Hall thruster technology: From classical to wall-less architecture

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Hall thruster features

Characteristics

- compact, simple and reliable device
- high efficiency ~ 70 % (decrease at low power: S to V ratio)
- scaling law: j_i =≈ 0.1 A/cm^2
- moderate specific impulse ~ 1500 - 2000 s
- large thrust-to-power ratio ~ 60 mN/kW

→ well-suited to missions such as station-keeping, orbit topping, orbit transfer

Main weak point of HTs: relatively limited lifetime (total impulse)

~ 10000 hours at 1.5 kW

Origin of lifetime limitation:

wear of the channel wall final section (acceleration layer) due to high energy ion bombardment

Lifetime lengthening

How to extend Hall thruster lifetime?

i) Wall material

- low sputtering yield under Xe^+ bombardment
  but other important properties: SEE yield, thermal conductivity, electrical resistivity…

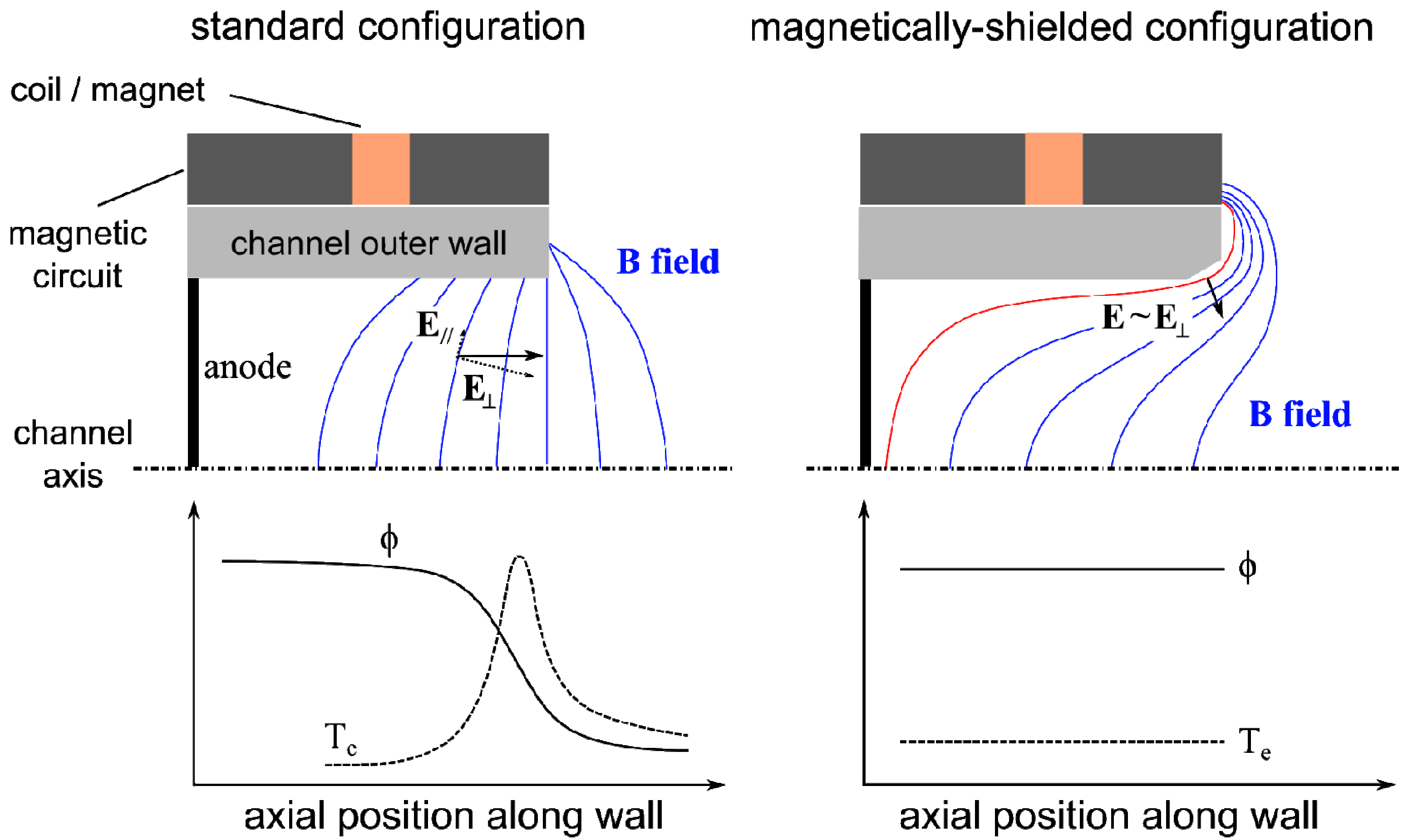
ii) **Magnetic shielding configuration**

- objective: to protect the wall against particle flux
  method: reduce the **E** field component towards the walls

iii) **Wall-less configuration**

- objective: to shift the discharge outside the channel
  method: anode placement with the appropriate **B** field topology

Magnetic shielding strategy



Magnetic shielding of the channel walls in a Hall plasma accelerator, I.G. Mikellides, I. Katz, R.R. Hofer, D.M. Goebel, K. de Grys, A. Mathers, Phys. Plasmas 18, 033501 (2011)
Magnetic Shielding of walls from the unmagnetized ion beam in a Hall thruster, I.G. Mikellides, I. Katz, R.R. Hofer, D.M. Goebel, Appl. Phys. Lett. **102**, 023509 (2013).
Magnetic shielding of a laboratory Hall thruster. II. Experiments, R.R. Hofer, D.M. Goebel, I.G. Mikellides, I. Katz, J. Appl. Phys. **115**, 043304 (2014).
Magnetic shielding of Hall thrusters at high discharge voltages, I.G. Mikellides, R.R. Hofer, I. Katz, D.M. Goebel, J. Appl. Phys. **116**, 053302 (2014).

MS validation (JPL)

Validation of the MS configuration at several power levels: 300 W, 6 kW, 12 kW, 20 kW

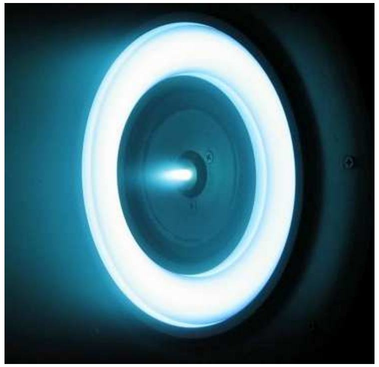
Performances are maintained

Erosion rate reduced by a factor 100-1000 (wall temperature drops ≈ 60°C)

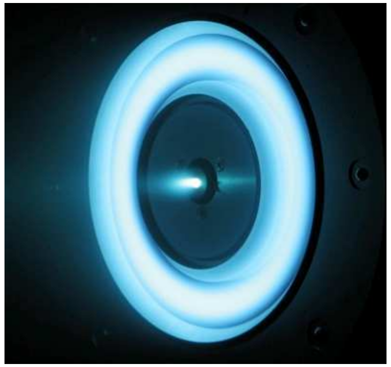
Carbon deposit (signature)

Carbon wall HT tested (H6c; the *black* edition)

Operation at high voltage (800 V, 9 kW)



