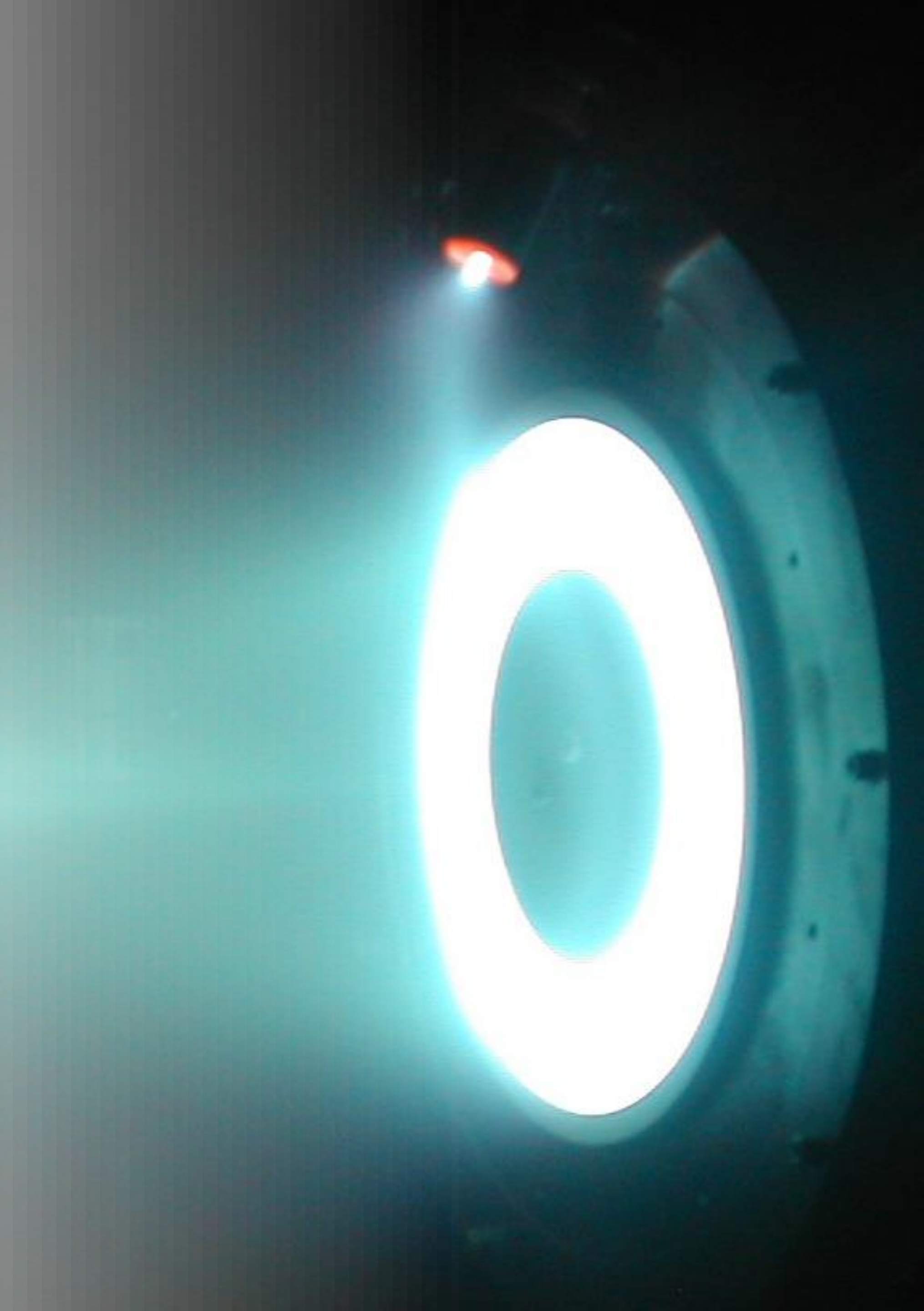
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Low Temperature Plasma IV: Applications

Yevgeny Raitses

PPPL



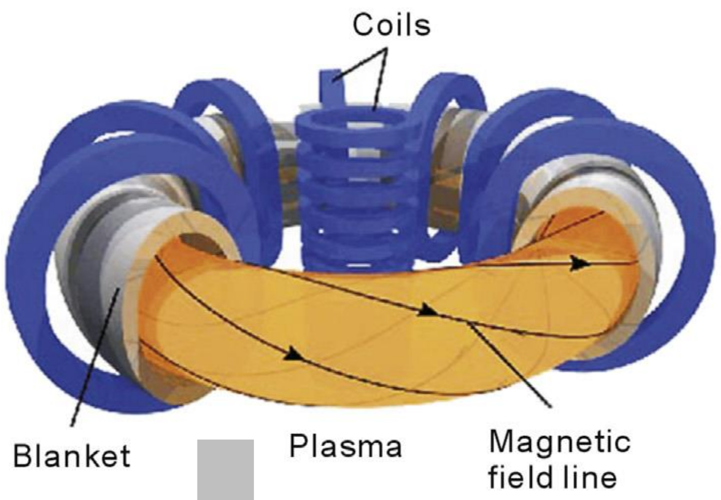
GSS, Princeton, August 2020

Synopsis

- **Magnetized plasma devices** $(r_L = \frac{mv}{qB} \ll L, \omega_c/\nu_t >> 1)$
- **Magnetically-controlled LTPs for material processing at atomic scale**
- **Electromagnetic plasma propulsion: *Hall thrusters***

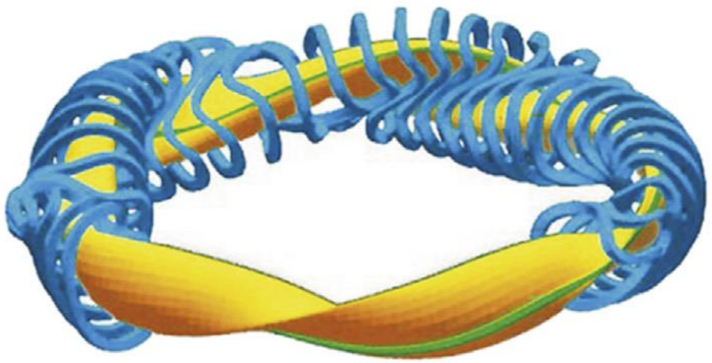
Fusion plasma devices with magnetic confinement

Tokamak



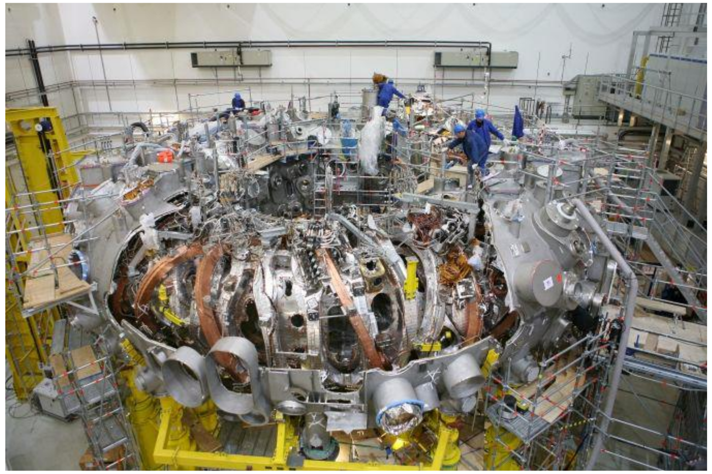
Y. Xu Matter Radiat 1, 192 (2016)

Stellarator

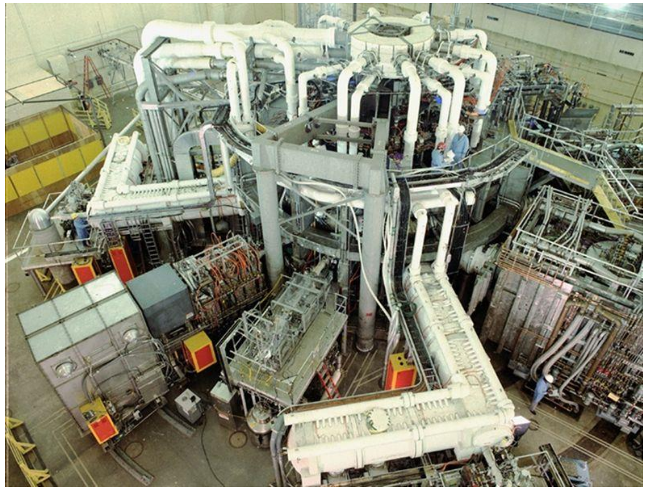


https://www.ipp.mpg.de/w7x

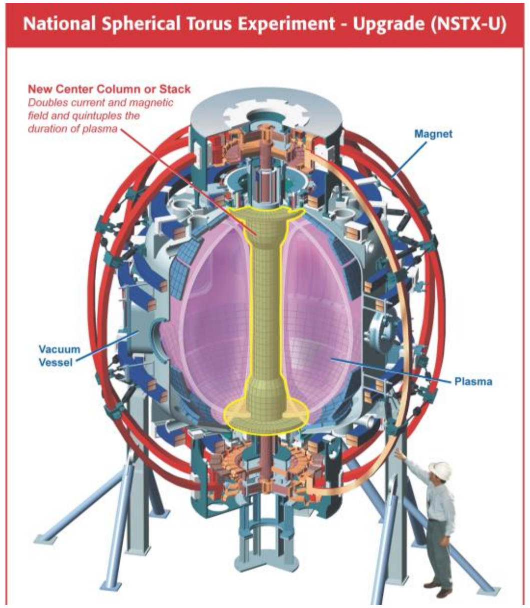
Wendelstein 7-X
Max Planck IPP, Germany, 2015



