The Wall-Less Hall thruster

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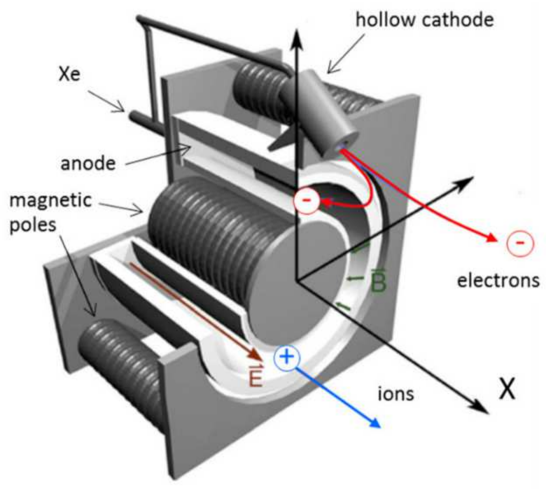
GDR Groupement de recherche
EMILI Étude des milieux ionisés
Plasmas froids créés par décharge et laser

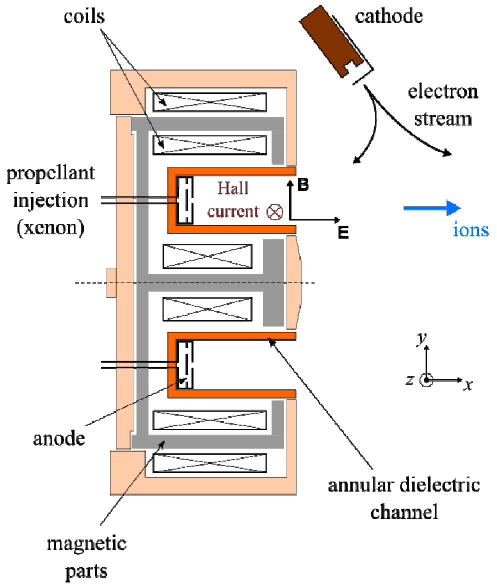
The Hall Thruster

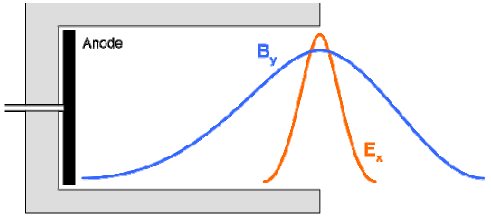
Principle

Gridless ion acceleration

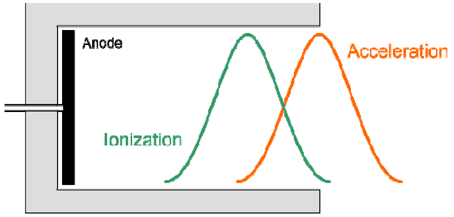
- No plasma sheath, no space-charge limit ➔ Large ion current (large thrust)
- Magnetized electrons
- Large E field due to low electron mobility
- E×B drift







E and B field distribution



I and A zones

Tutorial: Physics and modeling of Hall thrusters
J P Boeuf, J. Appl. Phys. 121 (2017)

