Plasma for Space Applications

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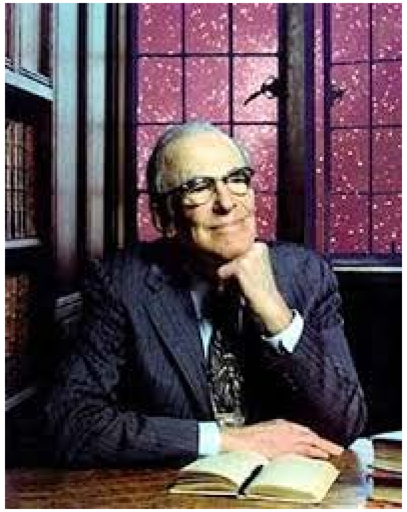
IAEA Technical Meeting on Emerging Applications of Plasma Science and Technology
19-22 September 2023, Vienna, Austria

PPPL- the US DOE magnetic confinement fusion Lab, but not only fusion



Interplanetary Travel Between Satellite Orbits[1]

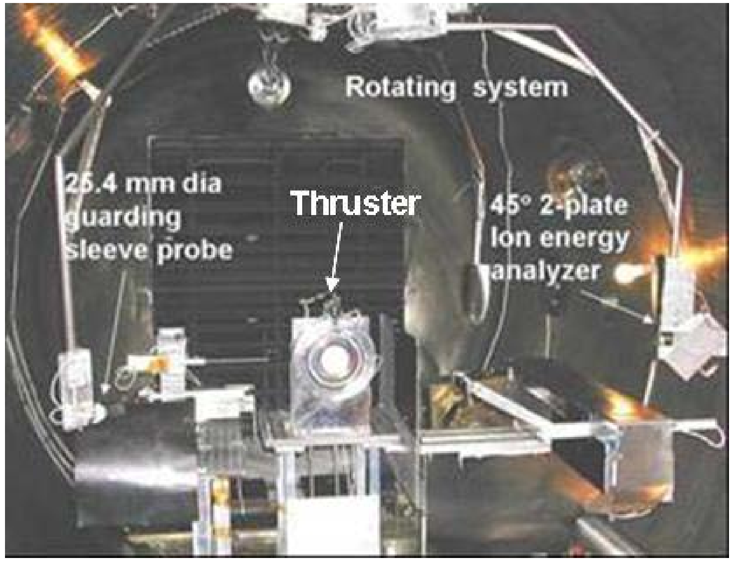
By LYMAN SPITZER, JR.[2]

Princeton University Observatory, Princeton, N. J.

An analysis is given of the performance to be expected of a rocket powered by nuclear energy, and utilizing an electrically accelerated ion beam to achieve a gas ejection velocity of 100 km/sec without the use of very high temperatures in the propellant gases. While such a rocket travel particularly feasible. It is well known that one of the chief limitations on a conventional rocket is the temperature which the rocket tubes can tolerate without melting or evaporating. A nuclear-powered

2nd International Congress on Aeronautics, London, UK, 1952

- Hall Thruster Experiment (HTX) in 1998 by N.J. Fisch and Y. Raitses and graduate students L. Dorf, A. Smirnov, A. Litvak and D. Staack
  - Goal: to develop scientific understanding of plasma thruster physics



http://htx.pppl.gov

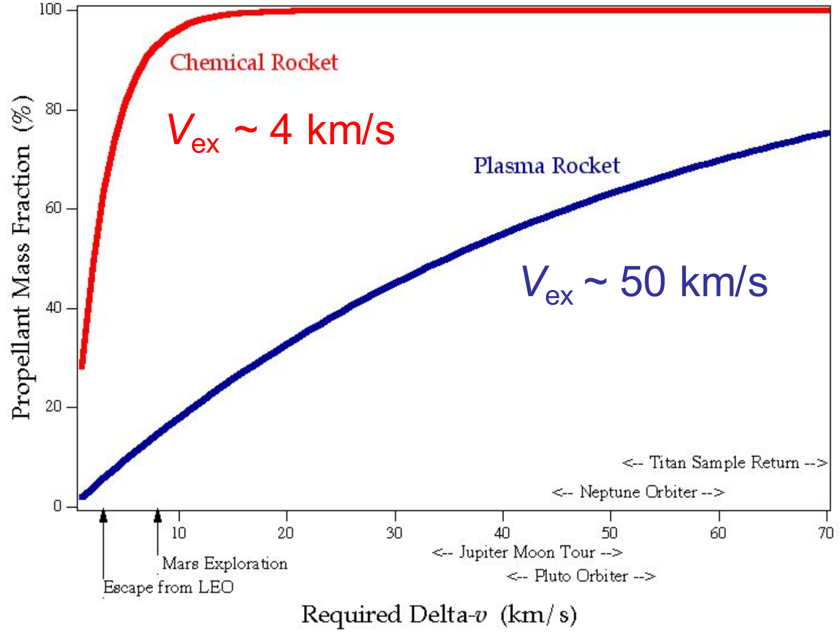
1999 → 2023

Outline

- Background
- Science topics to explore
  - Thruster density limits
    - Physics challenges
  - Sustainable plasma propulsion
- Summarizing remarks

Where do we use plasmas in space?

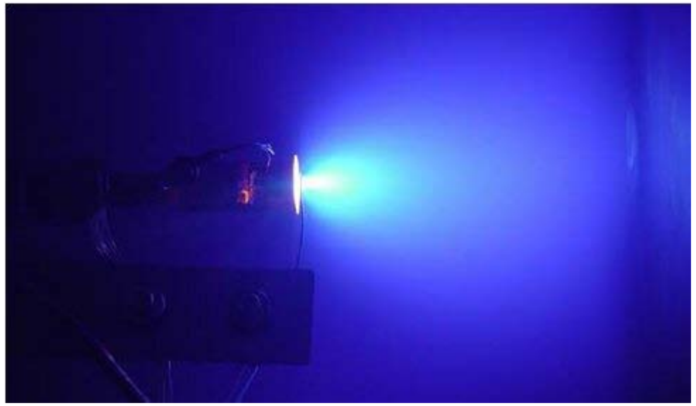
$$m_f = m_0 e^{-\Delta V / V_{ex}}$$



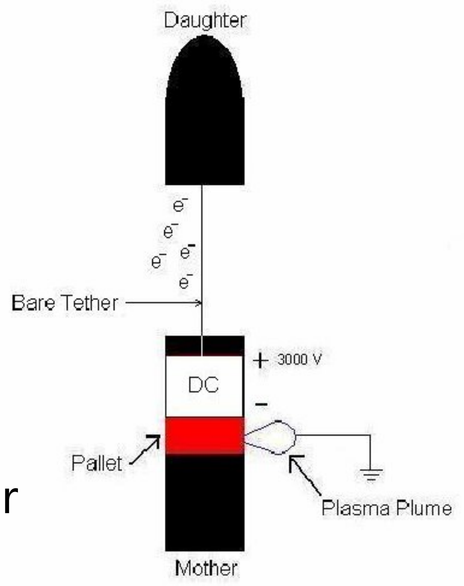
- **Electric and Plasma Propulsion**

- Station keeping
- Drag compensation
- Orbit transfer
- Interplanetary missions

- **Plasma contactor for tethers/neutralizers**



- Prevent electrical charging (and arcing) of large satellites, ISS
- Implement electromagnetic tether (orbit transfer, deorbiting)



