SEP CHALLENGES AND OPPORTUNITIES - ACADEMIA

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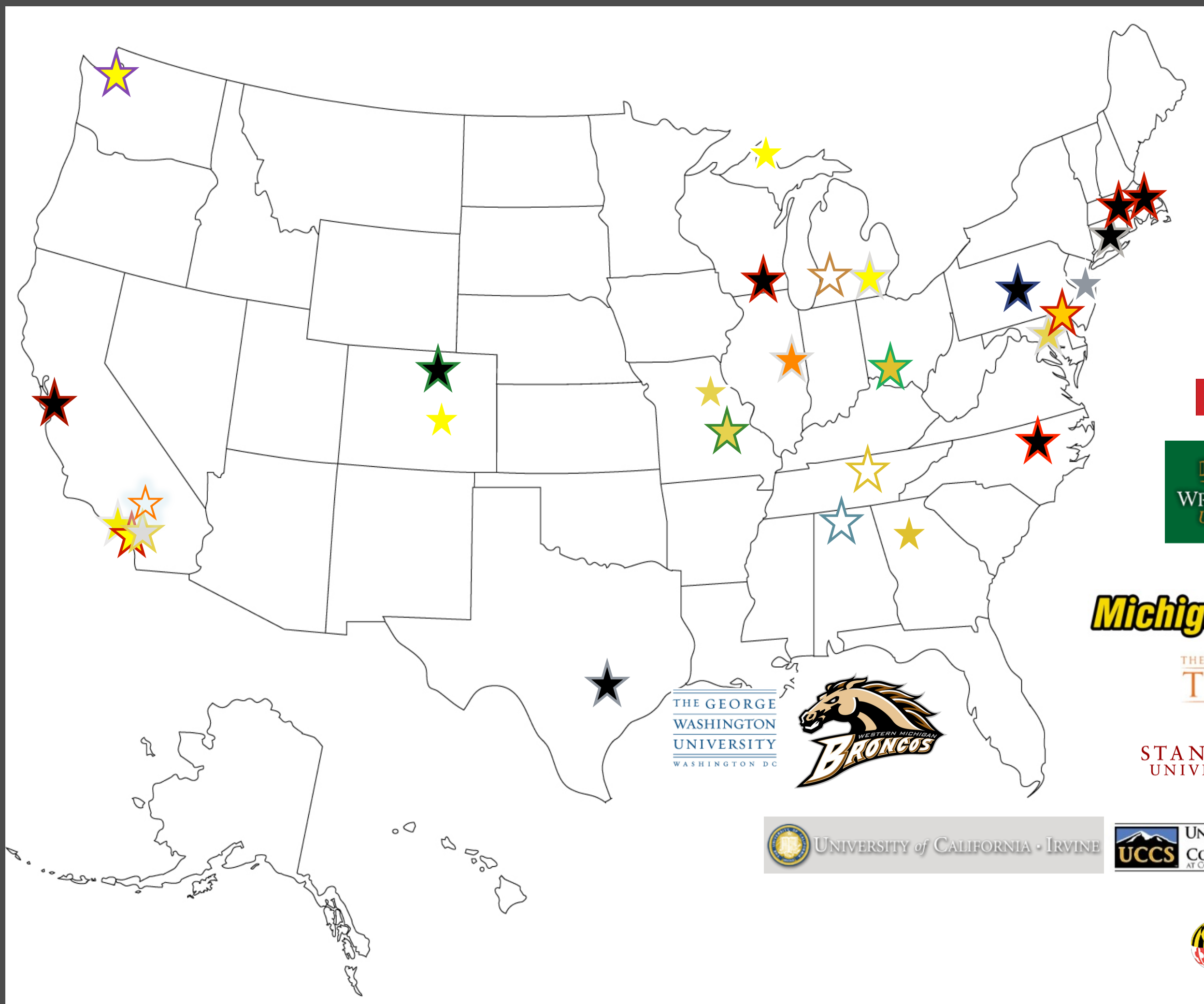
Department of Aerospace Engineering
University of Michigan

11 October 2013

AERONAUTICS AND SPACE ENGINEERING BOARD FALL 2013 MEETING

US Academic Programs Engaged in EP Research
30 Institutions, 40 Professors, >100 Graduate Students



MIT
Mizzou University of Missouri
WPI
Yale University
Princeton University
Penn State 1855
GT
NC State University
Vanderbilt University
Wright State University
Michigan
Illinois
Michigan Tech
Missouri S&T University of Science & Technology
The University of Wisconsin Madison
The University of Texas at Austin
The George Washington University Washington DC
Western Michigan Broncos
Stanford University
University of Washington
Colorado State University
University of California - Irvine
UCCS University of Colorado at Colorado Springs
UCLA
USC
University of Maryland
Caltech California Institute of Technology 1891
UAH Chargers

Sources of EP Research Funding

- DoD
  - Grants from AFOSR, AFRL, DARPA
  - Fellowships (NDSEG, SMART)
- NASA
  - Grants (OCT, NIAC, NRA)
  - Fellowships (NSTRF, Space Grant, EPSCoR)
- NSF & DoE
  - Grants and fellowships (GRFP)
- Industry
  - Thruster providers, primes, SBIR/STTR
- State Government

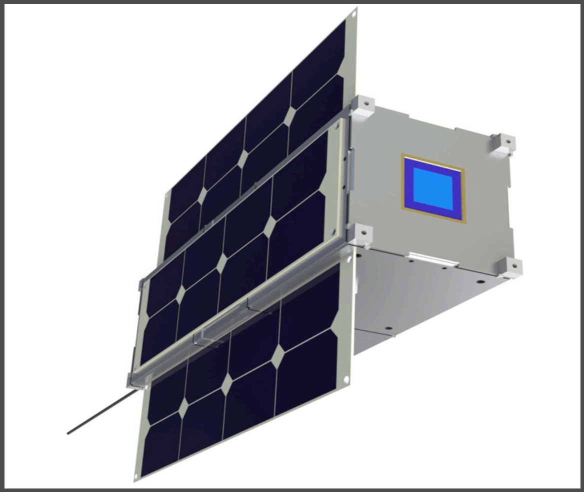
Domains of EP Research in Academia

- **Experimental**
  - Thruster development
  - Property measurement
  - Diagnostics
  - Canonical experiments
- **Modeling & Simulation**
  - Fluid
  - Particle-in-Cell
  - DSMC
  - Molecular Dynamics
  - Hybrid
  - Trajectory (low thrust)

EP research tends to be thruster specific

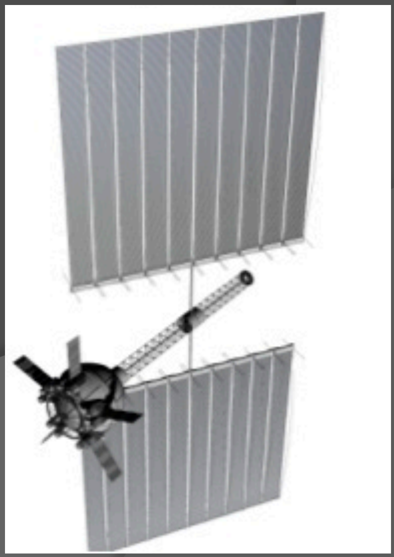
Domains of EP Research in Academia

- NANOSAT
  - <10 kg (spacecraft)
  - <50 W (spacecraft)
  - 10 W (thruster)
- SMALLSAT
  - <500 kg (spacecraft)
  - <1000 W (spacecraft)
  - 200 W (thruster)