H6 Hall thruster:
Unshielded



H6 Hall thruster:
Shielded

H6 in MS
Before testing

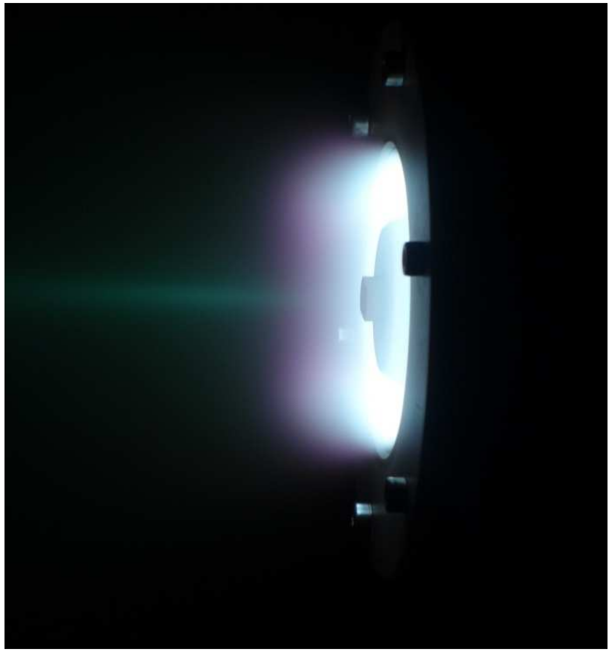
H6 in MS
After testing

MS: Shielded ISCT200 thruster

MS version of the ISCT200 thruster

200 W normal input power
Permanent magnets
$2S_0$ channel geometry
BN-SiO2 wall material
3D printed gas injector / anode

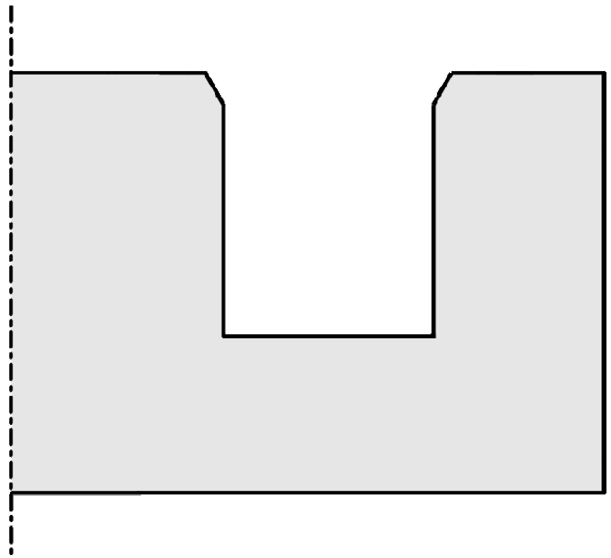
ISCT200-MS Hall thruster



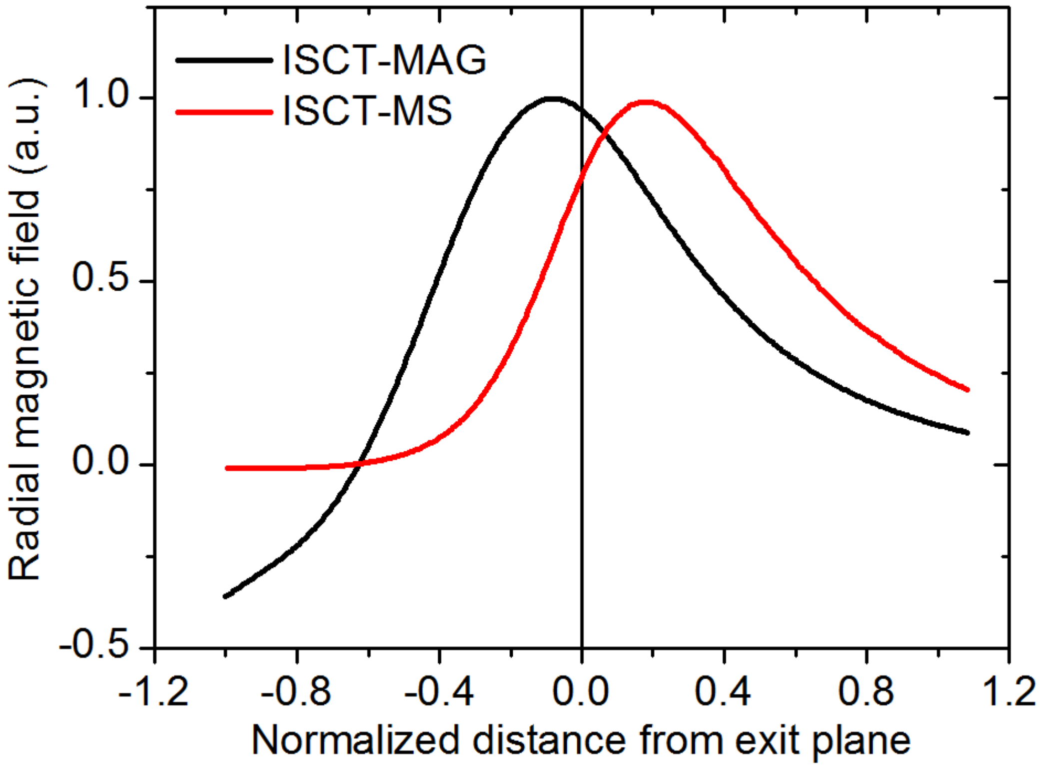
ISCT200-MS firing with Xe at 200 V applied voltage in the NExET vacuum chamber (background pressure = 2×10^{-5} mbar)

MS: ISCT200-MS design

Designed to have same **discharge channel geometry** and **magnetic field profile** along the center of the discharge channel as the ISCT200-Mag



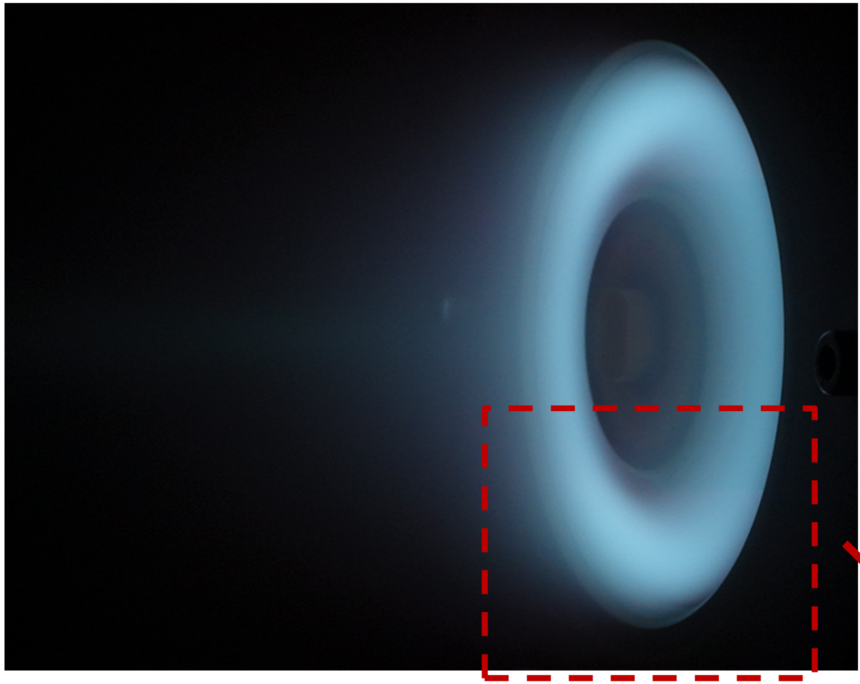
ISCT200-MS / Mag thruster discharge channel geometry



ISCT200-MS / Mag magnetic field distribution along the channel axis

MS: Visual evidence

Plasma-wall separation



ISCT200-MS firing in the NExET test chamber
(150 V, 1mg/s Xe)

Enlarged view of the plasma near the inner and outer channel walls

MS: Visual evidence

No erosion ring in the channel final section

After ~ 100 h of operation

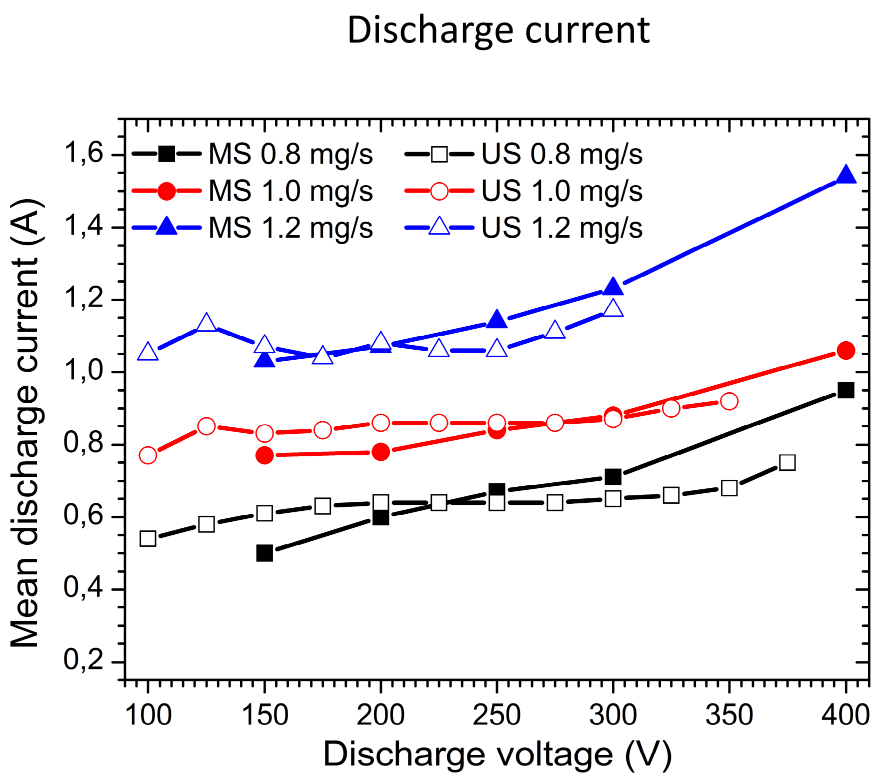
Formation of a thin layer of low resistance coating

