

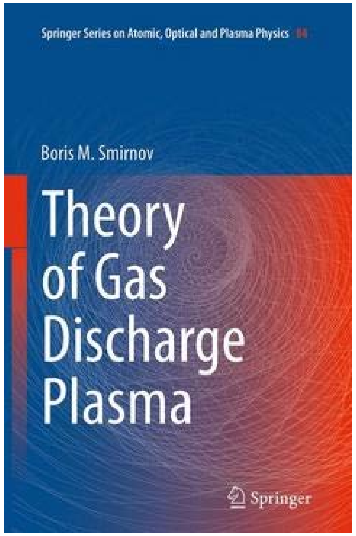
$$h_l \approx 0.86 \left[3 + \frac{1}{2}\frac{l}{\lambda_i} + \frac{1}{5}\frac{T_i}{T_e}\left(\frac{l}{\lambda_i}\right)^2 \right]^{-1/2}$$

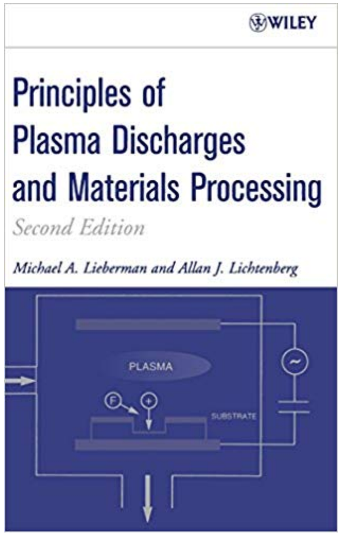


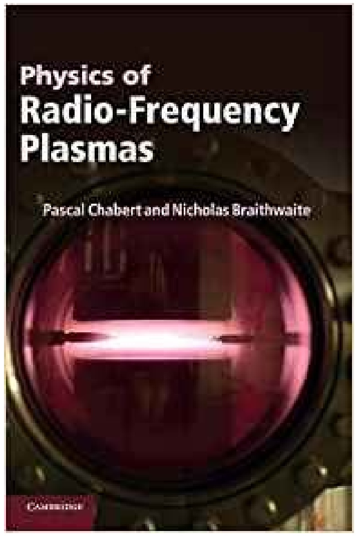
Assumptions in the above (textbook) theories

- Isothermal electrons
- Constant neutral gas density
- Electropositive plasmas
- One-dimensional discharges

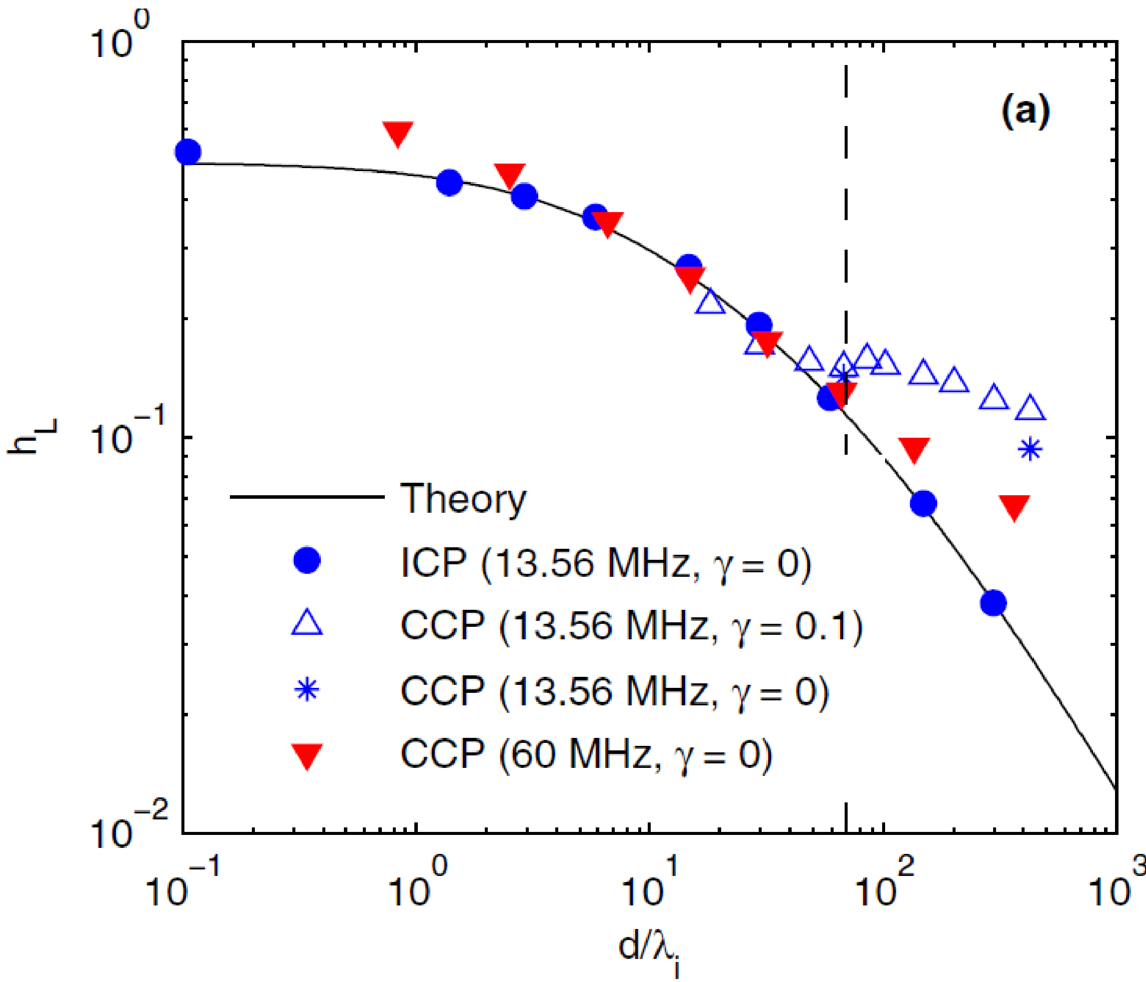




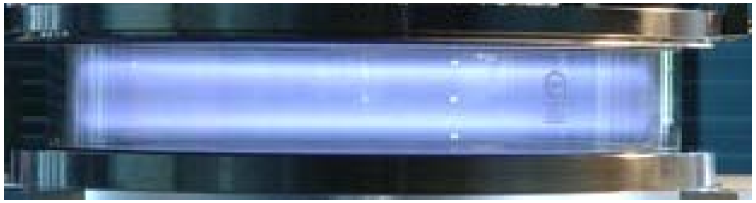


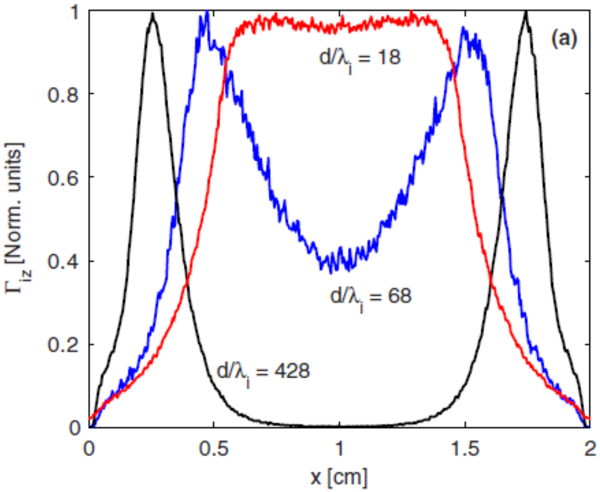


Isothermal electrons?



Strong heating near the sheath edge in CCPs





T. Lafleur and P. Chabert, Plasma Sources Science and Technology **24**, 025017 (2015)

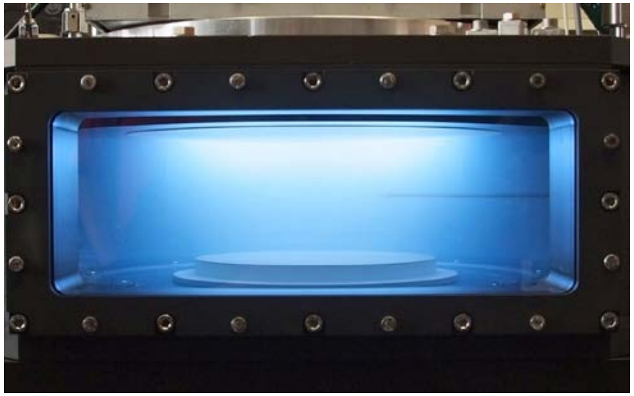
Constant neutral gas pressure?