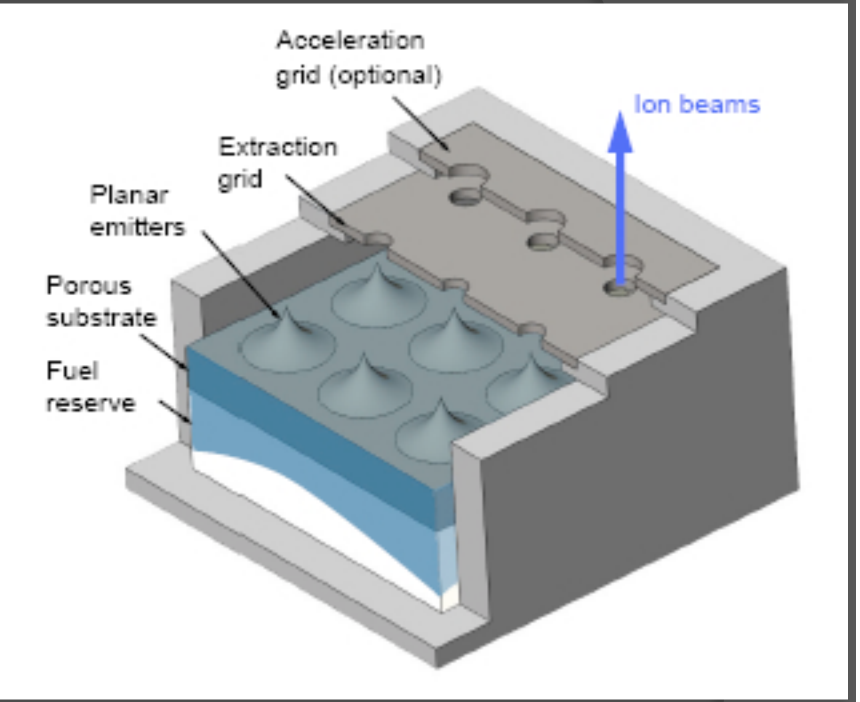
Domains of EP Research in Academia

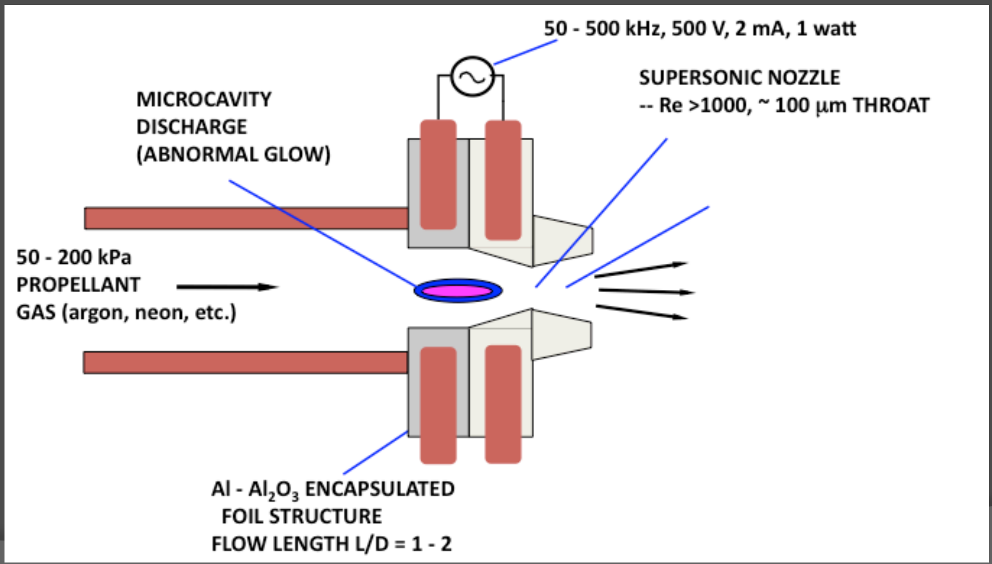
- MACROSAT
  - 1-10 Ton (spacecraft)
  - 3-25 kW (spacecraft)
  - 1-10 kW (thruster)
- MEGASAT
  - >100 Tons (spacecraft)
  - >100 kW (spacecraft)
  - >25 kW (thruster)

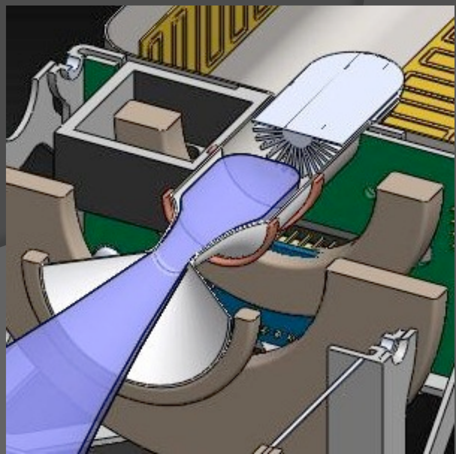


Domains of EP Research in Academia

- NANOSAT
  - Electrospray (MIT - Lozano)
  - RF (Michigan - Longmier)
  - Microwave thermal (Illinois - Burton)