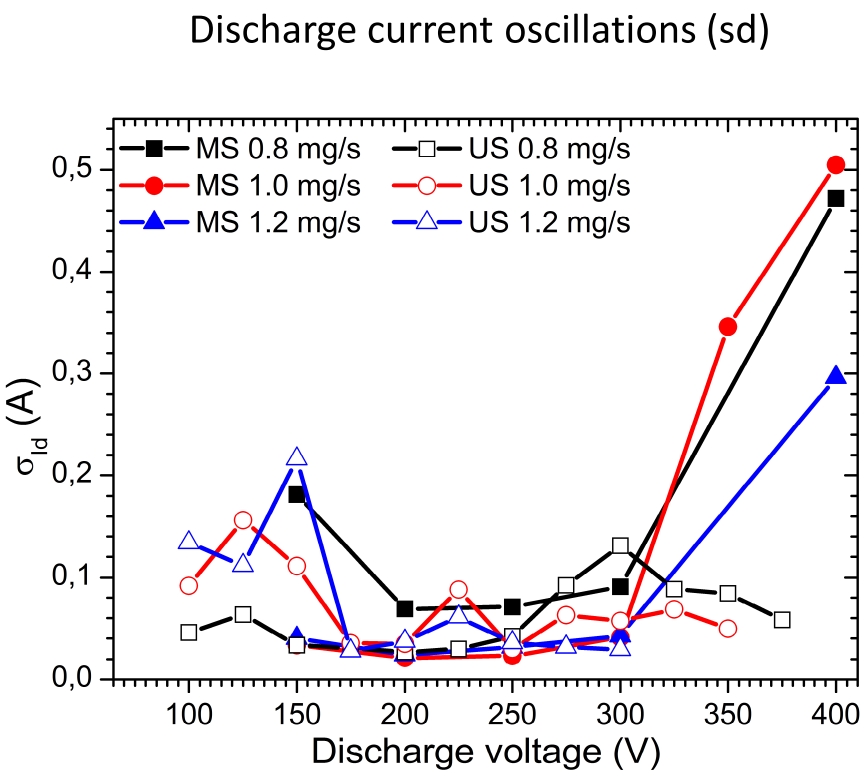
Internal wall

External wall

ISCT200-MS (left) and ISCT200-US (right) ceramic walls

Discharge current

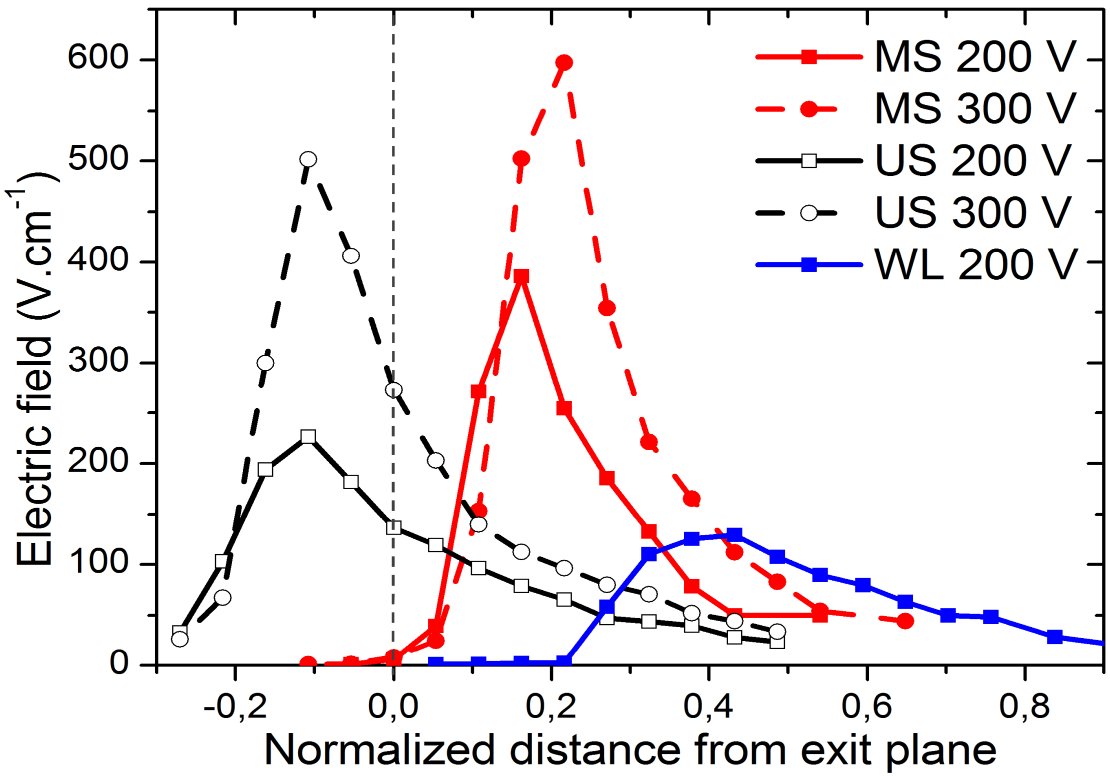




Similar discharge current and current dynamics for voltages between 200V and 300V and for Xenon flow rate above 0.8 mg/s

MS: Electric field profile

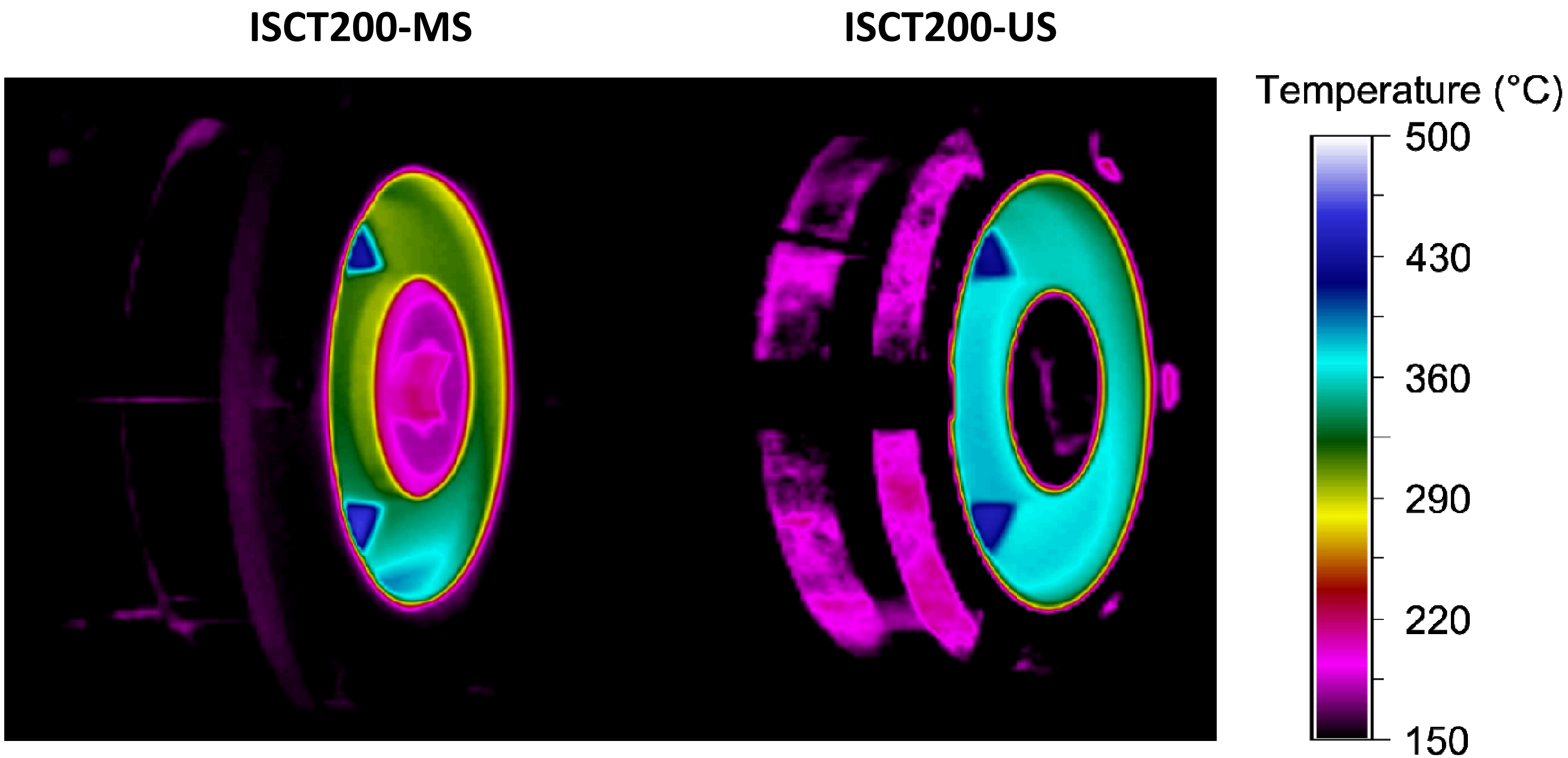
LIF spectroscopy on metastable Xe^+ ion at 834.7 nm
Electric field inferred from most probable velocity of the ion VDF [1]



MS: Wall temperature

Calibrated IR thermal imaging

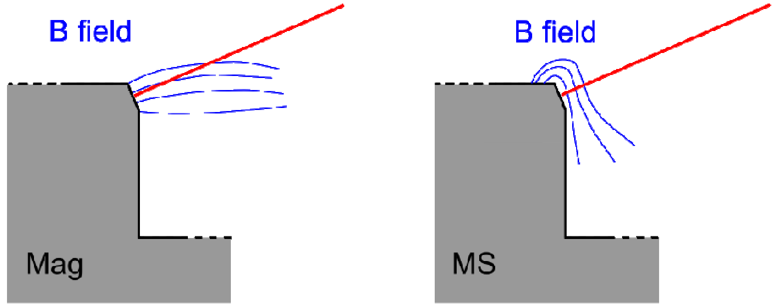
- Optris PI400 camera (7.5 - 13 μm range; 382x288 pixels)
- ZnSe optics
- spectral emissivity = 0.9 for $BN\text{-}SiO_2$