The Hall Thruster

Anomalous transport

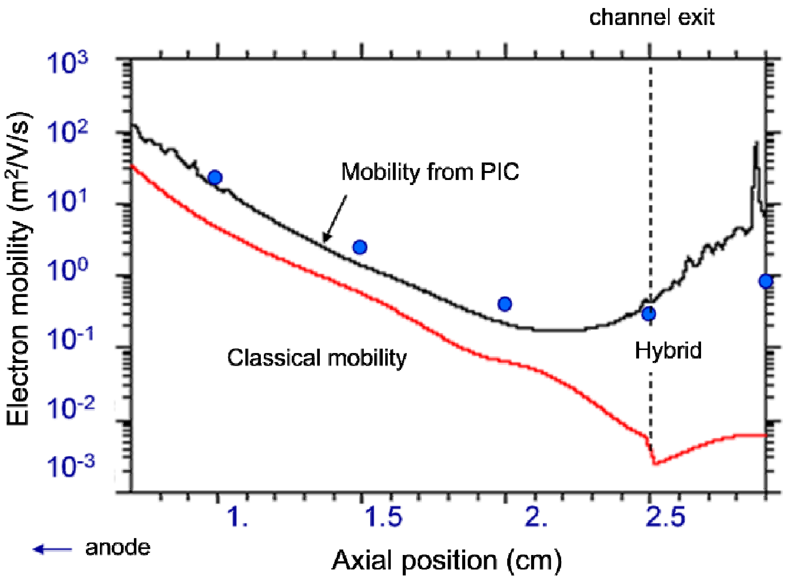
Electron diffusion

Experiment: $\mu_{e,\perp} \approx 0{,}2\ m^2s^{-1}V^{-1}$

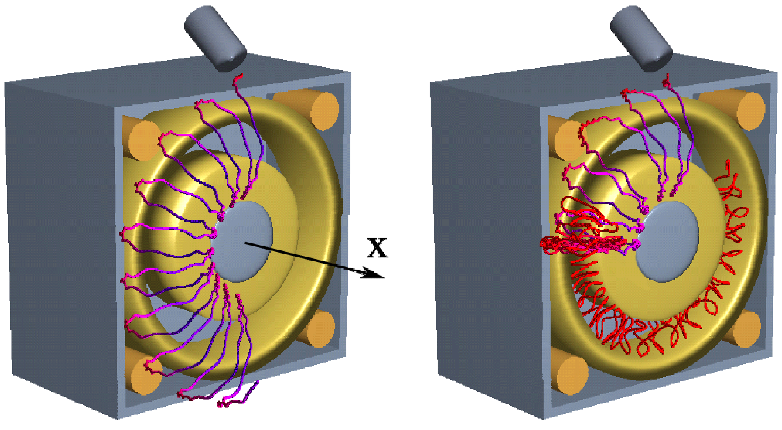
Calculation (collisions) : $\mu_{e,\perp} \approx 0{,}01\ m^2s^{-1}V^{-1}$

Explanation : instabilities and/or wall collisions

Turbulent E field in θ $\tilde{E}_z \quad \rightarrow \quad \mu \propto \frac{1}{B}$