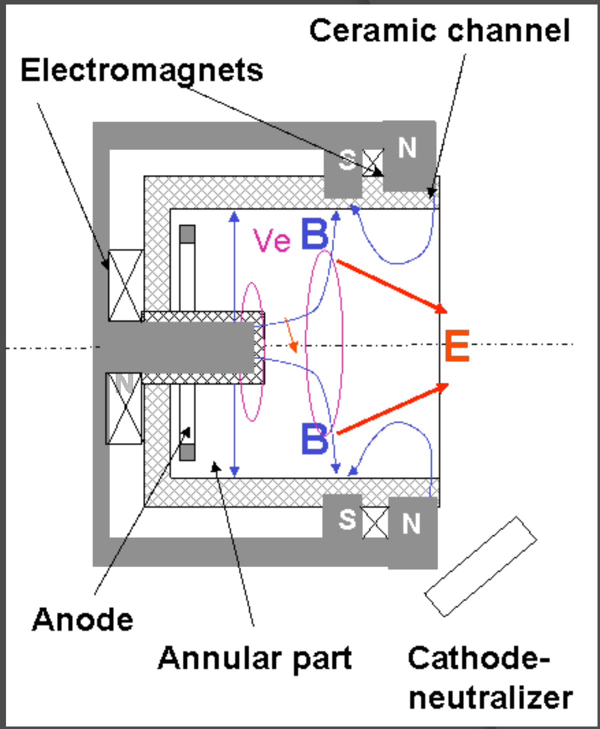


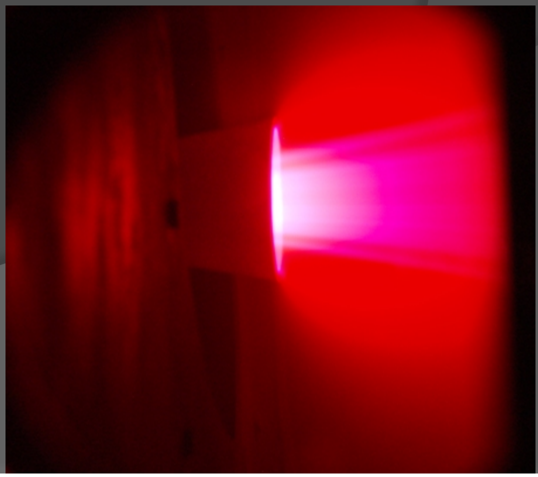


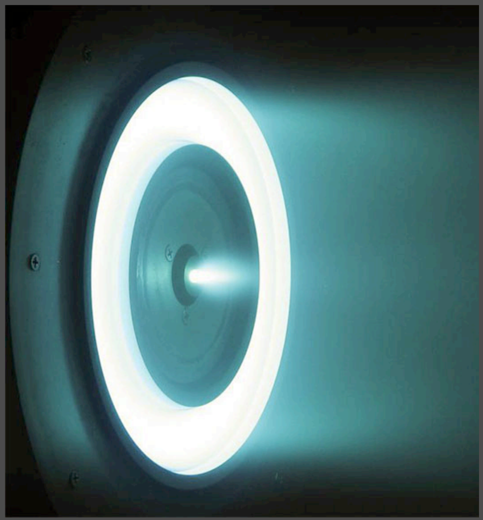


Domains of EP Research in Academia

- SMALLSAT
  - Cylindrical Hall Thruster (Princeton - Raitses)
  - Low-Power Hall Thruster (Stanford - Cappelli)
  - Small Ion Thruster (UCLA - Wirz)

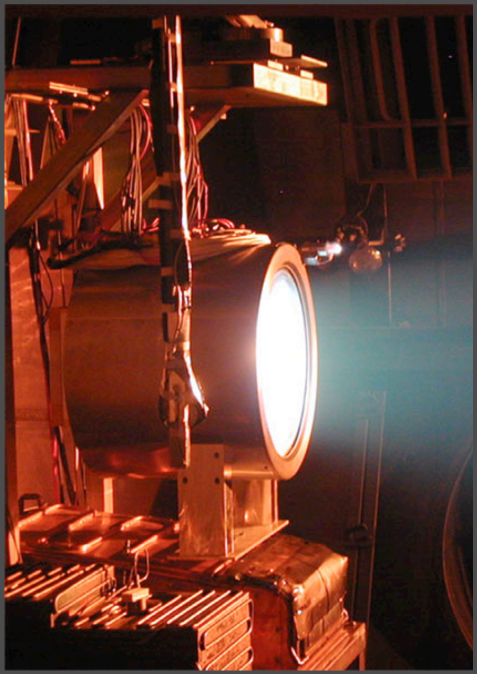


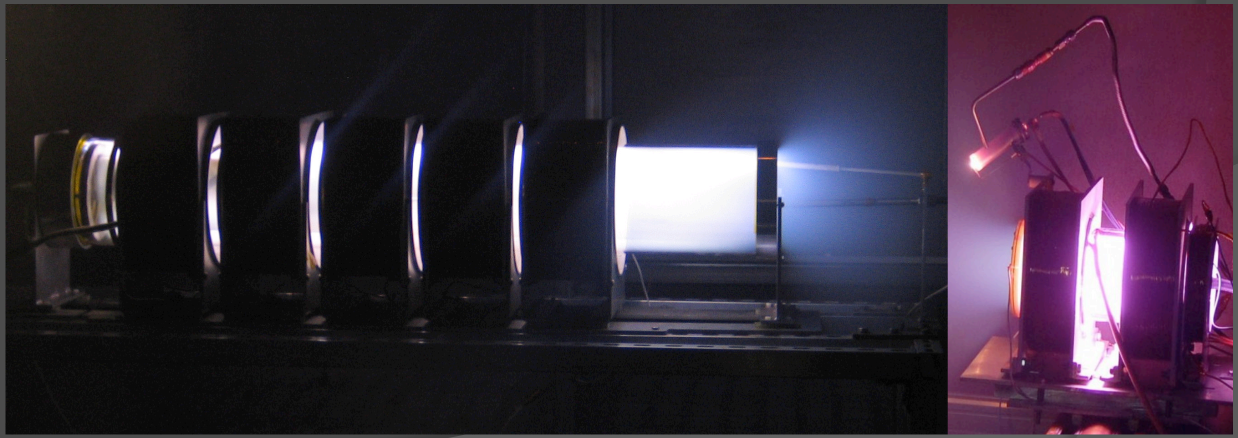




Domains of EP Research in Academia

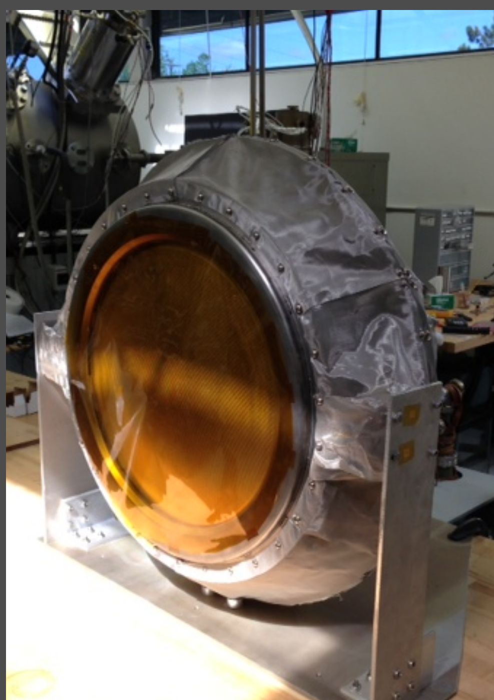
- MACROSAT
  - H6 Hall Thruster (Michigan - Gallimore)
  - NEXT Ion Thruster (Michigan - Gallimore)
  - Helicon/Gridded RF (Georgia Tech - Walker)

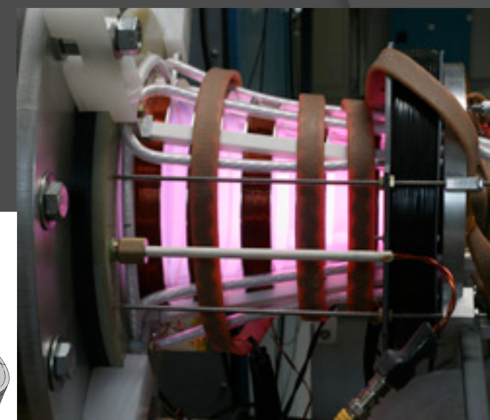




Domains of EP Research in Academia

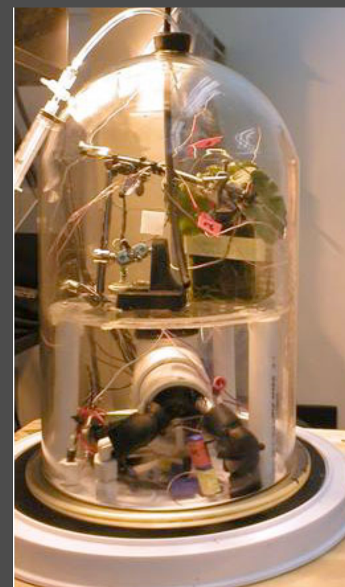
- MEGASAT
  - Electrodeless Lorentz Force Thruster (Washington - Slough)
  - 50-cm Ion Thruster (Michigan - Foster)
  - X3 Nested-Channel Hall (Michigan - Gallimore)

