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Hall Thrusters

Laurent Garrigues

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Hall Thrusters






Laurent Garrigues, Senior Scientist at CNRS



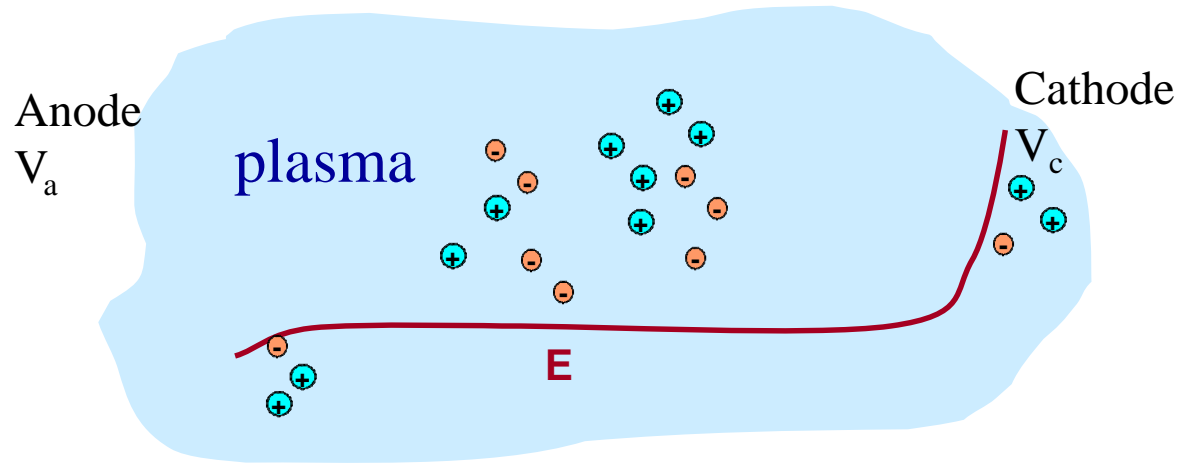
laurent.garrigues@laplace.univ-tlse.fr

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Université de Toulouse, CNRS-UPS-INPT
31062 Toulouse Cedex 09, France

Outline

- **Introduction** 
- **Thruster operation** 
- **Erosion** 
- **Cathode** 
- **Perspectives/on going activities** 

Electric field in a plasma

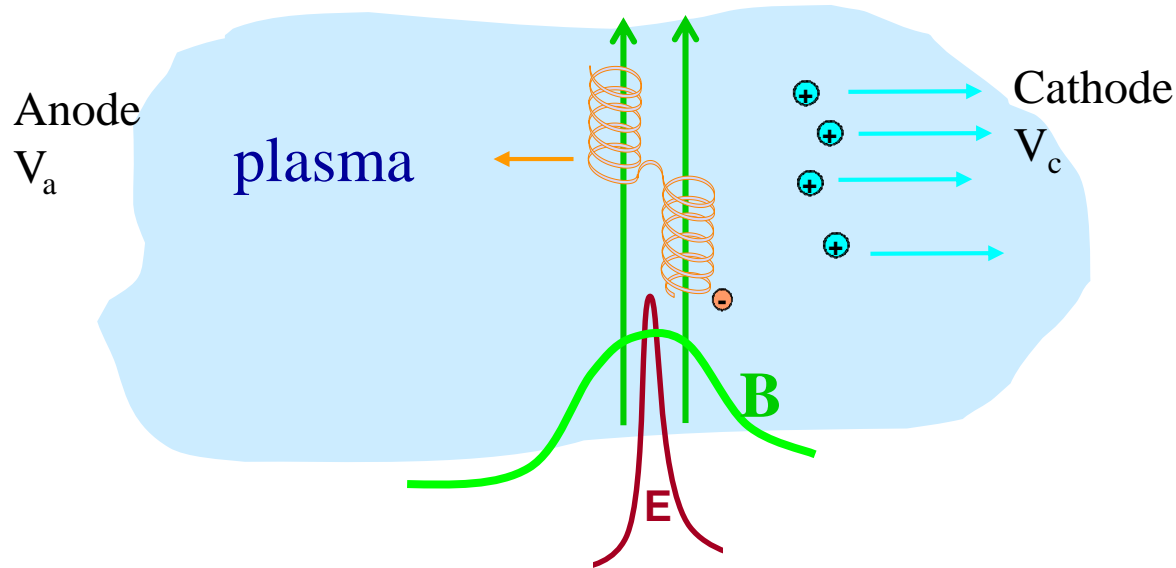


- Quasineutral plasma, E field in the sheath
 - Grid system to extraction ions – GIE
 - Child Langmuir law
- **Thrust/unit of surface limitation**

More details with Wallace

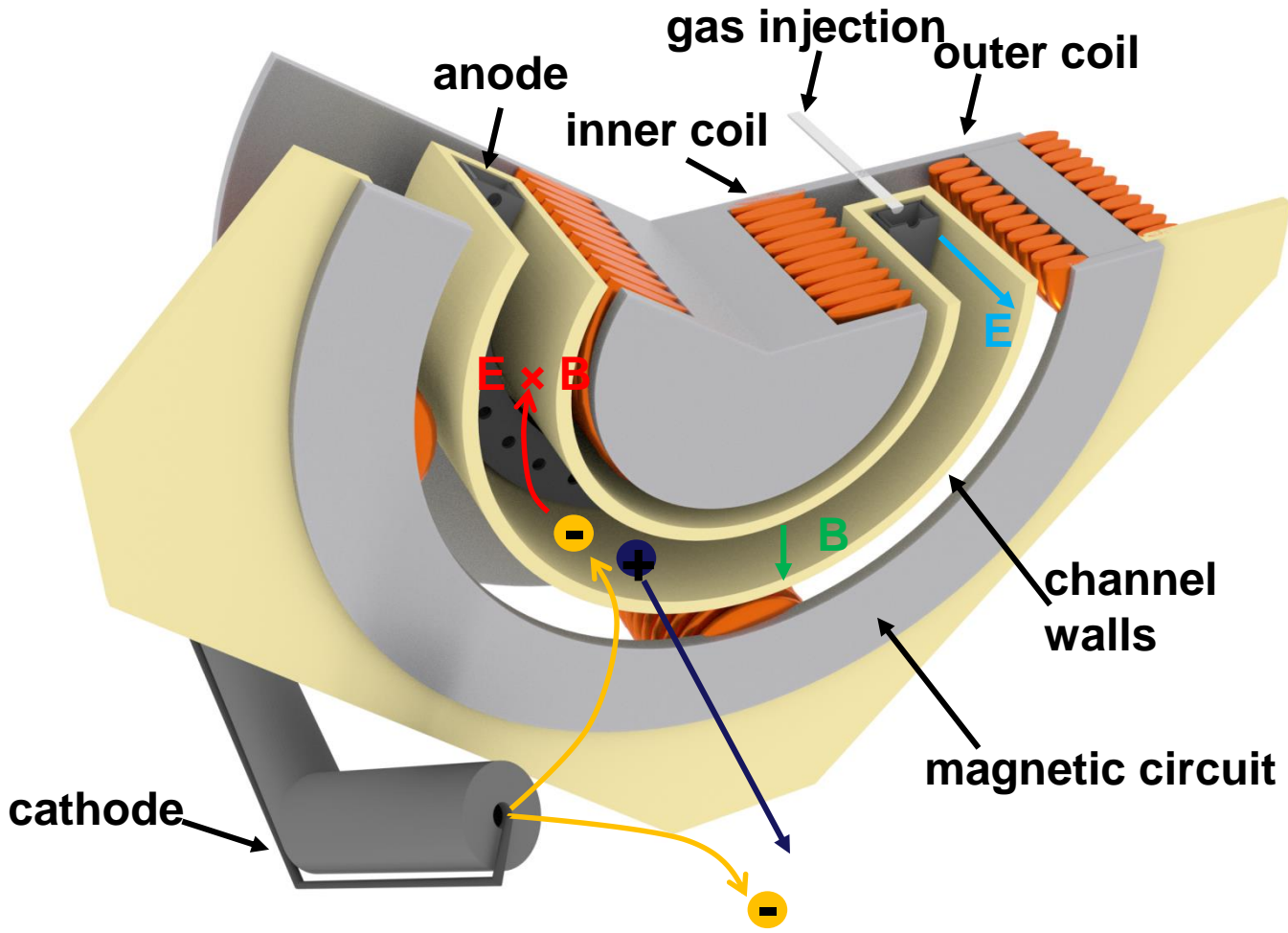
R. G. Jahn and E. Choueiri, Encyclopedia of Physical Science and Technology, 2002

Utilization of a magnetic field barrier



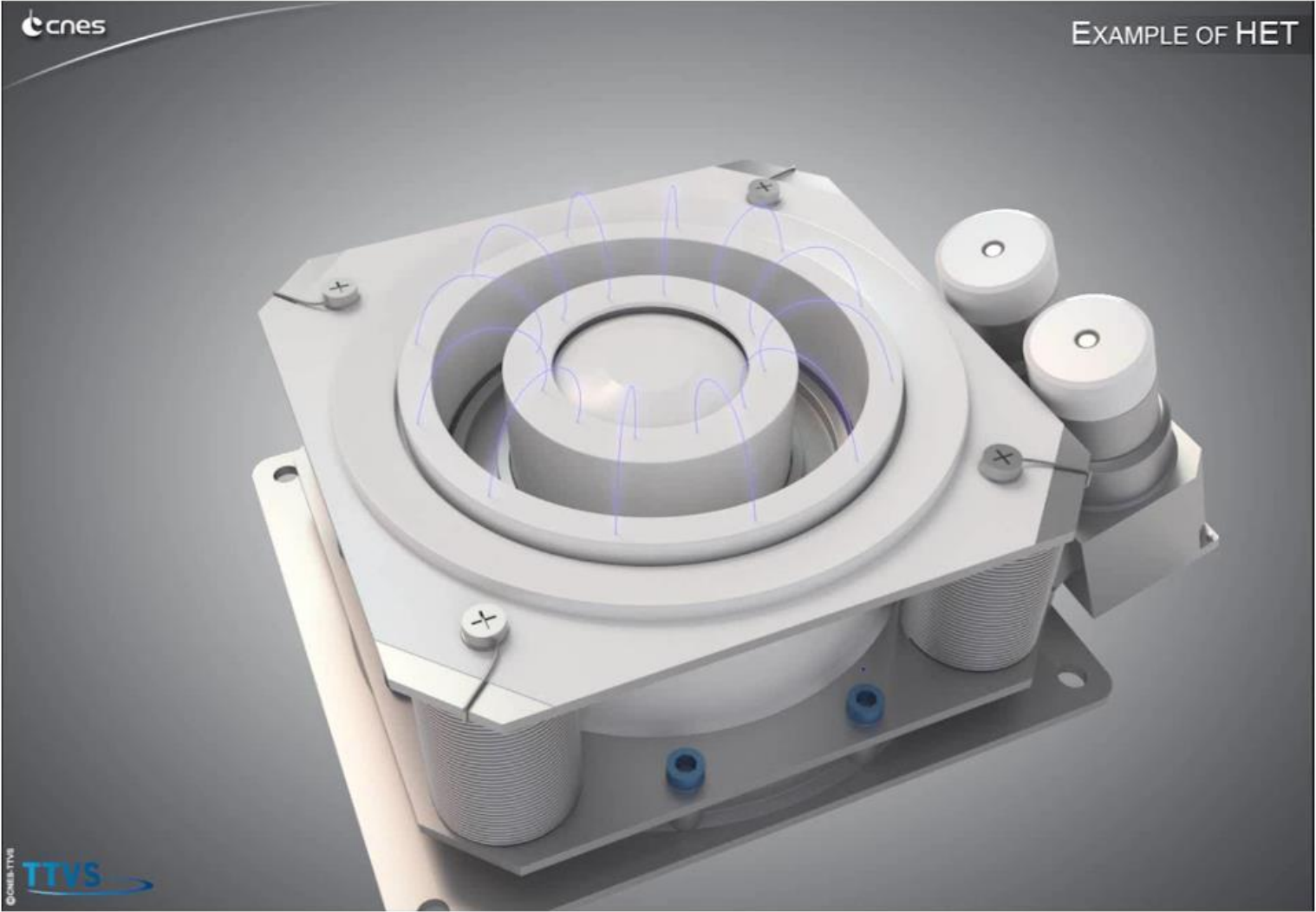
- **Using a localized magnetic field barrier**
 - Decrease of the electron local conductivity σ
 - Penetration of a local electric field - $E = j/\sigma$
➔ **no thrust/unit of surface limitation**
- **The electric field is used to**
 - Heat the electrons to ionize the propellant gas
 - Accelerate the ions to furnish the thrust

How a Hall Thruster works (1/2)

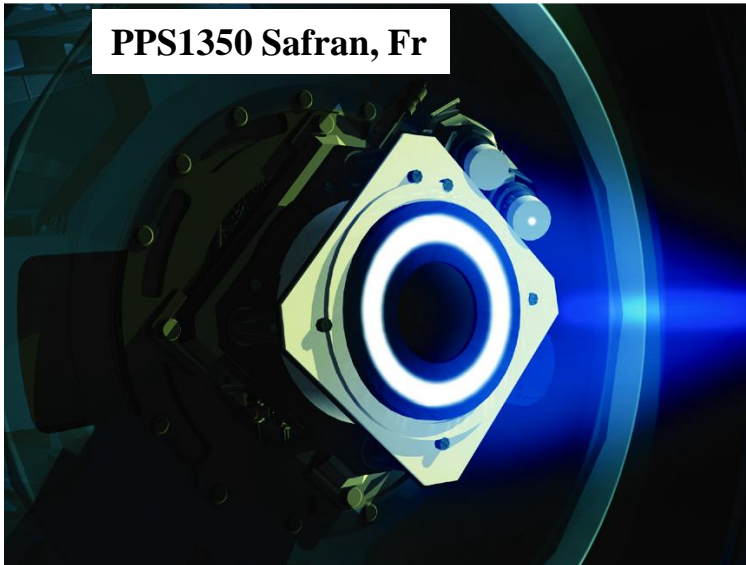


Credit: Alexandre Guglielmi

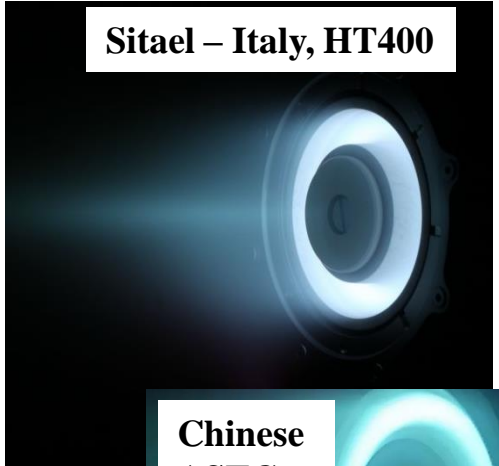
How a Hall Thruster works (2/2)