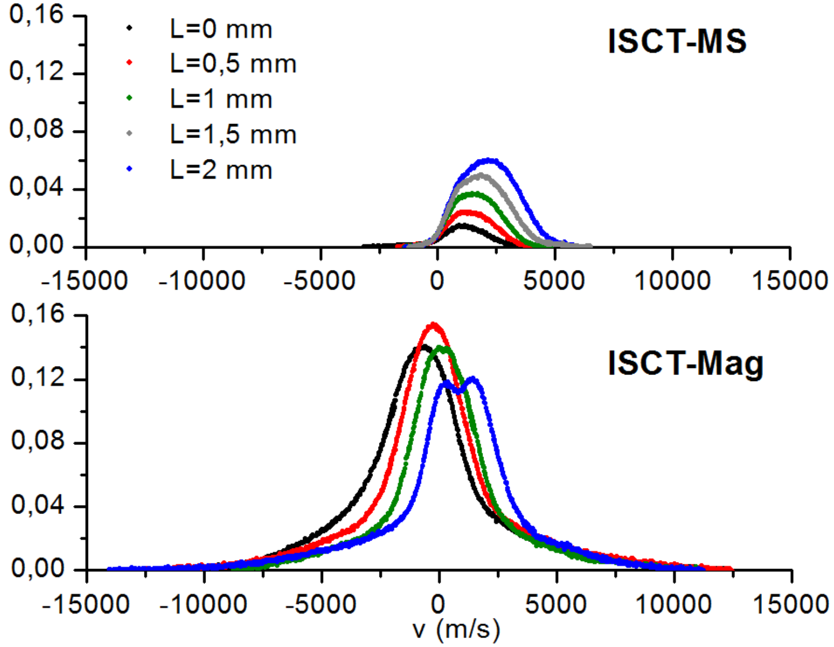


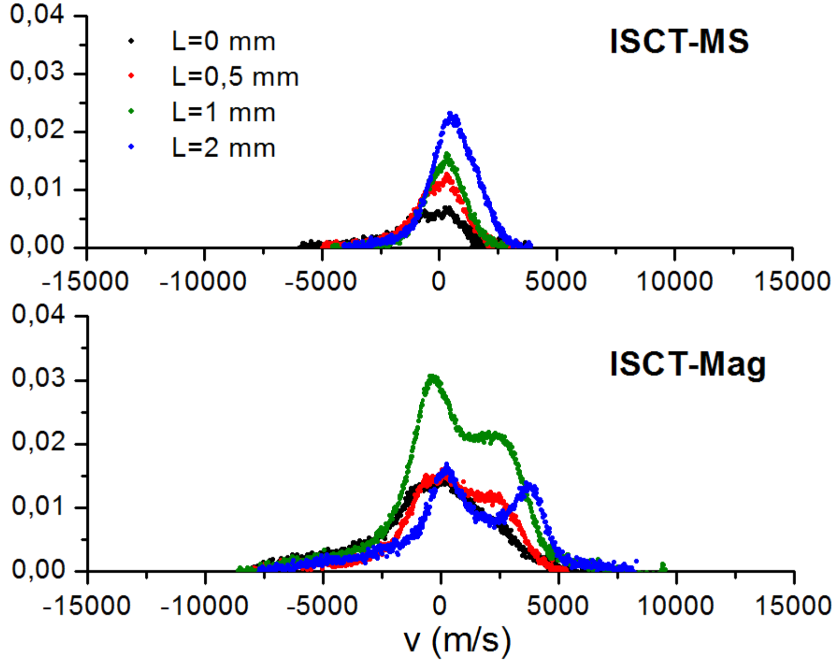
Firing with Xe at 200 V and 200 W

MS: Near wall ion velocity

Ion velocity **perpendicular** to walls in the channel final section (bevel-cut part)







Internal wall

External wall

MS: Near wall ion velocity

Ion velocity **paralell** to the outer wall in the channel final section (bevel-cut part)

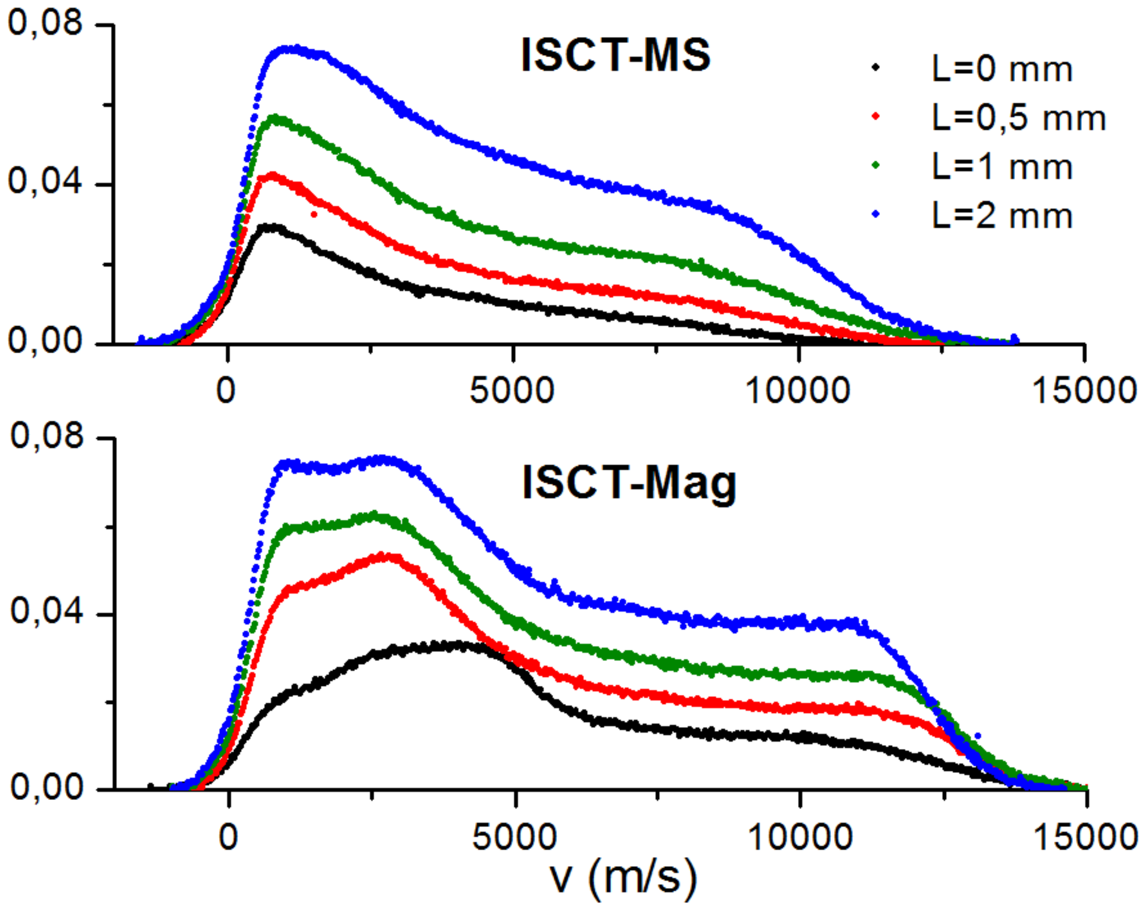
Ion temperature

$T_i \approx$ 15 eV in axial direction

If lineshape = VDF

But probably 2 ion populations or more

Need for LIF tomography



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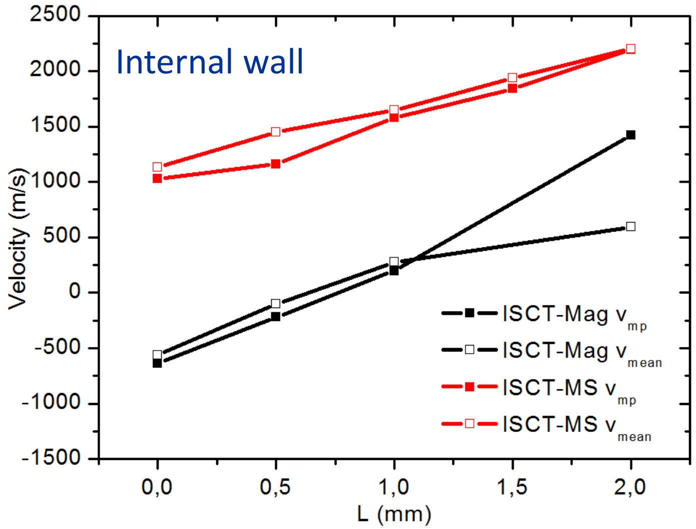
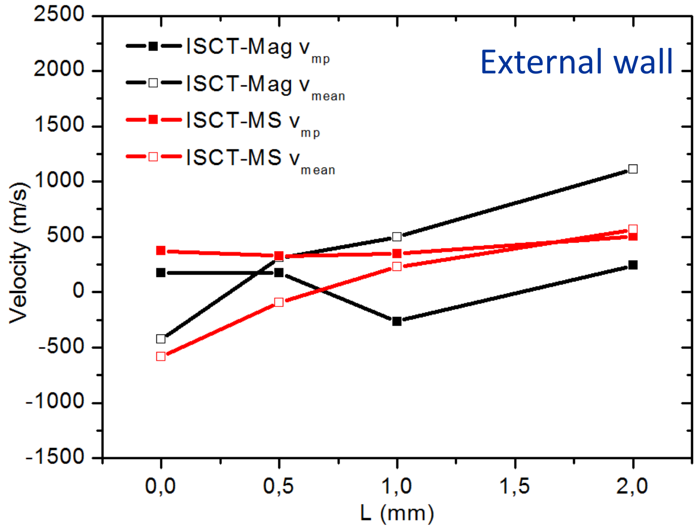
Ion velocity **perpendicular** to walls in the channel final section (bevel-cut part)



