Plasma Physics Modeling and Simulations of Electric Propulsion Over the Last Two Decades at the Jet Propulsion Laboratory

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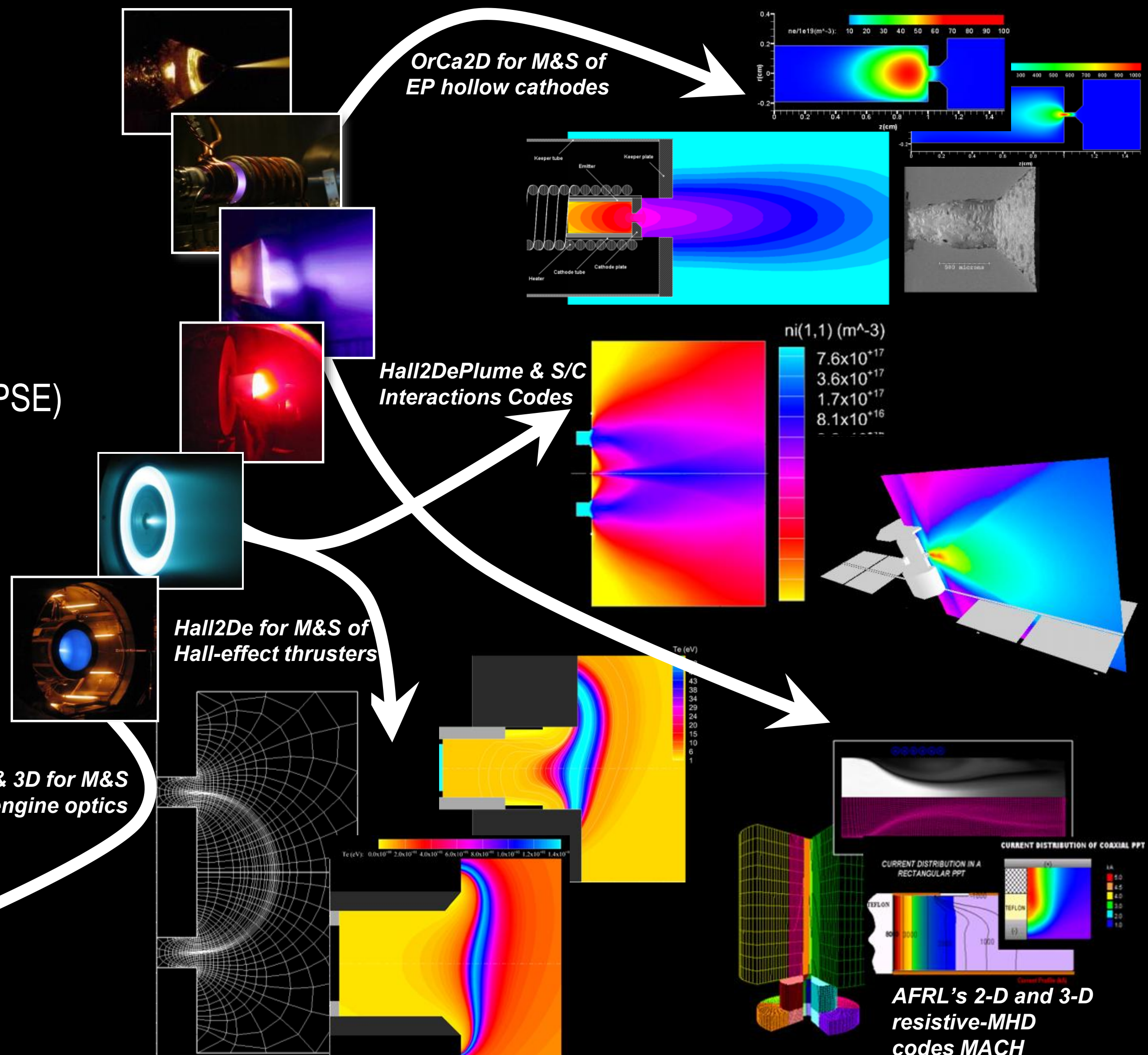
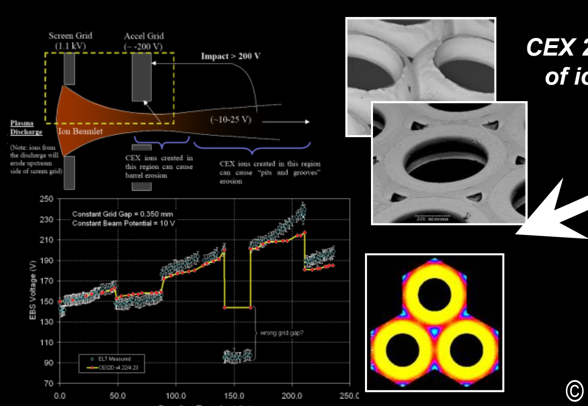




Electric Propulsion Fundamentals

- Electrical energy utilized to perform work on the propellant
- Thrust produced by "surface" forces ($\nabla \bullet P$) and/or "body" forces (e.g. Lorentz $\rho_e E + j \times B$)
- Unlike chemical propulsion, the working gas is in general not limited by the bond strengths of matter.

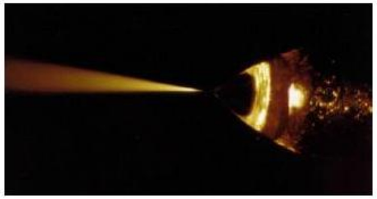
  → **Higher exhaust speeds (several km/s) can be attained**

  → **Higher mass fraction delivered**

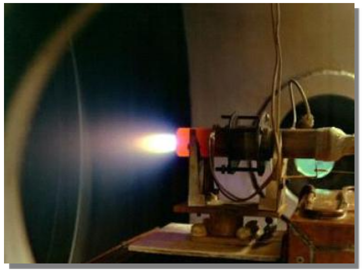
$$\frac{m_f}{m_0} = \exp\left(-\frac{\Delta V_{S/C}}{u_e}\right)$$

$\Delta V_{S/C}$ — Mission specified

u_e — Propulsion specified

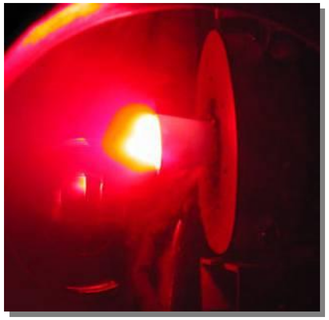


Electrospray Microthruster



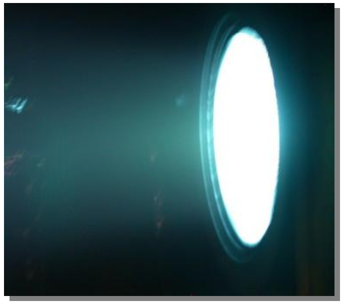
Electrothermal Arcjet

Pulsed Plasma Thruster



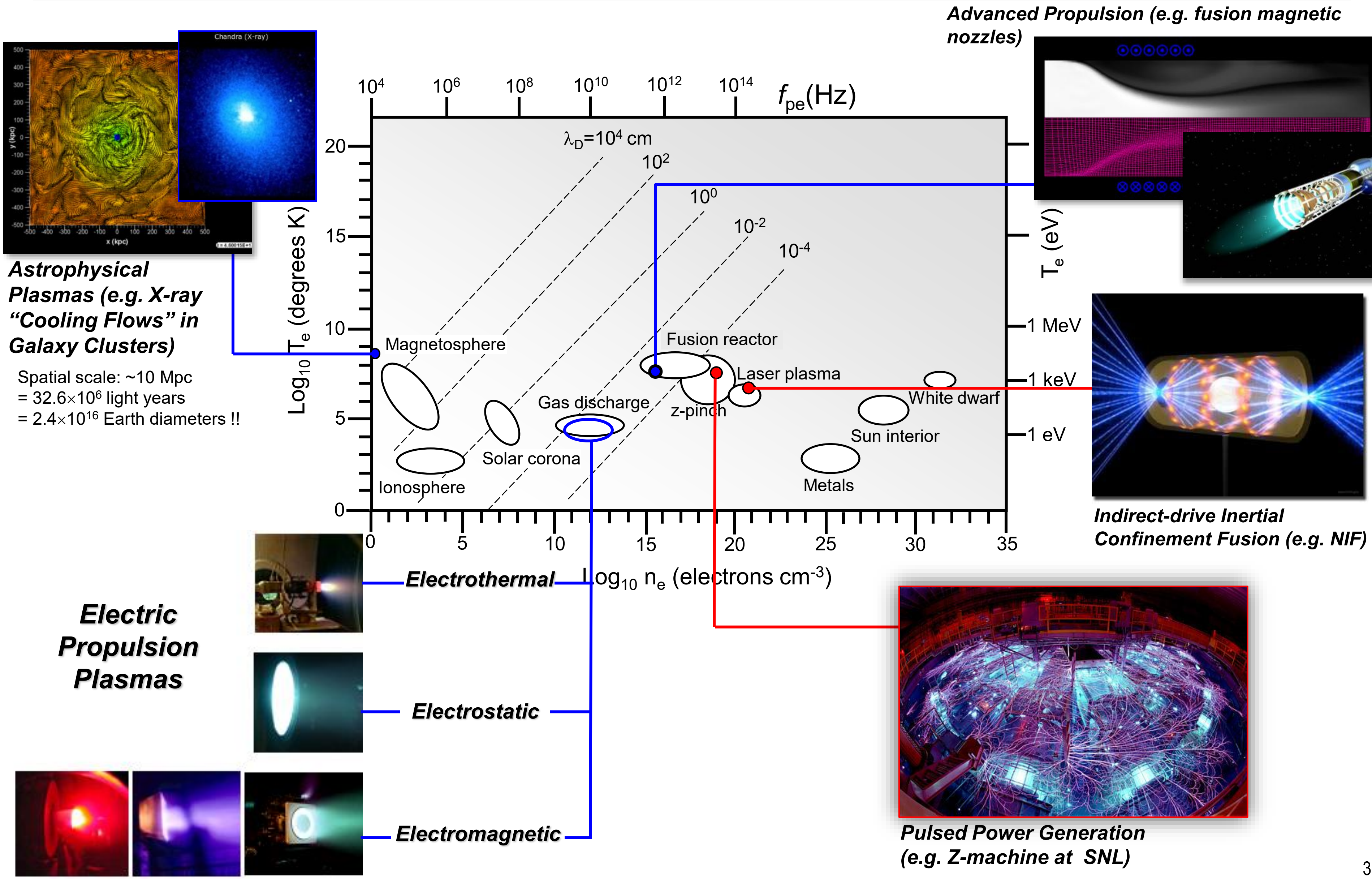
Magnetoplasmadynamic Thruster

Hall-Effect Thruster

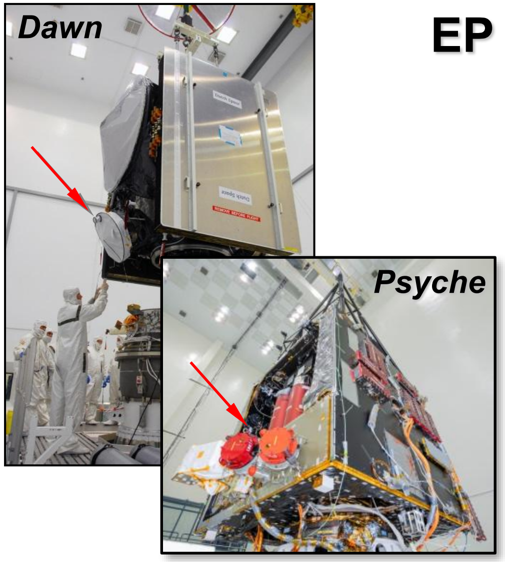


Ion Thruster

Relevant Conditions in Electric Propulsion Compared to Those in Other Fields of Plasma Physics

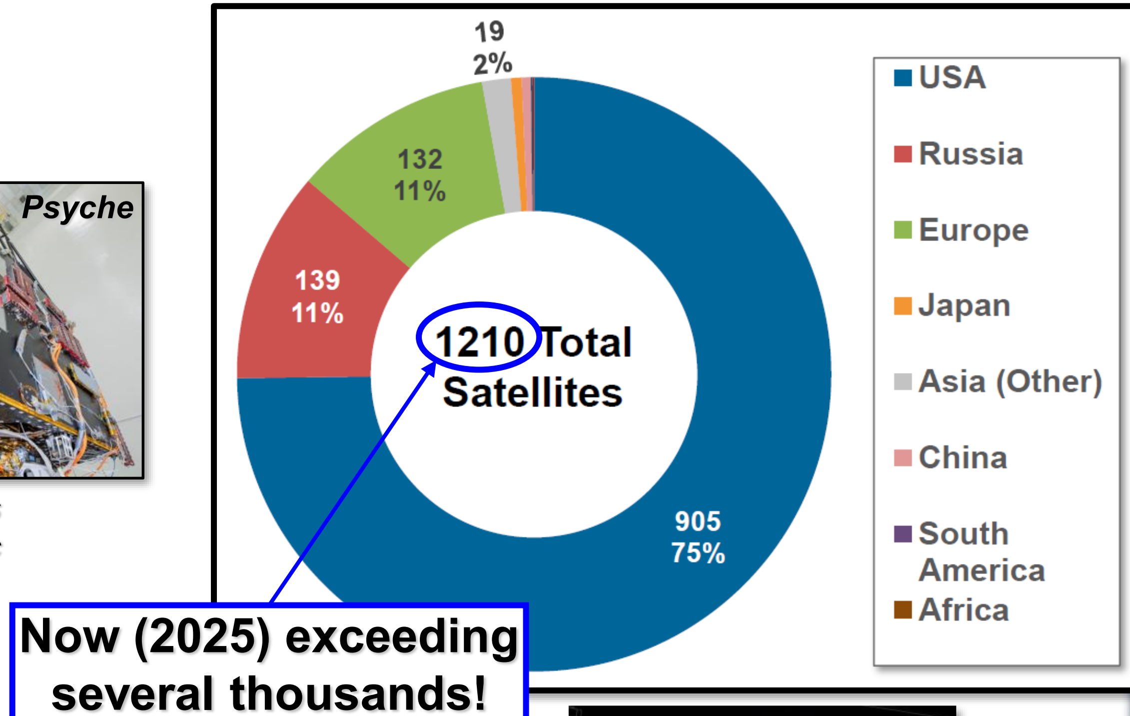


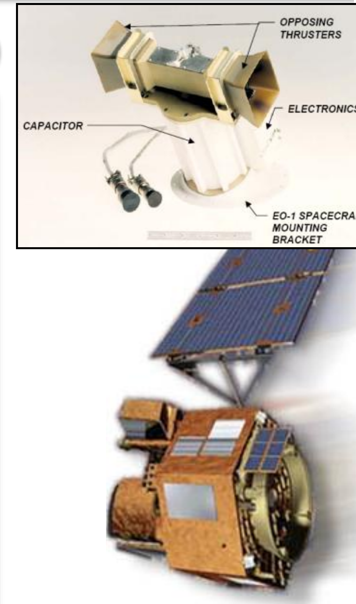
U.S. Governments and Industry Have all Benefited from Electric Propulsion



Ion and Hall Thrusters on NASA s/c

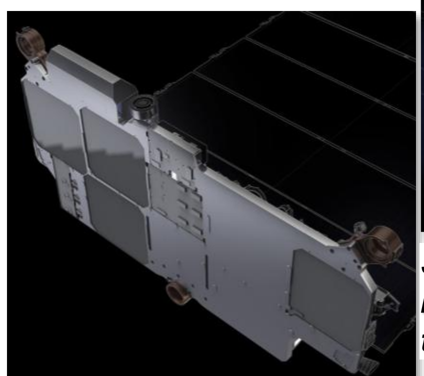
EP S/C by Manufacturer Region (June 30, 2020)

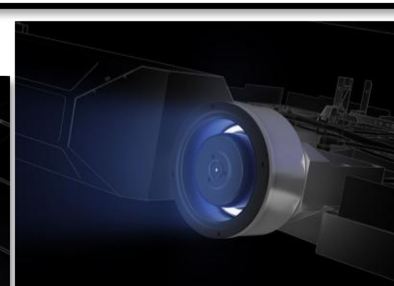




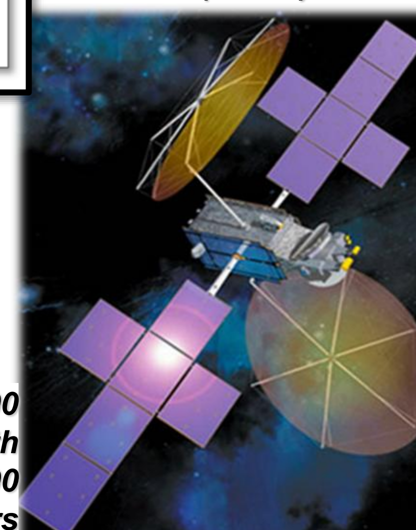
PPTs on EO-1 (NASA)

Arcjets on Telstar IV (Lockheed - US Commercial)