Simuations w and w/o E_θ field

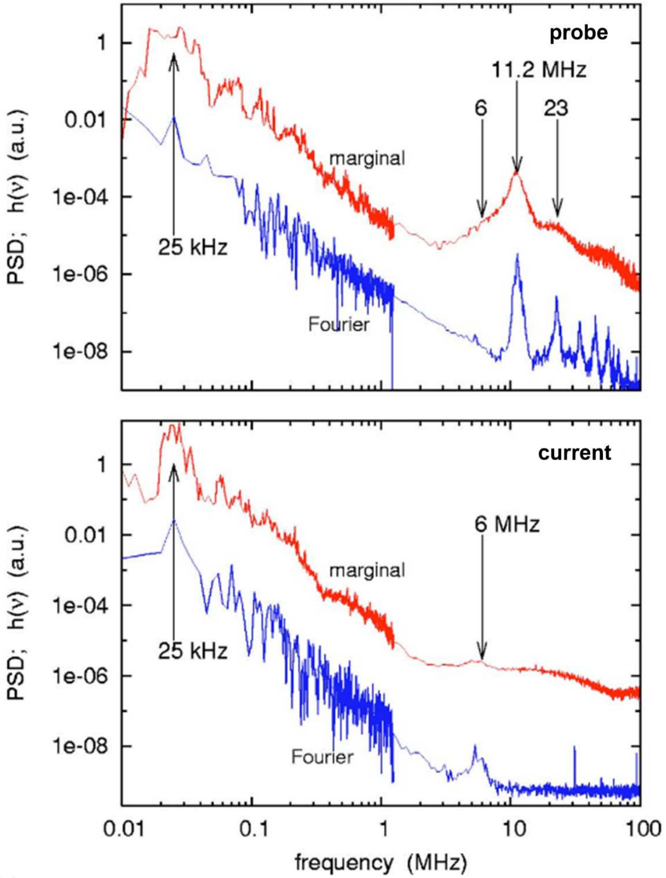


J. Pérez Luna, PhD thesis, LAPLACE, 2010

The Hall Thruster

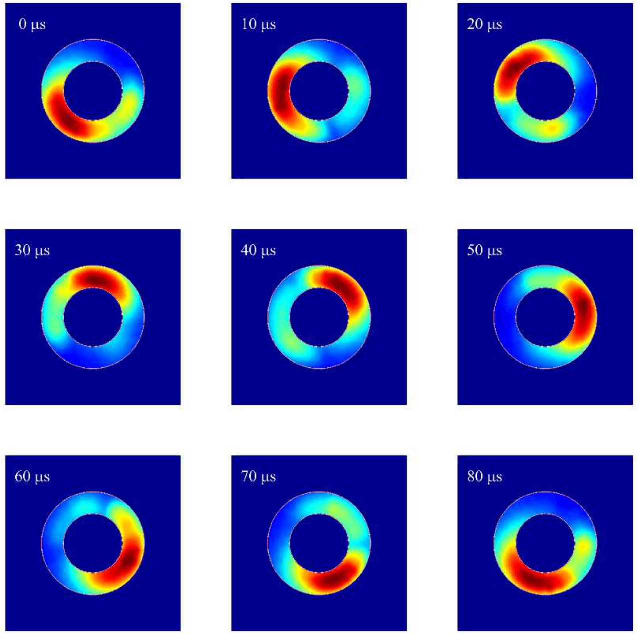
Oscillatory phenomena

Broad range of frequencies [kHz – GHz]
Various physical processes



Rotating spokes

Large scale (cm) low frequency (kHz) plasma instability
Observed in various crossed-field plasma discharges
Ionization type instability at low voltage



Fast camera imaging ISCT200 WLHT, Xe, 110 V, 1 A

Rotating spoke instabilities in a wall-less Hall thruster: experiments, S Mazouffre et al, PSST 28 054002 (2019)