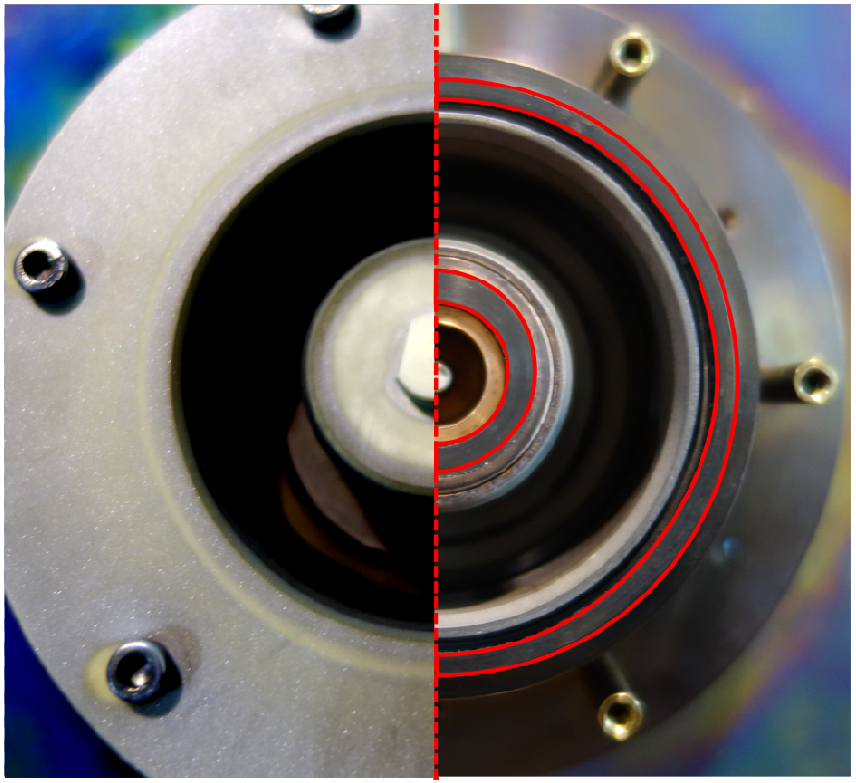


Ion fraction moving towards the wall (L = 0 mm)

Case	n_i (a.u.)	η_{v-}	$\eta_{<-30eV}$
ISCT200-US (inner wall)	723	0.63	0.022
ISCT200-MS (inner wall)	38	0.11	0
ISCT200-US (outer wall)	77	0.54	0.015
ISCT200-MS (outer wall)	19	0.62	0

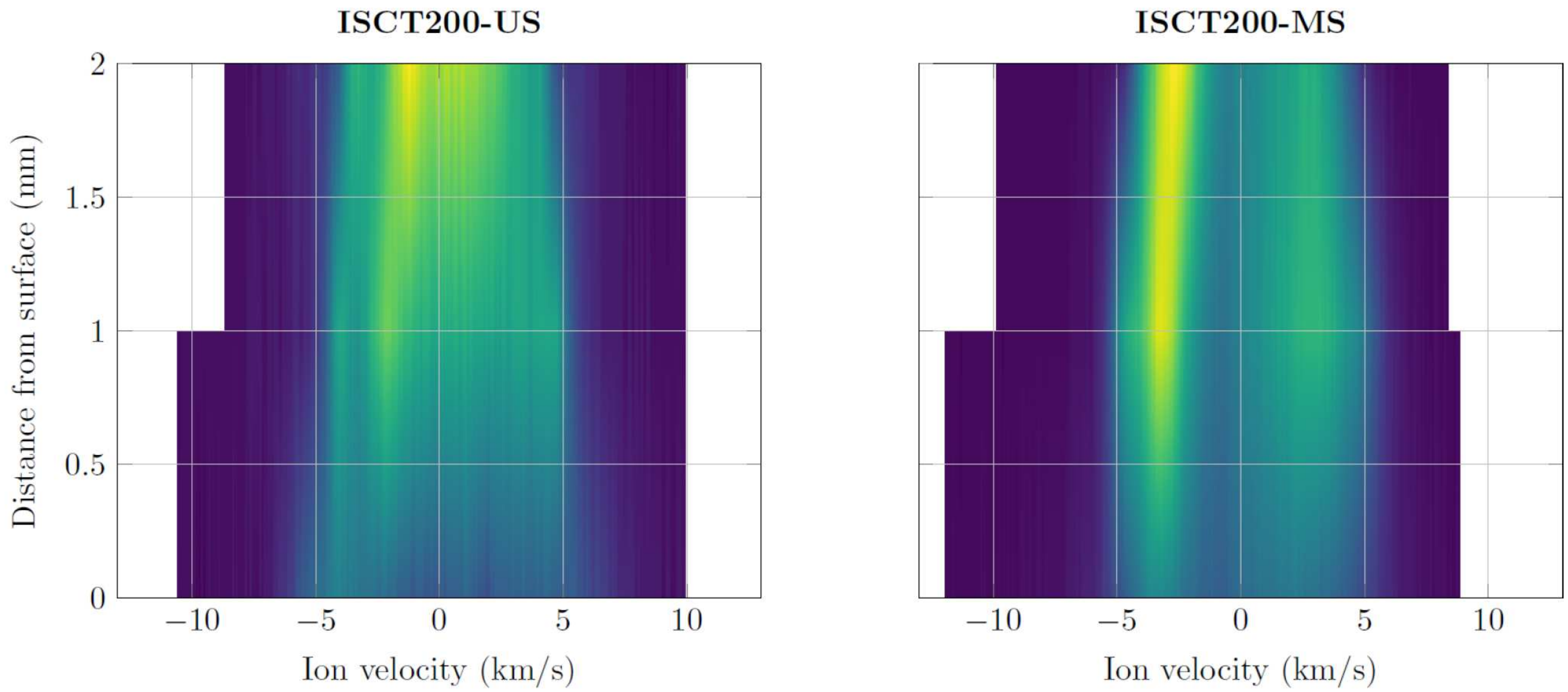
MS: Magnetic pole erosion

Visual evidence for strong erosion on top of the magnets
(i.e. where the B field is the strongest)



MS: Magnetic pole erosion

LIF on Xe^+ ions in front of the inner and outer magnetic poles

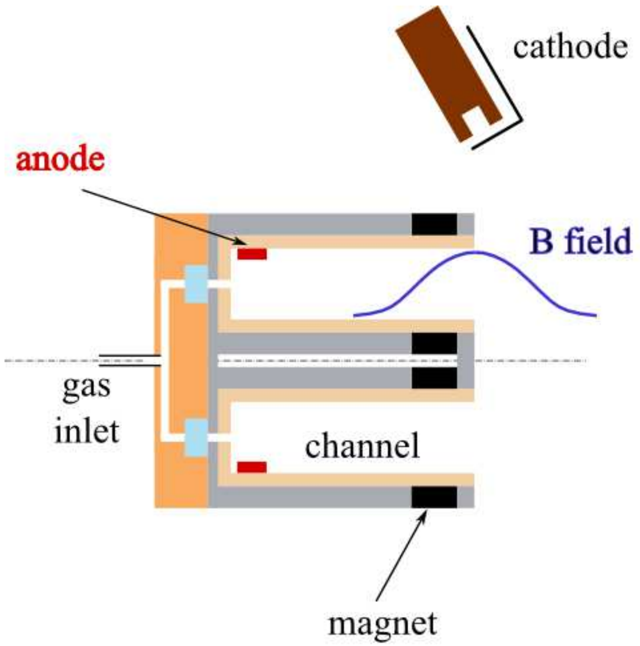


IVDF perpendicular to the inner magnetic pole surface

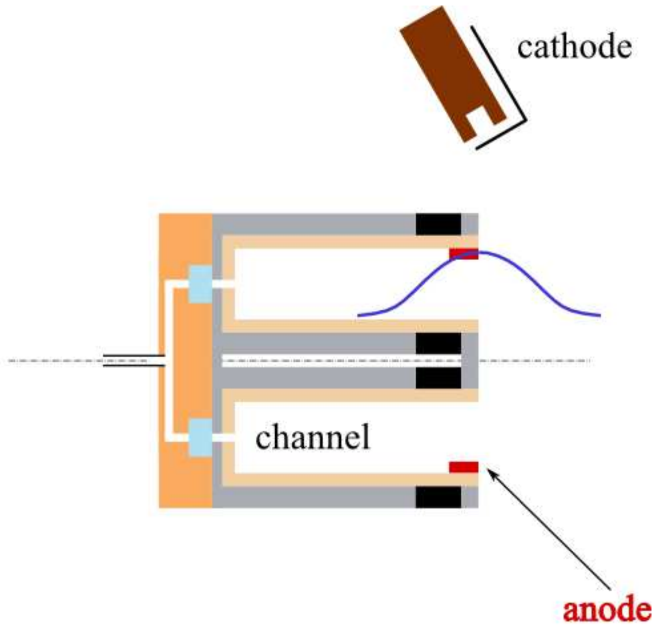
Wall-less Hall thruster concept

The WLHT is a Hall thruster with an external electric field

- **principle**: shift entire plasma discharge outside the channel
- **approach**: position the anode at the channel exit plane



standard configuration



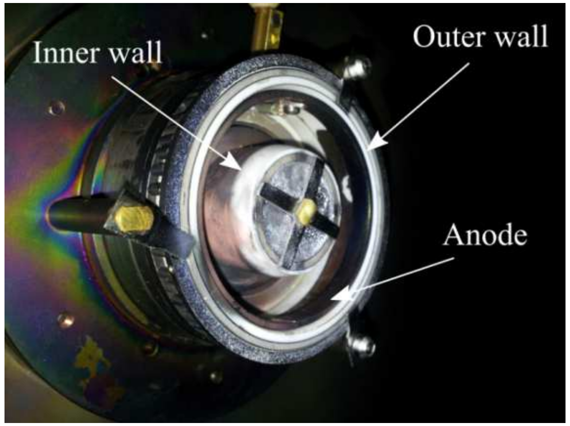
wall-less HT

Development and experimental characterization of a wall-less Hall thruster, S. Mazouffre, S. Tsikata, J. Vaudolon, J. Appl. Phys. **116**, 243302 (2014)