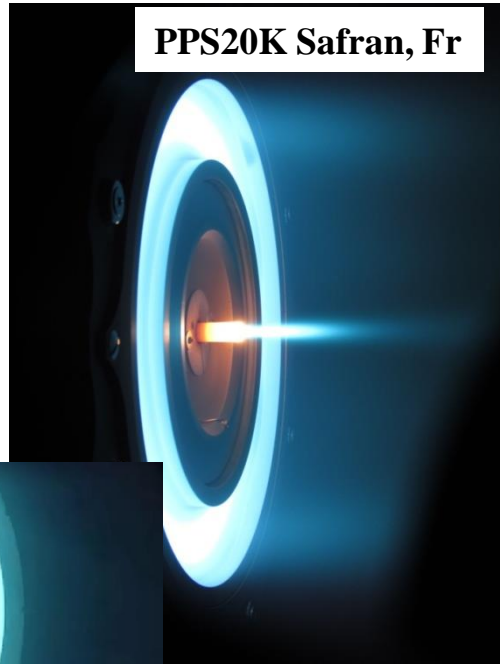
Hall Thrusters in the world



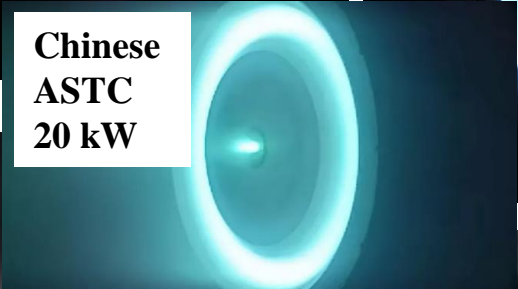
PPS1350 Safran, Fr



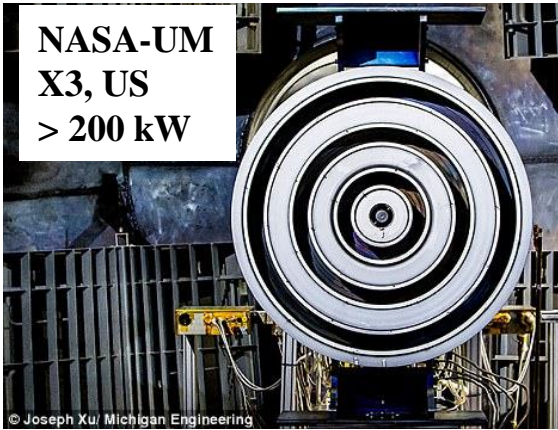
Sitael - Italy, HT400



PPS20K Safran, Fr

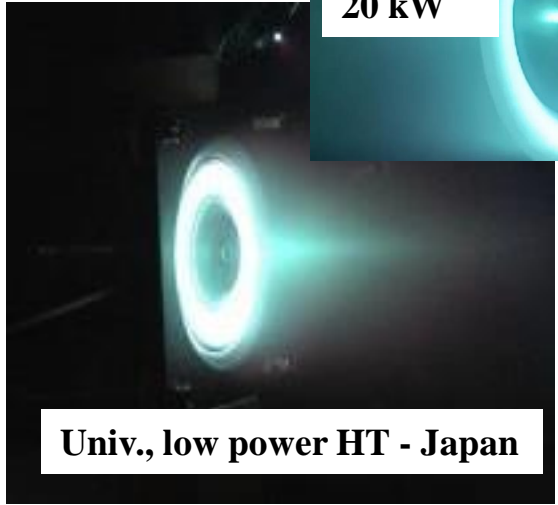


Chinese
ASTC
20 kW

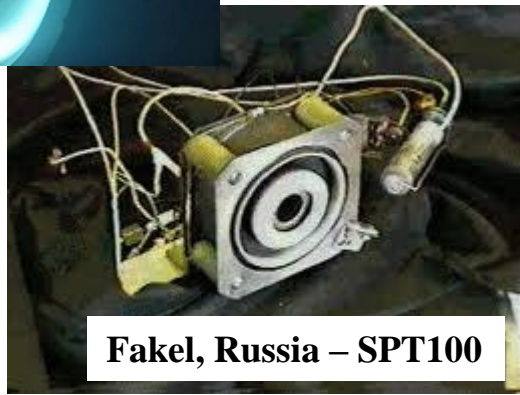


NASA-UM
X3, US
> 200 kW

© Joseph Xu / Michigan Engineering

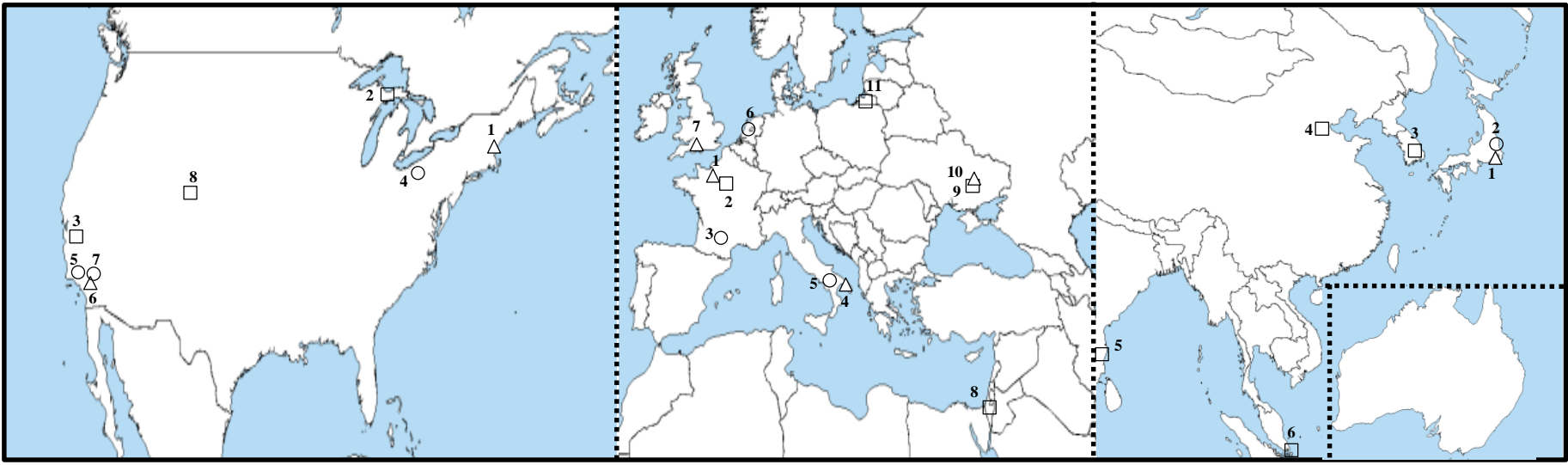


Univ., low power HT - Japan



Fakel, Russia - SPT100

Companies & agencies in the world



△ companies □ start-up ○ agencies

North America

- 1 Busek, Natick, MA
- 2 Orbion, Houghton, MI
- 3 Astra Space, Alameda, CA
- 4 NASA GRL, Cleveland, OH
- 5 NASA JPL, Pasadena, CA
- 6 Aerojet Rocket., El Segundo, CA
- 7 AFR, Edwards Base, CA
- 8 ExoTerra Res., Littelton, CO

Europe

- 1 Safran, Vernon, Fr
- 2 Exotrail, Palaiseau, Fr
- 3 Cnes, Toulouse, Fr
- 4 Sitael, Mola di Bari, It
- 5 CIRA, Capua, It
- 6 ESA, Noordwijk, Neth.
- 7 MarsSpace, South., UK

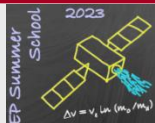
Russia-Ukraine-Israel

- 8 Rafael, Haifa, Is
- 9 SETS, Dnipro, Ukr
- 10 Seran Systems, Dnipro, Ukr
- 11 EDB Fakel, Kalinin., Ru

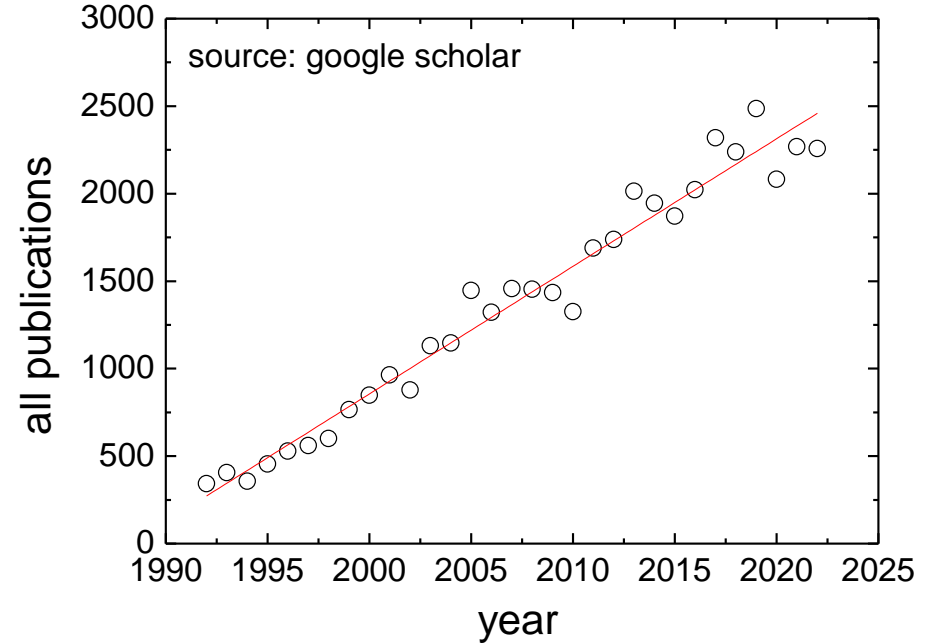
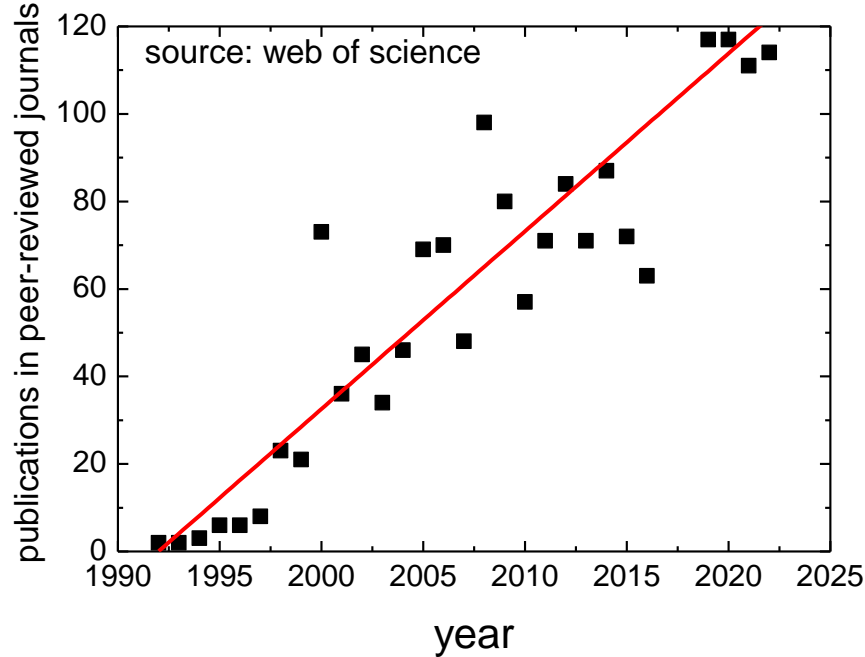
Asia

- 1 IHI Aerospace, Tokyo, Ja
- 2 Jaxa, Chofu, Ja
- 3 Satrec Initiative, Daejon, Ko
- 4 Aersopace Propulsion, Tianjing, Ch
- 5 Bellatrix Aerospace, Bengalore, In
- 6 Aliena, Singapore, Si

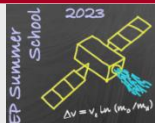
last update 2023



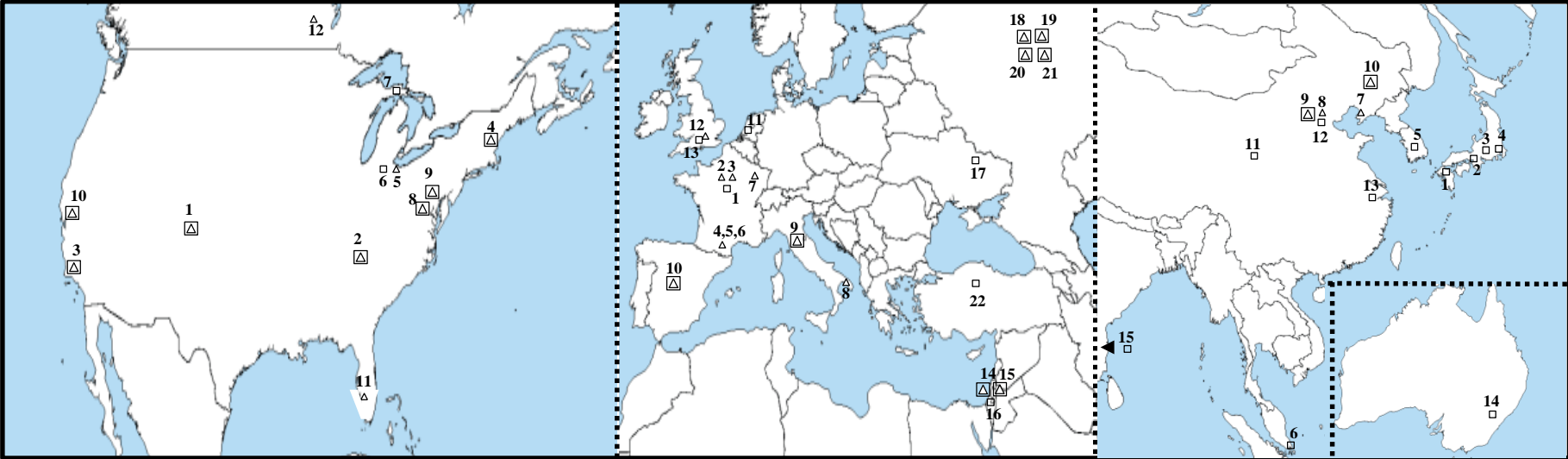
Hall Thruster: very active domain of research



Very active research domain



Research groups in the world



△ Modeling □ Experiments △□ Both

- North America**
- 1 EPPE, Colorado State Univ. Co
 - 2 CSTR, Georgia Institute of Tech., Ge
 - 3 NASA-JPL-Cal.Tech, Pasadena, Ca
 - 4 SPL, Massachusetts Institute of Tech., Ma
 - 5 PEPL, Univ. of Michigan, Mi
 - 6 NPPDG, Univ. of Michigan, Mi
 - 7 SSRG, Michigan Tech. Univ., Mi
 - 8 EPPDyL, Princeton Univ., NJ
 - 9 PPPL, Princeton Univ., NJ
 - 10 SPPL, Stanford Univ. Ca
 - 11 DMP, Eckert College, Fl
 - 12 PEP, Univ. Saskatchewan, Canada

- Europe**
- 1 ICARE, CNRS, Orléans, Fr
 - 2 DPHY-Onera, Palaiseau, Fr
 - 3 LPP, E. Polytech., Palaiseau, Fr
 - 4 LAPLACE, Univ. Toulouse, Fr
 - 5 DPHY-Onera, Toulouse, Fr
 - 6 CERFACSn Toulouse, Fr
 - 7 IJL, Univ. Nancy, Fr
 - 8 IMIP, Univ. Bari, It
 - 9 DCIE, Univ. Pisa, It
 - 10 EP2, Univ. Carlos III Madrid, Es
 - 11 ESA, Noordwijk, Neth.
 - 12 Imp. Coll., London, UK
 - 13 Univ. South., South., UK

- Russia-Ukr.-Tur.-Israel**
- 14 HIT, Holon, Is
 - 15 TIIT, Haifa, Is
 - 16 PPL, Soreq NRC, Is
 - 17 Khai, Aero. Univ. Kharkiv, Uk
 - 18 TsNIMASH, Moscow, Ru
 - 19 MIREA, Moscow, Ru
 - 20 RIAME-MAI, Moscow, Ru
 - 21 Keldysh Res. Center, Moscow, Ru
 - 22 Tubitak Uzay, Ankara, Tu

- Asia-Oceania**
- 1 ASPL, Kyushu Univ., Ja
 - 2 ARL, Osaka Univ., Ja
 - 3 AML, Gifu Univ., Ja
 - 4 DAA, Univ. Tokyo, Ja
 - 5 KAIST, Daejon, Ko
 - 6 NIE, Nanyang Univ., Si
 - 7 SS, Dalian Maritime Univ., Ch
 - 8 SA, Beihang Univ., Beijing, Ch
 - 9 BICE, China. Aereo. Space Sci., Beijing., Ch
 - 10 LPP, Harbin Instit. Tech., Ch
 - 11 Lanzhou Institute of Physics, Ch
 - 12 SSE, Beihang Univ., Beijing, Ch
 - 13 Shanghai Inst. of Space Prop., Ch
 - 14 UNSW, Canberra, Au
 - 15 LPSC-ISRO, Thiruvananthapuram, In

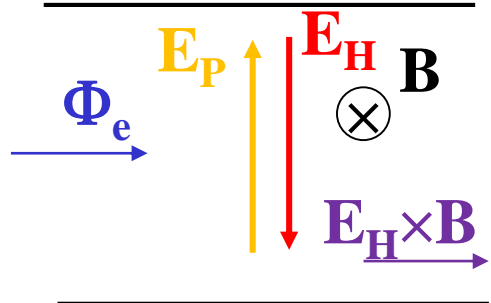
JP Luna, PhD Thesis, 2008, last update 2023



