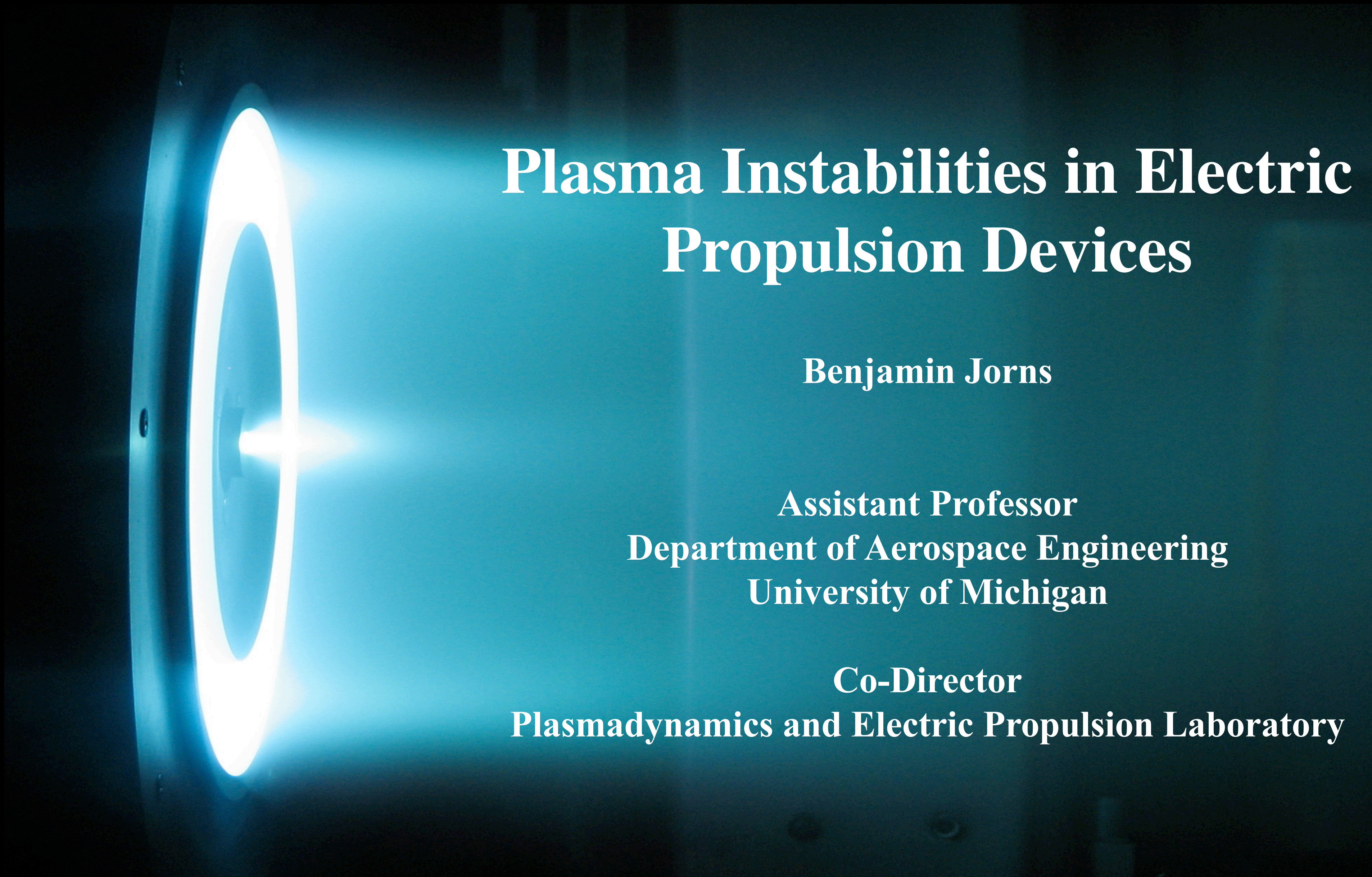
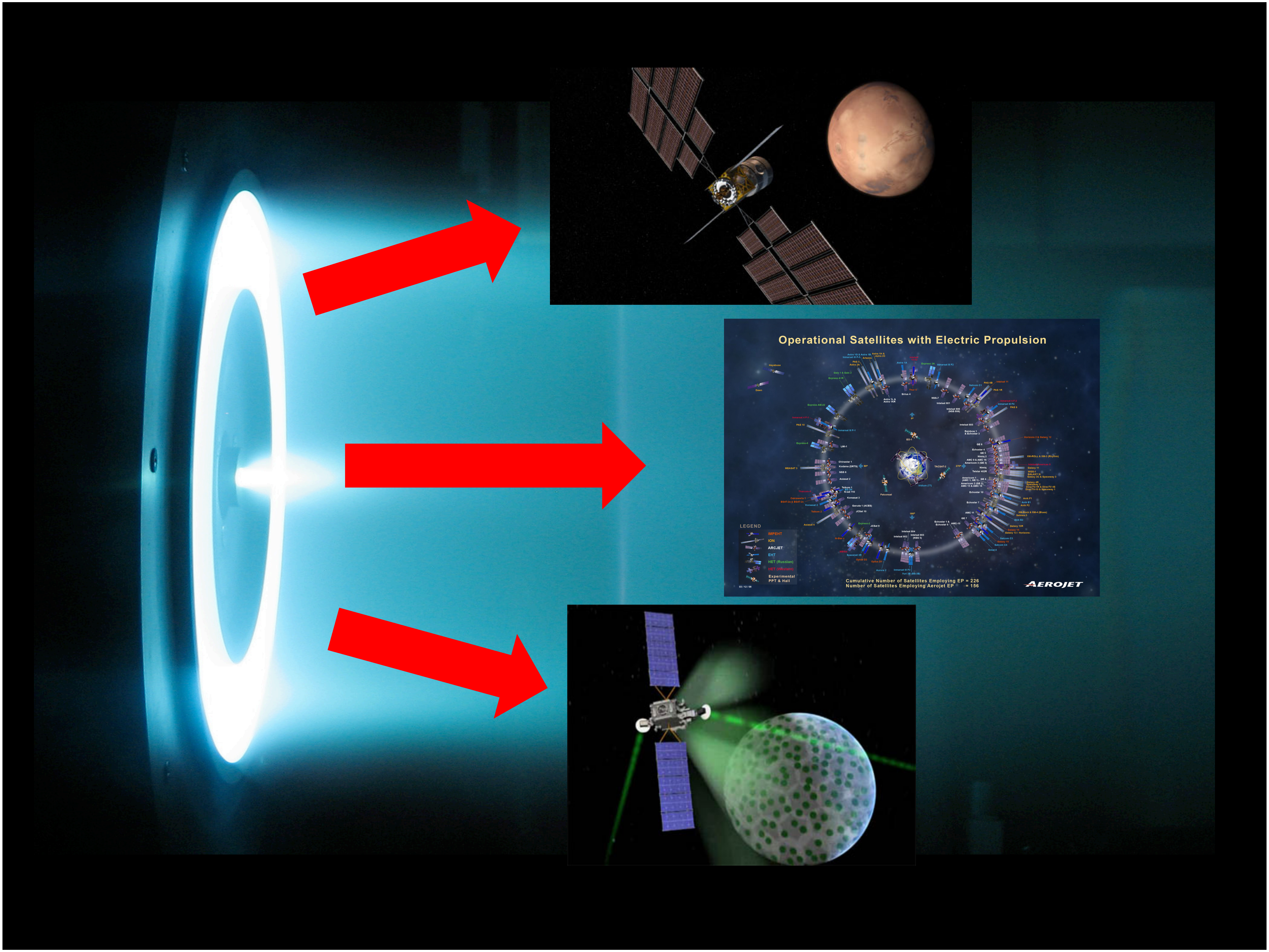