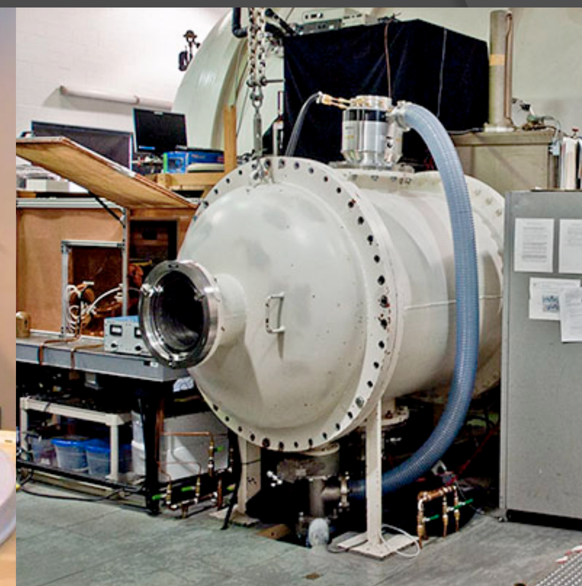


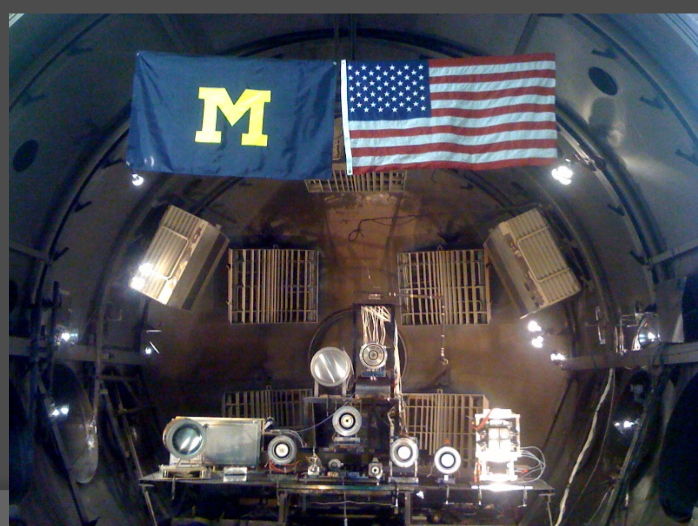



Domains of EP Research in Academia

- Test Facilities
  - Vacuum chambers
  - Thruster operation support
  - Diagnostics