A Hall thruster has no Hall effect

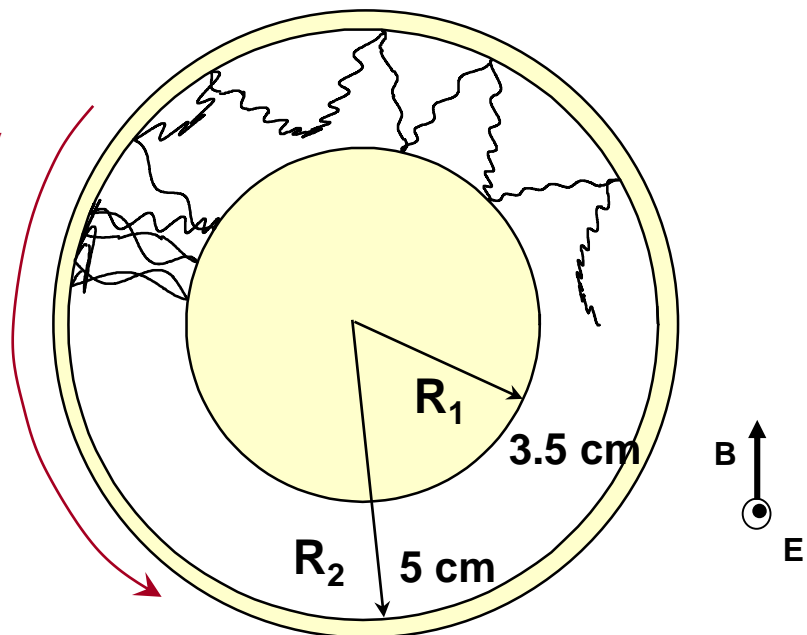
- The Hall effect takes place in a $E \times B$ discharge with a rectangular geometry
- Hall effect: electric field opposes to the polarization field
- Negative ion sources for fusion machines

G. Fubiani *et al.*, New J. Physics 19, 015002 (2017)



- The Hall effect does not take place in a $E \times B$ discharge with a cylindrical geometry

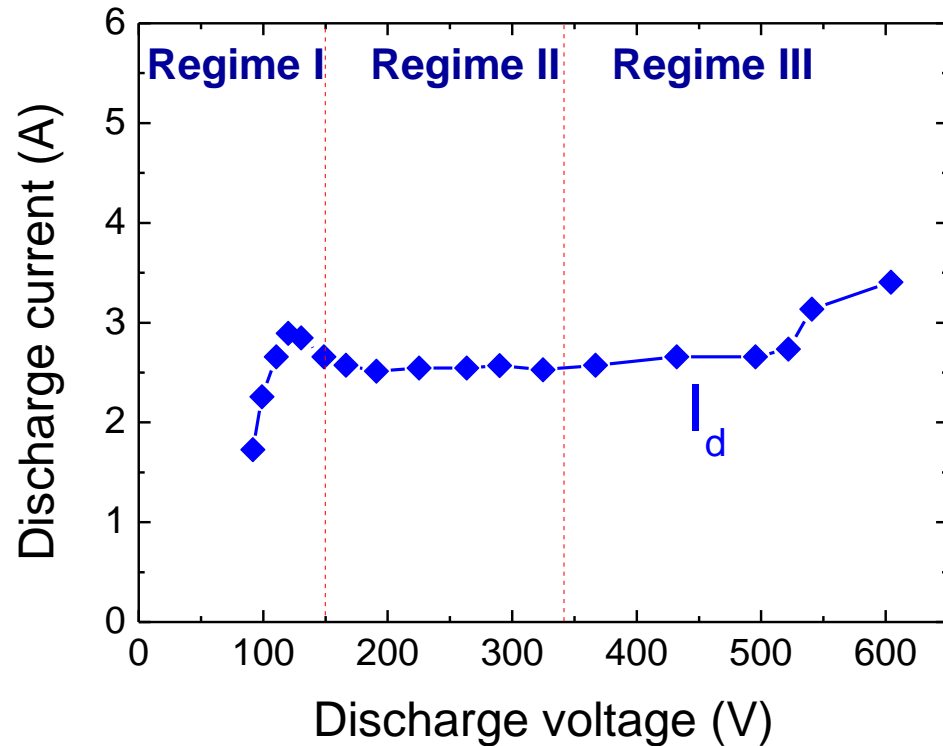
Hall thruster
Hall current thruster
Closed electron drift thruster



Hall current - uninterrupted electron drift

Measured current-voltage characteristic

SPT100, 3.5 mg/s



N. Gascon et al., PoP 10, 4123 (2003)

Regime I

- Incomplete ionization
- Instabilities

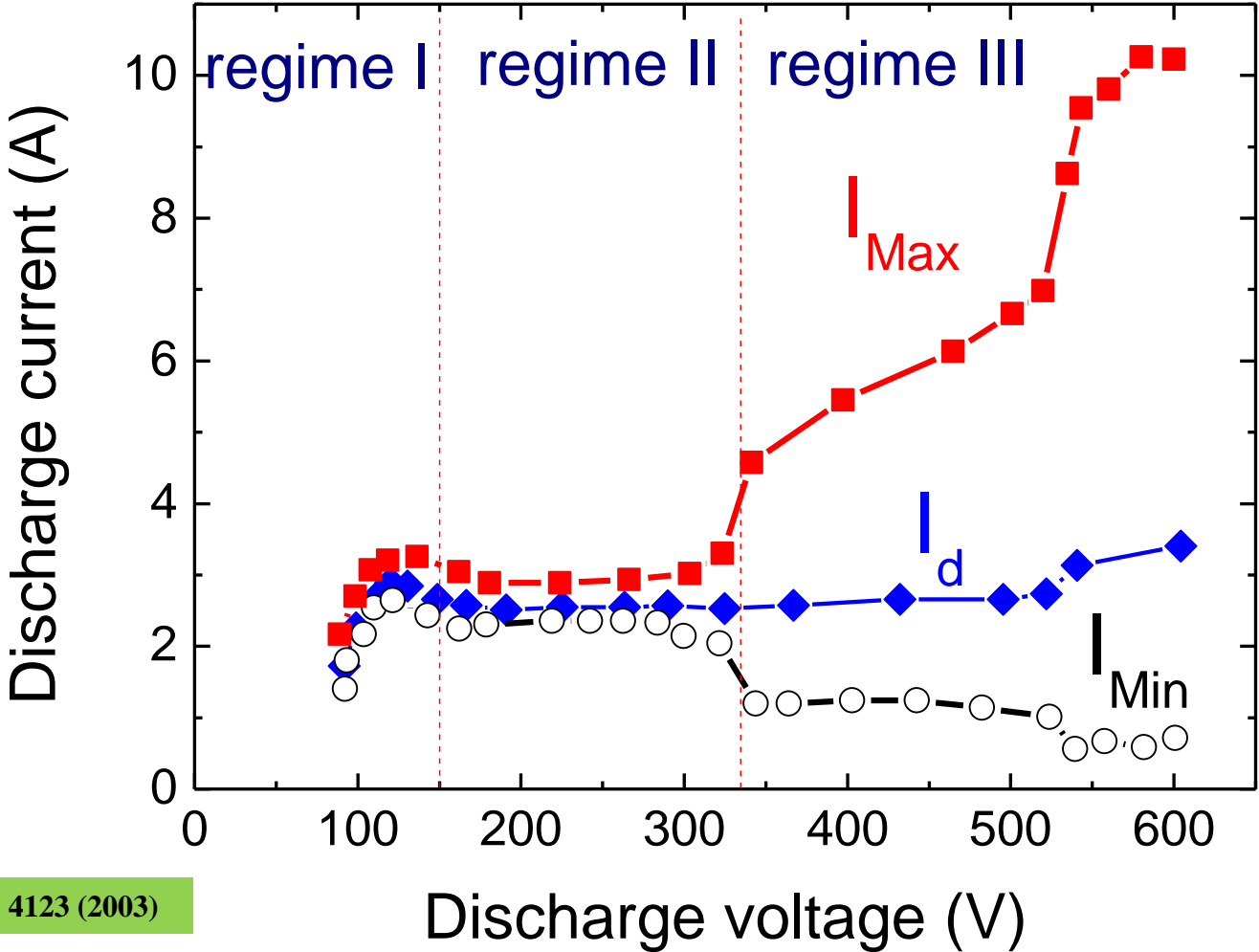
Regime II

- Nominal
- Max ionization efficiency
- $I_d \sim I_i$

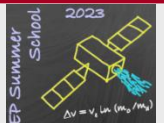
Regime III

- Low efficiency
- Role of SEE
- Multi-charged ions

Current oscillations (1/2)

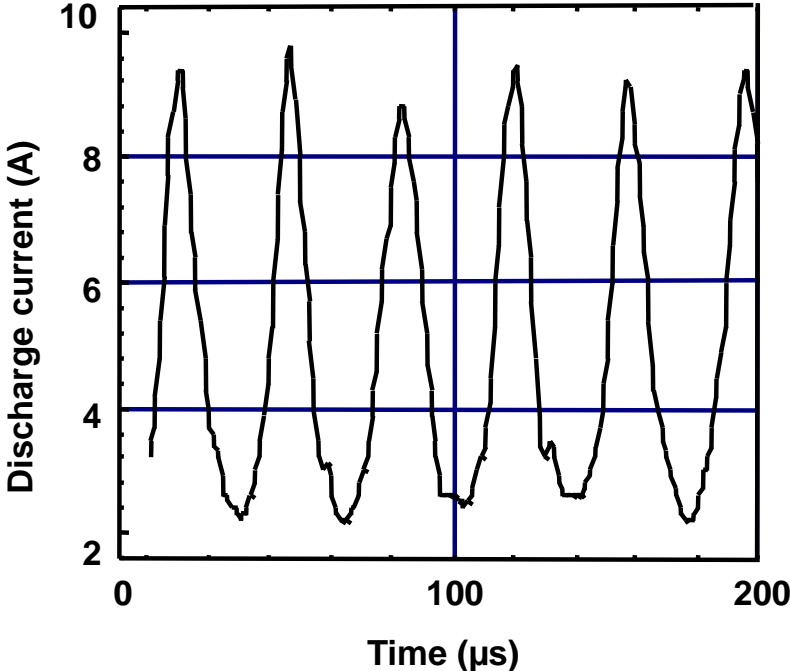


N. Gascon et al., PoP 10, 4123 (2003)



Current oscillations (2/2)

SPT100, 250 V, 5 mg/s

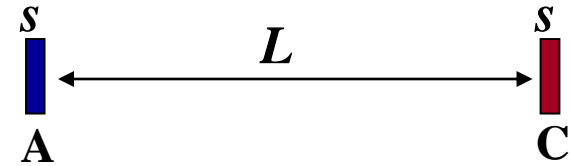


F. Darnon *et al.*, IEEE TPS 27, 98 (1999)

1D axial hybrid model

- **Hypothesis 1: quasineutral plasma**

- Sheath size $s \ll L$
- Electron density = ion density = plasma density



- **Hypothesis 2: fluid collisional transport of electrons**

- 3 first moments of the Boltzmann equation
- Maxwellian energy distribution function
- Electric field is coming from momentum equation of the electrons (Ohm's law)

- **Non collisional and un-magnetized ions – particle description**

- Calculate plasma density
- Constrains on time step (CFL- $\Delta t \sim \text{few } 10^{-8} \text{ s}$)

- **Transport of neutral atoms resolved**

- 90 % of the neutral flux is ionized

- **Static magnetic field**

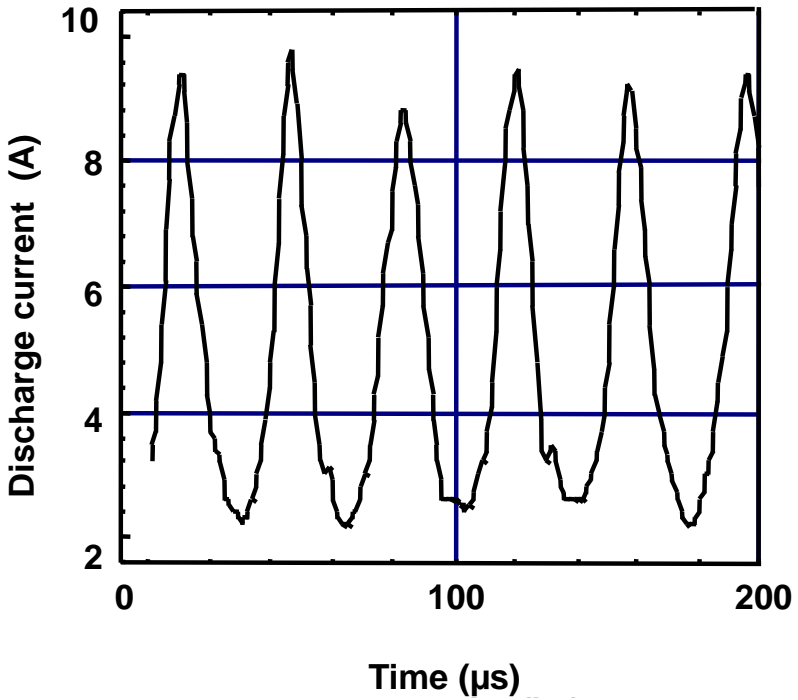
- Self-Magnetic field induced by Hall current negligible

More details with Ahedo
Tomorrow afternoon

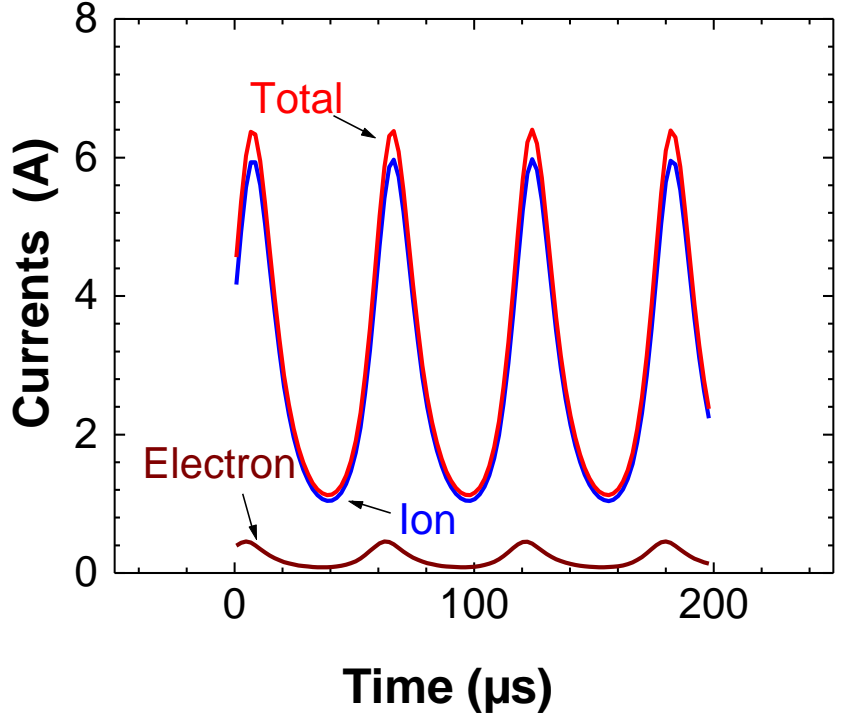
1D hybrid model

SPT100, 250 V, 5 mg/s

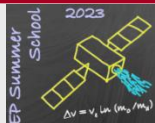
measurements



1D axial model of the channel



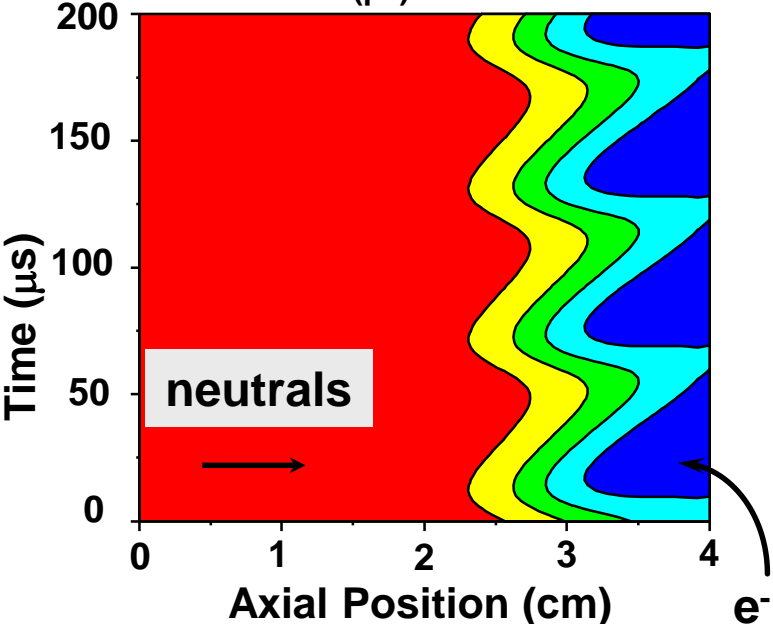
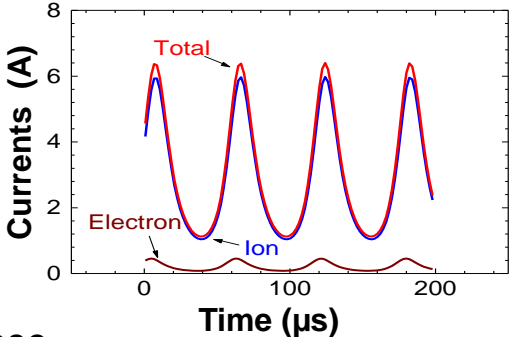
F. Darnon *et al.*, IEEE TPS 27, 98 (1999)



