Hybrid Modelling of Single and Double Stage Hall Thrusters

Laurent Garrigues, Directeur de Recherche CNRS

Laboratoire Plasma et Conversion d'Energie – LAPLACE
Université de Toulouse, CNRS-UPS-INPT
Bâtiment 3R2, 118 Route de Narbonne
31062 Toulouse Cedex 9, France

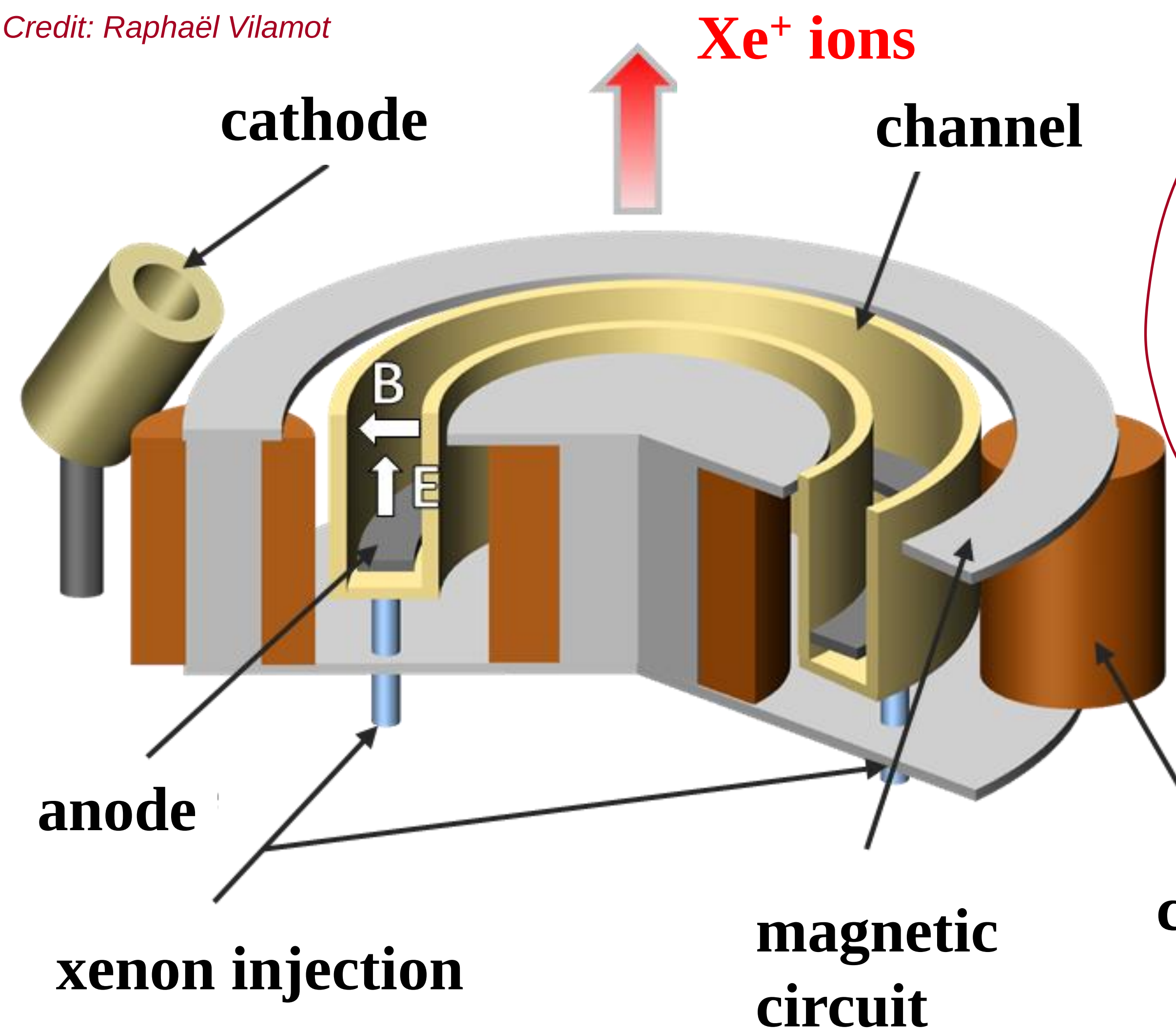
laurent.garrigues@laplace.univ-tlse.fr

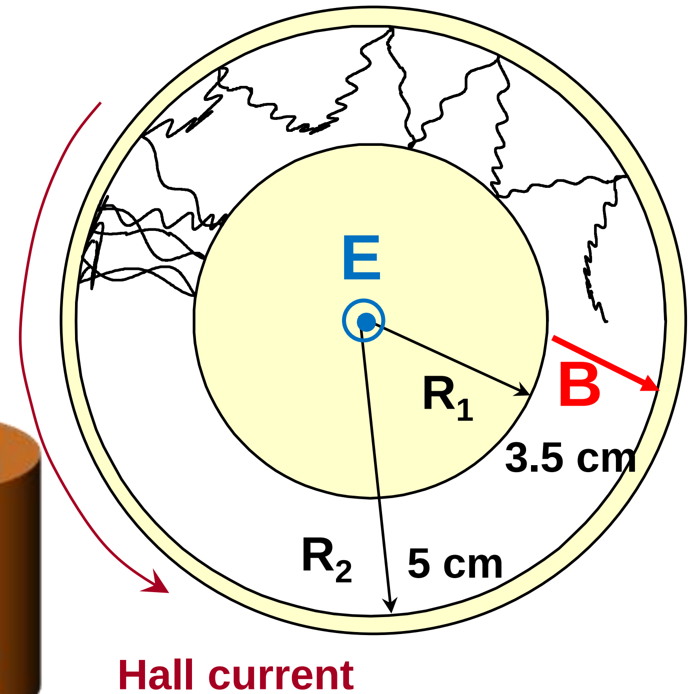
Outline

- How a Hall thruster works?
- Hybrid Model
- Single Stage Hall thruster
- Double Stage Hall thruster concepts
- Double Stage Hall thruster
- Conclusions and future work

A Single Stage Hall Thruster (HT)

Credit: Raphaël Vilamot





HT = closed electron drift thruster

Definitions

- Thrust: produced by the ejection of propellant at high velocity

$$T = \dot{m}v_e \quad [N]$$

propellant mass flow (kg/s) — $\dot{m}$

velocity of ejection (m/s) — v_e

- Specific impulse: related to the propellant velocity

$$I_{sp} = \frac{v_e}{g_0} \quad [s]$$

g_0: gravity on Earth (9.81 m/s^2)

- Efficiency: conversion of electric power in kinetic power of the jet

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

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

P_{elec}: electric power (W)

$$P_{elec} = I \times U$$

I — $\dot{m}$; U — v_e

Performances & HT missions

Performances	
Thruster	SPT-100
External diameter (mm)	100
Power (W)	1350
Isp (s)	1600
Thrust (mN)	80
Efficiency	0.5
Lifetime (hours)	9000

- Adapted to satellite station keeping and long trip missions (saving propellant mass thanks to high Isp)

- Near future: orbit transfer mission (replace chemical thruster)