Tokamak Fusion Test Reactor (TFTR)
at PPPL, 80's-90's

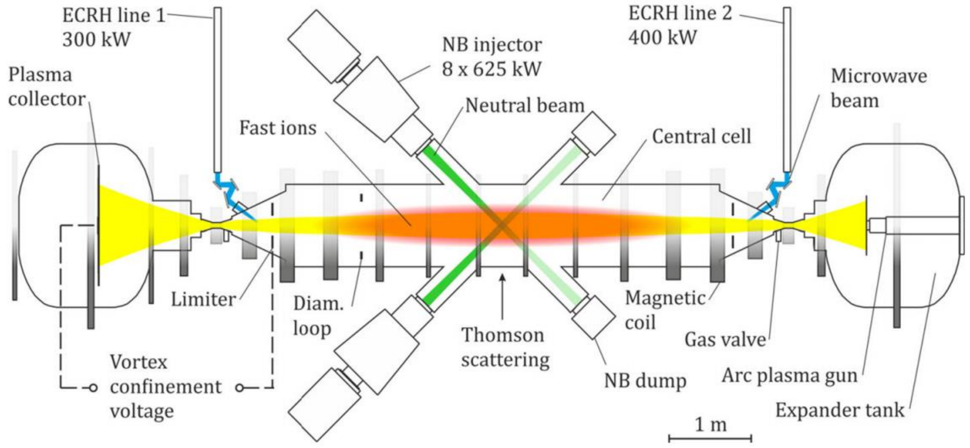


https://w3.pppl.gov/tftr/



http://www.pppl.gov/nstx-u

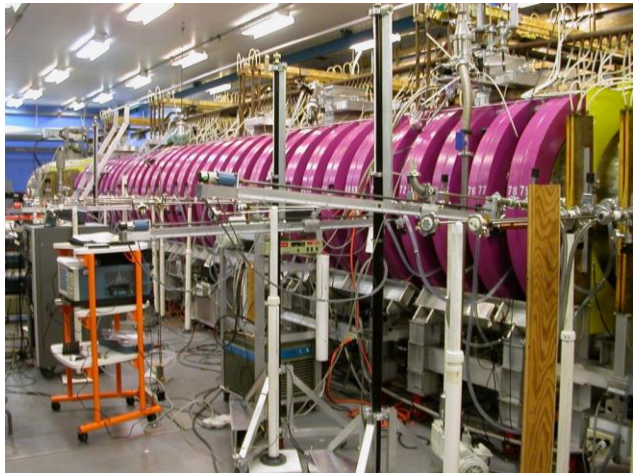
Gas Dynamic Trap (GDT), Budker, Russia



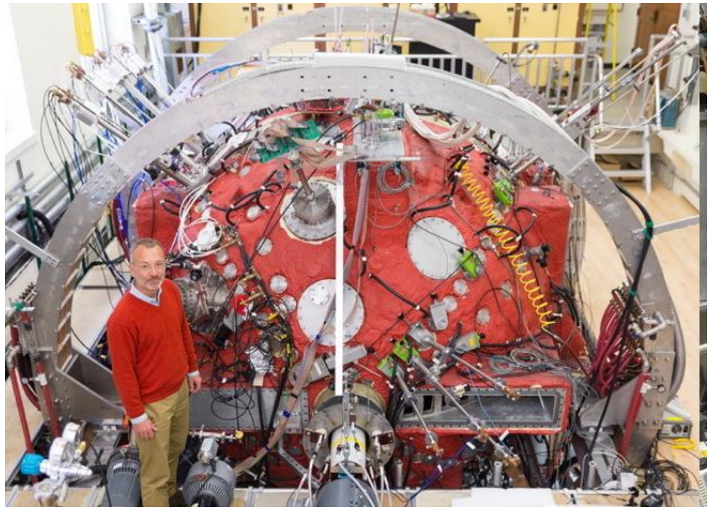
A. A. Ivanov and V. V. Prikhodko, Plasma Phys. Control. Fusion ***55*** *(2013)*

Basic science experiments with magnetized plasmas

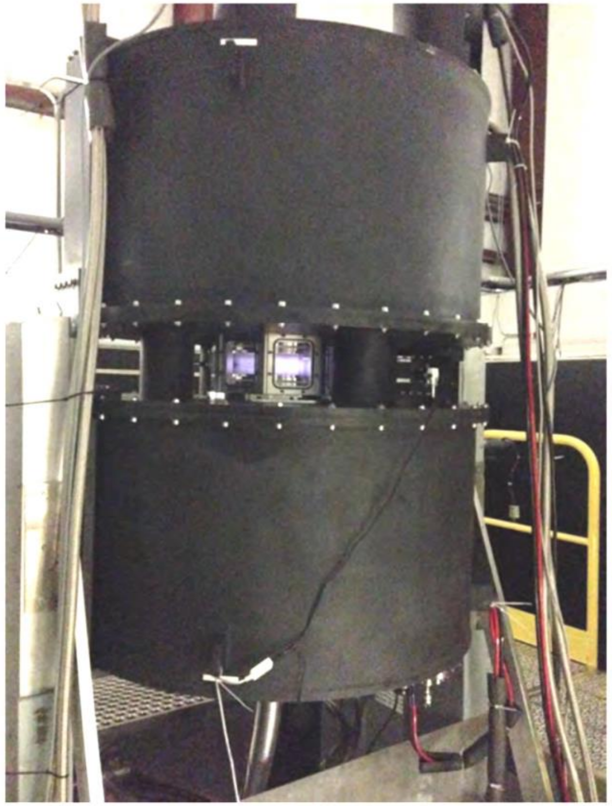
Large Area Plasma Device (LAPD)
UCLA, https://plasma.physics.ucla.edu/



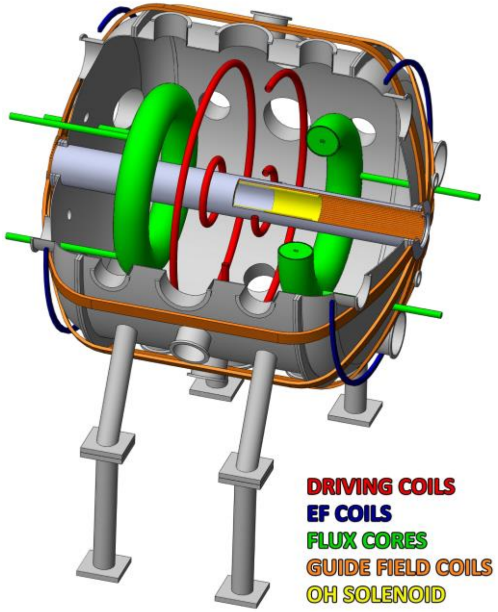
Big Red Ball (BRB)
Wisconsin, https://wippl.wisc.edu/big-red-ball-brb/

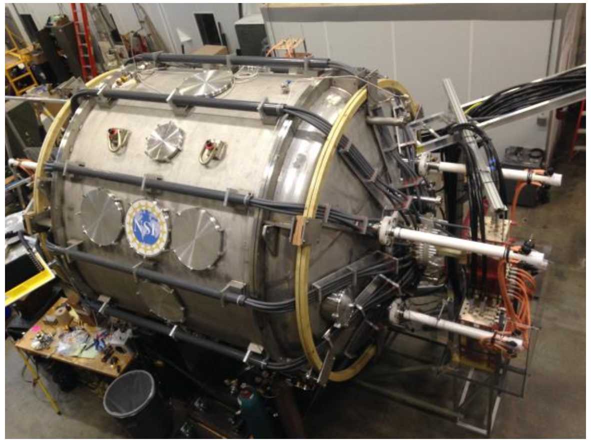


Magnetized Dusty Plasma Experiment (MDPX)
Auburn, http://wp.auburn.edu/mprl/



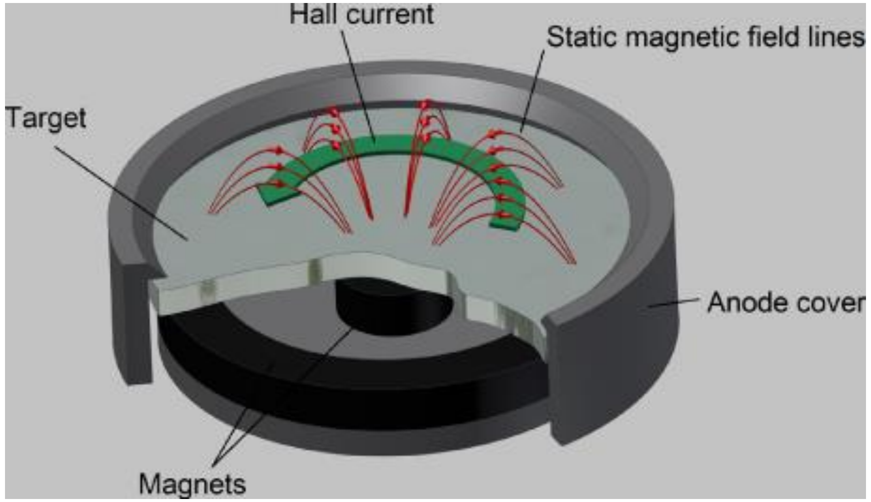
FLARE
PPPL, https://flare.pppl.gov/



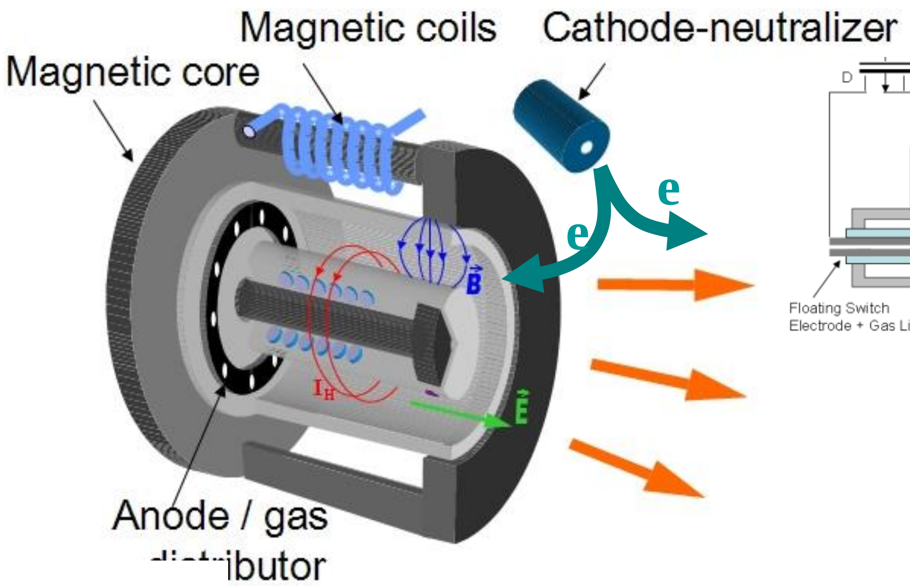


Why to apply magnetic field in LTP?