Breathing mode

J. P. Boeuf and L. Garrigues, JAP 84, 3541 (1998)

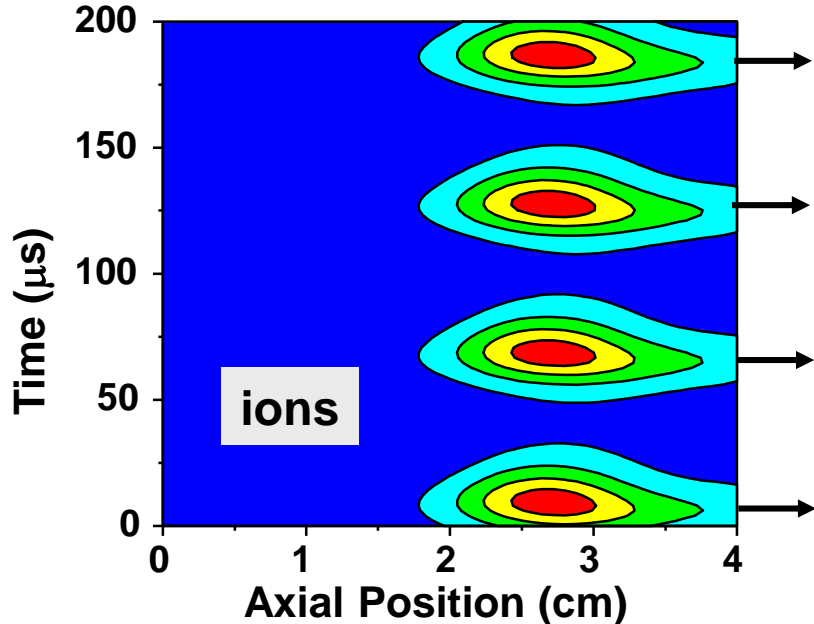
250 V, 5 mg/s



1.6 1.3 1.0 0.8 0.5 0.2



Xe Density ($\times 10^{19} \text{ m}^{-3}$)

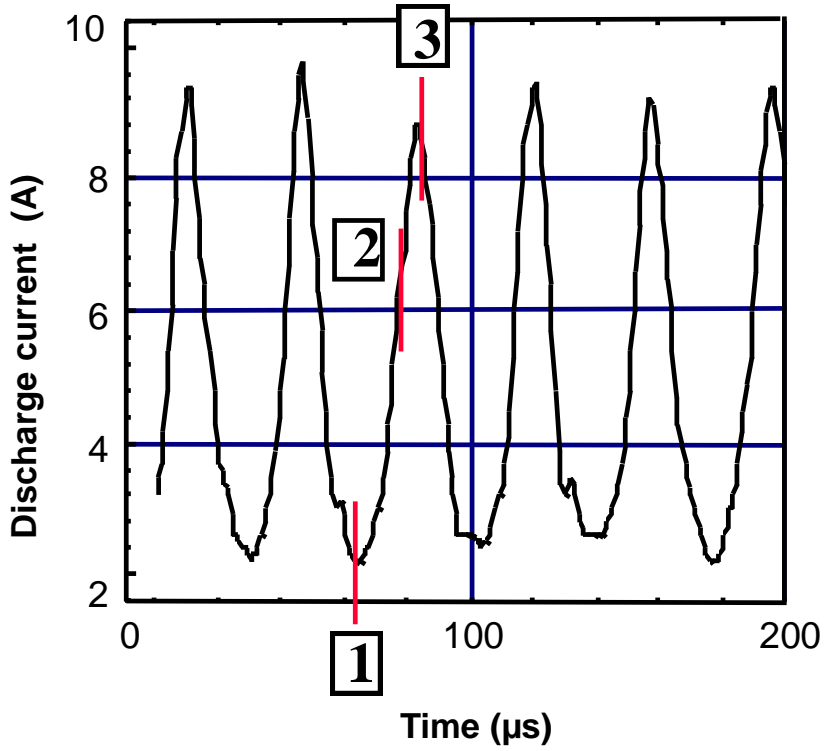


1.4 1.1 0.8 0.6 0.3 0.0

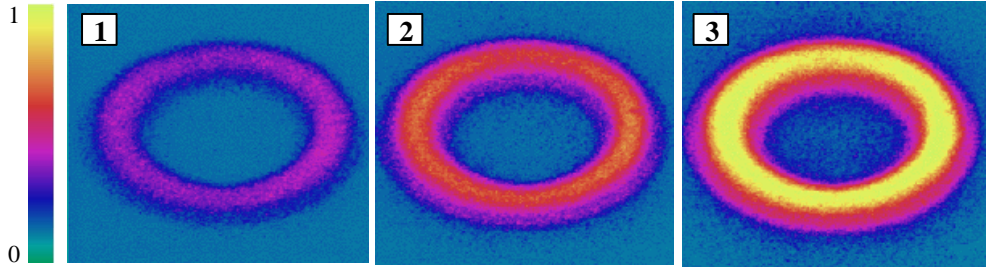


Xe⁺ Density ($\times 10^{18} \text{ m}^{-3}$)

Experimental evidence



250 V, 5 mg/s



Measurements of light emission

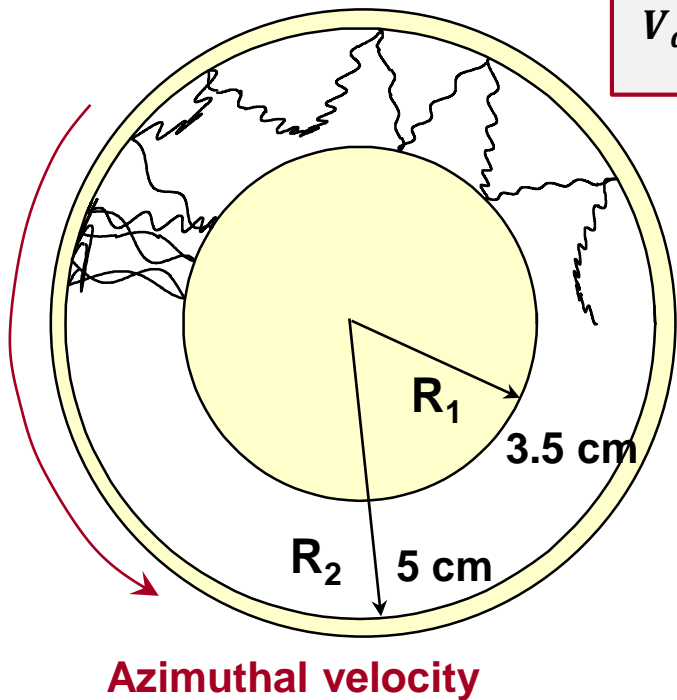
F. Darnon *et al.*,
IEEE TPS 27, 98 (1999)

Axial electron transport (1/2)

classical « collisional » conductivity

→ Azimuthal drift velocity independent from collision frequency

→ Axial drift velocity proportional to collision frequency
then to neutral density



$$V_{d,\theta} = \overline{v_{e,\theta}} = \frac{E}{B}$$

$$\omega = \frac{eB}{m}$$

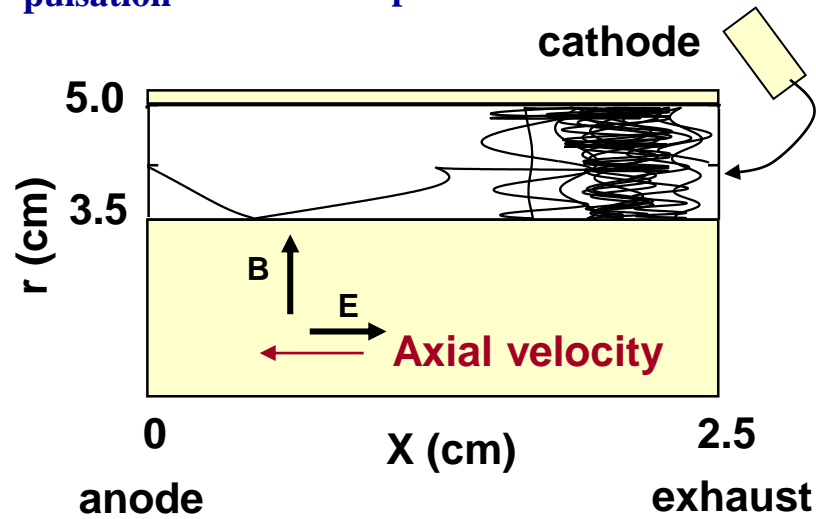
$$V_{d,x} = \overline{v_{e,x}}$$

$$= -\frac{E v}{B \omega} = -\frac{E}{B} \frac{1}{\Omega_{Hall}}$$

cyclotron pulsation

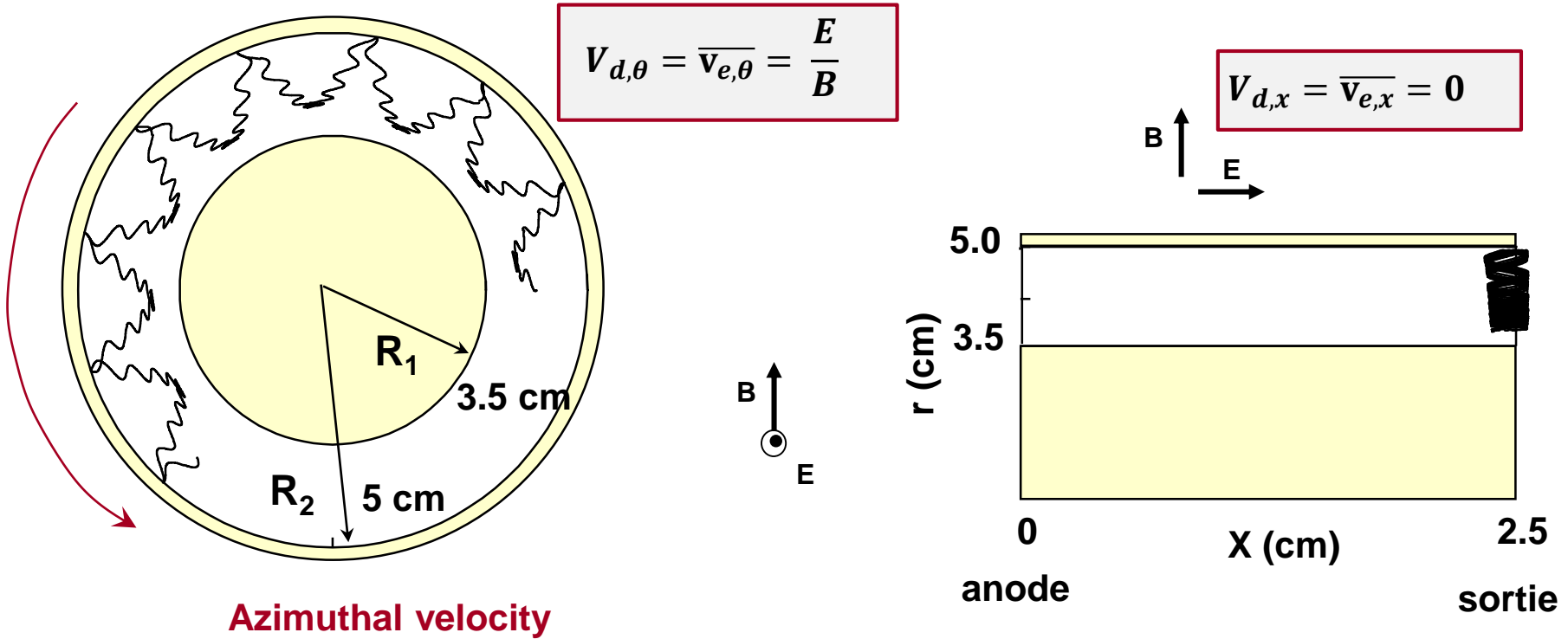
Hall parameter

collision frequency

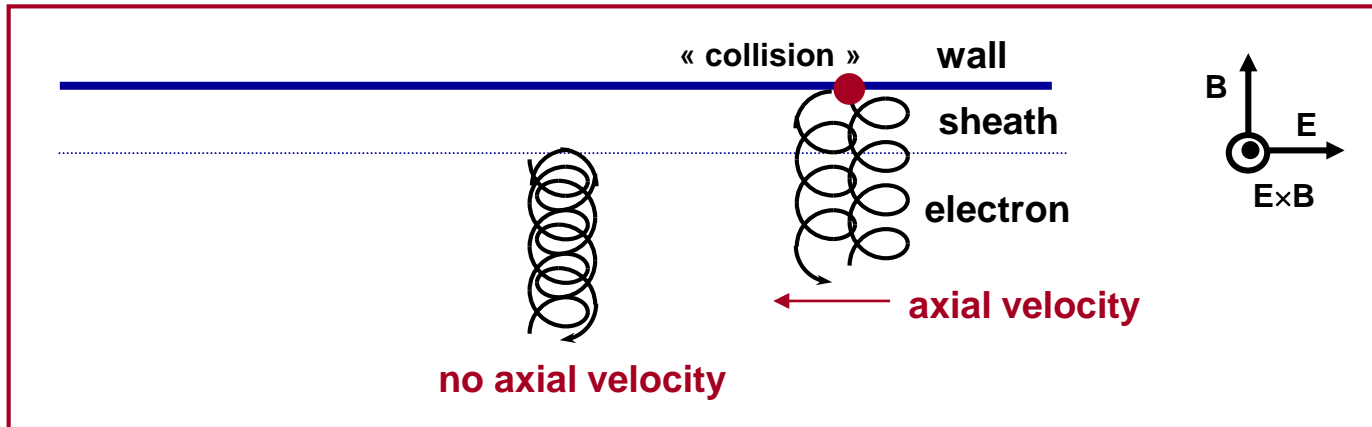


Axial electron transport (2/2)

- Azimuthal drift velocity independent from collision frequency
- Axial drift velocity is zero when neutral density is zero



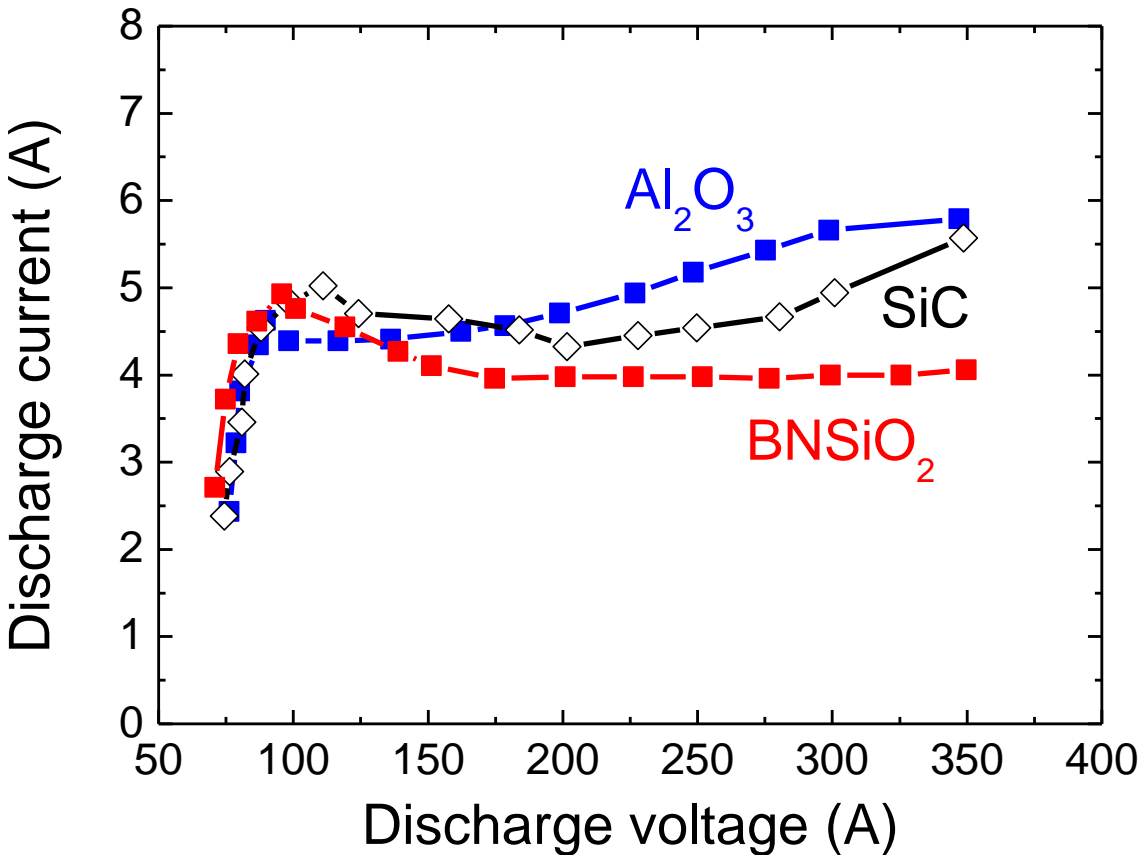
Electron-wall interactions (1/2)



- « wall conductivity » - Russian literature abundant (Morozov)
 - Transfer of momentum
 - Change of confined trajectories
- Secondary electron emission under high energetic electron impact
 - Influence on sheath potential
 - Consistent with studies on wall materials effects
- Empirical way to account for electron-wall interaction
 - « Effective » collision frequency
 - More refined models exist

$$v_{e-w} = \frac{\alpha v_{e,th}}{(R_2 - R_1)}$$

Electron-wall interactions (2/2)



- Strong influence of wall material
- Different SEE rate
- Abundant literature

E. Ahedo *et al.*, PoP 10, 3397 (2003)

S. Barral *et al.*, PoP 10, 4137 (2003)

Y. Raitses *et al.*, PoP 12, 073507 (2005)

Y. Raitses *et al.*, PoP 13, 014502 (2006)

F. I. Parra *et al.*, JAP 100, 023304 (2006)

L. Garrigues *et al.*, JAP 100, 123301 (2006)

D. Sydorenko *et al.*, PRL 103, 145004 (2009)

- Transport outside of the channel?