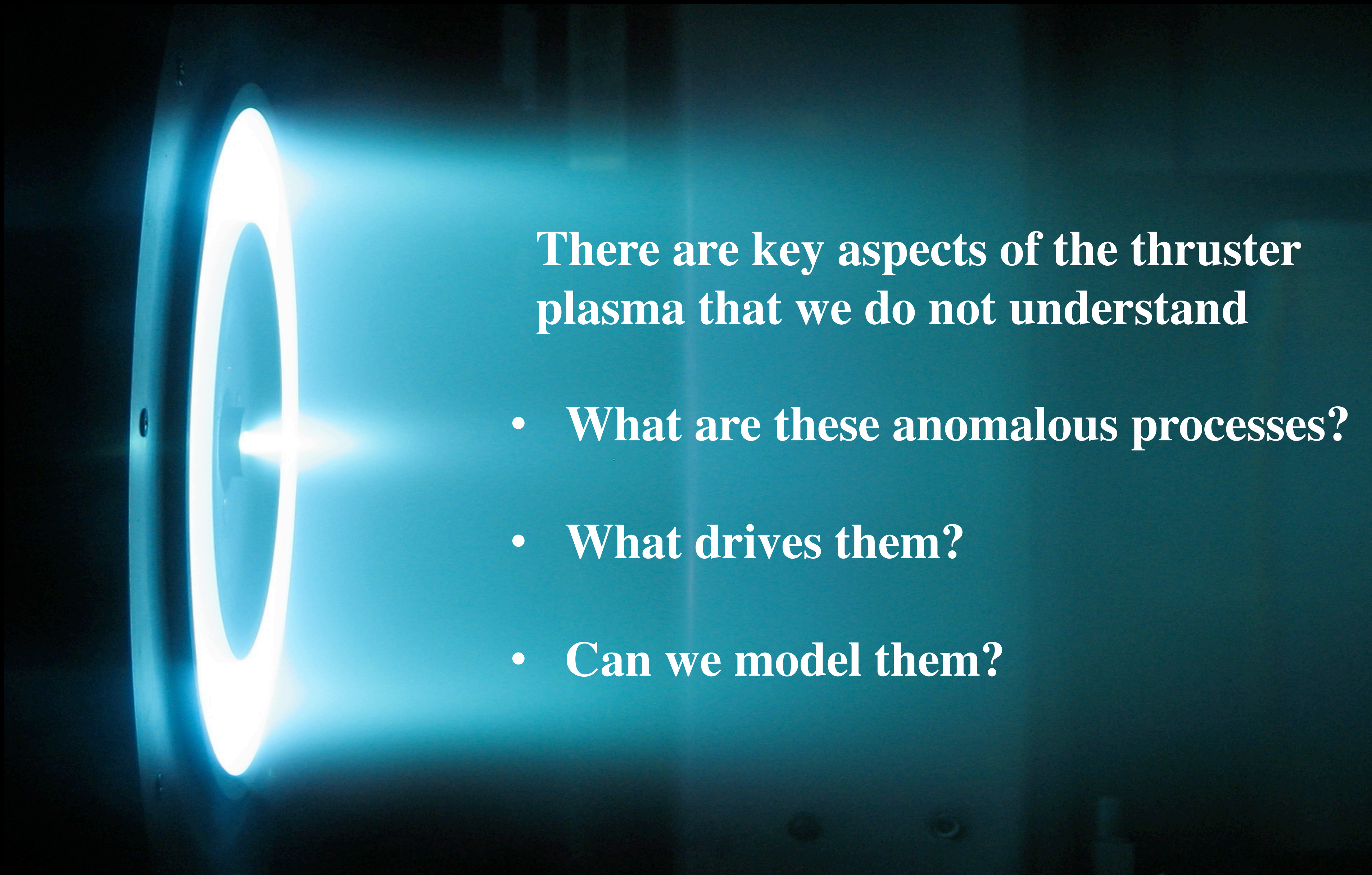
Plasma Instabilities in Electric Propulsion Devices