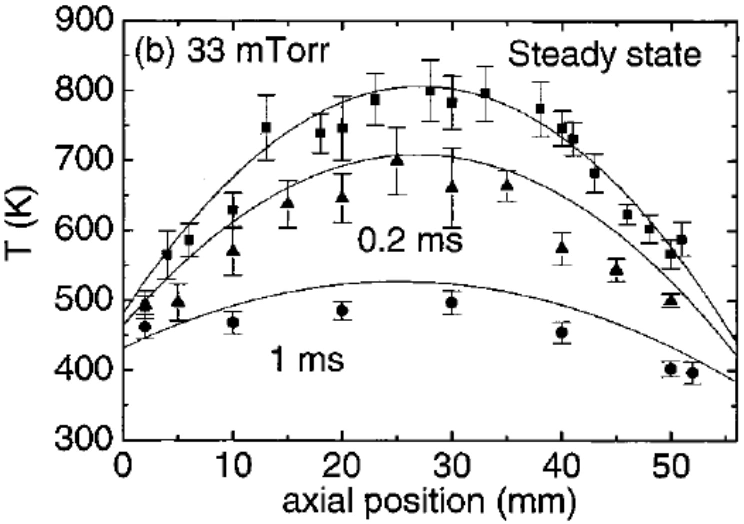
Neutral depletion in high density plasmas:

- Fruchtman , Makrinich , Chabert, Rax (2005)
Phys. Rev. Lett. **95** 115002

- Raimbault, Liard, Rax, Chabert, Fruchtman, Makrinich
Phys. Plasmas **14** (2007) 013503

- Liard, Raimbault, Rax, Chabert,
J. Phys. D: Appl. Phys. **40** (2007) 5192–5195





New formula with neutral depletion:

$$h_l \approx 0.88\left[3.1+\frac{L}{\lambda_{\rm in}}\left(1+0.83\frac{p_{\rm e0}}{p_{\rm gw}}\right)^{-1}\right]^{-1/2}$$

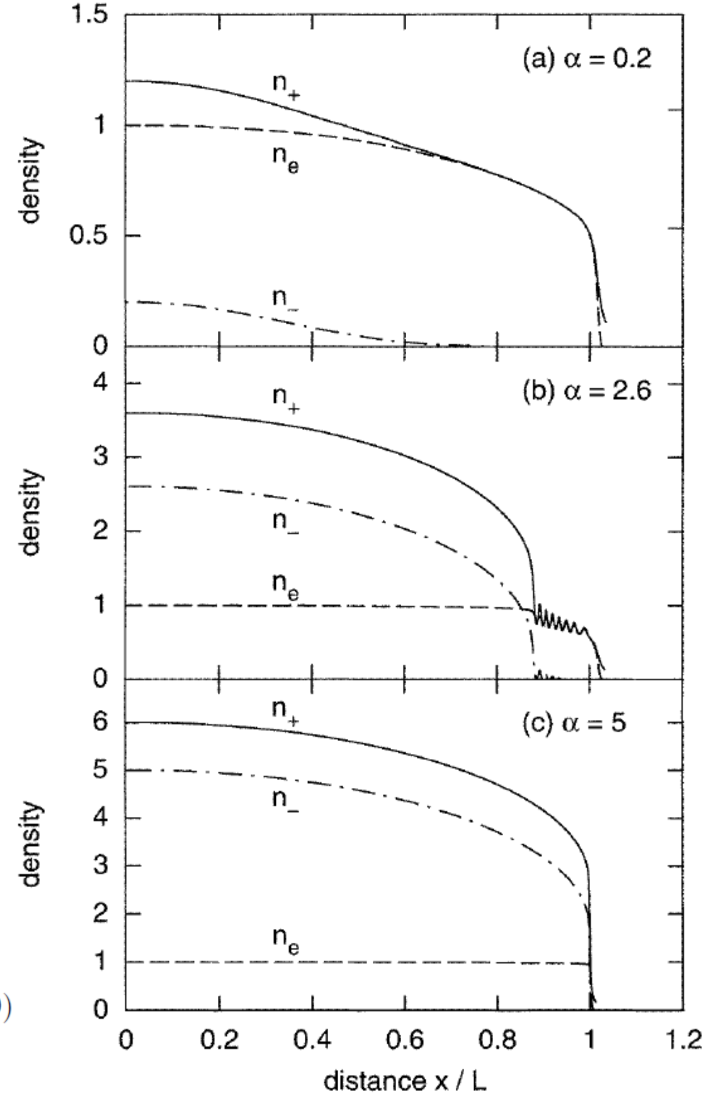
$$p_{\rm gw}=n_{\rm gw}k_BT_g \qquad p_{\rm e0}=n_0k_BT_e$$

Raimbault and Chabert, PSST **18** (2009) 014017

Gas heating measurements in ICPs
Abada et al., J. Appl. Phys., **92** (2002) 4223

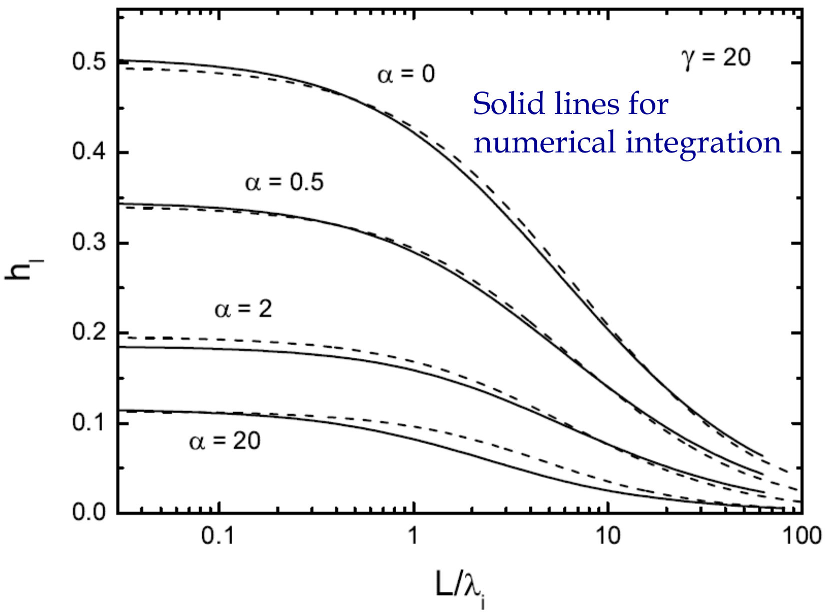
What happens with negative ions?

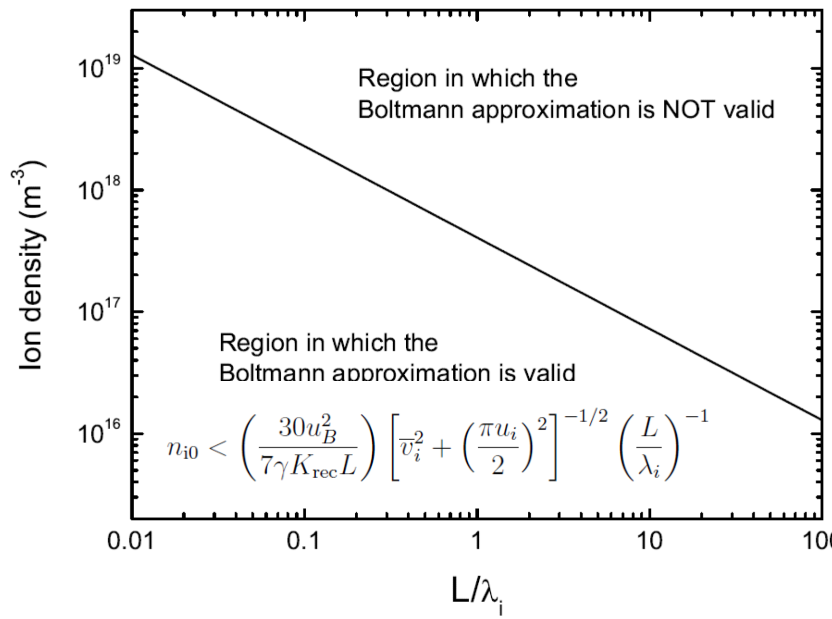
- Electronegative plasmas have a complex structure
- Analytical solution of the plasma transport is not easy (if possible at all)
- The generation and loss mechanisms of negative ions may have an important effect on the transport



T. Sheridan, P. Chabert, and R. Boswell, Plasma Sources Sci. Technol. **8**, 457 (1999)
Kouznetsov I, Lichtenberg A and Lieberman M *J. Appl. Phys.* **86** (1999) 4142
Franklin, J. Phys. D: Appl. Phys. 32 (1999) L71–L74.