Turbulence

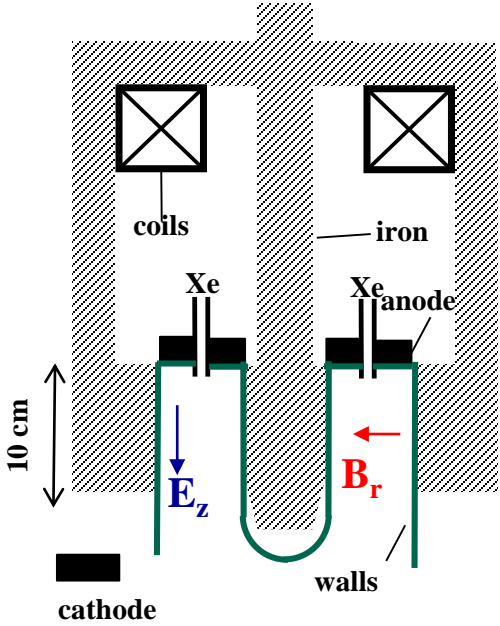
- Instabilities inside the plasma that induce a transport of electrons normally to the magnetic field

- Well known in plasma fusion
 - Tokamaks - ITER
 - Limitation of duration of plasma confinement

- In LTP – $E \times B$ configuration
 - Measurement of turbulence effect?
 - $V_{e,\theta} = E/B$, $V_{e,x} = -E\nu/B\omega$
 - $V_{e,\theta} / V_{e,x}$ ratio: Hall parameter
 - Abnormal diffusion: $\nu \gg \nu_{e\text{-atom}}$
 - $\Omega_{Hall} \sim \text{constant [0.1-0.3]}$
 - « Effective » collision frequency

$$\Omega_{Hall} = \frac{\omega}{\nu}$$

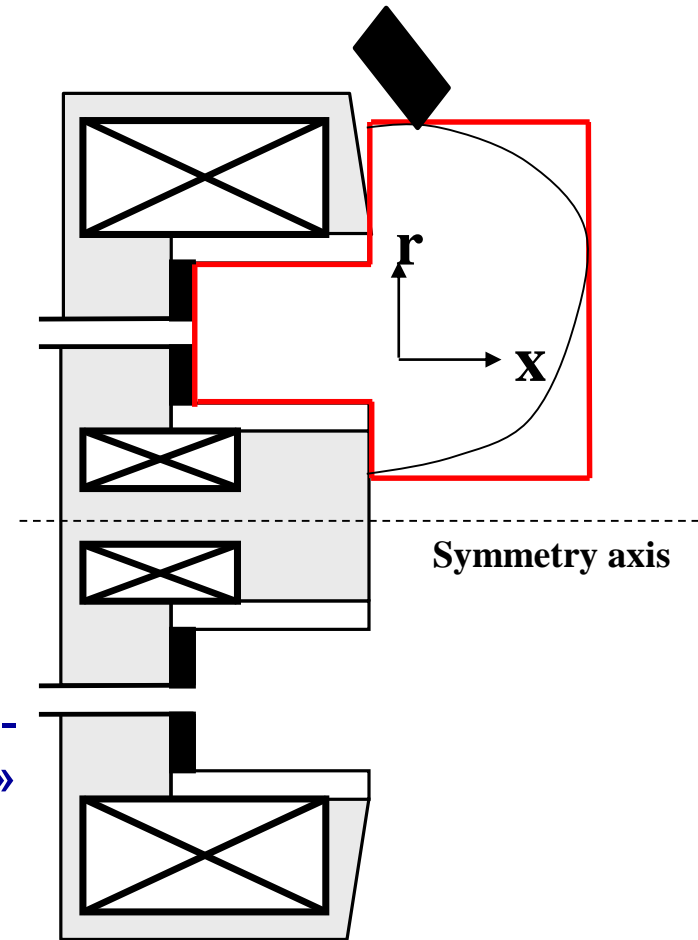
$$\nu_{turb} = k\omega$$



G. S. Janes and R. S. Lowder, PFL 9, 1115 (1966)

2D axial-radial hybrid model

- 2D axisymmetric – radial and axial directions
- Channel and near field regions
- Magnetostatic magnetic field
- Particle description: ions and neutrals
- Quasineutral plasma: $n = n_e = n_i$
- Electron fluid description including the electron-wall and turbulence effects with an « effective » collision-frequency
- Energy equation, Maxwellian EEDF ionization rate



G.J.M. Hagelaar *et al.*, JAP 91, 5592 (2002)

HALLIS software

- Open access, free download
- Graphical user interface
- Easy to use

<https://www.hallis-model.com>



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HALLIS SOFTWARE

DOWNLOAD

CONTACT

HALLIS Physics

The HALLIS software contains two independent modules for the 1D and 2D (axisymmetric) description of Hall ion sources. Both are based on a hybrid model where electrons are treated as a fluid and ions and neutral atoms are represented by pseudo-particles [1-5]. The electron fluid model consists in continuity, momentum, and energy equations (assuming a Maxwellian electron velocity distribution). The user can choose between the 1D and 2D models at the beginning of the simulation and the same graphical user interface is used for both.

Positive ion and neutral atom trajectories in phase space are obtained by integrating the equations of motion taking into account collisions and interactions with walls. For neutral atoms, only collisions with walls (specular or diffusive) are taken into account. For ions, collisions with neutral atoms and recombination at the wall (with atom generation) are considered. The model is quasineutral, i.e. the electric field is obtained from current continuity and not from Poisson's equation. Electron cross-field transport through the magnetic barrier is described by empirical coefficients (effective mobility and energy losses). These empirical coefficients are defined as in Refs. [1-4] but more complex models of anomalous transport models [5] are also implemented.

In the 2D model the Morozov approximation is made along the magnetic field lines, i.e. equilibrium between electric force and pressure gradient is assumed along the magnetic field lines.

The principles of the quasineutral hybrid model used in HALLIS are described in the references below:

[1] J. Boeuf and L. Garrigues, *J. Appl. Phys.* 84, 3541 (1998).

[2] G. J. M. Hagelaar, J. Bareilles, L. Garrigues, and J. P. Boeuf, *J. Appl. Phys.* 91, 5592 (2002).

[3] G. J. M. Hagelaar, J. Bareilles, L. Garrigues, and J. P. Boeuf, *J. Appl. Phys.* 93, 67 (2003).

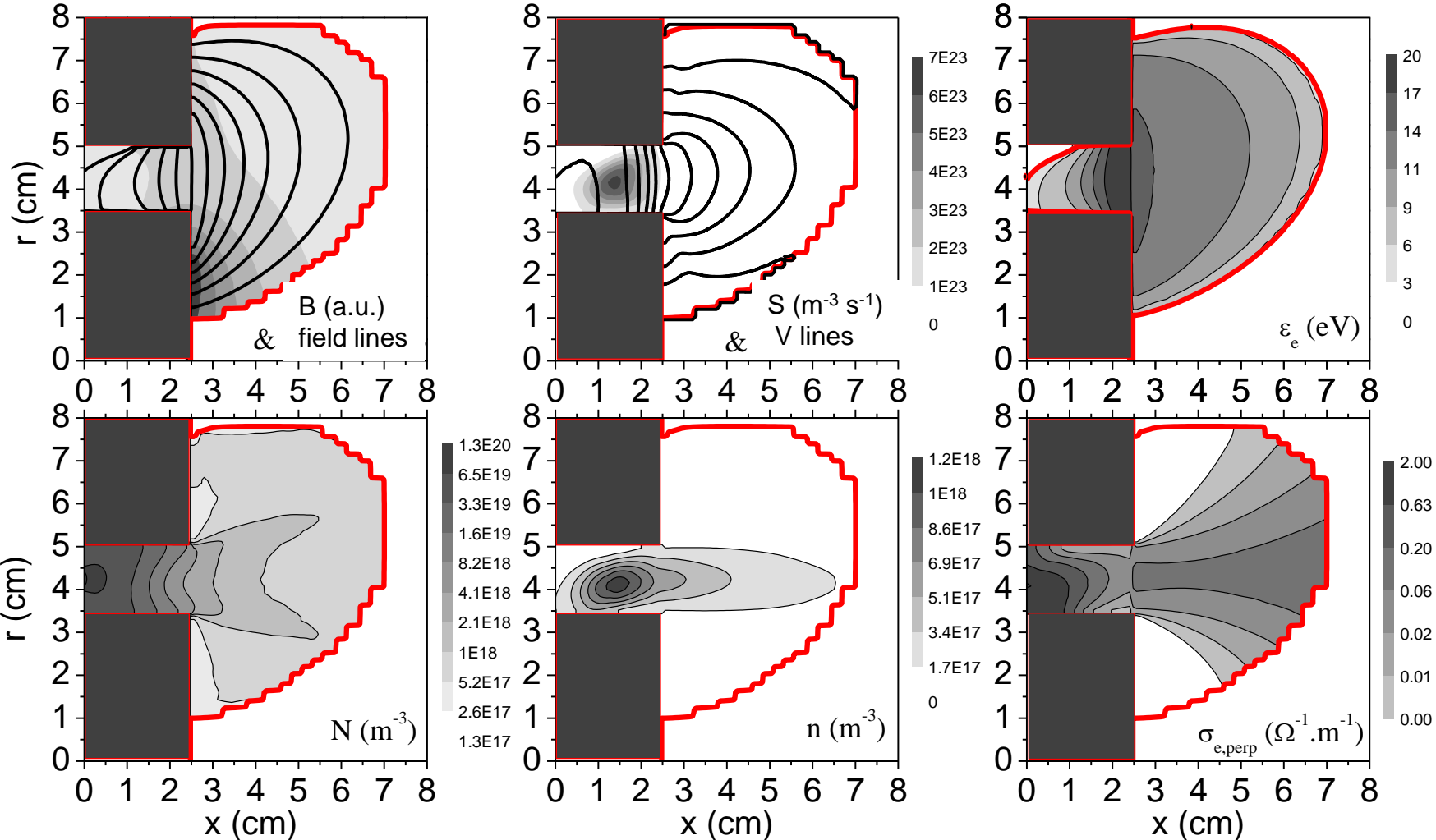
[4] J. Bareilles, G. J. M. Hagelaar, L. Garrigues, C. Boniface, N. Gascon and J. P. Boeuf, *Phys. Plasmas* 11 3035 (2004).

[5] J. P. Boeuf, *J. Appl. Phys.* 121 011101 (2017)

Nominal operation of the SPT100

J. Bareilles *et al.*, PoP 11, 3035 (2004)

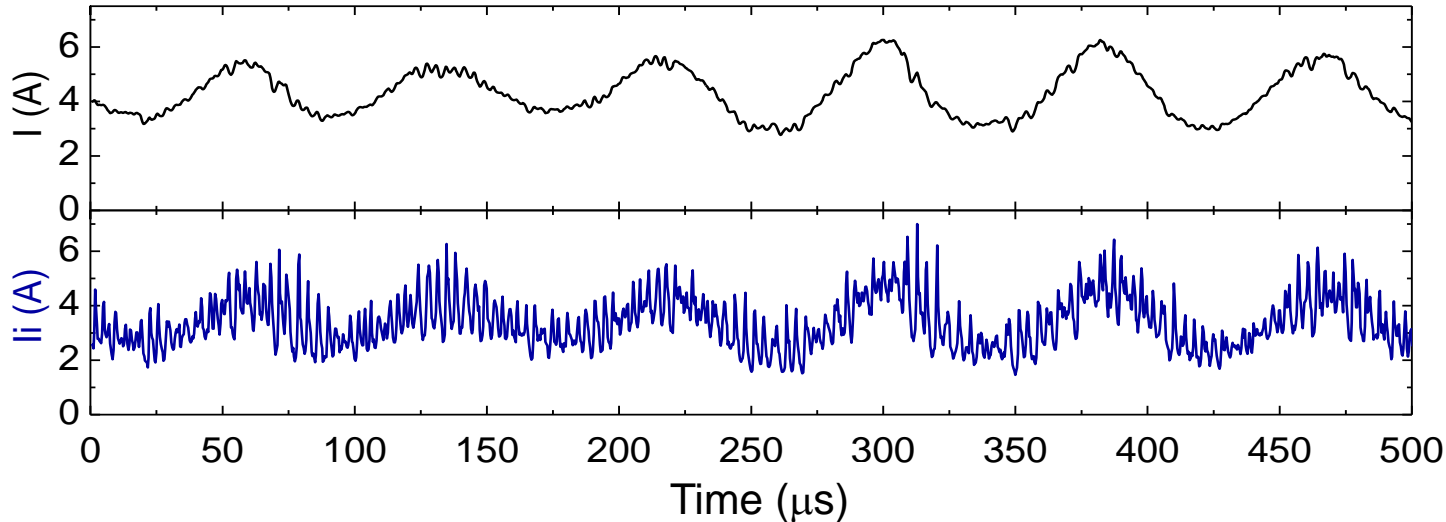
300 V, 5 mg/s



Nominal operation - transient behavior

J. Bareilles *et al.*, PoP 11, 3035 (2004)

300 V, 5 mg/s



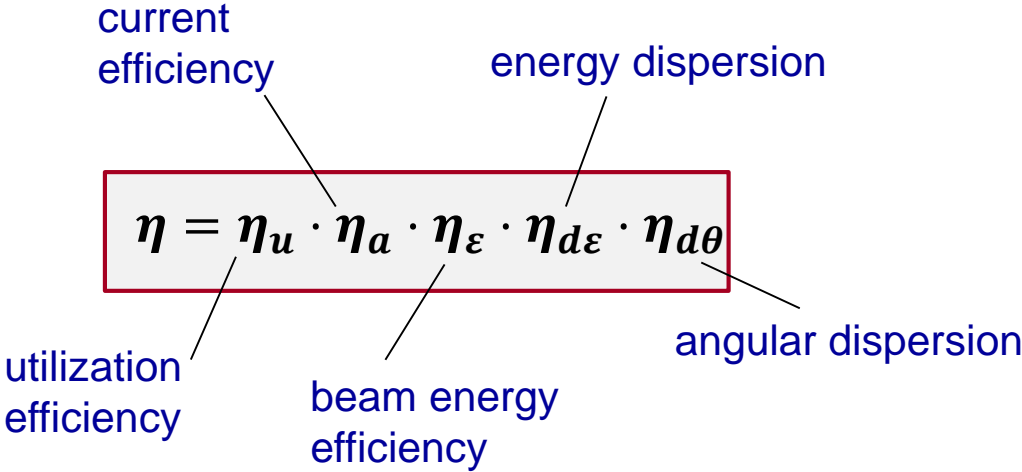
- **Low frequency oscillations 10 – 20 kHz**
 - Periodic depletion of atoms (scale of neutrals transit time)
 - Experimentally observed and predicted by 1D model
- **High frequency oscillations 100 – 400 kHz**
 - Periodic extraction of ions due to oscillations of acceleration region (ions transit time)
 - Experimentally observed (mainly in « old » Russian thrusters)
 - Responsible for the broadening of IEDF

Efficiency

300 V, 5 mg/s

$$\eta = \frac{T^2}{2\dot{m}P_{elec}}$$

$$\eta = \frac{T^2}{2\dot{m}P_{elec}} = \frac{T^2}{2\dot{m}IV} = \frac{m_i I_i}{e\dot{m}} \cdot \frac{I_i}{I} \cdot \frac{\frac{1}{2} m_i \bar{v}^2}{eV} \cdot \frac{\bar{v}^2}{v^2} \cdot \overline{\cos^2 \theta}$$



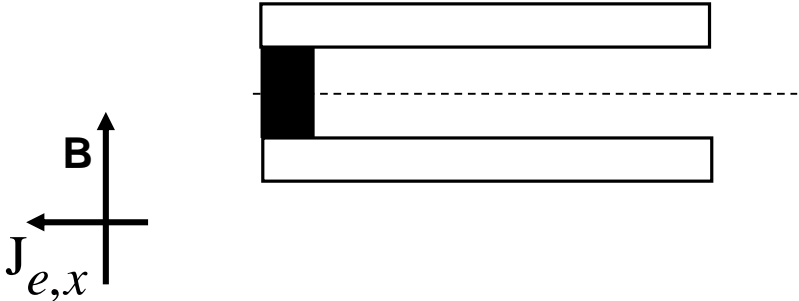
Nominal case

- $\eta_u \sim 0.9$
- $\eta_a \sim 0.8$
- $\eta_\epsilon \sim 0.8 \longrightarrow \eta \sim 0.5$
- $\eta_{d\epsilon} \sim 0.95$
- $\eta_{d\theta} \sim 0.9$

Direct measurement of the Hall parameter?