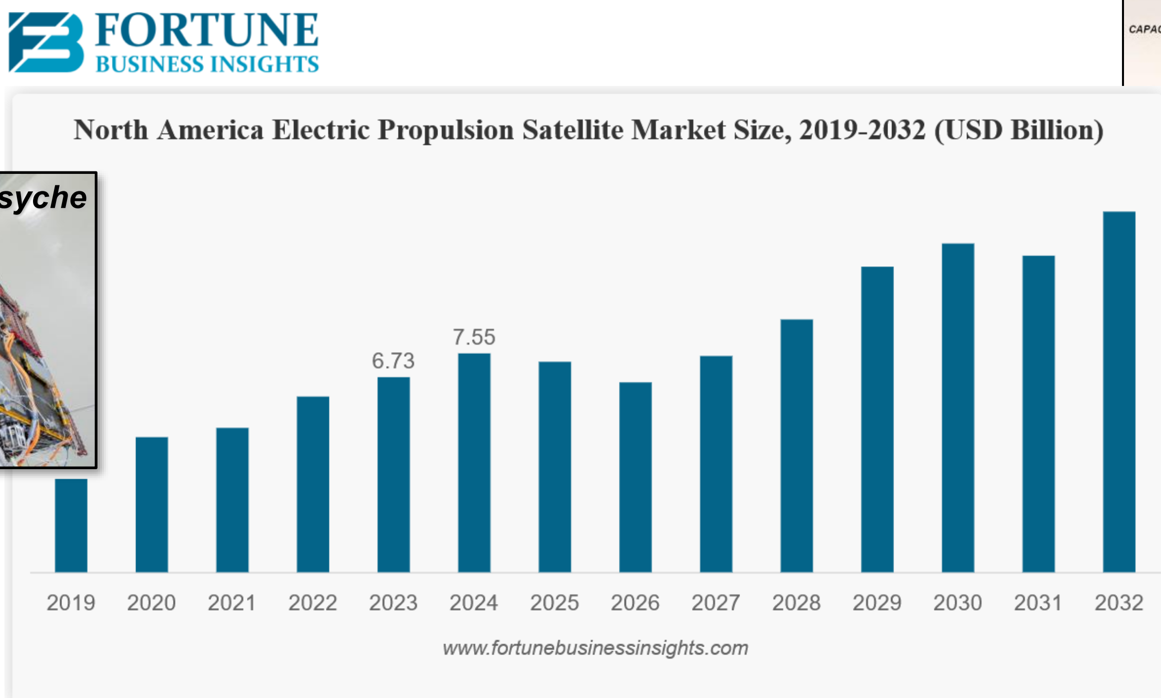
Space X Starlink Krypton Hall thrusters

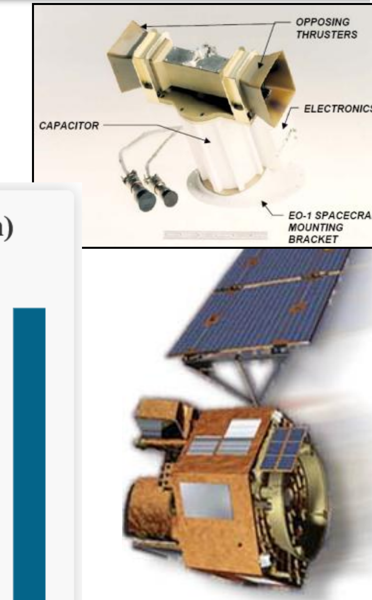


Loral FS1300 S/C bus with SPT-100 thrusters

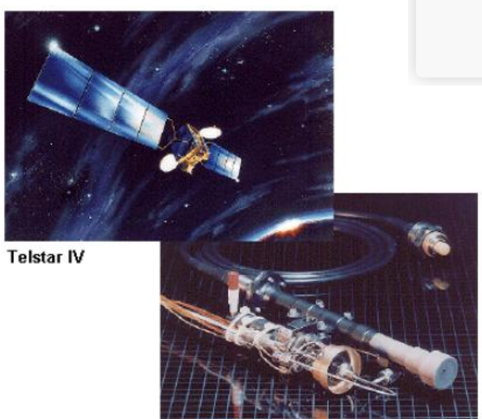
Investments in Electric Propulsion Expected to Grow in the Next Decade

Ion and Hall Thrusters on NASA s/c





PPTs on EO-1 (NASA)



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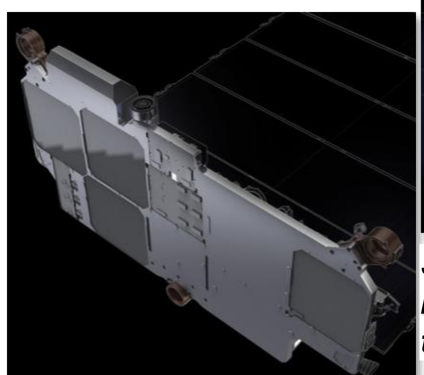
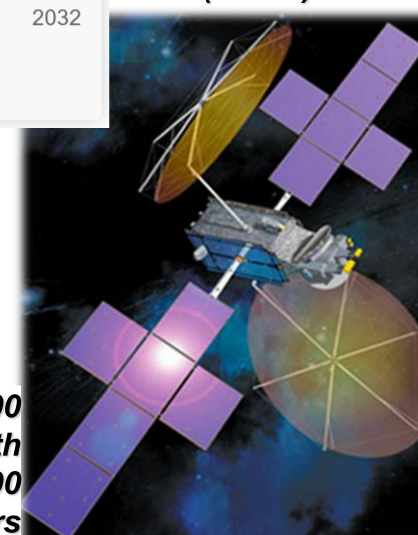


Space X Starlink Krypton Hall thrusters



Loral FS1300 S/C bus with SPT-100 thrusters

International Missions with Electric Propulsion

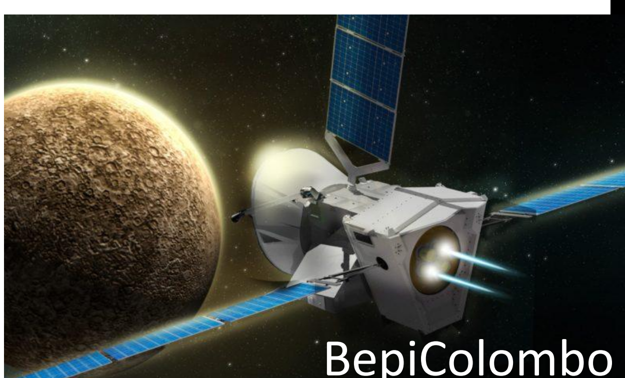
SMART-1: Technology demonstration mission (ESA)
- Launch: September 2003
- Propulsion: (PPS-1350G) Hall thruster

Hayabusa: Near-earth asteroid sample return (JAXA)
- Launched: May 2003; Return: June 2010
- Propulsion: Microwave electron cyclotron resonance Ion engines

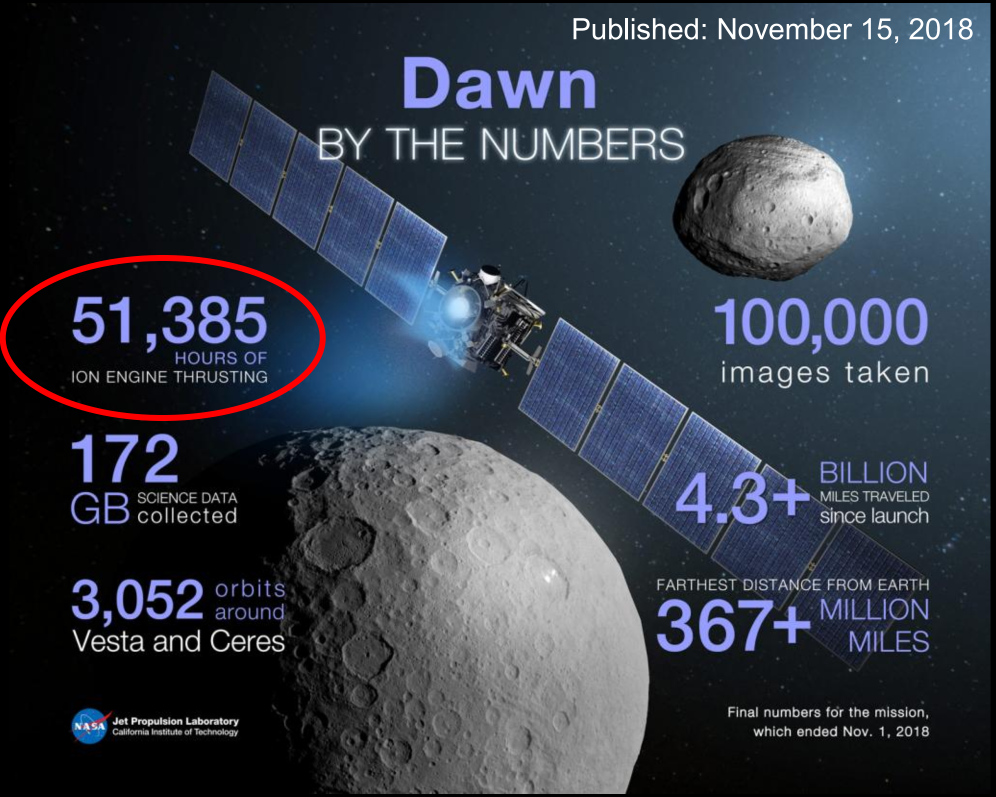
GOCE: Gravity field and Ocean Circulation Explorer (ESA)
- Launched: March 2009
- Propulsion: (T5) Kaufman Ion engines

LISA Pathfinder: Technology demonstration for the Laser Interferometer Space Antenna (ESA)
- Launched: December 2015
- Propulsion: Colloid thrusters and FEEPs

BepiColombo: Mission to Mercury (ESA/JAXA)
- Launched: October 2018
- Propulsion: (T6) Kaufman Ion engines



Deep-space Missions Need EP to Operate for Years



- Vesta & Ceres are the two most massive bodies in the main asteroid belt
  - Vesta ~ 560 km in diameter (350 miles)
  - Ceres ~ 970 km in diameter (600 miles)
- Dawn was the first mission to orbit a main belt asteroid and orbit two extraterrestrial bodies
- The mission was made possible by its ion propulsion system

Launched 9/27/2007

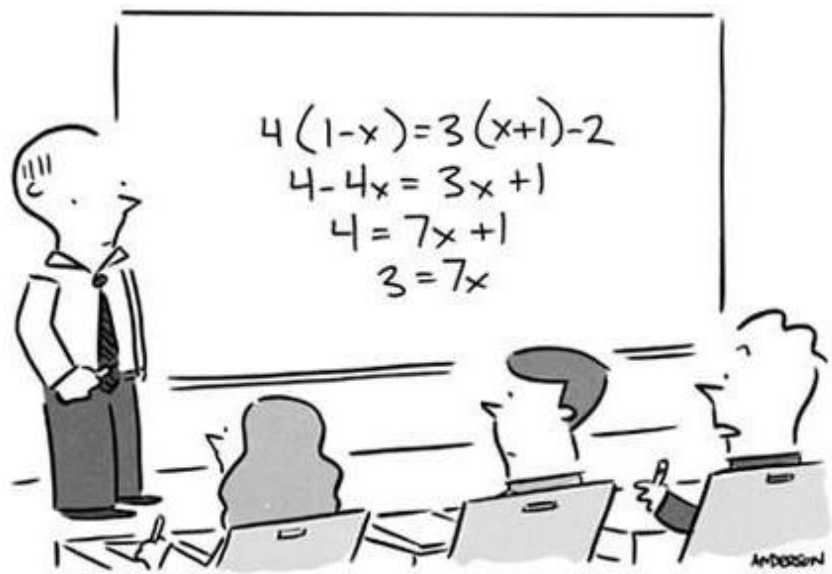
Overcoming the Challenge of Identifying and Mitigating Failure Modes in Electric Propulsion

EP Testing		EP Modeling (when properly validated!)	
Pros	Cons	Pros	Cons
Identifies failure modes/mechanism(s)	Cumbersome, costly, time consuming	Provides physics understanding to failure → reduces mission risk	Complex physics – validation cumbersome, long development time
Invaluable source for model guidance and validation	Only small samples of failure data usually possible	Allows for reliable test data extrapolations	
	Limited information about the driving physics	Allows assessment of changes in design and/or operating conditions	
	Effects of facility on failure not always clear	Helps interpretation of ambiguous test results	

A combination of physics-based modeling, wear tests and laboratory experiments offers the most cost-effective, timely and low-risk approach to the qualification of EP for deep-space flight.

Modeling of Plasmas in Electric Propulsion Can be Uniquely Challenging

- Complex physics
- Extensive mathematical governing laws
- Can be computationally intensive
- Wide-ranging spatial and temporal scales
  - Plasma-material interactions must be accounted for
- Model validation many times requires complicated diagnostics and/or facilities



"Wouldn't it be more efficient to just find who's complicating equations and ask them to stop?"

The Governing Equations of Hydrodynamics

Mass Continuity

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

Fluid Momentum

$$\rho \frac{\partial v^i}{\partial t} = -\rho v^j \nabla_j v^i + \nabla_j \left[-\left(P \right) \delta^{ij} + \sigma^{d\,ji} \right]$$

Specific Internal Energy

$$\rho \frac{\partial \varepsilon_i}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_i + \left[-\left(P_i \right) \delta^{ji} + \sigma^{d\,ji} \right] \nabla_i v_j + \nabla \cdot (\kappa_i \nabla T_i)$$

Stress tensor

$$\frac{\partial \sigma^d{}_{ij}}{\partial t} = 2\mu d^d_{ij} - v^k \nabla_k \sigma^d{}_{ij} \qquad \sigma_{ij} = \mu \left(u_{i,j} + u_{j,i} - \frac{2}{3} \delta_{ij} u_{k,k} \right)$$

The Governing Equations of Resistive-Magnetohydrodynamics

Mass Continuity

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

Fluid Momentum

$$\rho \frac{\partial v^i}{\partial t} = -\rho v^j \nabla_j v^i + \nabla_j \left[-\left(P + Q + \frac{1}{3} u_R \right) \delta^{ij} + \sigma^{d\,ji} + \frac{1}{\mu_0} \left(B^j B^i - \frac{1}{2} B^2 \delta^{ji} \right) \right]$$

Electron Specific Internal Energy

$$\rho \frac{\partial \varepsilon_e}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_e - P_e \delta^{ji} \nabla_i v_j + \eta J^2 - \vec{J} \cdot \left(\frac{\nabla P_e}{e n_e} \right) + \nabla \cdot (\kappa_e \nabla T_e) - \Phi_{eR} - \rho c_{v_e} \frac{(T_e - T_i)}{\tau_{ei}}$$

Ion Specific Internal Energy

$$\rho \frac{\partial \varepsilon_i}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_i + \left[-(P_i + Q)\delta^{ji} + \sigma^{d\,ji} \right] \nabla_i v_j + \nabla \cdot (\kappa_i \nabla T_i) + \rho c_{v_e} \frac{(T_e - T_i)}{\tau_{ei}}$$

Radiation Energy Density

$$\frac{\partial u_R}{\partial t} = -\rho \vec{v} \cdot \nabla u_R - \frac{4}{3} u_R \nabla \cdot \vec{v} + \nabla \cdot (\kappa_{rad} \nabla u_R) + \Phi_{eR} \qquad \Phi_{eR} = \alpha c \rho \chi_{planck} \left(T_e^4 - T_R^4 \right)$$

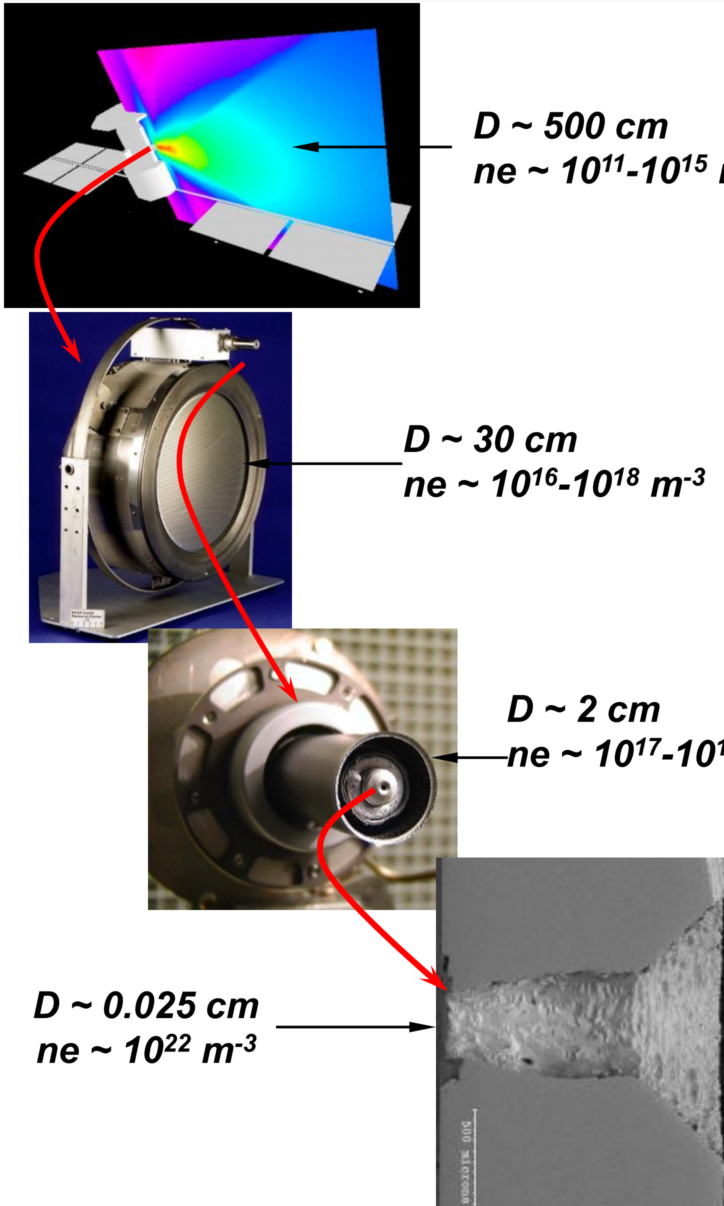
Magnetic Induction

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \nabla \times (\eta \vec{J}) - \nabla \times \left(\frac{\vec{J} \times \vec{B}}{e n_e} \right) + \nabla \times \left(\frac{\nabla P_e}{e n_e} \right)$$

Stress tensor

$$\frac{\partial \sigma^d{}_{ij}}{\partial t} = 2\mu d^d_{ij} - v^k \nabla_k \sigma^d{}_{ij} \qquad \sigma_{ij} = \mu \left(u_{i,j} + u_{j,i} - \frac{2}{3} \delta_{ij} u_{k,k} \right)$$

Physical Sizes, Plasma Conditions and Modeling Methodologies are Wide-ranging in Electric Propulsion