The Hall Thruster

Many open questions

Discharge oscillations and instabilities

Anomalous electron transport

Scaling laws

Plasma-wall interactions

Electron energy distribution function

Anomalous erosion of the wall

Cathode/discharge coupling

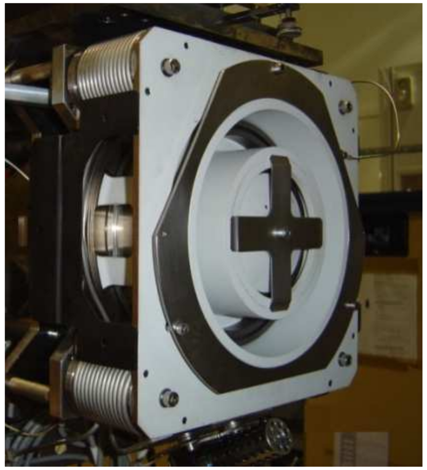
Simple and efficient technology

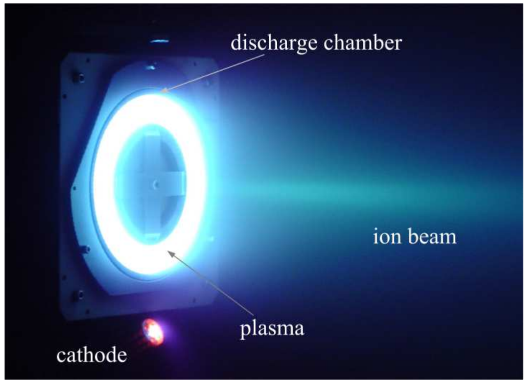
Complex and rich physics

The Hall Thruster

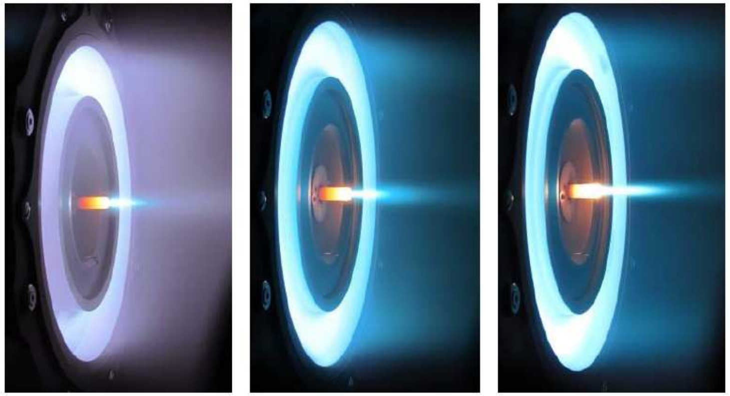
Devices

PPS$^{®}$X000-ML
SAFRAN – CNRS
5 kW





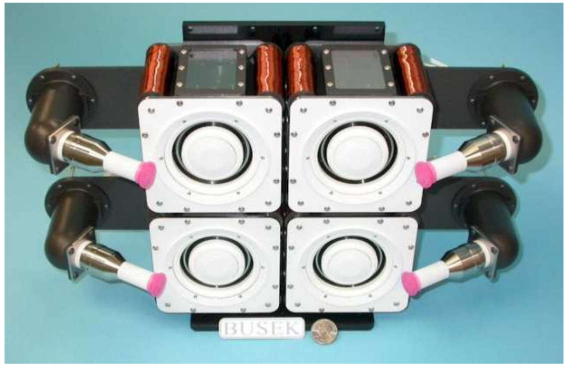
PPS-20K
SAFRAN – CNRS
20 kW, 1 N, 2500 s



The Hall Thruster

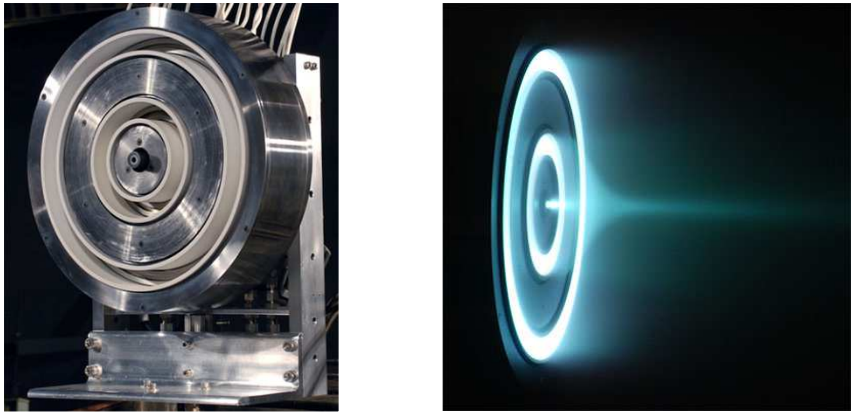
Devices

Large sizes
Moteur 457M
NASA
50 kW
2,5 N

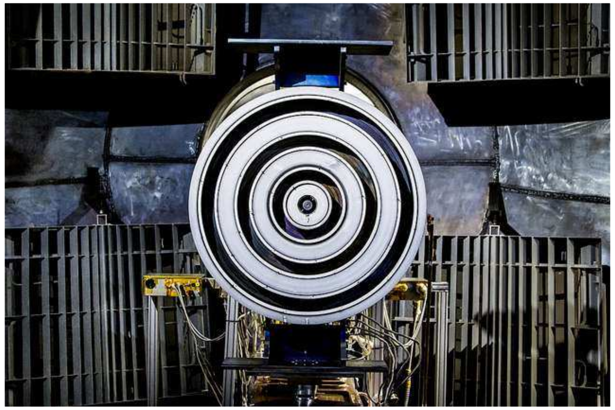


Cluster
Cluster of 4 BHT600
Hall thrusters from
Busek
Thrust addition
Versatility

Nested-channel Hall thrusters
Versatility; broad operating envelope



X2 Hall thruster: 2 channels (20 kW)
PEPL, University of Michigan



X3 Hall thruster: 3 channels (200 kW)
PEPL, University of Michigan

The Hall Thruster

Lifetime

main drawback 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

PPS®1350-E BOL

PPS®1350-E EOL

Review of Plasma-Induced Hall Thruster Erosion, N. P. Brown, M. L. R. Walker, Appl. Sci. 2020, 10(11), 3775

The Hall Thruster

How to extend HT Lifetime?