- **Sputtering magnetron**

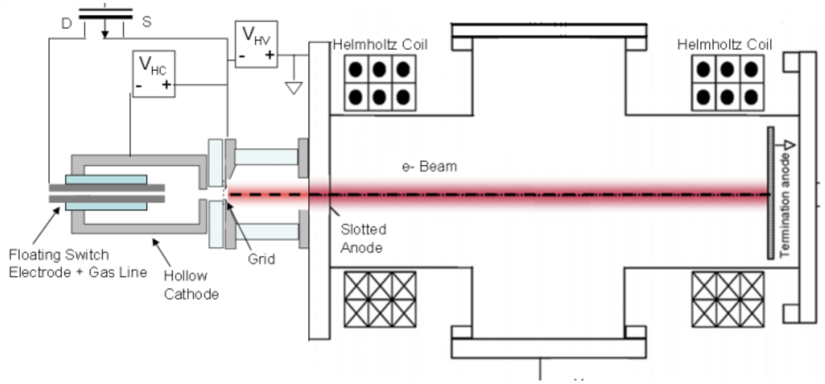


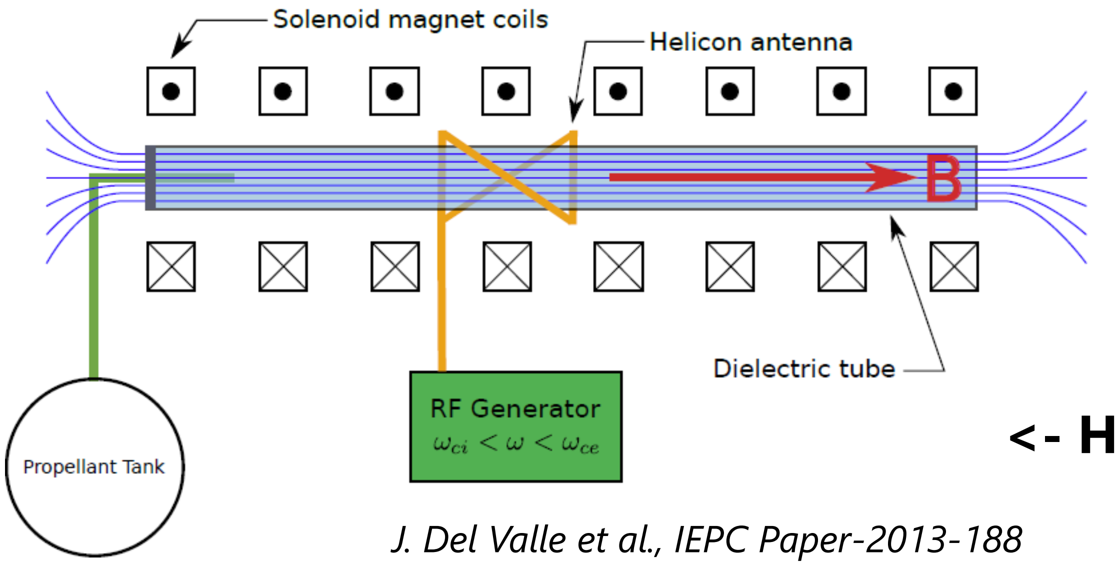
- **Hall thruster**



- **Beam-plasma for materials processing**

US Patent by S. Walton et al., 2009

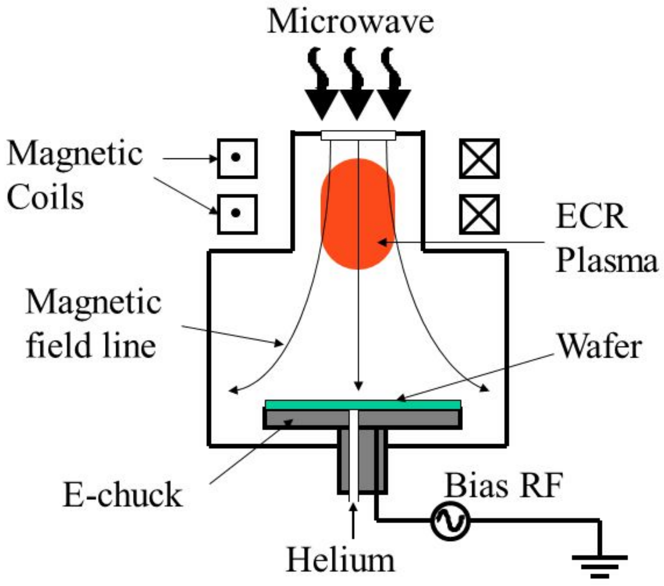




<- Helicon plasma source

J. Del Valle et al., IEPC Paper-2013-188

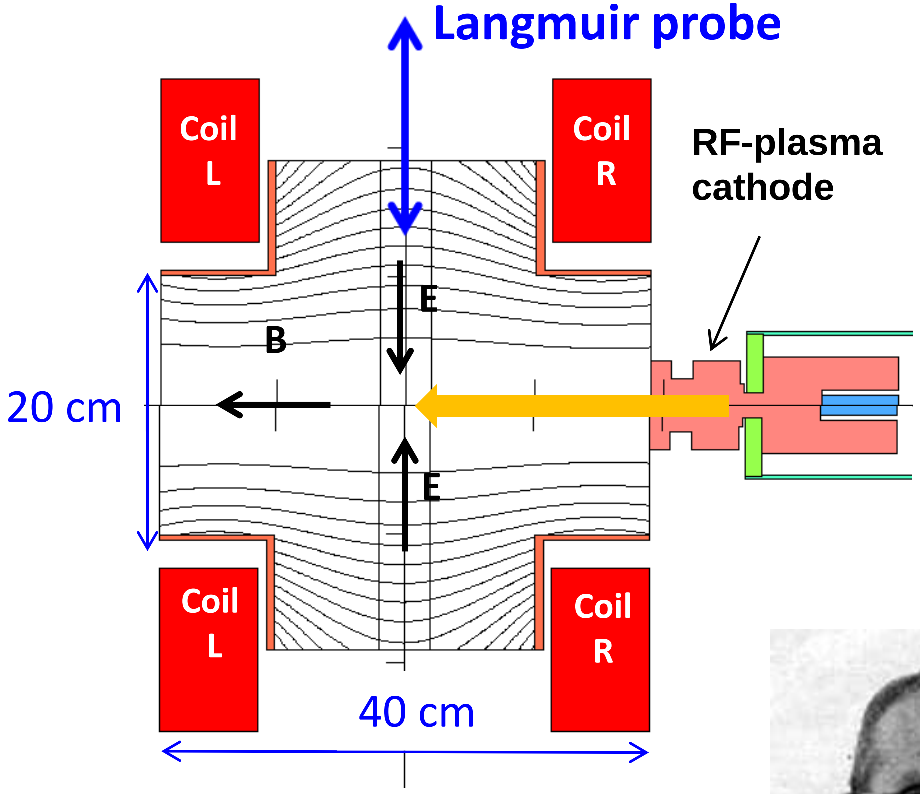
ECR plasma source ->



H. Xiao, PhD thesis, UT Austin

What is the use for the magnetic field in LTP?

- **e-Beam plasma source**

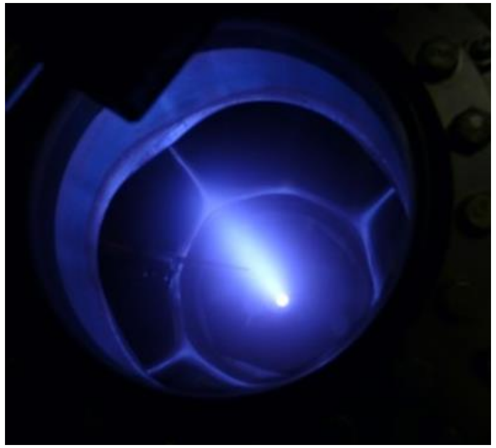


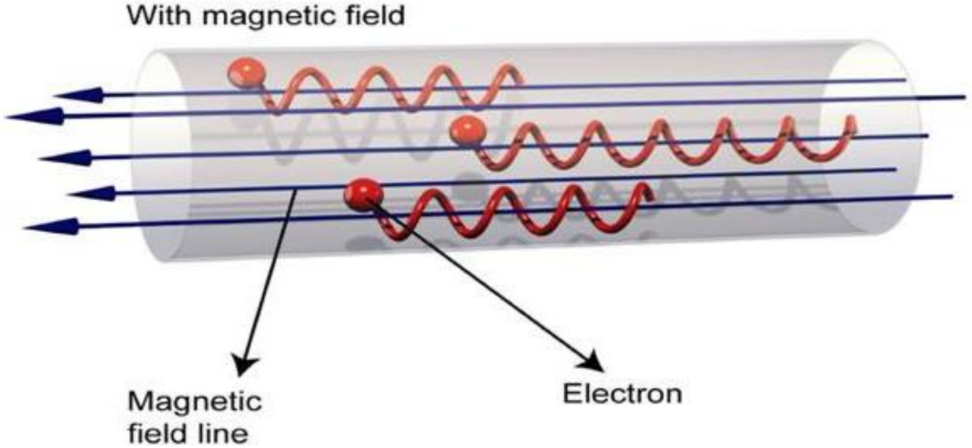
- Pressure: ~ mtorr
- Gas: 80% Ar+10% H_2
- Magnetic field ~ 10-15 G
- Electron Beam
  - Energy <10^2 eV
  - Current ~ 1 A

Frans Michel Penning
Philips, 40's -?

What to expect from the LTP with applied magnetic field?

- **e-Beam plasma source**





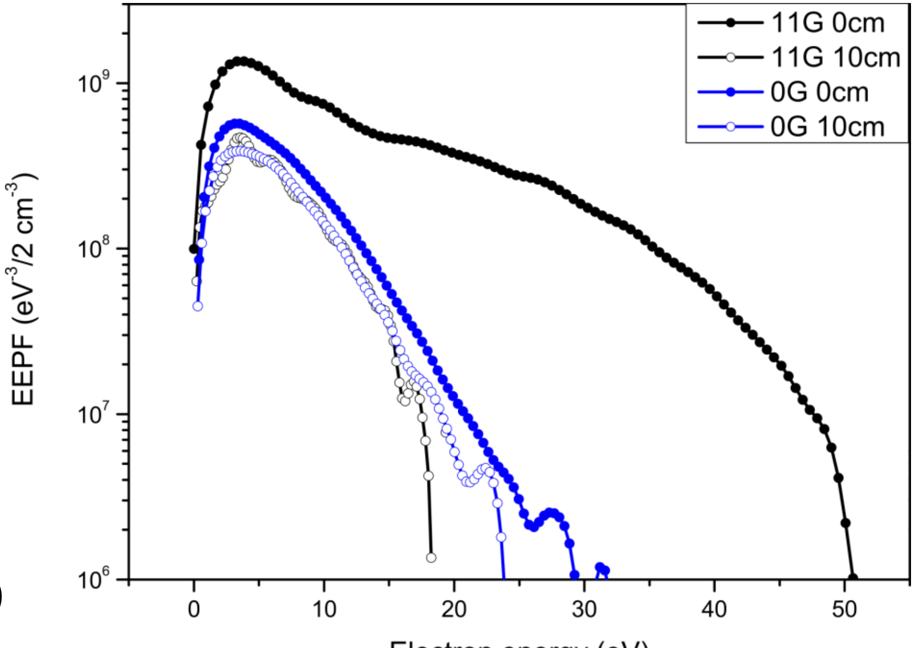
- **Langmuir probe measured electron energy distribution function (EEDF)**

$$N = \frac{2\sqrt{2m}}{|e|S_p}\int_0^{-\infty} I_e''(V)\sqrt{V/e}\,dV$$

$$T_e = \frac{4\sqrt{2m}}{3NS_p}\int_0^{-\infty} I_e''(V)(V/e)^{3/2}\,dV.$$

V. Godyak, V. Demidov, J. Phys. D: Appl. Phys. 44 (2011)

- **PPPL experiment**



- **Reduced transport across B-field**

$$\nu_t \propto n_g = P_g/kT_g$$

$$(\Omega_{ec}/\nu_t)^2 \gg 1$$

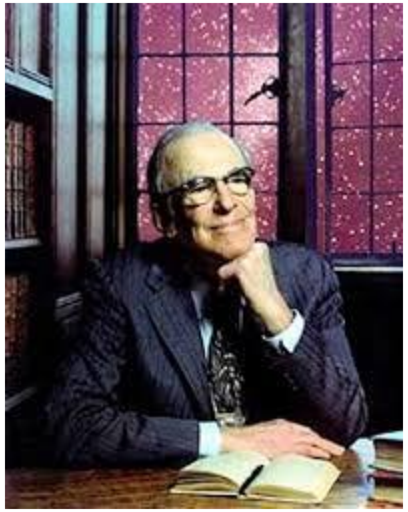
$$\mu_\perp \approx \frac{\mu}{(\Omega_{ec}/\nu_t)^2}$$

$$D_\perp \approx \frac{D}{(\Omega_{ec}/\nu_t)^2}$$

6-X higher plasma density and much more energetic electrons at the axis with B-field than without