Tether concept by JAXA in 90's, 00's

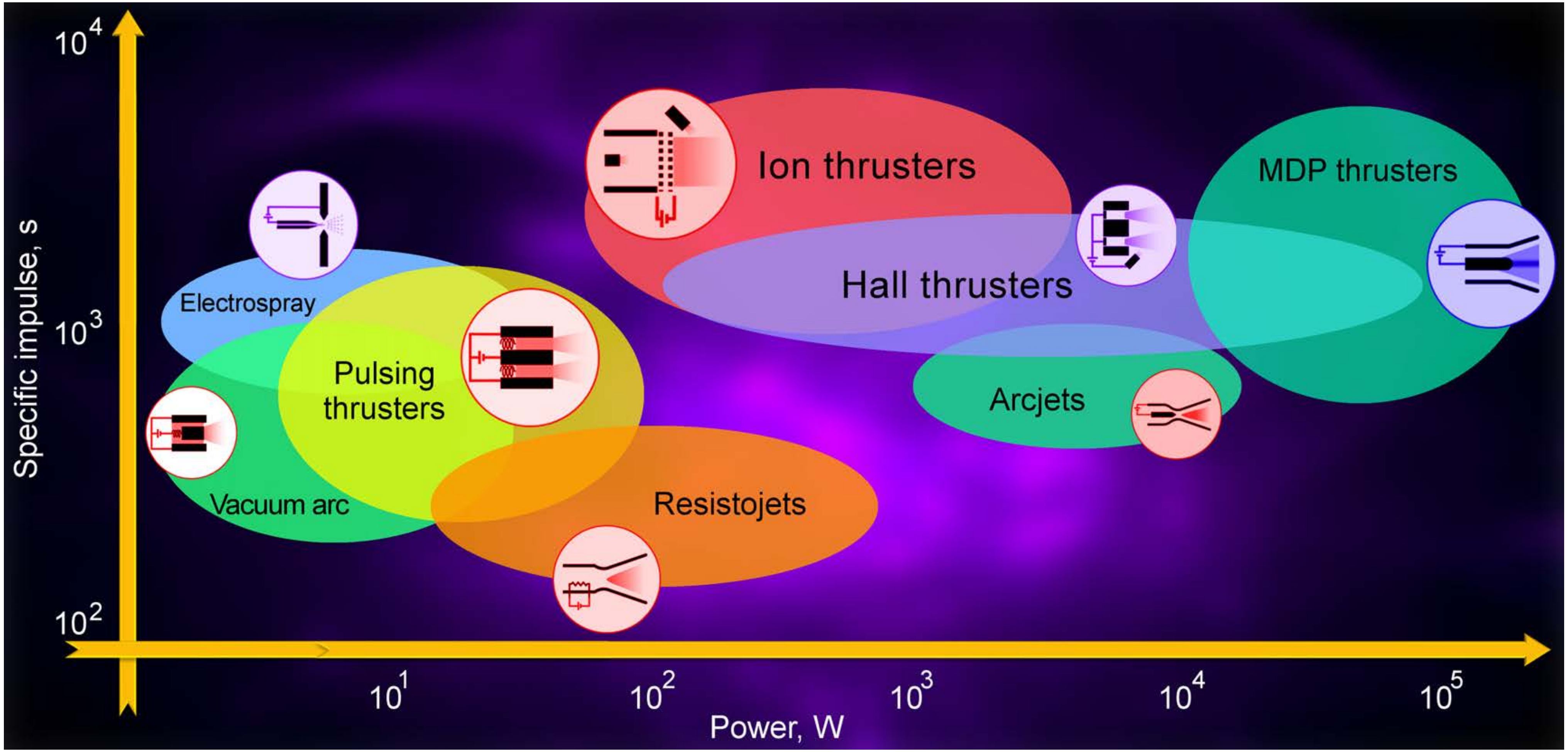
NASA ProSEDS concept

In 90's and later with Univ. Cubesats

Electric Propulsion – major types

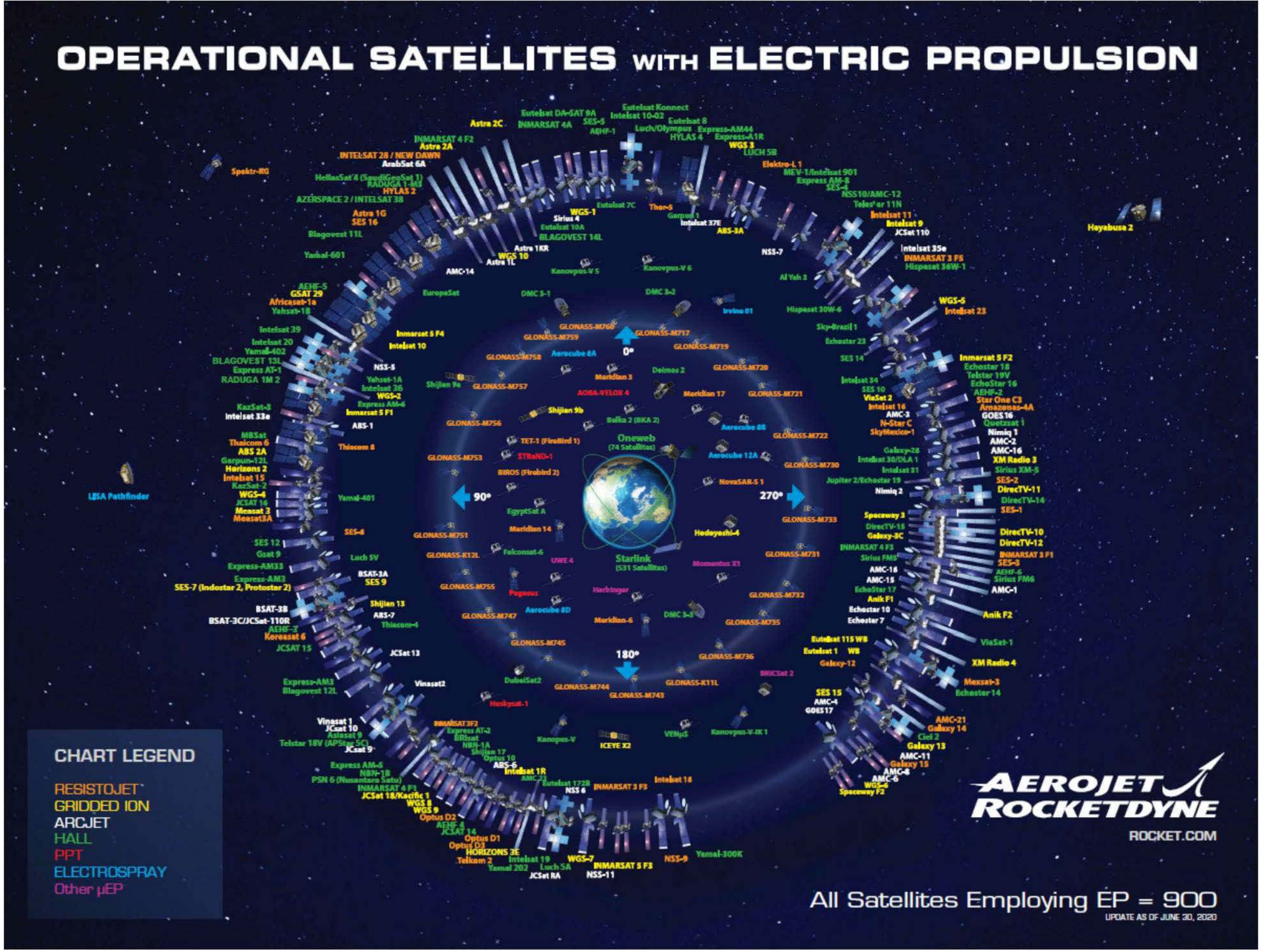
Specific impulse:

$$Isp \equiv \frac{T}{\dot{m}g} = \frac{V_{exaust}}{g}\text{, s}$$



Input Power: $P = IV$, W

I. Levchenko et al., Phys. Plasmas 27, 020601 (2020)



Note:

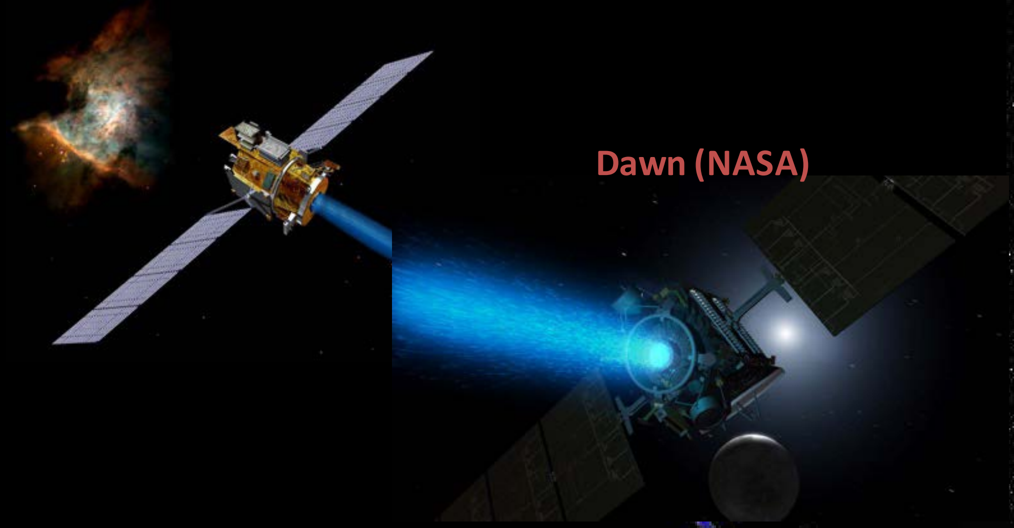
- By October 1, 2021, the number of EP propelled satellites more than doubled: 2363
- Hall thruster dominate in June 2020

B. R. Frongello, W. A. Hoskins, R. J. Cassady, K. Maliga and K. Kalkowska, ASCEND 2021

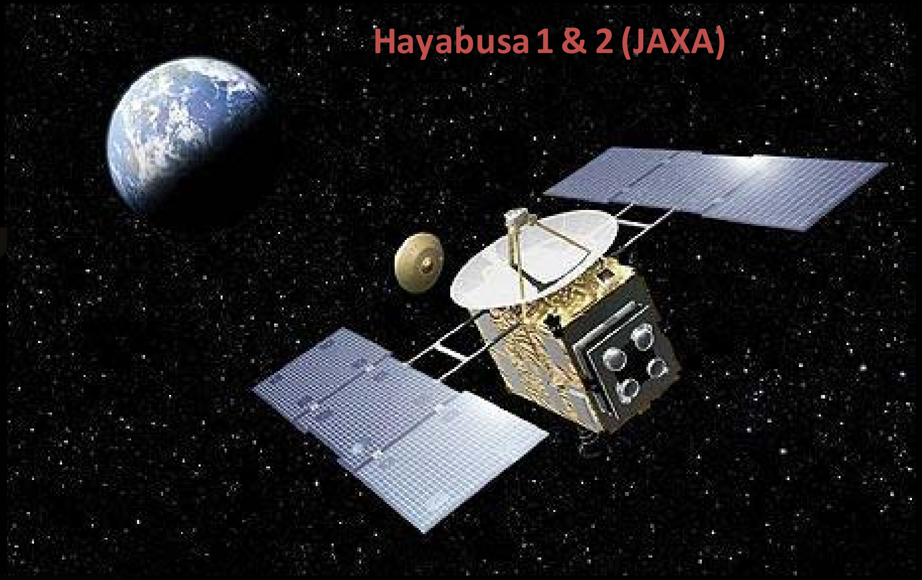
Deep Space Missions with Electric Propulsion

Deep Space 1 (NASA)

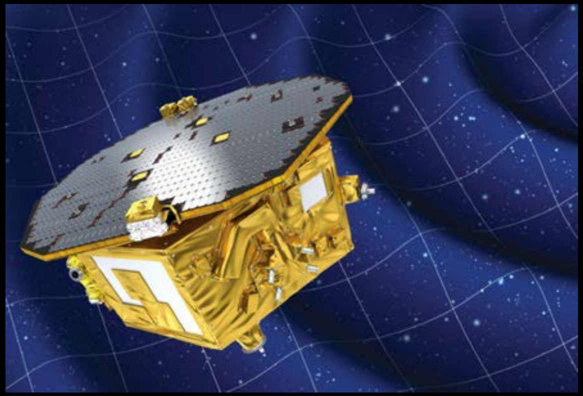
Dawn (NASA)



Hayabusa 1 & 2 (JAXA)

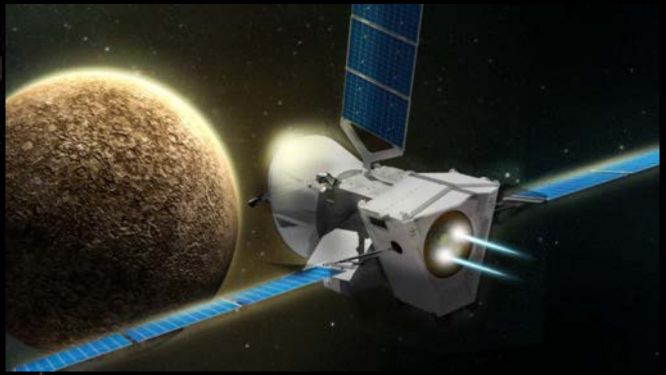


LISA Pathfinder (ESA)



SMART-1 (ESA)

Bepi Colombo (ESA)

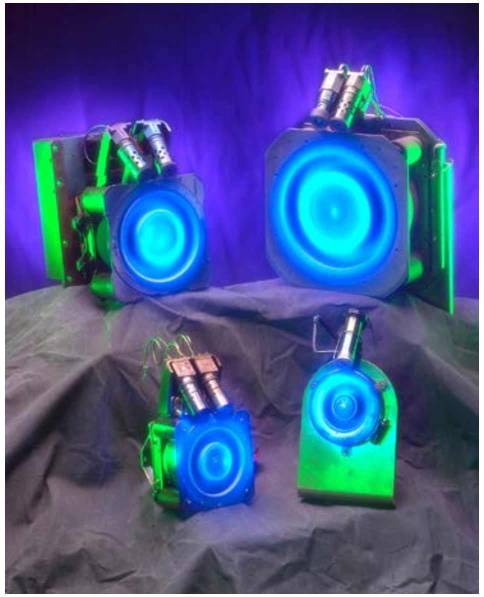


Courtesy Rich Hofer, NASA JPL

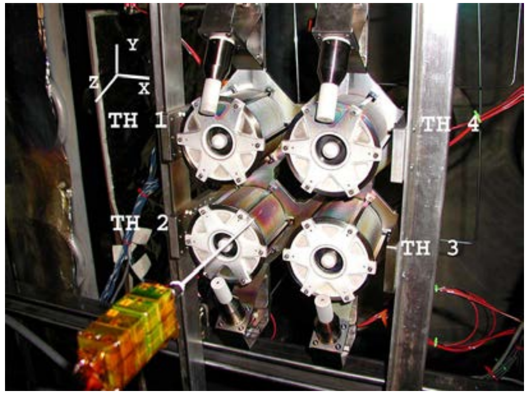
State-of-the-art Hall thrusters

- **Highly efficient: 40-70%, long lifetime: 2000-10000 hours**

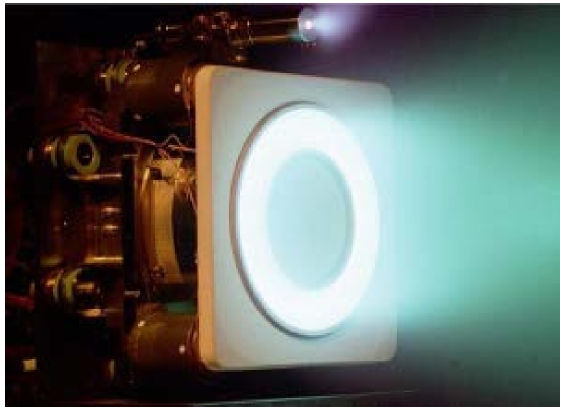
Russian **SPT Hall thrusters**
0.3-5 kW, 20-300 mN
5-14 cm diam



Busek BHT-200, 200 W, 13 mN



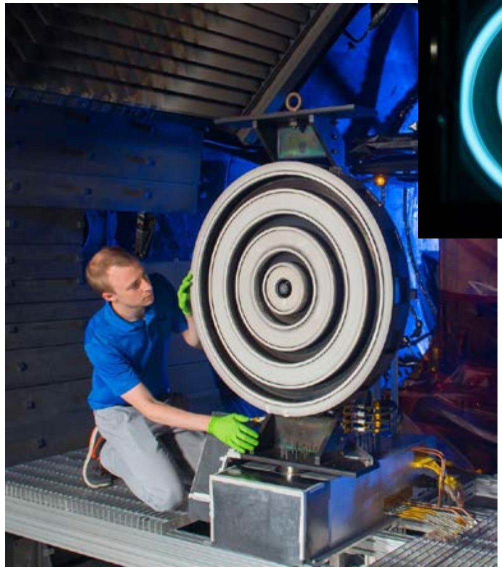
Aerojet XR5, 4.5 kW, 250 mN



MaSMi by JPL
150-750 W
9-33 mN

PPS-1350 Hall thruster
1.5 kW, 90 mN
10 cm diam

Snecma, France
SMART -1 mission by ESA



X-3 Hall thruster
2-200 kW, 0.2-10 N
80 cm diam, 250 kg
Aerojet, NASA, U Michigan