Benjamin Jorns

Assistant Professor
Department of Aerospace Engineering
University of Michigan

Co-Director
Plasmadynamics and Electric Propulsion Laboratory


Operational Satellites with Electric Propulsion
LEGEND
IMPEHT
ION
ARCJET
EHT
HET (Russian)
HET (Western)
Experimental PPT & Hall
03 / 12 / 08
Cumulative Number of Satellites Employing EP = 226
Number of Satellites Employing Aerojet EP = 156
AEROJET



There are key aspects of the thruster plasma that we do not understand

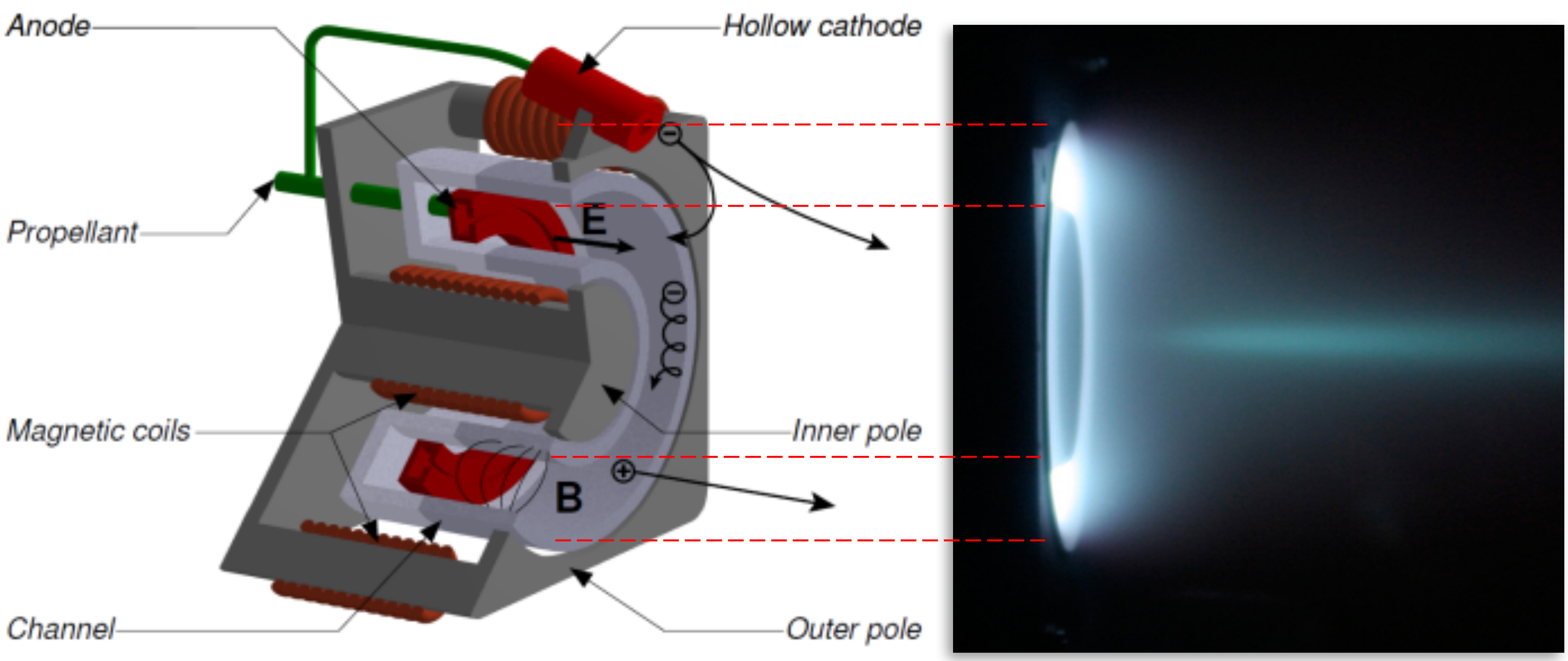
- What are these anomalous processes?
- What drives them?
- Can we model them?