Fang, Raitses, Tully, 2020

Plasma propulsion research at PPPL



Interplanetary Travel Between Satellite Orbits[1]

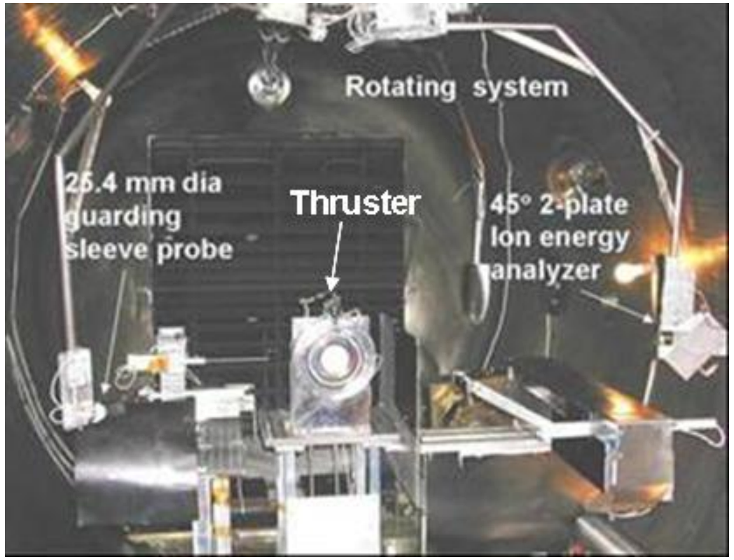
By LYMAN SPITZER, JR.[2]

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

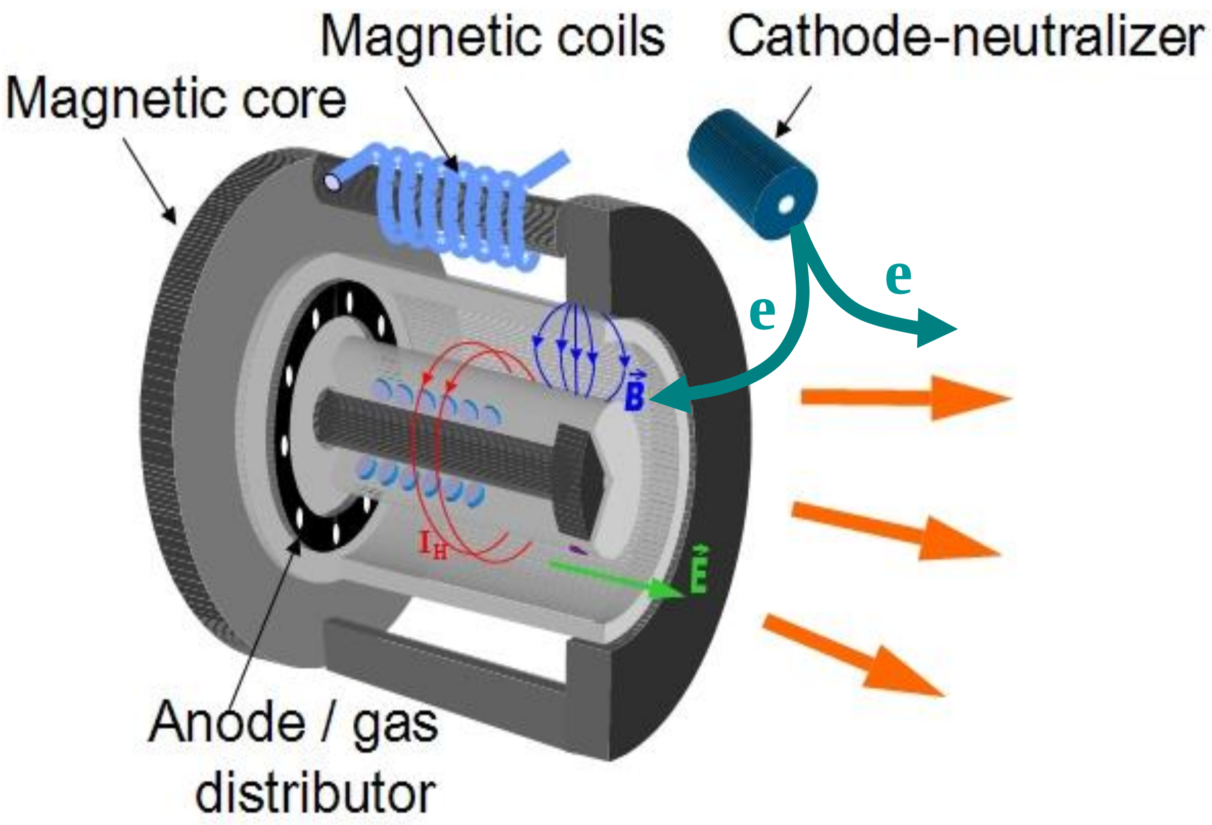
- Hall Thruster Experiment (HTX) in 1998 by N.J. Fisch and Y. Raitses and graduate students L. Dorf, A. Smirnov, A. Litvak and D. Staack
  - Goal: to develop scientific understanding of plasma thruster physics

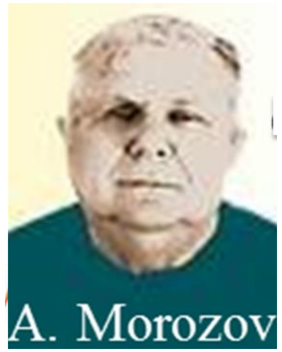


http://htx.pppl.gov

1999 → 2020

Hall thruster invented in 60's, flown in 70's





Xenon, Krypton
V ~ 100-1000 V
B ~ 10^2 Gauss

Dimensions:
L < 10 cm
D ~ 1-50 cm

Low gas pressure < 1 mtorr
– ions move without collisions

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

$$r_{Le} \ll L < r_{Li}$$

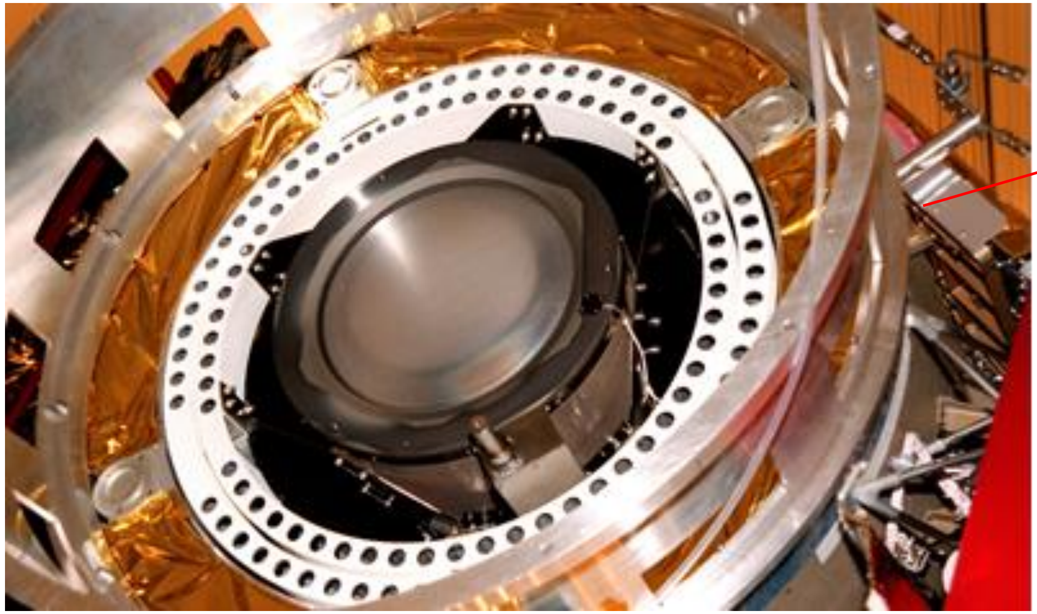
- Equipotential magnetic field surfaces

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

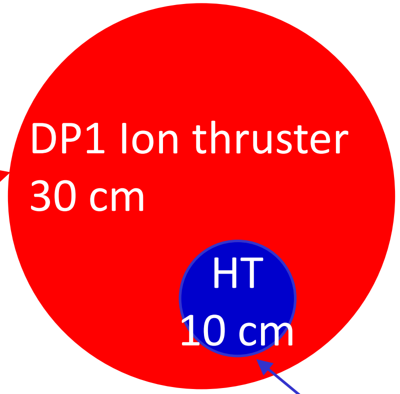
- Ions are accelerated by electric field
- Accelerated ion flux is neutralized by electrons
- Thrust force exerted on magnets

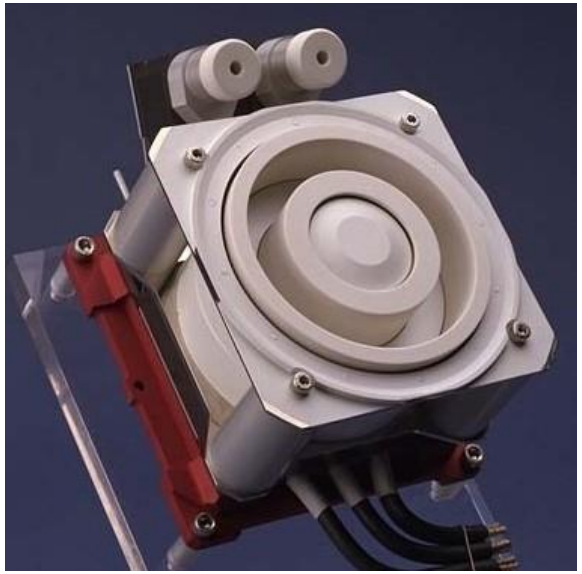
Comparing thrust densities for Hall and ion thrusters