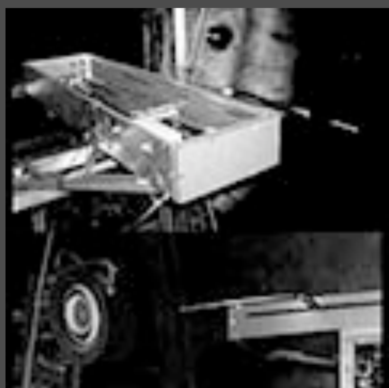


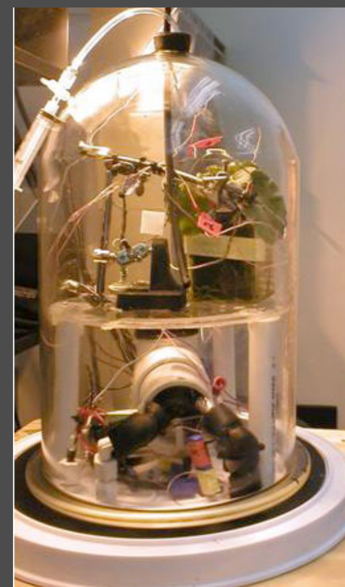


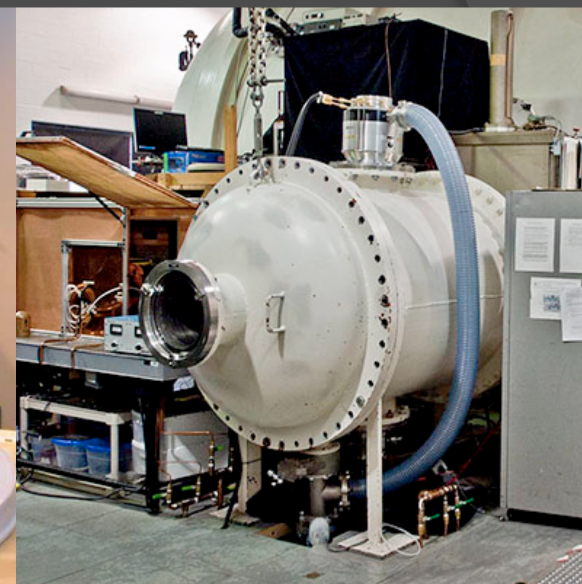


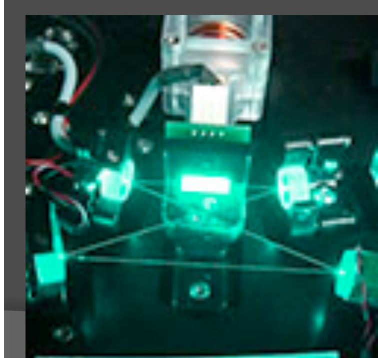
Domains of EP Research in Academia

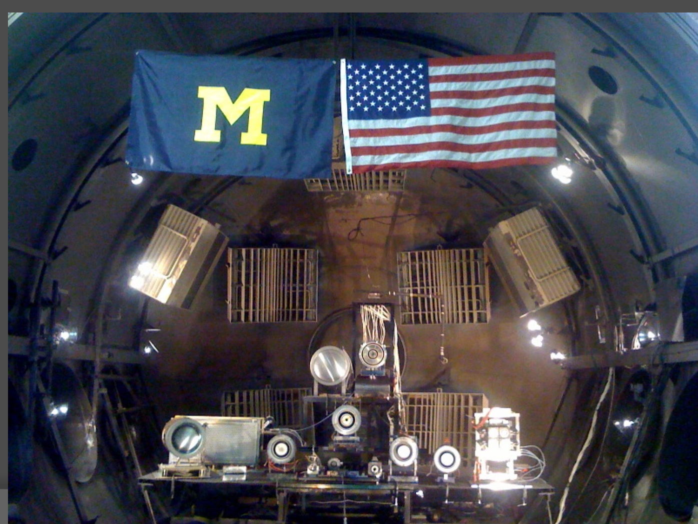
Test Facilities

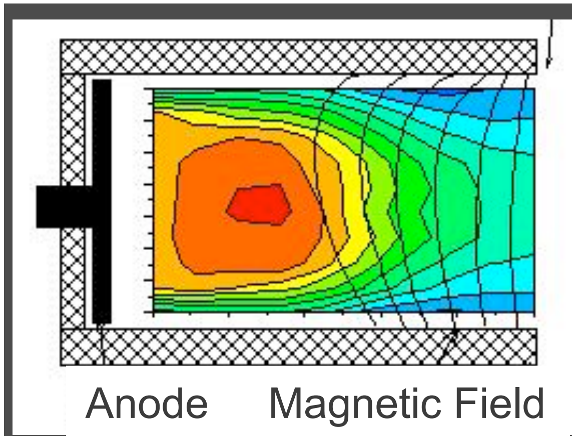




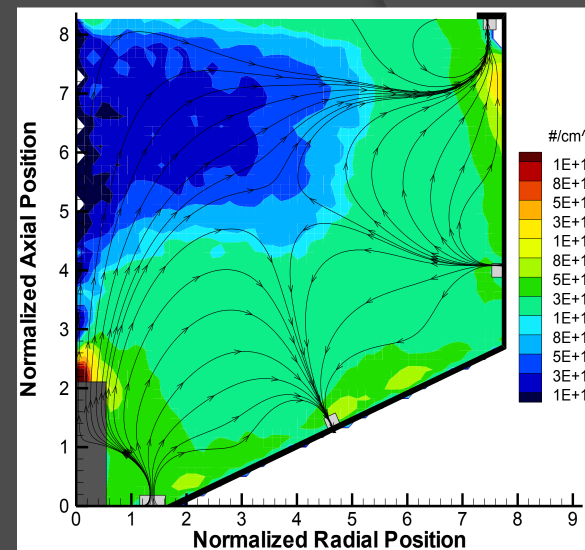




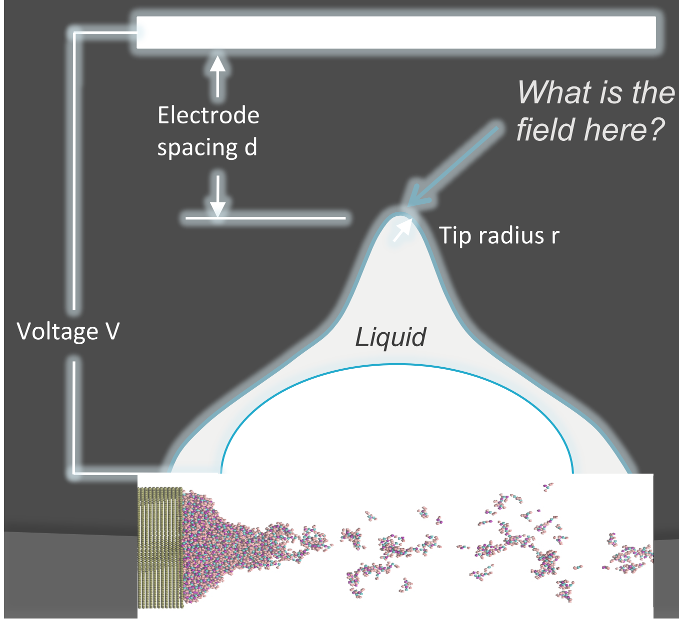


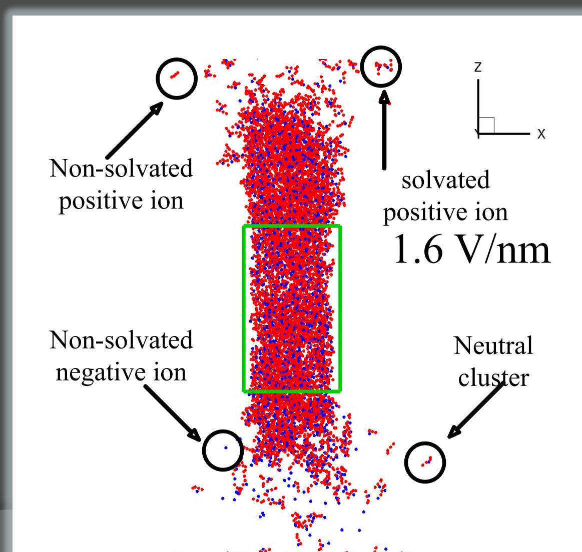


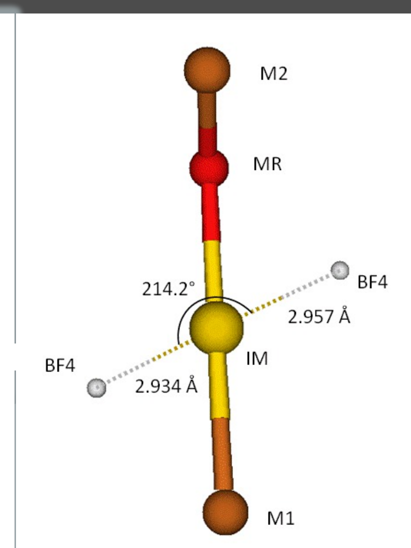
Domains of EP Research in Academia

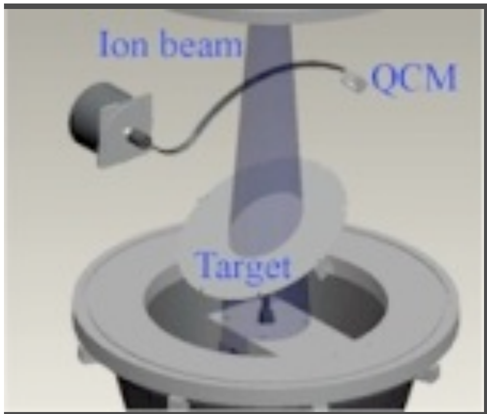


- Modeling & Simulation
  - Hybrid DSMC-PIC (Michigan - Boyd)
  - PIC-DSMC (Wright State - Menart)
  - Molecular Dynamics (Penn State - Levin)