- Current perpendicular to B

$$J_{e,x} = -en_e \overline{v_{e,x}} = en_e \frac{E_x v}{B_r \omega} = en_e \frac{E_x}{B_r} \frac{1}{\Omega_{Hall}}$$



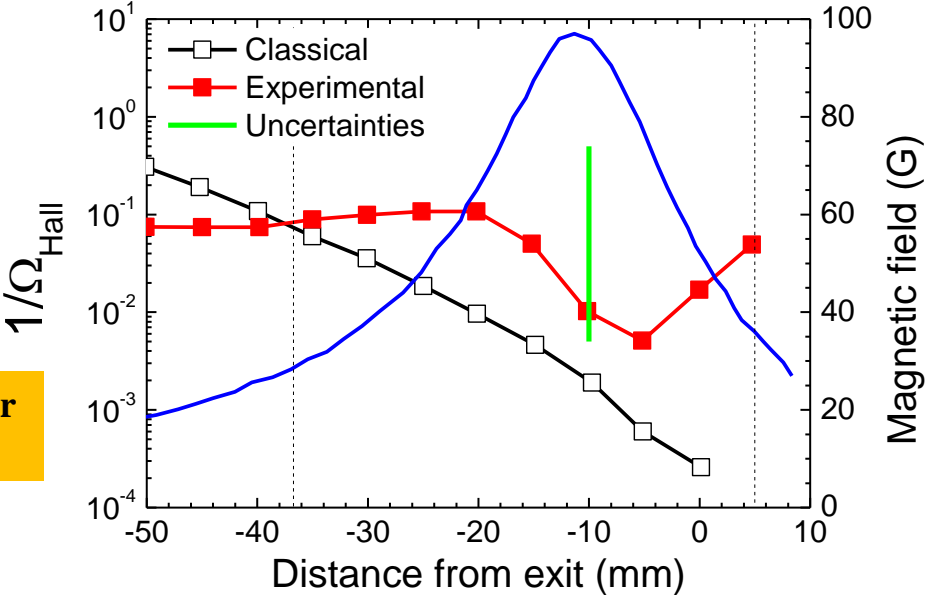
- Measurements very hard

- Large uncertainties
 - Probes perturbate the operation
 - Interpretation with B?
- Spatial resolution necessary

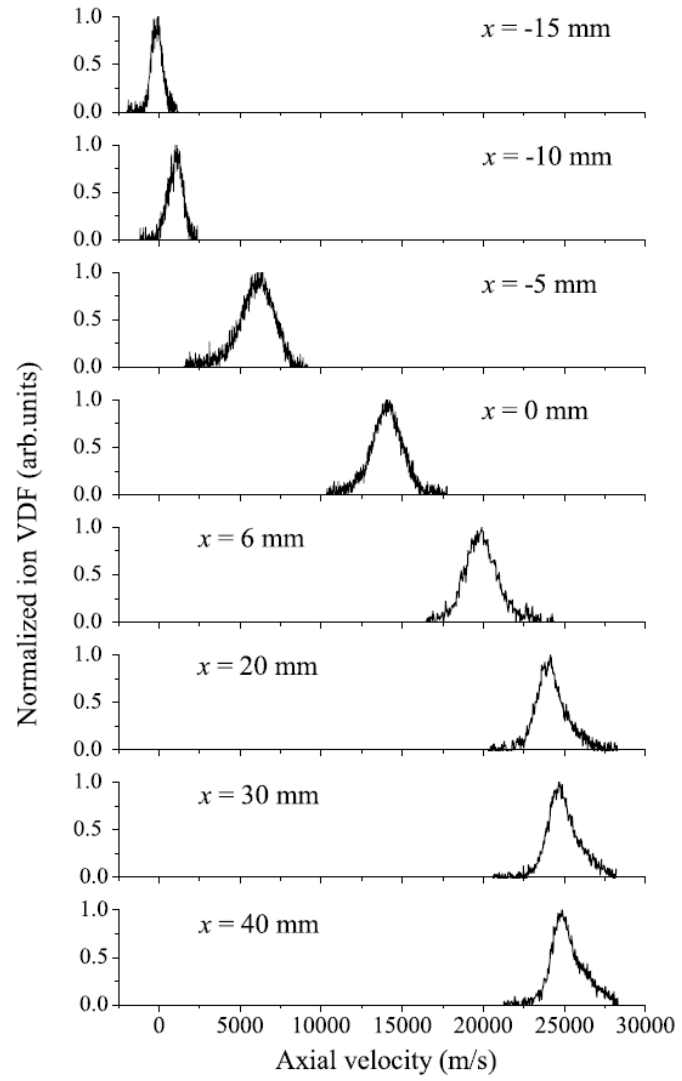
More details with Trottenberg and Dannenmeyer Tomorrow morning

- Qualitative but not quantitative informations

N. B. Meezan *et al.*, PRE 63, 026410 (2001)

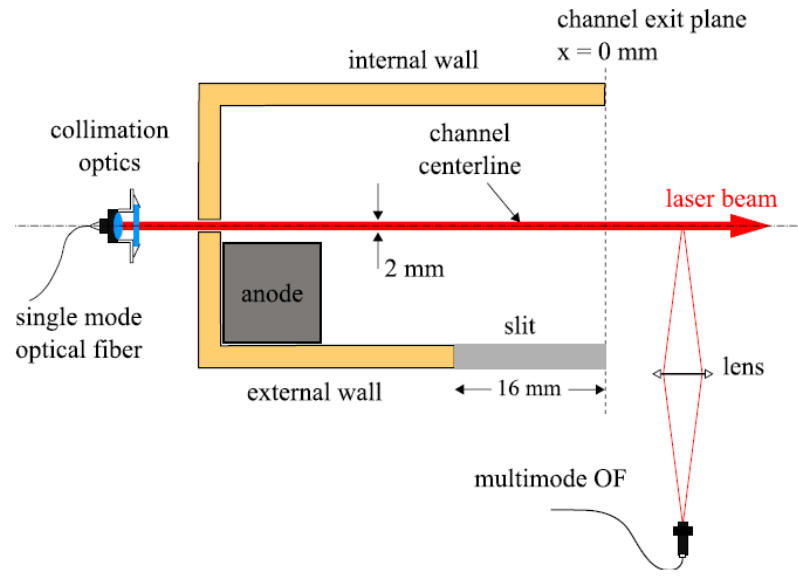


Ion velocity profile – LIF measurements



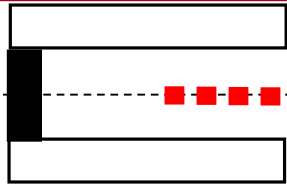
PPSX000, 500 V, 6 mg/s

More details with Mazouffre Tomorrow morning



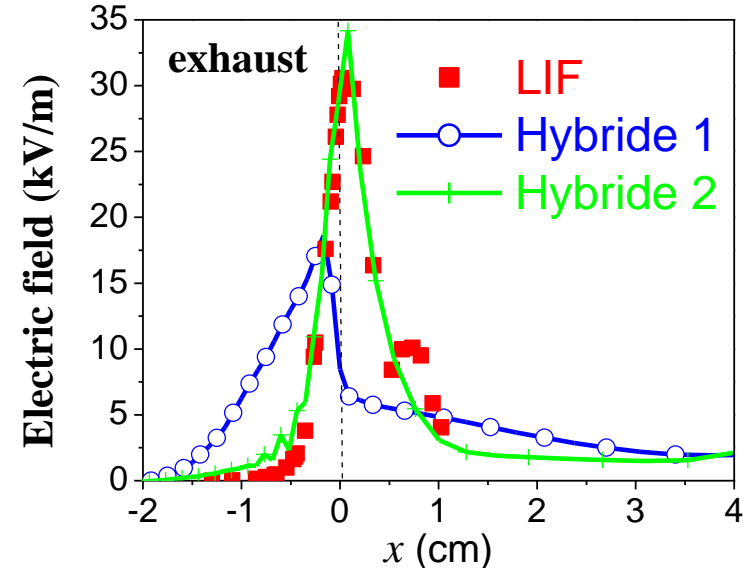
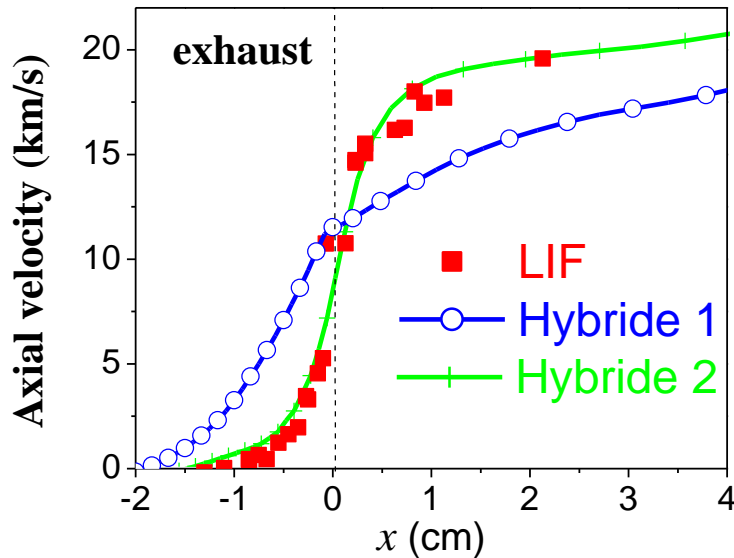
S. Mazouffre *et al.*, PSST 18, 034002 (2009)

Fitted anomalous transport mobility



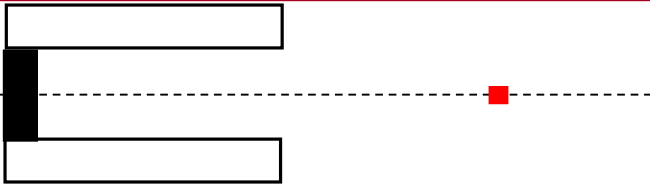
LIF measurements

L. Garrigues *et al.*,
APL 95, 141501 (2009)



- Approach with « adjustable parameters » does not properly describe plasma properties (ion velocity profiles differ)
- Space resolved LIF measurements: adjust an “effective” collision frequency

Ion energy distribution functions

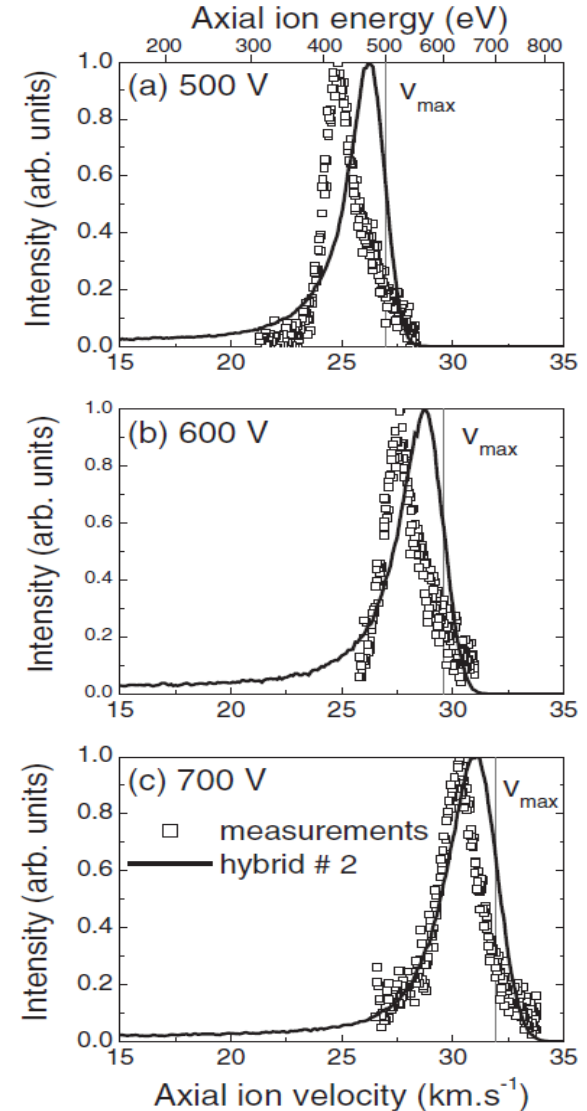


PPSX000, 6 mg/s

- Extendable to other operational conditions
- $\varepsilon > eV_{\max}$: ITT
- Mechanisms responsible for the electron transport?