Deep Space 1 NSTAR Ion thruster



At 1.5 kW, thrust ≈ 50 mN





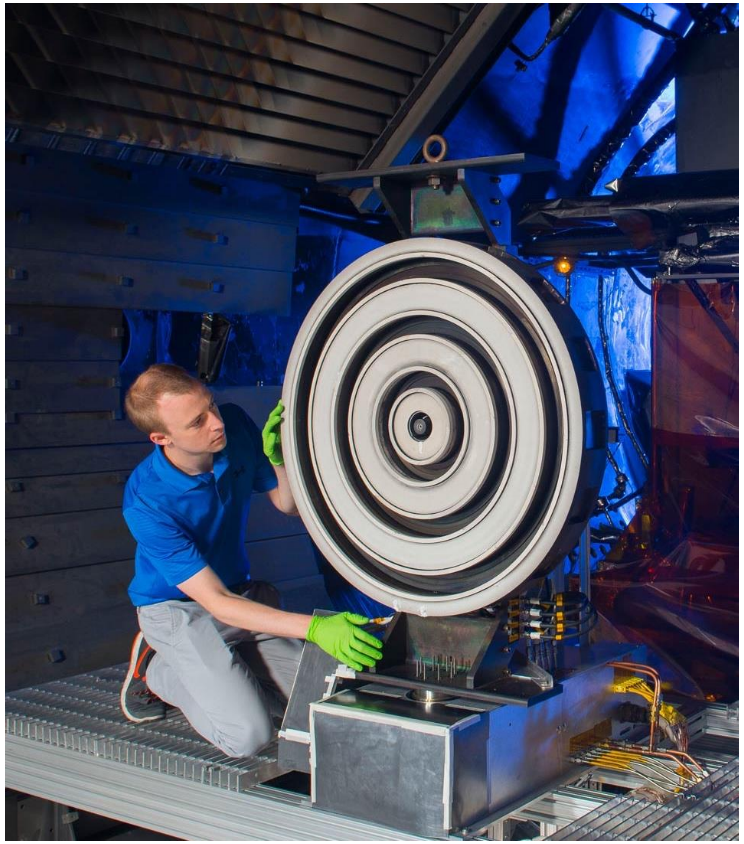
SMART -1, ESA
Hall thruster:
PPS-1350:
Power: 1500 W
OD = 10 cm
Thrust= 90 mN

Unlike ion thrusters, Hall thrusters are not space charged limited
They have also a simpler design than ion thrusters

Operational Satellites with Electric/ Plasma Propulsion (2008)

World's largest and most powerful Hall thruster: X-3

Nested Hall thruster, X-3



Power	2-200 kW
Efficiency	> 60%
Thrust	0.2 N– 10 N
Isp	1550 – 3500 s for **Xe**
Diameter	0.80 m
Thrust density	Up to ≈ **20 N/m²**
Mass	250 kg

At higher power levels (over 600 kW, provided by a few X3s clustered together), the X3 has the potential to actually carry astronauts to Mars

Courtesy Prof. Ben Jorns of Univ. Michigan Ann Arbor

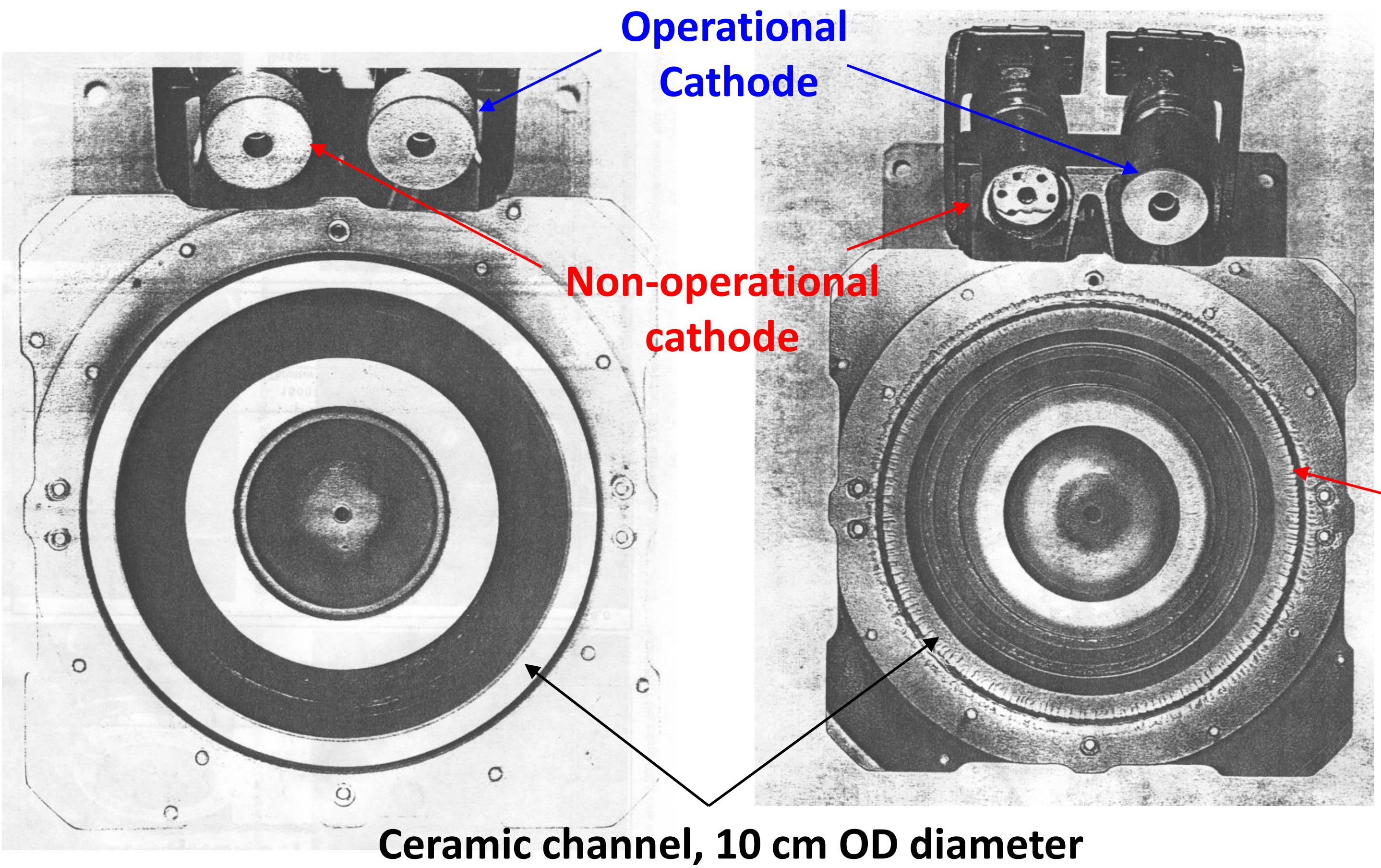
Key obstacles for the development of high thrust density and higher power Hall thrusters

- **Ion-induced erosion of the thruster parts limiting the thruster lifetime**
- **Turbulent fluctuations and related anomalous transport phenomena, and plasma structures critically affecting the thruster performance and lifetime**
- **Enhanced plasma wall losses in scaled down miniaturized Hall thruster – much less efficient low power thrusters than their larger counterparts**
- **Facility effects making difficult reliable testing of mid (10's kW) and high power (> 100 kW) thrusters**

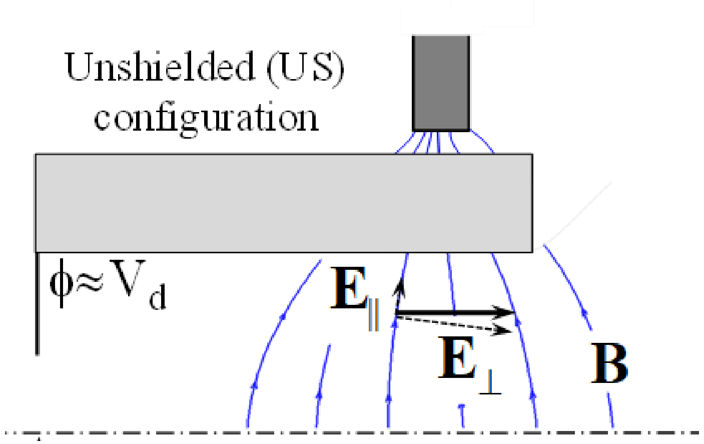
Ion-induced erosion of the thruster channel

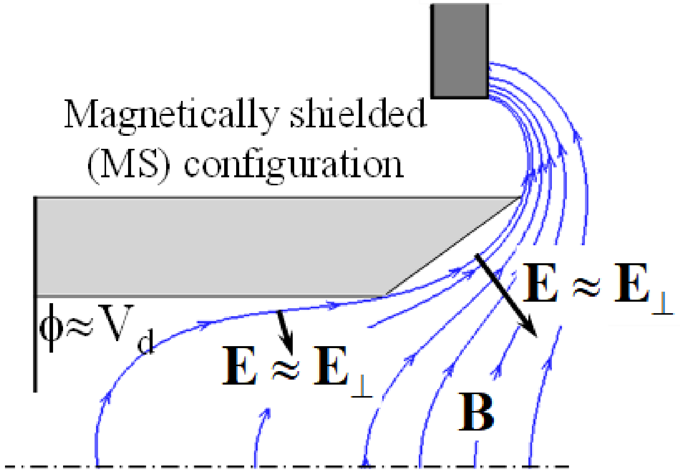
1.35-kW SPT-100 New **1.35-kW SPT-100 5,700 Hrs**

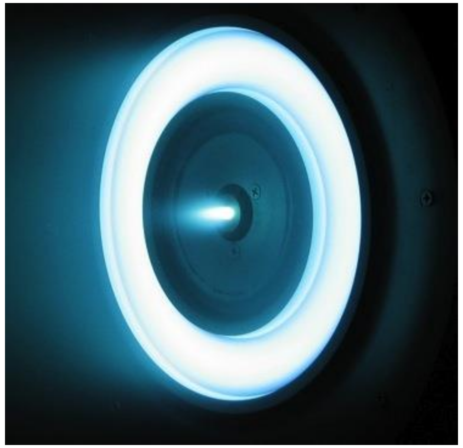
Courtesy:
L. King
F. Taccagona
Y. Mikellides