Physics of Plasmas PERSPECTIVE scitation.org/journal/php

Physics of E × B discharges relevant to plasma propulsion and similar technologies

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25 co-authors

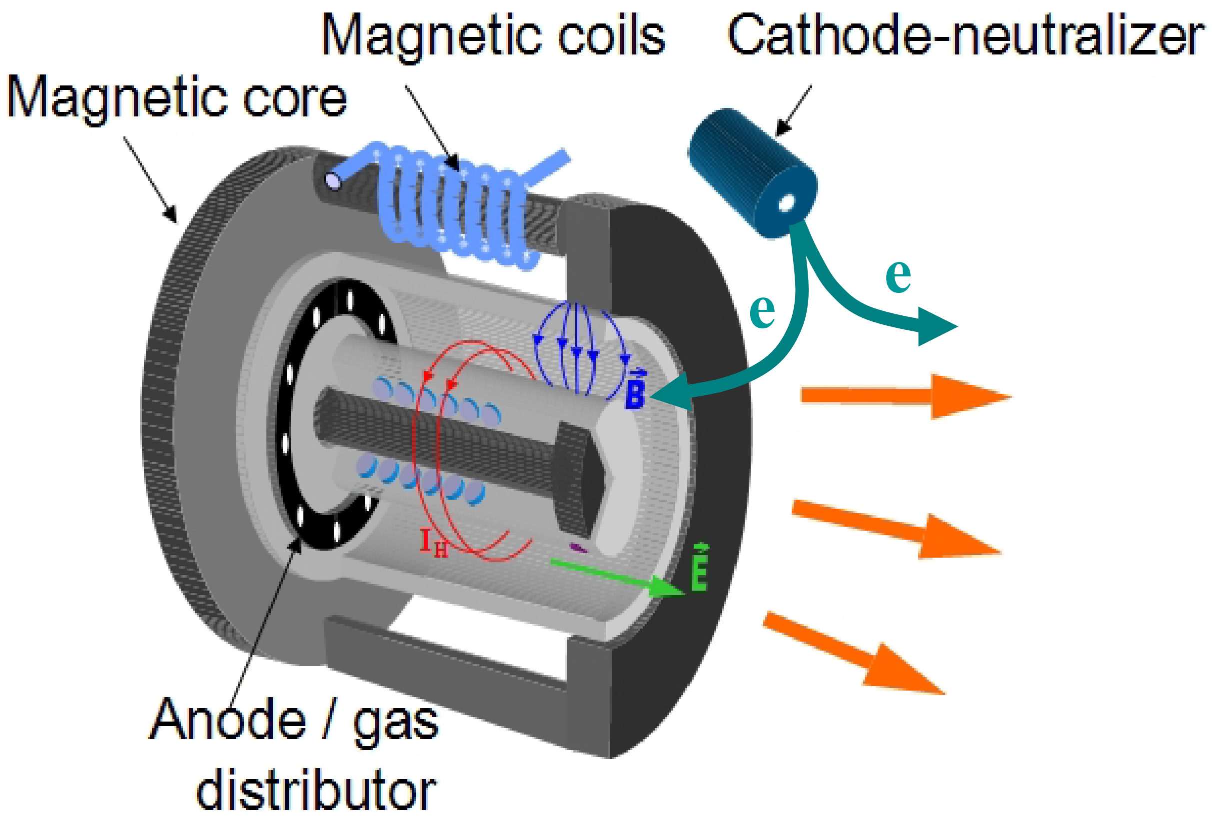
16 research organizations

9 countries

Correspondingly, this perspective article discusses nine topics, which represent major directions for the electric propulsion community:

1. Plasma–wall interactions in E × B discharges relevant to propulsion plasma devices
2. Low-frequency oscillations in E × B discharges
3. Experiments in turbulence in low temperature, E × B devices
4. Electron drift instabilities in E × B plasmas: mechanisms, nonlinear Saturation, and turbulent transport
5. Fluid and hybrid (fluid–kinetic) modeling of E × B discharges
6. Toward full three-dimensional modeling of Hall thruster E × B discharges
7. E × B configurations for plasma mass separation applications
8. Validation and verification procedures for discharge modeling
9. Magnetic nozzles for electric propulsion.

Hall Thruster working principle in glance



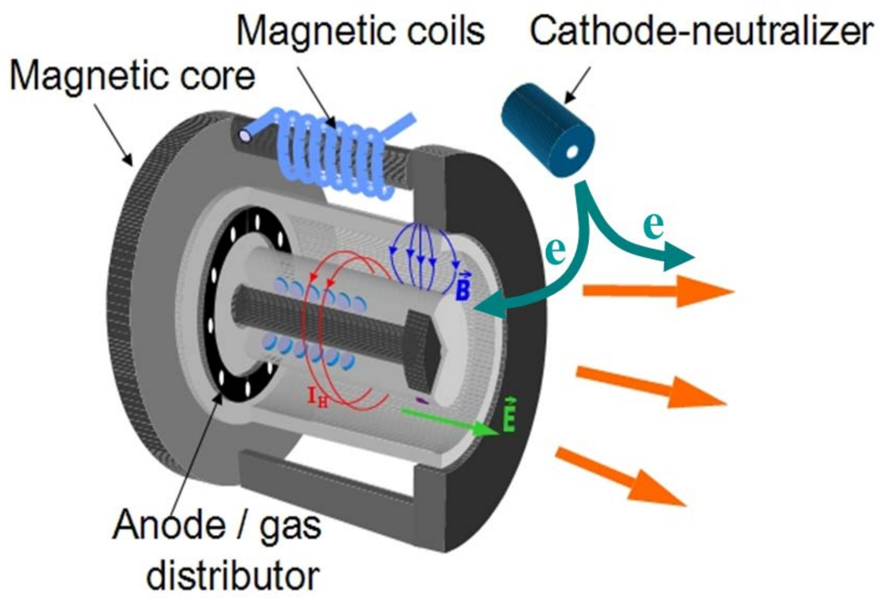
- **Electromagnetic thrust force exerted on thruster magnetic circuit**

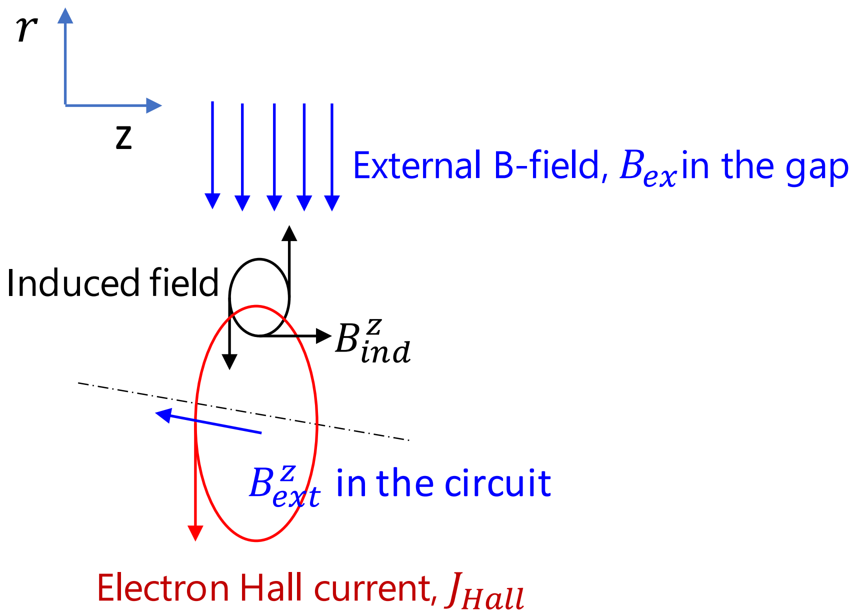
- Low pressure ~ 10^{-1} mtorr
- Gases: Xe, Kr, Ar
- Applied DC (stationary) $\mathbf{E} \times \mathbf{B}$ fields
  - B~ 100 Gauss, V~ 0.1-1 kV
- Quasineutral plasma: $n_e \approx n_i \sim 10^{10} - 10^{12}\ cm^{-3}$
- Electrons are magnetized
- Ideally, equipotential magnetic field surfaces

$$\mathbf{E} = -\mathbf{V_e} \times \mathbf{B}$$

- Ions are not magnetized, accelerated by E- field
- Electron temperature ~ 10-10^2 eV

Thrust density limit – *an idealized thruster case*





- When the induced B-field approaches the applied (external) B-field, **the thrust density:**

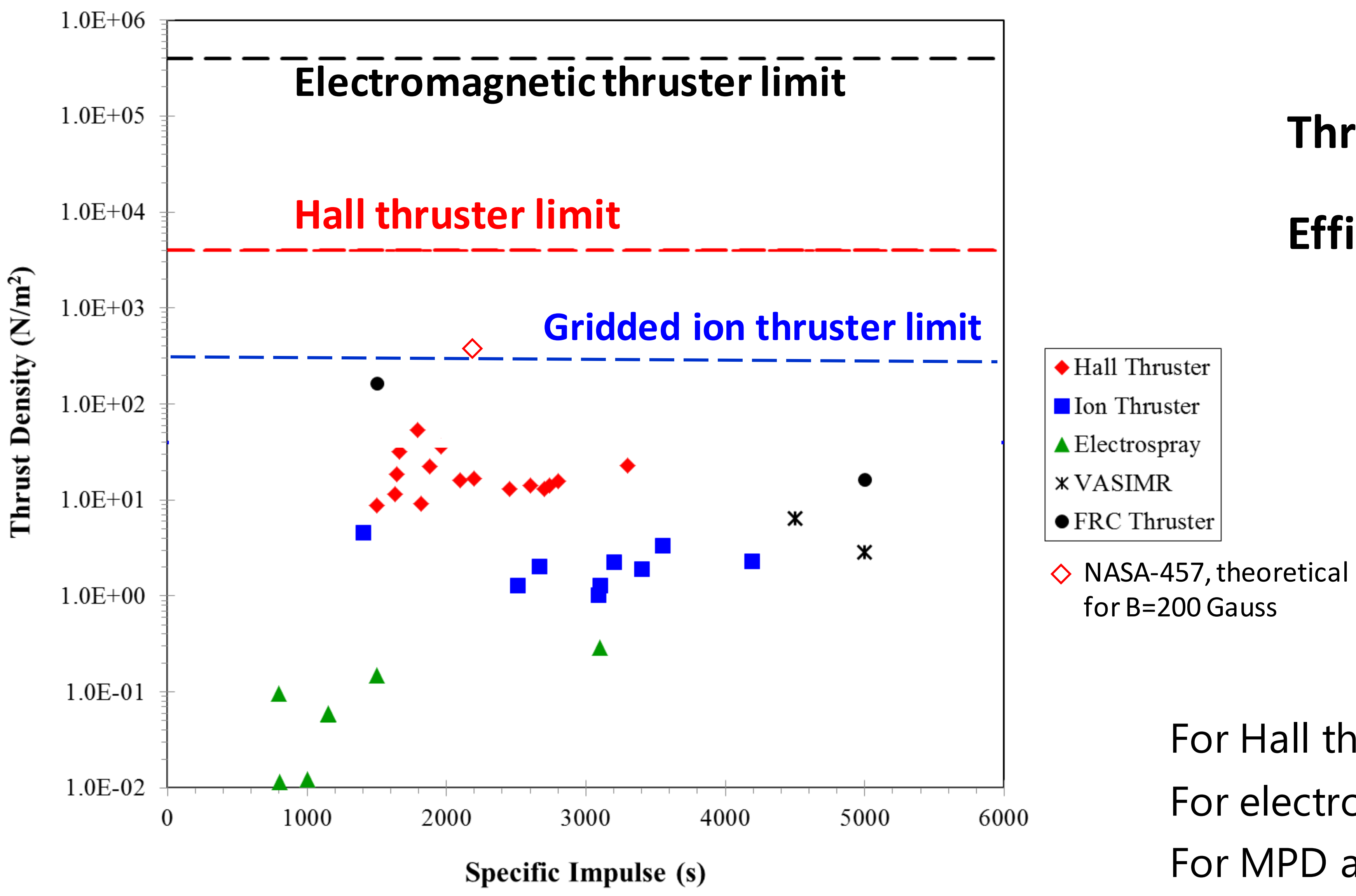
$$\left(\frac{T}{A}\right)_{max} \rightarrow \frac{B^2}{2\mu_0}$$

- B is limited by magnetic properties of the magnetic core
- Larger thrust density -> smaller thruster for a given thrust
- **Relevant to high power thrusters (~ 1 m diameter for 100 kW) and low power thrusters (~ 1 cm diam for 50 W)**

A. Zharinov, Sov. Phys. Tech. Phys. (1967)

J. Simmonds, Y. Raitses, and A. Smolyakov, J. Electric Propul. ***2,*** *12 (2023)*

Thrust density limits: *theoretical vs achieved*



Thrust: $T = \dot{m}V_{exaust}$, N

Efficiency: $\eta \equiv \frac{TV_{jet}}{2P_e}$

For Hall thrusters , efficiency ~ 10-70%

For electrostatic thrusters, efficiency > 50%

For MPD and FRC, < 40 %

What if we would build HT to operate at $B^2/2\mu_0$ limit?