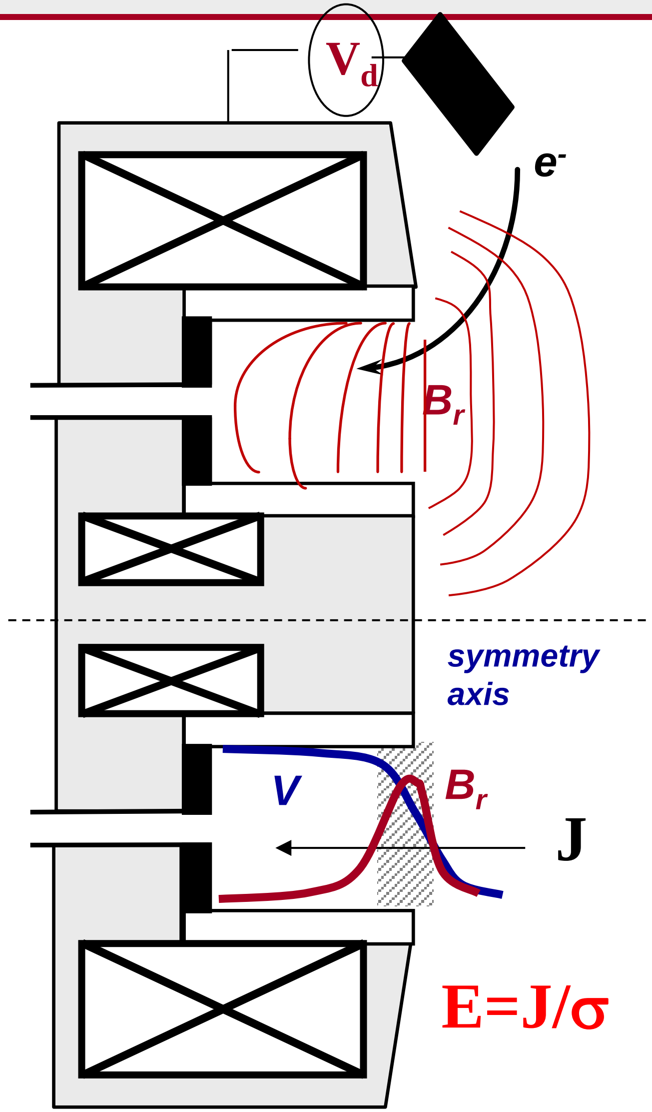
2D Hybrid modelling hypotheses

- **hypothesis 1: quasineutral plasma**
  - **Sheath size *s* << *L***
- **hypothesis 2: fluid description of electrons**
  - **Maxwellian EEDF**
  - **Electric field obtained from Ohm's Law**
- **transport of ions: kinetic description**
  - **Calculation of plasma density**
  - **Time step constrain (CFL- $\Delta t \sim$ few 10^{-8} s)**
- **transport of atoms: kinetic description**

(90 % of neutral flux is ionized)

- **static magnetic field**

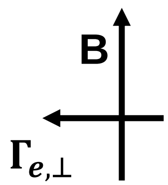
(induced magnetic field from Hall current negligible)

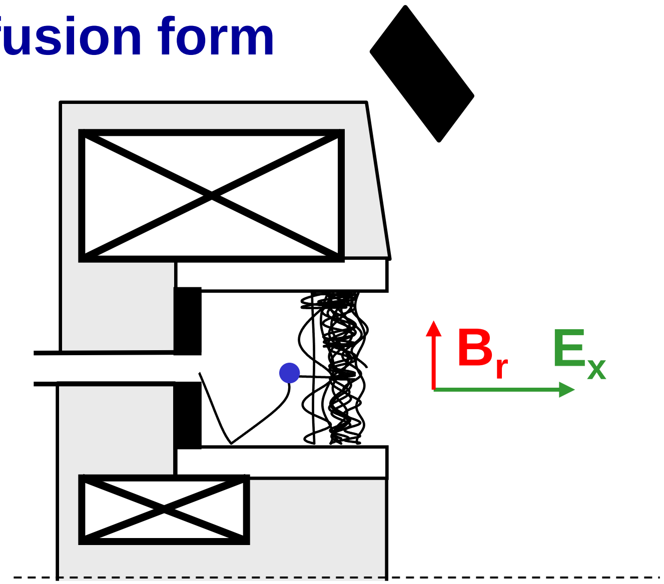


Anomalous transport

- **flux normal to the magnetic field – drift-diffusion form**

$$\Gamma_{e,\perp} = -\mu_{e,\perp}\left(nE_\perp + \nabla_\perp (nT_e)\right)$$





- **mobility**

$$\mu_{e,\perp} = \frac{e}{m\nu}\frac{1}{1+(\omega/\nu)^2} \approx \frac{e}{m}\frac{\nu}{\omega^2}$$

- **ν frequency of momentum exchange**

$$\nu = \nu_{coll} + \nu_{ano}$$

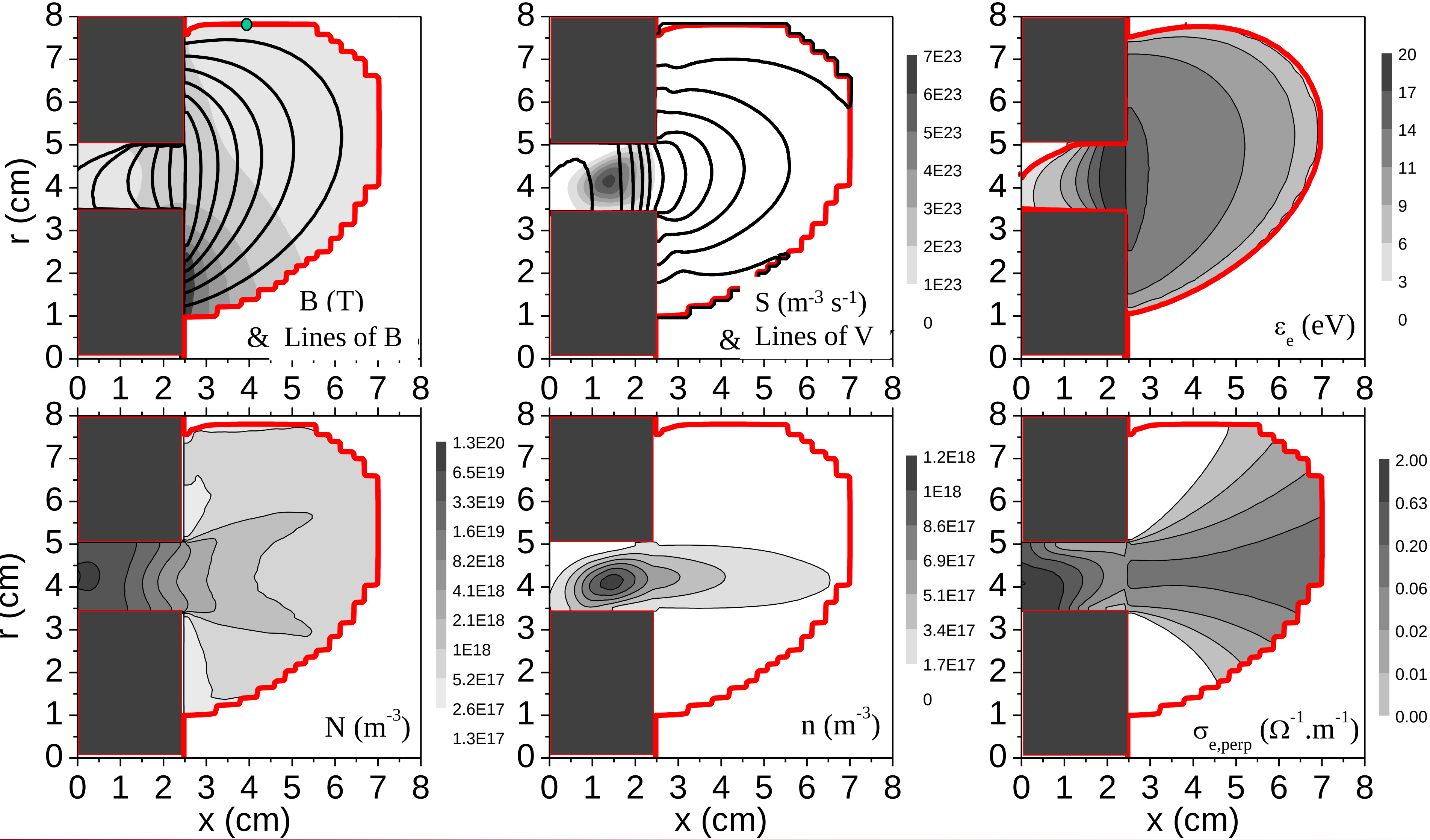
$$\mu_{e-w} \propto \alpha\,\nu_{e-w}/B^2$$