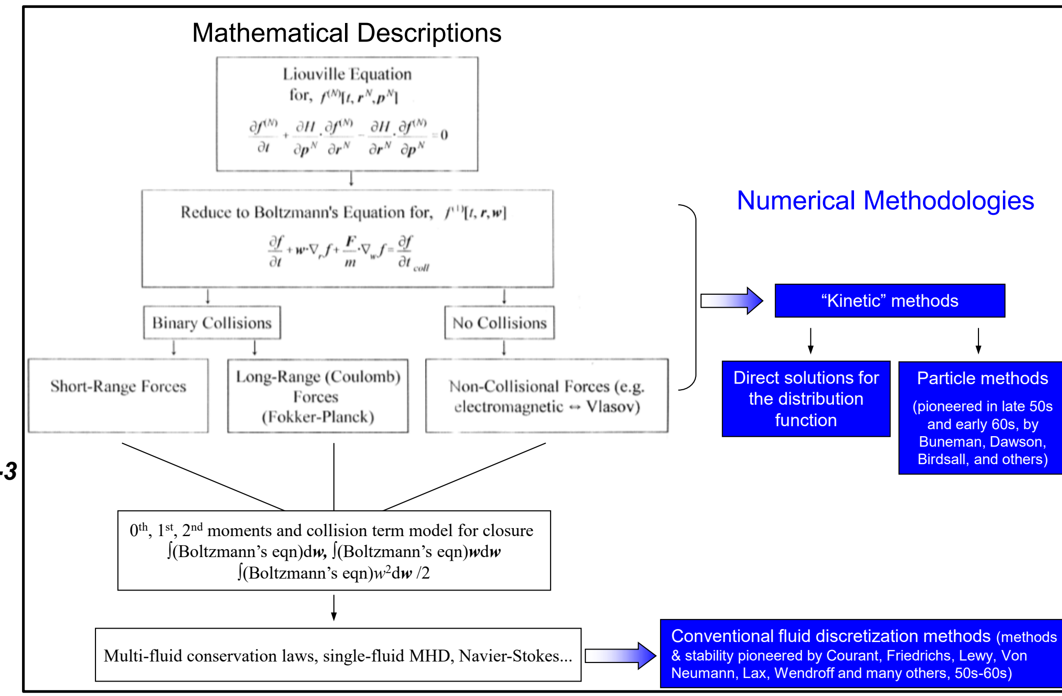


D ~ 500 cm
ne ~ 10^{11}-10^{15} m^{-3}

D ~ 30 cm
ne ~ 10^{16}-10^{18} m^{-3}

D ~ 2 cm
ne ~ 10^{17}-10^{19} m^{-3}

D ~ 0.025 cm
ne ~ 10^{22} m^{-3}



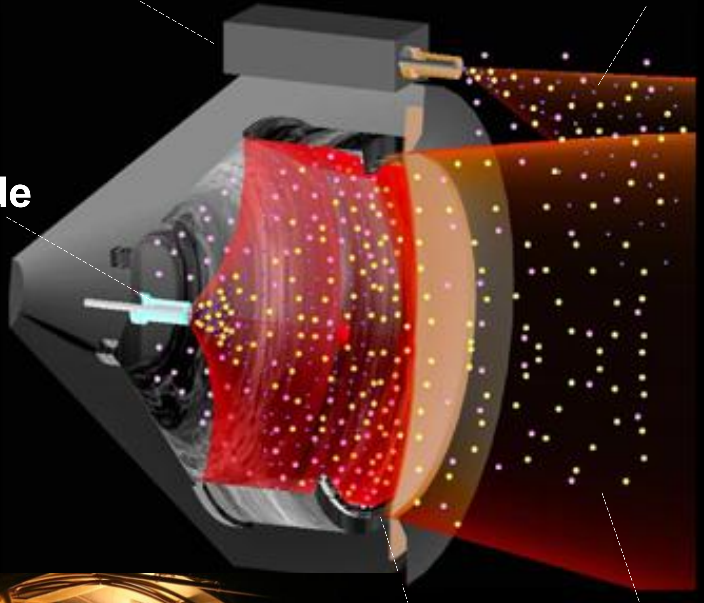
“ Professor Oberth has been right with so many of his early proposals; I wouldn’t be a bit surprised if one day we flew to Mars electrically! ”

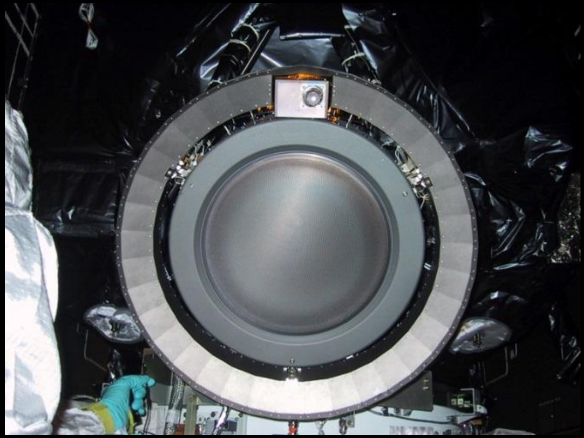
— Wernher von Braun to Ernst Stuhlinger in reference to Hermann Oberth’s ideas on “electric spaceship propulsion”, 1947 at the Army Camp Fort Bliss, TX.

Front: Hermann Oberth
Middle left: Ernst Stuhlinger
Middle right: Wernher von Braun
Back-left: (General) Holger Toftoy
Back-right: Eberhard Rees.

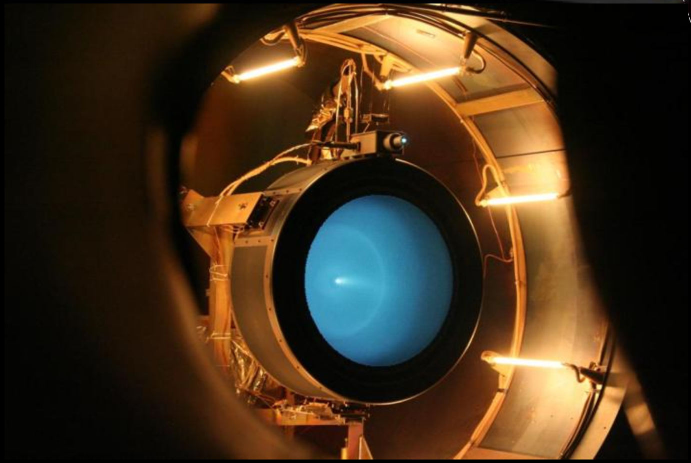
Gridded Ion Engines Accelerate Ions Electrostatically

DS-1 NSTAR



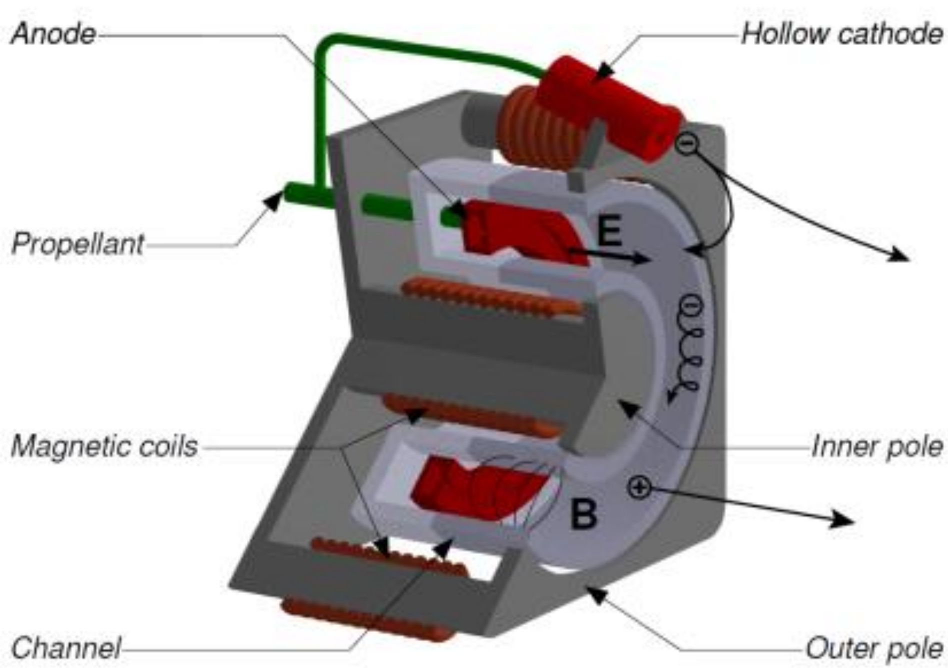


DAWN



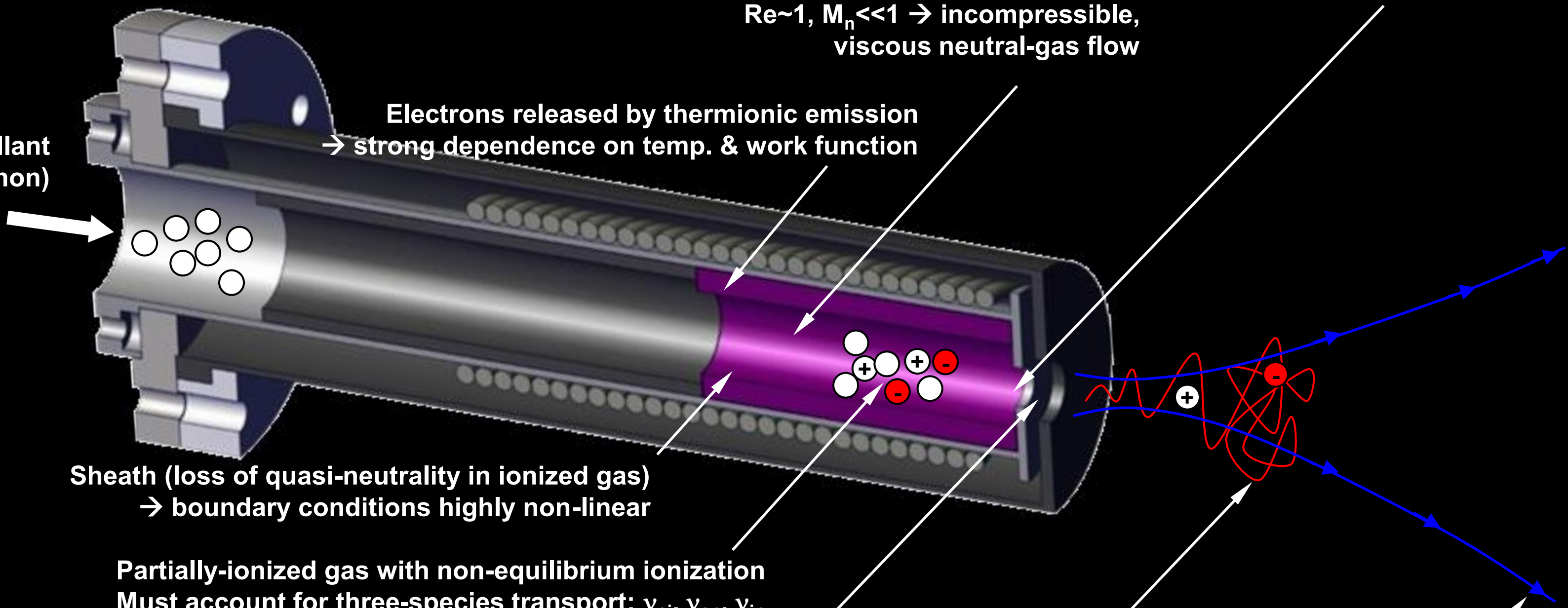
NEXT

Hall Thrusters Accelerate Ions Electromagnetically



- **Hall thrusters produce a high-energy ion beam using crossed electric (E) and applied magnetic (B) fields.**
  - Strong applied **B** acts as resistance to <u>magnetized electron</u> motion across it
  - **E**×**B** drift of electrons generates Hall current which interacts with **B → (jxB)**
  - <u>Un-magnetized</u> ions free to accelerate axially to high energy by component of **E=-**$\nabla\phi$ $\perp$ to **B** according to Ohm's law.

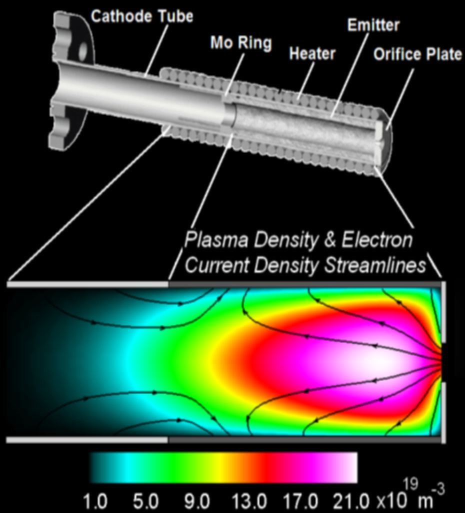
Hollow Cathodes Produce Electrons by Thermionic Emission and are Absolutely Critical for the Operation of Ion and Hall Thrusters



“By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work — that is, correctly to describe phenomena from a reasonably wide area.”

— John von Neumann ('Method in the Physical Sciences', in John von Neumann and L. Leary (ed.), The Unity of Knowledge, 1955)

With the 2-D **Or**ificed **Ca**thode (**OrCa2D**) Code JPL Pioneered the Simulation of Plasma Physics in EP Hollow Cathodes



- Code development began in 2004 at JPL [1]
- OrCa2D firsts at the time:
  - solved the most comprehensive system of conservation laws in these devices
  - used largest 2-D axisymmetric domain, encompassing cathode interior and exterior
  - accounted for applied magnetic field
  - revealed the 2-D structure of the interior plasma
- About a decade later similar codes emerged in China and France

The OrCa2D Governing Equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{u}_i) = \dot{n}$$

$$\frac{\partial n_n}{\partial t} + \nabla \cdot (n_n\boldsymbol{u}_n) = -\dot{n}$$

$$\frac{\partial (nm\boldsymbol{u})_i}{\partial t} + \nabla \cdot (nm\boldsymbol{u}\boldsymbol{u})_i = -en\nabla\phi - \nabla p_i + \boldsymbol{R}_i$$

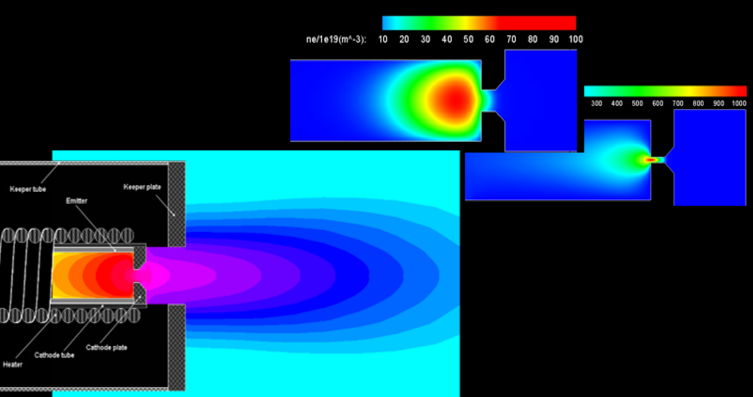
$$\frac{\partial (nm\boldsymbol{u})_e}{\partial t} + \nabla \cdot (nm\boldsymbol{u}\boldsymbol{u})_e = en\nabla\phi - \nabla p_e + \boldsymbol{R}_e - \boldsymbol{u}_e \times \boldsymbol{B} = 0$$

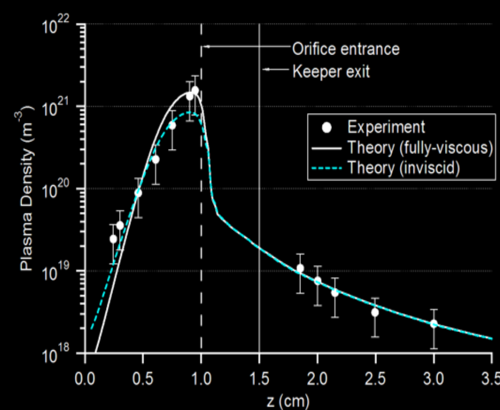
$$\frac{\partial (nm\boldsymbol{u})_n}{\partial t} + \nabla \cdot (nm\boldsymbol{u}\boldsymbol{u})_n = -\nabla p_n + \nabla \cdot \overline{\boldsymbol{\tau}}_n + \boldsymbol{R}_n$$

$$\nabla \cdot (en\boldsymbol{u}_i - en\boldsymbol{u}_e) = 0$$

$$\frac{3}{2}\frac{\partial p_e}{\partial t} + \nabla \cdot \left(\frac{5}{2}p_e\boldsymbol{u}_e + \boldsymbol{q}_e\right) = Q_e + \boldsymbol{u}_e \cdot \nabla p_e - \dot{n}\left(e\varepsilon_i - \frac{m_e u_e^2}{2}\right)$$

$$\frac{3}{2}\frac{\partial p_{i/n}}{\partial t} + \nabla \cdot \left(\frac{5}{2}p_{i/n}\boldsymbol{u}_{i/n} + \boldsymbol{q}_{i/n}\right) = Q_{i/n} + \boldsymbol{u}_{i/n} \cdot \nabla p_{i/n}$$

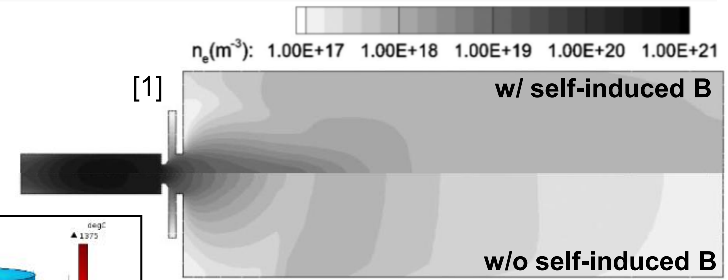




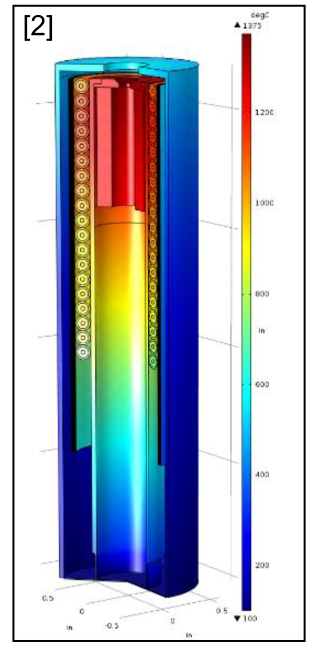
[1] First journal article on OrCa2D: Mikellides, I. G., Katz, I., Goebel, D. M., and Polk, J. E., "Hollow Cathode Theory and Experiment, II. A Two-Dimensional Theoretical Model of the Emitter Region," *Journal of Applied Physics*, Vol. 98, No. 11, 2005, pp. 113303 (1-14).