Soulas et al. (2012)

NASA 457M Hall Thruster

Power: 50kW

45.7 cm

Squeeze

9 cm

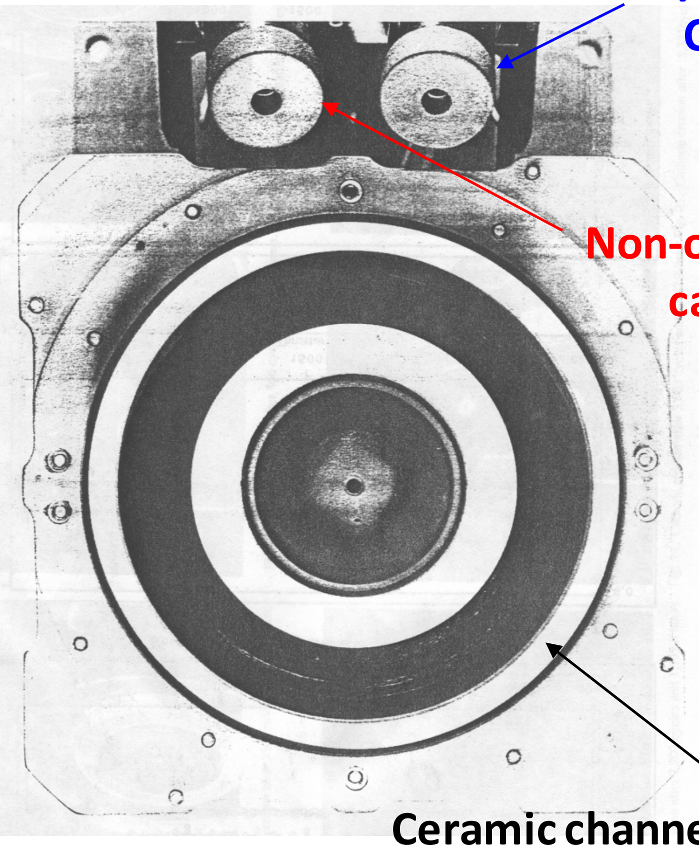
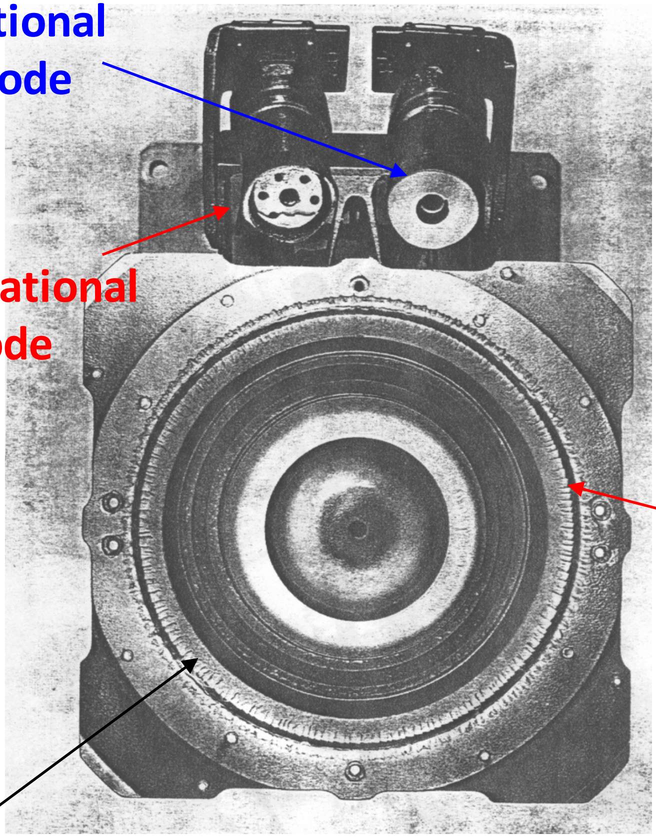
- We assumed

  for NASA thruster, B~ 200 Gauss,

  for a hypothetical thruster, B~ 1 kGauss

Plasma-wall interaction: *lifetime limiting ion-induced erosion*

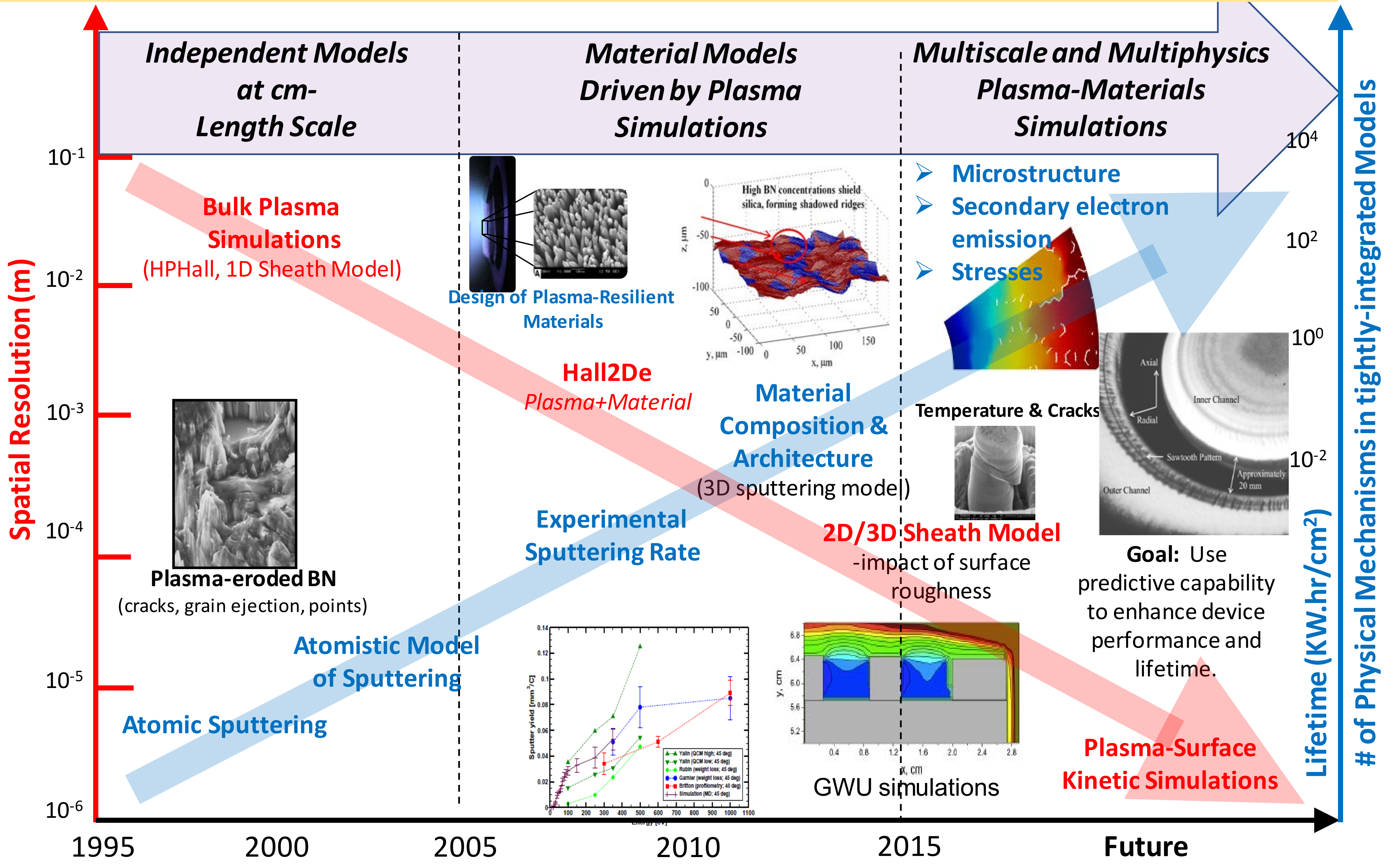
1.35-kW SPT-100 New | **1.35-kW SPT-100 5,700 Hrs**

Courtesy:
L. King
F. Taccagona
Y. Mikellides

MichiganTech
IMIP IPP
JPL
Jet Propulsion Laboratory
California Institute of Technology

Towards Tightly-Coupled Plasma-Material Interaction Science for Space Propulsion



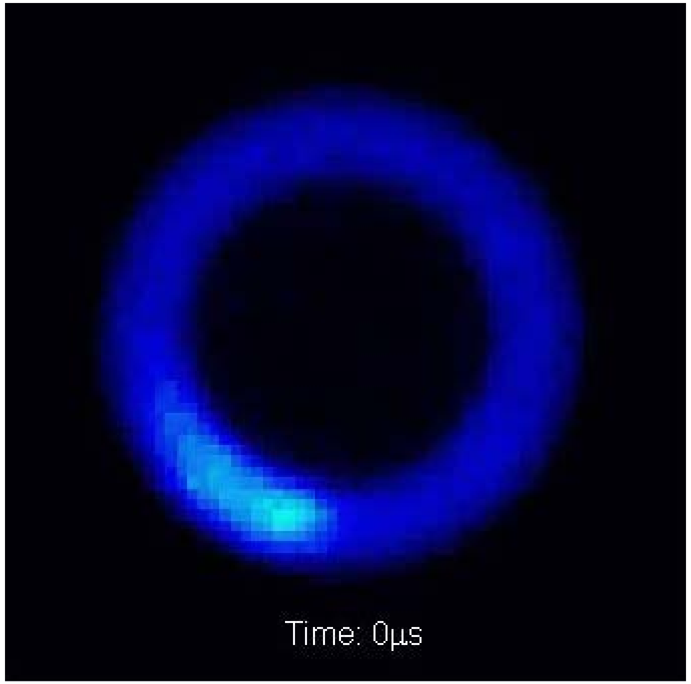
Efficiency limiting anomalous electron cross-field transport

$$\eta \equiv \frac{T V_{jet}}{2 P_e} \propto \frac{I_i}{I_i + I_{e\perp}}$$

$$I_{e\perp} \propto \mu_{e\perp} \approx \frac{\nu_{ano}}{\omega_{ce} B}$$

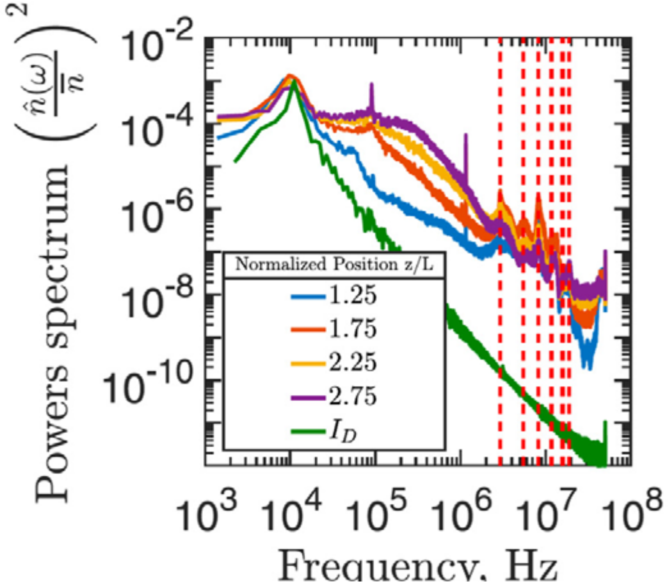
Large scale plasma structures

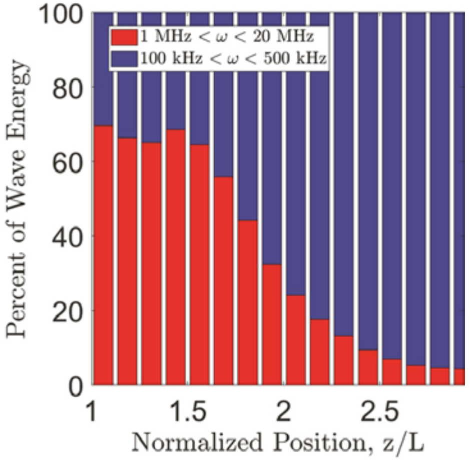
ExB rotating spoke in a 12 cm diameter 2 kW Hall thruster