$$\mu_{turb} \propto k\,\nu_{turb}/B^2 \propto k/B$$

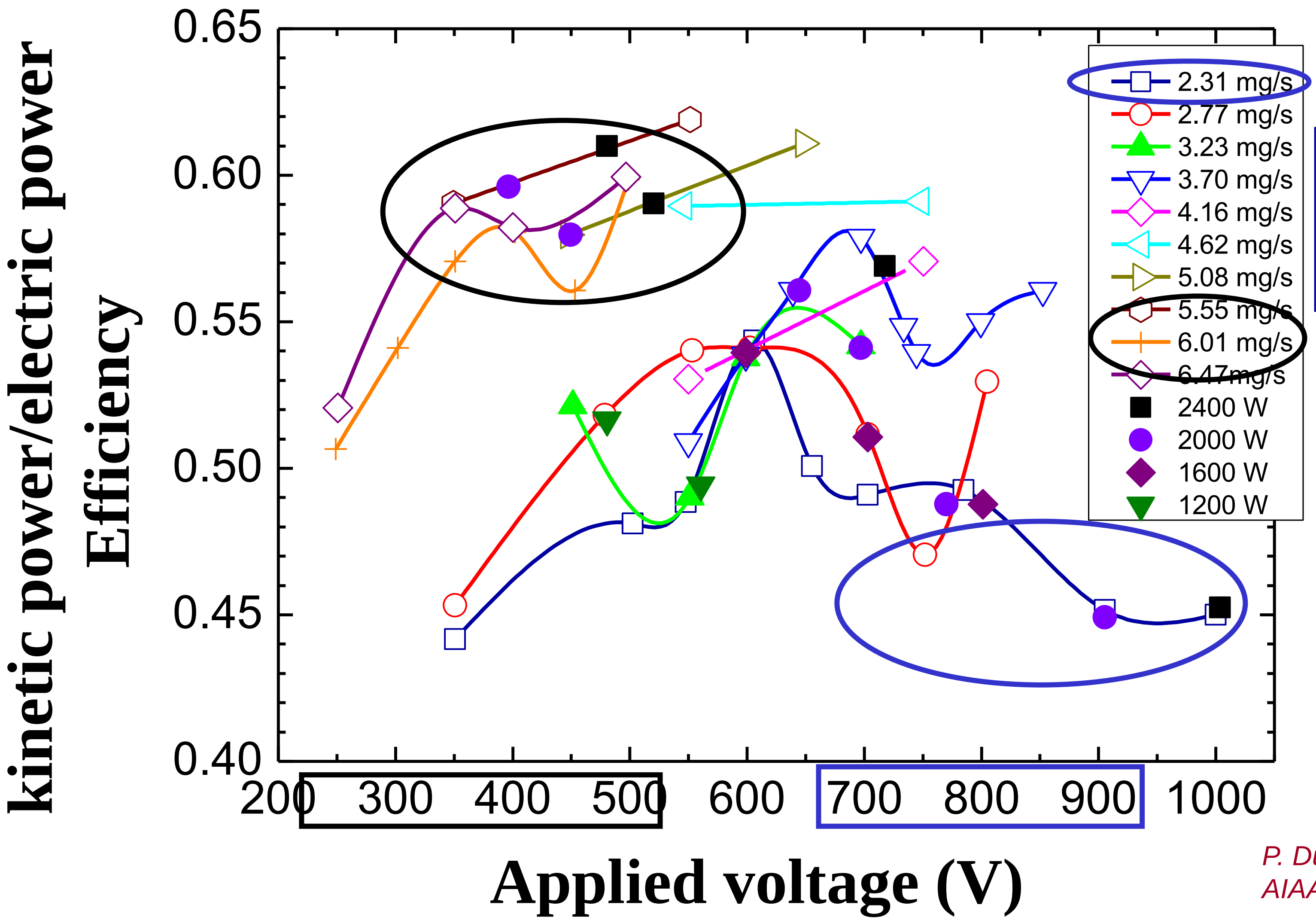
- **ν_{ano} frequency of effective collisions**
  - Wall and turbulence effects
  - Empirical way to account for them (adjustable coefficients)
  - Mobility profile deduced from LIF experiments

HT operation @ 300V, 5 mg/s

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



Single Stage HT in different regimes



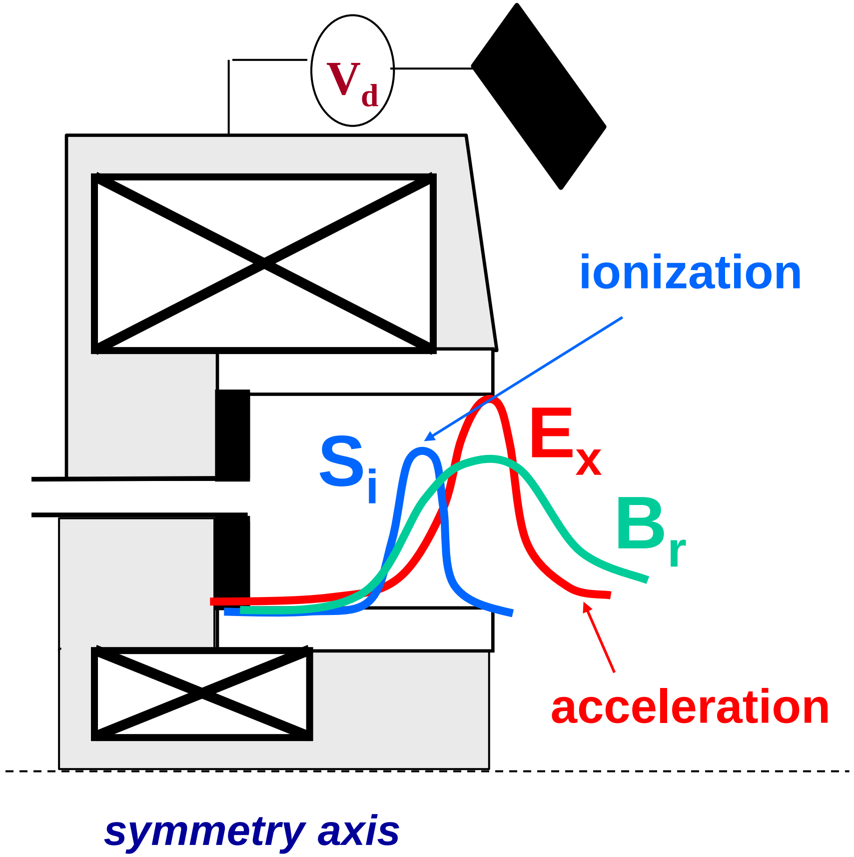
PPS®1350
PIVOINE
Orléans

P. Dumazert et al.
AIAA (2003)

Limit of (conventional) SSHT

Future missions need a versatile thruster

- High T, low Isp: orbit transfer (large $\dot{m}$ and low applied voltage)
- Low T, high Isp : station keeping (low $\dot{m}$ and large applied voltage)



magnetic field

↓

electric field

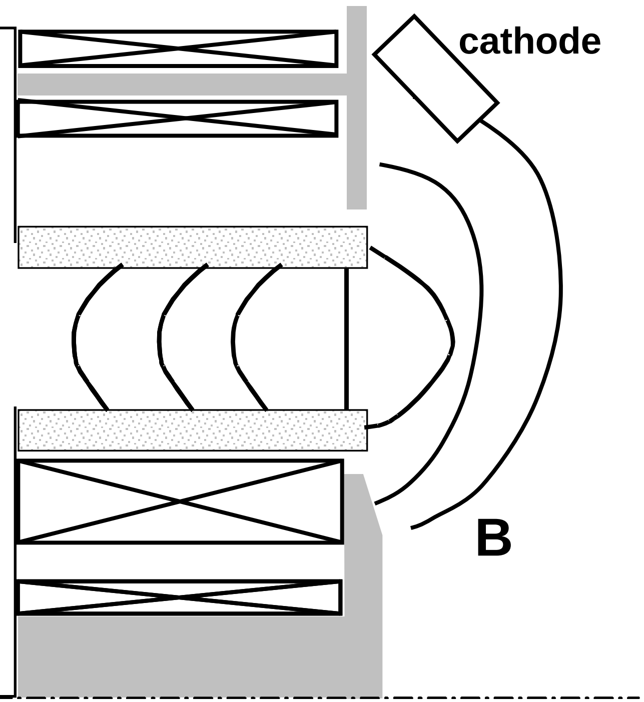
acceleration of ions | Heat electrons & ionization