Thesis: Plasma instabilities are a major driver

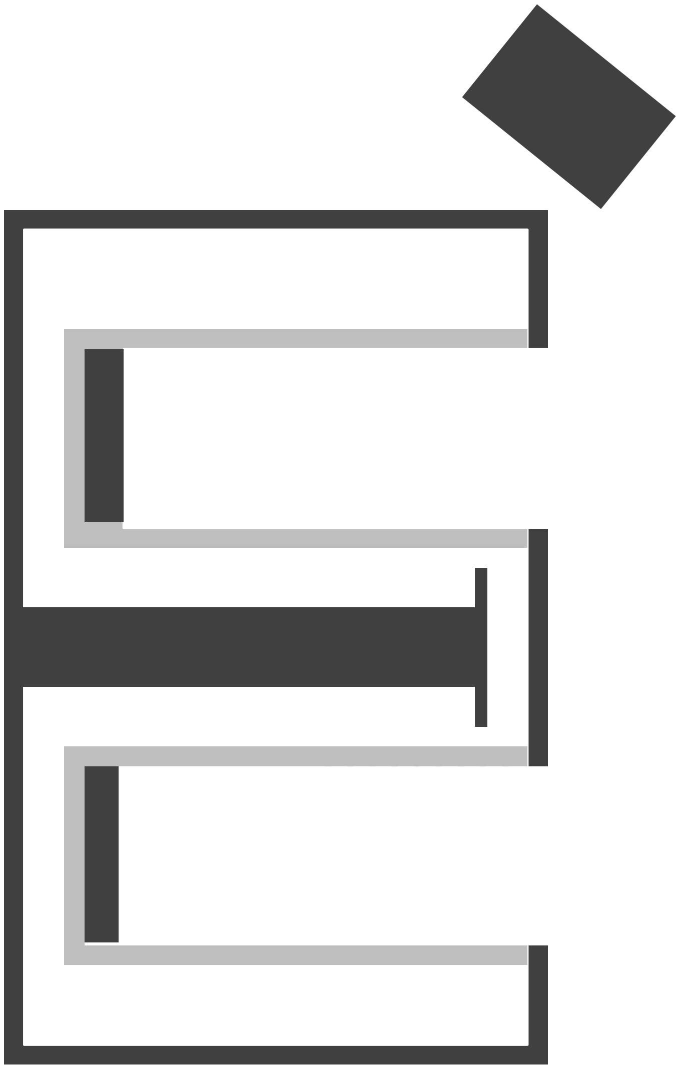
Overview

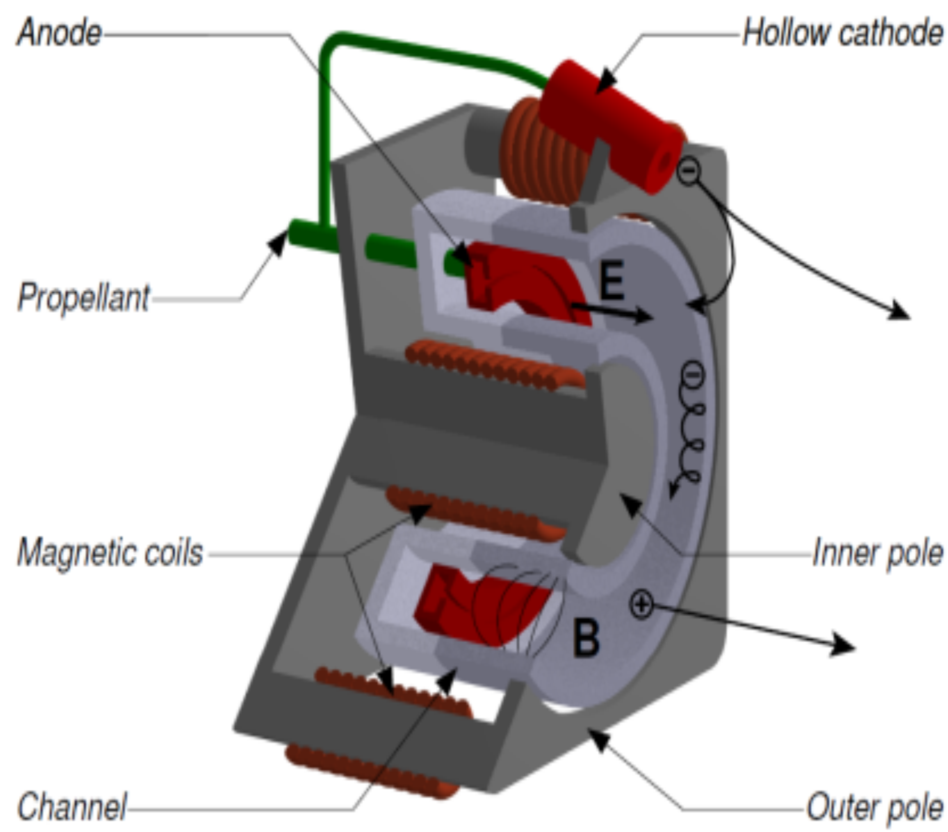
- Hall thruster principle of operation
- Anomalous processes in Hall thruster operation
- Role of plasma instabilities