More details
Tomorrow afternoon

L. Garrigues *et al.*,
APL 95, 141501 (2009)



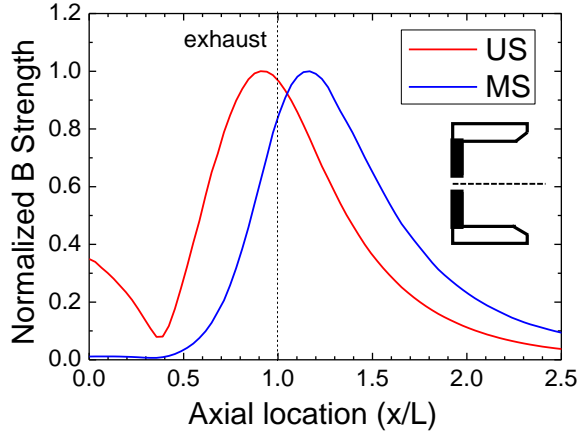
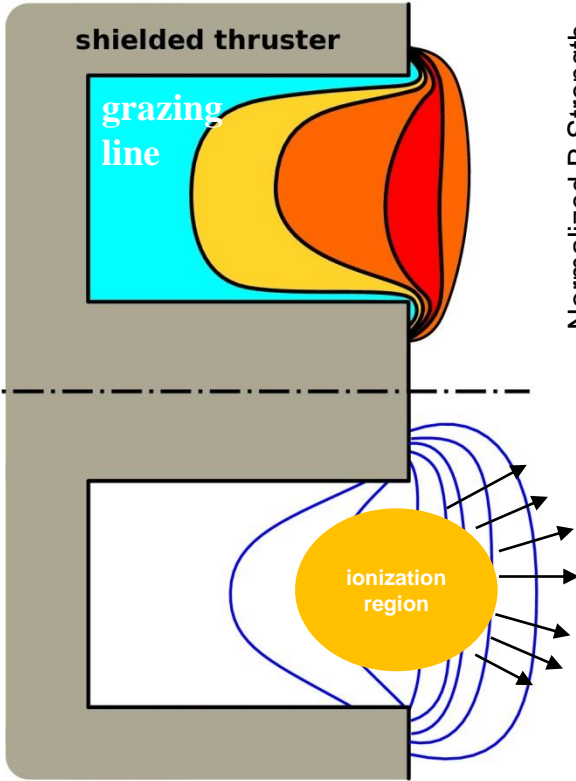
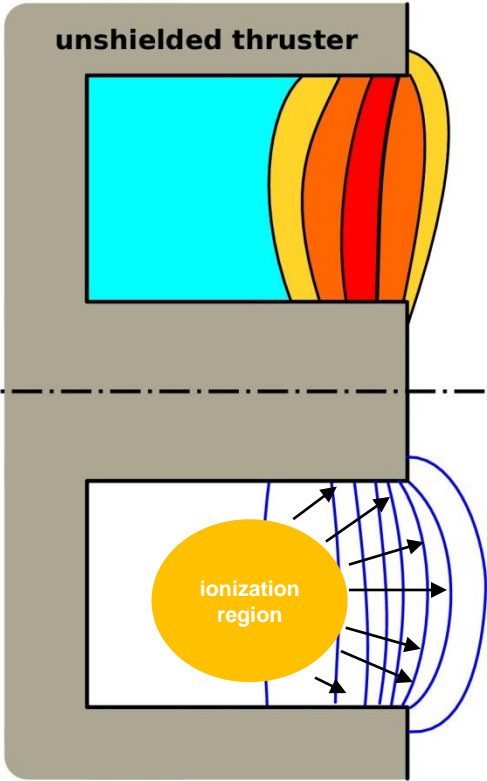
Magnetic shielded configurations

Electron temperature profile

T_e

high

low



Electric isopotential lines & Ionization source term

I. G. Mikellides *et al.*,
PoP 18, 033501 (2011)

R. R. Hofer *et al.*,
JAP 115, 043303 (2014)

R. W. Conversano *et al.*, JPP 33, 975 & 992 (2017)

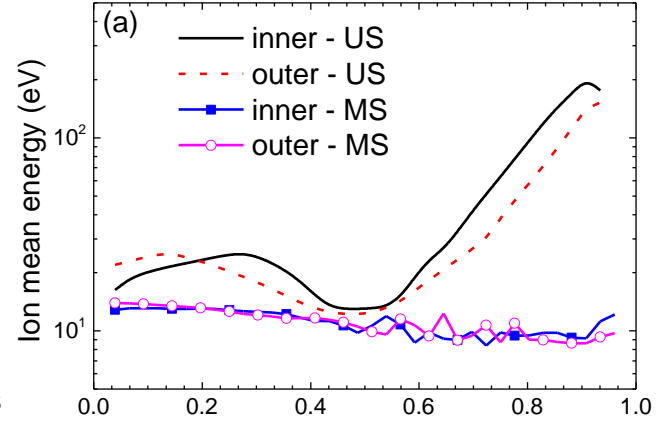
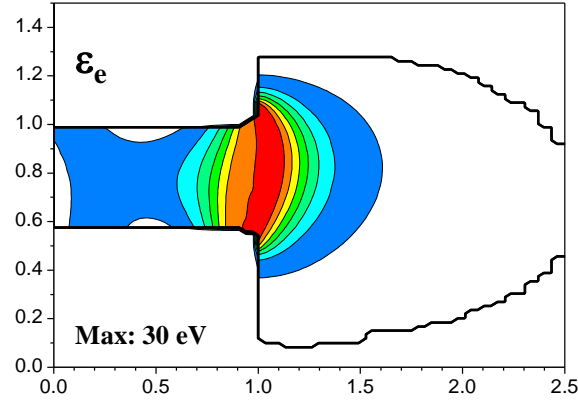
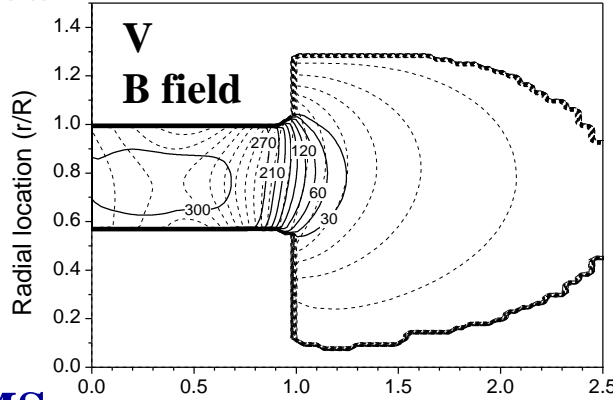
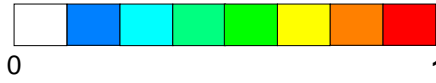
L. Grimaud *et al.*, PSST 26, 055020 (2017)

S. Mazouffre *et al.*, IEEE TPS 46, 330 (2018)

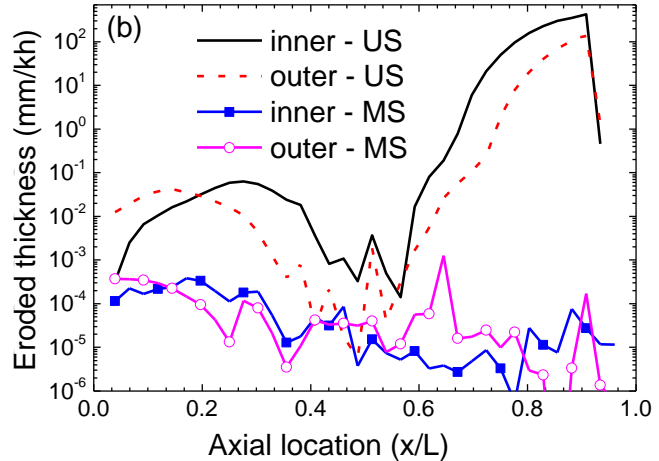
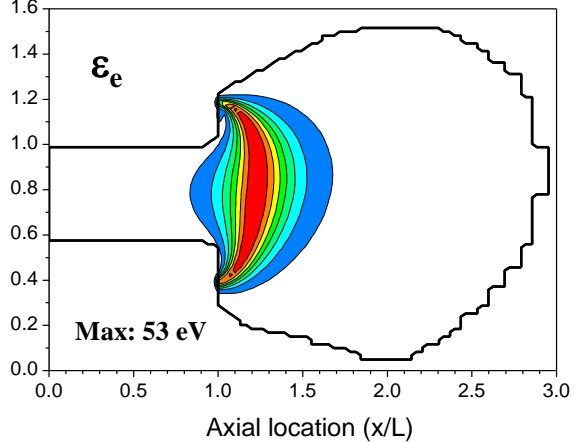
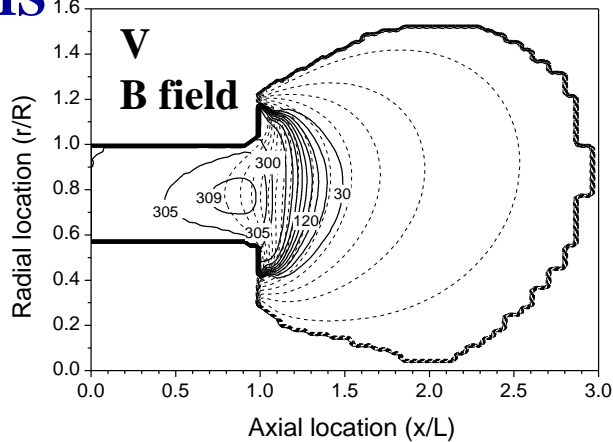


Plasma Properties – US vs MS @300 V, 1 mg/s

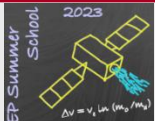
US



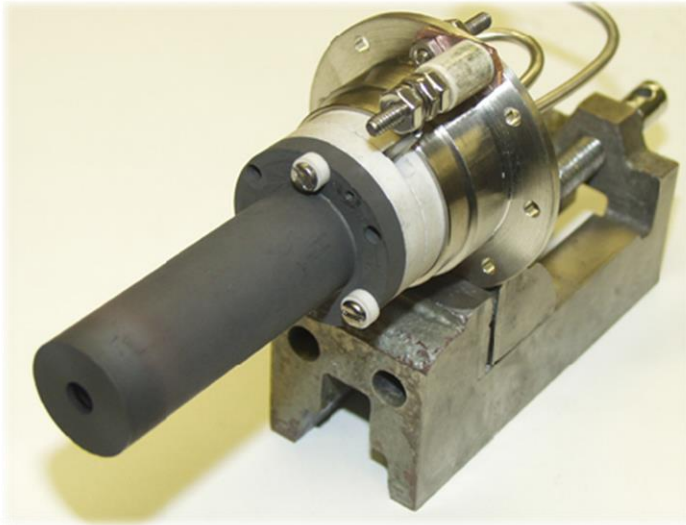
MS



L. Garrigues *et al.*, PSST 28, 034003 (2018)



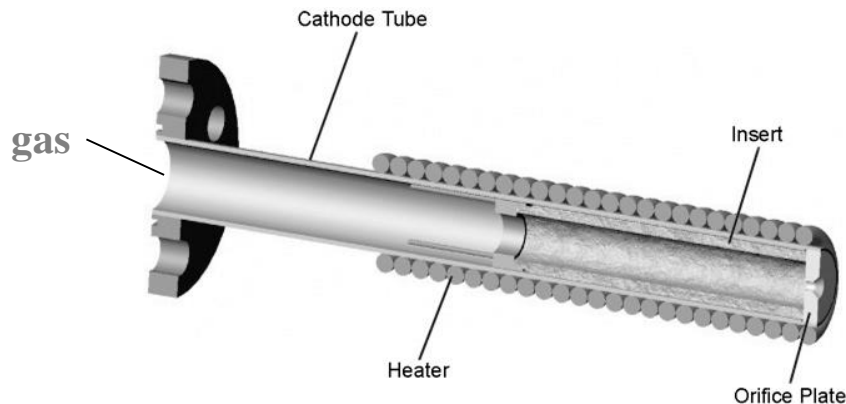
Cathode characteristic



LaB₆ emitting cathode

J. Polk *et al.* AIAA 2006-5150, 2006

- Currents: 1 – 100 A
- Dimensions
 - Radius : mm/cm
 - Length : ~ few to 10 cm
- Plasma density: $> 10^{21} \text{ m}^{-3}$
- Pressure: ~ 1000 Pa
- Flight model: self-heating
- Strong coupling plasma/thermal
- Lifetime: several kh

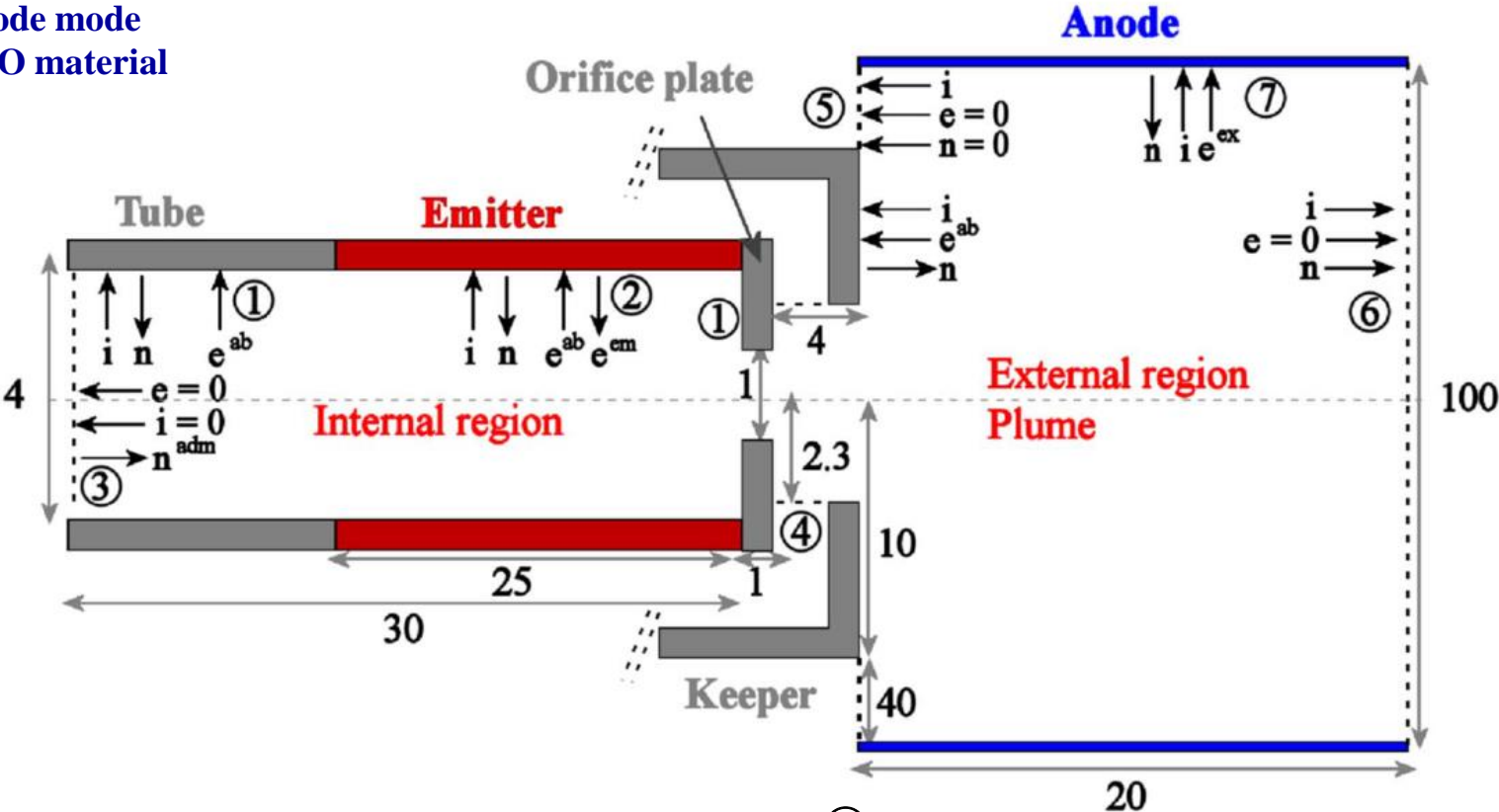


2D model

- **Quasi-neutral fully fluid approach** I. G. Mikellides, PoP 16, 013501 (2009)
- **2D axisymmetric model**
3 species: Xe, Xe⁺, e⁻
- **Highly collisional: Maxwellian distributions**
- **Inter-species collisions are considered (e-n, e-i, i-n)**
- **Cathode plume: fluid description – strong approximation (more qualitatively)** G. Sary *et al.*, PSST 26, 055007 (2017)
- **Plasma sheath: analytical (non-collisional) + thermionic emission (current density given by Richardson-Dushman law)**
- **Fluid model coupled with thermal (heat conservation law)**