difficult to adjust separately thrust and specific impulse

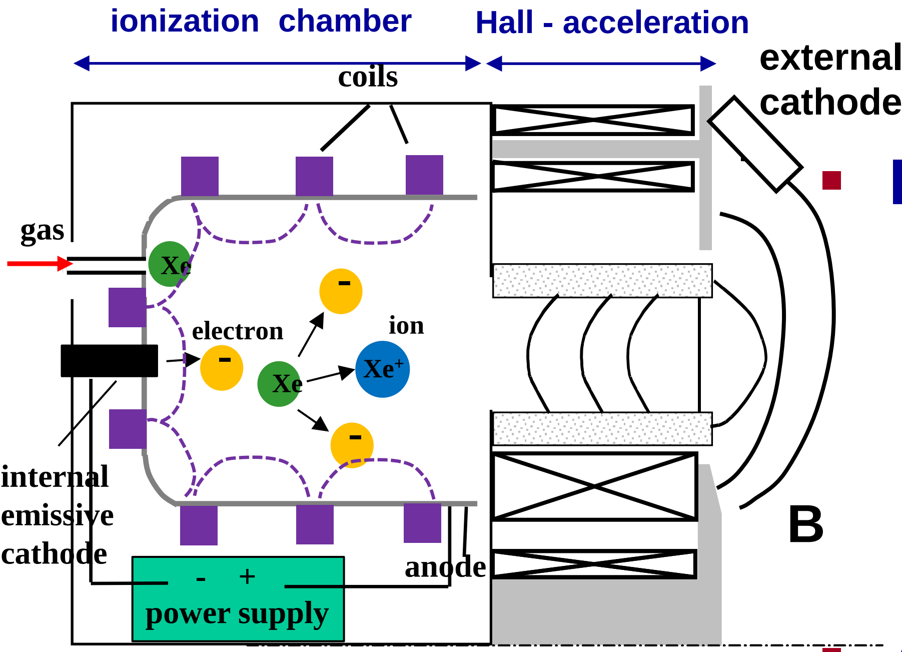
Double Stage Hall Thruster concepts (DSHT)

ionization stage | **Hall stage - acceleration**

- **Microwave source?**
  (Kuwano, IEPC-2007-085)
- **Helicon source?**
  (Palmer, JPP 30-664, 2014)
  (Peterson, IEPC-2011-269)
- **Kaufman source?**
- **magnetic confinement?**



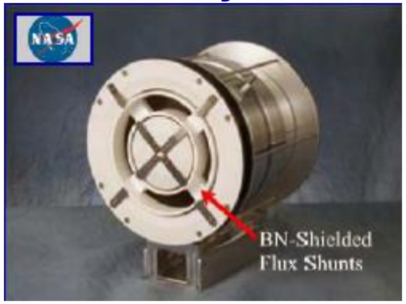
- **Acceleration stage : magnetic barrier as standard HT**
- **Ionization stage: generates a plasma**



- **Ionization chamber – Kaufman**
  - Same as GIE for NSTAR mission
  - Internal emissive cathode
  - DC power supply (low voltage)
  - Magnetic confinement – multicusp shape
- **Acceleration stage – Hall stage**
  - Emissive external cathode
  - Magnetic field barrier as in standard SSHT

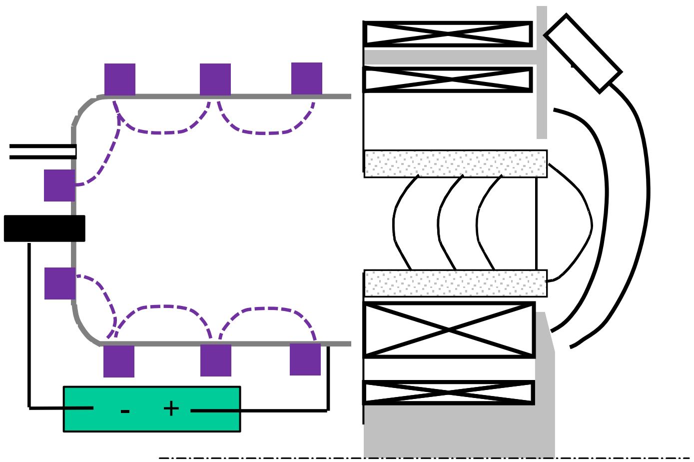
LGIT = Kaufman + HT

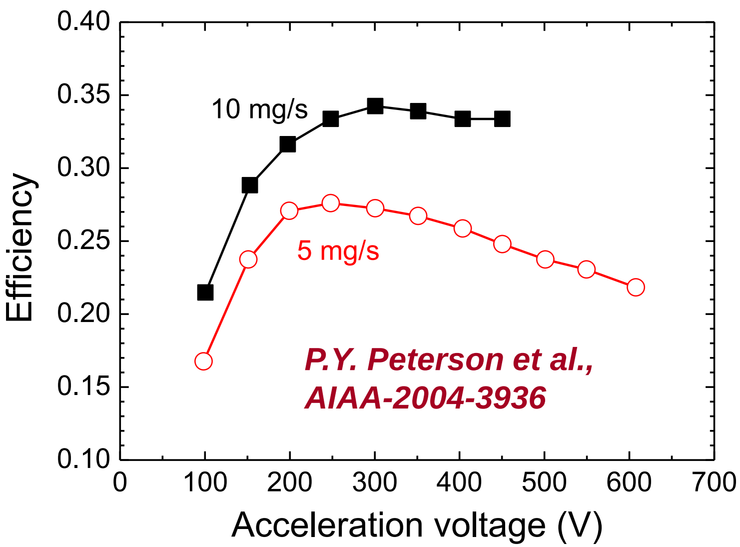
Laboratory Gridless Ion Thruster



P.Y. Peterson et al., AIAA-2004-3936

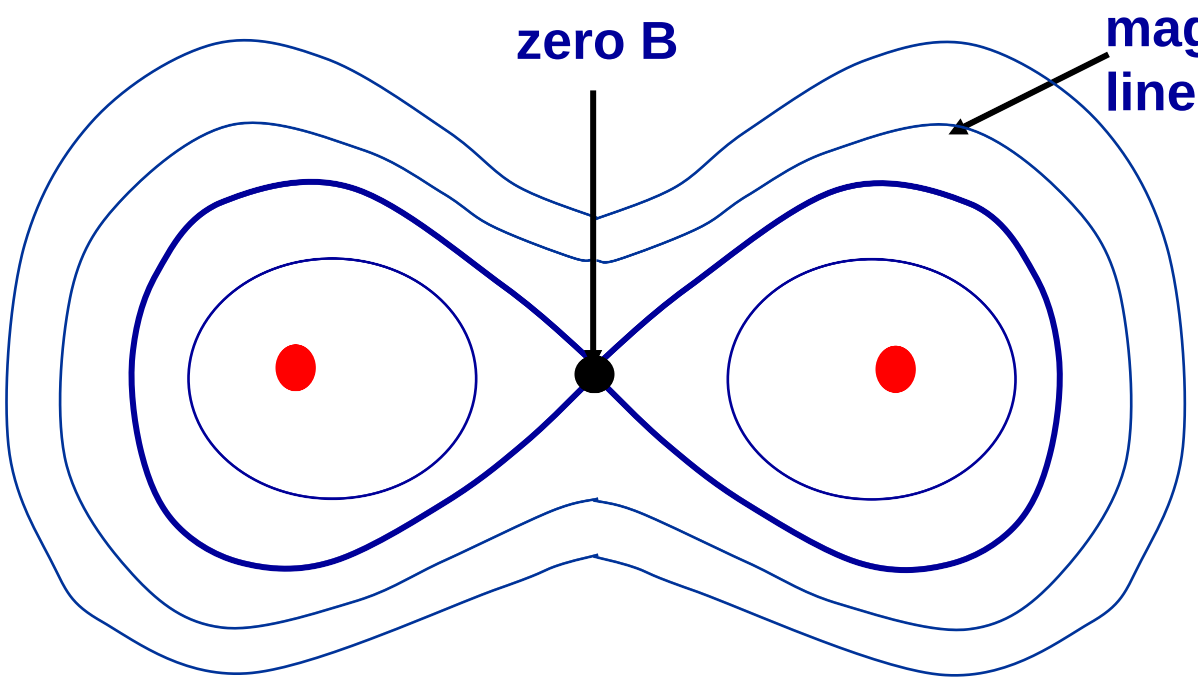
Operation of the LGIT





- **Two modes tested**
  - single stage
    - external cathode: e- for discharge and neutralization
    - disconnect DC power supply and coils
    - floating internal cathode
  - double stage
    - external cathode: e- for neutralization
    - connect DC power supply (few ten's of V) and coils
    - Internal cathode: e- for discharge
- **Performances in DS mode**
  - low efficiency: ion trajectories un-controlled
  - interface between ionization and acceleration
- **Helicon Hall Thruster**
  - promising results @ high mass flow ($\eta \sim 0.5$)
  - different gases tested