Noteworthy Firsts with OrCa2D Over the Last Decade

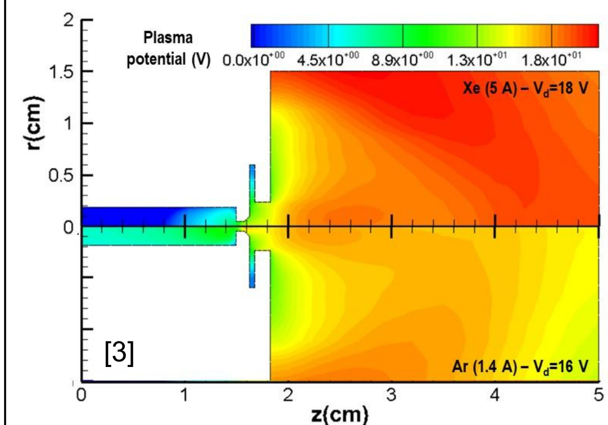
- First simulations of high-current cathodes (>100-A) capturing the effect of the induced azimuthal B [1]



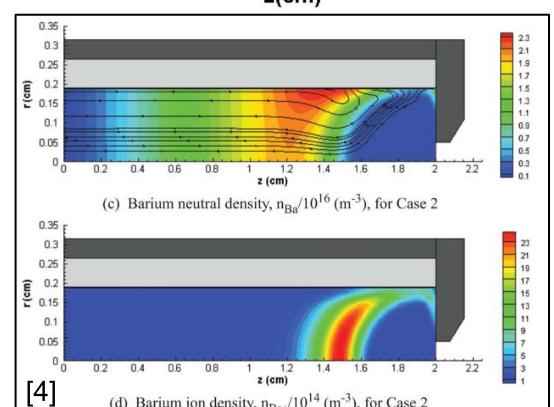
- First fully coupled plasma-thermal simulations [2]



- First 2-D simulations of a hollow cathode operating with argon [3]



- First simulations of barium transport in a hollow cathode with a BaO-impregnated tungsten insert operating with ionized xenon propellant [4]

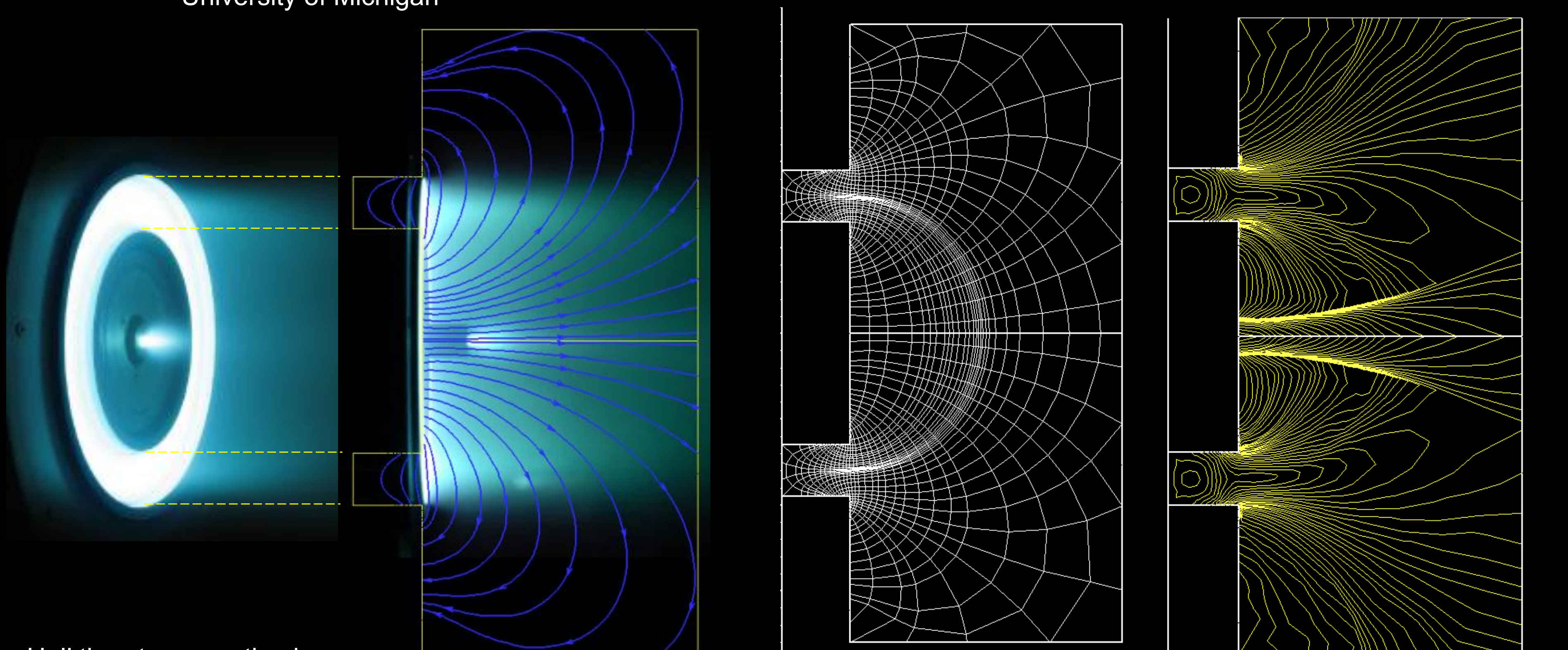


[1] Lopez Ortega, et al., "Hollow Cathode Simulations with a First-Principles Model of Ion-Acoustic Anomalous Resistivity," *J. Prop. Power*, 34 (2018).
[2] Guerrero, P., et al., "Hollow cathode thermal modelling and self-consistent plasma solution: two step neutralization modelling", IEPC Paper 301(2019).
[3] Rajagopalan, S. "OrCa2D Simulations with Argon for Sputter Deposition Industrial Applications using Gas Flow Hollow Cathodes (GFHC)," JPL Visiting Student Research Internship (JVSRP) presentation, 2020.
[4] Polk, J. E., et al., "Barium Depletion in Hollow Cathode Emitters," *J. Appl. Phys*. Vol. 119 (2016).

With the 2-D Code Hall2De JPL Pioneered Simulations of Large-scale Anisotropic Plasma Physics and Wall Erosion in Hall Thrusters

- Code development began in 2008 at JPL [1]. About a decade later a similar code was developed in Europe (Spain).
- Versions of Hall2De licensed to
  - Lockheed Martin and Aerospace Corporations
  - NASA Glenn Research Center
  - Lawrence Livermore National Laboratory
  - University of Michigan

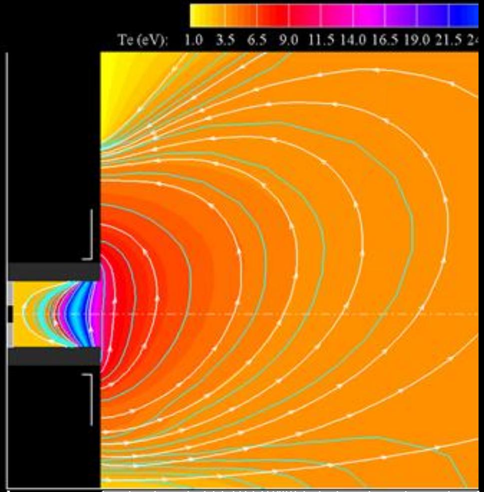
[1] First journal article on Hall2De: Mikellides, I. G. and Katz, I., "Simulation of Hall-effect Plasma Accelerators on a Magnetic-field-aligned Mesh," *Physical Review E*, Vol. 86, No. 4, 2012, pp. 046703 (1-17).

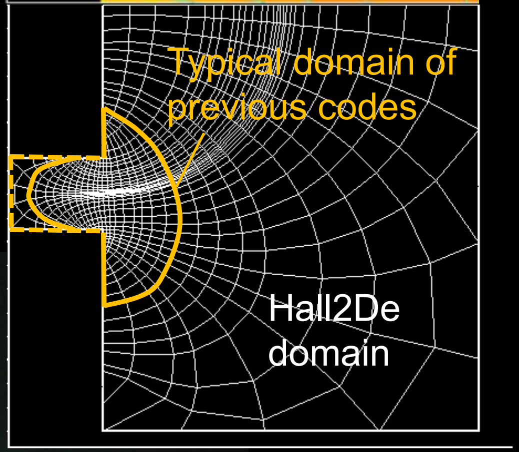


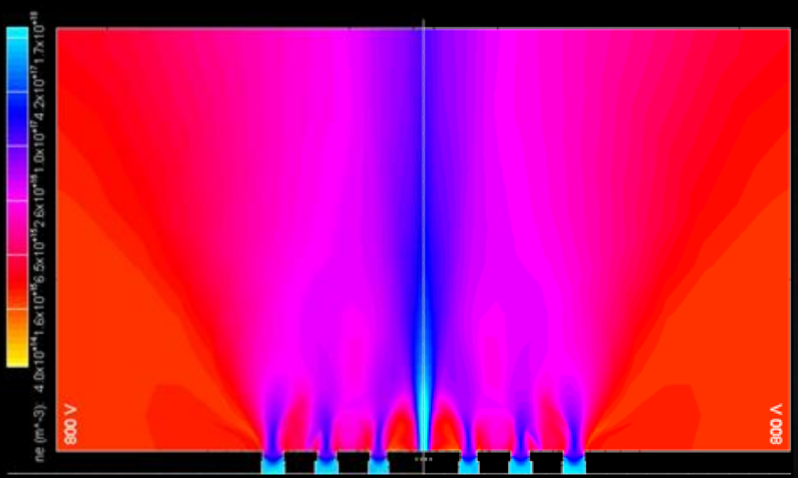
Hall thruster operating in a vacuum facility | Magnetic field streamlines | Computational mesh | Ion density line contours

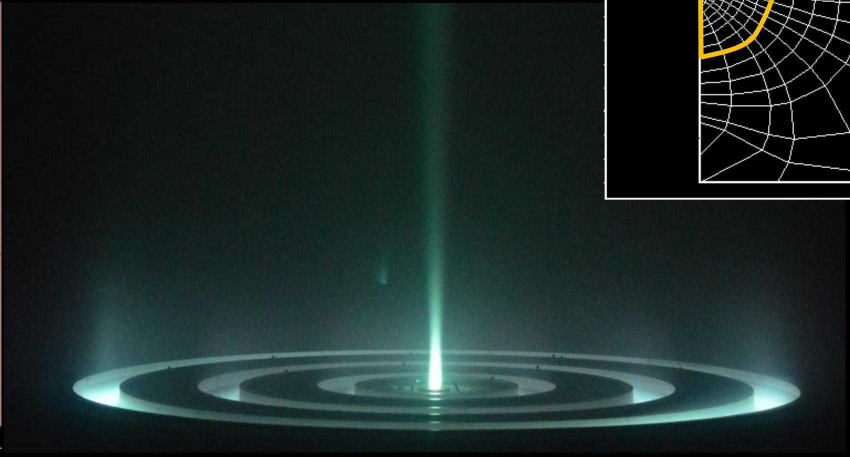
Hall2De Has Enabled…

- **First simulation of Hall thrusters on a Magnetic Field Aligned Mesh (MFAM)**
  - revealed regions where long-standing assumptions failed
  - allowed simulation of thrusters w/ complex magnetic fields
- **First simulation with large enough computational domain to encompass the hollow cathode**
  - allowed investigations of hollow cathode and thruster plume interactions not possible in the past
- **First simulation of a nested Hall thruster**
  - allowed investigations of multi-channel plasma interactions and first assessments of channel erosion in such thrusters



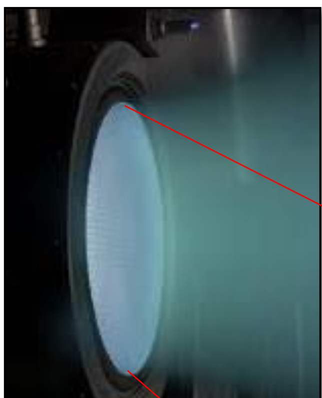




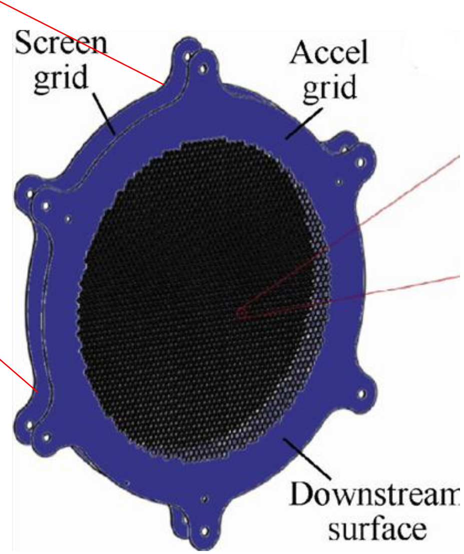


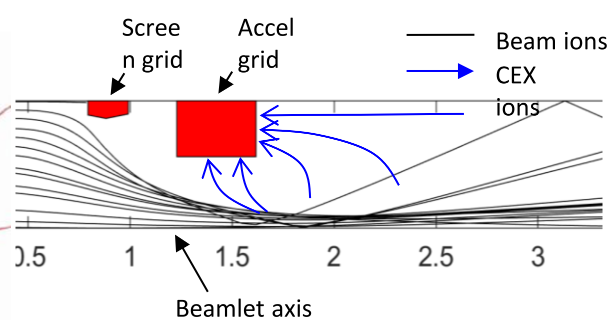
JPL's Ion Optics Codes CEX2D and CEX3D Have Revolutionized Grid Life Modeling in Ion Thrusters

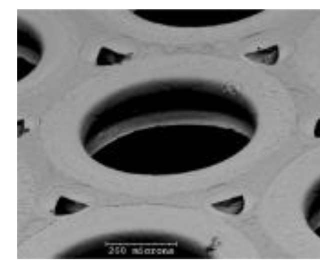
- CEX2D and CEX3D codes (named after the "charge exchange" process that produces most of the eroding ions) developed at JPL in the early 2000's [1,2].
- Enabling modeling capability in the qualification of gridded ion thrusters for deep-space flight
  - prediction of grid life in space (different from laboratory) for entire mission profiles
  - design and optimization of grid geometries

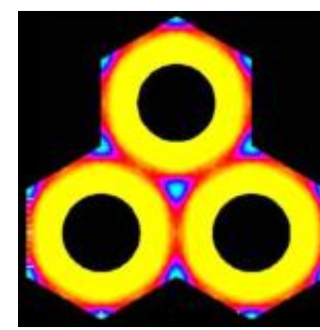


First publications:
[1] Brophy, J. R., Katz, I., Polk, J. E., Anderson, J.R., "Numerical Simulations of Ion Thruster Accelerator Grid Erosion," AIAA Paper 4261, 2002.
[2] Anderson, J., Katz, I, and Goebel, D., "Numerical Simulation of Two-Grid Ion Optics Using a 3D Code," AIAA Paper 3782, 2004.

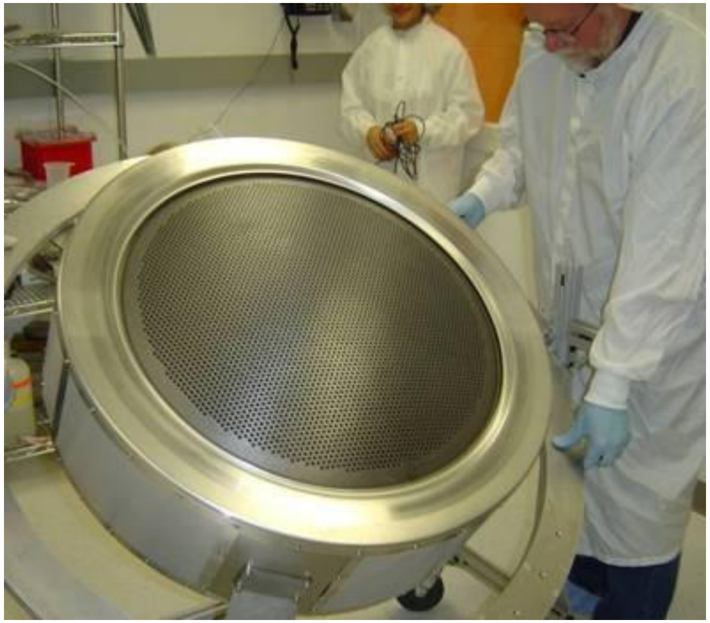








Ion Optics Codes Enable Rapid Thruster Development with a Single Design Iteration



- **The Nuclear Electric Xenon Ion System (NEXIS) becomes the first ion engine to be designed using physics modeling tools**
- Developed in 2003-2005 for Outer planet robotic NEP missions like JIMO
  - 6000-9000 s Isp range; 7500 s nominal
  - 20 kWe per engine
  - 100,000 hour life
- Design validated in extensive subscale and full-scale tests [1, 2]

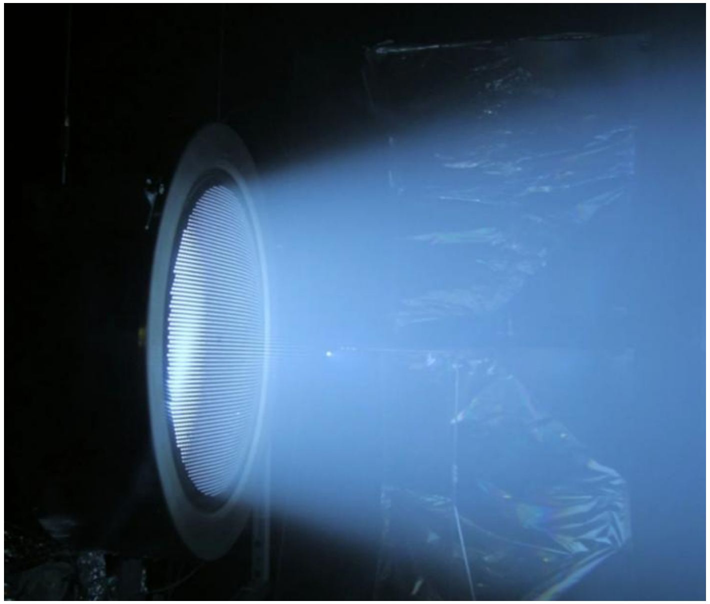
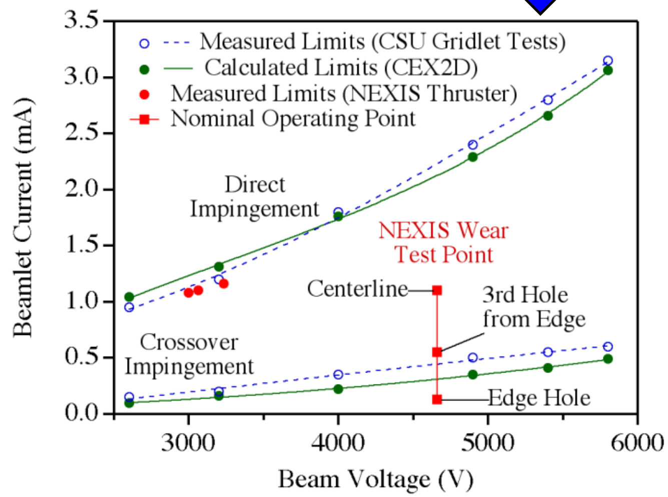
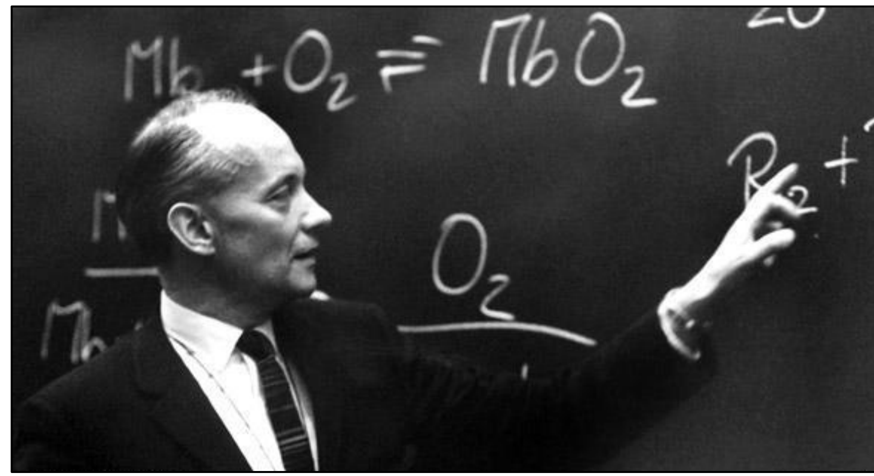


Figure 16. Post-Test Inspection Photograph of Upstream Surface of Accelerator Grid. Note pristine, un-arced condition of surface.