i) Wall material

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

ii) Magnetic shielding configuration

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

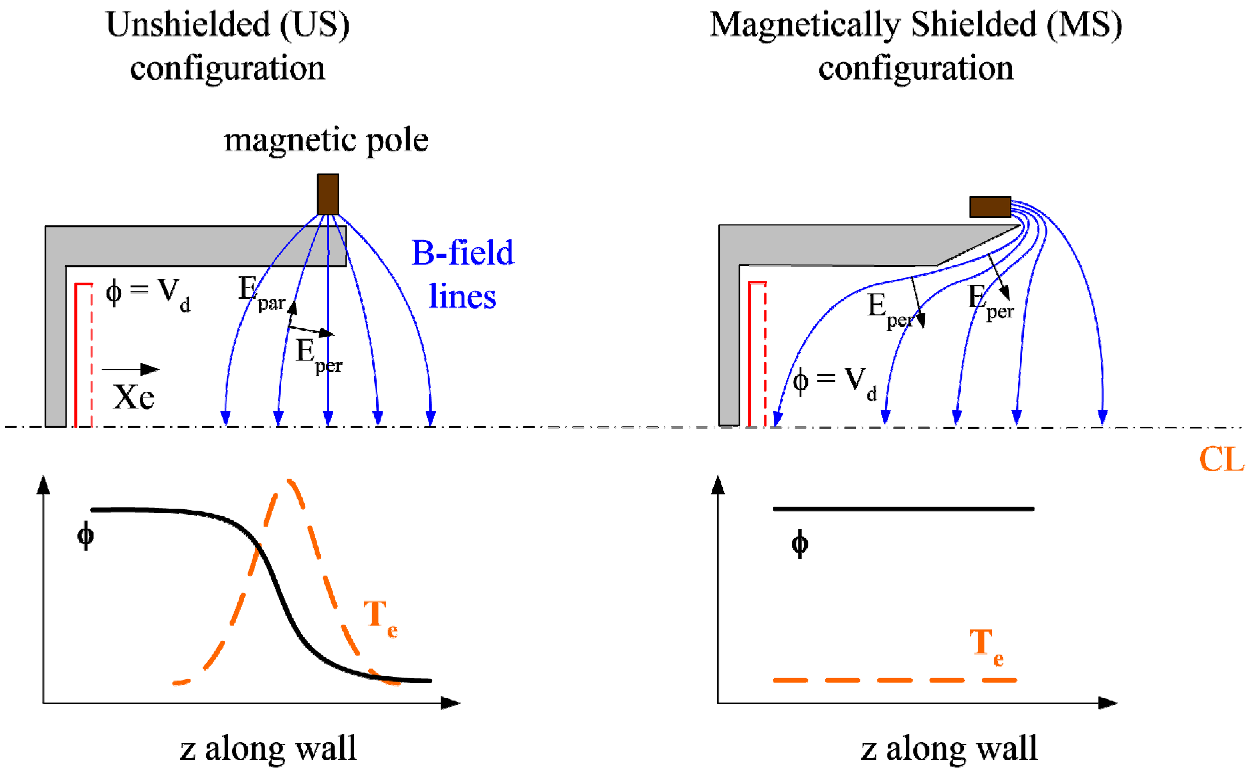
iii) **Wall-less configuration**

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

advantage: possibility to probe the plasma discharge

The Hall Thruster

Magnetic shielding



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 (2001)

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).

The Hall Thruster

Magnetic shielding

Works at ICARE with the ISCT-200-MS

- First MS HT in Europe; smallest in the world (200 W)
- Investigation of magnetic pole pieces erosion + conducting walls
- LIF experiments: ion energy below sputtering threshold

ISTC-200-MS
Magnets ; 2S_0 ; 200 W

ISTC-200-MS
Operation with Xe

standard configuration

MS configuration

Visual evidence of magnetic shielding with the PPS-Flex Hall thruster
S. Mazouffre et al, IEEE Trans. Plasma Sci. 42, 2668 (2014)

Ion behavior in low-power magnetically shielded and unshielded Hall thrusters
L. Grimaud, S. Mazouffre; Plasma Sources Sci. Technol. 26, 055020 (2017)

Conducting wall Hall thrusters in magnetic shielding and standard configurations
L. Grimaud, S. Mazouffre, J. Appl. Phys. 122, 033305 (2017)

