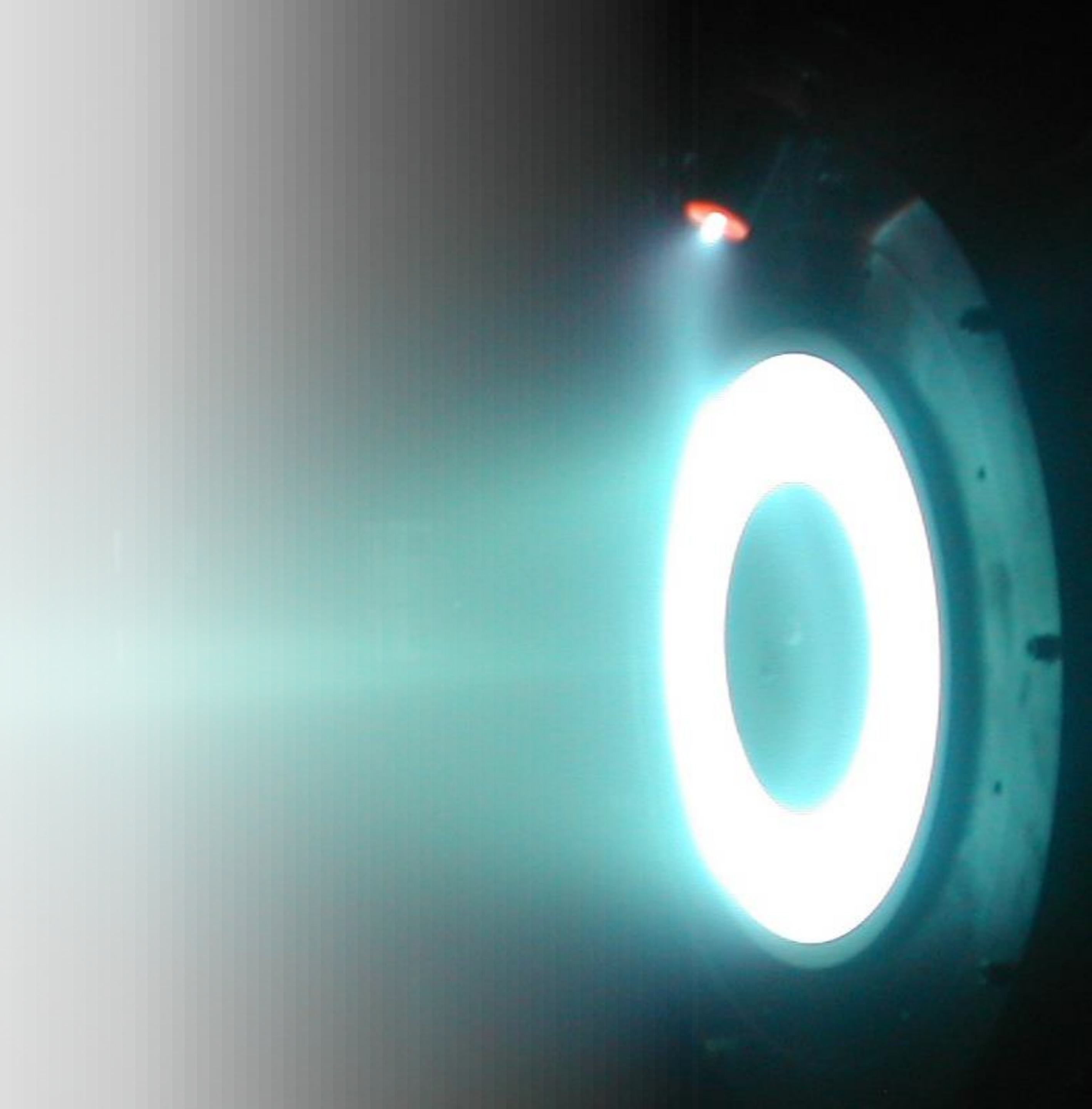
Plasma Propulsion for Satellites

Yevgeny Raitses

PPPL



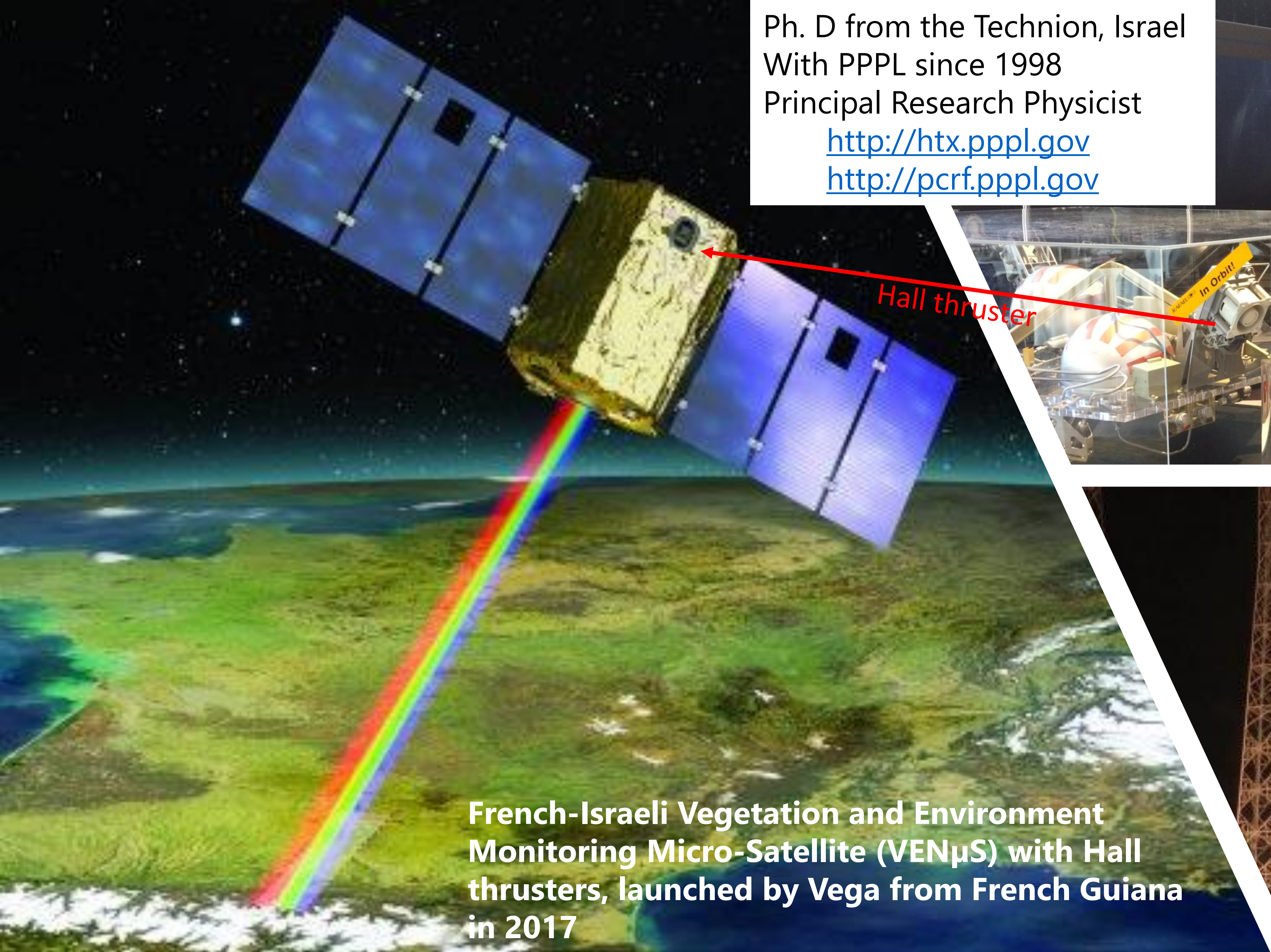
SULI, Princeton, June 2020

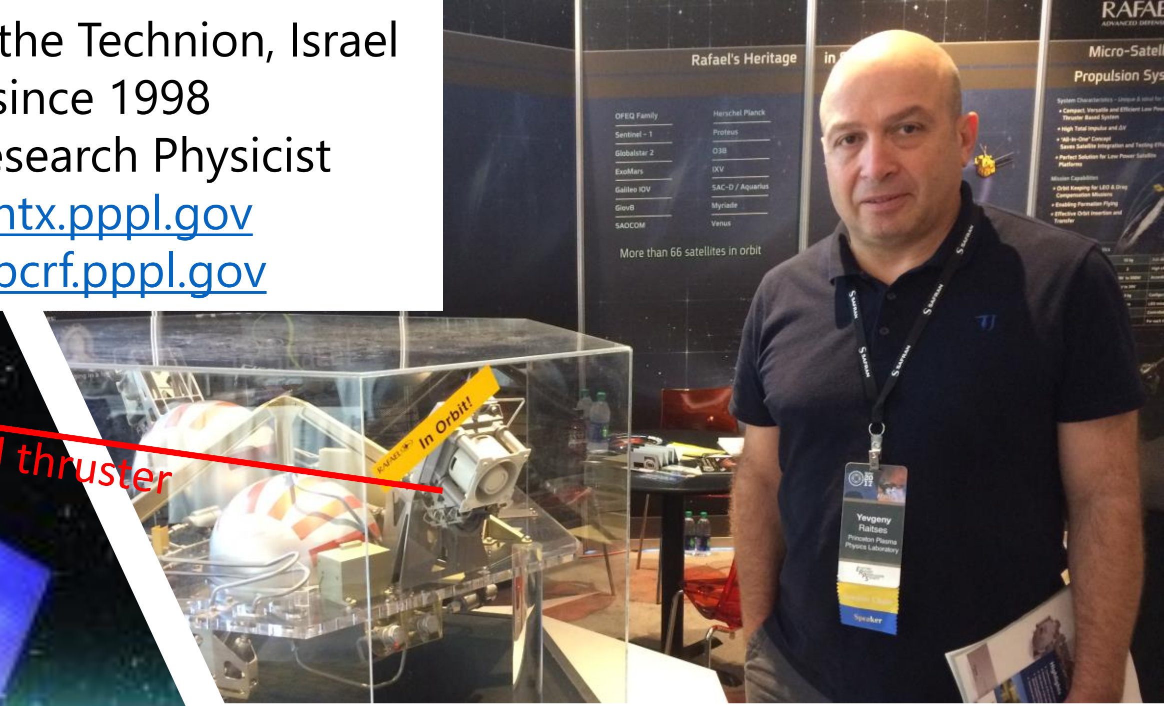
Operational Satellites with Electric/ Plasma Propulsion (2008)

Ph. D from the Technion, Israel
With PPPL since 1998
Principal Research Physicist

http://htx.pppl.gov

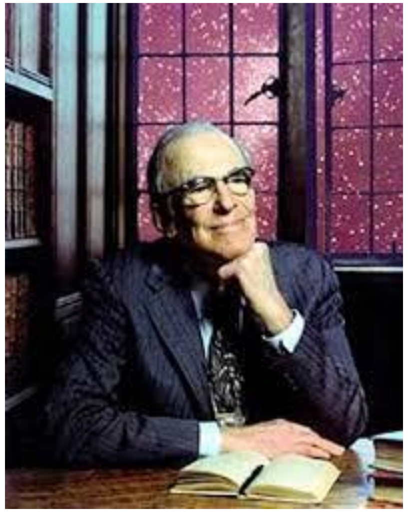
http://pcrf.pppl.gov





French-Israeli Vegetation and Environment Monitoring Micro-Satellite (VENμS) with Hall thrusters, launched by Vega from French Guiana in 2017

Plasma propulsion research at PPPL



Interplanetary Travel Between Satellite Orbits[1]

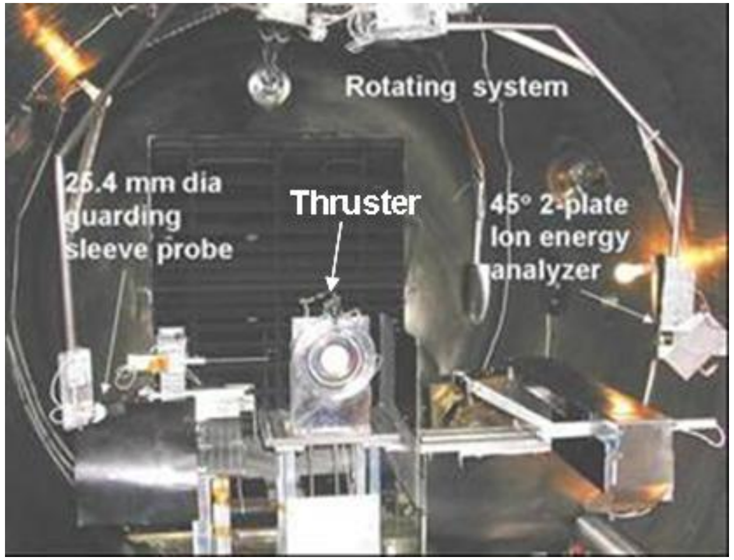
By LYMAN SPITZER, JR.[2]