Galatea – magnetic confinement

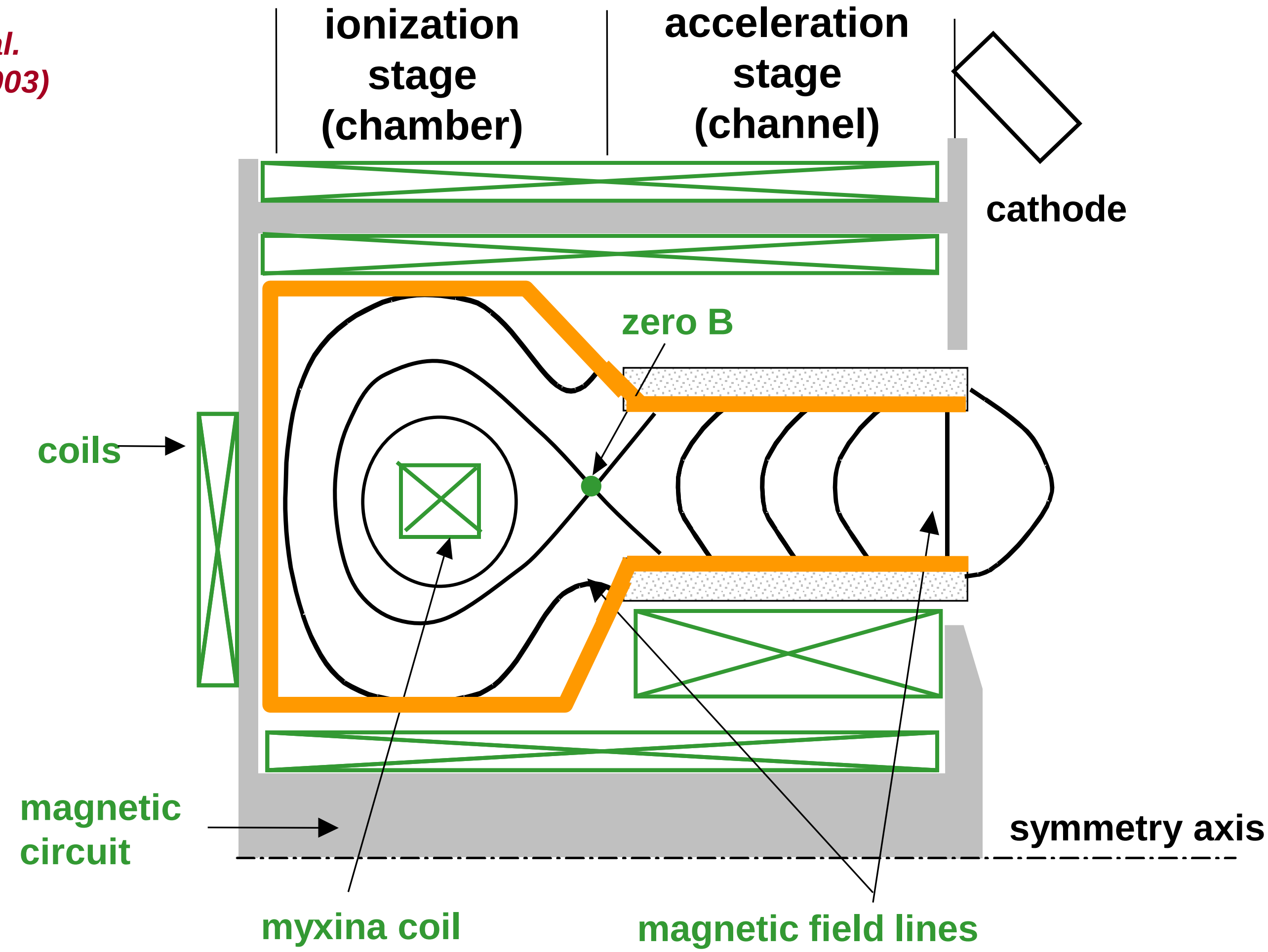


A.I. Morozov et al., Physics Uspekhi (2003)

- **Magnetic confinement system proposed in 60-70' (Sov. Union) for fusion machine**
- **Trap electrons to reach very high plasma densities**
- **Tokamak systems prefered**