Theory with negative ions





Dashed lines:

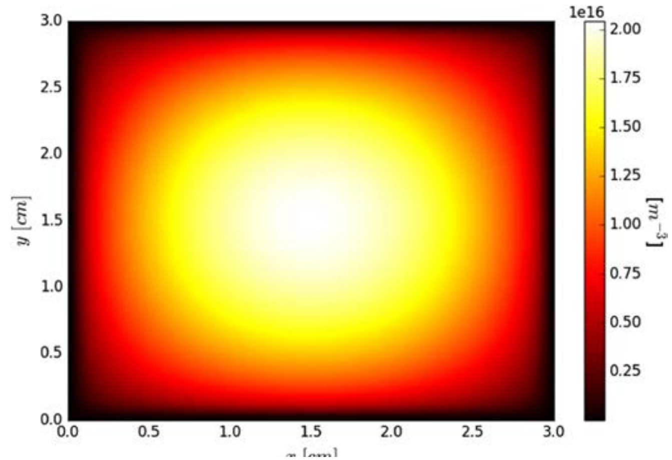
$$h_l = 0.86\left[3 + L/\lambda_i + (1+\alpha)^{1/2}\frac{1}{5}\frac{T_i}{T_e}\left(\frac{2L}{\lambda_i}\right)^2\right]^{-1/2}\left[\frac{\gamma-1}{\gamma(1+\alpha)^2} + \frac{1}{\gamma}\right]^{1/2}$$

Chabert, Plasma Sources Sci. Technol. **25** (2016) 025010

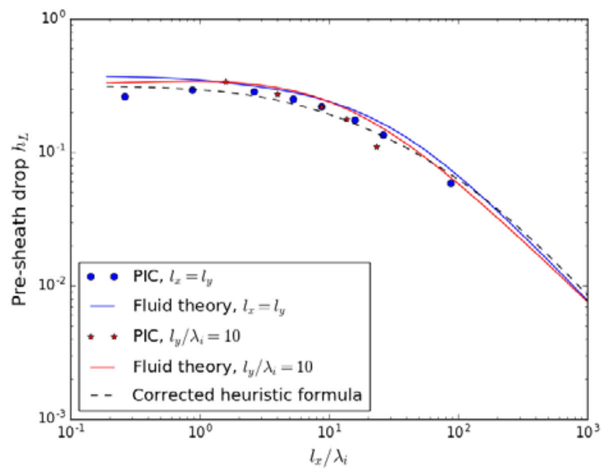
$$\alpha = \frac{n_{n0}}{n_{e0}} \qquad \gamma = \frac{T_e}{T_n}$$

See also
Kim S, Lieberman M and Lichtenberg A J. Vac. Sci.Technol. A **24** (2006) 2025
Monahan and Turner, Plasma Sources Sci. Technol. 17 (2008) 045003

Geometry: 2D Effects



(a)

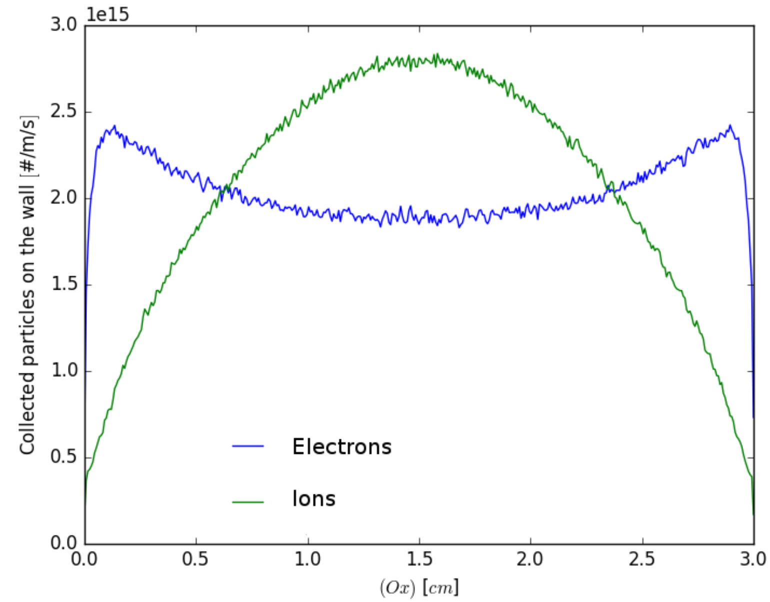


(b)

R Lucken *et al* 2018 *Plasma Sources Sci. Technol.* **27** 035004

See also Sternberg and Godyak PSST **20** (2011) 015018

Non ambipolar diffusion due to 2D effects



$$h_{L,\text{heur},x} = 0.55\left[3 + 0.5\frac{l_y}{\lambda_i} + 0.2\frac{T_i}{T_e}\left(\frac{l_y}{\lambda_i}\right)^2\right]^{-1/2}$$

$$h_{L,\text{heur},y} = 0.55\left[3 + 0.5\frac{l_x}{\lambda_i} + 0.2\frac{T_i}{T_e}\left(\frac{l_x}{\lambda_i}\right)^2\right]^{-1/2}$$

$$h_{2D,\text{heur}} = \frac{l_x h_{L,\text{heur},x} + l_y h_{L,\text{heur},y}}{l_x + l_y}$$