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

2[nd] 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



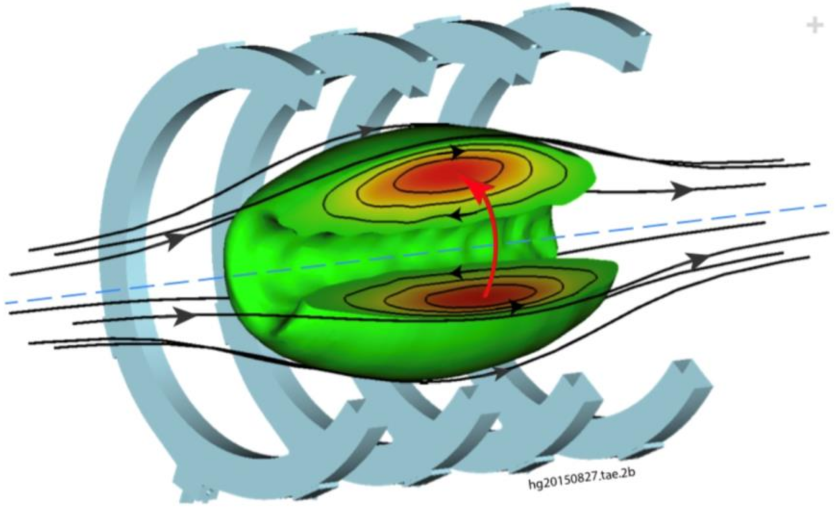
http://htx.pppl.gov

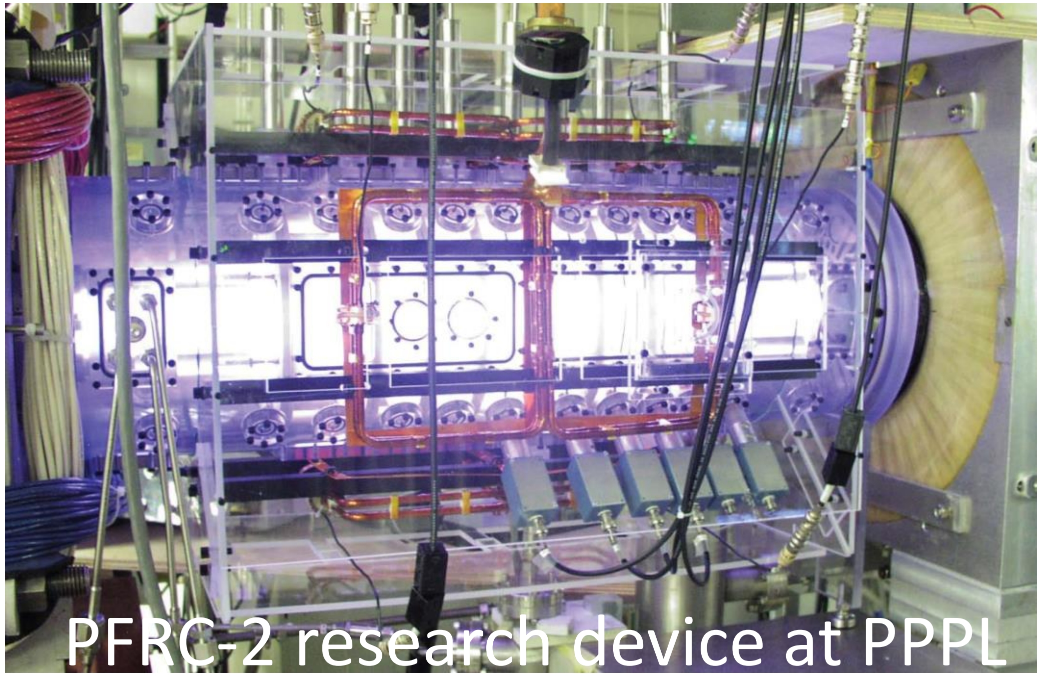
1999 → 2020

Direct Fusion Drive: power and propulsion

Princeton Field Reversed Configuration (PFRC)
Quasi-toroidal plasma: Closed magnetic field lines
Goal: PFRC fusion reactor (truck-sized), 1-10 MW
High β required to burn D-^{3}He
^{3}He supply ~ 100 MW/year
Low neutron damage-Long component lifetime
Thrust 10 N/MW
Remote planet exploration

Dr. Sam Cohen
PPPL
scohen@pppl.gov



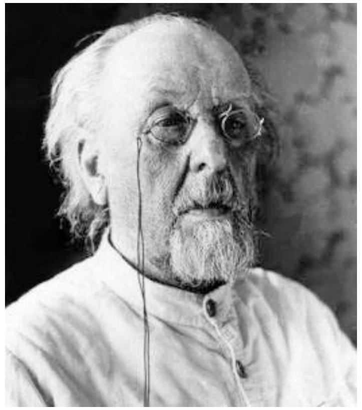


Derek Sutherland's lecture on alternative concepts, 06/18

Synopsis

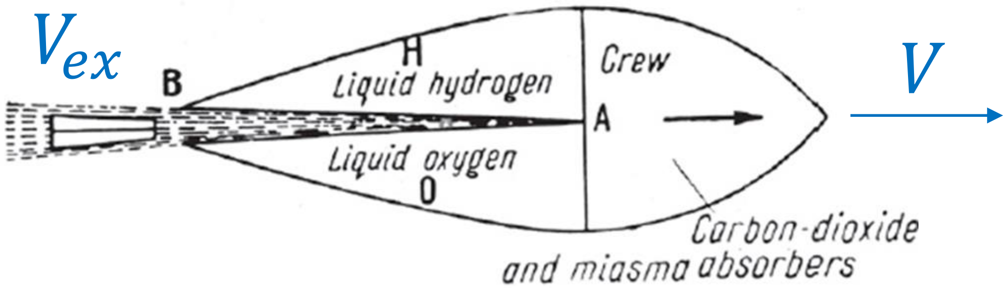
- ✓ Personal and Group introduction
- Plasma propulsion - why and what for
- Fundamental limits on thrust density for ion and Hall thrusters
- Superior Hall thruster technology – what is beyond?

Stimulus for electric/plasma propulsion



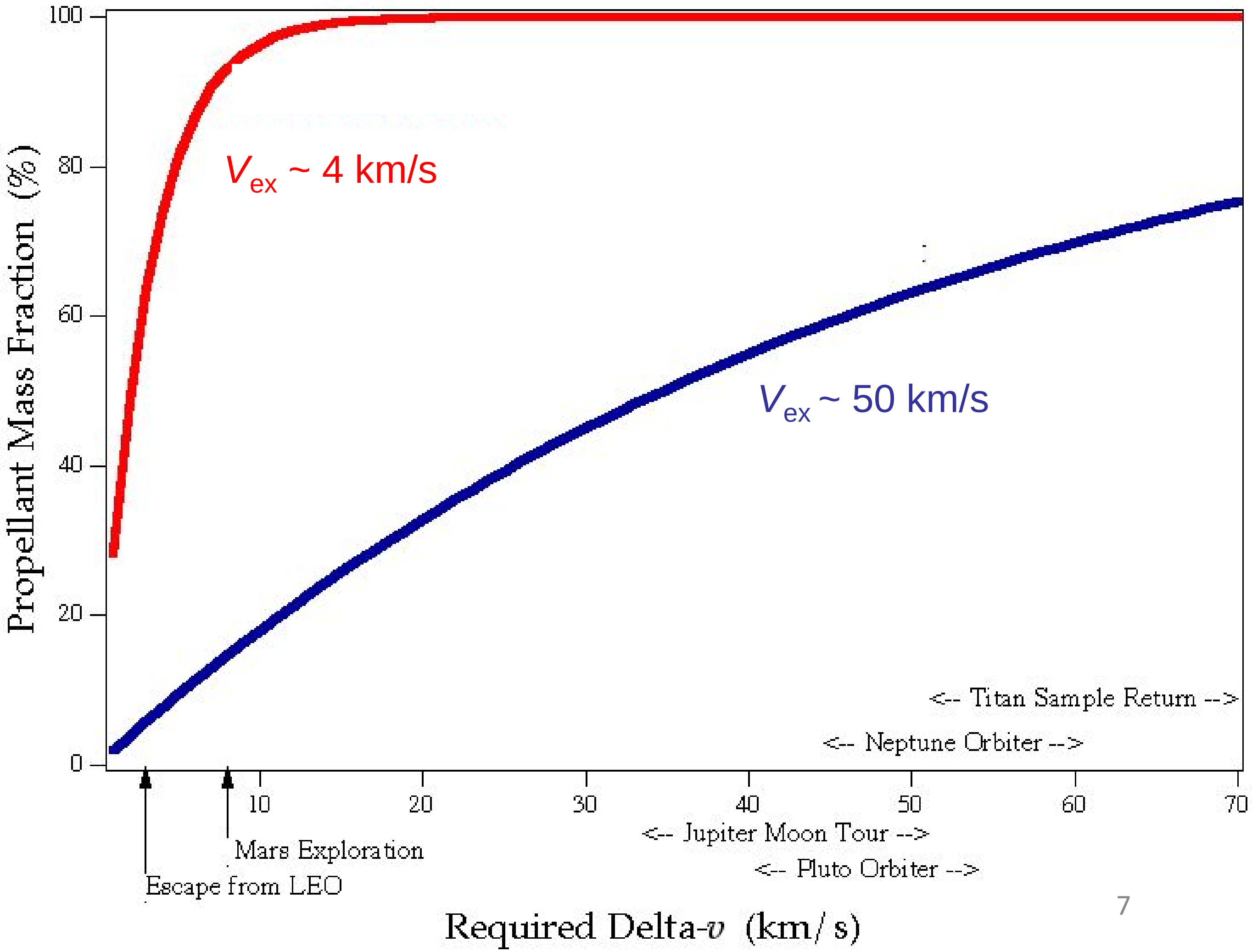
Konstantin Tsiolkovsly
Rocket equation, 1903

Robert Goddard
Electric propulsion, 1906



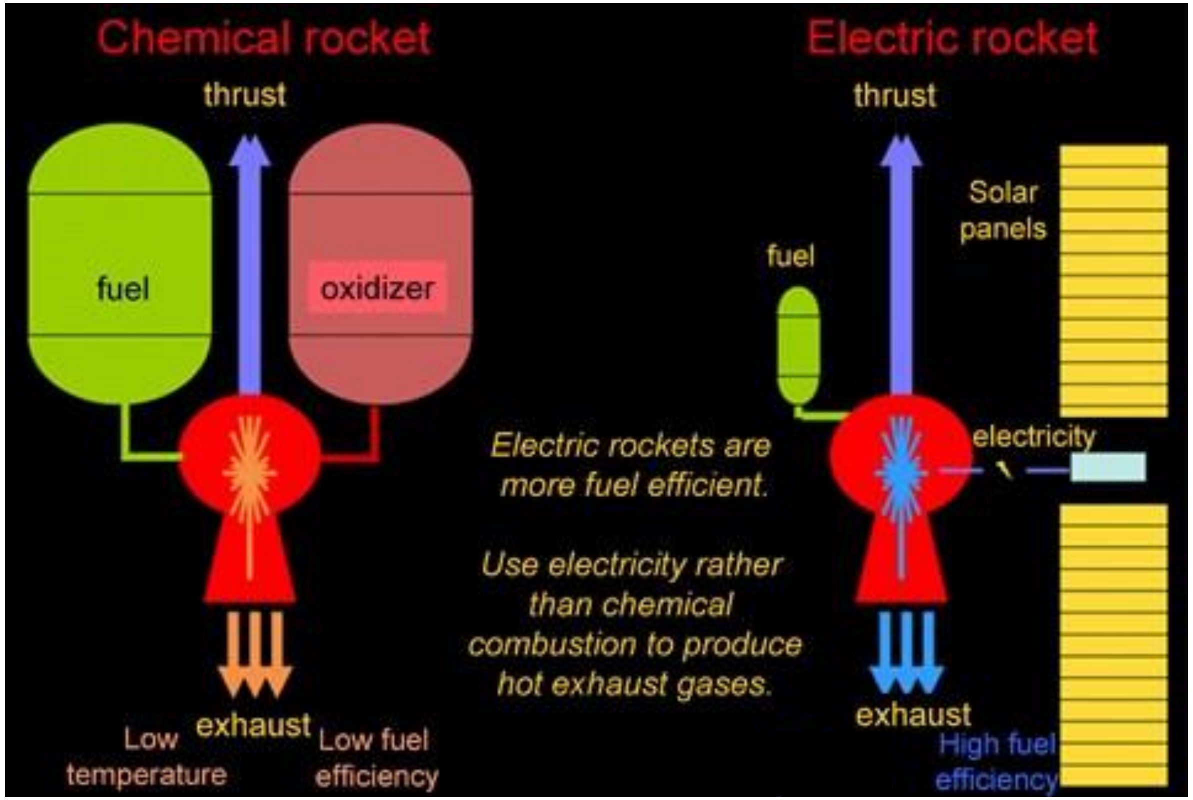
$$M\frac{dV}{dt} = thrust = -\frac{dM}{dt}V_{ex}$$

$$\frac{propellant\ mass}{inital\ sat\ mass} = \frac{M_p}{M_i} = 1 - e^{-\Delta V/V_{ex}}$$



Electric/plasma propulsion

Acceleration of gases for propulsion by electrical heating and/or by electric and magnetic forces



Robert G. Jahn,
Physics of Electric Propulsion
New York, McGraw-Hill (1968)

Chemical rocket:

Energy source is in fuel/ oxidizer chemical reactions

V_{ex} - limited by the propellant energy density

For H_2+O_2, $V_{ex}^{max} \approx 4\ km/s$

Solar electric rocket:

Energy source and fuel are separate

V_{ex} - limited by the on-board power

$V_{ex} \approx 5 - 100\ km/s$

Electric propulsion: *fuel efficient, power limited*

Convert input electric power, P_e, to output thrust power:

$$\eta P_e = \frac{\dot{m}{V_{ex}}^2}{2} = \frac{TV_{ex}}{2}$$

Efficiency $\eta < 1$

$$Isp \equiv V_{ex}/\text{g}, \ \text{[s]}$$

$$\eta P_e \sim const, \ Isp \uparrow \quad T \downarrow$$

Space mission: $\Delta V \approx a\Delta t = \frac{T}{M}\Delta t$

Mission time

Solar power from 10 W to 10's kW

Near future available $P_e \geq 10^2$ kW

Electric thrusters – low thrust propulsion

Low thrust – low acceleration

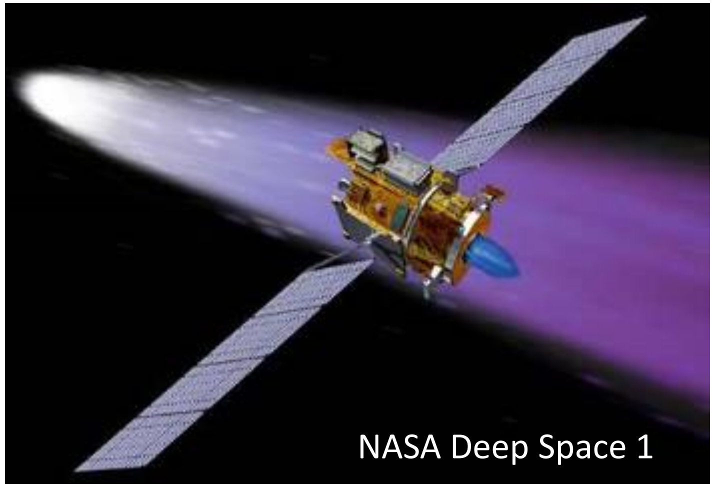
Low acceleration – longer mission time

Longer mission time – longer thruster lifetime (needed)

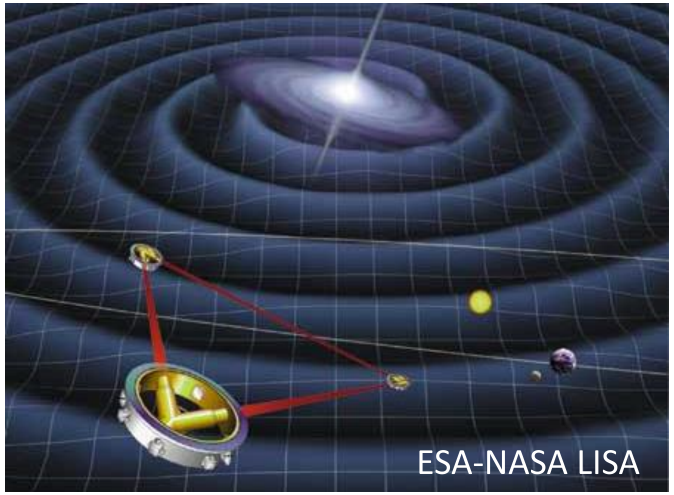
Use of electric thrusters

High ΔV space missions

1998
Ion thruster



High precision control

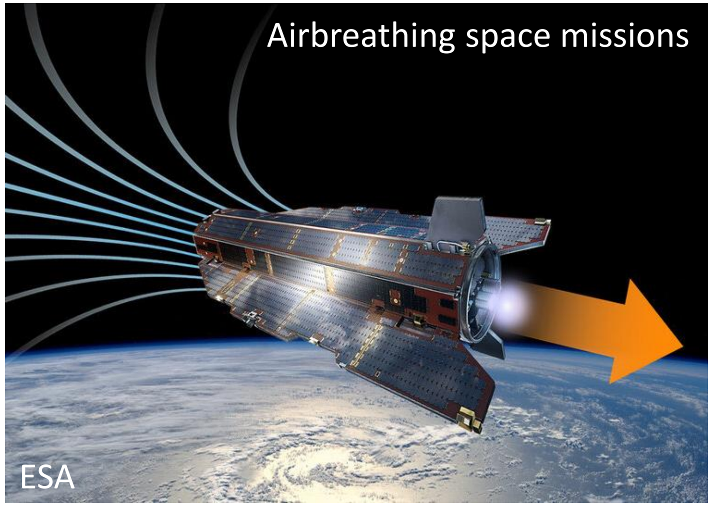


Planned: 2034
2015-Pathfinder
Electrospray thruster

Station keeping and orbit rising

2019
Hall thruster

Drag compensation at low orbits



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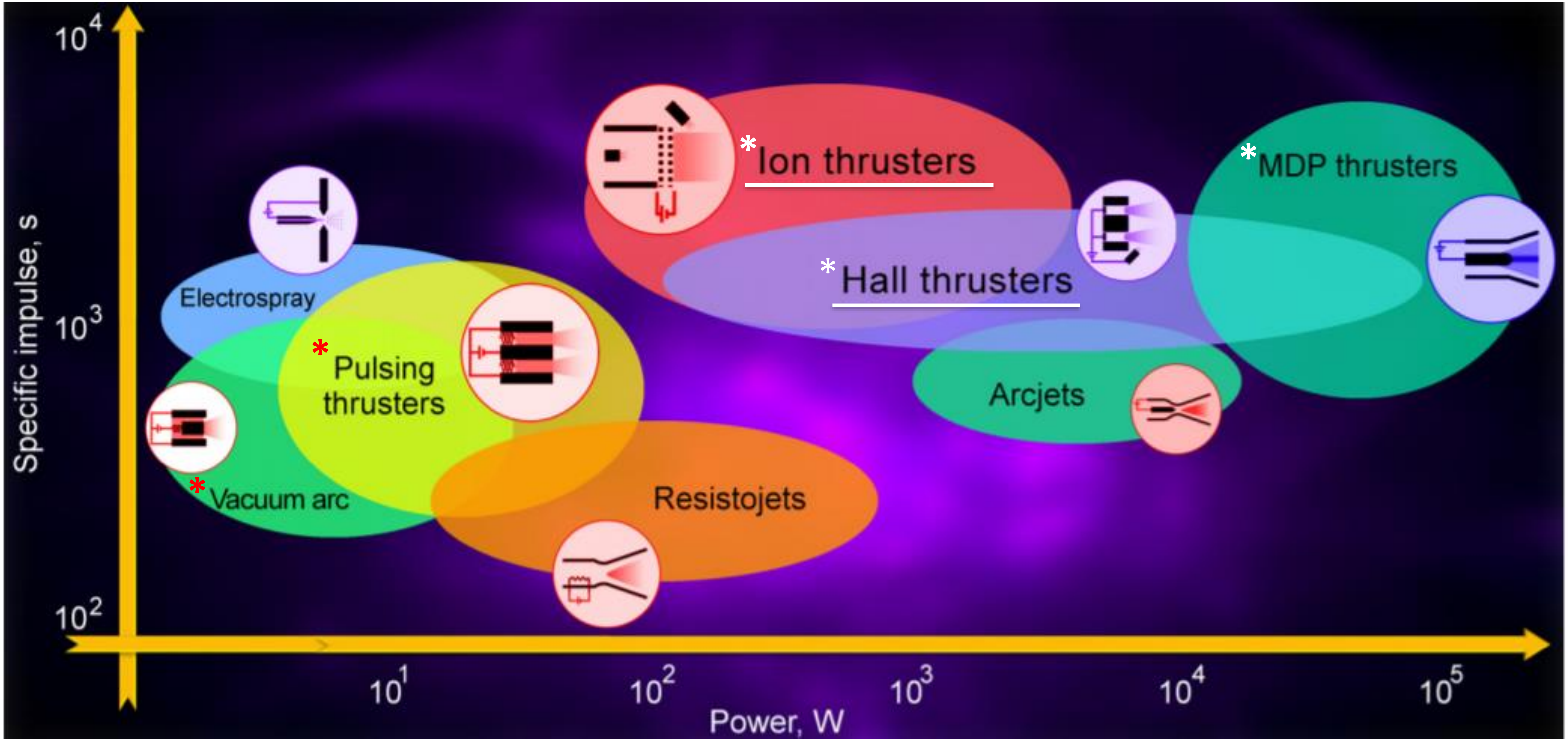
Propulsion: Electric vs Plasma (*)

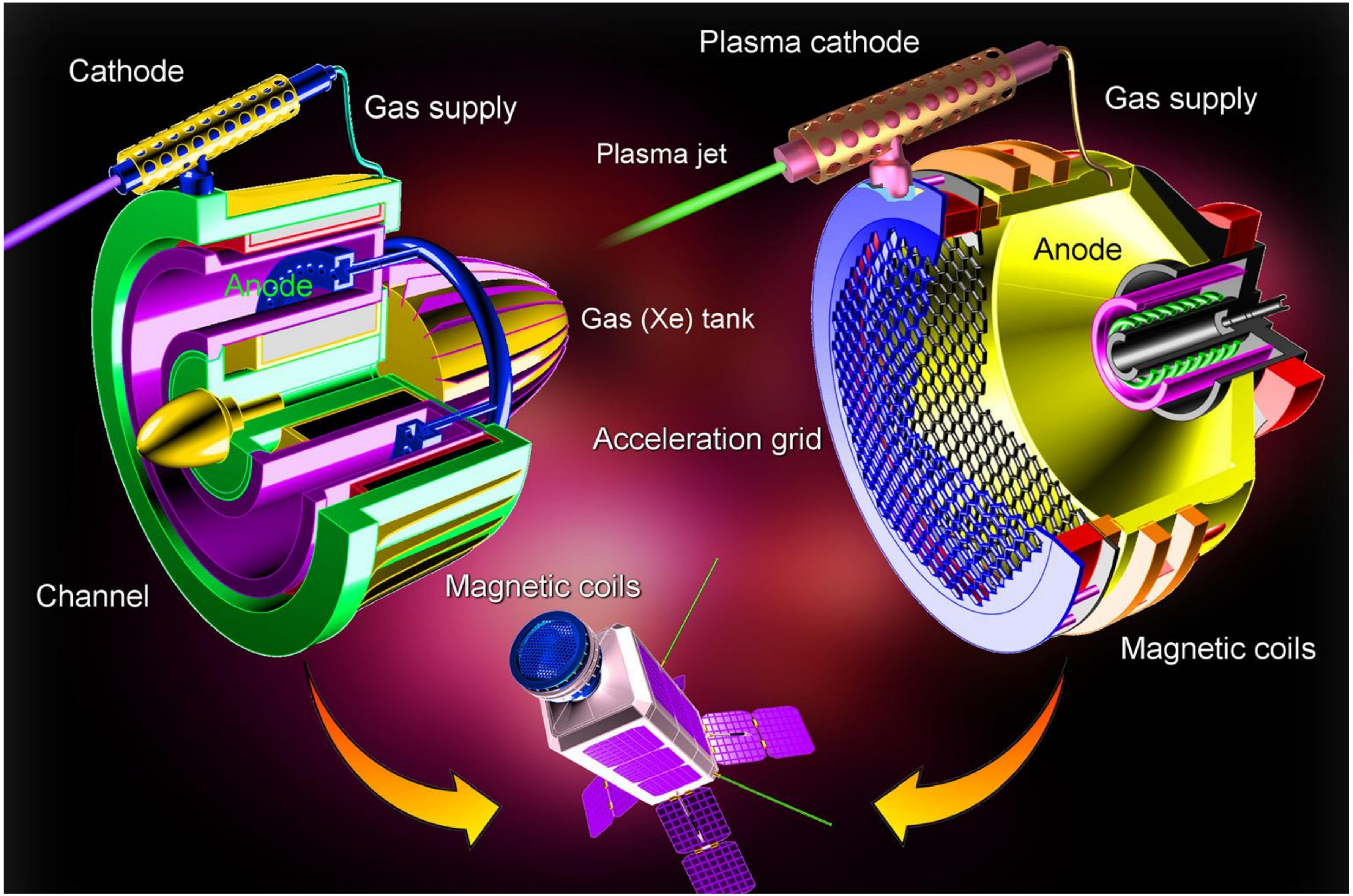


*I. Levchenko et al., Phys. Plasmas **27**, 020601 (2020)*

Hall thruster and Ion thruster

Hall thruster:

- **Scale dim.**
  (diameter)
  1-50 cm
- **Power**
  0.1-100 kW
- **Propellant**
  Xe, Kr
- **Efficiency**
  20-70%



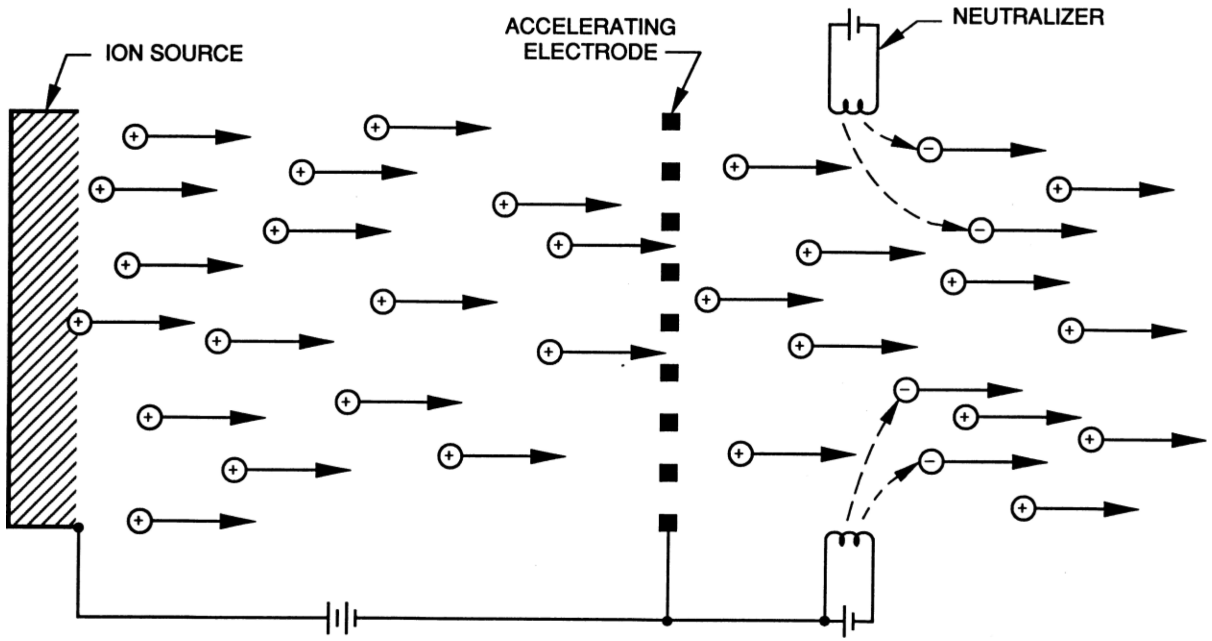
Ion thruster:

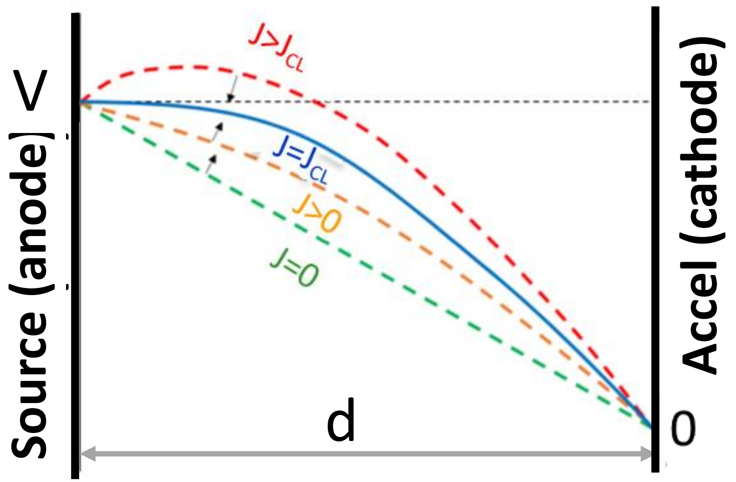
- **Scale dim.**
  (diameter)
  1-40 cm
- **Power**
  0.1-10 kW
- **Propellant**
  Xenon
- **Efficiency**
  60-80%

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

Ion thruster – electrostatic thrust force on electrodes

Ion current **Ion flux=electron flux**





From ion energy conservation, $v_i(x=0)=0$, the maximum ***Isp*** is the ion velocity at the accel grid:

$$Isp^{max} \approx v_{max}/g = \frac{1}{g}\left(\frac{2eV_d}{M_{ion}}\right)^{1/2}$$

Child-Langmuir space charge limit on the ion current density at $E_s = 0$:

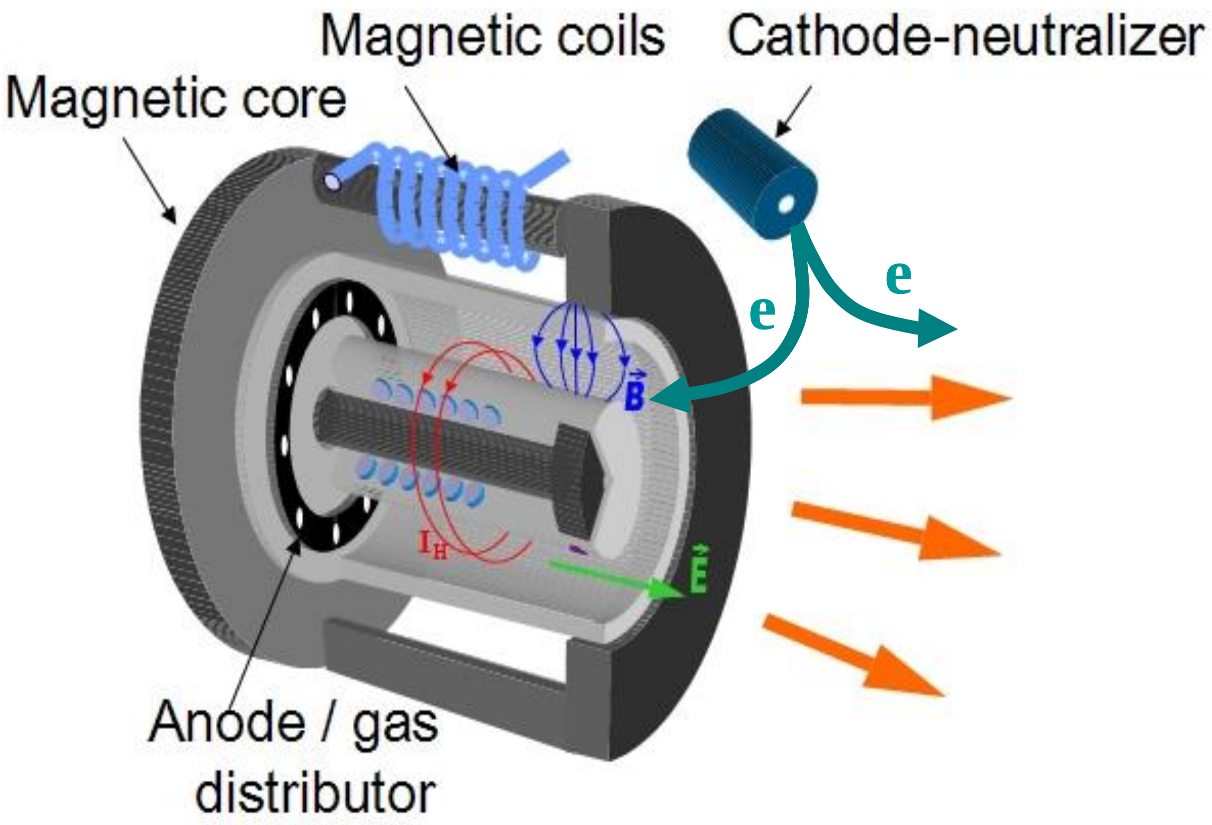
$$J_i^{max} = J_{CL} = \frac{4\varepsilon_0}{9}\left(\frac{2e}{M_{ion}}\right)^{1/2}\frac{V_d^{3/2}}{d^2}$$

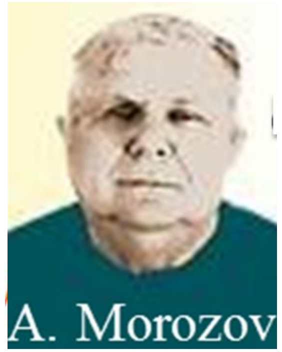
Maximum thrust density when $E_s = 0$,

Electrostatic pressure on electrodes

$$\frac{T_{max}}{A} = M_{ion}\frac{J_i}{e}v_i = -\frac{\varepsilon_0}{2}E_a^2 \approx -\frac{\varepsilon_0}{2}\frac{V_d^2}{d^2}$$

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: $n_e \approx n_i$

Will Fox's lecture on 6/16

- Electrons **ExB** drift in azimuthal direction
- Heavier ions almost unaffected by B-field

$$r_{Le} \ll L < r_{Li} = \frac{m_i v_\perp}{eB}$$

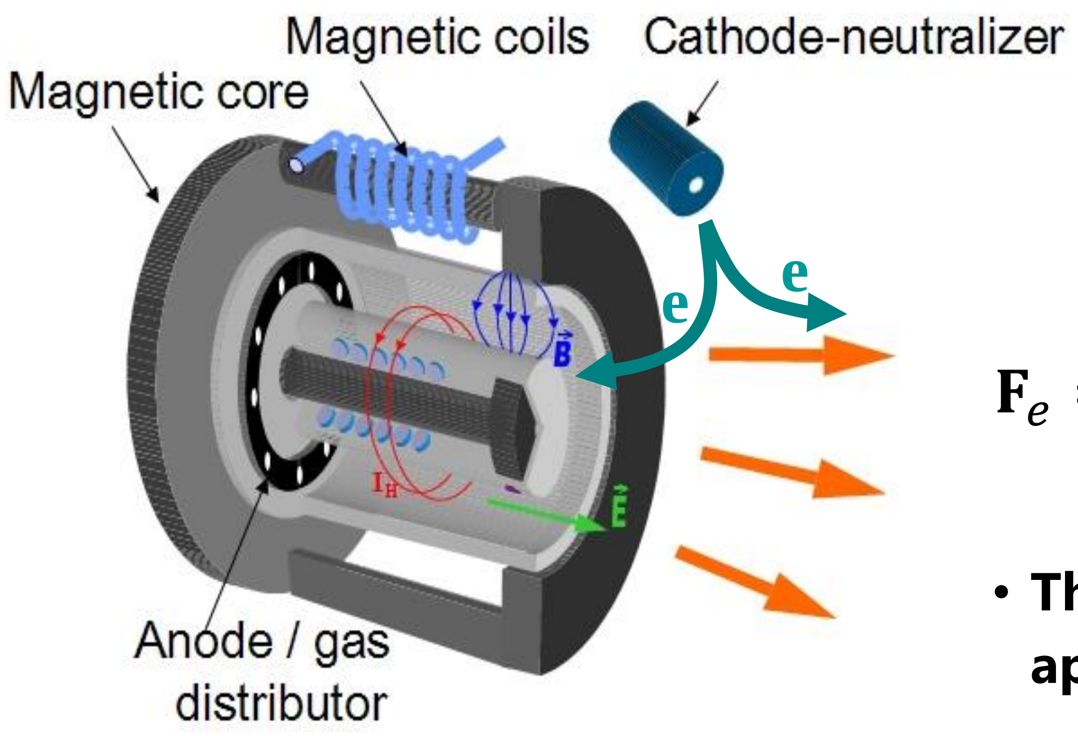
- Equipotential magnetic field surfaces

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

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

$$\text{ion flux} = \text{electron flux}$$

Hall thruster –thrust force on magnet



- Force on ions (q=e):

$$\mathbf{F}_{ion} = 2\pi \iint e n_i \mathbf{E}\, r dr dz$$

- Forces on electrons (*q*=-*e*):

$$\mathbf{F}_e = -2\pi \iint e n_e \mathbf{E}\, r dr dz - 2\pi \iint e n_e \mathbf{v}_e \times \mathbf{B}\, r dr dz = 0$$

- **Thrust is a reaction force to the ion acceleration applied to electromagnet:**

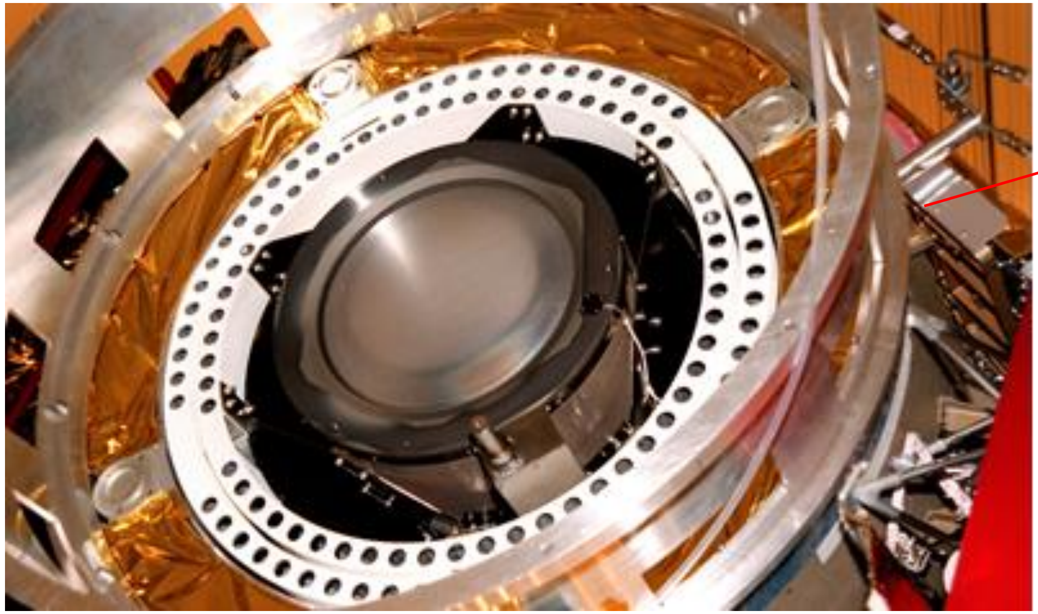
$$\mathbf{T} = -\mathbf{F}_{ion} \approx \mathbf{I}_{\mathbf{Hall}} \times \mathbf{B}\,(2\pi r_m)$$

- The maximum achievable thrust density in Hall thruster is limited not by space charge, but by the magnetic field:

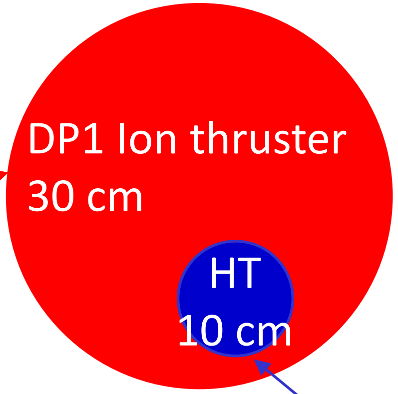
$$\left(\frac{T}{A}\right)_{max} \sim \frac{B_{max}^2}{2\mu_0}$$