[1] Goebel, D., Polk, J., Sengupta, A., AIAA Paper 3813, 2004.
[2] Polk, J., Goebel, D., Snyder, J., Schneider, A., Sengupta, A., AIAA Paper 4393, 2005.

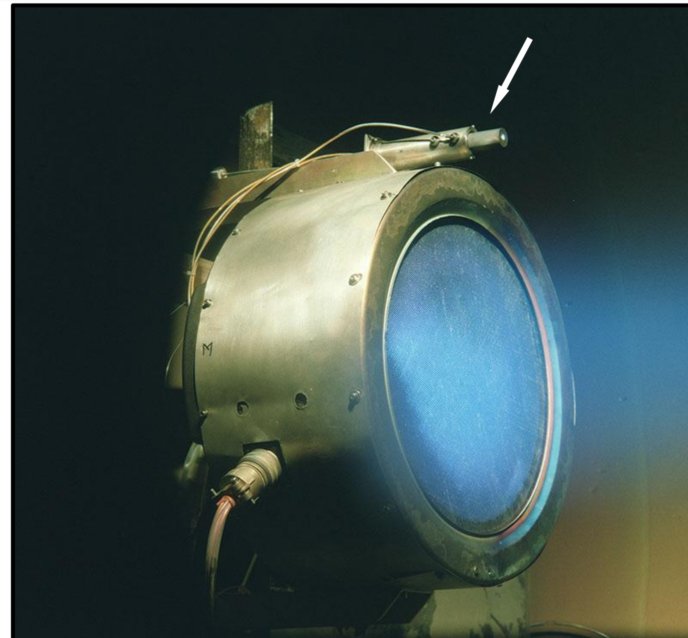
"A theory has only the alternative of being right or wrong. A model has a third possibility: it may be right, but irrelevant."

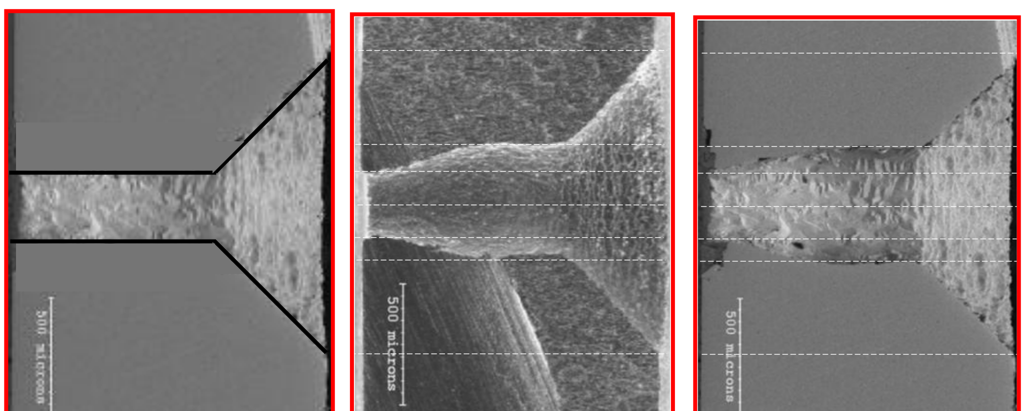


— Manfred Eigen (1967 Nobel Prize in Chemistry)

Understanding Failure Modes

- NASA's Extended Life Test of NSTAR in late 1990s lasted >30,000 h – longest test of ion engine at the time [1].
- Revealed possible failure mechanisms that were not understood → risk to future missions
  - neutralizer cathode orifice plate eroded but then stopped
  - discharge main cathode orifice plate did not erode
  - region not accessible to plasma diagnostics

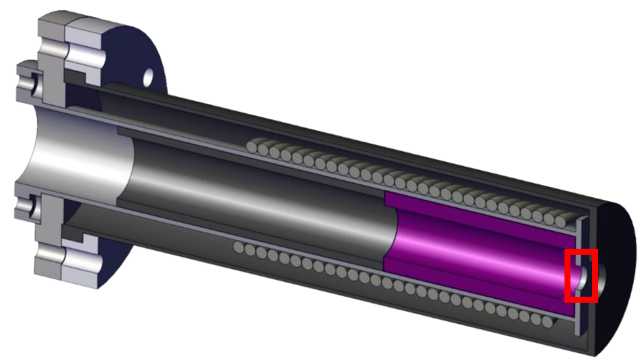




0 hrs

8,192 hrs (JPL 1997-1998)

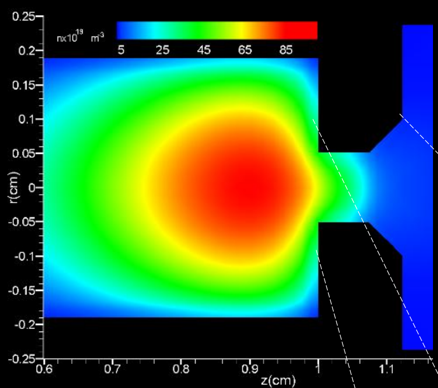
30,352 hrs (JPL 2000-2004)

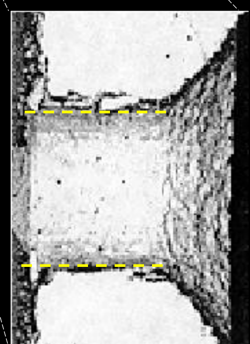


[1] Sengupta, A., Brophy, J. R., Goodfellow, K. D., "Status of the Extended Life Test of the Deep Space 1 Flight Spare Ion Engine After 30,352 Hours of Operation," AIAA 2003-4558.

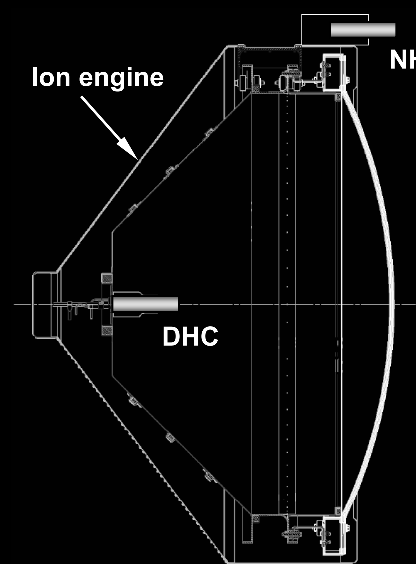
Plasma Simulations of Hollow Cathodes Explain Wear Observed in Long-duration Tests, Reducing Mission Risk [1]

Discharge Hollow Cathode (DHC)

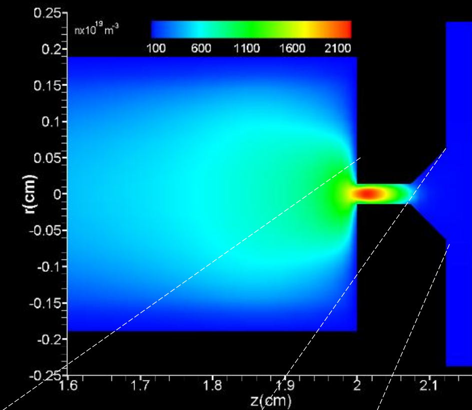


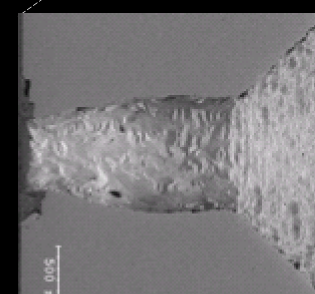


Life-Demonstration Test
8,192 hrs
(JPL 1997-1998)

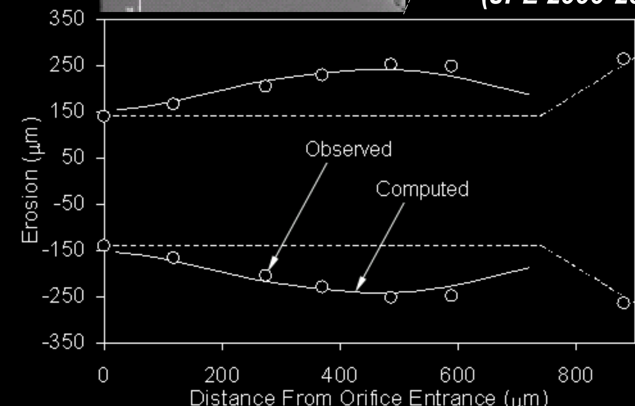


Neutralizer Hollow Cathode (NHC)





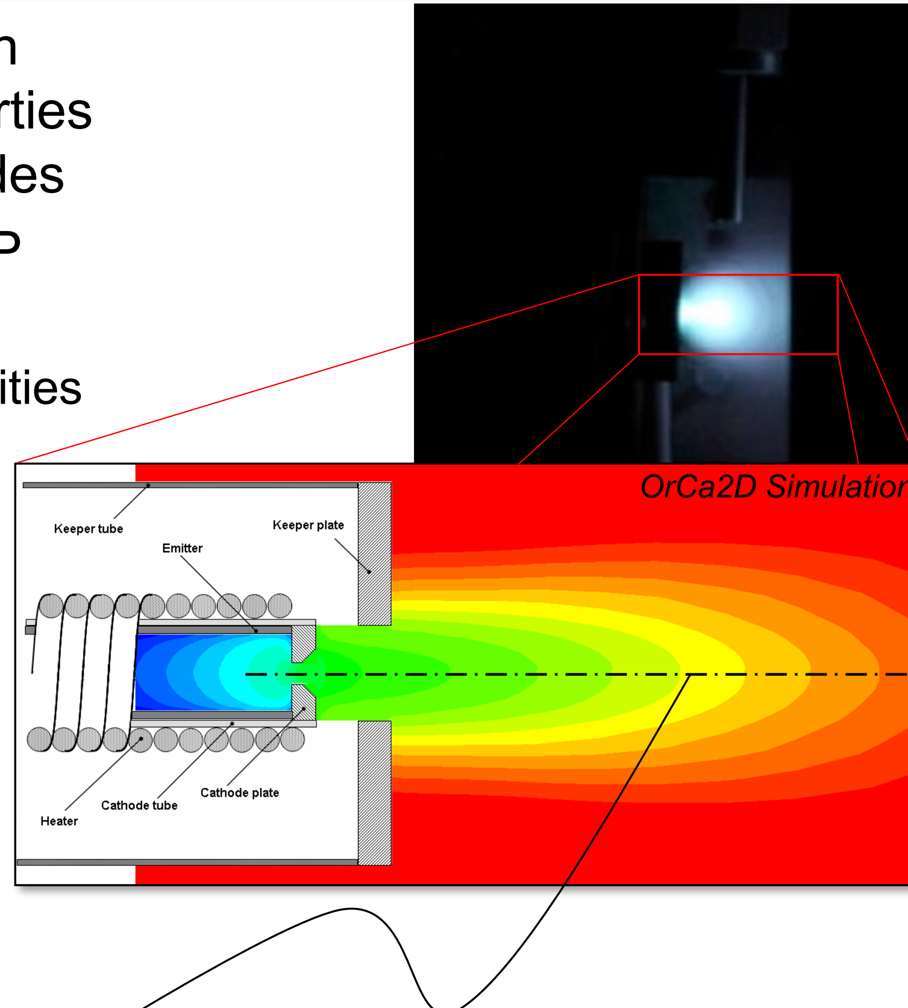
Extended-Life Test
30,352 hrs
(JPL 2000-2004)

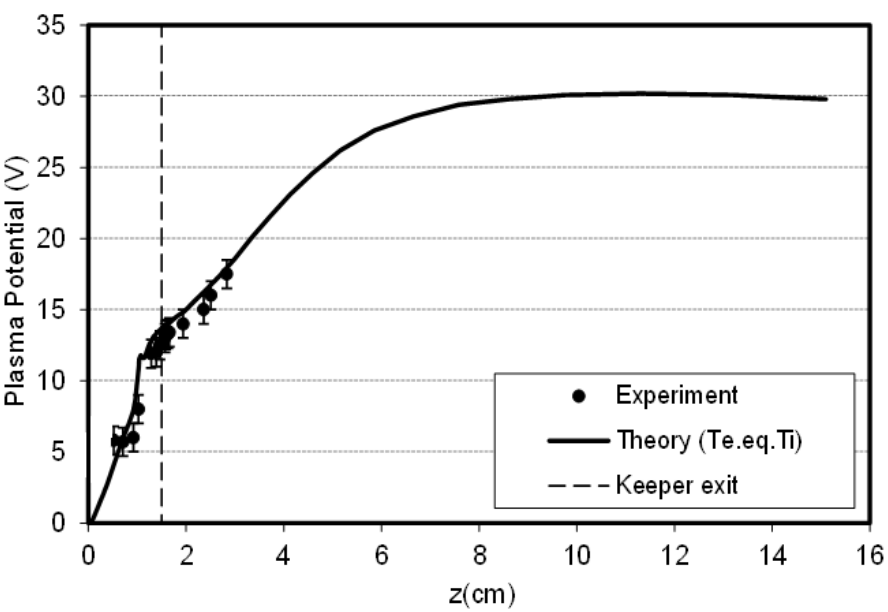


[1] Mikellides, I. G., and Katz, I., "The Partially-Ionized Gas and Associated Wear in Electron Sources for Ion Propulsion, I: Neutralizer Hollow Cathode," ***Journal of Propulsion and Power***, Vol. 24, No. 4, 2008.

Physics Driving Anomalous Resistive Drop in Cathode Plumes First Predicted at JPL Based on OrCa2D Simulations

- Classical plasma physics had been unable to explain the plume properties of the cathode discharge for decades
- Using OrCa2D simulations, JPL EP modeling team first to predict [1-3]
  - current-driven ion acoustic instabilities
  - Ion Acoustic Turbulence (IAT) and anomalous resistivity

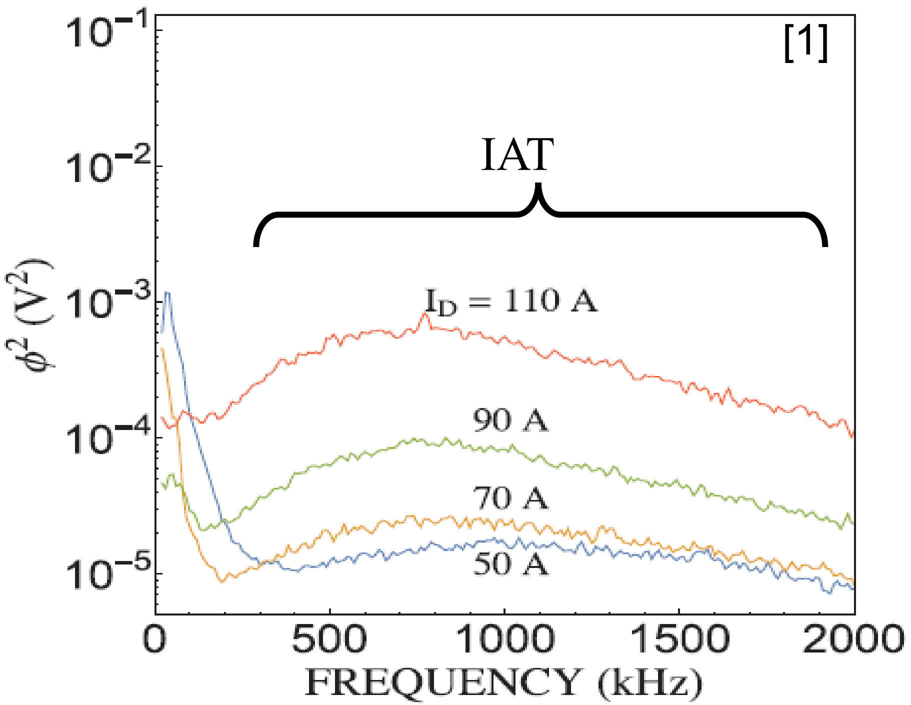




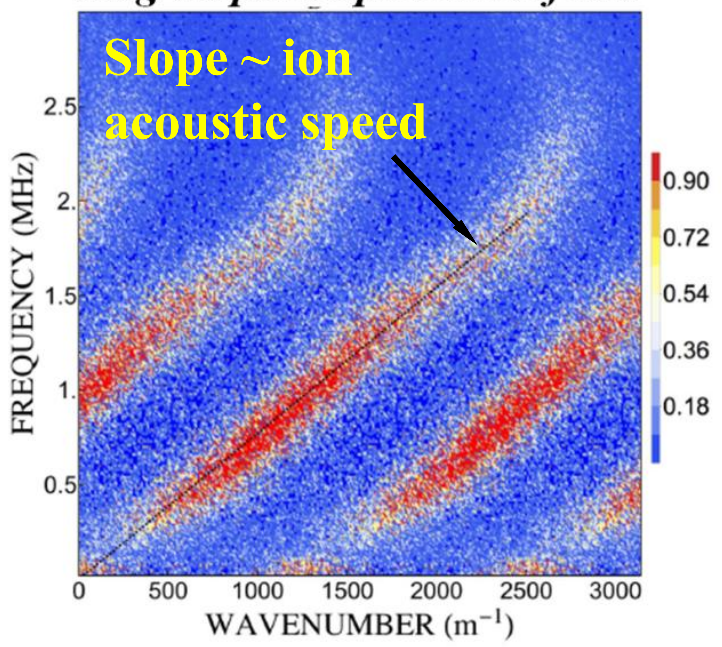
[1] Mikellides, I. G., Katz, I., Goebel, D. M., and Jameson, K. K., *J. Appl. Physics*, Vol. 101, No. 6 (2007).
[2] Mikellides, I. G., Katz, I., Goebel, D. M., Jameson, K. K., and Polk, J. E., *J. Prop. Power*, 24 (2008).
[3] Lopez Ortega, A., Jorns, B. A., and Mikellides, I. G., *J. Prop. Power*, 34 (2018).