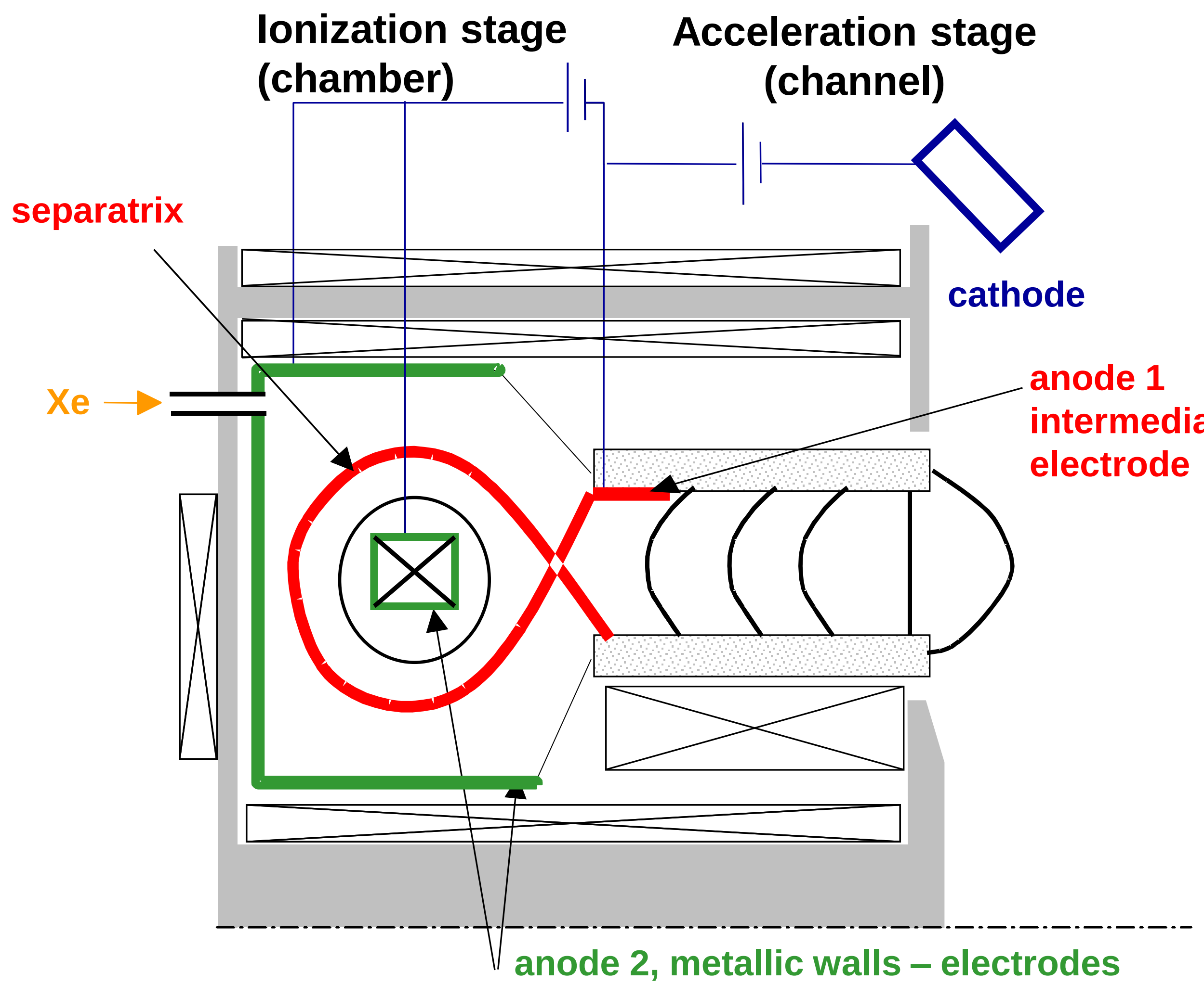
SPT-MAG – magnetic configuration

O. Secheresse et al.
Snecma Patent (2003)

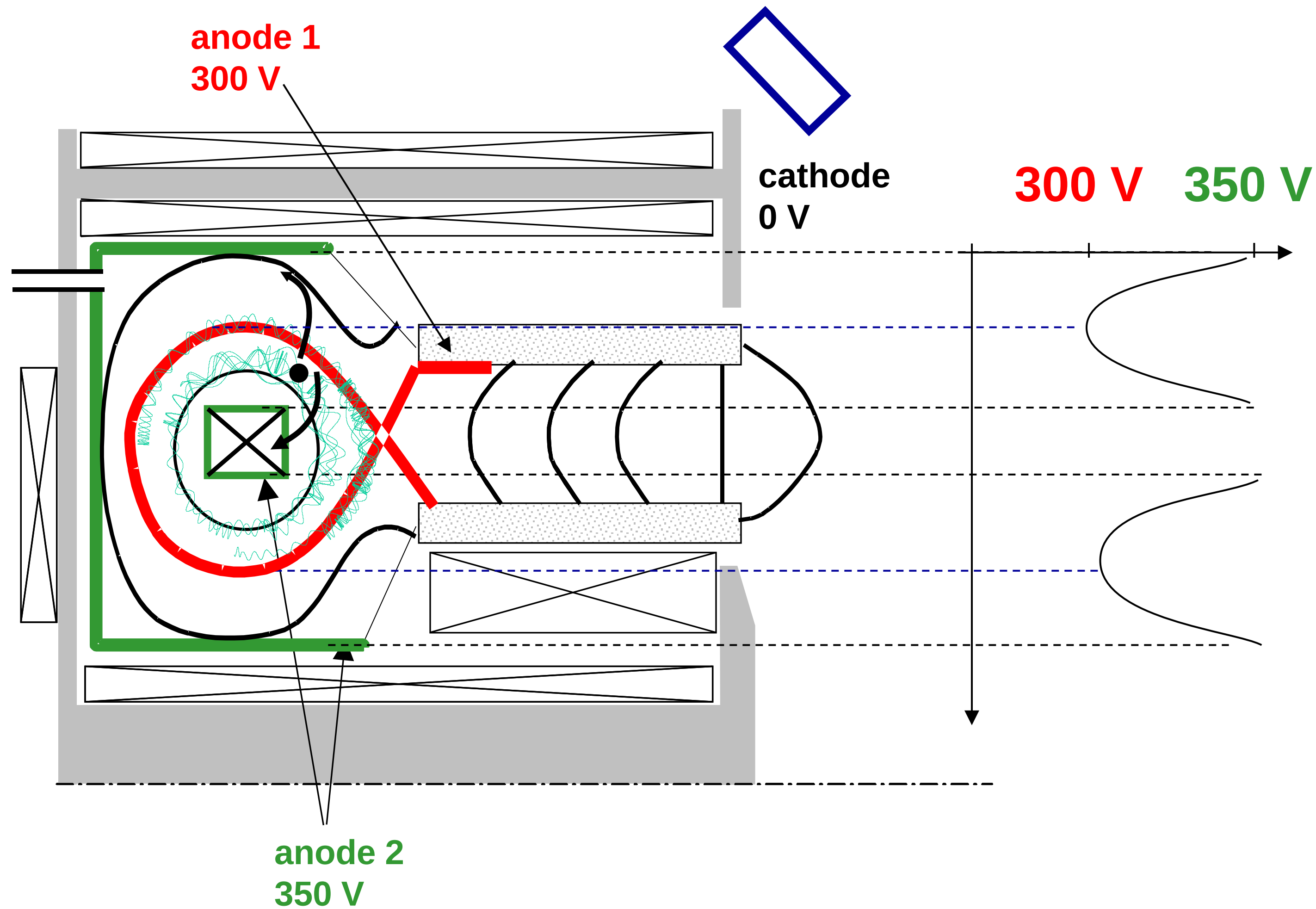


SPT-MAG = half-GALATEA + HT

SPT-MAG - electrodes



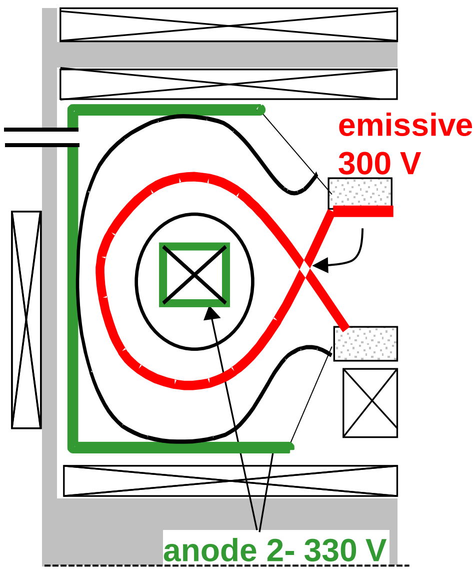
Electron trajectories

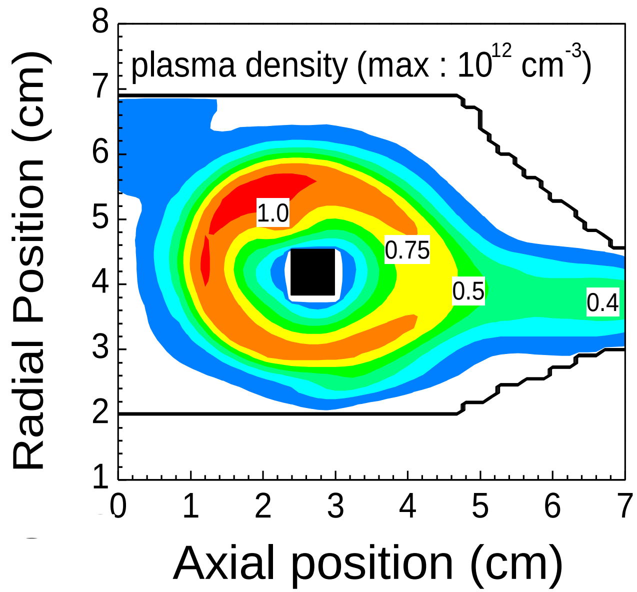


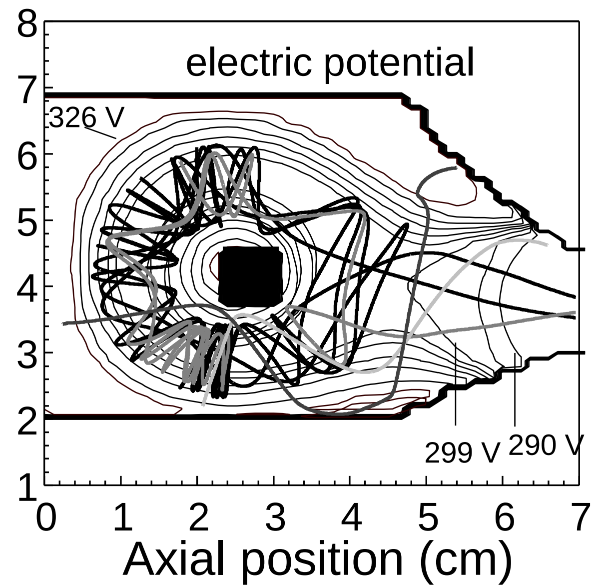
magnetic field lines ~ same electric potential