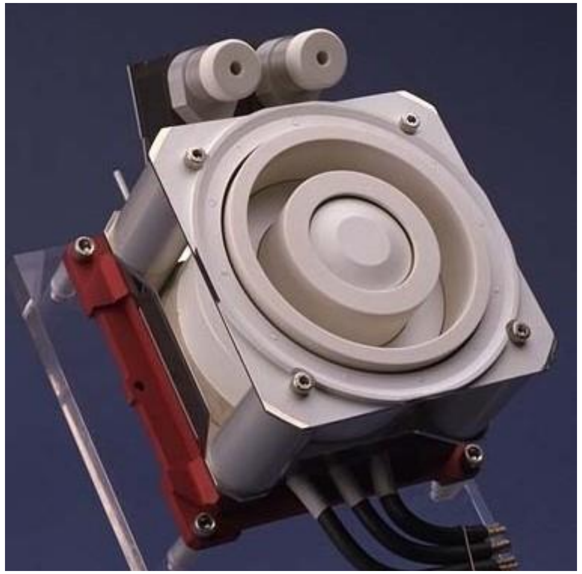
Comparing thrust densities for Hall and ion thrusters

Deep Space 1 NSTAR Ion thruster



At 1.5 kW, thrust ≈ 50 mN
At 2.3 kW, thrust ≈ 90 mN



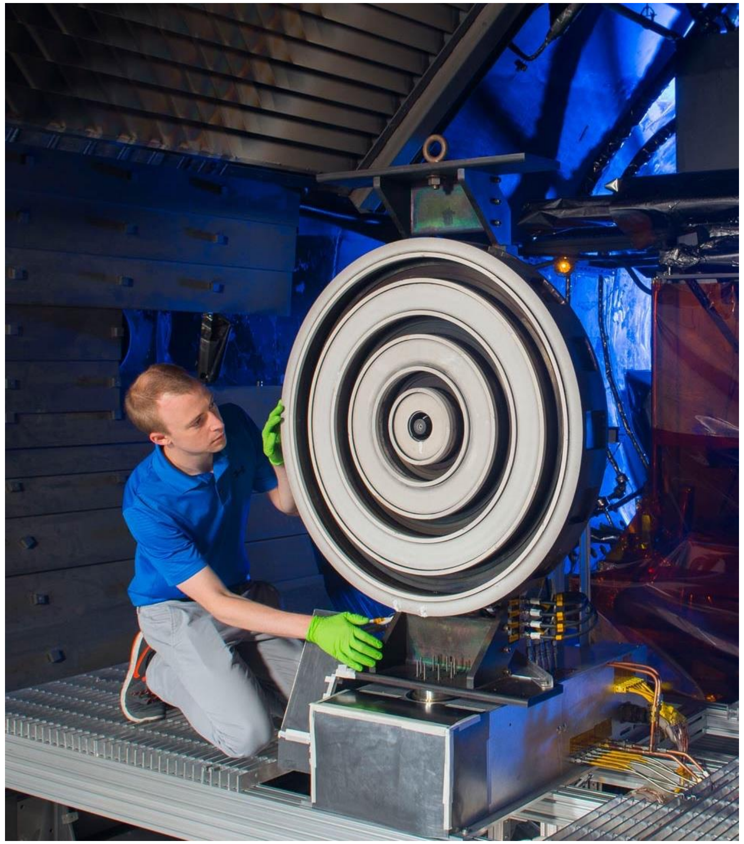


SMART -1, ESA
Hall thruster:
PPS-1350:
Power: 1500 W
OD = 10 cm
Thrust= 90 mN

Hall thrusters are also advantageously simpler than ion thrusters

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

Nested Hall thruster, X-3

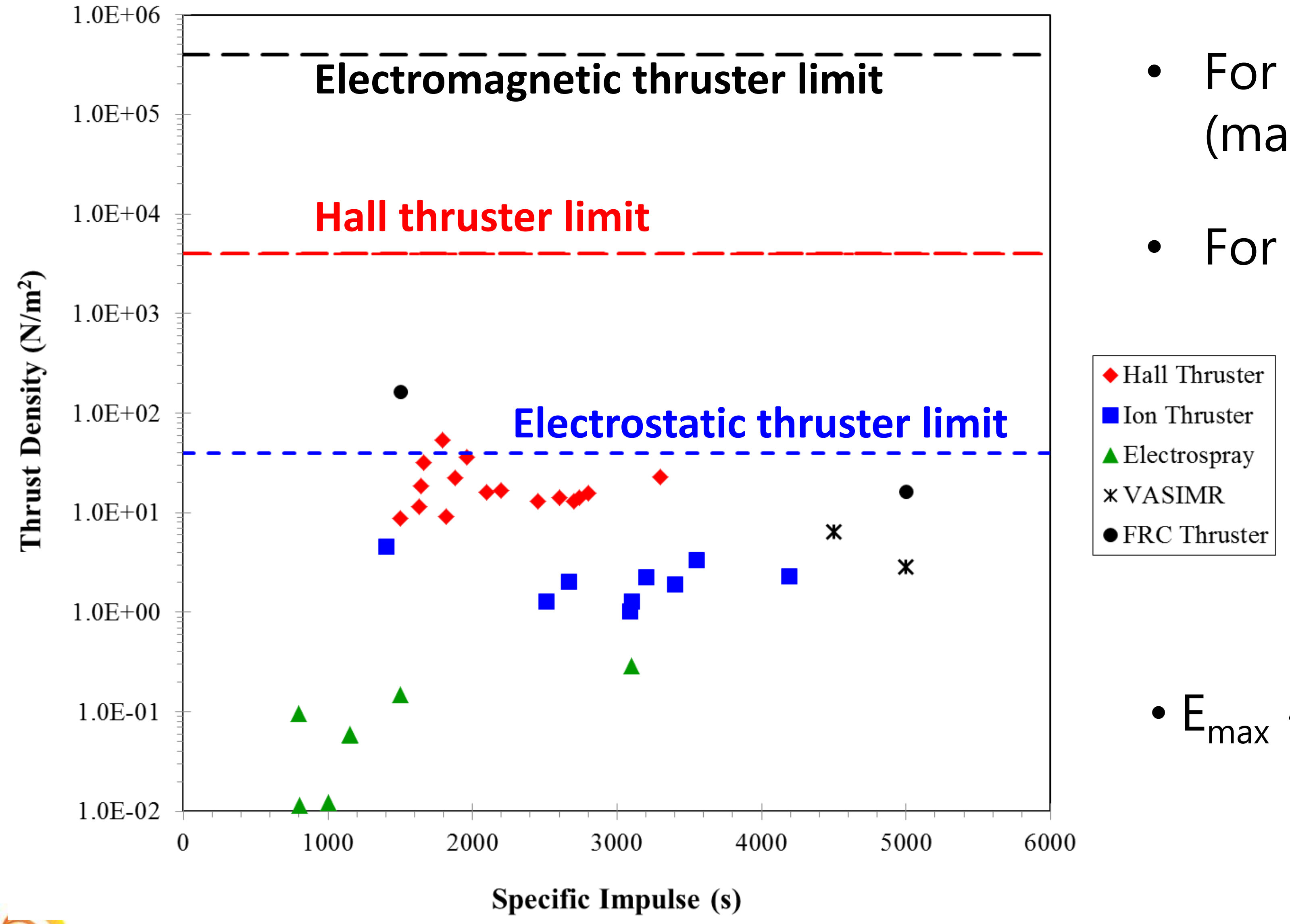


Power	2-200 kW
Efficiency	> 60%
Thrust	0.2 N– 10 N
Isp	1550 – 3500 s for **Xe**
Diameter	0.80 m
Thrust density	Up to ≈ **20 N/m²**
Mass	250 kg

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

Thrust Density Limits: *achieved vs feasible*



- For Hall thrusters, B_{max} ~ 0.1 T (magnetic core material saturation)
- For FRC, MPD, B_{max} ~ 1 T
- E_{max} ~ 10^6-10^7 V/m (breakdown of gap)

Is Hall thruster a mature technology?

NASA 457M Hall Thruster

Power: 50kW

45.7 cm

Squeeze

3.8 cm

For the same thrust, we could make much more compact thruster if it could operate at the fundamental thrust density limit, with B_{max} =1 kGauss!

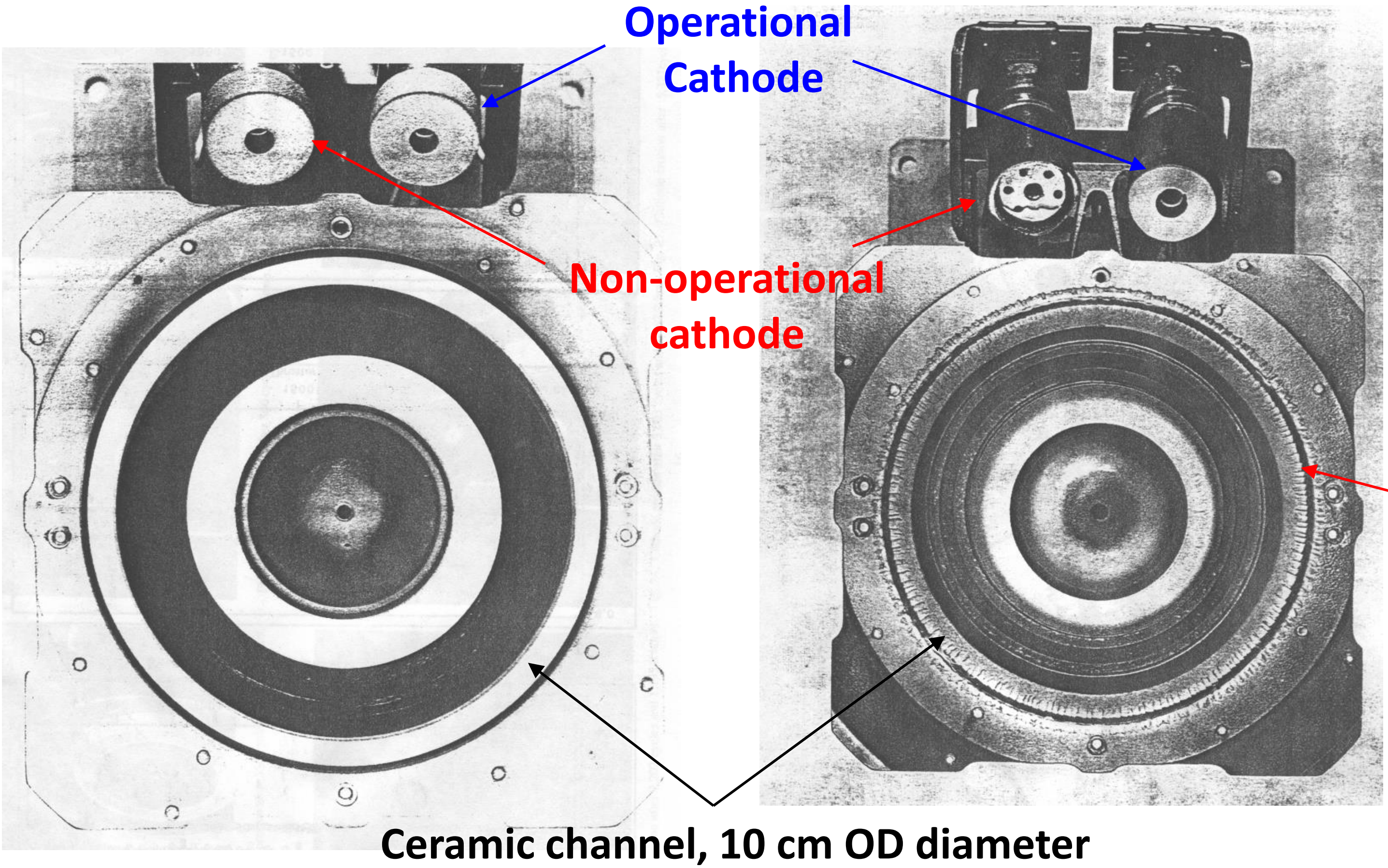
Key obstacles for the development of high thrust density, compact Hall thrusters

- **Plasma-wall interactions:** Ion-induced erosion of the thruster channel and the thruster heating – both limiting the thruster lifetime, scaling down of thruster dimensions (i.e. thruster compactness, high thrust density)
- **Turbulent fluctuations and related anomalous transport phenomena, and plasma structures** critically affecting the thruster performance and lifetime
    - Typical operation is limited to B_{max} ~ 100-200 Gauss, because of violent instabilities developed at stronger magnetic fields