Transport instabilities and pattern formation

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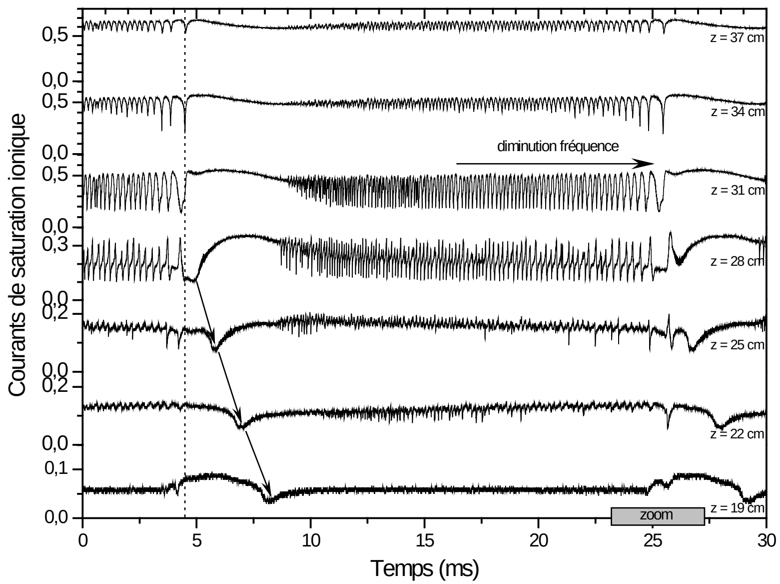
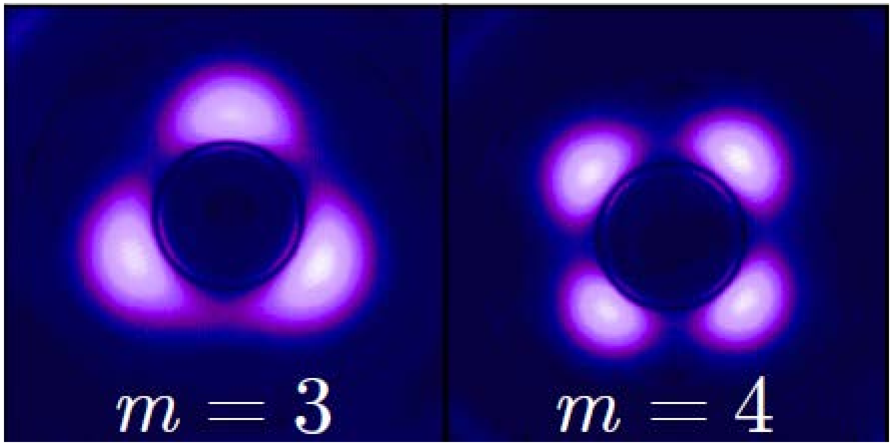
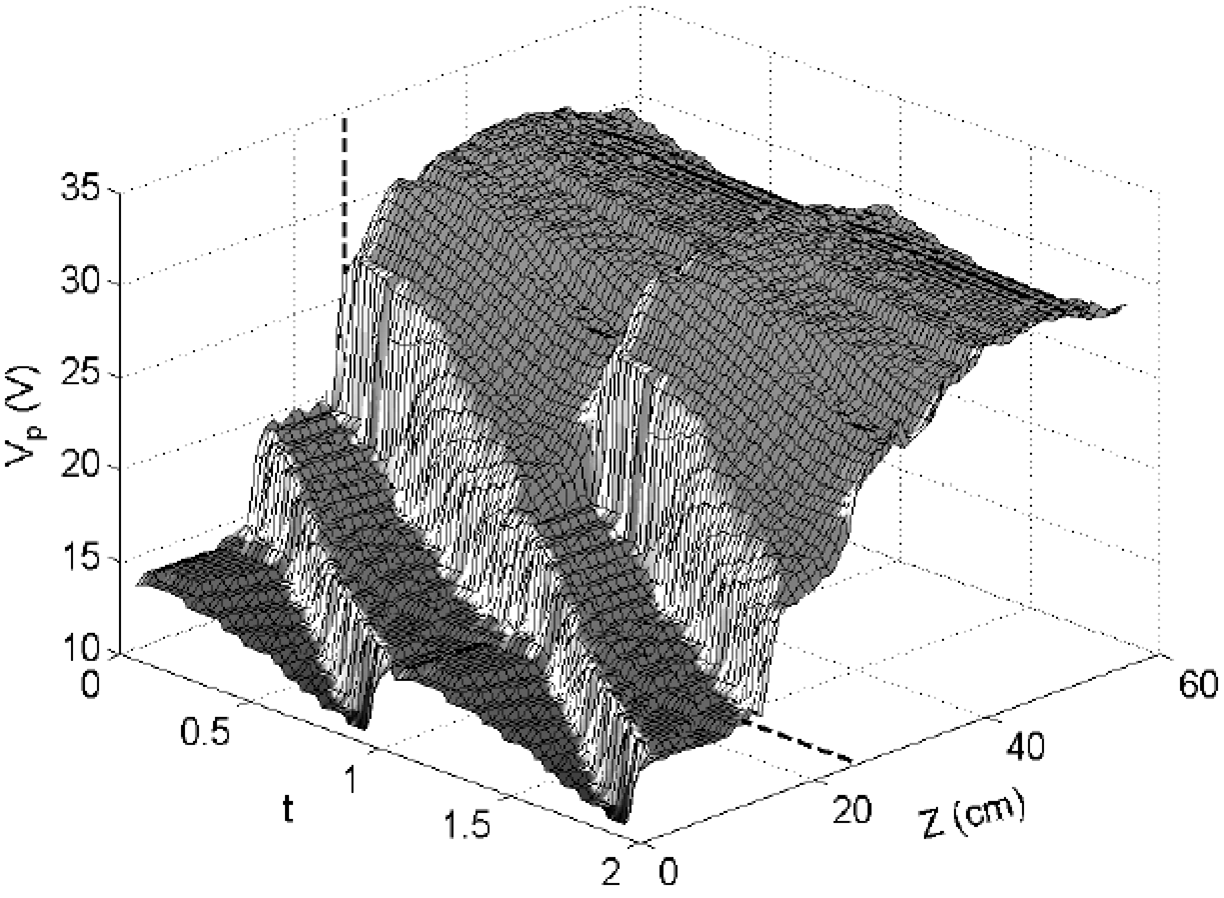
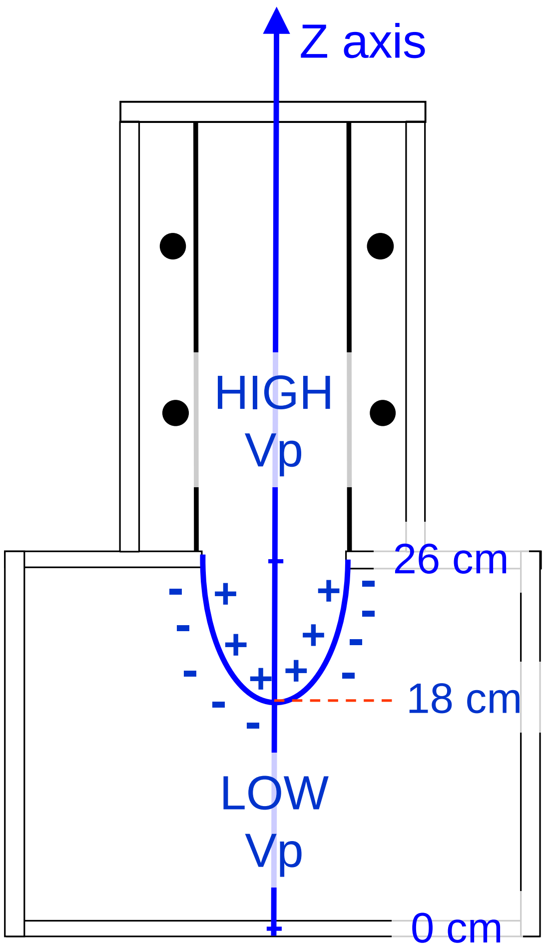




Propagating double layers in expanding electronegative plasmas

Propagating speed = 150 m/s

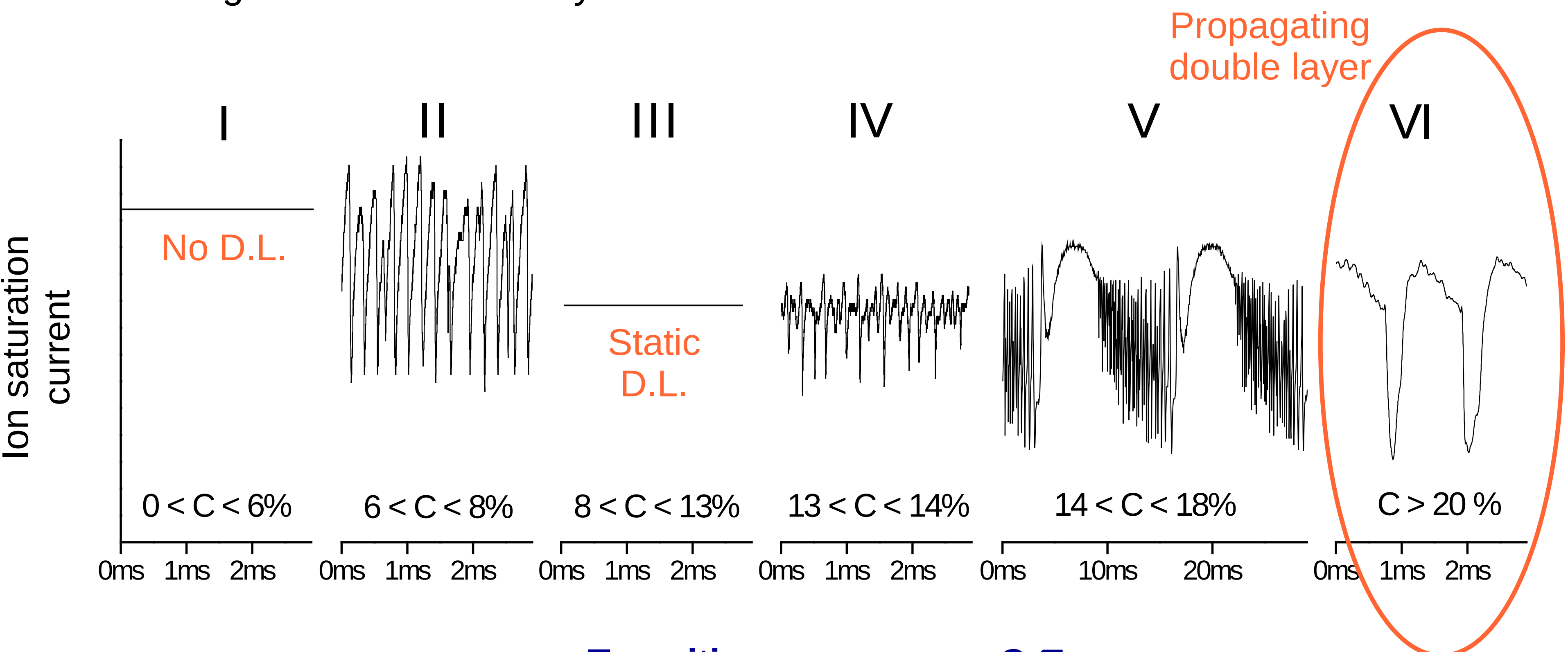




Plihon, Corr, Chabert, Raimbault, J. Appl. Phys. **98**, 023306 (2005)