WLHT: Design

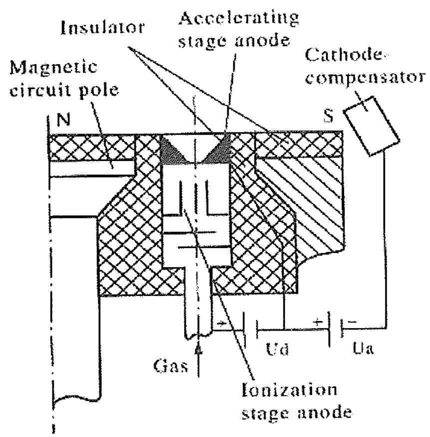
Prototype based on the PPI thruster architecture: 200 W thruster with permanent magnets

- broad channel ($2S_0$ geometry)
- $BN-SiO_2$ channel wall
- porous ceramic as gas injector
- anode = metal ring
- standard magnetic field topology



Ionization and acceleration processes in a small, variable channel width, permanent magnet Hall thruster.
S. Mazouffre, G. Bourgeois, K. Dannenmayer, A. Lejeune, J. Phys. D: Appl. Physics **45**, 185203 (2012).

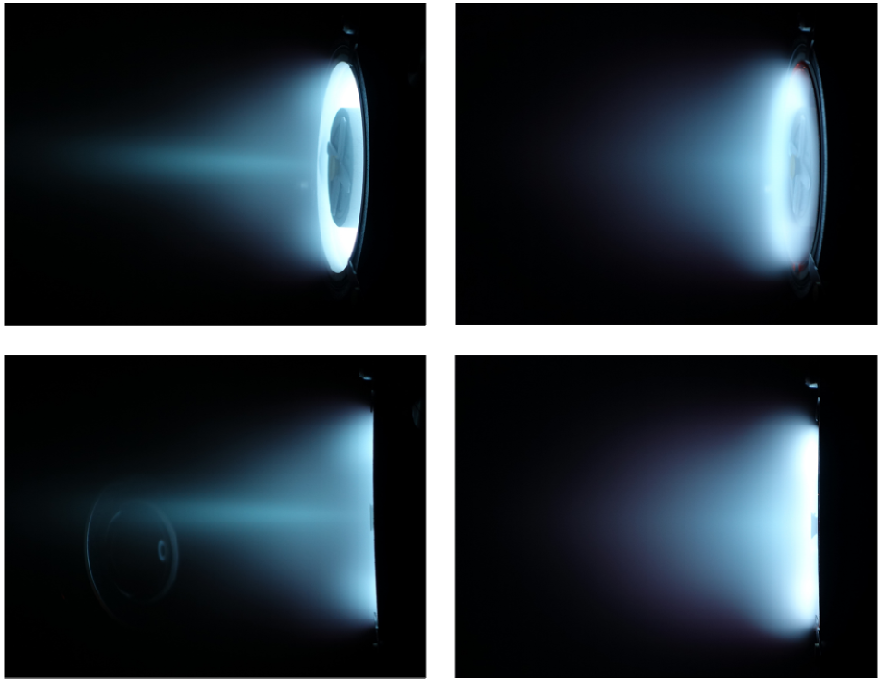
- the idea of shifting the discharge outside the cavity was explored in another form by Kapulkin and colleagues in 1995



Outside electric field thruster
A. M. Kapulkin, A. D. Griskevich and V. F. Prisnyakov et al., Space Technol. **15**, 391 (1995)

WLHT: Proof-of-concept

Testing of the prototype in the NExET test-bench (200 V, 1 mg/s-Xe), Summer 2013



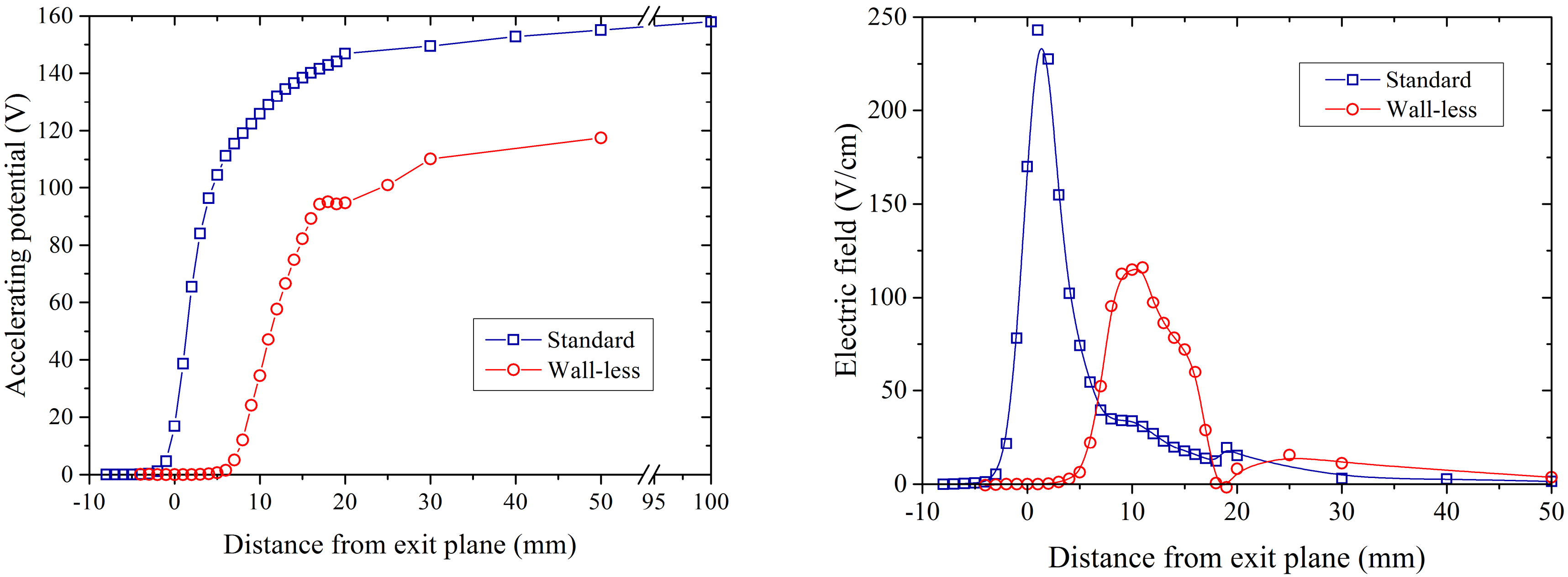
standard configuration wall-less configuration

- discharge stable over a broad operating envelope
- identical level of breathing mode oscillation amplitude to standard thruster

WLHT: E field profile

Wall-less HT prototype firing with Xe: 200 V, 1 mg/s

LIF spectroscopy on metastable Xe^+ ion in the near infrared: VDF → electric field profile

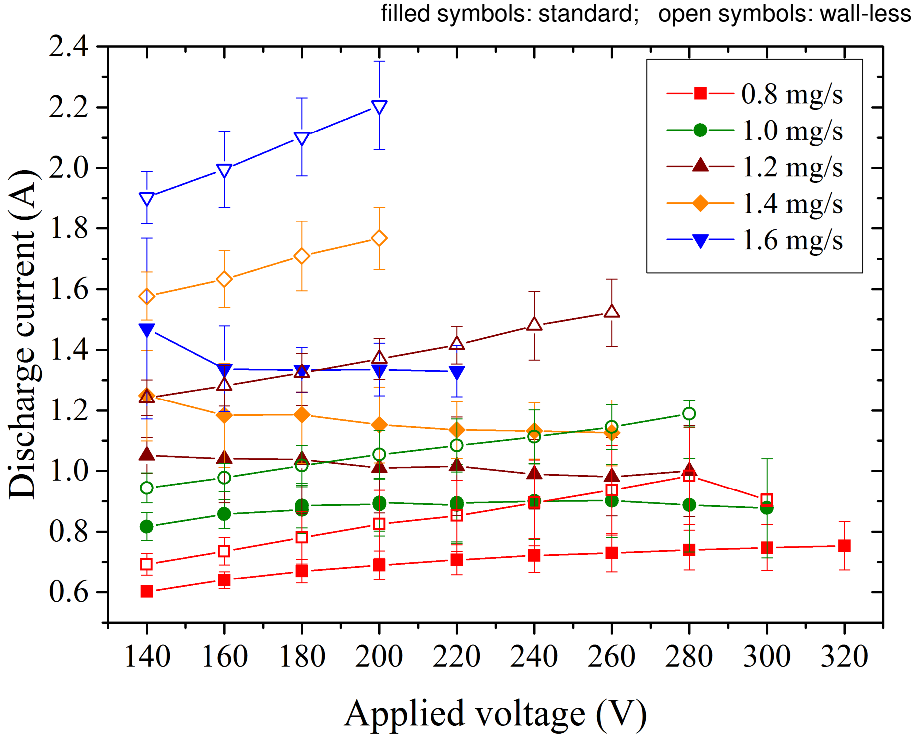


- E field shifted outwards
- good agreement with PIC simulations (Garrigues: IEPC paper 311-2015)
- beam energy