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

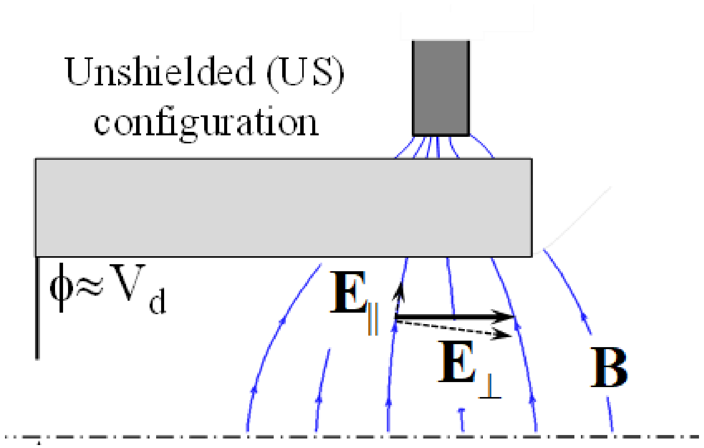


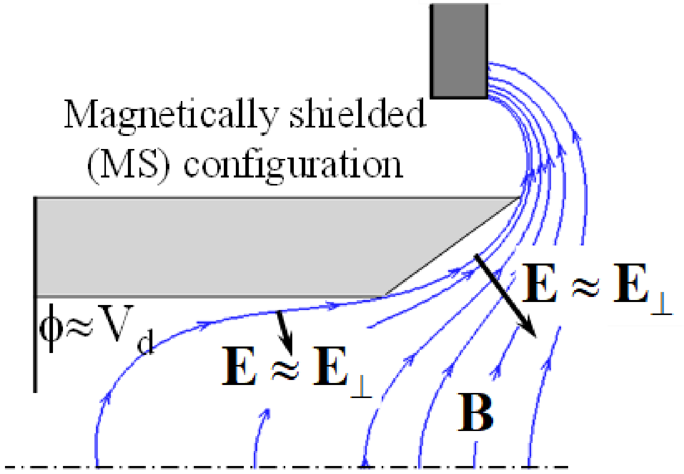
Ceramic channel, 10 cm OD diameter

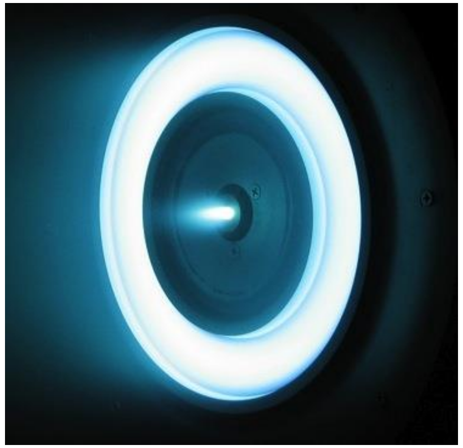
7 mm

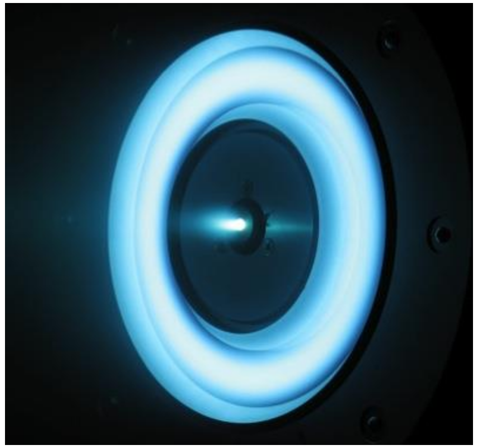
Jet Propulsion Laboratory
California Institute of Technology

Magnetically-shielded Hall thruster









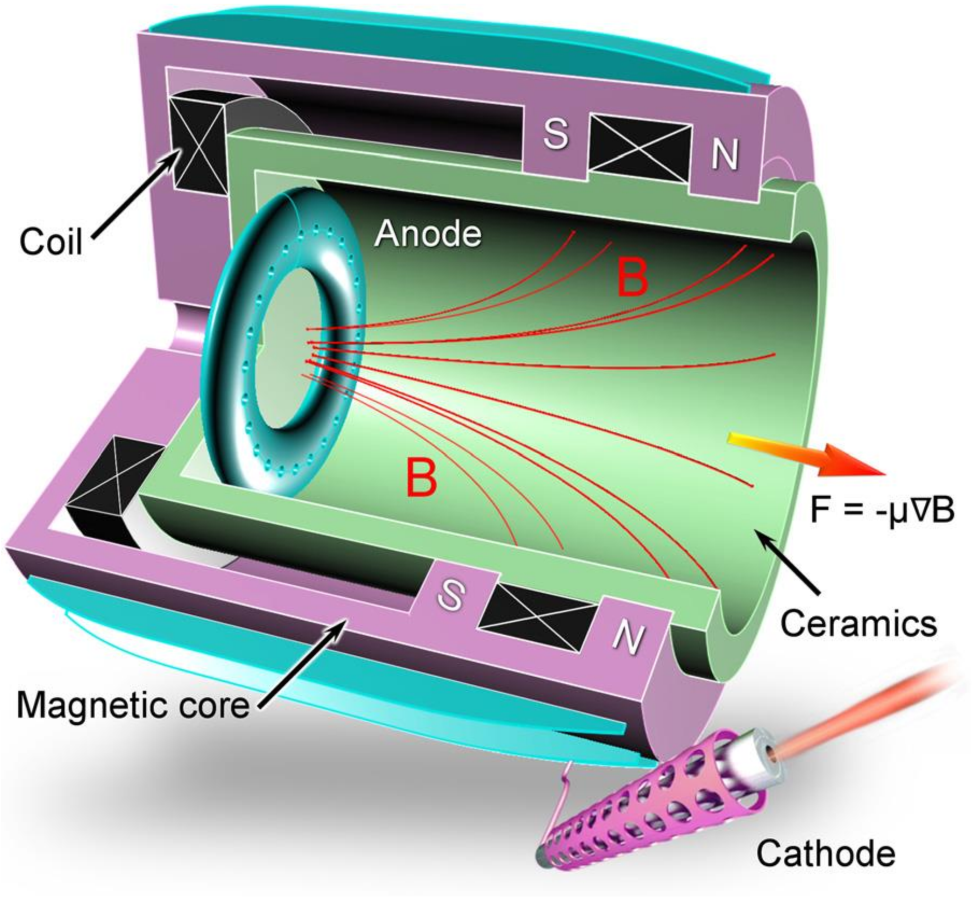
Courtesy:
Vernon Chaplin
Richard Hofer
Yaingos Mikellides

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

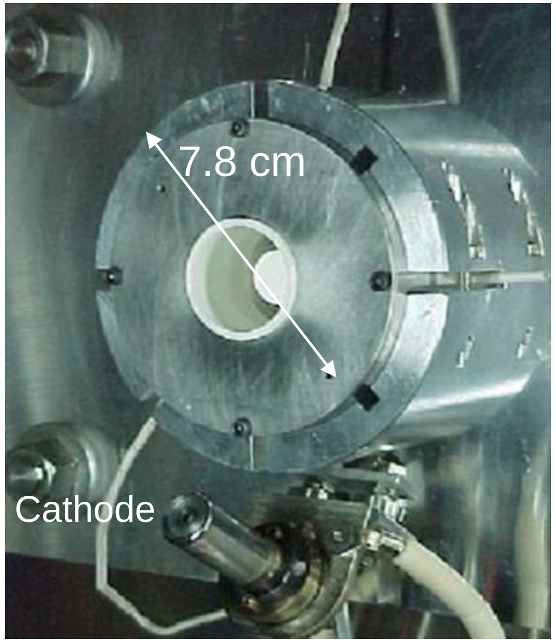
Central pole piece erosion is still a concern!

Jet Propulsion Laboratory
California Institute of Technology

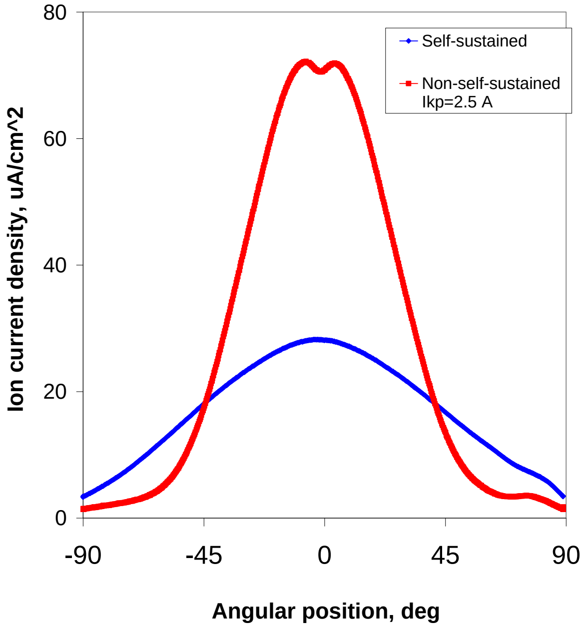
Cylindrical Hall thruster



- 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 current in the plasma plume

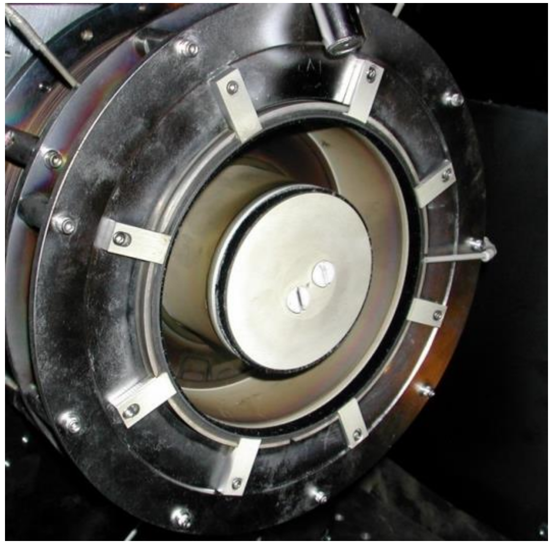


Maximum thrust density: 15 N/m^2

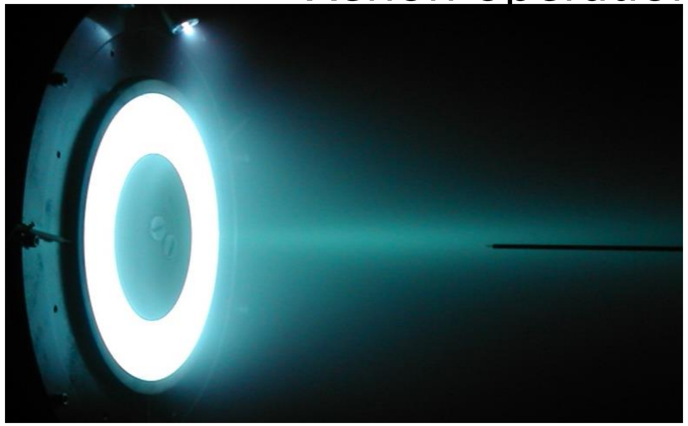
Y Raitses and N. J. Fisch, Phys. Plasmas, 8, 2579 (2001)
A. Smirnov, Y. Raitses, and N.J. Fisch, Phys. Plasmas **14**, 057106 (2007)

Plasma structures and anomalous cross-field current

12 cm diameter, 2kW Hall thruster



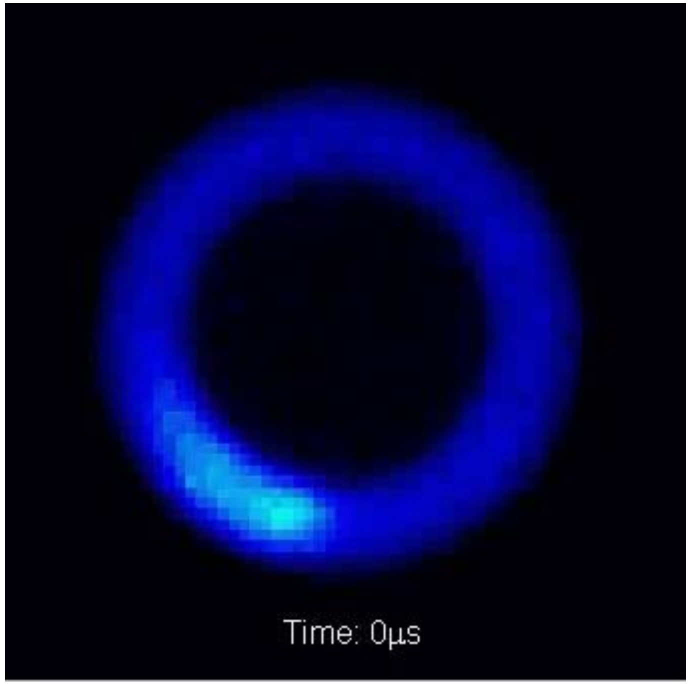
Xenon operation



Plasma non-uniformity

Current conducting ExB rotating "spoke"