SPT-MAG Modelling – emissive cathode

L. Garrigues et al. PoP ***15****, 113502 (2008)*



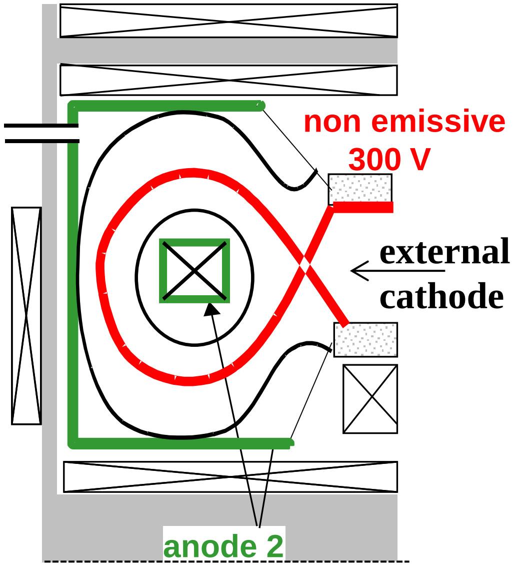


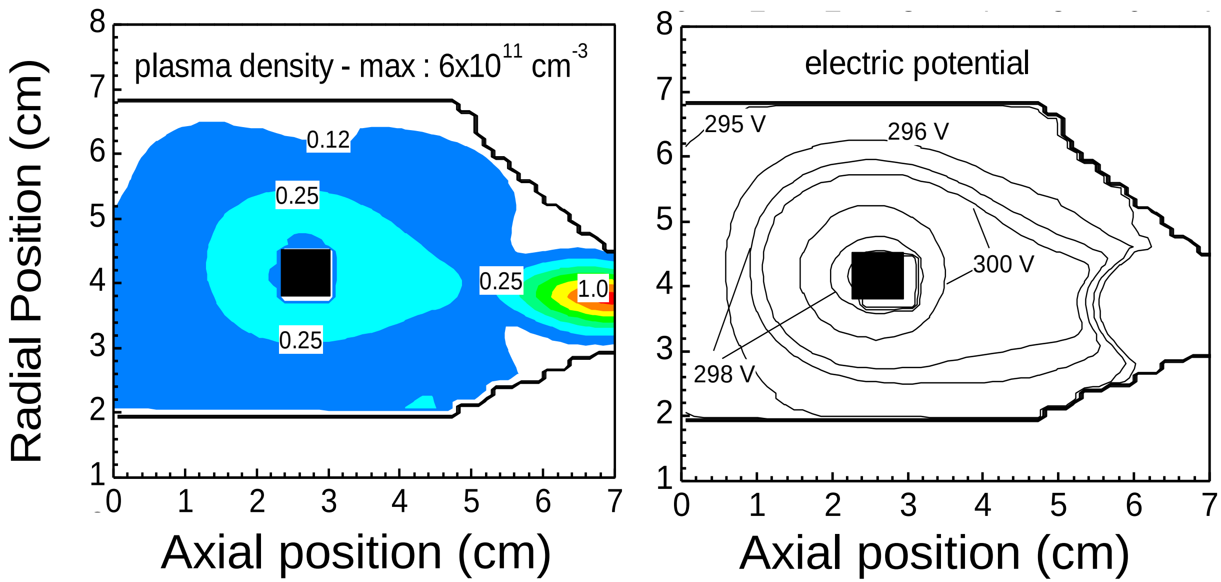


- **Simulations predict the formation of a potential well (magnetic field lines are almost equipotentials)**
- **Plasma density ~ 10^{12} cm^3**
- **Ions are guided towards the acceleration stage**
- **300 W needed to form the plasma**

SPT-MAG Modelling – non emissive cathode

*L. Garrigues et al. PoP **15**, 113502 (2008)*





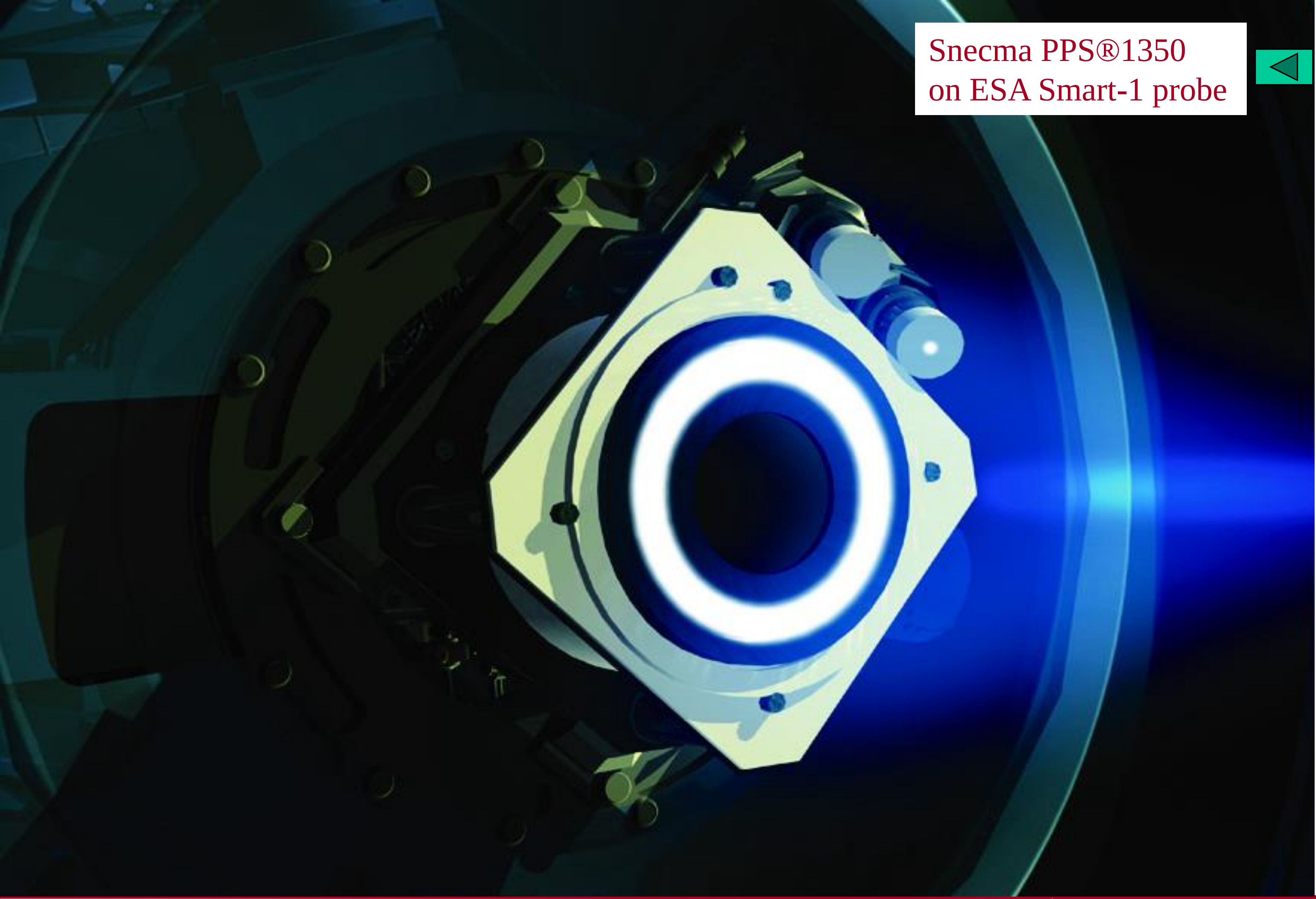
- **No electric potential well is formed**
- **Large ion losses on walls**
- **Ionization takes place at the entrance of acceleration stage**
- **Interest for a ionization stage?**
- **Separate the two stage operations if the ignition is influenced by the external cathode?**

Conclusions and future work

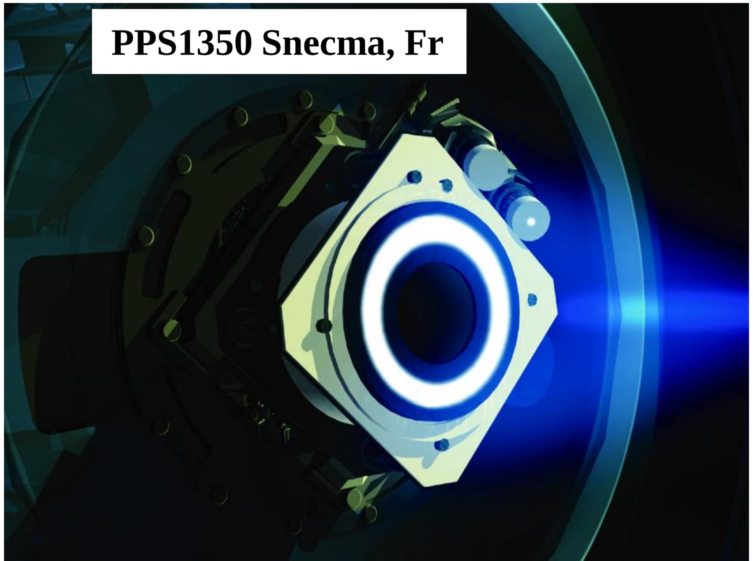
- **Hybrid model**
  - Able to describe the thruster working (linked with experiments)
  - Need improvements in electron anomalous transport (electron drift instability, see Vivien Croes Talk)

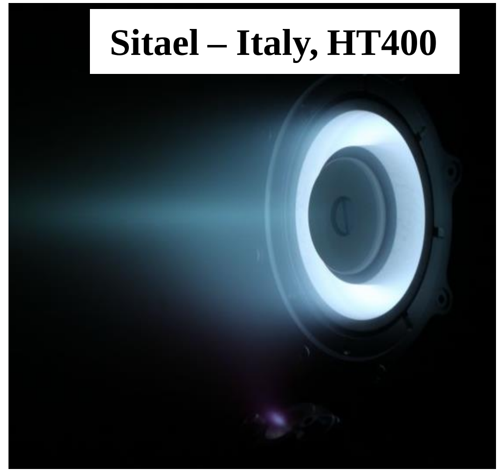
- **Double stage Hall thruster**
  - Demonstration of efficiency not achieved
  - Role of ionization stage? Electric power cost?
  - Key issue of DSHT: guide the ions towards the acceleration stage
  - Joint project between Laplace & Icare laboratories, France, with Cnes funding is starting