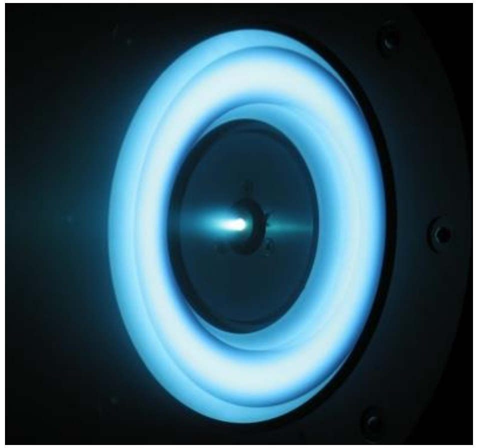


Magnetically-shielded Hall thruster









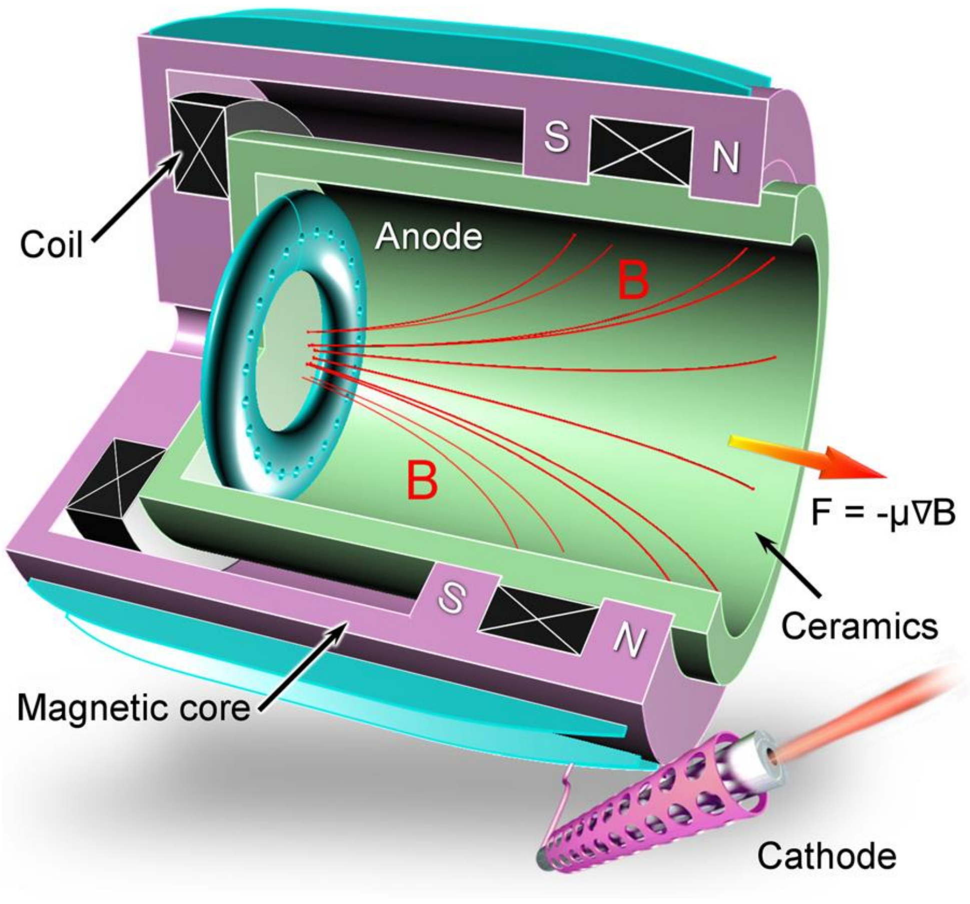
Courtesy:
Vernon Chaplin
Richard Hofer
Yaingos Mikellides

Magnetic shielding has been shown to dramatically reduce discharge channel wall erosion

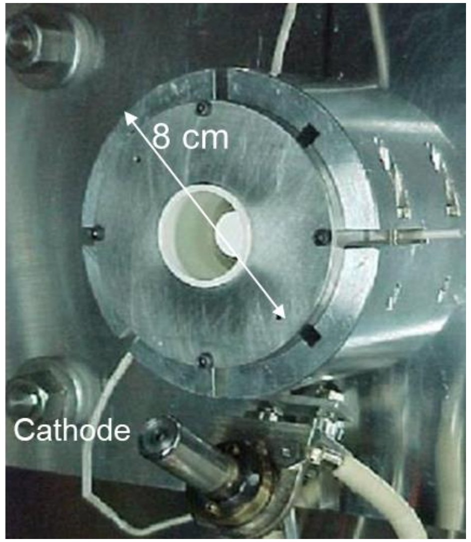
Central pole piece erosion is still a concern!

Jet Propulsion Laboratory
California Institute of Technology

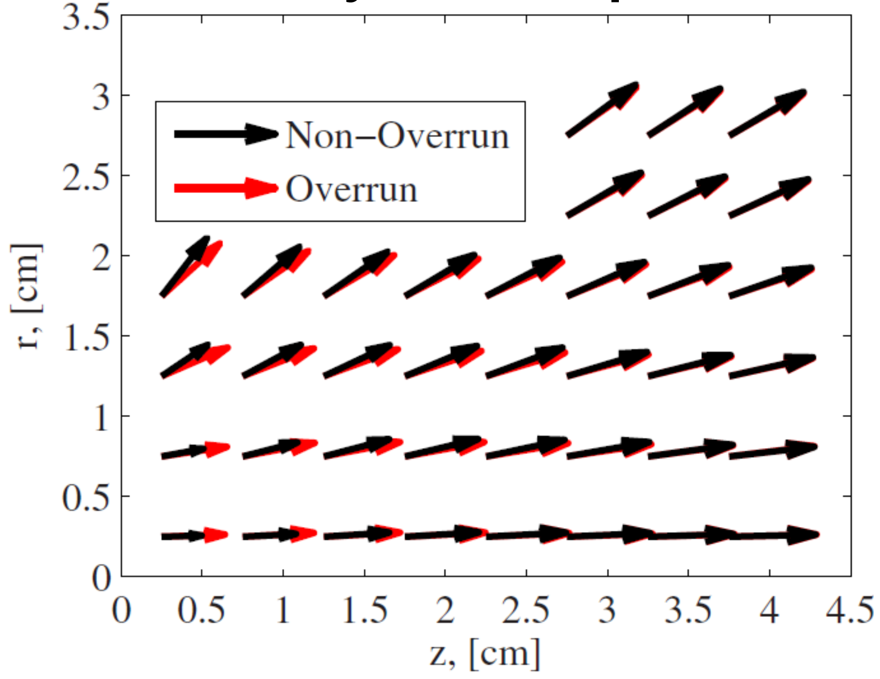
Cylindrical Hall thruster



- 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



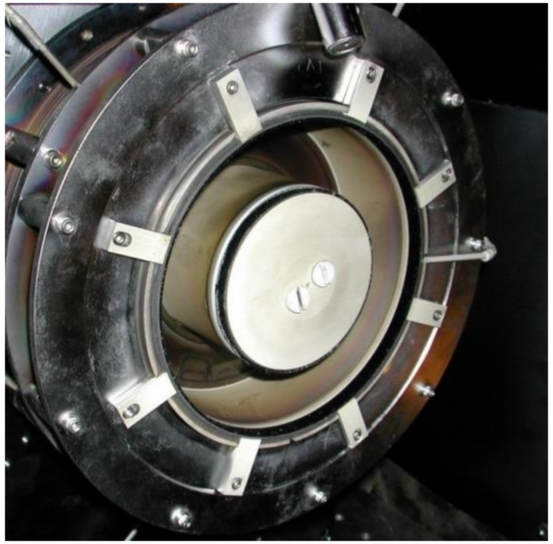
Ion velocity vector map from LIF



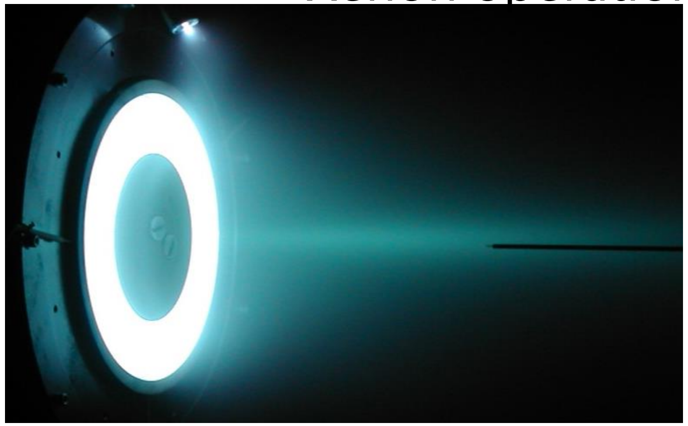
Y Raitses and N. J. Fisch, Phys. Plasmas, 8, 2579 (2001)
A. Smirnov, Y. Raitses, and N.J. Fisch, Phys. Plasmas **14**, 057106 (2007)
R. Spektor et al., Phys. Plasmas **17**, 093502 (2010)

Plasma structures and anomalous cross-field current

12 cm diameter, 2kW Hall thruster



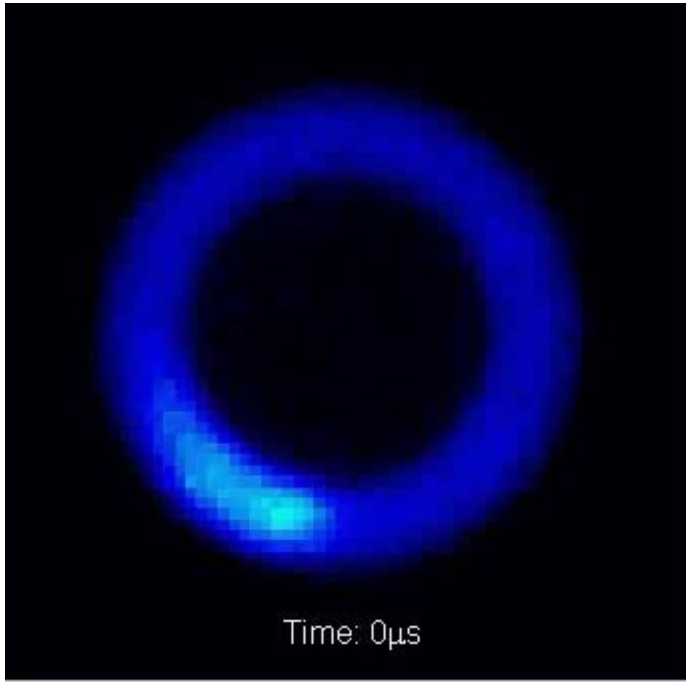
Xenon operation



Plasma non-uniformity

Current conducting ExB rotating “spoke”