Fast frame imaging 60 kfps



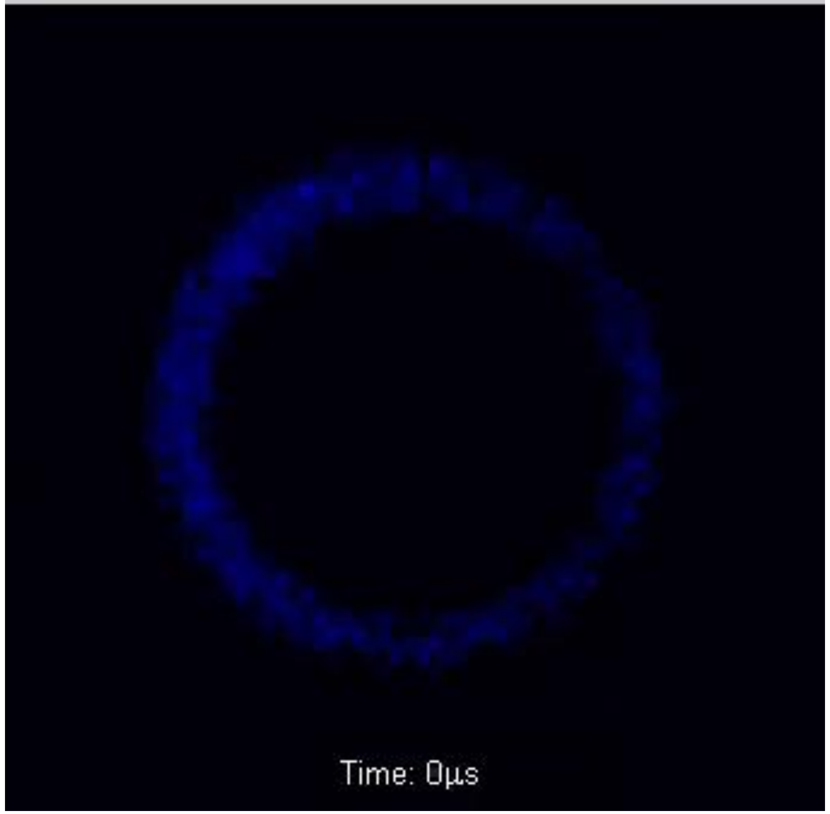
Thruster efficiency

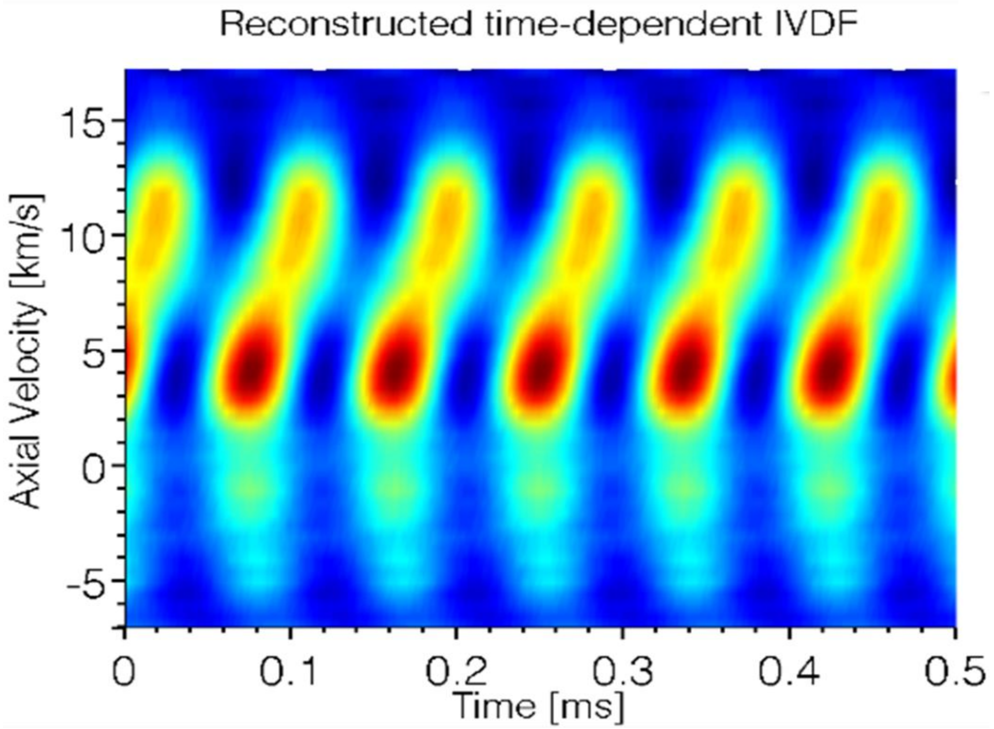
$$\eta \equiv \frac{TV_{jet}}{2P_e} \propto \frac{I_i}{I_i + I_{e\perp}}$$

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

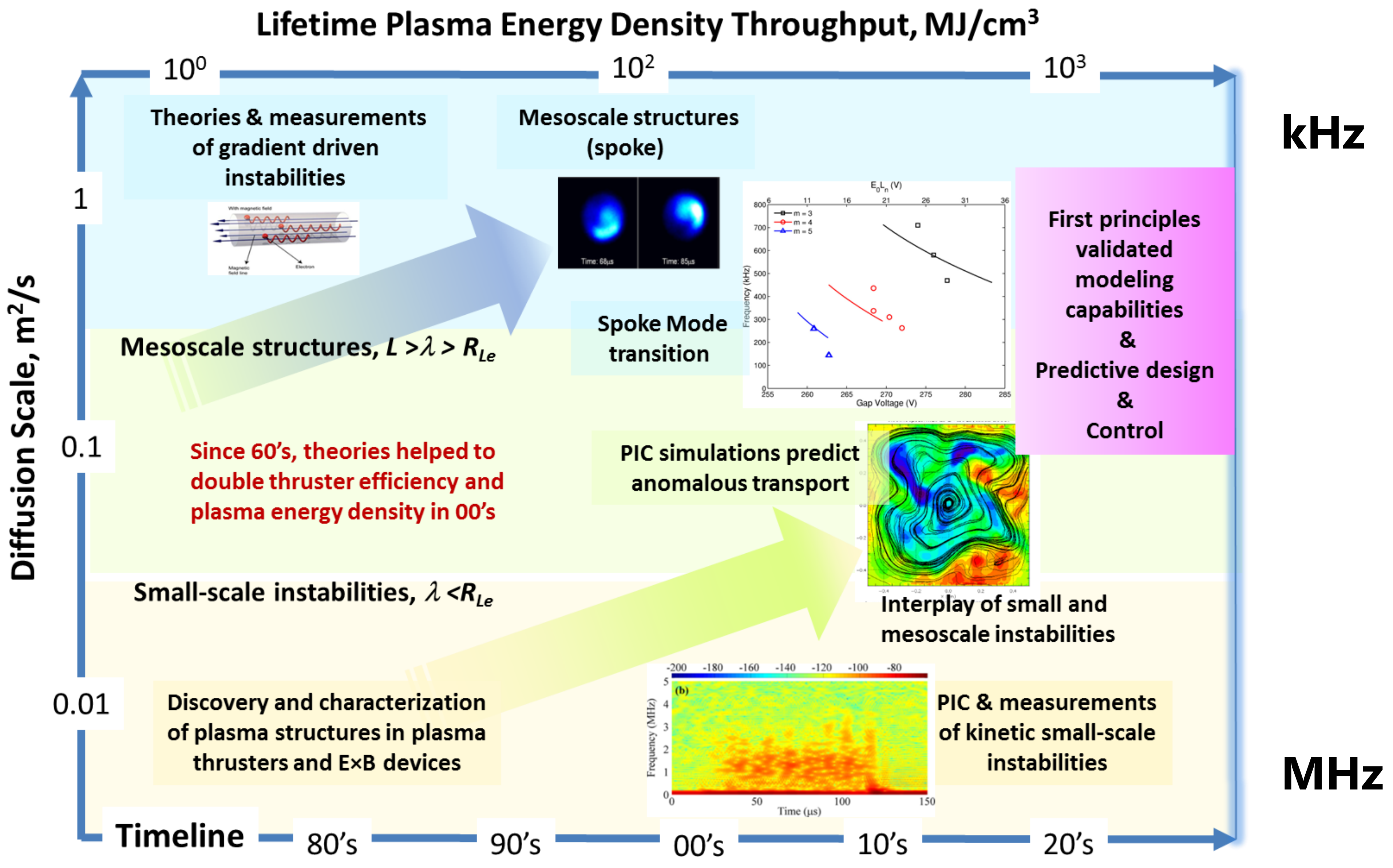




Powerful breathing oscillations of the discharge current due to ionization instability affects temporal evolution of ion velocity distribution

Y. Shi, Y. Raitses, and A. Diallo, Plasma Sources Sci. Technol. ***27,*** *104006 (2018)*

Towards understanding and control of electron ExB transport



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 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 mitigate/suppress plasma instabilities?**
    - Advance understanding of instabilities, develop active and passive engineering solutions (e.g. electrical circuitry, segmented electrodes)

Hall thruster of the future ?

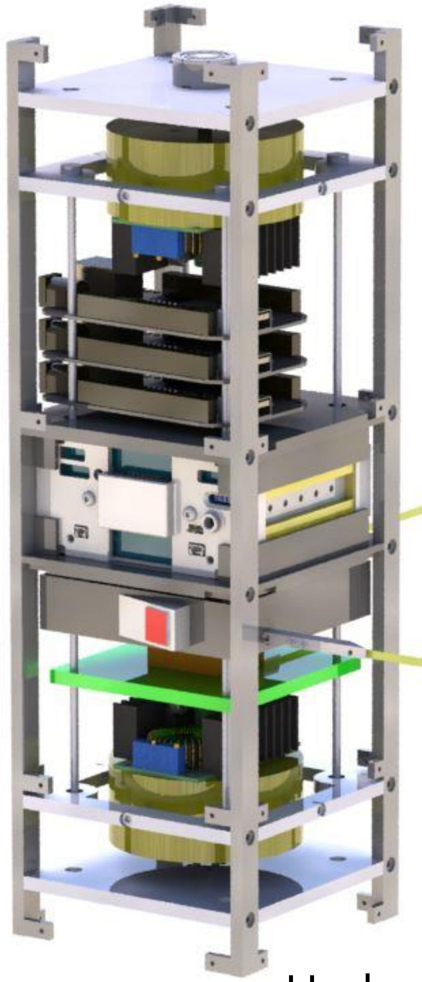
- **How to make much more compact, higher thrust density Hall thruster than state-of-the-art counterparts?**
  - Need to explore operating regimes relevant to the fundamental limit/s (e.g. strong B-fields > 1 kGauss, high plasma density, > 10^{12} cm^{-3})
  - Revisit physics of instabilities, transport for these extreme regimes
  - Develop experimentally validated predictive modeling capabilities
  - May require new thruster materials (e.g. diamond or cubic boron nitride for channel walls, high temperature permanent magnets)

Mini Hall thruster, TigerSat, magnetic reconnection,…

Miniaturized PPPL Hall thruster for nano/micro satellites, (1-50 kg)

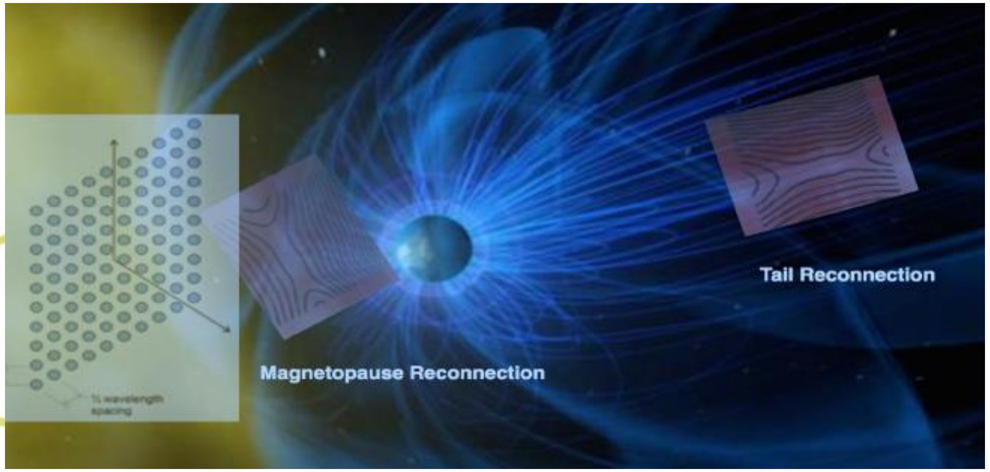
Thruster development by Princeton PhD student Jacob Simmonds and Dr. Y. Raitses

Princeton University TigerSat



Under development by Princeton students supervised by Prof. Daniel Marlow

- Supercluster of 100 CubeSats to measure magnetic reconnection



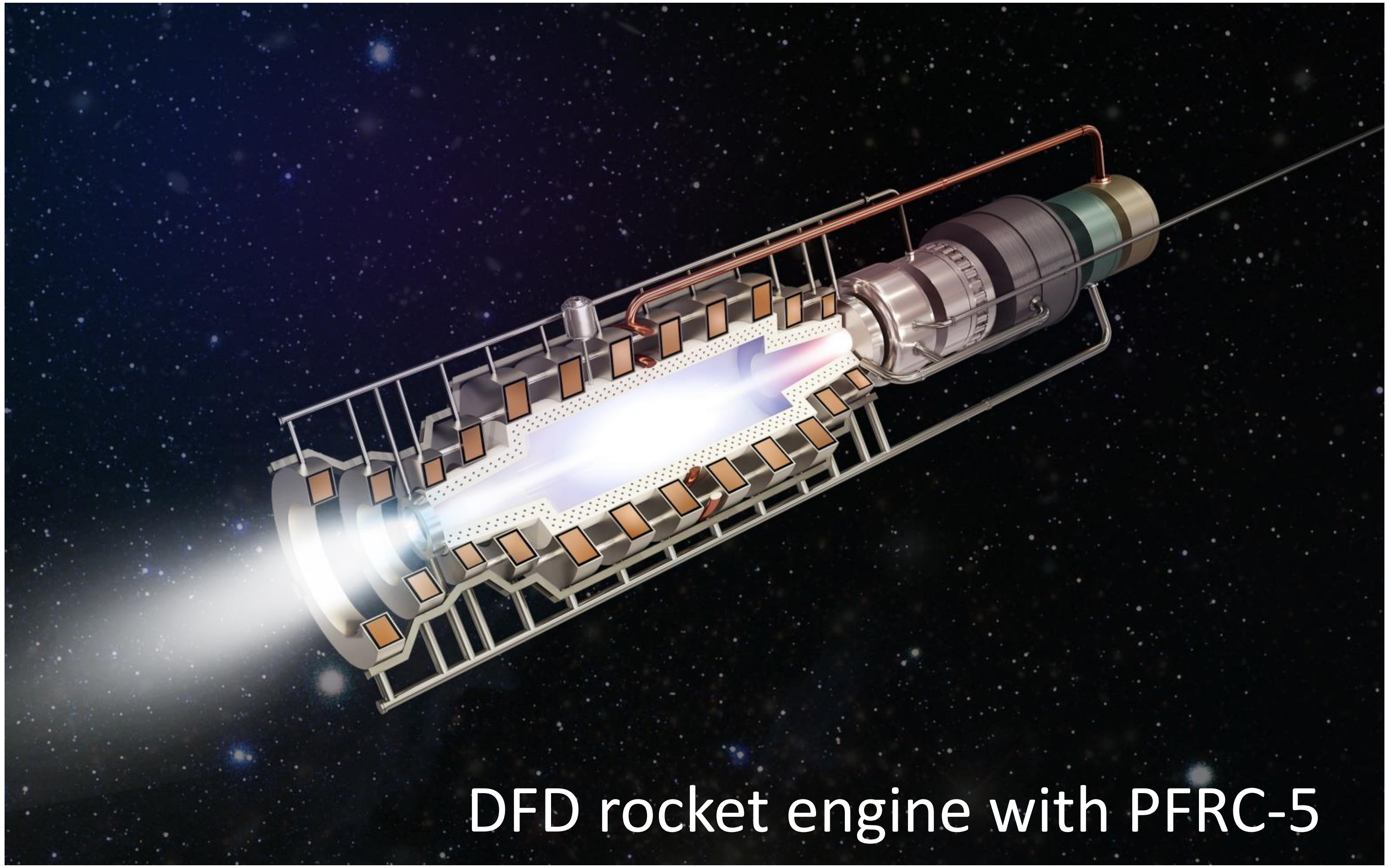
PPPL Dr. Masaaki Yamada's concept

Pluto Orbiter and Lander mission

Mission parameters

Payload	1000 kg
Fusion Power	2 MW
Total Trip Time	4 years
Acceleration Time	292 days
Specific Power	0.7 kW/kg
Thrust Efficiency	0.5
Total ΔV	74 km/s