Small scale fluctuations

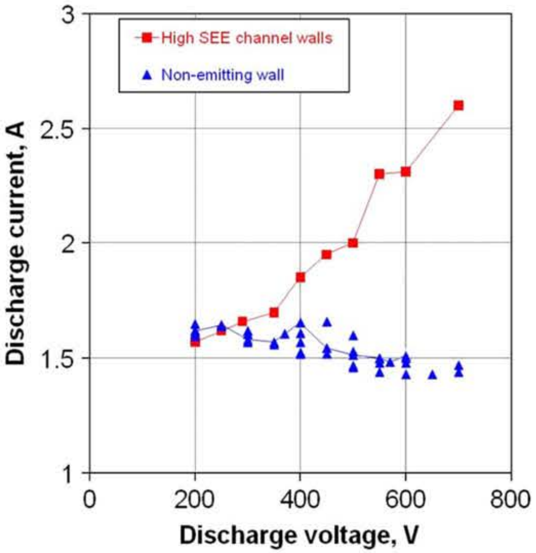
Plasma density oscillations and possible inverse energy cascade in a 9 kW Hall thruster

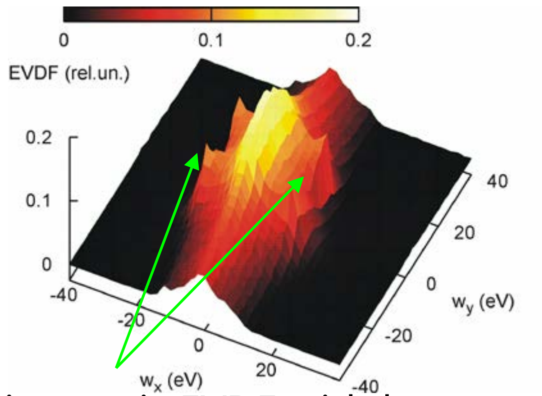




Wall-induced effect on electron cross-field transport

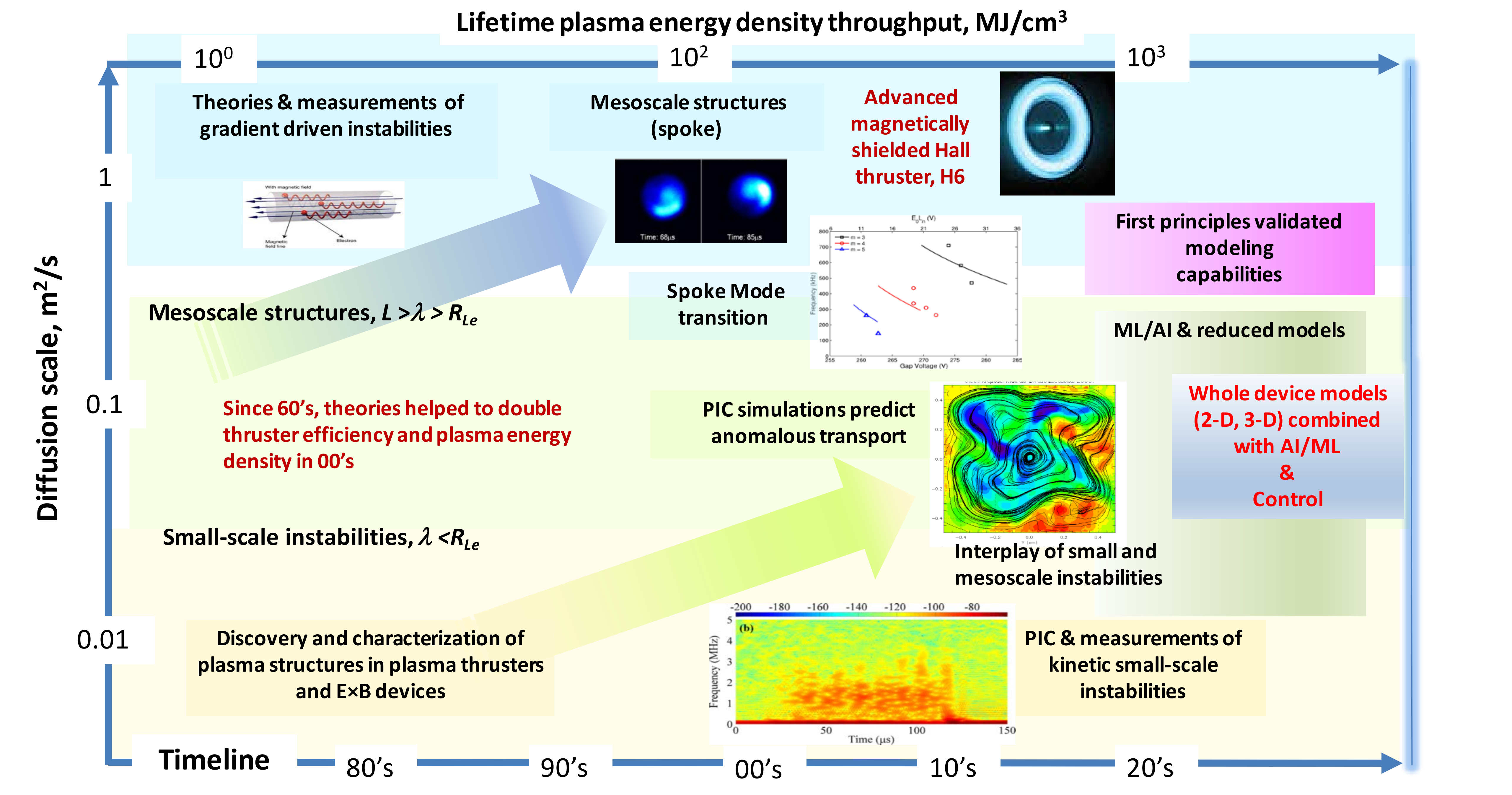
in a 2 kW Hall thruster





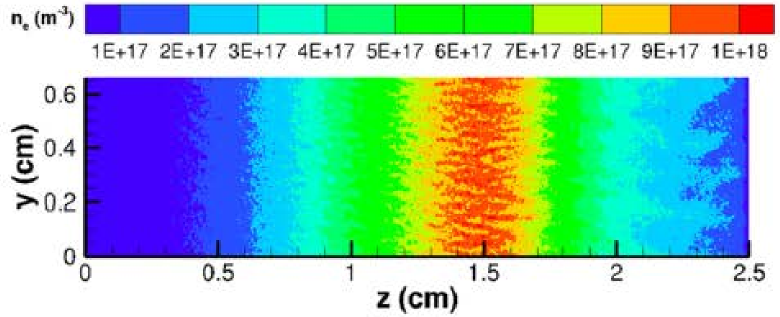
Anisotropic EVDF with beams of SEE electrons driving near-wall conductivity

Cross-field Transport: *Towards Predictive Modeling and Design of Powerful Plasma Devices*



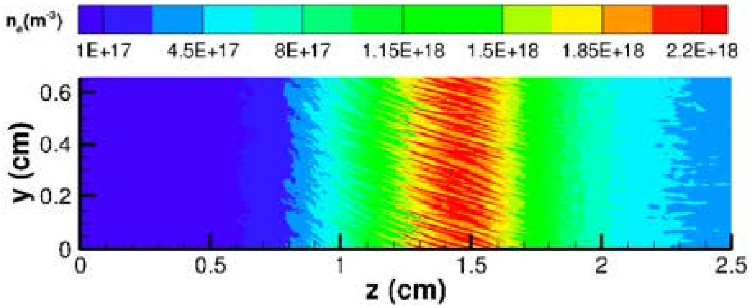
Importance of 3-D realistic size Particle-in-Cell modeling: *comparison of cross-field mobilities for SPT-100*

3-D **2-D**



$\mu_{\perp,3D}$=0.4 $m^2V^{-1}s^{-1}$

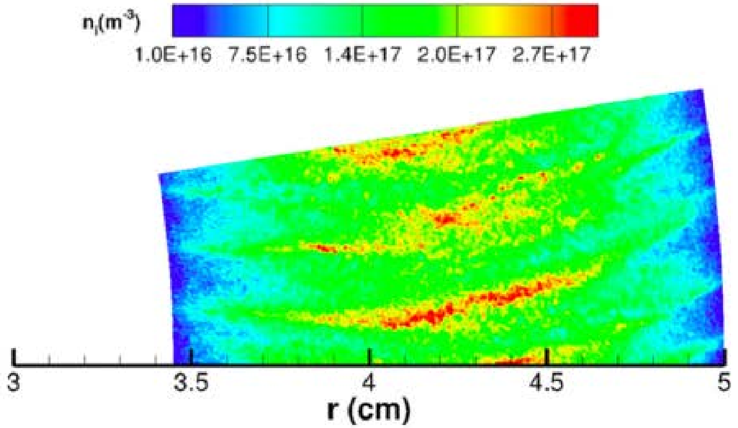
(a)



$\mu_{\perp,2D}$=2.2 $m^2V^{-1}s^{-1}$

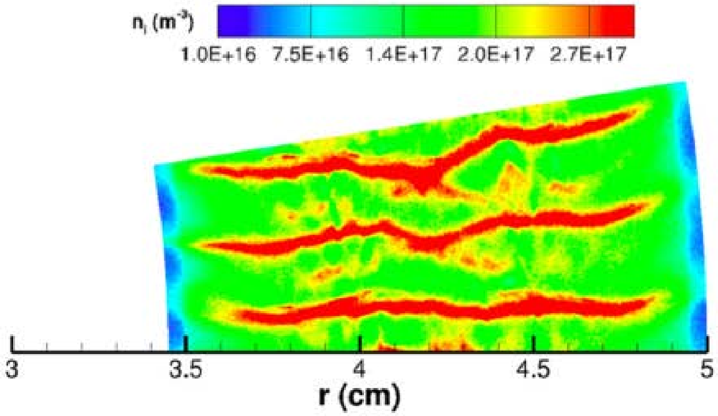
(b)

1/40th of the channel
In azimuthal direction



$\mu_{\perp,3D}$=0.4 $m^2V^{-1}s^{-1}$

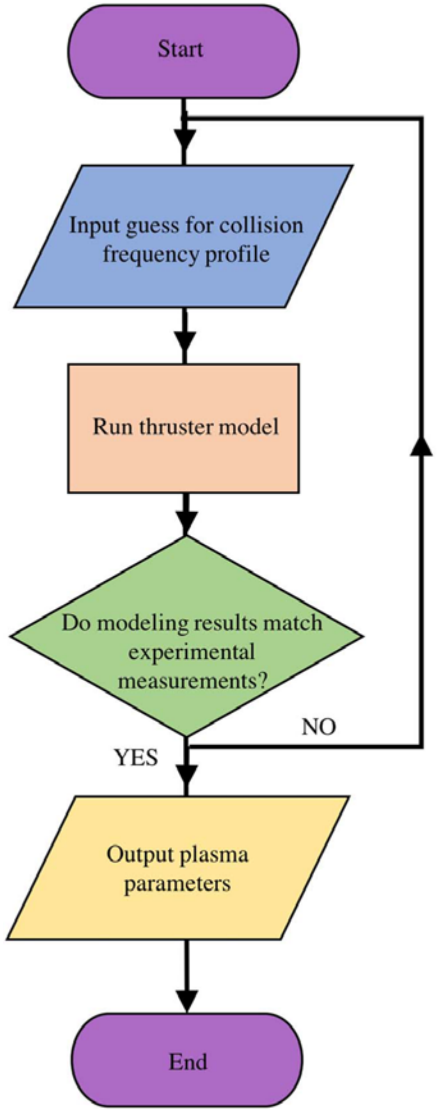
(c)