Performance comparison between standard and magnetically shielded 200 W Hall thrusters with BN-SiO2 and graphite channel walls
L. Grimaud, S. Mazouffre, Vacuum 155, 514-523 (2018)

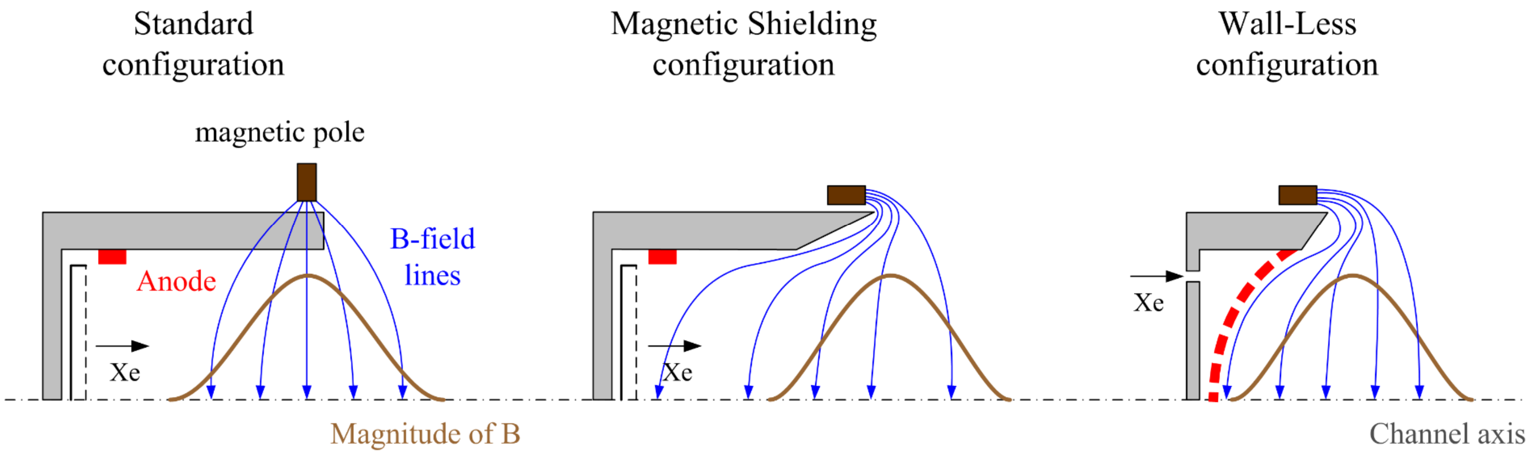
Incoherent Thomson Scattering measurements of electron properties in a conventional and magnetically-shielded Hall thruster
B. Vincent, S. Tsikata, S. Mazouffre, Plasma Sources Sci. Technol. 29 035015 (2020)

The Wall-Less Hall Thruster

Principle

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



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

Optimization of a wall-less Hall thruster
J. Vaudolon, S. Mazouffre, C. Hénaux, D. Harribey, A. Rossi, Appl. Phys. Lett. **107**, 174103 (2015)

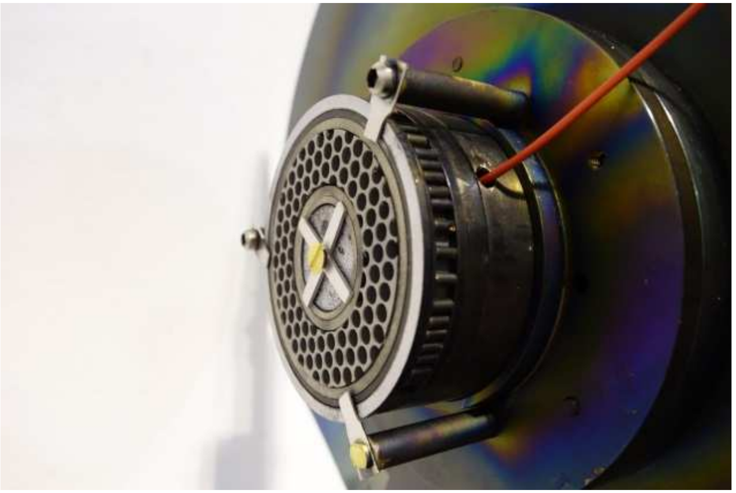
Rotating spoke instabilities in a wall-less Hall thruster: Experiments
S. Mazouffre, L. Grimaud, S. Tsikata, K. Matyash, R. Schneider, Plasma Sources Sci. Technol. **28**, 054002 (2019)