Transport instabilities

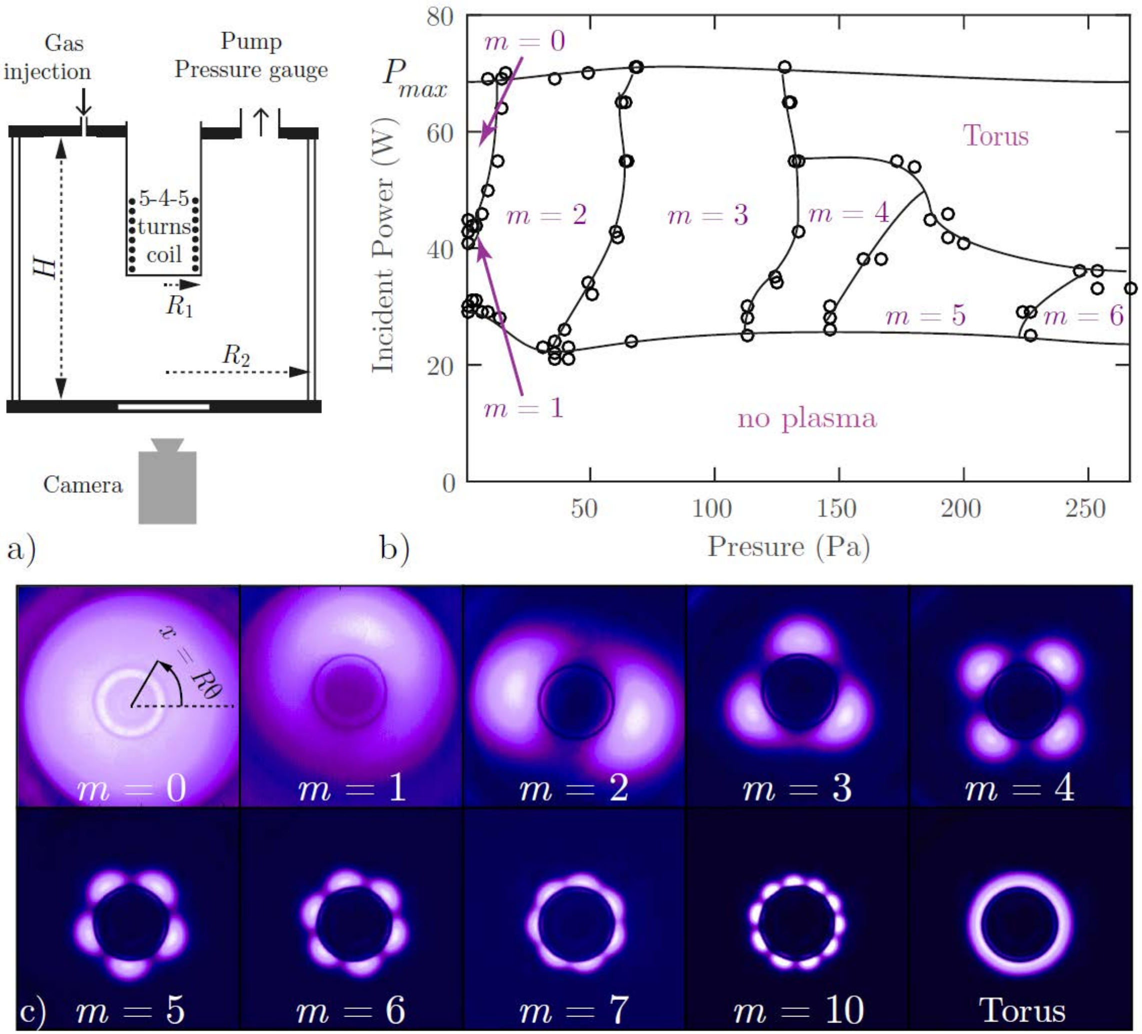
- A complex dynamic develops as a function of the SF_6 concentration C
- Strong ion acoustic activity

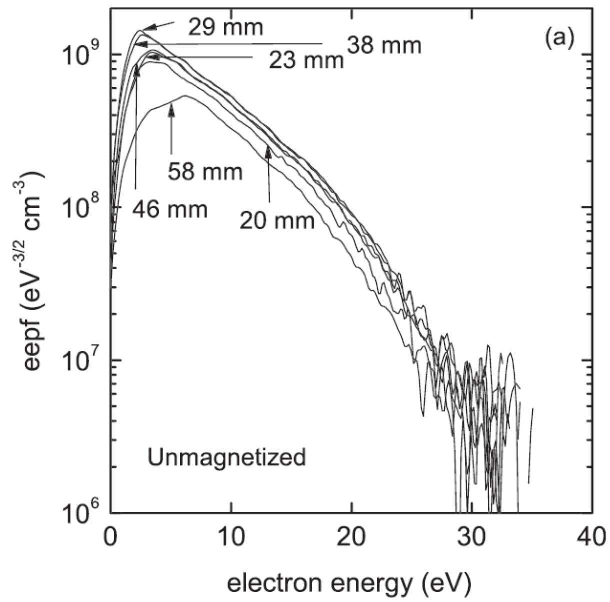


Transition sequence C ↗

Tuszewski *et al. Phys. Plasmas* **10** 539 (2003)
Plihon and Chabert, Phys. Plasmas **18**, 082102 (2011)

Pattern formation in cylindrical ICP





Arancibia Monreal, Chabert, and Godyak
Phys. Plasmas **20** 103504 (2013)

Song, Yang, Chabert and Kushner
Phys. Plasmas **21** 093512 (2014)

Desangle, Raimbault, Poyé, Chabert and
Plihon, Phys. Rev. Lett. **123** (2019) 265001

Pattern formation in cylindrical ICP

$$\partial_t n_e + \partial_x \Gamma_e = (\nu_{iz}(T_e) - \nu_r) n_e,$$
$$\partial_t (3/2 n_e T_e) + \partial_x H_e = P_0 n_e^B - n_e \nu_{iz}(T_e) \mathcal{E}_c(T_e)$$