  standard: 160 V

  wall-less: 120 V → lower acceleration efficiency

WLHT: I-V envelope



• I_d much larger in wall-less configuration

→ increase in electron current due to poor confinement

B-field lines perpendicular to the dielectric channel walls (they intercept the anode)

narrower magnetic layer (lower resistor)

high pressure in front of the anode → increased transport

Development and experimental characterization of a wall-less Hall thruster, S. Mazouffre, S. Tsikata, J. Vaudolon, J. Appl. Phys. **116**, 243302 (2014)

WLHT prototype: overview

WLHT prototype experiments so far show:

- the wall-less operation mode is stable
- electric field and ionization zone shifted outwards
- similar $I_d(t)$ oscillation spectrum to a standard thruster

but:

- large discharge current
- high thermal load
- low beam energy

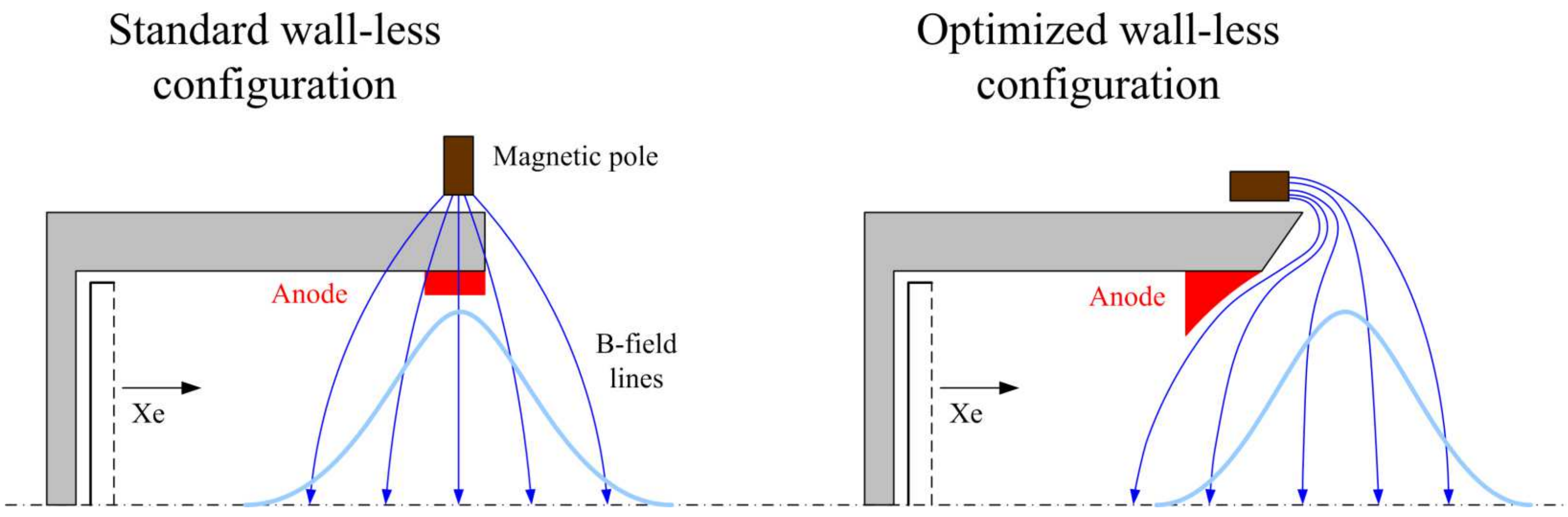
low expected efficiency and lifetime

→ **optimization required**

WLHT: Optimization

Optimization approaches:

- anode geometry
- magnetic field topology

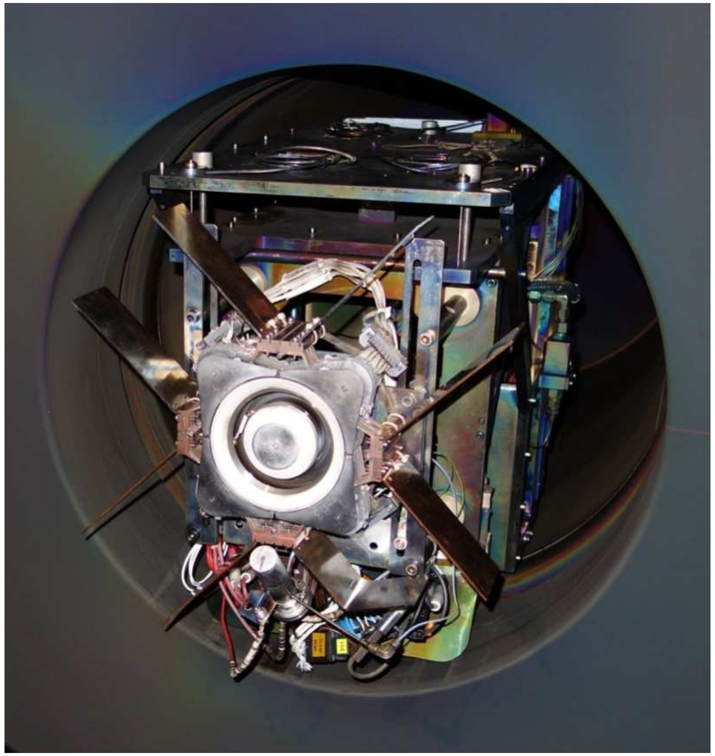


Development and testing of a Hall thruster with flexible magnetic field configuration, S. Mazouffre, G. Bourgeois, J. Vaudolon, L. Garrigues, C. Hénaux, D. Harribey, R. Vilamot, A. Rossi, S. Zurbach, and D. Le Méhauté, J. Propulsion Power, 31, 1167 (2015).

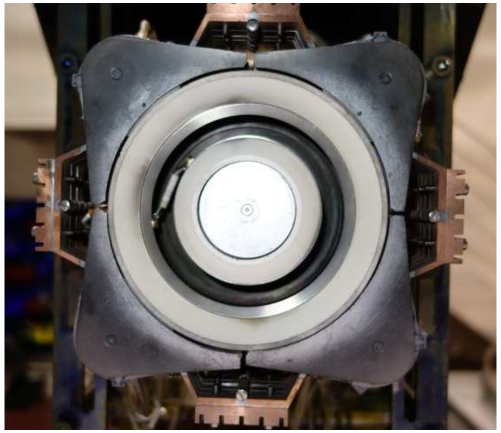
WLHT: PPS-Flex version

PPS-Flex thruster in WL configuration

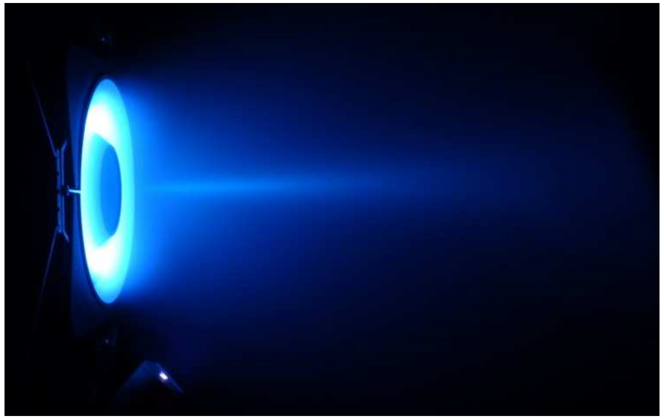
- curved anode (inner and outer rings) at the exit plane
- optimization of the magnetic field topology
- range of operation: U_d = [200 – 500] V, F_a = [2 – 3.5] mg/s, P = [400 – 1500] W



PPS-Flex installed on thrust stand inside the PIVOINE-2G vacuum chamber (Orléans)