Fast frame imaging 60 kfps



Thruster efficiency

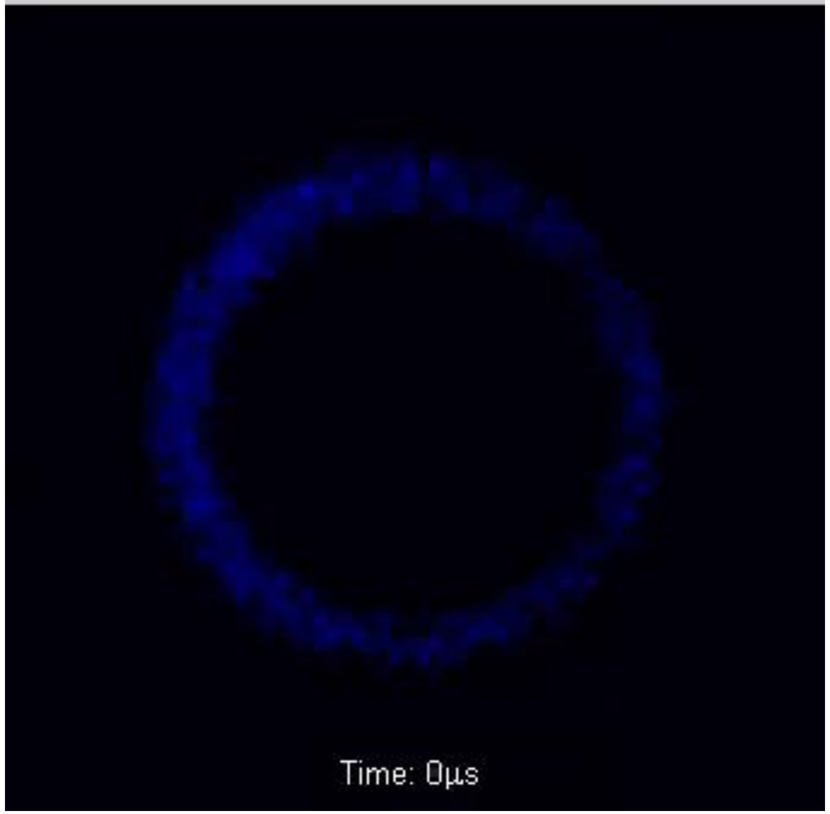
$$\eta \equiv \frac{TV_{jet}}{2P_e} \propto \frac{I_i}{I_i + I_{e\perp}}$$

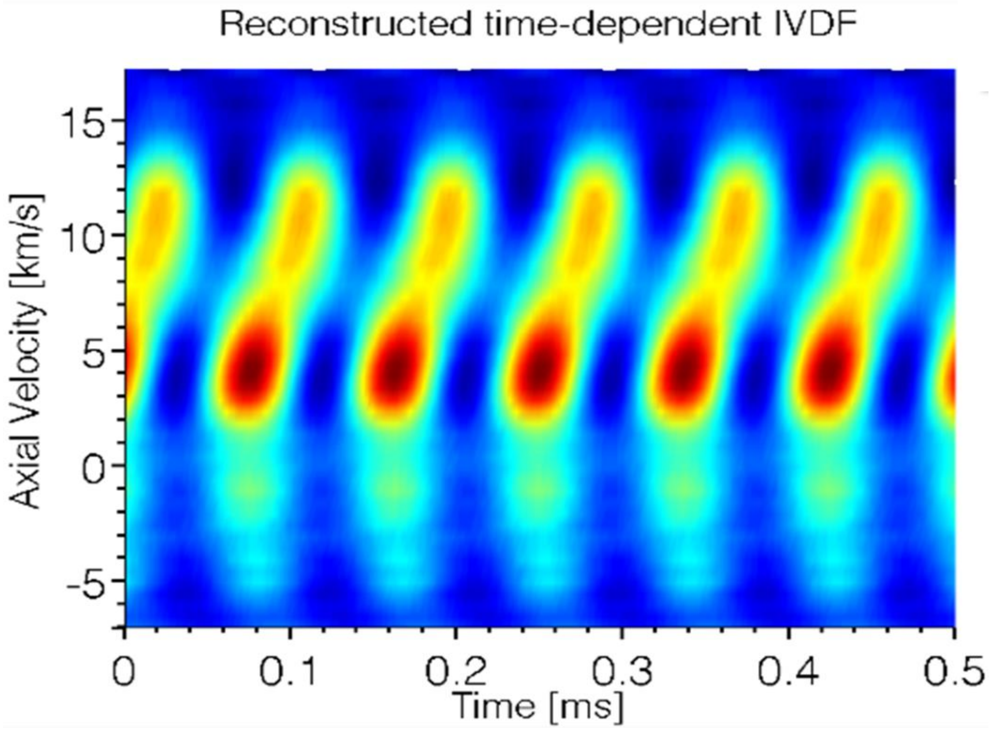
Electron cross-field current

- Spoke frequency ~ 10 kHz
- 10’s times slower than E/B
- Conduct > 50-70% of the discharge current

Hall thruster DC inputs, but highly oscillatory operation

Breathing oscillations associated with ionization instability, 10-20 kHz



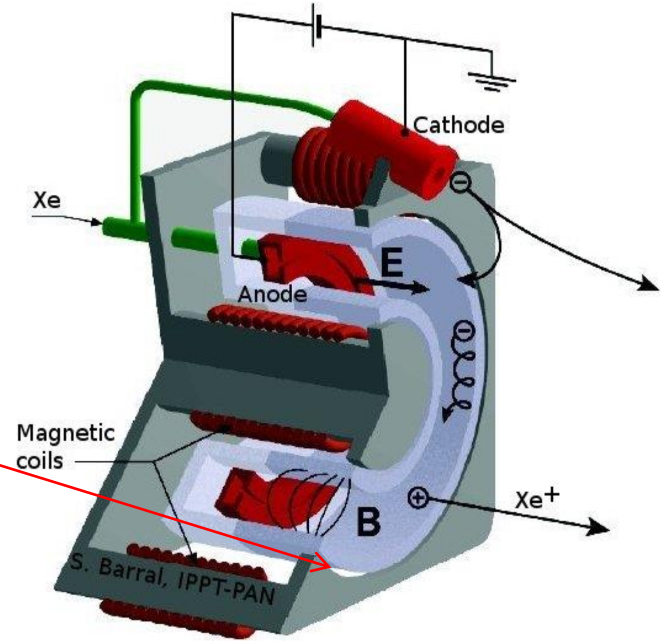


Powerful breathing oscillations of the discharge current due to ionization instability affects temporal evolution of ion velocity distribution

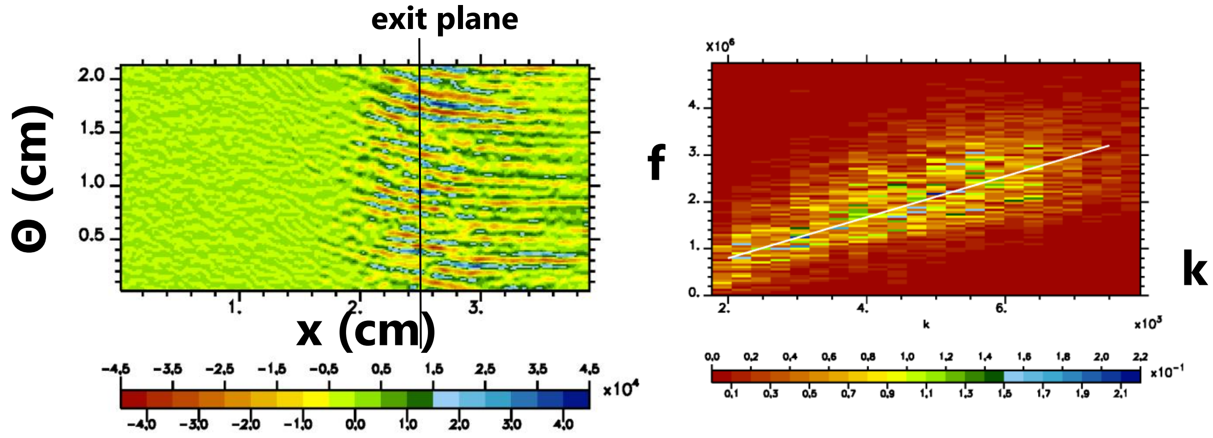
A. Dialo et al., Rev. Sci. Instrum. 86, 033506 (2015)

Small scale fluctuations

Outside the channel and in the near-field plume:
Small scale fluctuations ,~ 10 MHz, ion-sound and lower hybrid instabilities