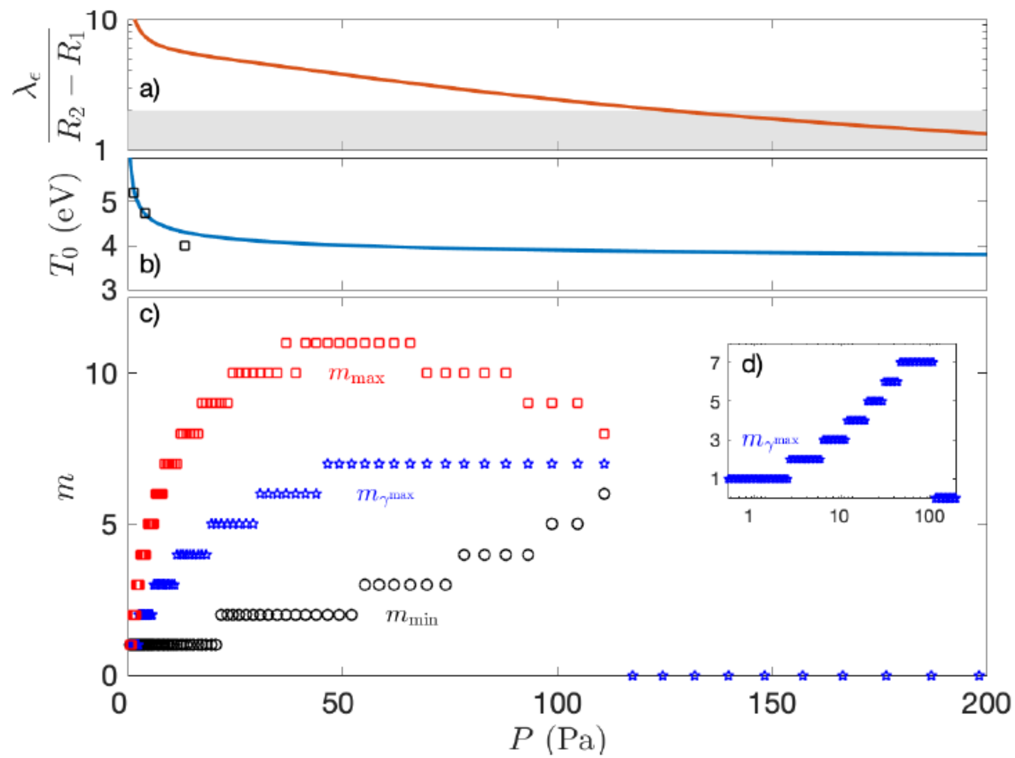
- For non-Maxwellian distributions:

$$\Gamma_e = -D_a \partial_x n_e - \eta_e \partial_x T_e$$
$$H_e = -\chi_e \partial_x n_e - \kappa_e \partial_x T_e,$$

J. H. Ingold, Phys. Rev. E 56, 5932 (1997)

- A linear stability analysis shows that the system is unstable if :

$$\chi_e^0 < \left(\left.\frac{\partial \nu_{iz}}{\partial T}\right|_{T_0} \right)^{-1} \left(-D_a^0 \left.\frac{\partial (\nu_{iz} \mathcal{E}_c)}{\partial T}\right|_{T_0} - \sqrt{\frac{6 D_a^0 \kappa_e^0}{n_0} \mathcal{E}_c^0 \nu_{iz}^0 \left.\frac{\partial \nu_{iz}}{\partial T}\right|_{T_0}} \right)$$



D. Mackey, L. Plantie, and M. Turner, Applied Mathematics Letters **18**, 865 (2005)
Desangle, Raimbault, Poyé, Chabert and Plihon, Physical Review Letters , Phys. Rev. Lett. **123** (2019) 265001

Magnetized plasma column

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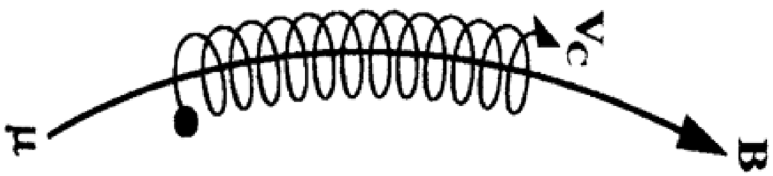
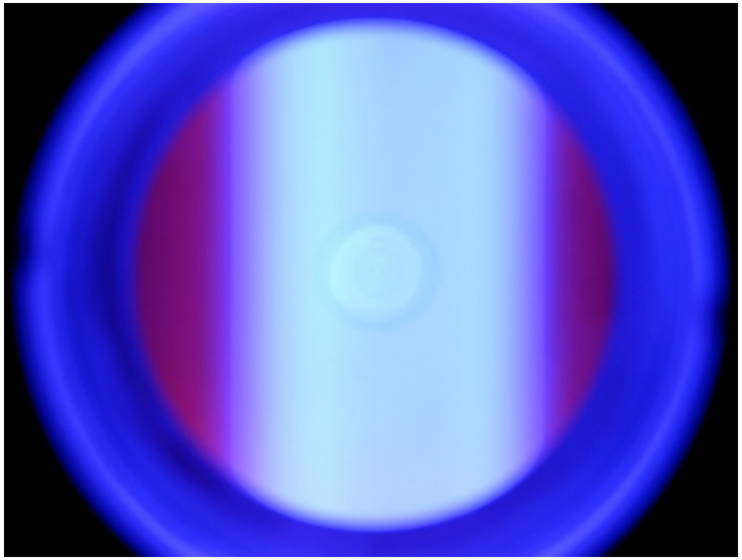




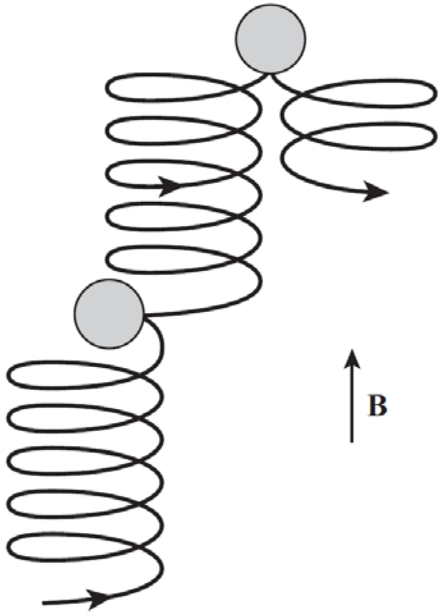
Effect of the magnetic field

- The motion parallel to magnetic field lines is not affected

- The transport perpendicular to magnetic field lines is strongly reduced – but possible due to collisions

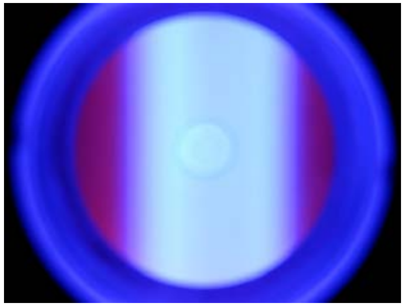
- Standard theory predicts the following perpendicular transport coefficients for electrons:

$$\mu_e^* = \frac{e\nu_e}{m\omega_{ce}^2}, \quad D_e^* = \frac{kT_e\nu_e}{m\omega_{ce}^2}$$



A. Fruchtman, G. Makrinich, and J. Ashkenazy. Two-dimensional equilibrium of a low temperature magnetized plasma. Plasma Sources Sci. Technol., 14(1):152, 2005.

N. Sternberg, V. Godyak, and D. Homan. Magnetic field effects on gas discharge plasmas, Phys. Plasmas, 13(6):063511, June 2006.