Prediction of IAT and Anomalous Resistivity Confirmed Experimentally Several Years Later [1]

- Findings spawned new research programs at U.S. universities
- Plasma codes similar to OrCa2D developed years later in France and China, all incorporating some form of IAT-driven anomalous resistivity



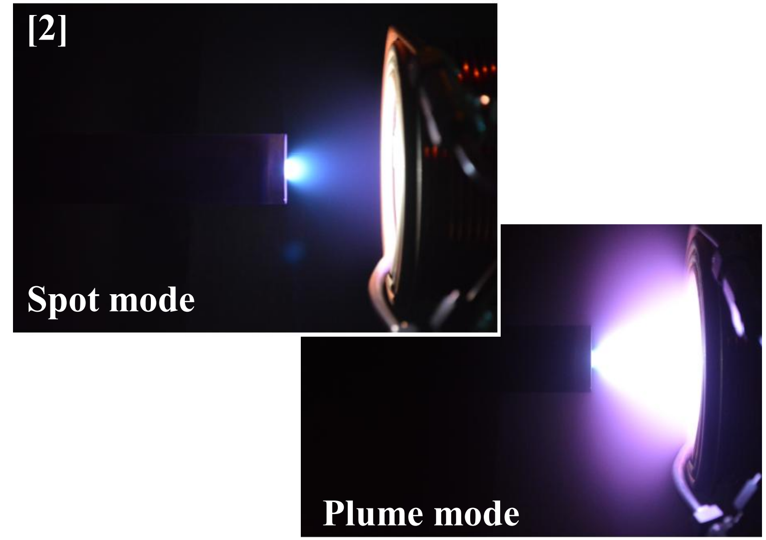
Wave dispersion diagnostics confirm long-suspected presence of IAT



[1] Jorns, B. A., Mikellides, I. G., and Goebel, D. M., "Ion Acoustic Turbulence in a 100-A LaB6 Hollow Cathode," *Physical Review E*, Vol. 90, 2014, pp. 063106 (1-10).

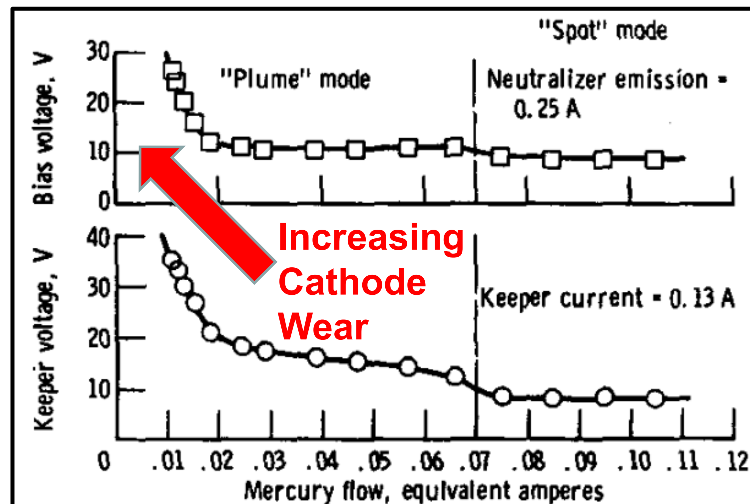
Physics of Mode Transitions in EP Cathode Discharges Remained Elusive for Decades

- As far back as the late 1960's [1] discharge mode transitions found to lead to cathode failure
  - at high flow rates only a "small spot" of plasma visible at the orifice
  - at low flow rates a pronounced "plume of plasma" develops
    - *discharge oscillations and cathode wear increase*



- For over four decades no *ab initio* physics models could be developed that predict these mode transitions

- Approach to evading failure mode: Test, test and then test again!



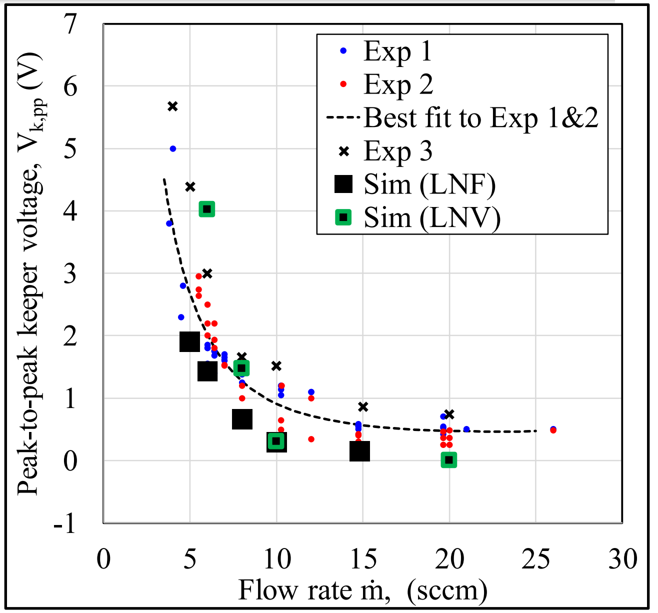
(a) Keeper and bias voltages as a function of mercury vapor flow. Normal thruster operation.

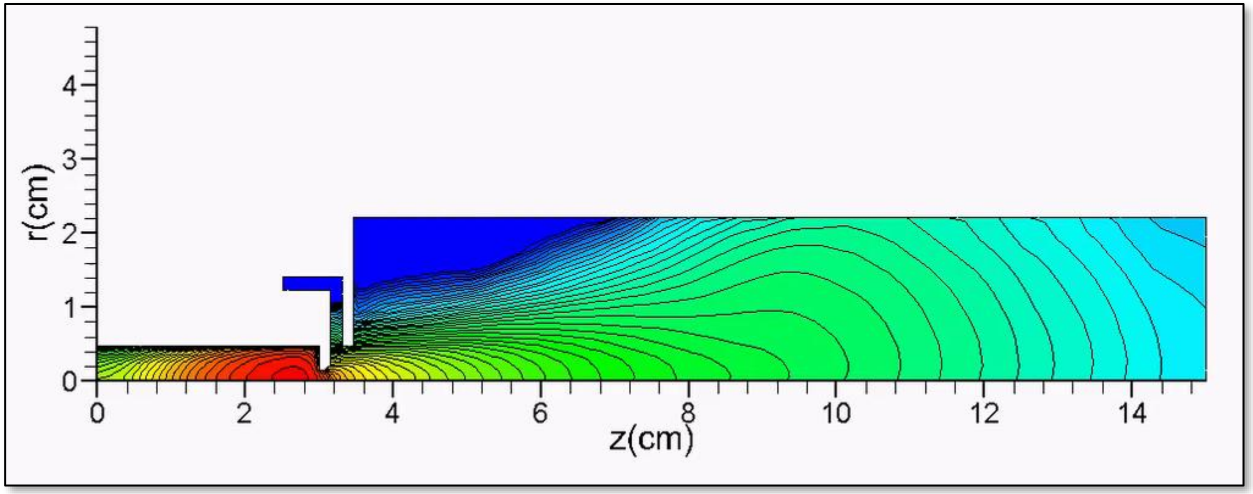
[1] E. V. Pawlik, and V. K. Rawlin, "A Mercury plasma-bridge neutralizer," *Journal of Spacecraft and Rockets,* vol. 5, no. 7, pp. 814-820, 1968/07/01, 1968.

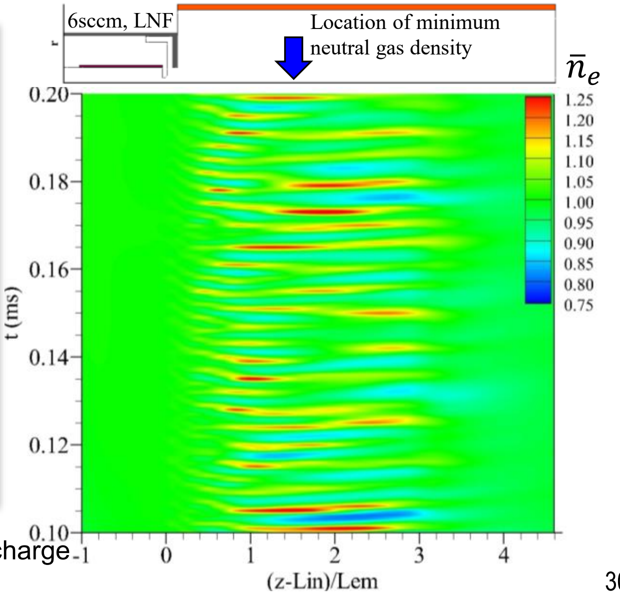
[2] M. P. Georgin, B. A. Jorns, and A. D. Gallimore, IEPC-2017-298, October 2017.

First Simulation of Spot-to-plume Mode Transition Performed at JPL

- OrCa2D simulations at JPL in 2018 achieve for the first time agreement between first-principles models with measurements of spot-to-plume mode transition [1]
- Computed waves are longitudinal, 100-300 kHz in frequency and wavelengths of several centimeters (phase velocity 11 km/s> ion acoustic speed)

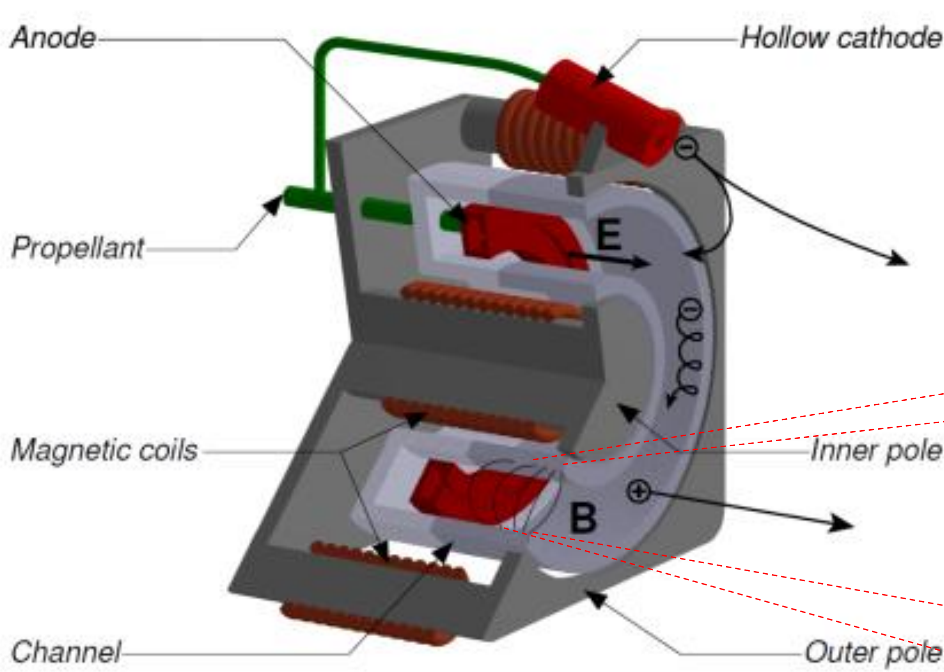


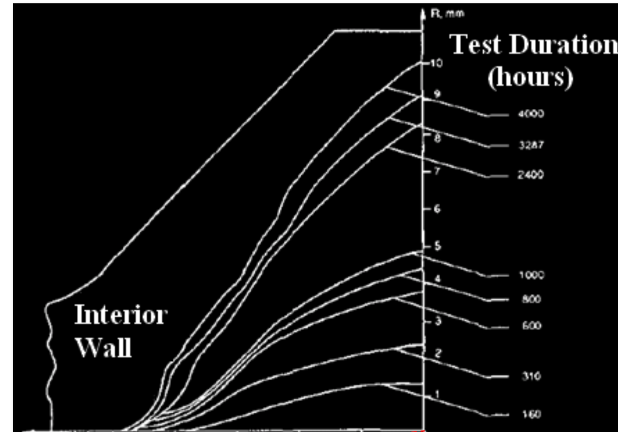


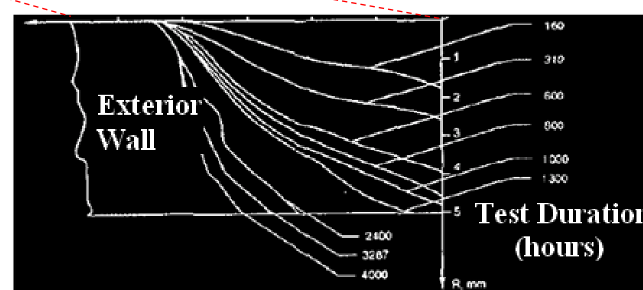


[1] Mikellides, I. G., Lopez Ortega, A., Goebel, D. M., and Becatti, G., "Dynamics of a Hollow Cathode Discharge in the Frequency Range of 1-500 kHz," *Plasma Sources Science and Technology*, Vol. 29, No. 3, (2020).

Erosion of the Acceleration Channel Has Been the Major Life-limiting Process in Hall Thrusters for Over 50 Years!

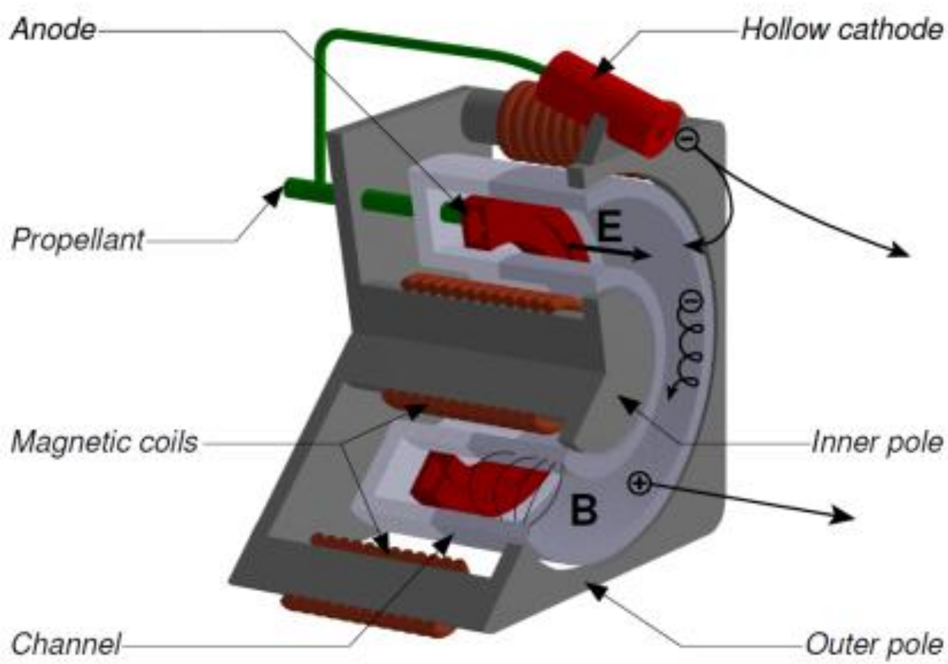






- Some beam ions strike the channel walls with high energy and erode the acceleration channel.
- The engine fails when magnetic circuit components are exposed to the ion beam.
- Life expectancy of typical Hall thrusters < 5-8 kh

Erosion of the Acceleration Channel Has Been the Major Life-limiting Process in Hall Thrusters for Over 50 Years!



- Some beam ions strike the channel walls with high energy and erode the acceleration channel.
- The engine fails when magnetic circuit components are exposed to the ion beam.
- Life expectancy of typical Hall thrusters < 5-8 kh

0 h

10,530 h

PPS-1350G showed heavy internal pole erosion and eventual erosion of inner magnet coil at 10,530 h

CHANNEL EROSION IS THE MAIN REASON THAT NO HALL THRUSTER PROPELLED A S/C ON A DEEP-SPACE MISSION FOR OVER 5 DECADES!

The Longstanding Problem of Anomalous Transport in Hall Thrusters Has Prohibited Fully Predictive Erosion Simulations

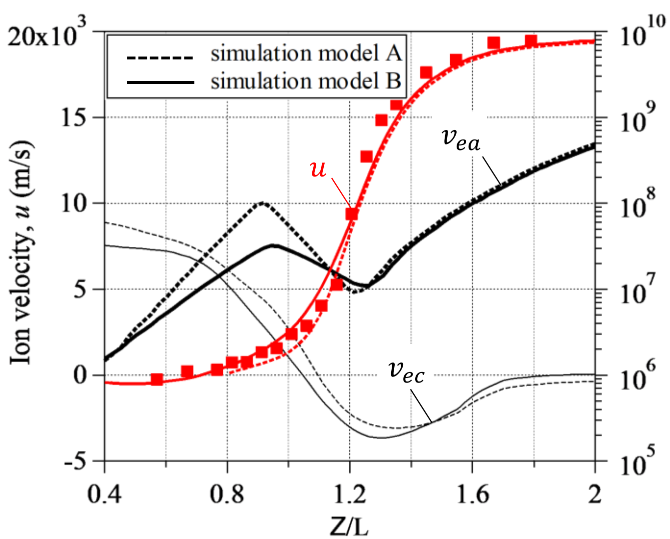
- **The need**: analytical closure models of the anomalous momentum and heat transfer in the electron fluid to allow for *ab initio* 2-D axisymmetric hybrid simulations
  - Fully-kinetic simulations not yet capable of offering practical support
  - Axisymmetric 2-D (axial-radial) hybrid simulations:
    - offer the only practical approach for all-encompassing calculations
    - suffer from the closure problem in Ohm's law, driven by the elusive anomalous electron transport physics
    - require input from plasma diagnostics for every different HET and operating condition

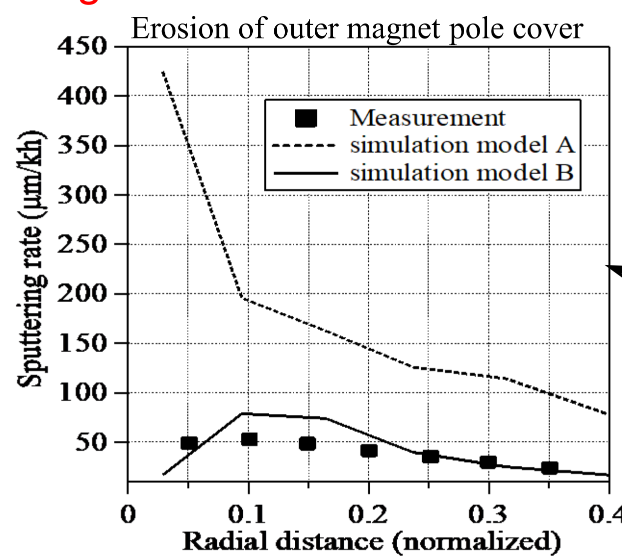
$$\boldsymbol{E}'_{\perp} \simeq \eta\Omega_e^2 \boldsymbol{j}_{e\perp} = \frac{B^2}{m_e n_e \nu_e} \boldsymbol{j}_{e\perp}$$