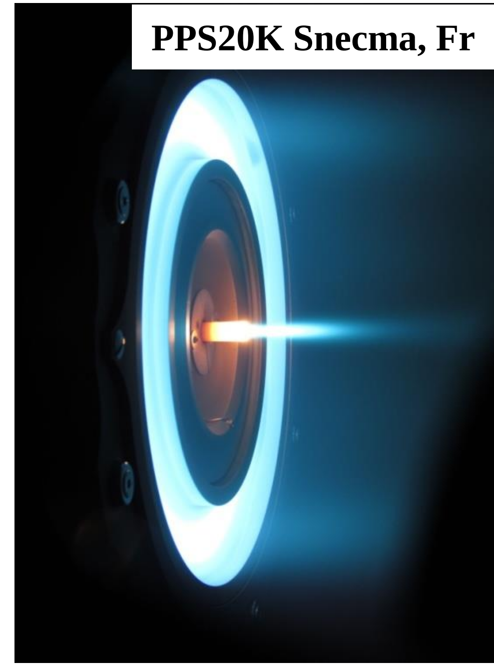
Snecma PPS®1350 on ESA Smart-1 probe

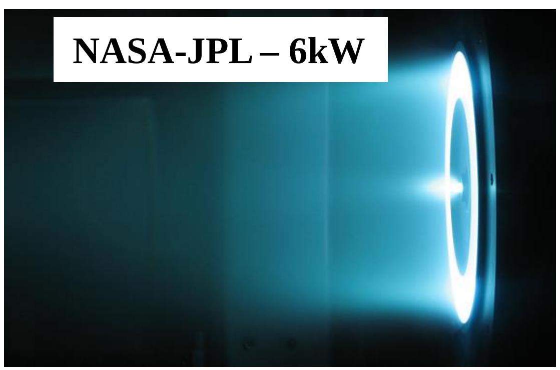


Hall Thruster in the world

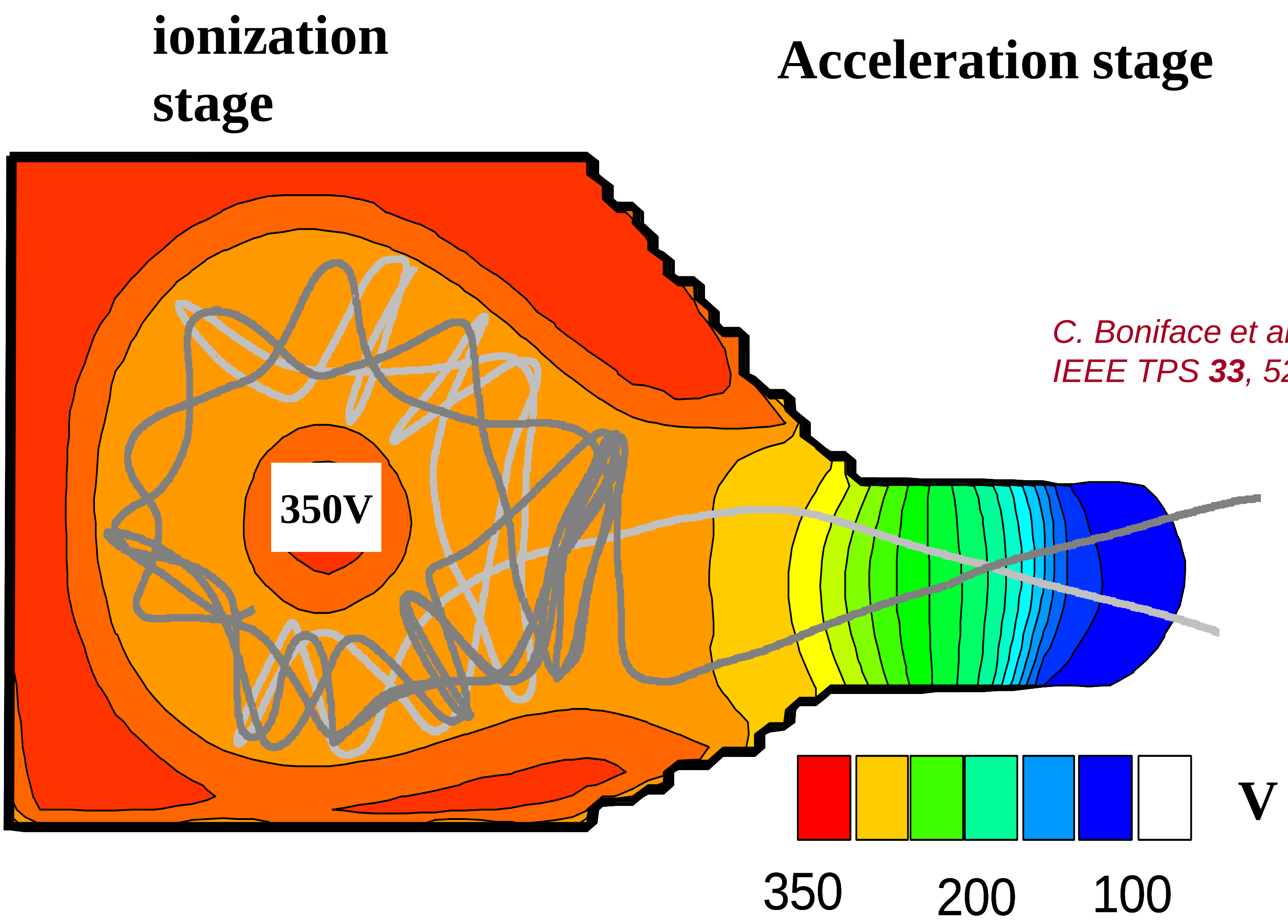






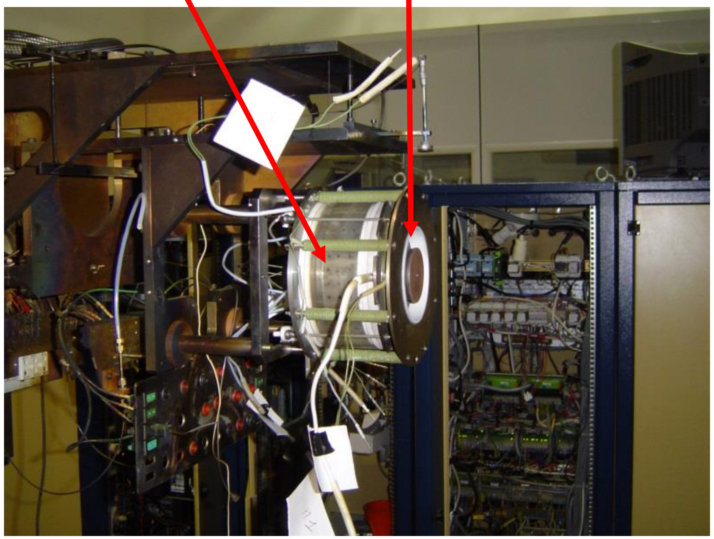


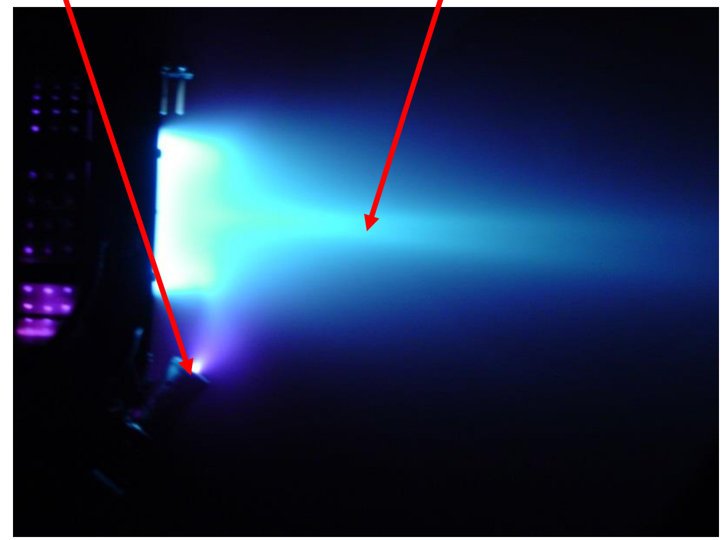
Ion trajectories



C. Boniface et al.
*IEEE TPS **33**, 522 (2005)*

SPT-MAG tested in the PIVOINE facility





- **Conditions**
  - Xenon mass flow: 4 mg/s
  - Voltage in the acceleration stage: 300 V
  - Voltage in the ionization stage: 50 V