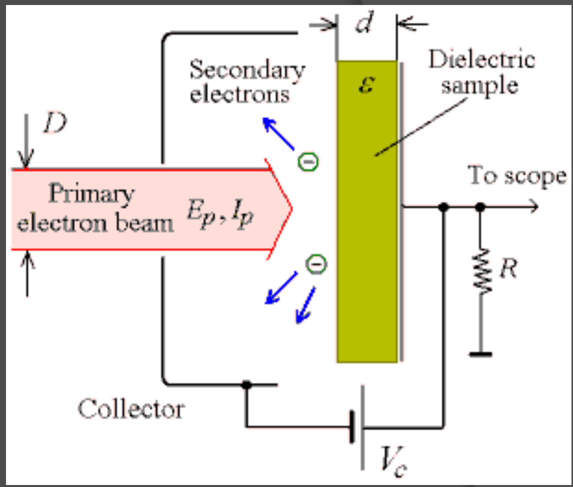




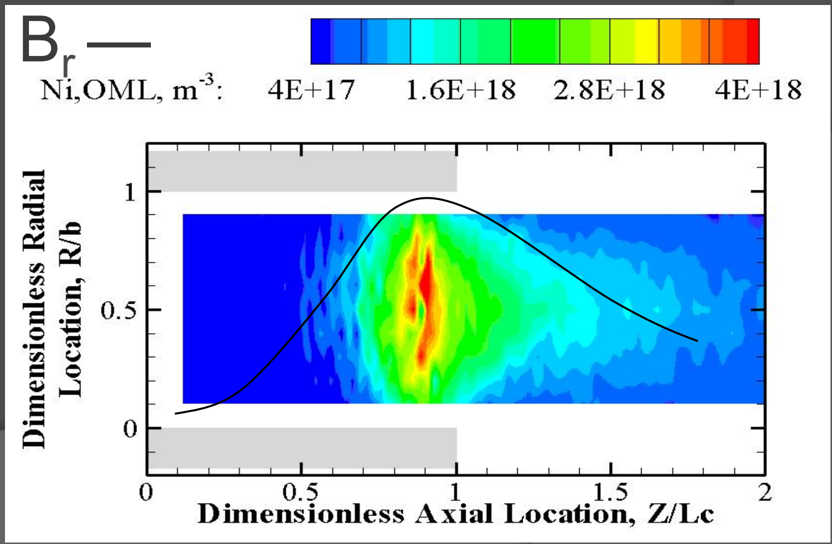




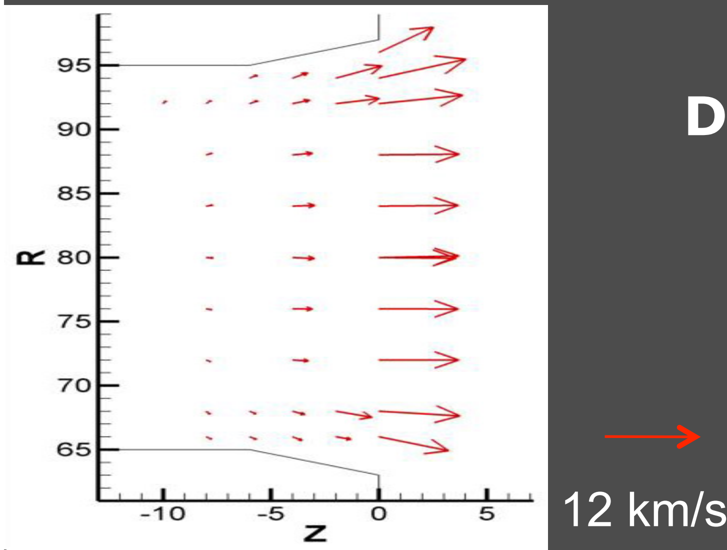
Domains of EP Research in Academia



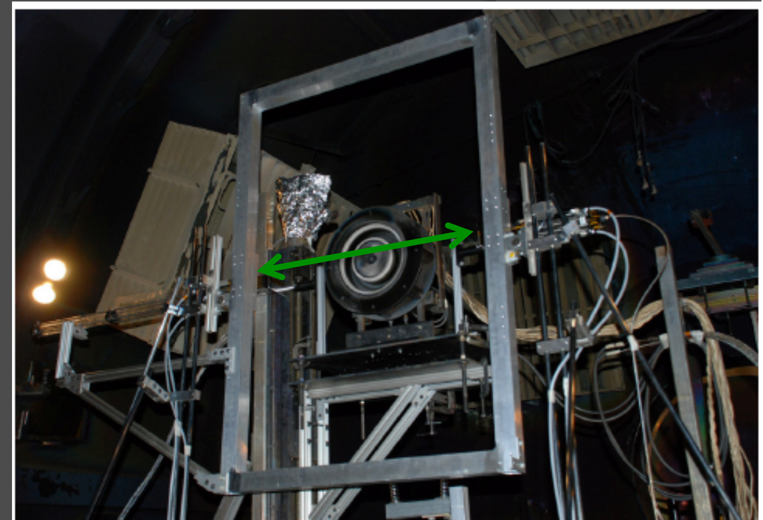
- Property Measurements
  - Thruster material (Colorado State - Yalin)
  - Secondary electrons (Princeton - Raitses)
  - Plasma (Michigan - Gallimore)
  - Propellants (Michigan Tech - King)

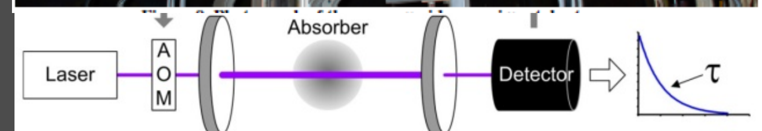


Domains of EP Research in Academia

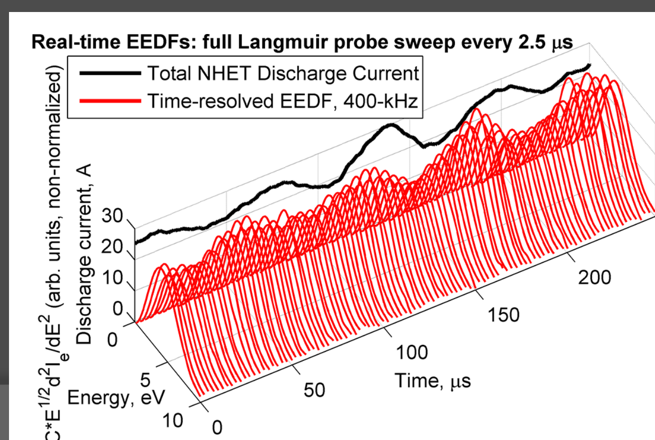


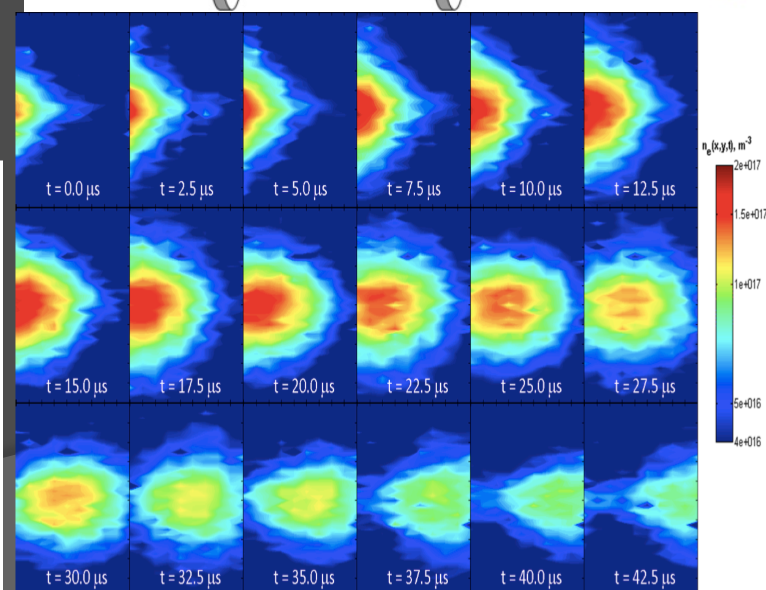
Hall Thruster Channel





- Diagnostics
  - LIF (Stanford - Cappelli)
  - CRDS (Colorado State - Yalin)
  - Probes (Michigan - Gallimore)





Domains of EP Research in Academia

- Some key technical challenges academia is not addressing (adequately)
  - New ways of evaluating thruster life
  - Facility effects/spacecraft environment
  - Power electronics
  - Solar array technology for SEP
  - Propellant management
  - Advanced materials
  - Systems

Domains of EP Research in Academia

- Some (possibly) new opportunities for EP researchers in academia
  - Interdisciplinarity - MEMS, materials, diagnostics, electronics
  - Advanced diagnostics - thruster and canonical experiments
  - Computing power - more sophisticated computer models that are *predictive*
  - Flight opportunities - Cubesats as EP test vehicles
  - Solar array technology for SEP
  - NASA?
  - Industry?

Domains of EP Research in Academia

- What is holding us back?
  - Steady funding
  - Lack of stable direction and set of priorities from government agencies
  - ITAR?
  - Limited collaboration with industry
  - Diffusion of EP talent to other fields
- Foreign progress
  - Half of the attendees of the IEPC were non-US
  - Europe and Japan have robust EP programs
  - China is serious about EP

In Summary

- EP remains an active and diverse academic endeavor in the US
- EP is a draw to top talent, particularly domestic students
- EP researchers remain creative in their work and in finding ways to support it
- Opportunities and challenges abound
- The rest of the world is not waiting for us

What they all mean

AFOSR - Air Force Office of Scientific Research
AFRL - Air Force Research Laboratory
CRDS - Cavity Ring-Down Spectroscopy
DARPA - Defense Advanced Research Projects Agency
DoD - Department of Defense
DoE - Department of Energy
DSMC - Direct Simulation Monte Carlo
EPSCoR - Experimental Program to Stimulate Competitive Research
GRFP - Graduate Research Fellowship Program (NSF)
LIF - Laser Induced Fluorescence
NASA - National Aeronautics and Space Administration
NDSEG - National Defense Science and Engineering Graduate (DoD)
NEXT - NASA Evolutionary Xenon Thruster (NASA)
NIAC - NASA Innovative Advanced Concepts
NRA - NASA Research Announcement
NSF - National Science Foundation
NSTRF - NASA Space Technology Research Fellowships
OCT - Office of the Chief Technologist (NASA)
PIC - Particle in Cell
SBIR - Small Business Innovative Research
SMART - Science, Mathematics And Research for Transformation (DoD)
STTR - Small Business Technology Transfer

DISCLAIMER

The following opinions are mine alone. They should not be considered the views of the University of Michigan.