Hall thruster principle of operation

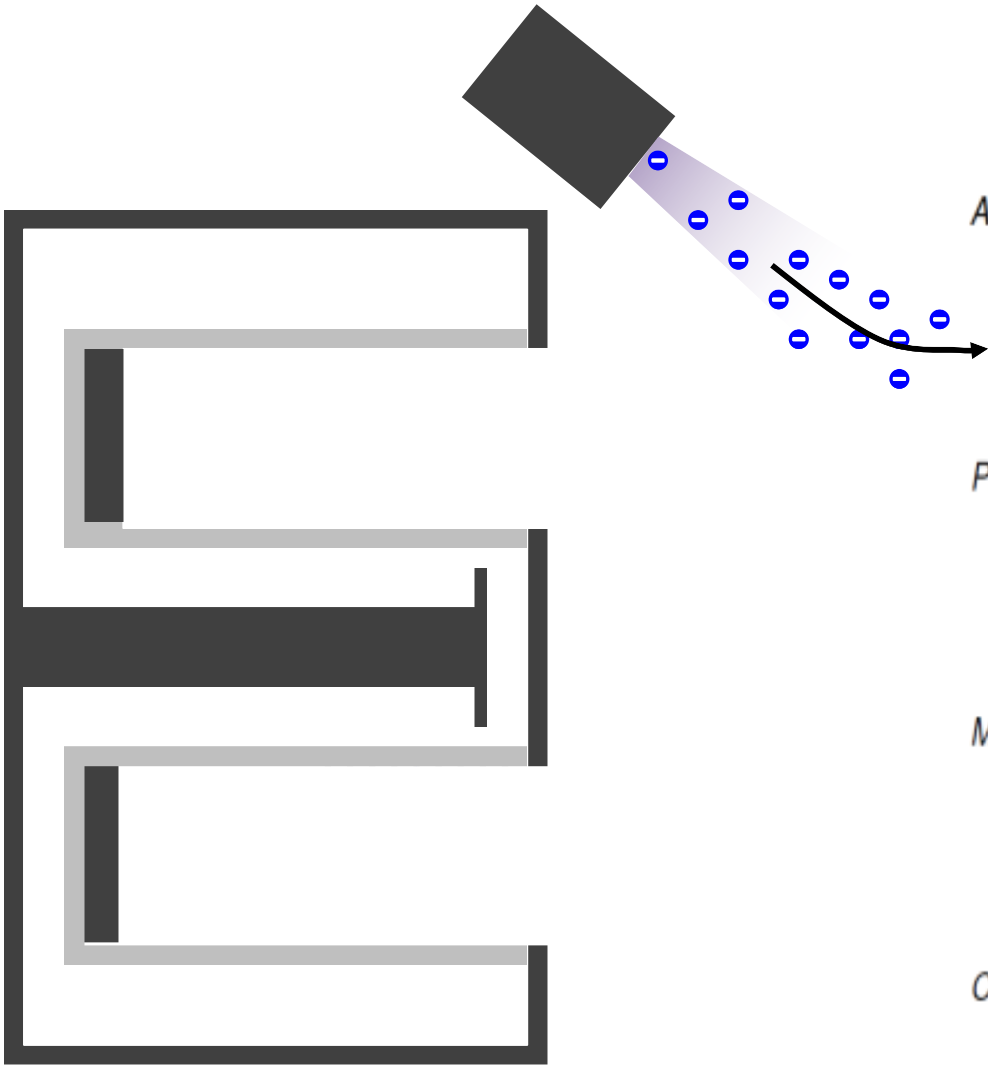


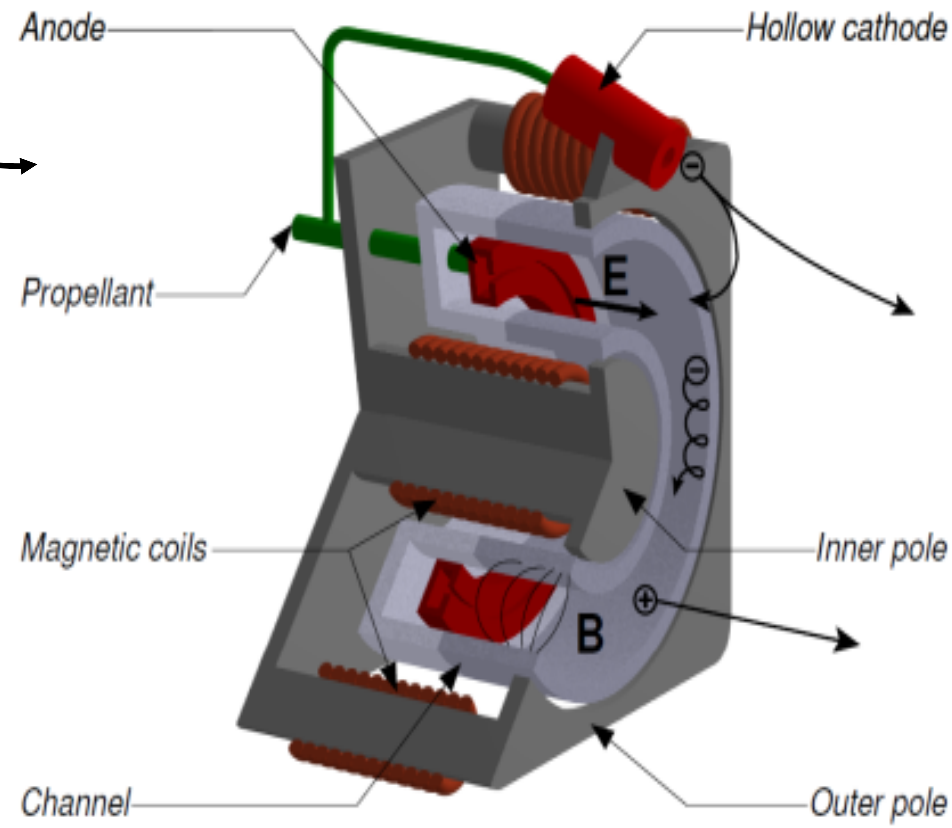
Hall thruster principle of operation