Thrust	16.2 N
Isp	12,554 s
Total Mass	7158.7 kg
Engine Mass	2857.1 kg
Fuel Mass	3236.9 kg
Quantity ^{3}He	0.4 kg



DFD rocket engine with PFRC-5

Place roving lander on surface

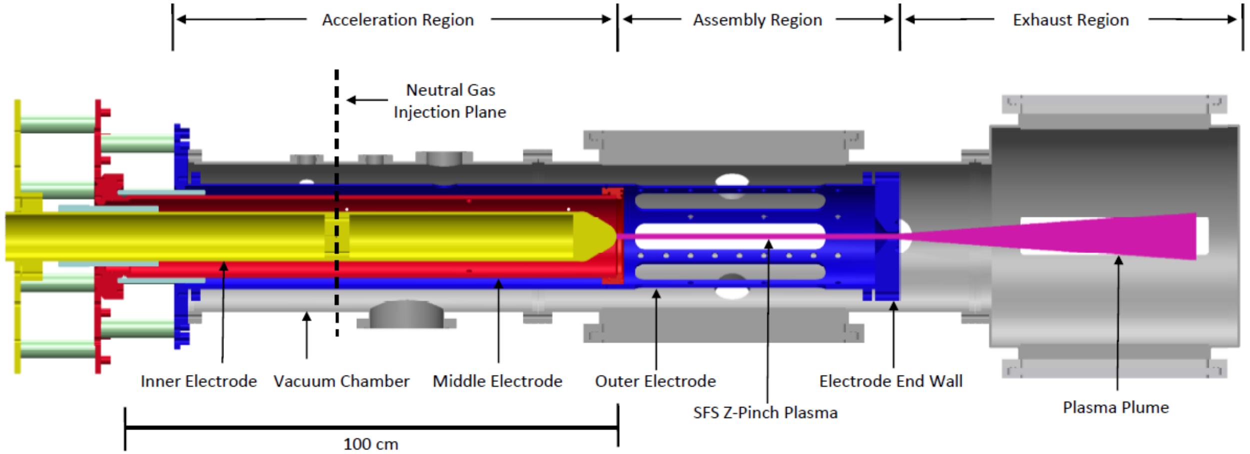
Provide power to lander

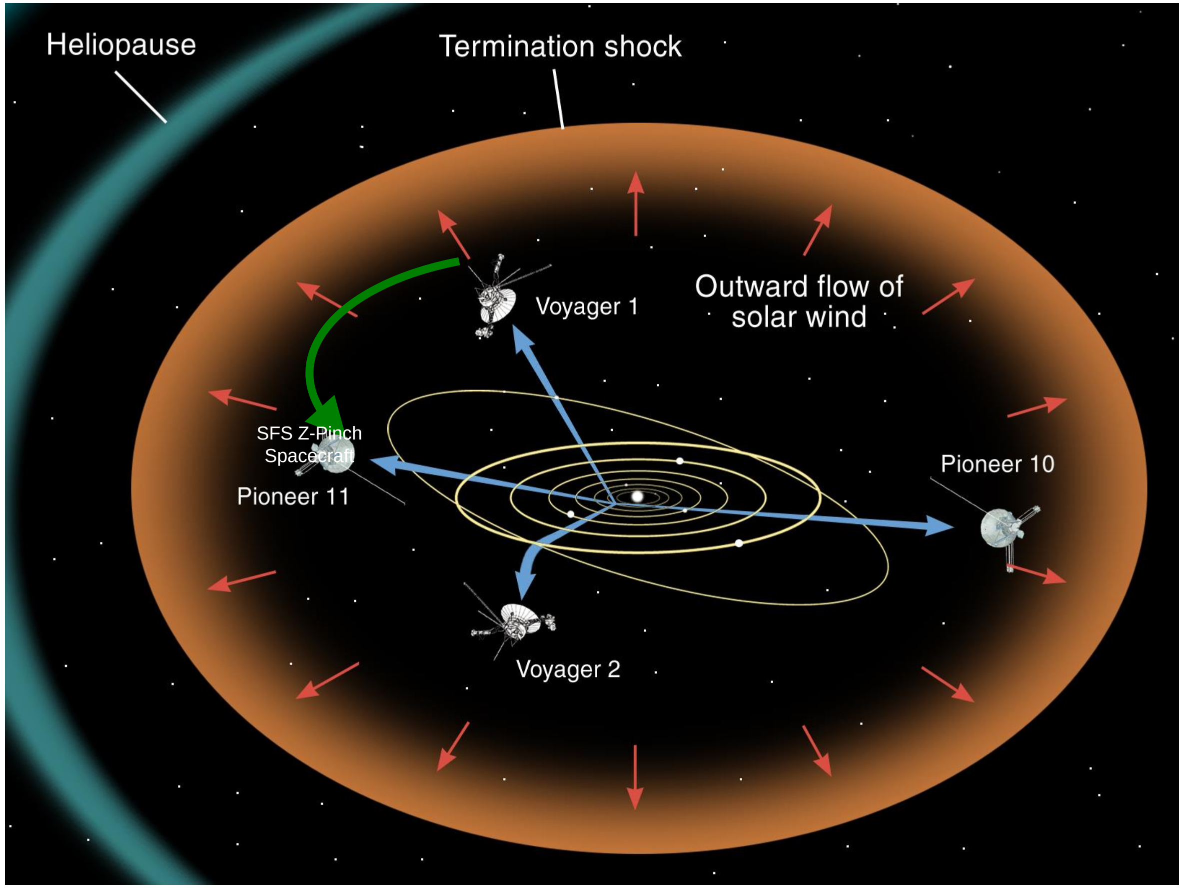
Beam back data

SFS Z-Pinch Fusion Space Propulsion System

Adam Sefkow's lecture on pinches, June 19

Operating at 1 Hz with a 0.001% duty cycle, a 4 MA (Q=10) SFS Z-pinch fusion thruster **could deliver a 2,100 kg payload to a 125 AU orbit** (interstellar space) in 9 years with a 70,000 kg spacecraft





Towards SFS Z-Pinch thruster: Need to maintaining plasma stability and control at higher pinch currents (MA's)

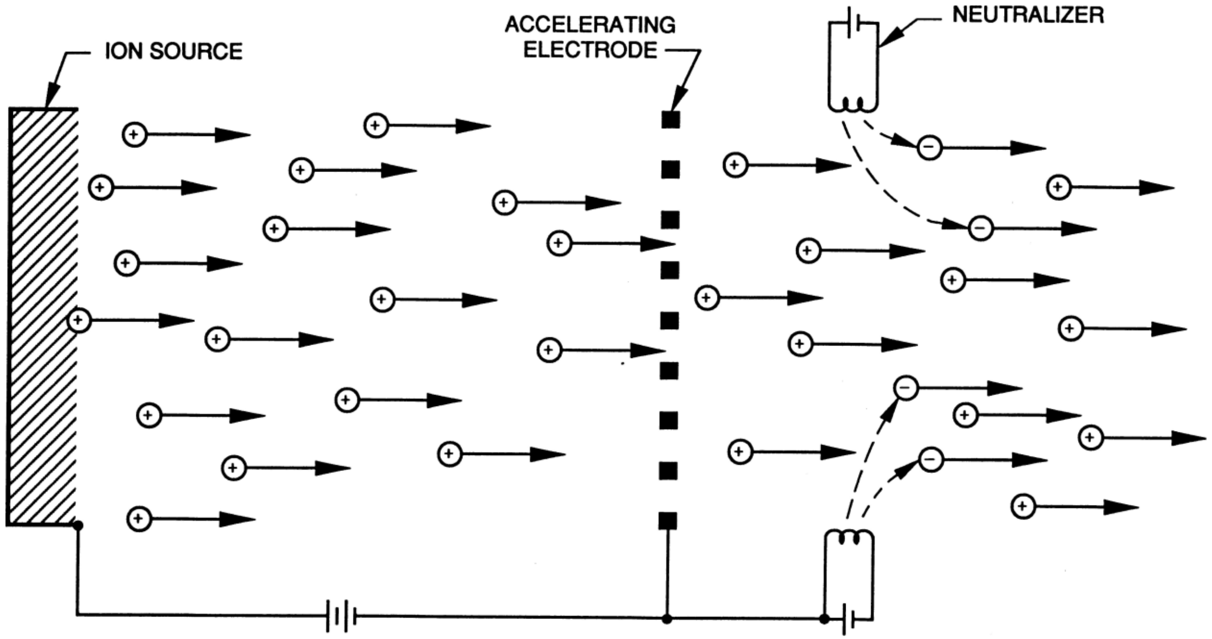
$$T/A \approx \frac{B^2}{2\mu}$$

Steve Cowley's lecture, June 6

Supplemental material

Ion thruster – electrostatic thrust force on electrodes

Ion current **Ion flux=electron flux**



Low gas pressure < 1 mtorr
– ions move without collisions

Poisson's equation $\nabla \cdot \boldsymbol{E} = \dfrac{\boldsymbol{\rho}}{\varepsilon}$

In 1- D $\rightarrow \dfrac{dE}{dx} = \dfrac{q n_i(x)}{\varepsilon_0}$

Force on ions, $q=e$

$$F_{ion}/A = e\int_0^d n_i(x)E(x)dx$$

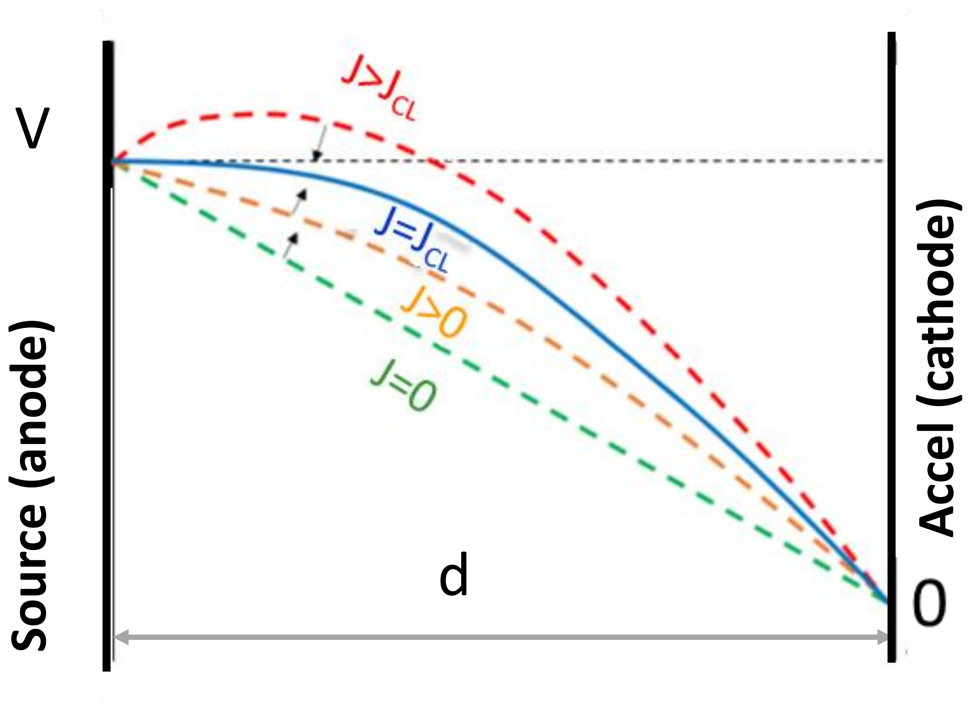
$$\rightarrow = \varepsilon_0 \int_0^d \frac{dE(x)}{dx} E(x)dx = \varepsilon_0 \int_{E_s}^{E_a} EdE$$

Ion thrust – the reaction force to acceleration of ions applied to the thruster electrodes

$$T = -F_{ion} = -\frac{\varepsilon_0}{2}(E_a^2 - E_s^2)A$$

Dan M. Goebel and Ira Katz
Fundamentals of Electric Propulsion
JPL series (2008)

Space charge-limited thrust density



Maximum thrust density when $E_s = 0$,

$$\frac{T_{max}}{A} = M\frac{J_i}{e}v_i = -\frac{\varepsilon_0}{2}E_a^2 \approx -\frac{\varepsilon_0}{2}\frac{V^2}{d^2}$$

Child-Langmuir space charge limit on the ion current density:

$$J_i^{max} = J_{CL} = \frac{4\varepsilon_0}{9}\left(\frac{2e}{M_{ion}}\right)^{1/2}\frac{V_d^{3/2}}{d^2}$$

From ion energy conservation, $v_i(x=0)=0$, the maximum Isp is the ion velocity at the accel grid:

$$Isp^{max} \approx v_{max}/g = \frac{1}{g}\left(\frac{2eV_d}{M_{ion}}\right)^{1/2}$$