Who am I?

- Professor of Aerospace Engineering at Michigan
- Expert in electric propulsion (EP) and plasma physics
- Ph.D. from Princeton
- Michigan faculty member since January 1992
- Founder and director of the Plasmadynamics and Electric Propulsion Laboratory at Michigan
- AIAA Fellow
- Graduated 35 Ph.D. students and 11 M.S. students.

Sample Projects

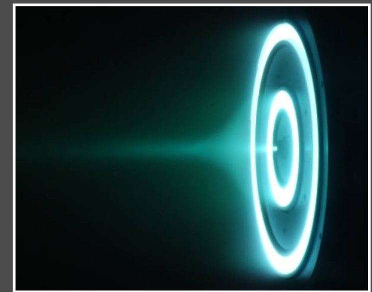
Institution	Project	Experiment	Modeling
MIT	Divergent Cusped Field Thruster	✓	✓
	Electrospray Propulsion	✓	✓
WPI	Flows in micro/nano nozzles and plumes		✓
	Plasma and gaseous microjets	✓	
	EEDF in hollow cathode plume	✓	
Georgia Tech	Field emission from carbon nanotubes	✓	
	ion focusing in discharge channel of a Hall Effect Thruster	✓	
	Concentric Channel Hall Thruster	✓	
	Increasing propellant residence time in Hall Thruster	✓	
	Dual-use Propulsion system for responsive space	✓	
	Hall Thruster Thermal Analysis	✓	
	Ambient Atmosphere Ion Thruster	✓	
Missouri S&T	Heavy-gas FRC plasmas	✓	
	Dual-mode ionic liquid propulsion	✓	✓
	Boron Nitride surface roughness/erosion studies for HETs	✓	
Michigan	Michigan AFRL Center for Excellence in EP		✓
	Ion Thruster Microwave plasma cathode	✓	
	Ion Thruster magnetic cusp collection studies	✓	
	Microwave plasma thruster	✓	
	50-cm ion thruster discharge chamber study	✓	
	Nested Channel Hall Thrusters	✓	
	Nanoparticle field emission thruster	✓	✓
	Hall Thruster Electron physics studies	✓	✓
	Neutral Gas in Hall Thruster Discharge Channel	✓	
	Magnetic Nozzle Detachment in RF plasma	✓	
	Time-resolved Plasma Diagnostics	✓	
	Erosion studies of Hall Thruster Discharge Channel	✓	
Wright State	NEXT ion engine PIC/MCC		✓
Illinois	Gallium Electromagnetic Thruster	✓	
	Microcavity discharge thruster	✓	✓

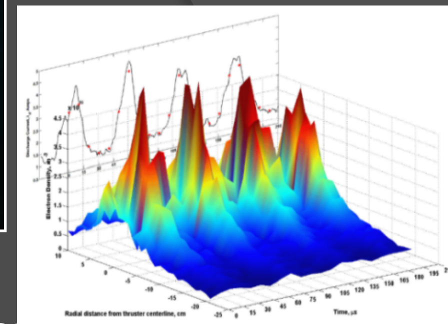
>70 EP-Related Projects (75%) Primarily Experimental

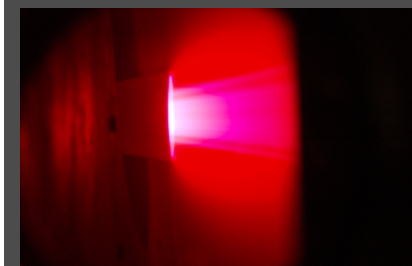
Institution	Project	Experiment	Modeling
Caltech	Cathode Physics for Electric Propulsion	✓	
Colorado State	CRDS diagnostic development	✓	
	Sputter yield characterization	✓	
	Hollow Cathode plasma measurements	✓	
	Ion optics and grid erosion in ion thrusters		✓
Wisconsin	Advanced Helicon Thruster Performance	✓	
UC at Colorado Springs	Liquid Droplet Thrusters	✓	✓
	Radiometric force production	✓	✓
Michigan Tech	Re-generable Field Emission Cathodes for Low-power EP	✓	
	Xenon, Bismuth, and alternate metal Hall Thrusters	✓	
	Hall Thruster thermal modeling		✓
	Electron Dynamics in Hall-effect accelerator	✓	
	annular Field-reversed Configuration plasma	✓	
	Carbon nanotubes for sputter erosion resistance	✓	
Stanford	Physics of Divergent Cusped Thrusters	✓	✓
	Coaxial Plasma Accelerator	✓	
Washington	Electrodeless Lorentz Force Thruster	✓	✓
Princeton	Segmented Electrode Hall Thruster	✓	
	Cylindrical Hall Thruster	✓	
	High Frequency oscillations in Hall Thrusters	✓	
	Near-Anode Processes in Hall Thrusters	✓	
	Secondary Electron Emission	✓	
	Ferroelectric Plasma Sources	✓	
	Magnetic Nozzle Acceleration and Detachment	✓	
	Lithium Lorentz Force Acceleration and Detachment	✓	
	Plasma Heating using Beating Electrostatic Waves	✓	
	Conical Theta Pinch Faraday Accelerator with RF Assisted Discharge	✓	
UT Austin	Plasma Actuators for supersonic/hypersonic flow	✓	✓
UCLA	Plasma Actuators	✓	✓
University of Missouri at Columbia	Ferroelectric Plasma Thruster	✓	
George Washington University	Micro-Vacuum Arc Thruster	✓	
	Hall Thruster 1D Kinetic Code		✓

Sample Efforts

Michigan/AFRL Center of Excellence in Electric Propulsion (MACEEP) — Michigan (Lead), Colorado State, Michigan Tech, Penn State, Washington, UCLA, MSNW