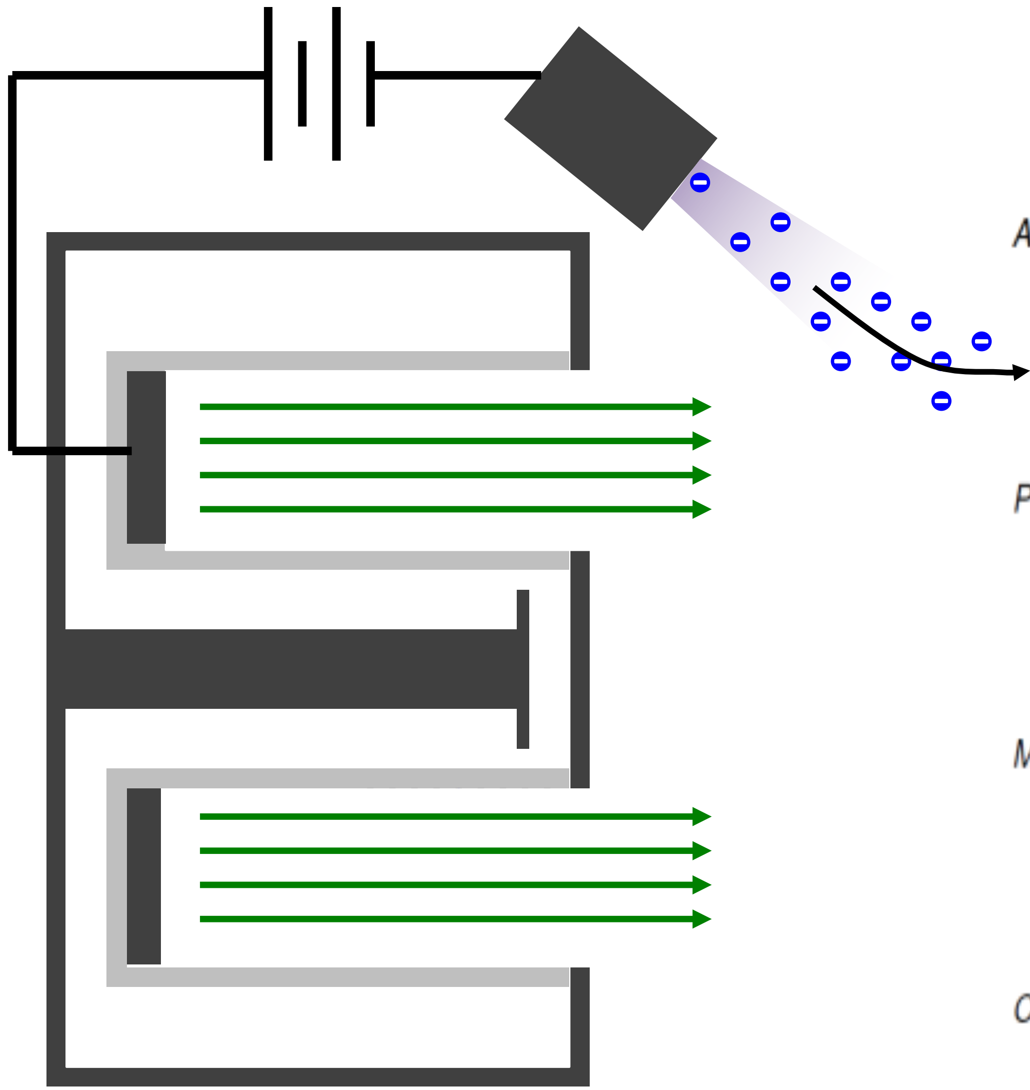
Hall thruster principle of operation

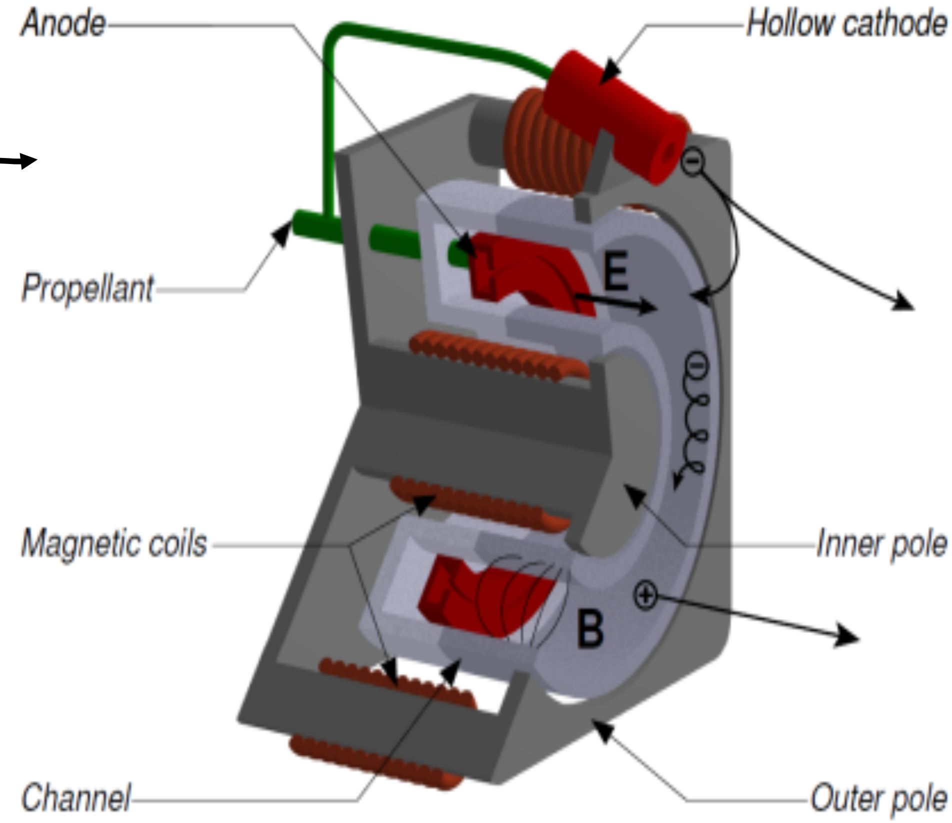