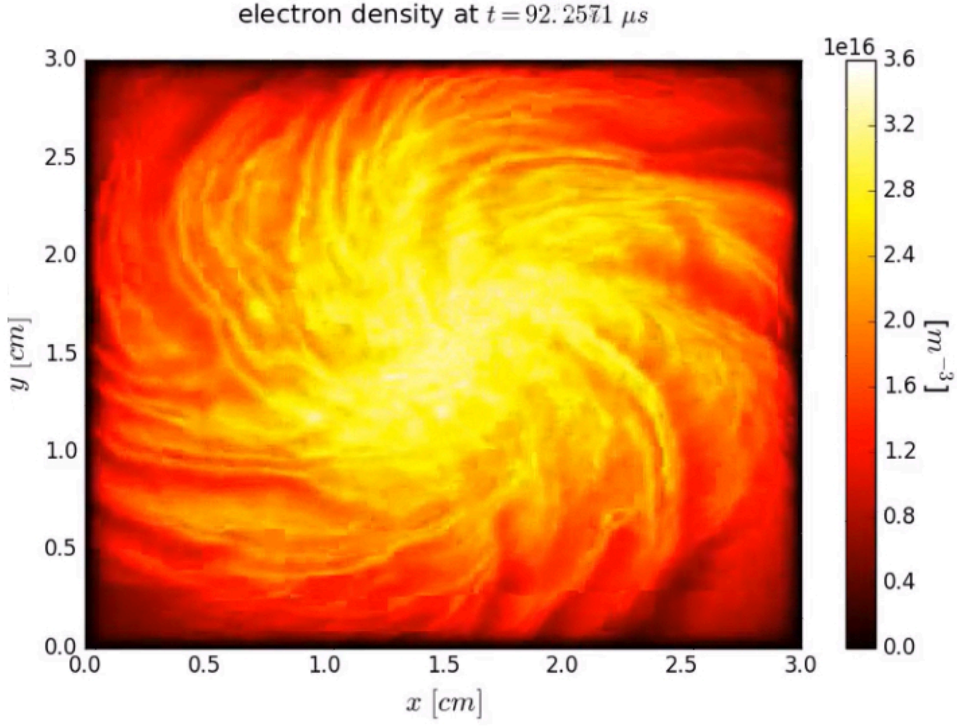


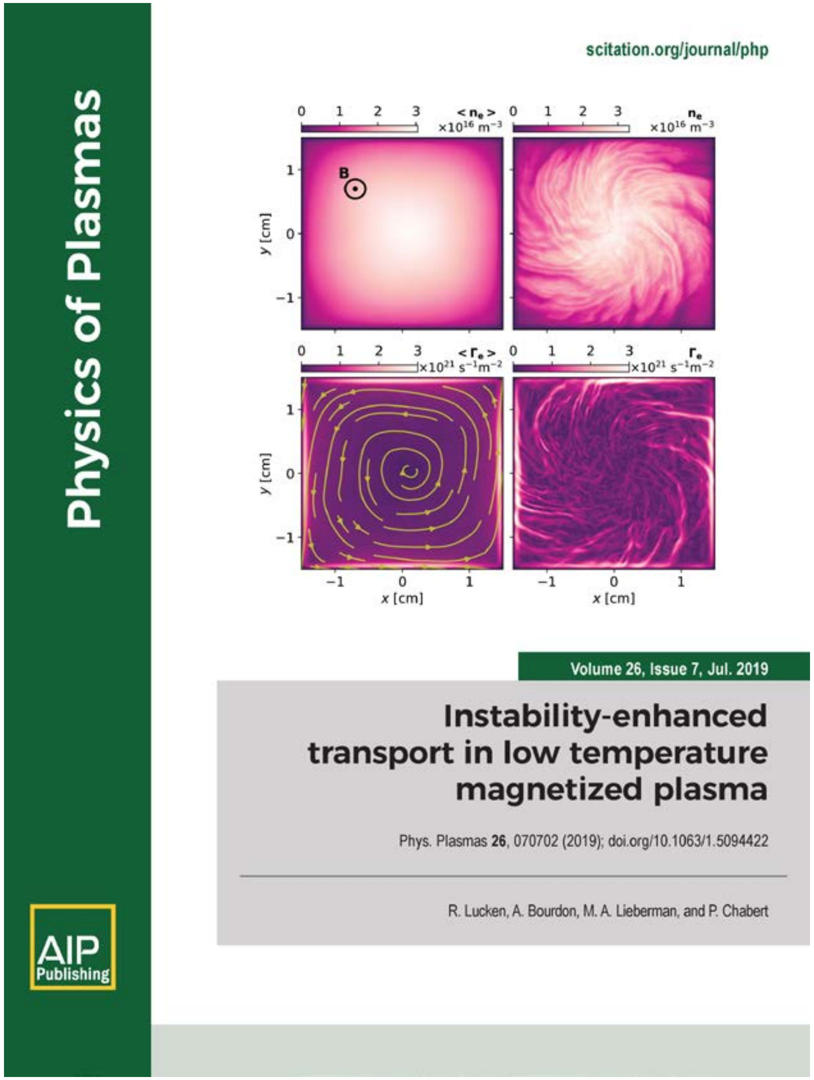
- However, anomalous transport is observed

D. Bohm. The Characteristics Of Electrical Discharges In Magnetic Fields. R. K. Wakerling, A. Guthrie, Mcgraw-hill Book Company, Inc., rst edition edition, 1949.