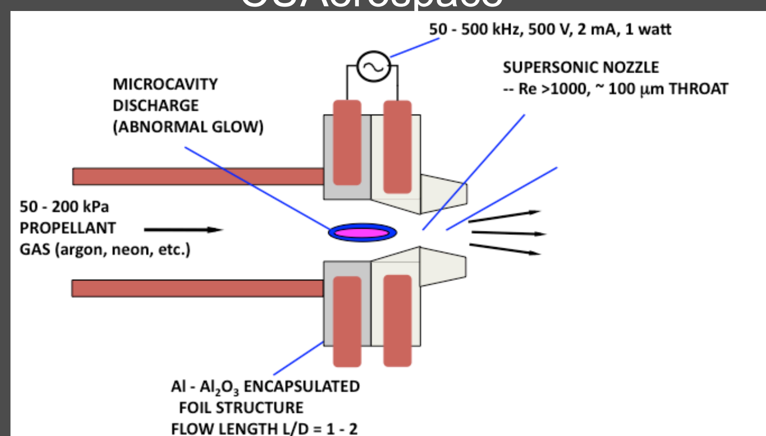


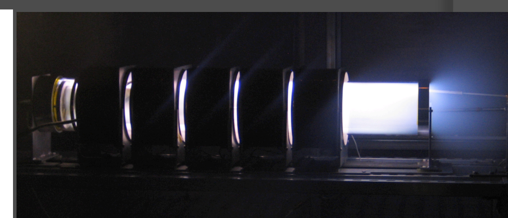


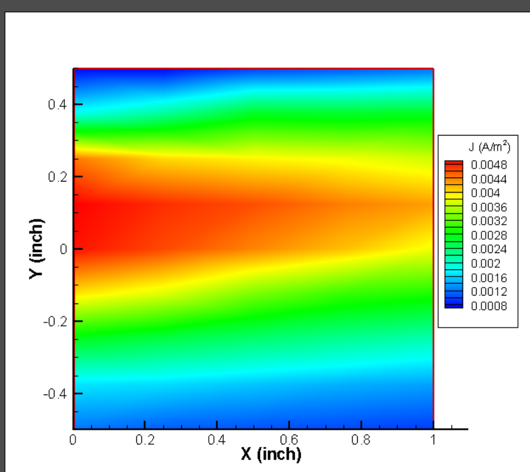
Magnetic Mirroring-Based Divergent Cusped Concept — Princeton, MIT, Stanford, George Washington

Advanced Helicon Thruster Characterization — Georgia Tech and Wisconsin

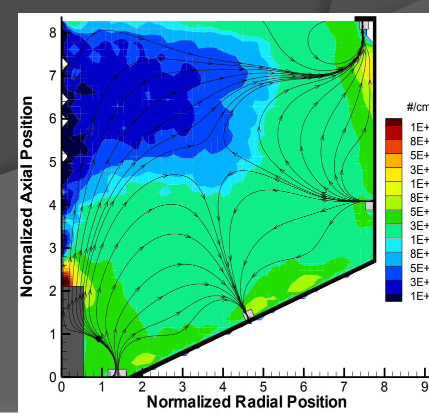
Microcavity Discharge Thruster — Illinois, Texas, CUAerospace







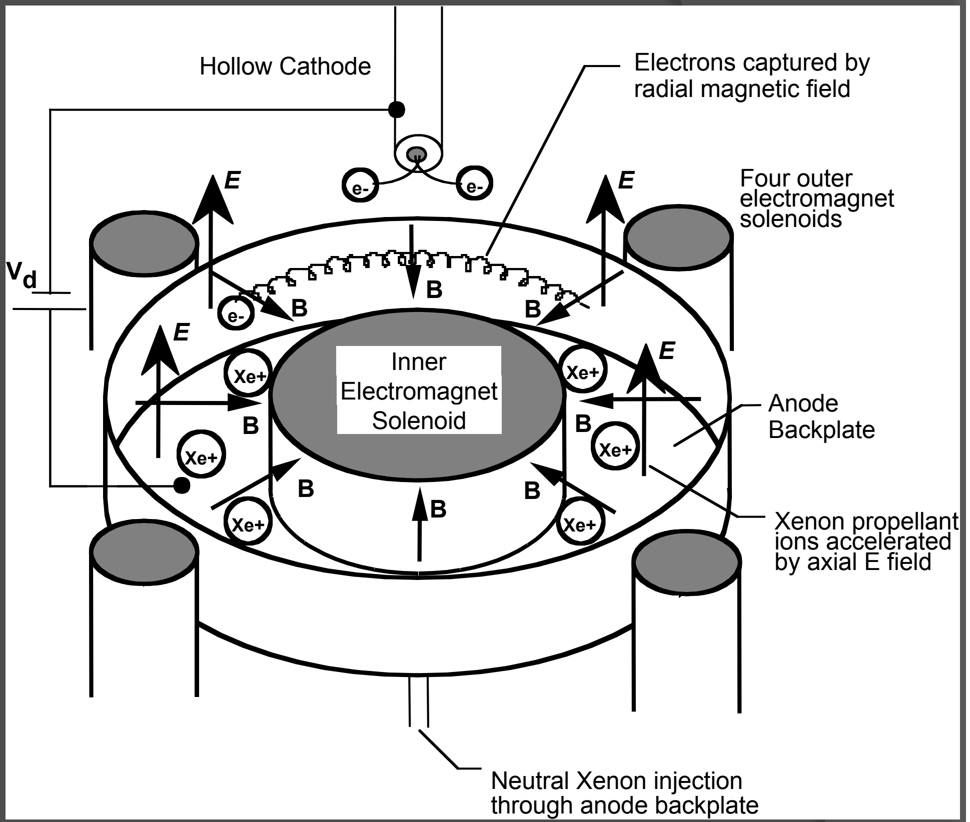
Ion Thruster Discharge Chamber Modeling — Wright State

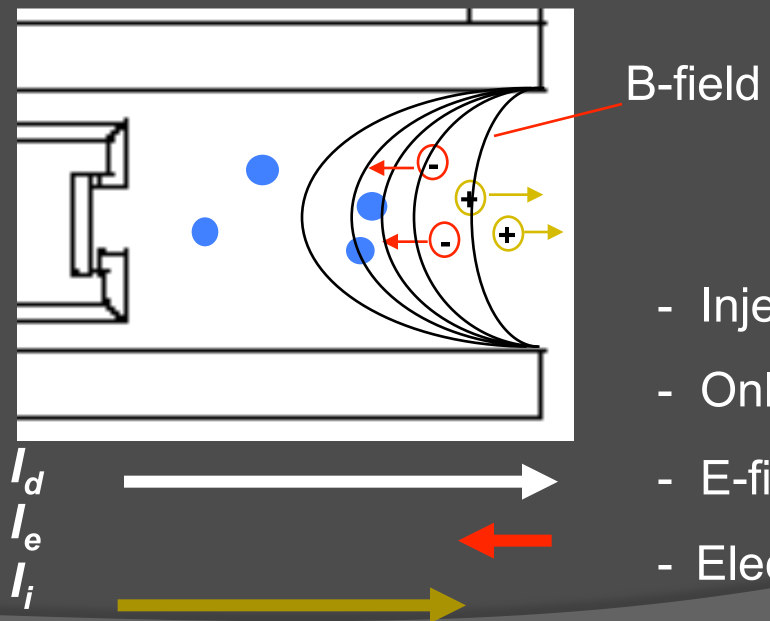


Ion Beam Neutralization Modeling — USC

HALL THRUSTER PHYSICS

- Radial magnetic field from inner and outer electromagnets
- Axial electric field established between anode and external cathode
- Electron motion toward anode impeded by radial magnetic field – azimuthal **E**x**B** drift (HALL CURRENT)





- Injected neutrals ionized by Hall current
- Only electrons are magnetized → B-field
- E-field accelerates ions (I_i) → Thrust
- Electron backstreaming (I_e) saps performance
- Cathode supplies electrons to neutralize beam

What academics think is needed or have identified as challenges…

- *Long-term sustained programs (like they have in Europe/ Japan) are needed in the U.S.*
- *U.S. EP program has fallen behind European/Japanese programs in terms of funding and in coordination*
- *Consideration of systems aspects often missing in academic EP research (too many "pet thrusters?")*
- *No clear path to space missions…lack of sustained support in any one technology…no agency leaders/champions*
- *EP technical challenges of interest to civil space, DOD, and industry largely unknown to academics*
- *Looking to NASA to join the Air Force in providing sustained funding to academic research programs*
- *Lack of consistent sustained support risks loss of heritage and expertise as investigators are drawn to other sources of funding*