Hollow cathode heated until thermionically emitting electrons

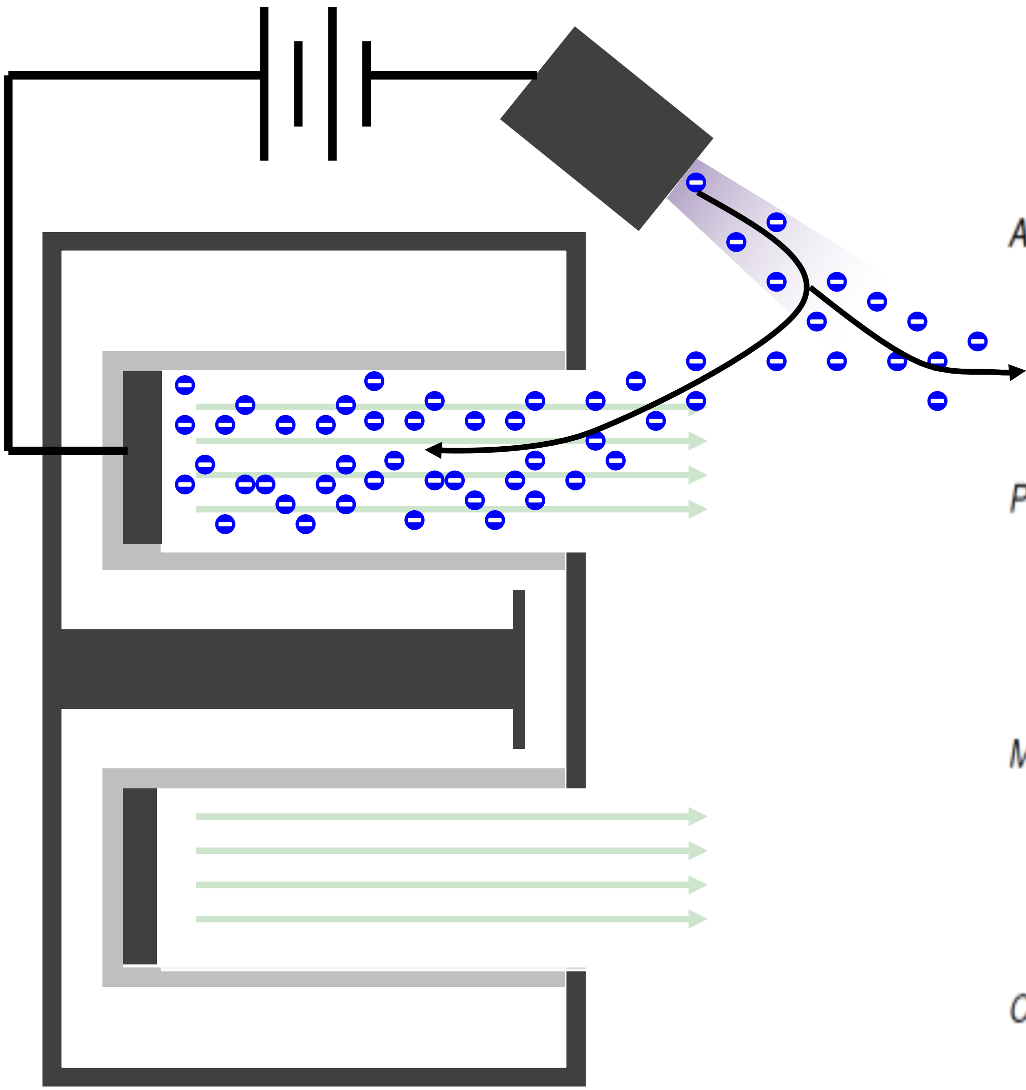
Hall thruster principle of operation