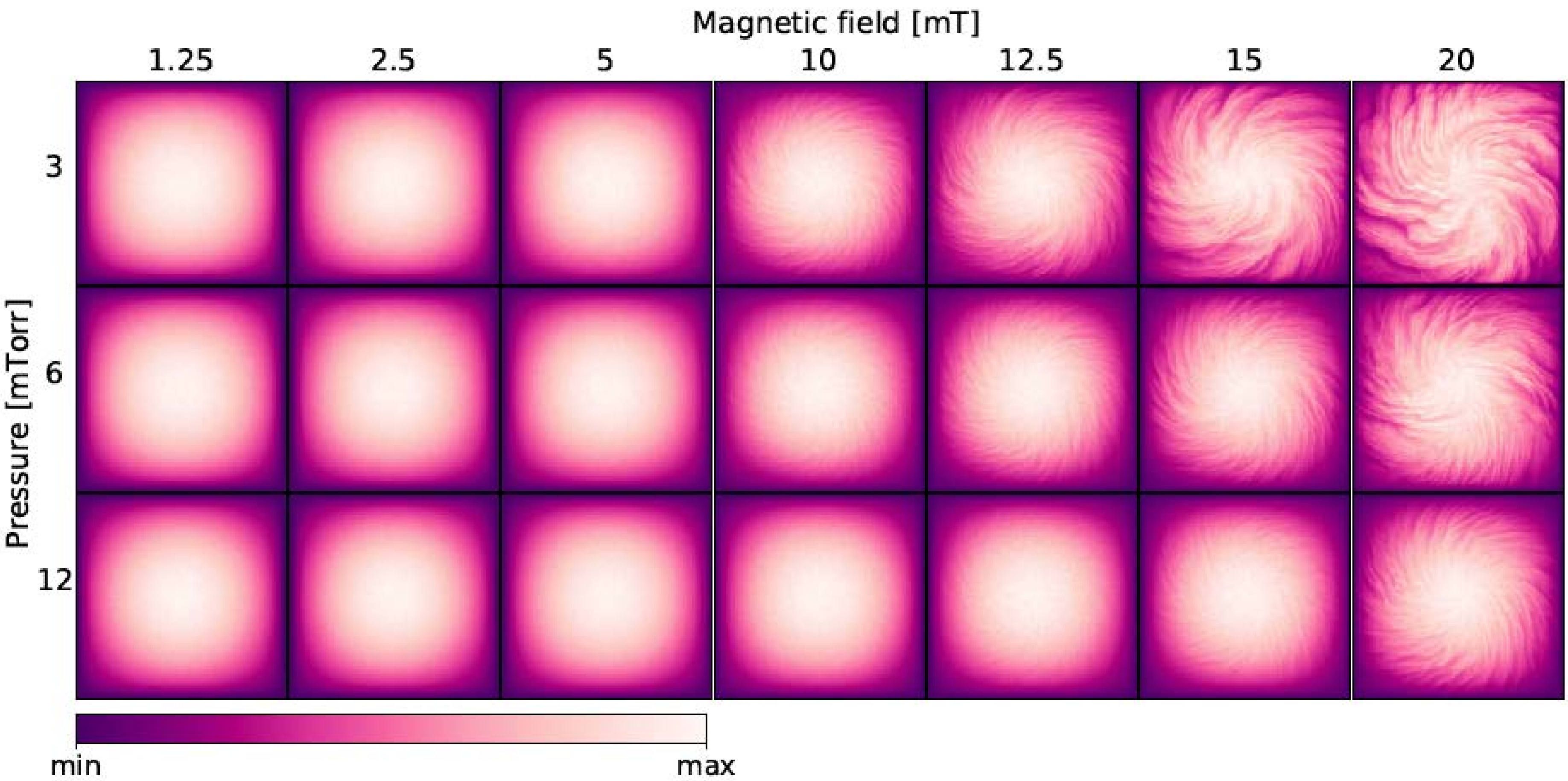
Effect of the magnetic field

Development of the diamagnetic resistive drift instability

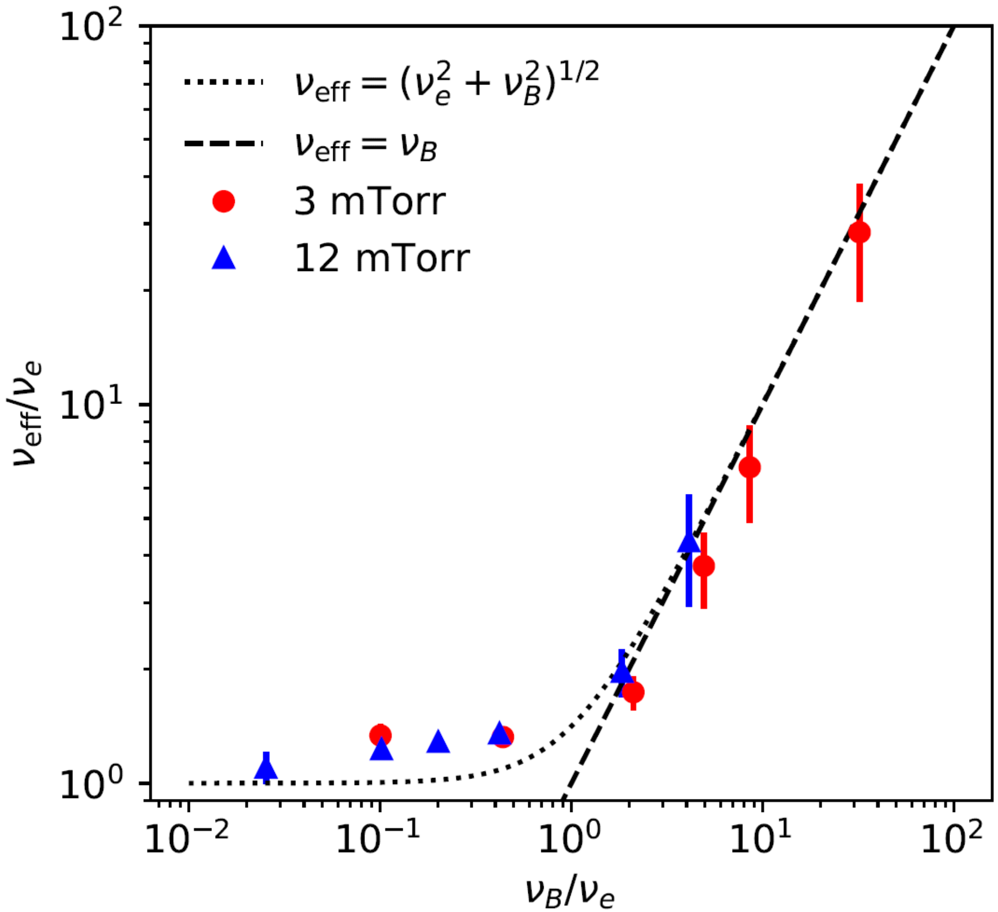




Onset of the instability



Anomalous collision frequency



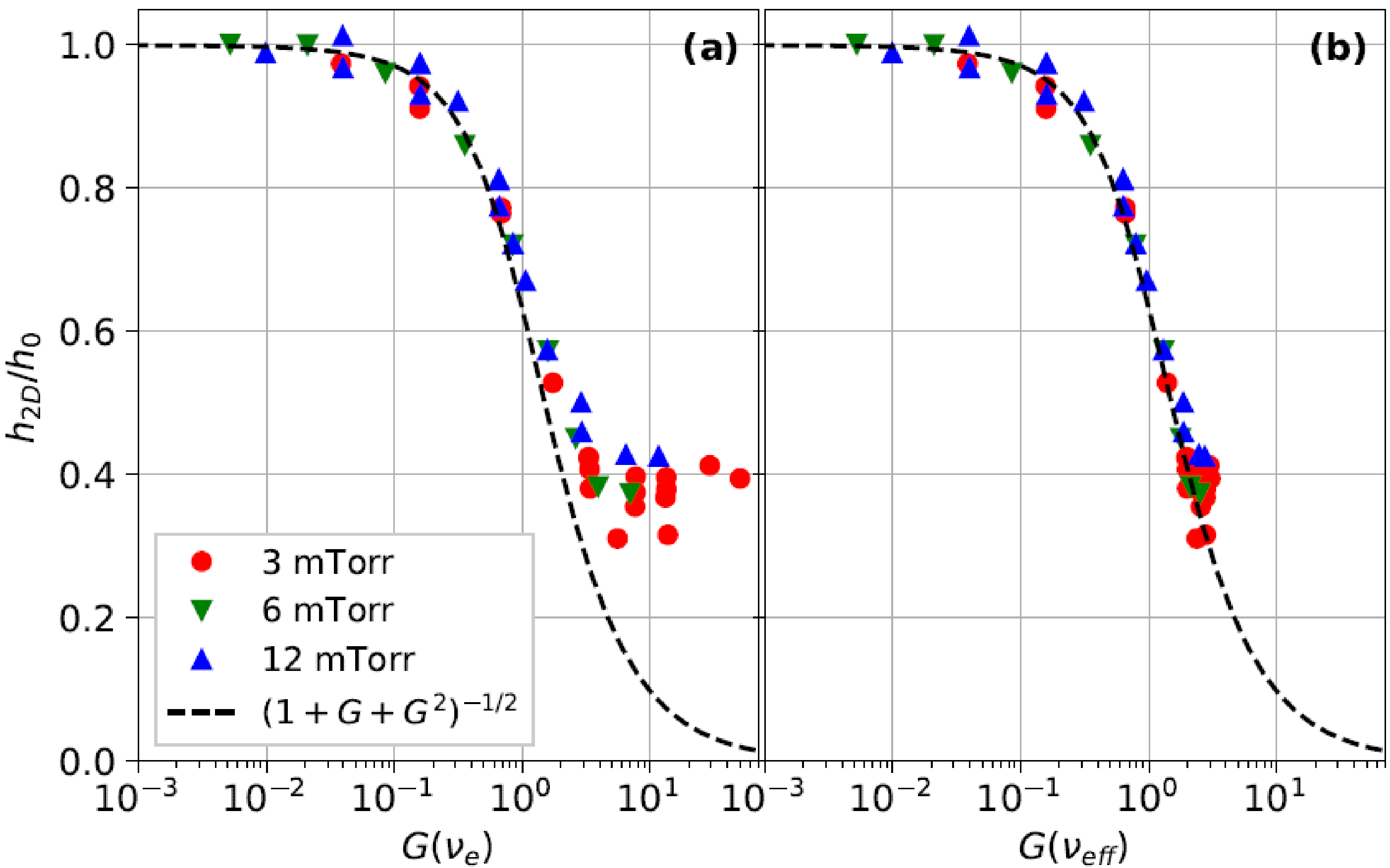
The effective collision frequency is given by the following formula at high magnetic field:

$$\nu_B = \frac{l h_m \omega_{ce}^2}{v_{Te}} \left(\frac{m_e}{m_i}\right)^{1/2}$$

The h_m factor is bounded at high magnetic field (h_0 is the un-magnetized h factor):

$$0.32 < h_m/h_0 < 0.42$$

The h factor saturates at high B field



Dashed line from:

R. Lucken et al. Saturation of the magnetic confinement in weakly ionized plasma. PSST 2019.

N. Sternberg, V. Godyak, and D. Homan. Magnetic field effects on gas discharge plasmas, Phys. Plasmas, 13(6):063511, June 2006.

Conclusions

- Même le plus ancien des sujets de physique des décharges que l'on trouve dans les livres, "la diffusion ambipolaire", peut (et doit) être revisité

- Il est donc très important de faire de la recherche fondamentale en physique des décharges – et d'écrire de nouveaux livres

- Cependant, il est possible qu'un(e) jeune chercheur(se) qui soumettrait un projet ANR JCJC ou ERC Starting Grant sur un sujet de cette nature reçoive les évaluations suivantes:

    - Originalité et qualité scientifique : 0/5 (connu depuis 1920)
    - Impact sociétal et ambition: 0/5 (aucune application mentionnée, l'humanité ne sera pas transformée, la planète ne sera pas sauvée)
    - Organisation du projet: 0/5 (le(la) candidat(e) ne semble pas savoir ce qu'est un workpackage, une tâche, et un livrable)
    - Valorisation et impact économique: 0/5 (pas de brevets, pas de start-up)

A side question arose when preparing this talk: is "new" required to do fundamental research

- To motivate good students, to raise research funds, or even maybe to reinvigorate our own motivation for research, we seem to need something **new and promising** that requires **scientific breakthrough**!

- What is **new and promising** ? Something that does not work (yet), something unexplored, something with high social impact, to "save the world"

- In preparing this talk, I realized that so far I worked mostly on things that already work (plasma processing, plasma thrusters), i.e. **not** new and promising

- However, over the years, I have seen significant **scientific progress** (breakthrough?), all based on fundamental research, both in plasma processing and in plasma thrusters.

- I therefore came to a somewhat counter-intuitive conclusion: It is possible and even necessary to do fundamental research in "working applications"