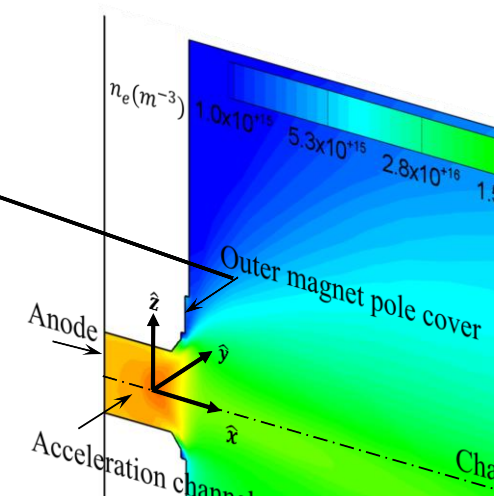
resistivity

momentum-transfer collision frequency (MTCF)

$$\nu_e = \nu_{ec} + \nu_{ea} \;?$$



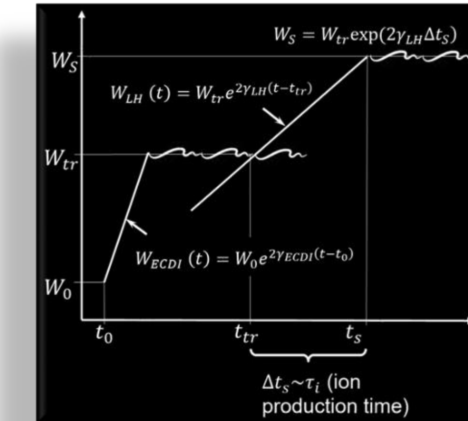




Hall2De Simulations, LIF Measurements, and Plasma Wave Theory Enable Derivation of a First-principles Closure Model for Anomalous Momentum and Heat Transport in Hall Thrusters.

$$\nu_{ea(fld)} = C_{ea}(2\bar{T}_e)^{1/2} e^{(C_{qe}\omega_{LH}\tau_i)}(c/v_{ey})\omega_{ce} \quad [1]$$

$$\nu_{ea(kin)} = C_{ea} e^{[C_{qe}(1-a_{Ti})\omega_{LH}\tau_i]}(v_{Ti}/v_{ey})\omega_{ce}$$



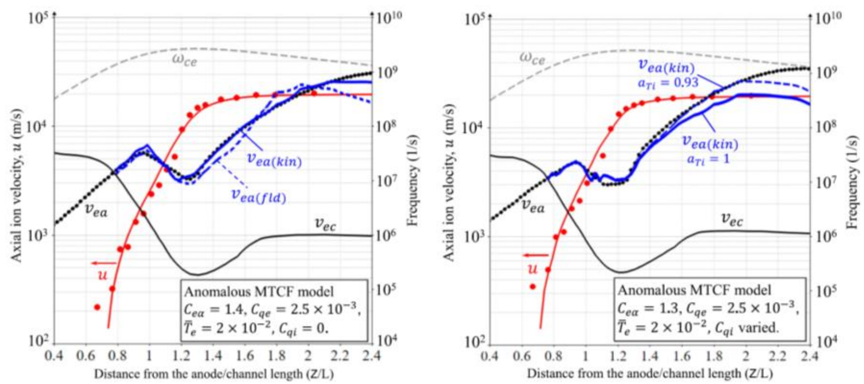
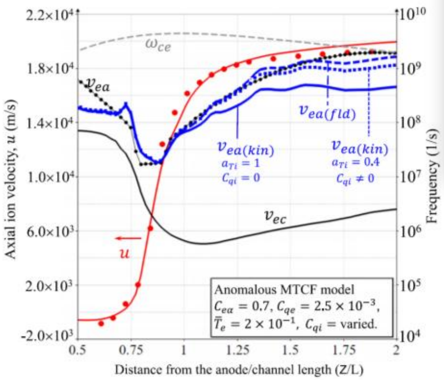
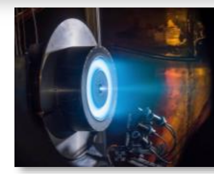
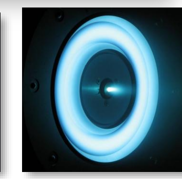


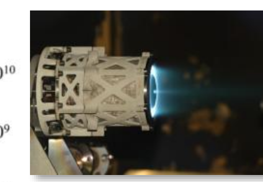
FIG. 10. 12.5-kW MS HET operating at 300 V and 20.8 A. Left: $\bar{B}_{r,max} = 0.75$. Right: $\bar{B}_{r,max} = 1.0$.

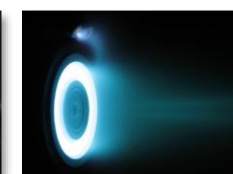


SPT-140 Unshielded Hall Thruster









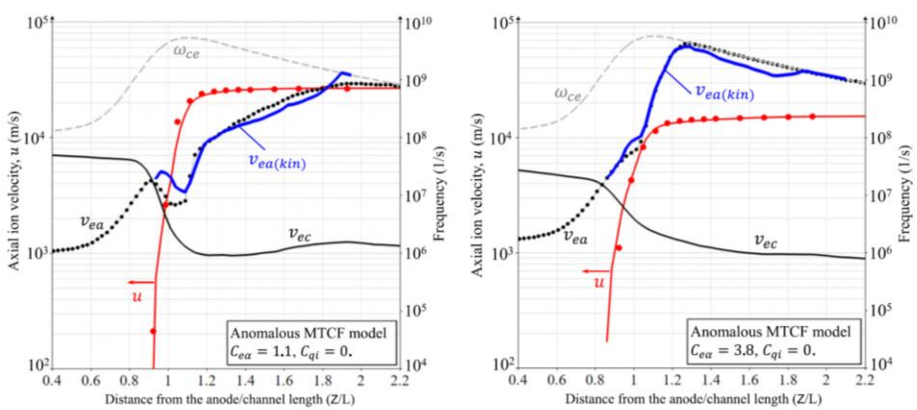


FIG. 12. 1-kW miniature MS HET operating at 500 V, 2 A, $\bar{B}_{r,max} = 1.0$ (left), and 200 V, 1.0 A, and $\bar{B}_{r,max} = 1.1$ (right).

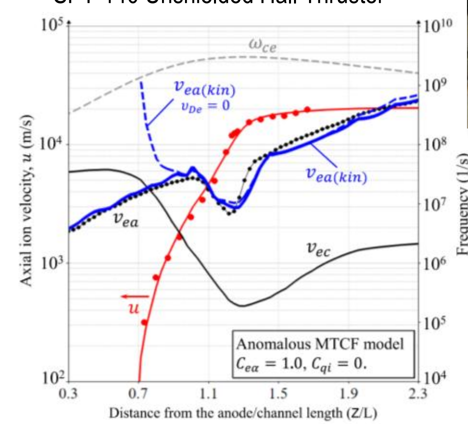
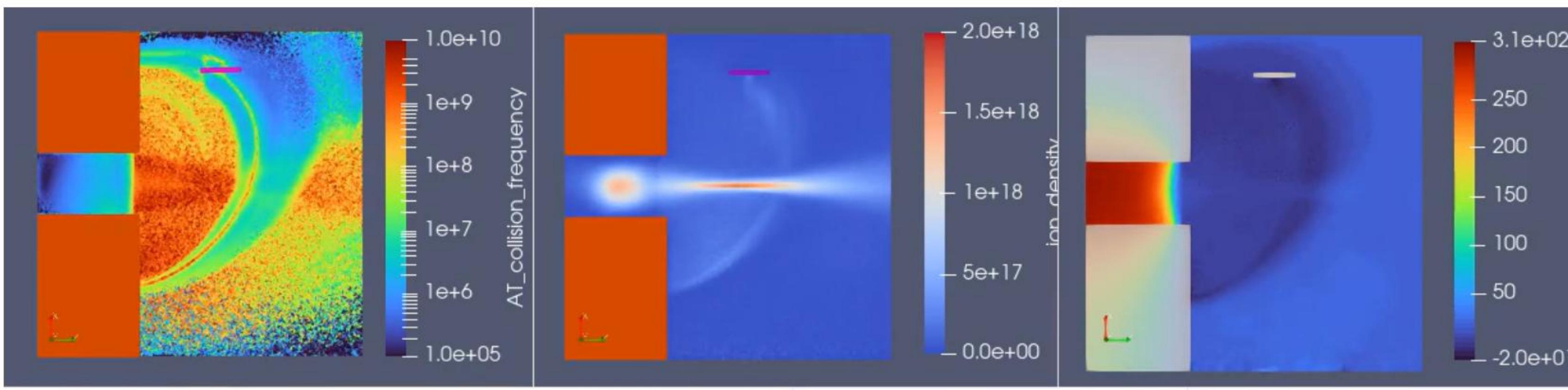


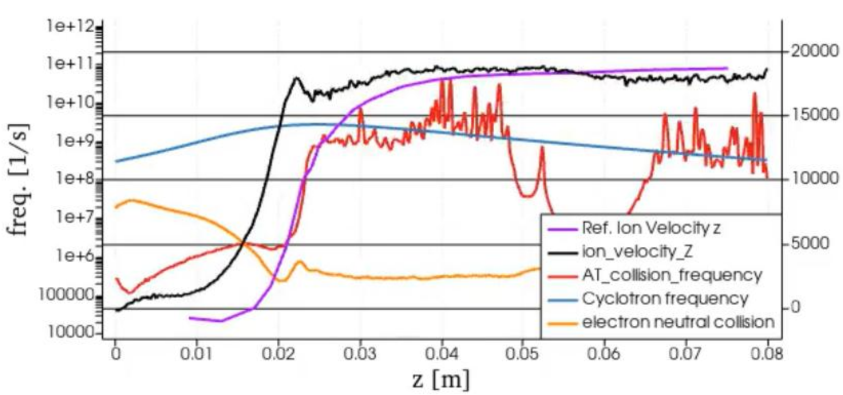
FIG. 13. 6-kW laboratory MS HET operating at 300 V, 20 A, and nominal $\bar{B}_{r,max}$.

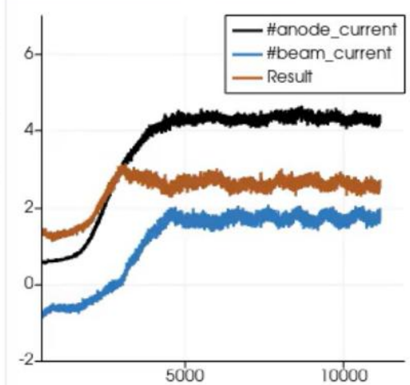
[1] Mikellides, I. G., Lopez Ortega, A., and Chaplin, V., "Theory of the Anomalous Momentum Exchange from Wave-particle Interactions in Hall-effect Ion Accelerators and Comparisons with Measurements," *Physics of Fluids*, Vol. 36, No. 7 (2024). [Selected as "Editor's Pick" by the American Institute of Physics]

Research at JPL on Anomalous Transport in Hall Thrusters is Garnering International Attention

- Implementation of closure model in a 2-D axisymmetric code like Hall2De (fluid electrons, generalized Ohm’s law framework), is challenging.
- VSTRAP-HET, a 2½-D, fully-PIC code for HET simulations developed by SPARC Industries SARL (https://sparc-industries.com/) was the first code of its kind to implement the JPL closure model using an MCC operator, and the results show great promise [1].





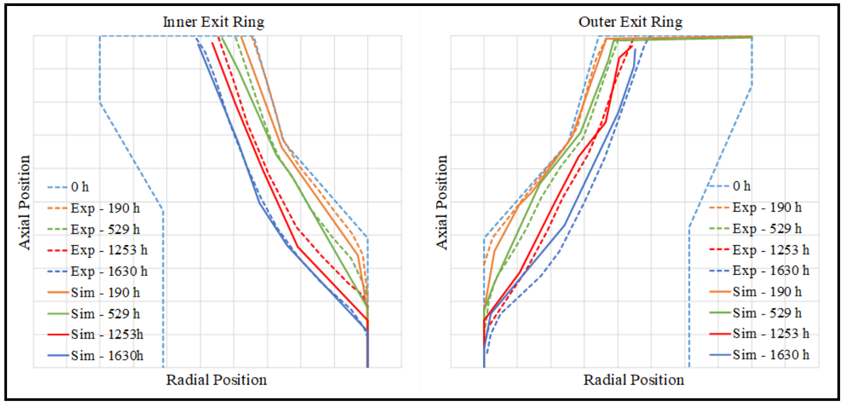


SPARC INDUSTRIES SÀRL

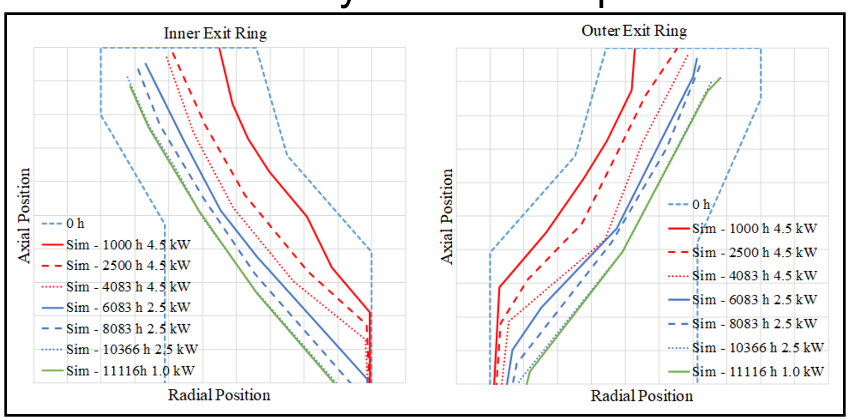
[1] Siems, U. et al., “Fully Kinetic Simulation of the SPT-100: A Validation Case Study with VSTRAP-HET," IEPC-2025-465.

Plasma Modeling Plays Key Role in the SPT-140 Risk and Life Assessments for the Psyche Mission

Simulations first validated with existing SPT-140 wear test data



Simulations then used to predict SPT-140 wear for Psyche mission profiles

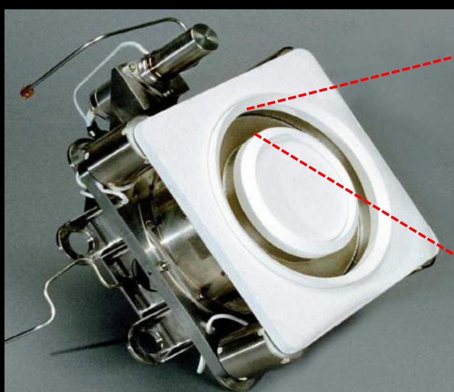


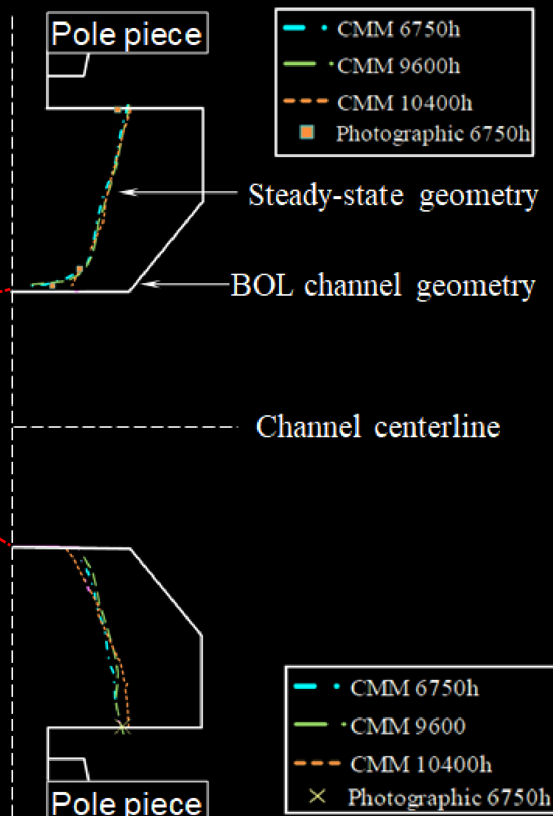
- Required lifetime/thruster: ~7kh
- Successful operation demonstrated on-ground: 10.3 kh
- Plasma and channel erosion modeling with Hall2De used to:
  - Predict wear rates for a candidate Psyche mission profile; rates found to be tolerable for the mission [1,2]
  - Assess the effects of zero pressure on wear rates and thruster performance [1-3]

[1] Lopez Ortega, A., et al., *Plasma Sources Sci Technol*, Vol. 29, No. 3 (2020).
[2] Lopez Ortega, A., et al., IEPC 2019-263, Vienna, Austria, Sept. 15-20 (2019).
[3] Mikellides, I. G., et al., *Plasma Sources Sci Technol*, Vol. 29, No. 3 (2020).

Unexpected Wear Test Results of a Commercial Hall Thruster Underscored our Poor Understanding of Channel Erosion

AR's BPT-4000
Commercial Hall Thruster



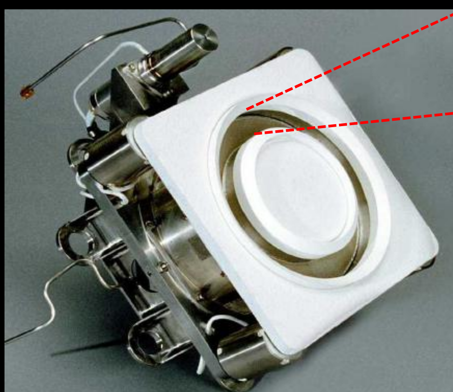


- During a life test to qualify their commercial Hall thruster for space flight, Aerojet-Rocketdyne (AR) observed that channel erosion stopped after ~5000 h [1]
- Result was unexpected and not understood
  - a non-reproducible anomaly?
  - a facility effect?
  - other..?
- Implications immense for deep-space missions

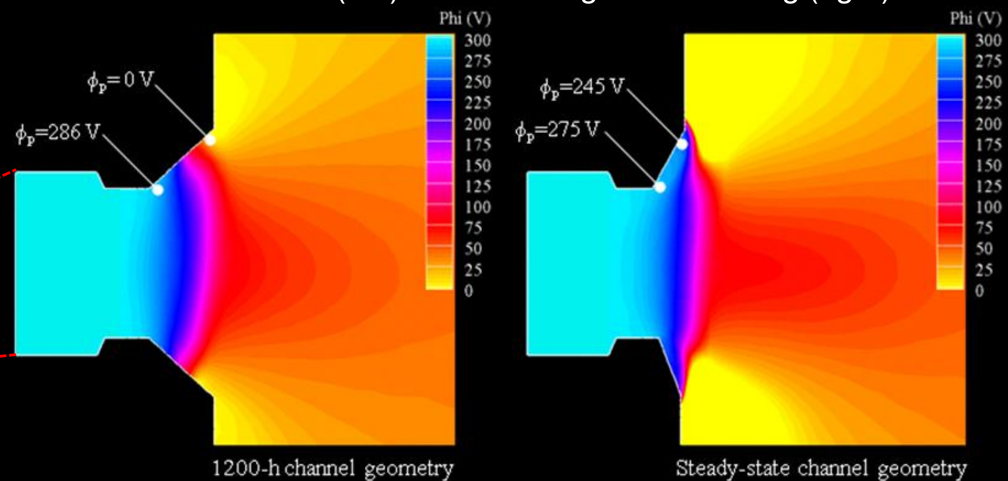
[1] K. de Grys, A. Mathers, B. Welander and V. Khayms., AIAA Paper 2010-6698.