Patent WO 2018/069642 – US 2020/0040877
Ion thruster with an external plasma discharge
S. Mazouffre, S. Tsikata

The Wall-Less Hall Thruster

Prototype

Prototype based on the ISCT200 architecture
- broad channel ($2S_0$ geometry)
- $BN\text{-}SiO_2$ channel wall
- porous ceramic as gas injector
- anode = metal ring or curved grid
- standard magnetic field topology



ISCT200-WL thruster
- 200 W; magnets; $2S_0$
- gridded anode (exit plane)
- curved anode shape (parallel to $\mathbf{B}$ lines)

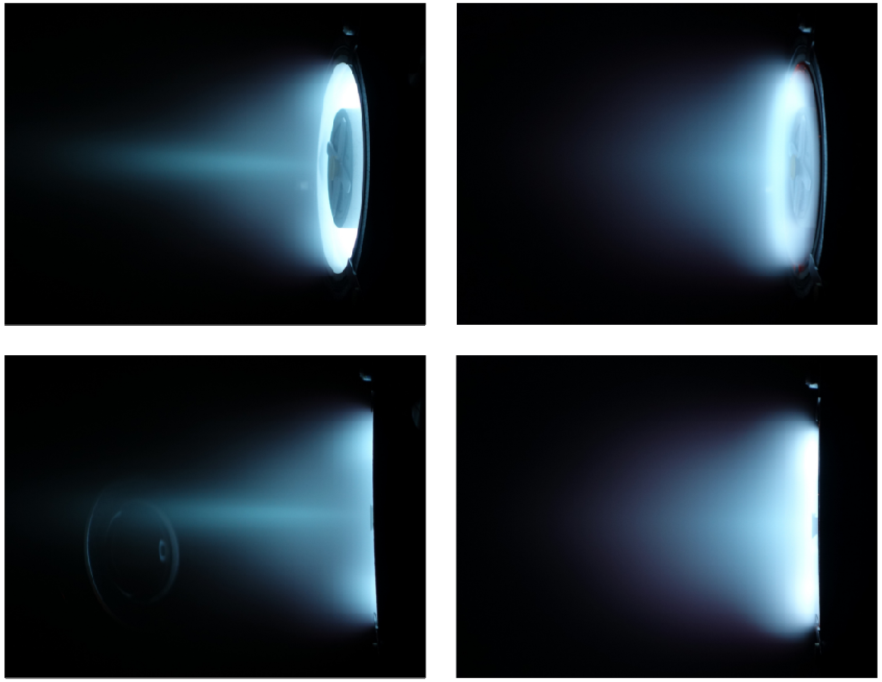
The idea of shifting the discharge outside the cavity was explored in another form by Kapulkin in 1995

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

The Wall-Less Hall Thruster

Operation with xenon

Testing of a prototype in the NExET chamber (200 V, 1 mg/s-Xe)



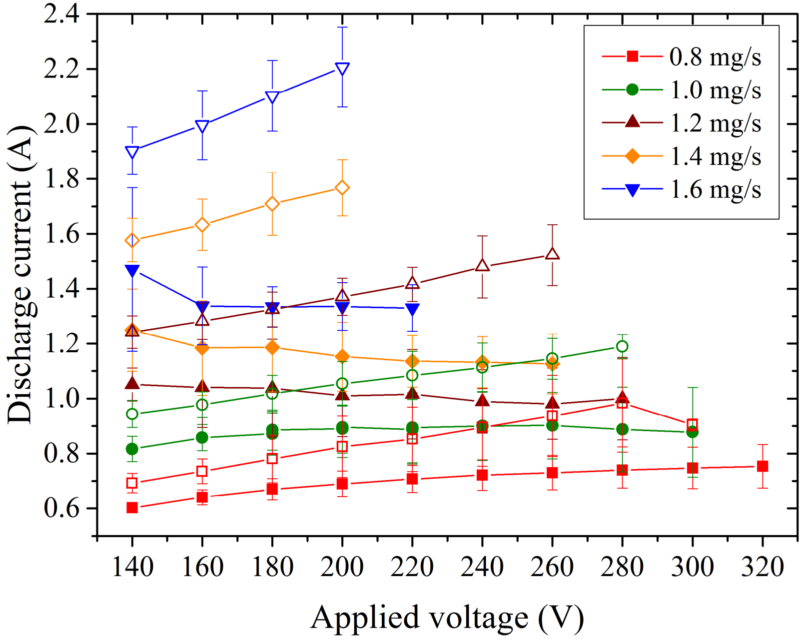
Standard configuration Wall-less configuration