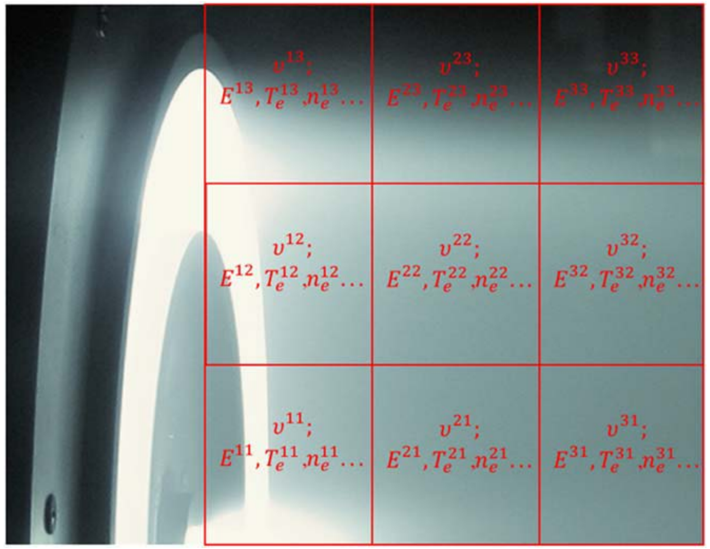
$\mu_{\perp,2D}$=3.4 $m^2V^{-1}s^{-1}$

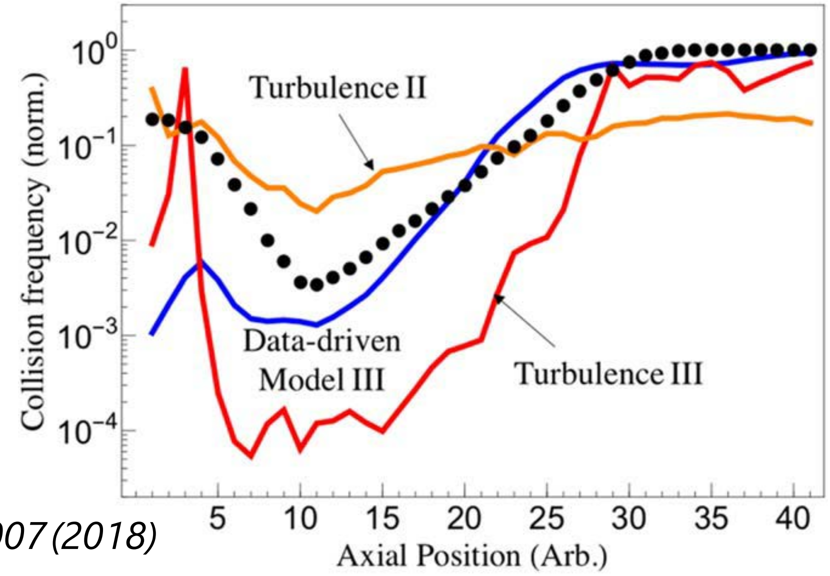
(d)

Data-driven modeling of anomalous transport



- Comparison with first-principles models





$$I_{e\perp} \propto \mu_{e\perp} \approx \frac{\nu_{ano}}{\omega_{ce} B}$$

From a correlation analysis of different data driven models (ML regression):

$$\nu_{ano} \propto \omega_{ce} \left(\frac{u_{ion}}{\upsilon_{ExB}}\right)^2$$

- Not apparent physics meaning
- Explore the applicability to other regimes and thrusters
- Need to add wall effects

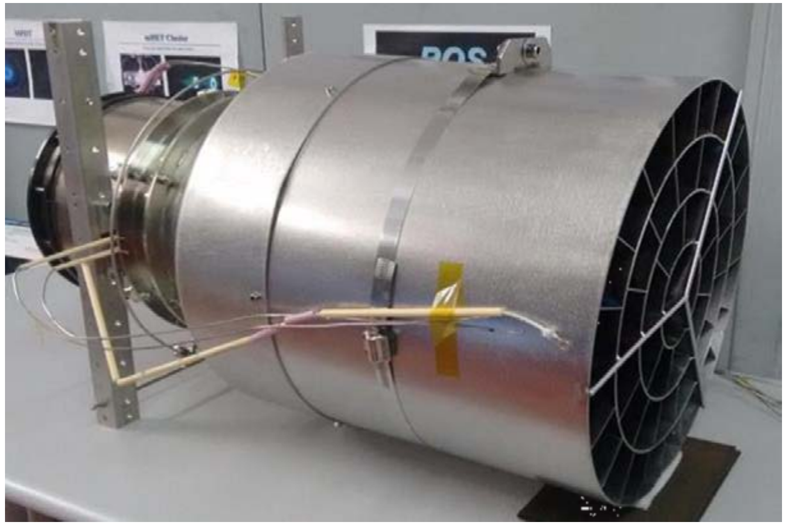
B. Jorns, Plasma Sources Sci. Technol. 27 104007 (2018)

Sustainable plasma propulsion will have to use molecular propellants (e.g. air, water, CO_2)

- Xe and Kr are traditional propellants for Hall and ion thrusters
  - Heavy atoms (longer residence time in the channel), large cross sections with ionization potentials, 12.1 eV and 13.9 eV, respectively
- Expensive and limited supply
- Looking for propellants with inexhaustible abundance on and at near Earth and in Solar system

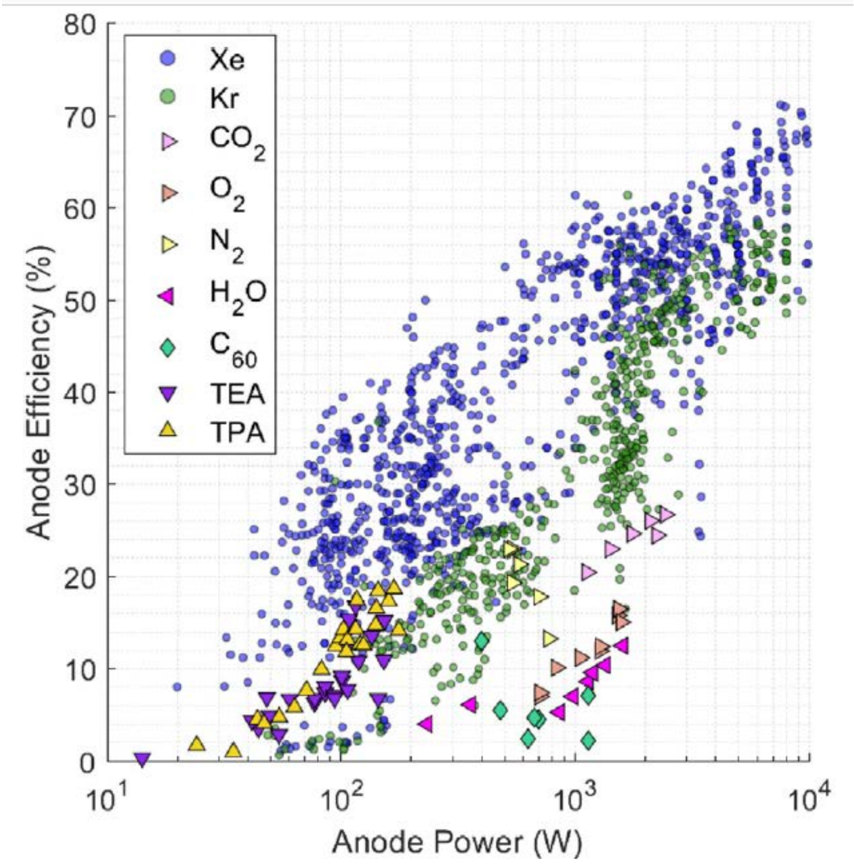
J.M. Tejeda and A. Knoll, Acta Astronautica, 211, 702 (2023)

- Airbreathing plasma propulsion by ESA/Sitael

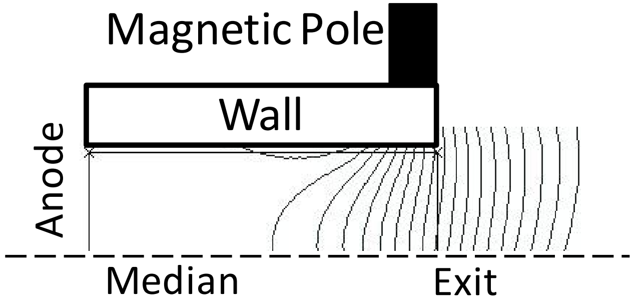


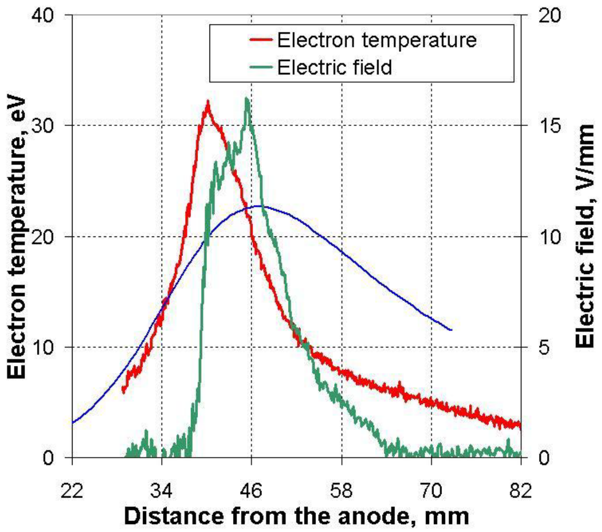
Need novel thruster configurations to sustain high ionization of molecular propellants and achieve high performance

- Efficiency of Hall thrusters with alternative propellants



- Typical distribution of electron temperature and electric field measured in Xe Hall thruster





- For high ionization,

$$\frac{\lambda_{iz}}{L} \gg 1$$

$$\lambda_{iz} = \frac{\upsilon_a}{n_e \langle \sigma_{iz} \upsilon_e \rangle}$$

$$\upsilon_a = \sqrt{kT_a/M_a}$$

- For plasma stability,

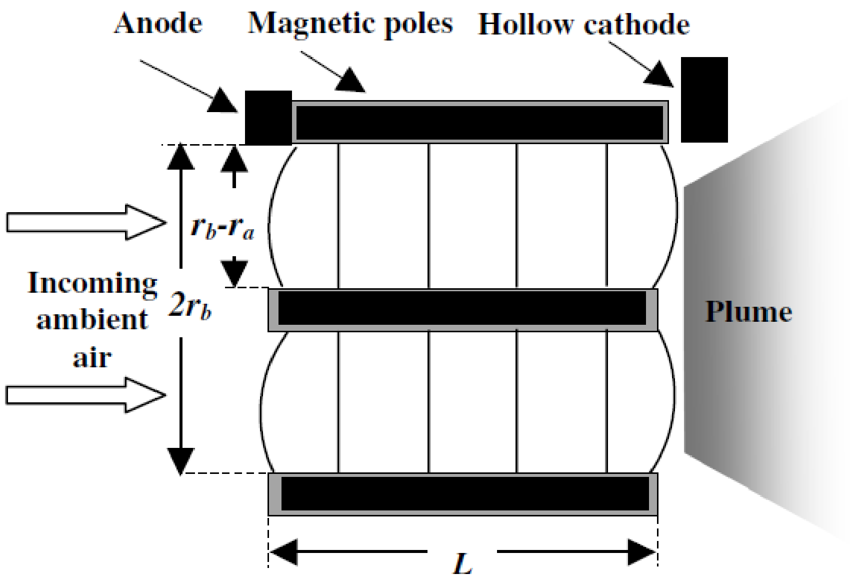
$$\frac{dB_r}{dz} > 1$$

V-G. Tirila, A. Demairé and Ch. N. Ryan, *Acta Astronautica* 212, 284 (2023)