Numerical Simulations at JPL Explain the BPT-4000 Life Test Results and Lead to Breakthrough *Magnetic Shielding* Physics in Hall Thrusters [1,2]

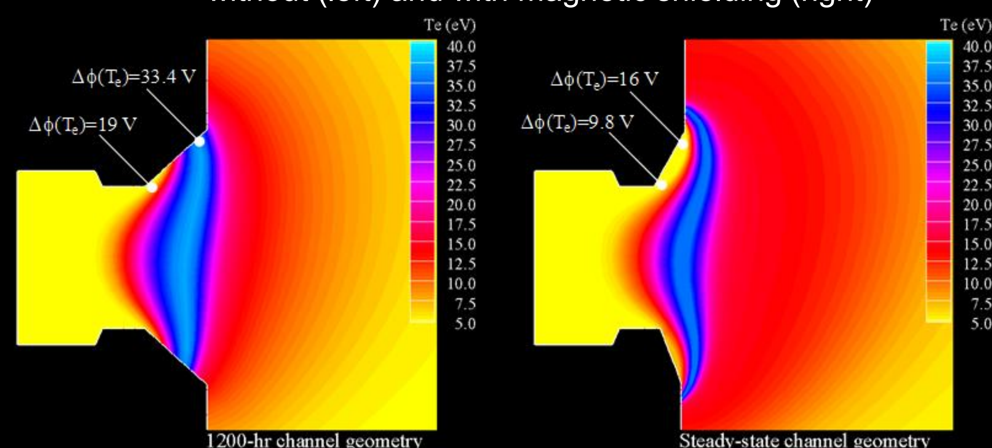
AR's BPT-4000
Commercial Hall Thruster



JPL numerical simulation of the plasma potential in the BPT-4000 without (left) and with magnetic shielding (right)



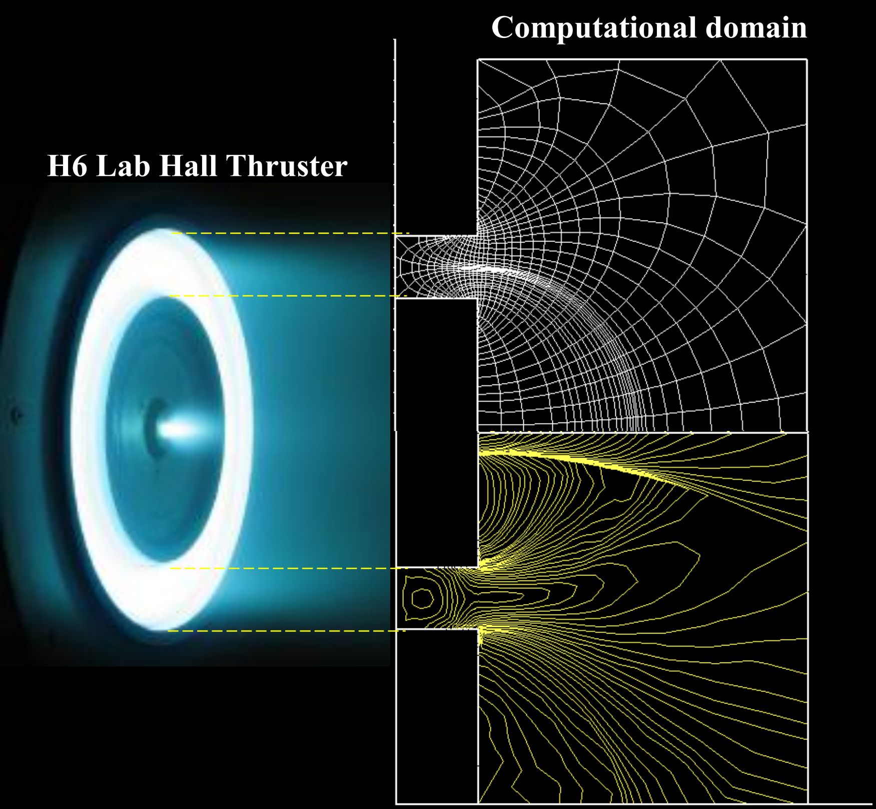
JPL numerical simulation of the electron temperature in the BPT-4000 without (left) and with magnetic shielding (right)

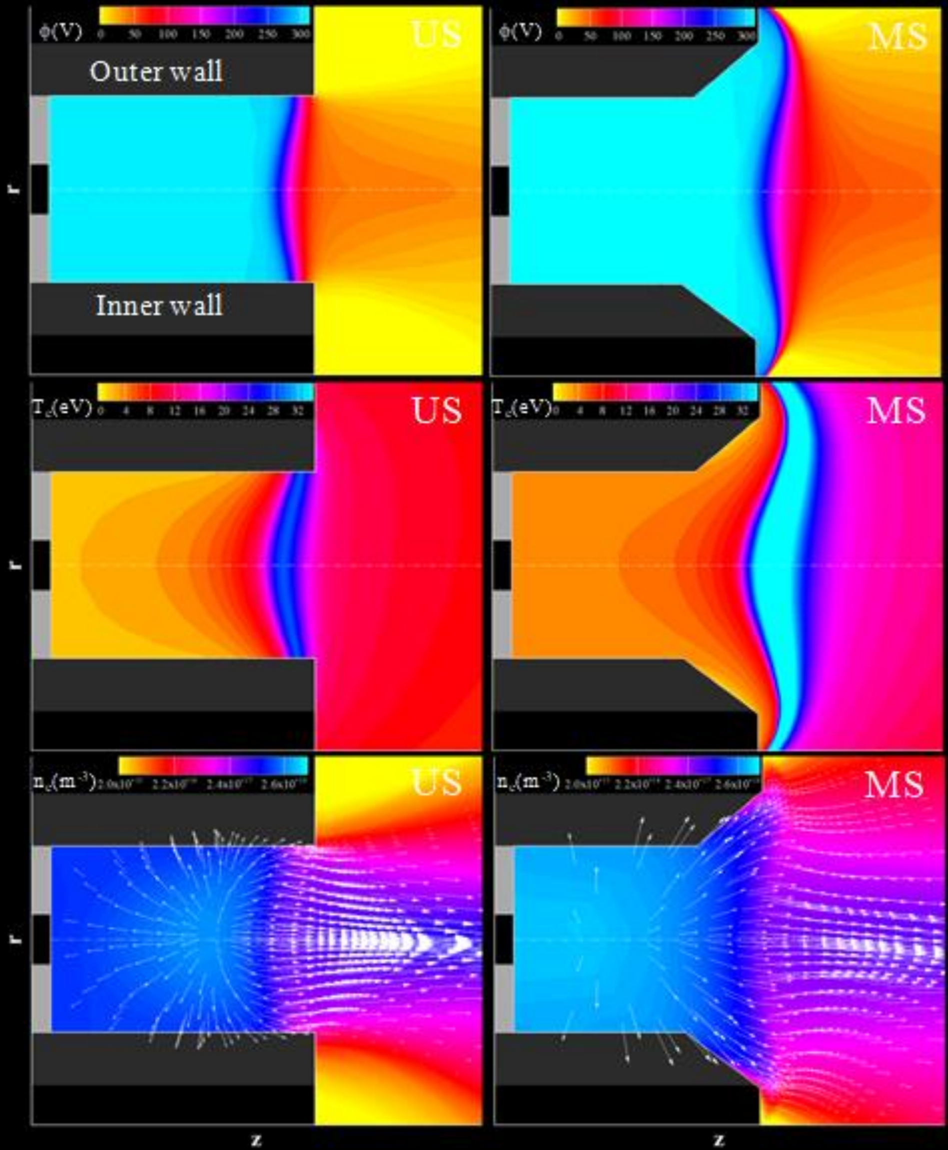


[1] Mikellides, I. G., Katz, I., Hofer, R. R., Goebel, D. M., de Grys, K., and Mathers, A., "Magnetic Shielding of the Channel Walls in a Hall Plasma Accelerator," *Phys. Plasmas*, **18**, 2011, pp. 033501 (1-18).
[2] Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Hall-Effect Thruster Simulations with 2-D Electron Transport and Hydrodynamic Ions," IEPC Paper 2009-114. **(IEPC AWARD FOR BEST PAPER IN ELECTRIC PROPULSION, 2009)**

Numerical Simulations Guided Modifications of an Existing Hall Thruster to Demonstrate at Magnetic Shielding at JPL Facilities [1]

US=Unshielded Thruster
MS=Magnetically Shielded Thruster





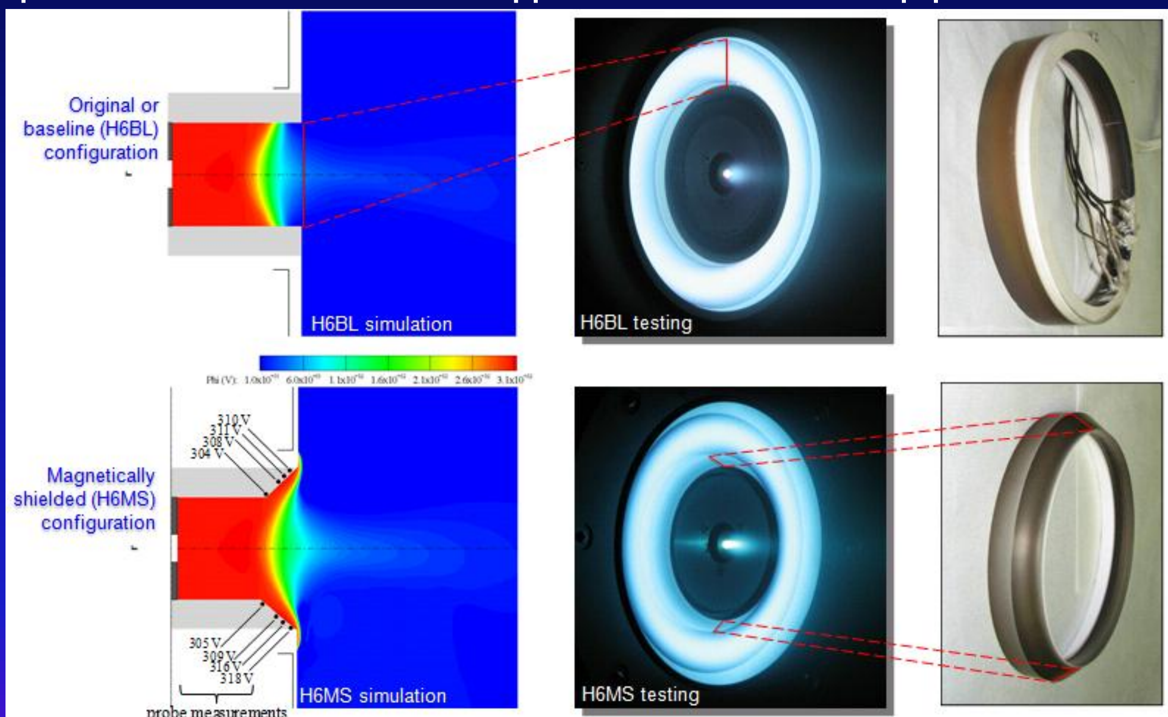
[1] Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Magnetic Shielding of a Laboratory Hall Thruster. I. Theory and Validation," *J. Appl. Phys.*, Vol. 115, 2014, pp. 043303 (1-20).

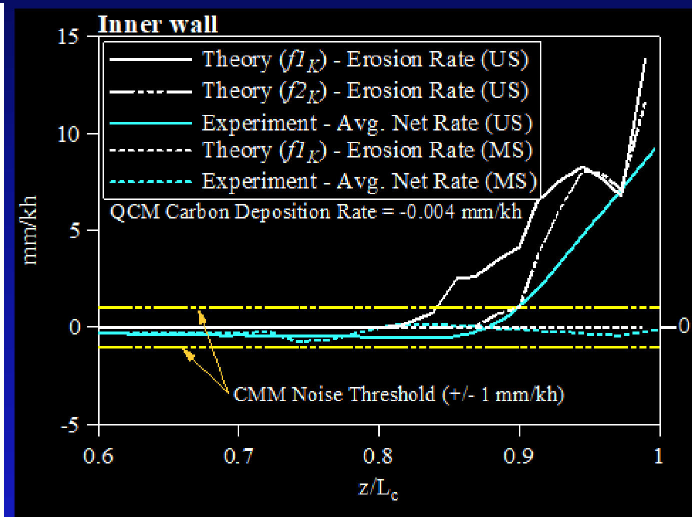
Magnetic Shielding Physics, Derived by Modeling and Simulations, Were Demonstrated at JPL EP Facilities in 2010-2012 [1-4].

Modeling & simulations guide MS thruster design

Thruster testing performed to validate MS

Plasma and erosion diagnostics confirm MS with only small changes in performance

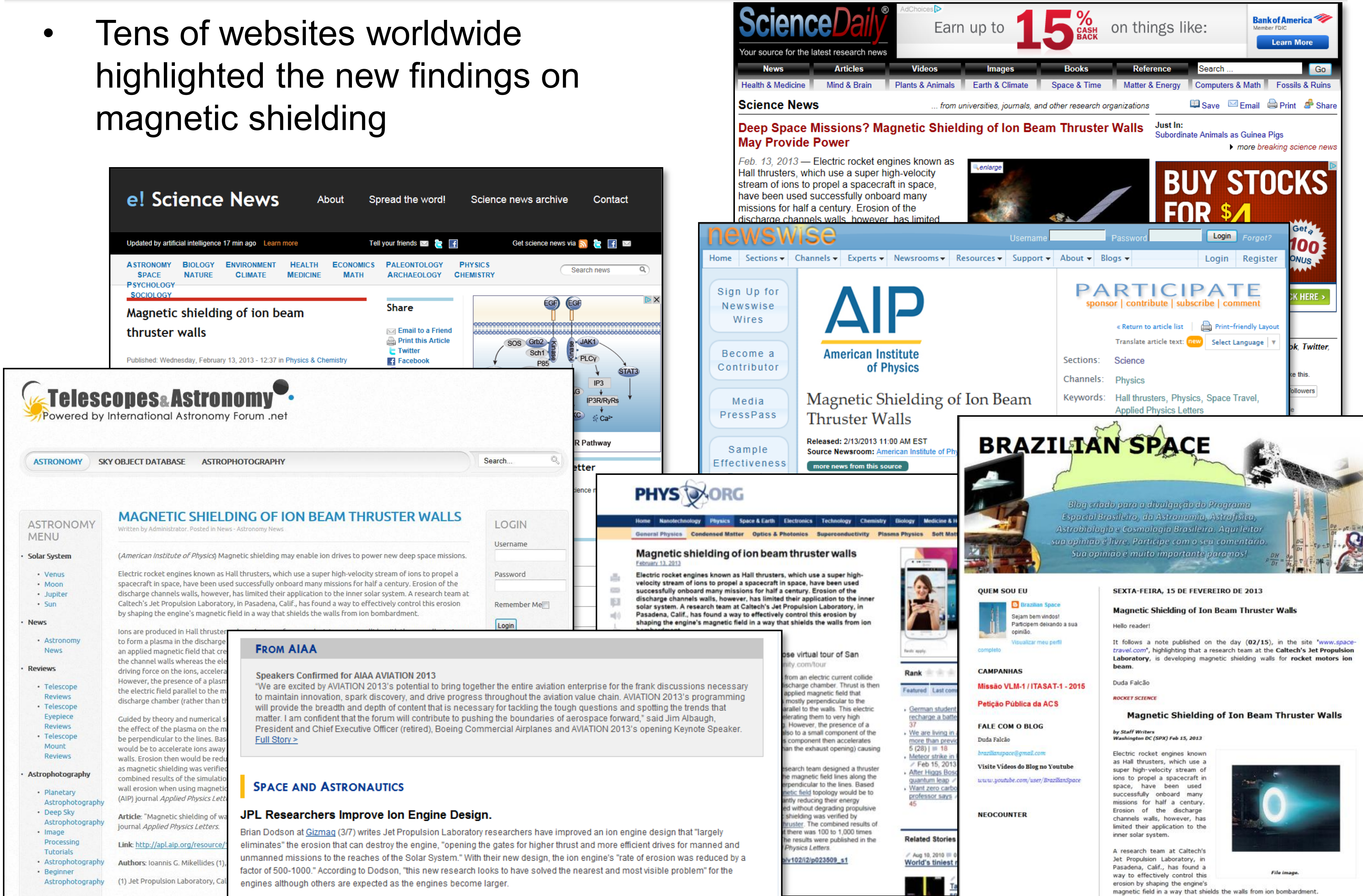




[1] Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Magnetic Shielding of Walls from the Unmagnetized Ion Beam in a Hall Thruster," *Applied Physics Letters*, **102**, 023509, 2013.
[2] Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase III: Comparison of Theory with Experiments," AIAA Paper No. 12-3789 (2012). (**AIAA AWARD FOR BEST PAPER IN ELECTRIC PROPULSION, 2012**)
[3] Hofer, R. R., Goebel, D. M., Mikellides, I. G., and Katz, I., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase II: Experiments," AIAA Paper No. 12-3788(2012).
[4] Mikellides, I. G., Katz, I., and Hofer, R. R.., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase I: Numerical Simulations," AIAA Paper No. 11-5809 (2011).

Breakthrough Recognized by the Science and Engineering Community Worldwide

- Tens of websites worldwide highlighted the new findings on magnetic shielding



Magnetic Shielding in Hall Thrusters now Actively Pursued Worldwide

- 2009-2011: JPL Research Program on Magnetic Shielding (MS)
- 2011-2012: JPL Research Program to assess MS in Metallic-wall Hall thruster
- 2012-2013: NASA GRC/JPL Collaborative Program to assess MS at higher power & discharge voltage (20-kW NASA 300M)
- 2014-2016: NASA GRC/JPL Collaborative Program to assess MS in high-voltage thrusters (HiVHAc-MS)
- 2014-present: NASA JPL/GRC Collaborative Program to develop a high-power MS Hall thruster for PPE and beyond [Hall Effect Rocket with Magnetic Shielding (HERMeS)], now part of the AEPS
- 2018-2021: JPL ASTRAEUS SR&TD to develop a fully integrated EP system based on the MaSMi (Magnetically Shielded Miniature) Hall thruster.
- After 2015: MS Programs emerge in Europe and Asia

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

"There are two kinds of people in the world: Johnny von Neumann and the rest of us" Eugene Wigner, Nobel Prize – winning physicist.