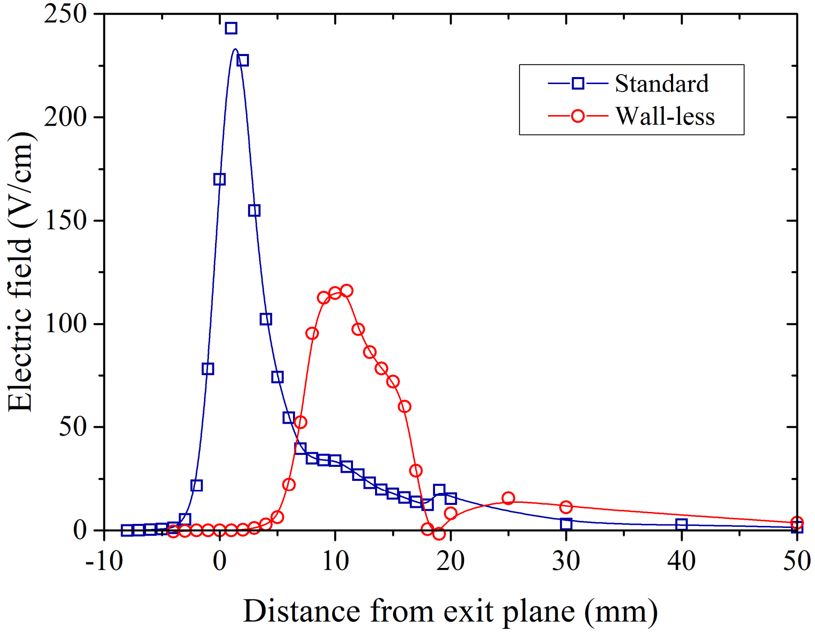
Discharge stable over a broad operating envelope
Identical level of breathing mode oscillation amplitude to standard thruster

The Wall-Less Hall Thruster

Operation with xenon (200 V, 1 mg/s)

filled symbols: standard; open symbols: wall-less





I_d much larger in wall-less configuration

Increase in electron current due to poor confinement (improvement with B field optimization)

E field shifted outwards

good agreement with PIC simulations (LAPLACE)

Beam energy

standard: 160 V

wall-less: 120 V

➔ lower acceleration efficiency

The Wall-Less Hall Thruster

Operation with xenon

WLHT prototype experiments 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
Large beam divergence

} low expected efficiency and lifetime

➔ **optimization required**

Conclusion

Advantages of the WL concept

- more compact, lighter than standard HTs
- external plasma discharge; weak PSI
- *extended lifetime*
- *possible operation at high-voltage*
- *use of alternative propellants*

Current status

- research all around the word (UK, China, US)
- increase in performance at low power (PPPL)
- design improvements

Open questions

- electron/ion properties and nature of instabilities?
- wall losses?
- optimum anode shape and B field map?
- long-term discharge stability?

Recent publications

Performance characteristics of no-wall-losses Hall Thruster
Yongjie Ding et al
Eur. Phys. J. Special Topics 226, 2945–2953 (2017)

Thrust performance, propellant ionization, and thruster erosion of an external discharge plasma thruster
B. Karadag, S. Cho, I. Funaki
J. Appl. Phys. 123, 153302 (2018)

Effect of auxiliary gas injection on the operation of a Hall current plasma accelerator
B. Karadag
J. Phys. D: Appl. Phys. 54 435204 (2021)

Ion acceleration in a wall-less Hall thruster
J. Simmonds, Y. Raitses
J. Appl. Phys. 130, 093302 (2021)