Y. Raitses, D. Staack, M. Keidar, and N.J. Fisch, Phys. Plasmas 12, 057104 (2005)

Alternative concepts, examples: *beam generated air plasmas*

- Off board beam powered Hall thruster

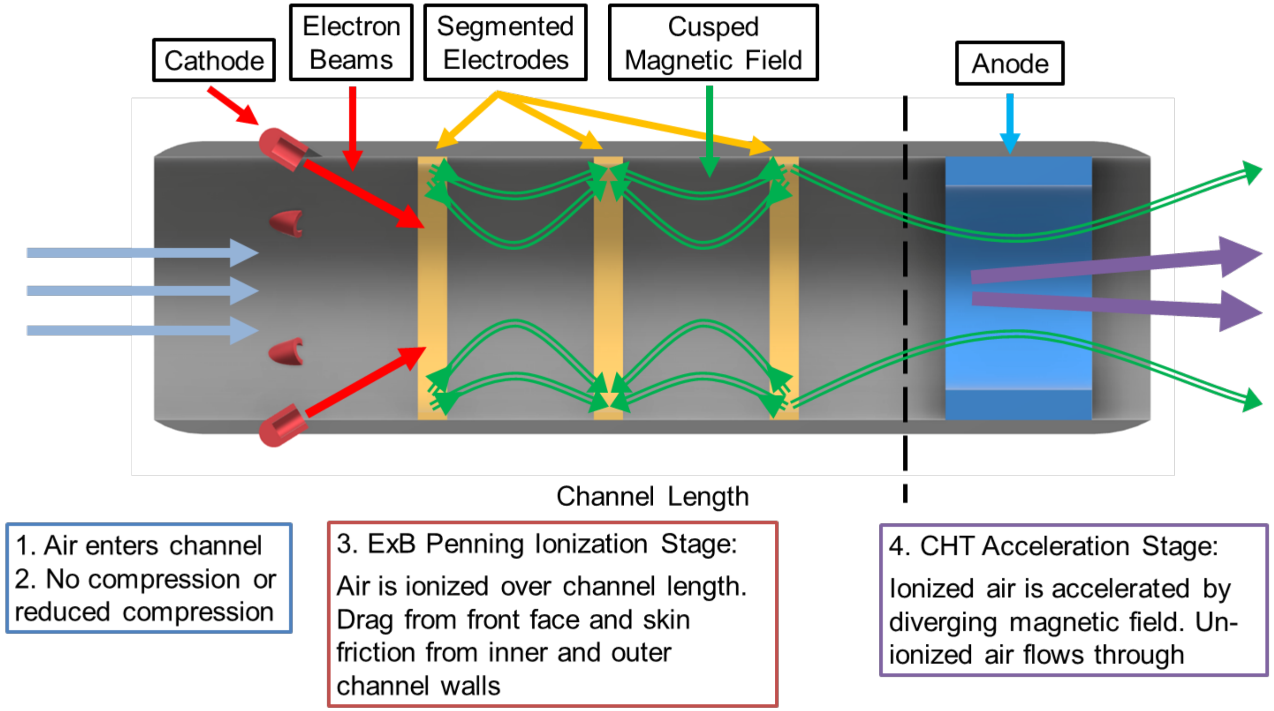


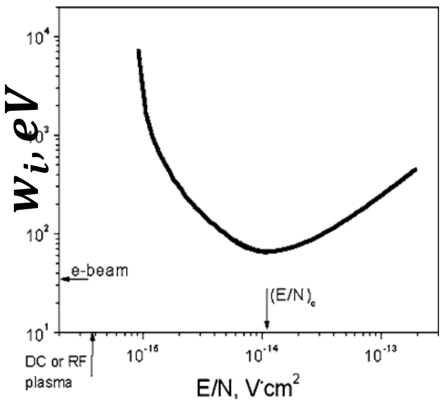
S. Macheret, M. Shneider, R. Miles, Phys. Plasmas 13 (2006)

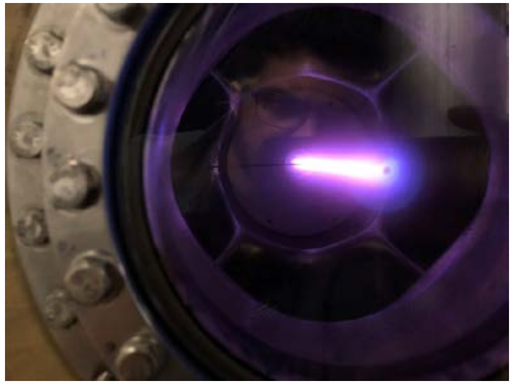
L. Pekker and M. Keidar, Propuls. Power, 28 (2012)

Y. Raitses, J. Simmonds, N. Chopra. IEPC-2022-443, June 2022

- On-board electron beam generated airbreathing plasma







Concluding remarks

- Plasma propulsion is a critical technology for space exploration with low power (nano, micro, small) and higher power satellites (for interplanetary missions such as to Mars)
- Needs:
  - Experimentally validated, whole device models to make predictable design, performance, lifetime
    - coupled with materials models
    - supported by data-driven ML models
  - High thrust density regimes relevant to high power and low power
  - Diagnostic tools for model validation and monitoring of thruster health
- Novel approaches:
  - **Sustainable plasma propulsion** requires understanding of generation and acceleration of molecular plasmas in space propulsion environments
- Novel propulsion concepts (e.g. magnetic reconnection plasma thruster)

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Princeton Collaborative Low Temperature Plasma Research Facility (PCRF)

2024 Call of User Proposals

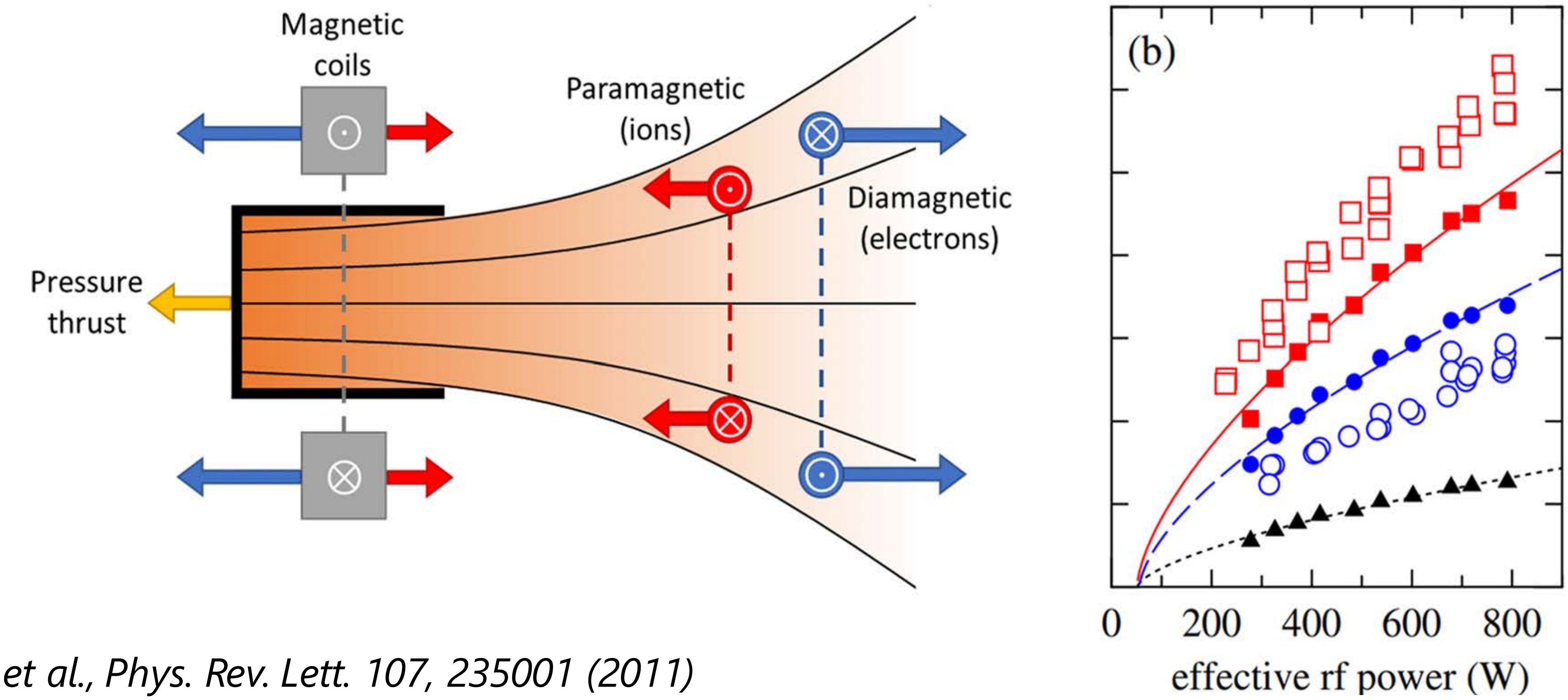
- Call for proposals opens: October 9th , 2023
- Call for proposals closes: December 15th, 2023
- External Independent Panel Review: ~1.5 month
- Notification of Principal Investigators: by February 5, 2024
- PCRF facility considers also out-of-cycle proposals throughout the year depending on facility utilization.

http://pcrf.pppl.gov

PCRF

Backup slides

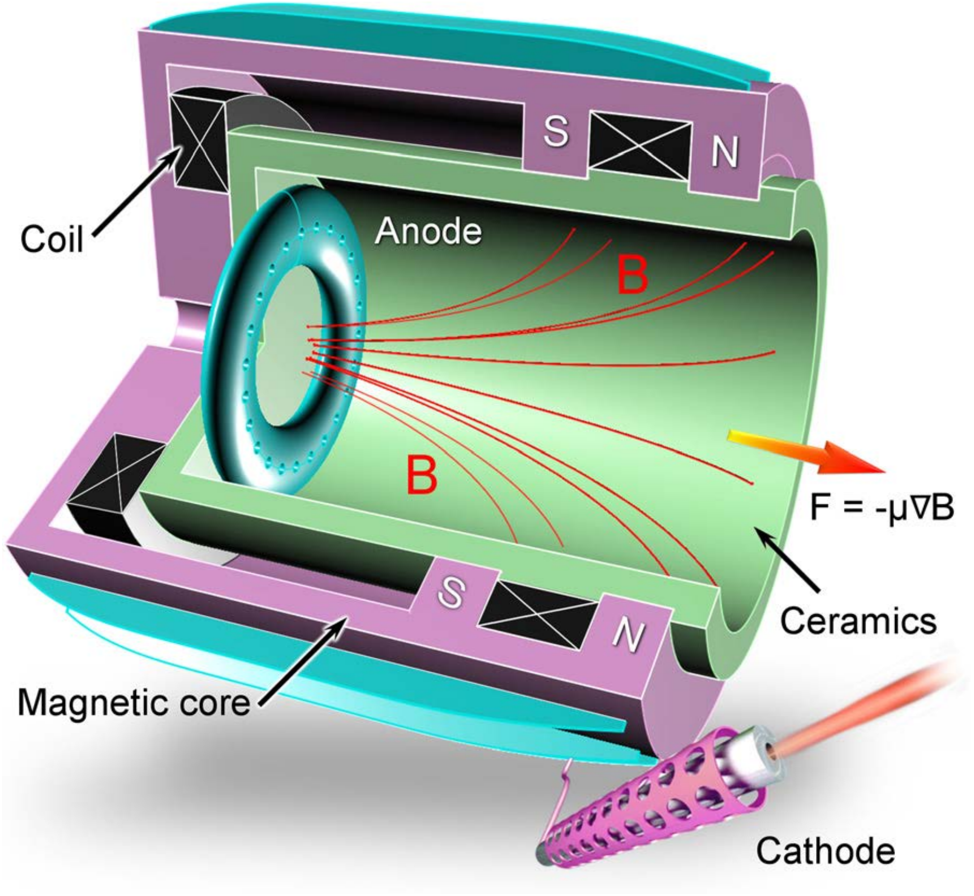
Magnetic nozzle



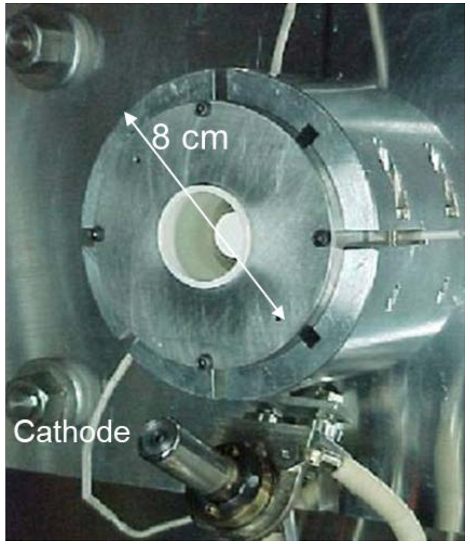
Takahashi et al., Phys. Rev. Lett. 107, 235001 (2011)

FIG. 28. (Left): schematic of the azimuthal currents in the magnetic coils and in the plasma of a divergent MN. Paramagnetic azimuthal currents rotate in the same direction as coil currents and attract each other, producing magnetic drag (negative magnetic thrust). Ions develop a small paramagnetic current in, e.g., HPTs and ECRTs. Diamagnetic azimuthal currents rotate in the opposite direction as coil currents and repel each other, producing magnetic thrust. Electron azimuthal current is diamagnetic and dominates in the plasma. Additionally, the plasma creates pressure thrust on the chamber walls. (Right): experimentally measured magnetic thrust (open blue circles) and total thrust (open red squares) from Ref. 345 in a helicon plasma thruster. Reproduced with permission from Takahashi *et al.*, Phys. Rev. Lett. **107**, 235001 (2011). Copyright 2011 American Physical Society. The solid blue circles and solid red squares correspond to the expected values from a model. The black triangles represent the modeled pressure thrust.