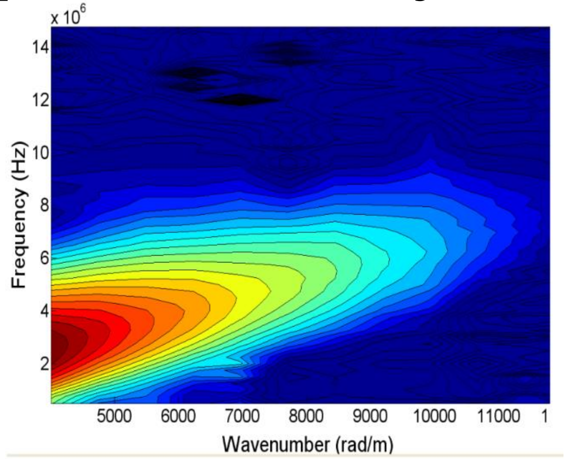


- **2-D self-consistent PIC simulations**



electric field **potential**

- **Experiment: Density fluctuations**

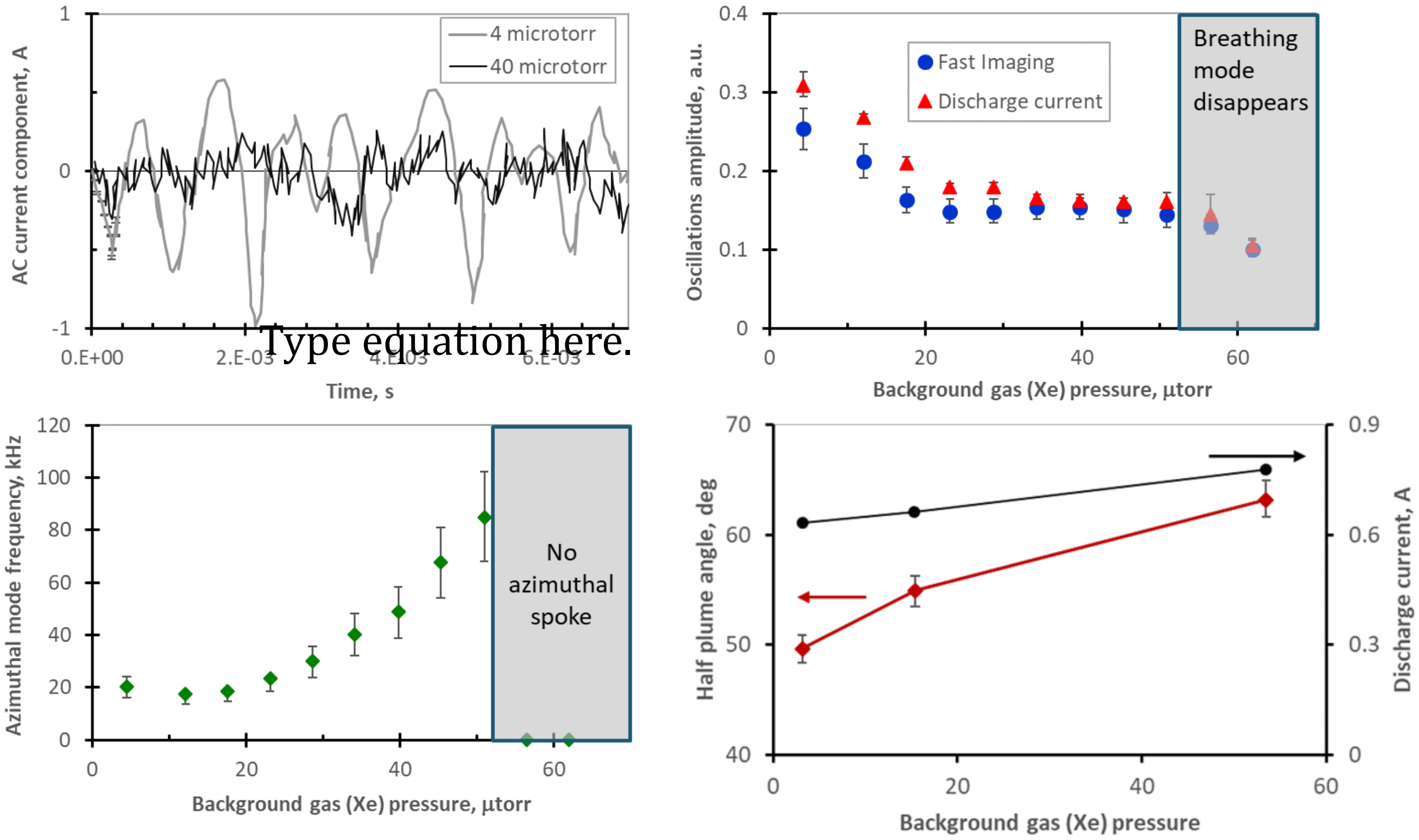


Adam, Héron and Laval, Phys. Plasmas (2004)
Tsikata, et al., Phys. Plasmas (2009)

Facility effects

PPPL 28 m^3 , 66000 l/s for Xenon
Base pressure: 10^{-8} torr
< 5 x 10^{-6} torr for 200 W thruster

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



Y. Raitses, J. B. Parker, E. Davis, E. and N. J. Fisch, AIAA 2010-6775, July 2010.

Testing capabilities for high power plasma propulsion

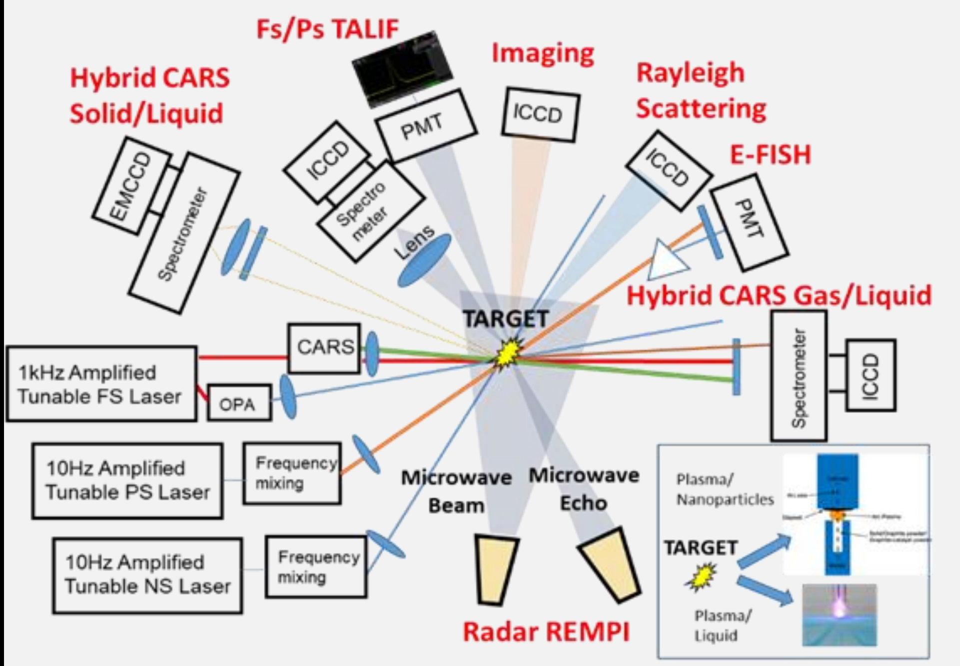
NASA’s Glenn Research Center Vacuum Chamber 5 (4.6 m diam by 18.3 m long, pumping 700 kL/s) provides a testing environment for advanced Solar Electric Propulsion needed for future space missions

Critical challenges of modern Hall thruster technology

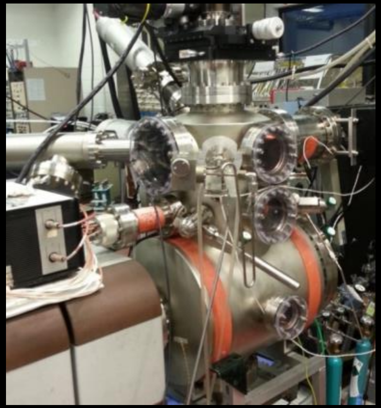
- **How to make predictive Hall thruster designs for various power levels of interest (space mission relevant)?**
  - Need experimentally validated predictive modeling capabilities (e.g. 3-D kinetic codes for plasma, atomistic simulations for materials)
- **How to mitigate/suppress plasma instabilities?**
  - Advance understanding of instabilities, develop active and passive engineering solutions (e.g. electrical circuitry, segmented electrodes)
- **How to make accelerated thruster lifetime tests (e.g. 10's -100's hours instead of 1000's hours)?**
  - Need experimental validated physics models and codes
- **How to improve efficiency of miniaturized Hall thrusters**
  - Need alternative operating regimes, new ExB configurations

PPPL-Princeton Collaborative LTP Research Facility (PCRF)

Advanced *fs-ps-ns-cw* diagnostics of plasma species, flow, nanoparticles

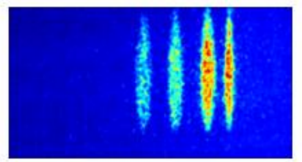


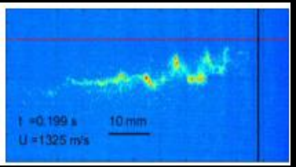
PFC properties



- *fs*- Laser Electronic Excitation Tagging flow measurements

Laminar flow *Turbulent flow*



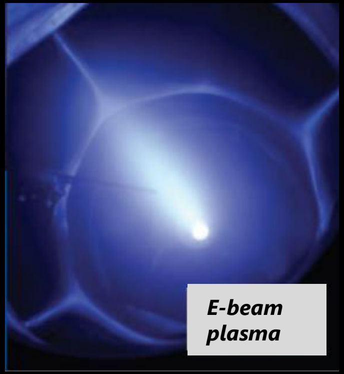


- ns-discharge in gas bubble

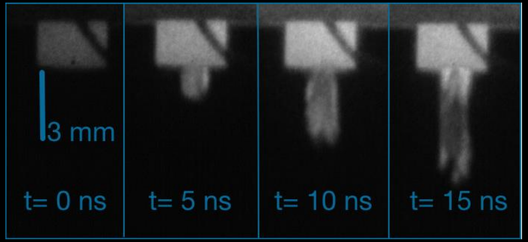
Plasma sources

- Atmospheric pressure plasma: DBD, jets, arcs

- Low pressure LTPs: magnetized, e-beam, DC/RF microscale

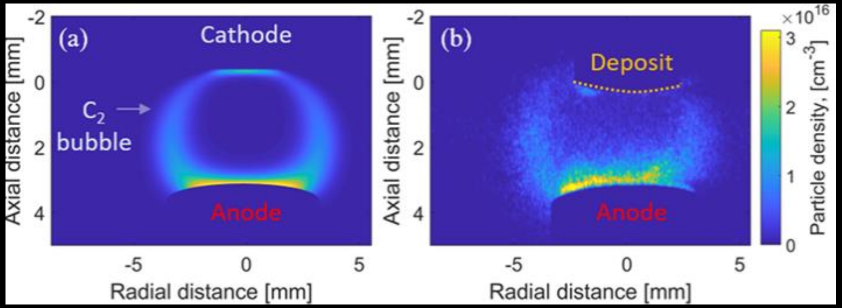


- Streamer in plasma jet

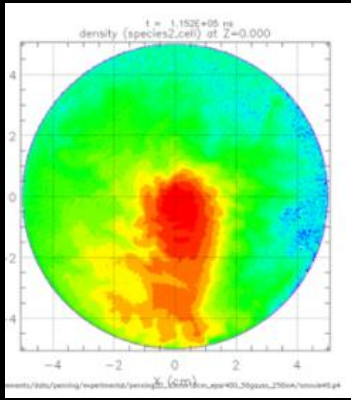


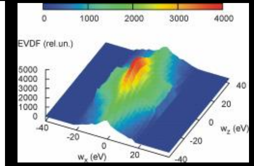
Unique measurements/simulations

- Plasmas with complex chemistry: *arc discharge* 2D CFD simulations (left) and LIF measurements (right)



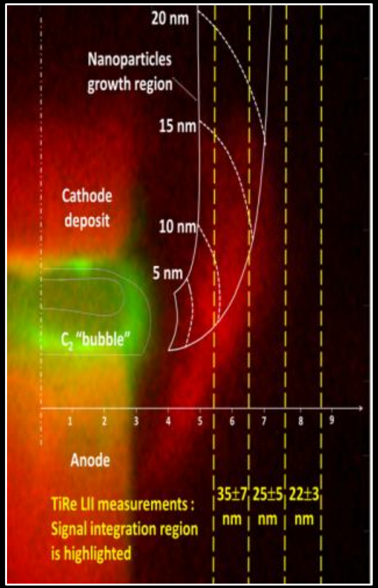
- 1D, 2D, 3D Kinetic simulations





EVDF

- Nanoparticles synthesis in arc: *modeling, OES and LII measurements*



- Atomistic simulations

Princeton Collaborative Research Facility (PCRF)

The PCRF mission is to provide the scientific community access to specialized, world-class diagnostics, instruments, computational tools, and related expertise

Upcoming Call for Collaborative Proposals

Opening call for proposals: November 2020

Closing call for proposals: December 20, 2020

Review of proposals (tentative): December 21, 2020 to January 25, 2021

Deadline for decisions (tentative): by February 8, 2021

http://pcrf.pppl.gov

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