Simulation domain – NSTAR cathode

Diode mode
BaO material

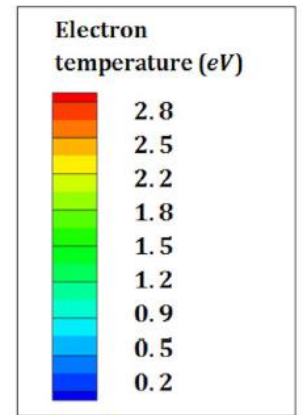
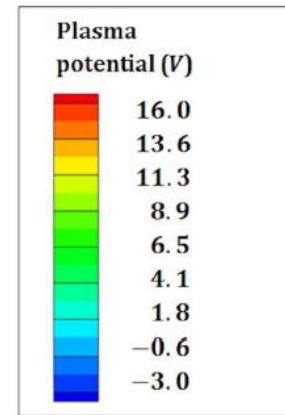
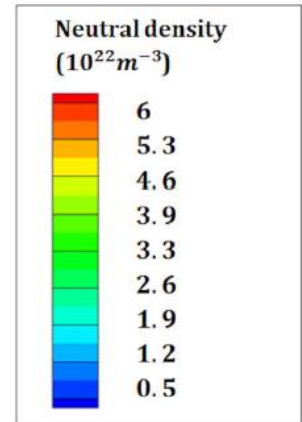
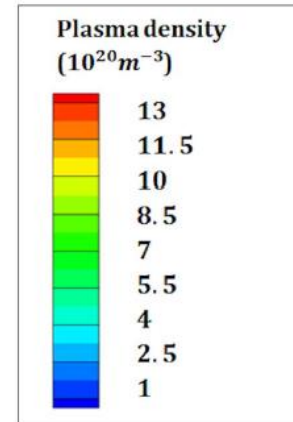
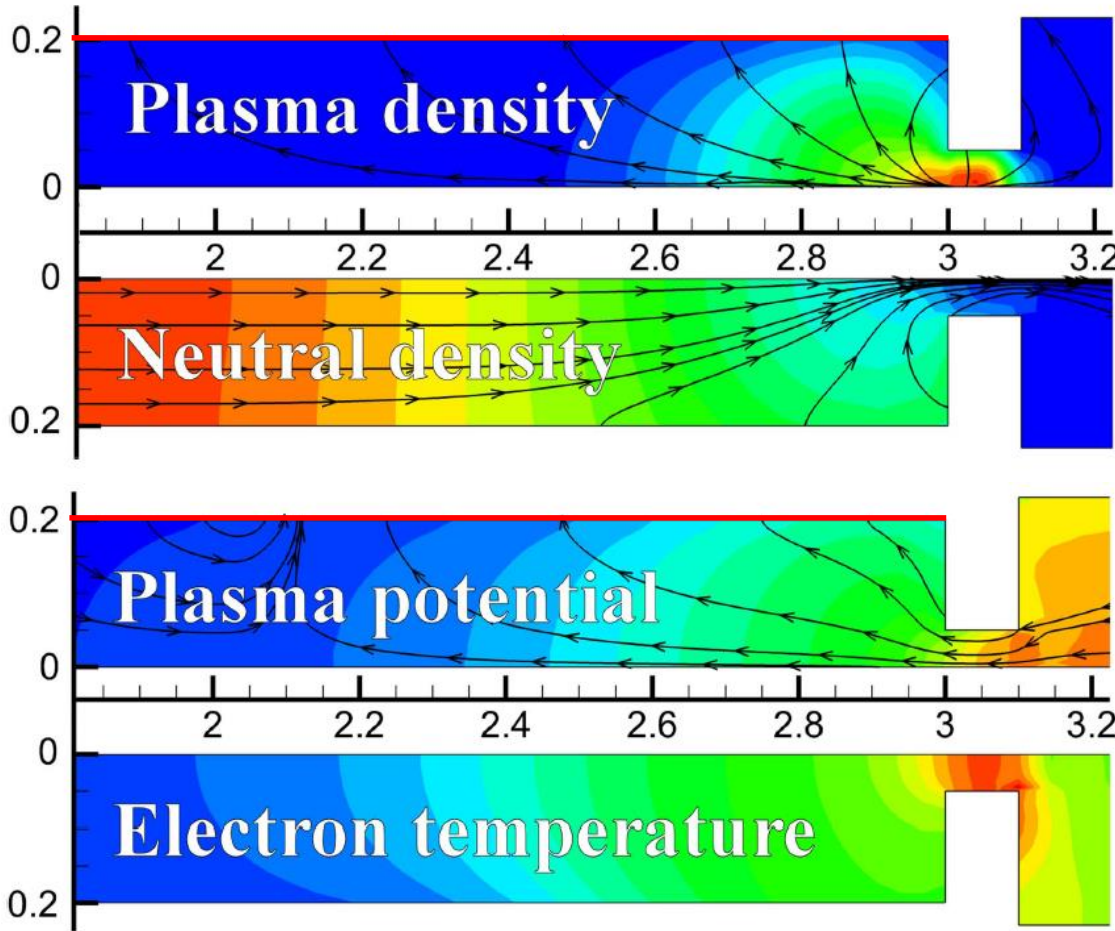


- ① : Grounded metal wall
- ② : Thermionic emitter (grounded)
- ③ : Injection of xenon (Q_{Xe} : 3.6 SCCM)
- ④ : Keeper, external electrode (fixed current)
- ⑤ : Fictitious absorbing border

- ⑥ : Gas expansion region
 - ⑦ : Anode (current density imposed \vec{j}_e , total $I_e = 13 A$)
- Dimensions in mm

G. Sary et al., PSST 26, 055007 (2017)

Plasma properties

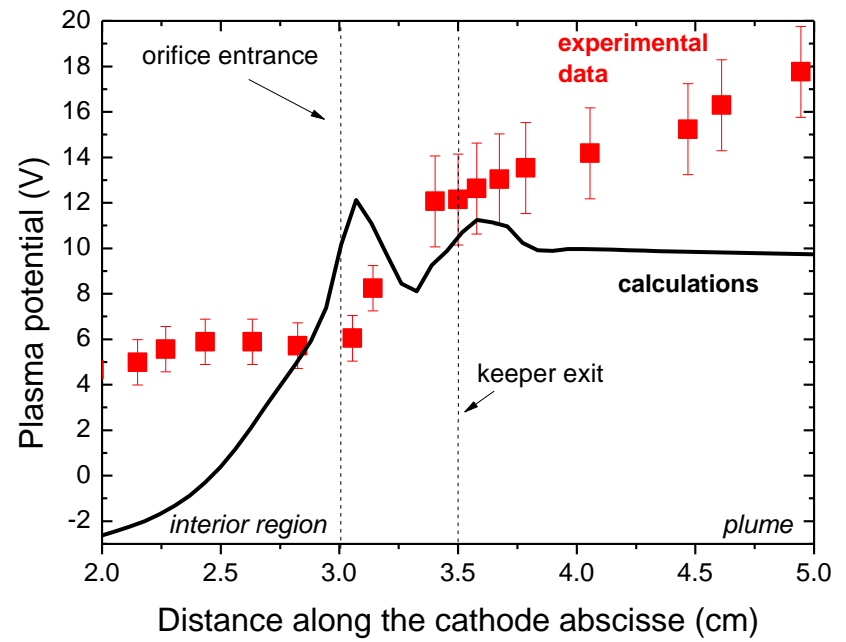
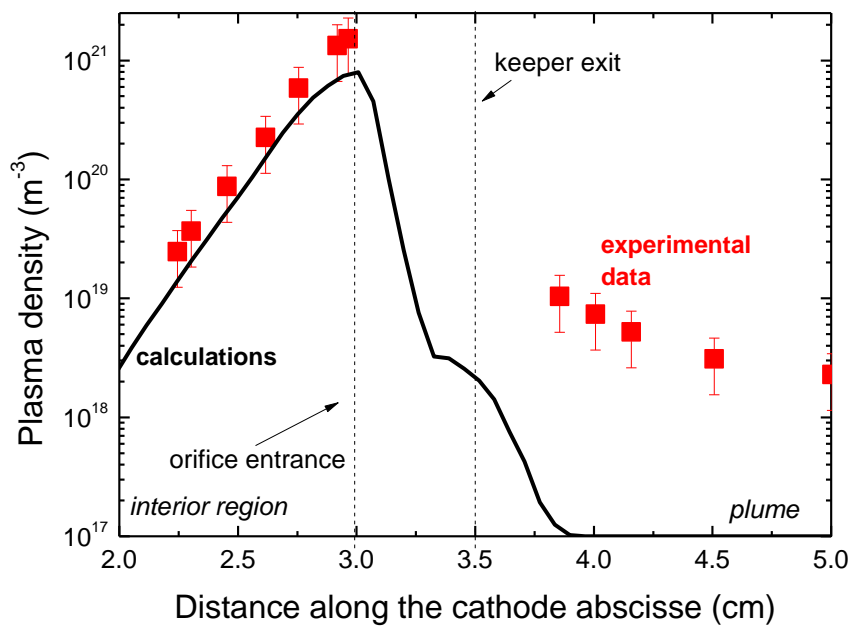
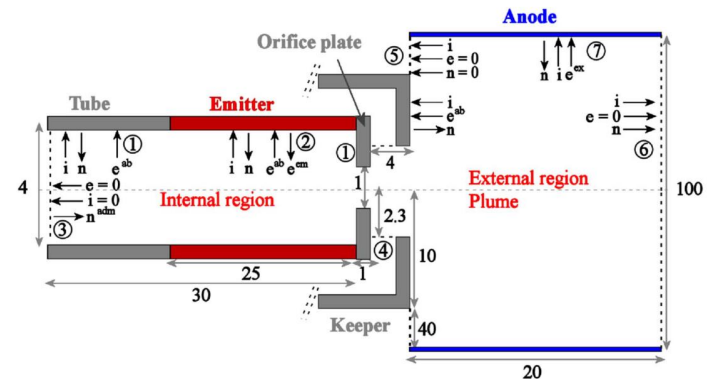


Dimensions in cm

G. Sary *et al.*, PSST 26, 055008 (2017)

Comparisons with experiments

- **Inside the cathode**
 - Correctly reproduces measurements
 - Importance of electronic emission at the wall
 - Low volume multiplication
 - Partial use of the emitter
- **Outside the cathode**
 - Large disagreement!

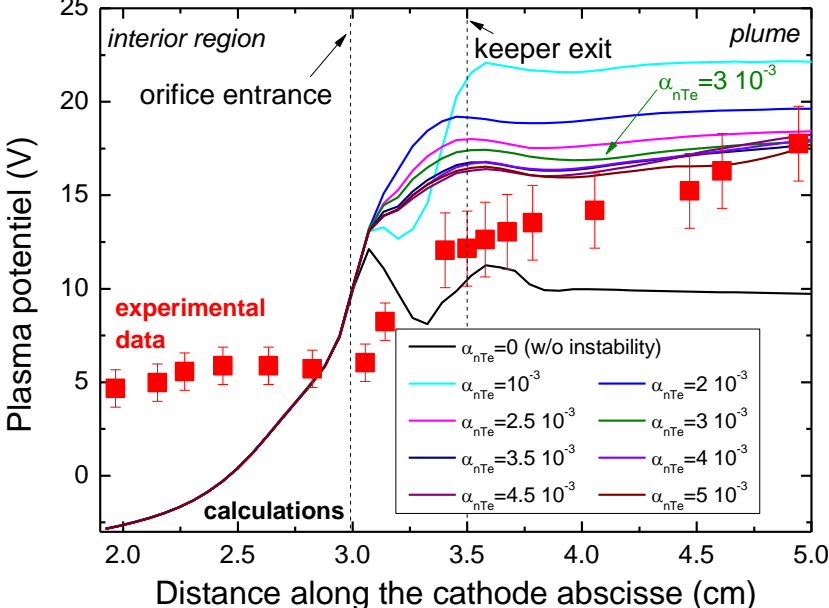
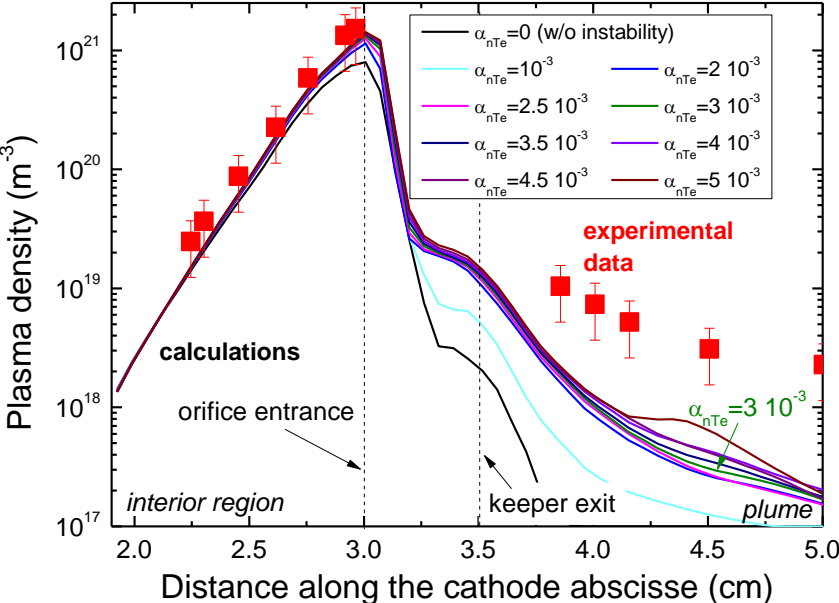


Ion acoustic instability

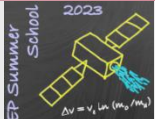
- IAI taken into account

- Previous work in the literature
- Linear regime - additional terms in equations (momentum, energy)
- Non-linear effects (saturation - adjustable coefficient α_{nTe} [10^{-3} - 10^{-2}])

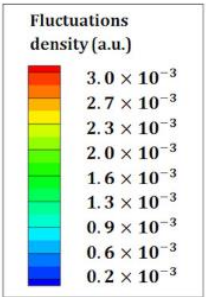
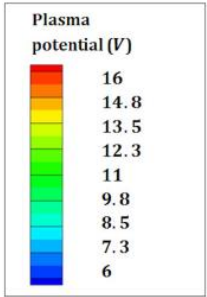
R. C. Davidson and N. A. Krall,
Nucl. Fusion 17, 1313 (1977)



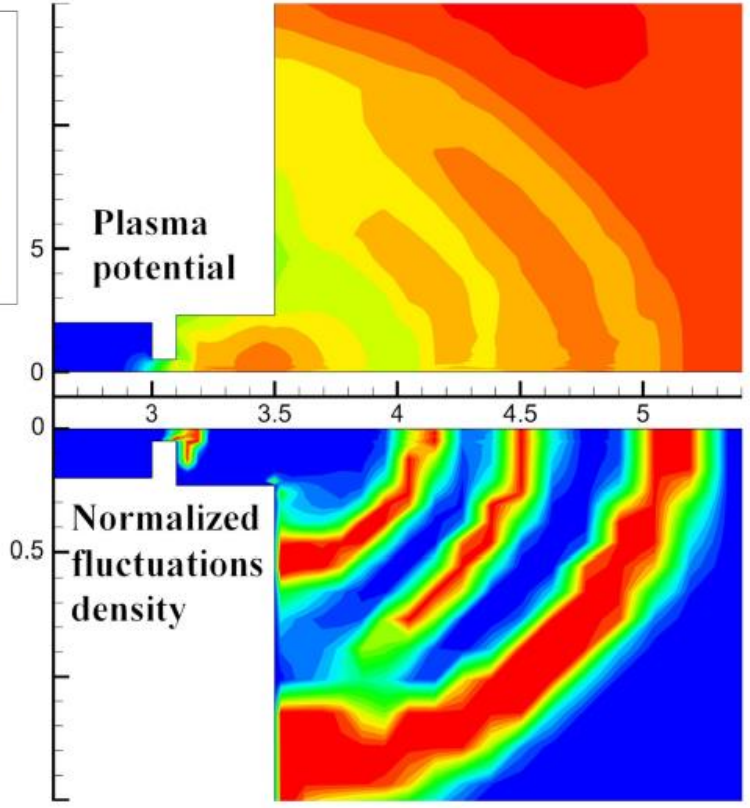
G. Sary et al., PSST 26, 055007 (2017)



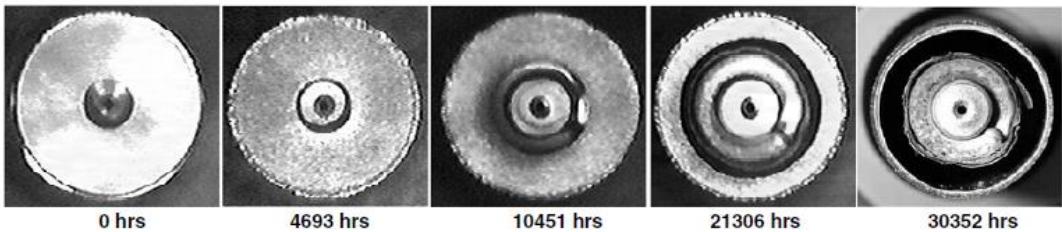
Cathode plume



- Oscillations starts close to the orifice
- No instability inside (as expected)
- Electron heating (non-visible here)
- Ion backflow



Explanation of the erosion observed in experiments?



I. G. Mikellides *et. al.* JPP 24, 866 (2008)



■ Alternative propellant to xenon

- International event – Russia/Ukraine war: Xe rare and expensive
- Iodine seems a good candidate – solid storage (positive return from GIE)
- New cathode concept?

■ Self-induced magnetic field

- Negligible for few kW HTs
- Still for very high power HTs?

L. Garrigues *et al.*, JAP 111, 113301 (2012)

■ Fluid/hybrid are very versatile, low computation time

- Models are more descriptive
- How to improve the predictive capabilities?
- Combine model capability with data-driven for anomalous transport through AI approaches?

B. Jorns, PSST 27, 104007 (2018)