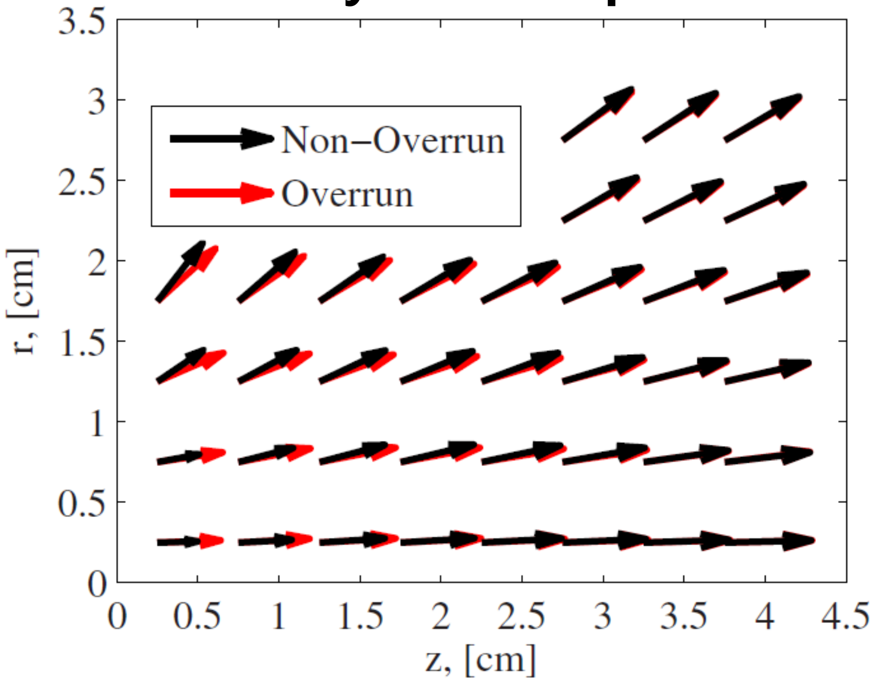
Possible solution to erosion: *cylindrical Hall thruster*



- Diverging magnetic field topology
- No central channel wall
- Closed **E**×**B** drift (like in conventional Hall thruster)
- Electrons confined in a magneto-electrostatic trap
- Ion acceleration in a large volume-to-surface channel
- Plume focusing controlled by the cathode mode

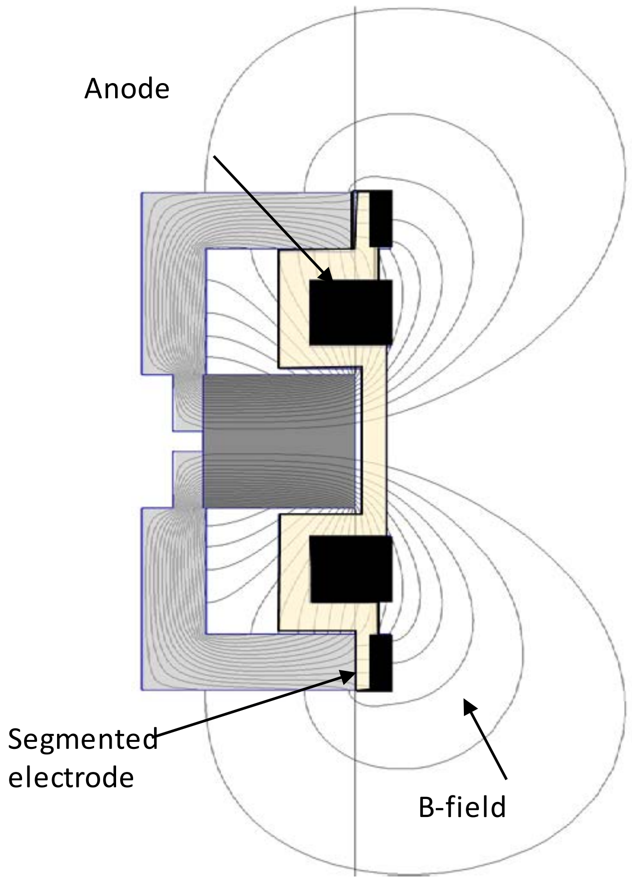


Ion velocity vector map from LIF

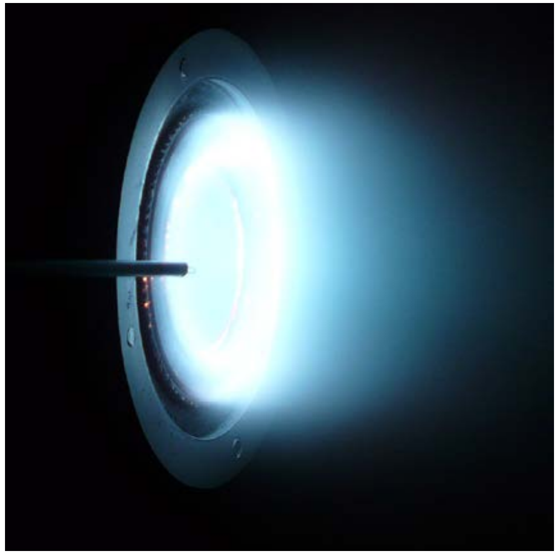


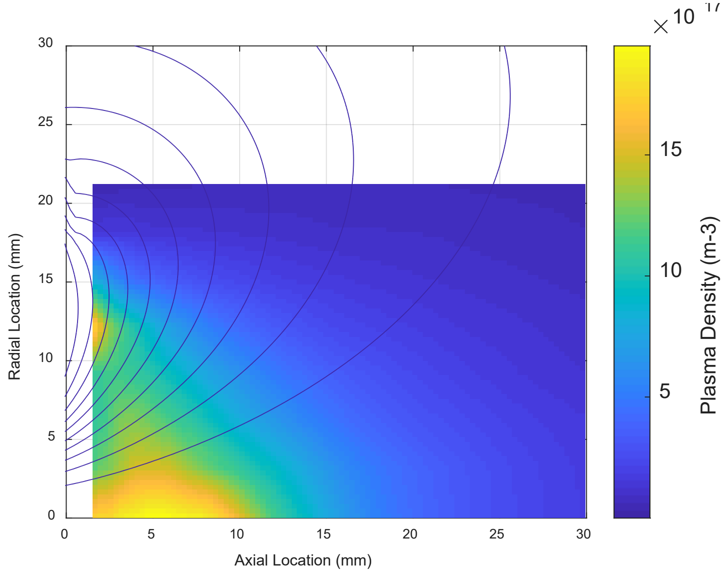
Y Raitses and N. J. Fisch, Phys. Plasmas, 8, 2579 (2001)
A. Smirnov, Y. Raitses, and N.J. Fisch, Phys. Plasmas **14**, 057106 (2007)
R. Spektor et al., Phys. Plasmas **17**, 093502 (2010)

Possible solution to erosion and heat: *wall-less Hall thruster*



3 cm diam., 200 W wall-less Hall thruster operating with Xe





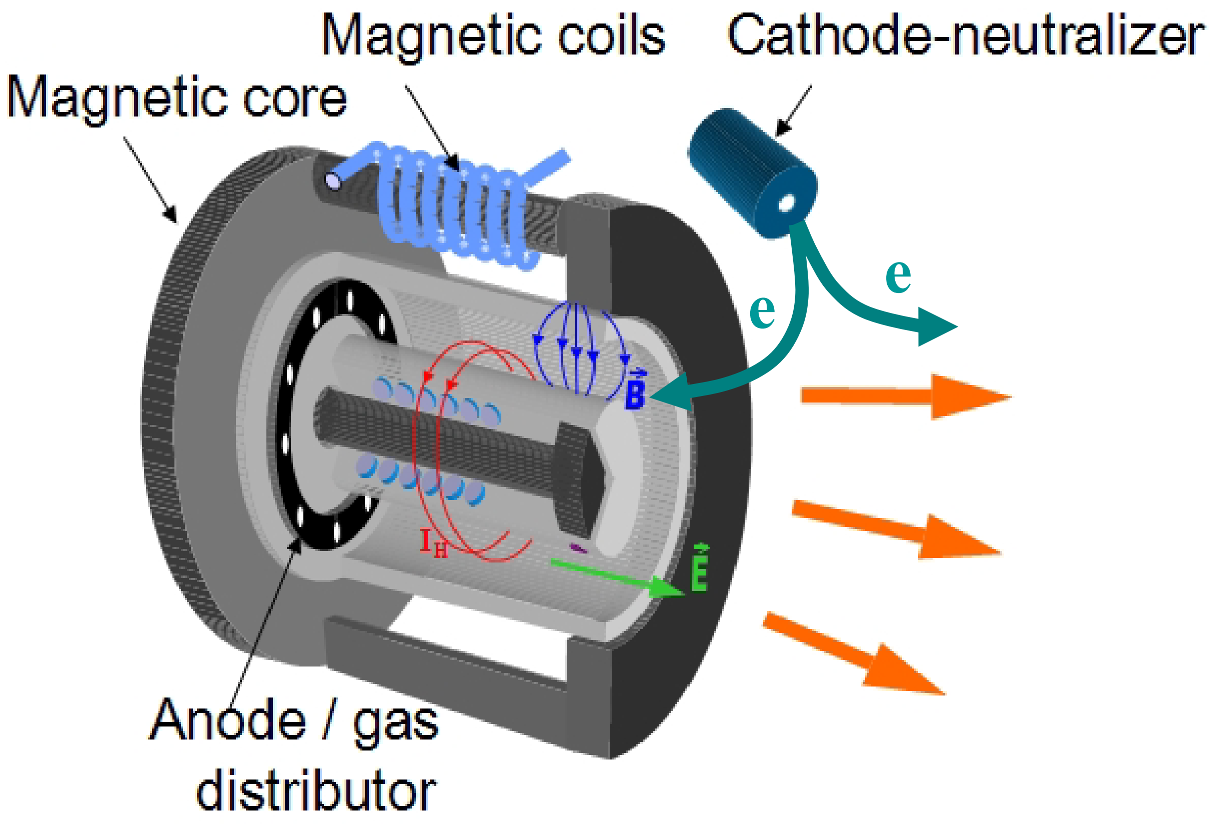
Measured ion density in the wall-less thruster

- No side walls – no erosion
- Plasma in a strong magnetic field ~ 1-3 kGauss
- Two thrust mechanisms: 1) by $E \times B$ (Hall acceleration) at the anode and 2) plasma expansion in diverging magnetic field at the axis

$$T/A \sim n_e k T_e \ln(B_{max}/B_{min})$$

Simmonds and Raitses, 2021

Hall Thruster working principle in glance



- **Electromagnetic thrust force exerted on thruster magnetic circuit**

- Applied DC (stationary) fields: $\mathbf{E} \times \mathbf{B}$
- Quasineutral plasma: $n_e \approx n_i$
- Electrons **E×B** drift in azimuthal direction
- Heavier ions almost unaffected by B-field

$$r_{Li} > L \gg r_{Le} = \frac{m_e v_\perp}{eB}$$

- Equipotential magnetic field surfaces

$$\mathbf{E} = -\mathbf{V_e} \times \mathbf{B}$$

- Ions are accelerated by electric field
- Accelerated ion flux is neutralized by electrons

$$\Gamma_e = \Gamma_{ion}$$