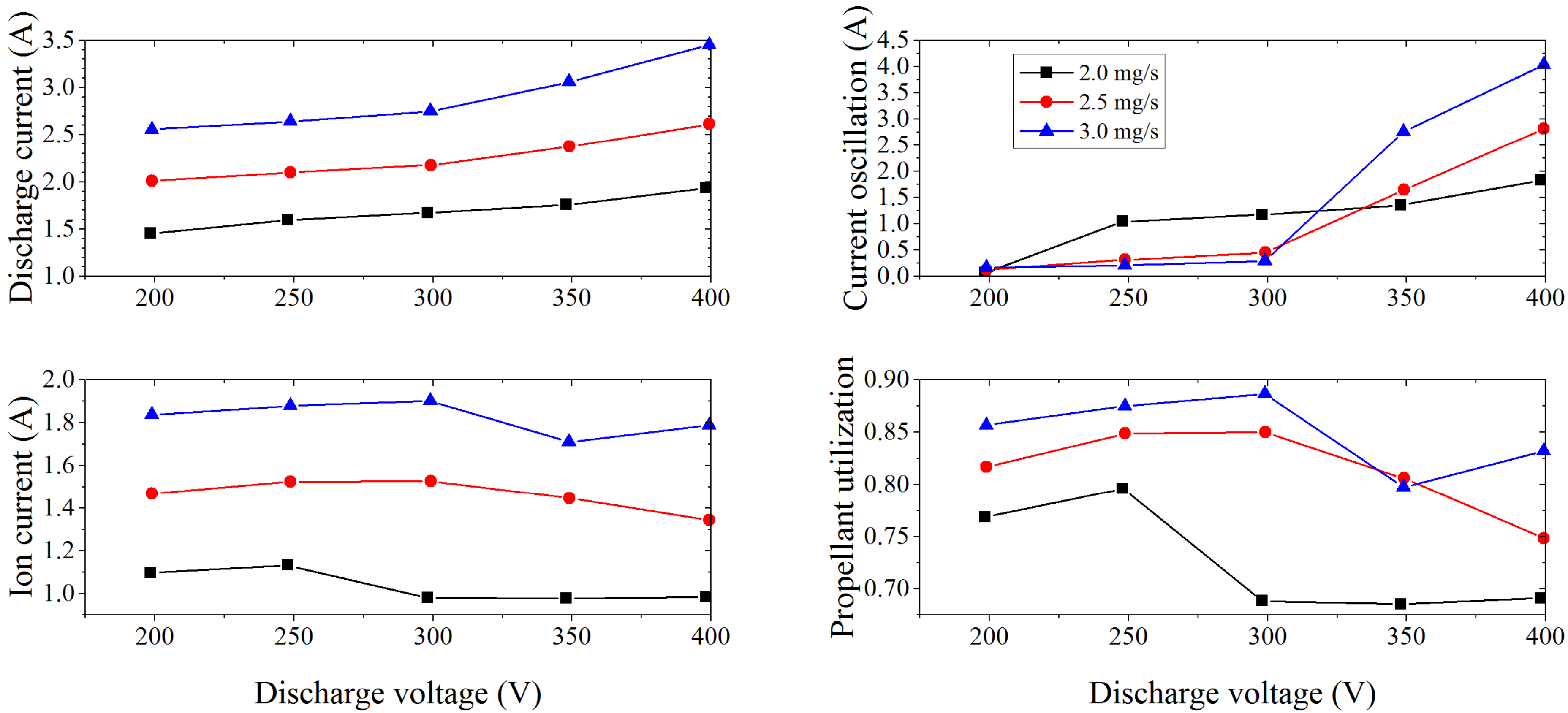
PPS-Flex with the curved anodes



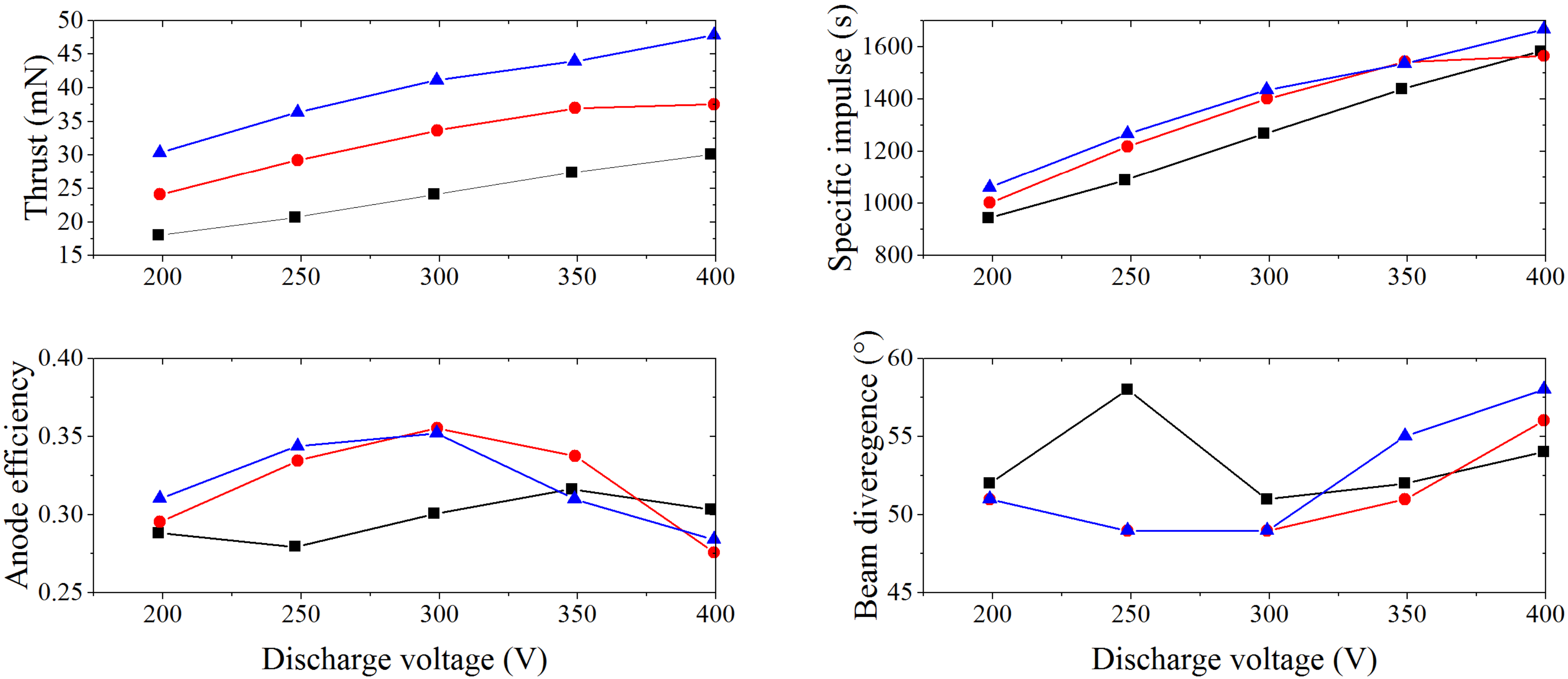
PPS-Flex in WL configuration firing with Xe

350 V, 2.5 mg/s

WLHT: characteristics and performances



WLHT: characteristics and performances



WLHT: characteristics and performances

Overview

- satisfactory performance levels
- anode efficiency = 35%
- relatively large beam divergence
- relatively strong discharge current oscillation

in addition:

- discharge stability test: 1h at 830 W (300 V, 3 mg/s)
- relatively low anode temperature (thermal imaging)

but:

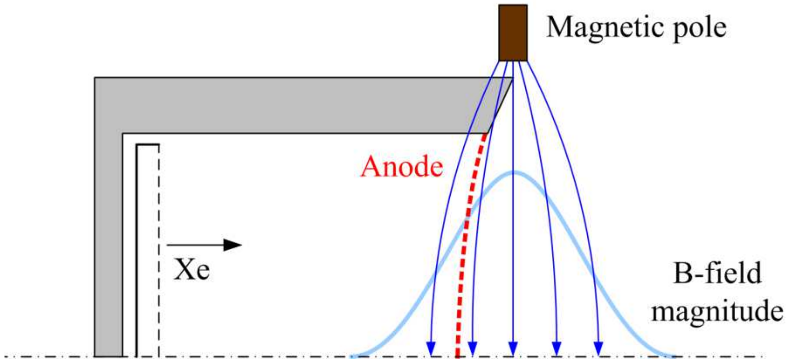
- tests made at low B-field strength (≈ 70 G) due to current PPS-Flex design

$\rightarrow$ need for another version of the WLHT

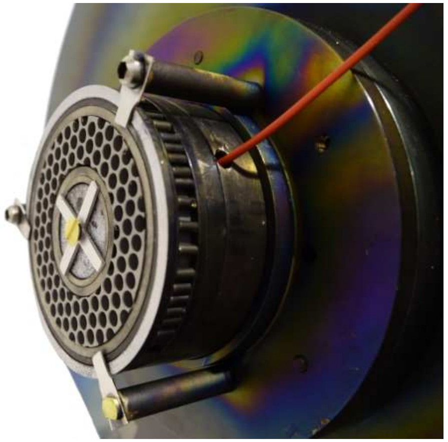
Towards the WL ion accelerator

New anode design
curved gridded anode, carbon

Optimization of the B-field
strong magnitude, gradient



Tested successfully
very stable discharge
reasonable performances



→ Wall-less ion accelerator (patent pending)
Very compact, simple DC thruster in ExB configuration
(inverted magnetron discharge)

Conclusion & perspectives

Wall-Less

- realistic solution
- decrease in losses at walls
- extended lifetime
- possible operation at high-voltage
- use of alternate propellants (high T_e)
- ***suitable test bench for HT physics***

Magnetic Shielding

- Characterization of a 200 W permanent magnet HT in MS
- Low near-wall ion flux in MS
- Pole erosion: MS = US
- Divergence angle: MS = US

Future

Development of the WLIA
Performances / Optimization
Physics / Simulations

- Thrust measurements, divergence
- Conducting walls