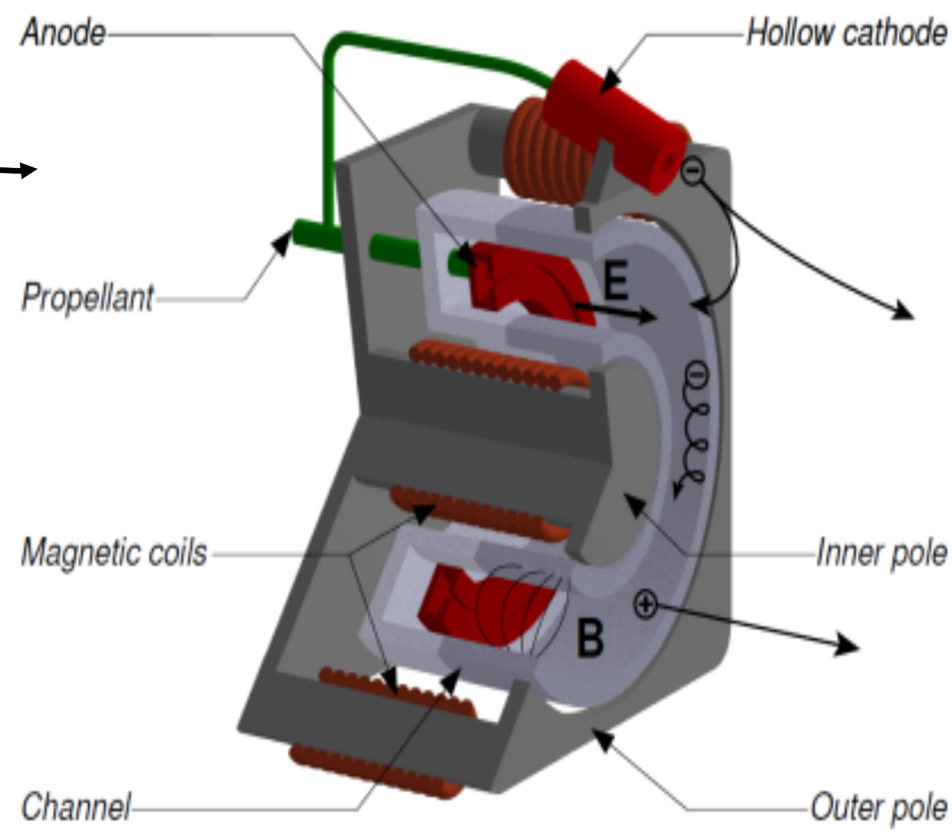




Electric field applied between anode and cathode

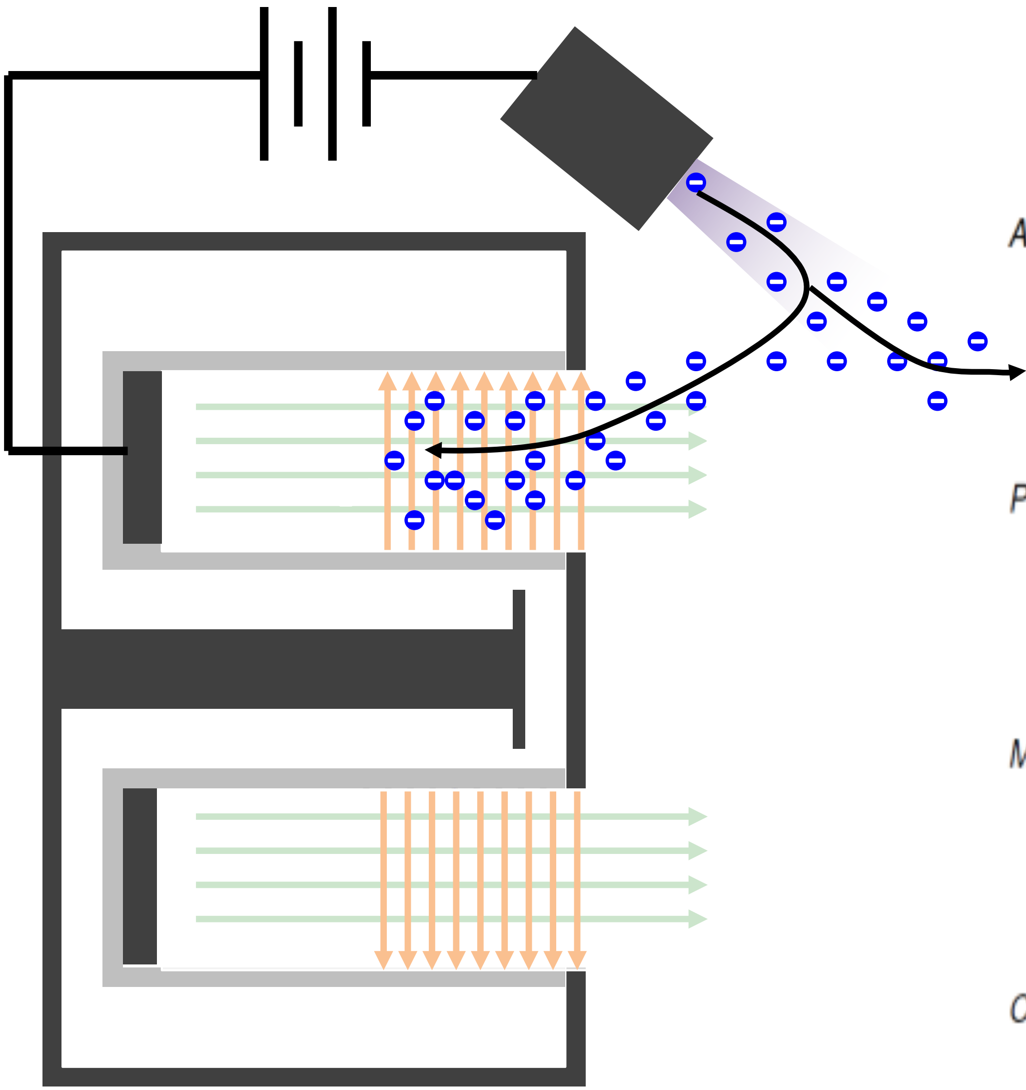
Hall thruster principle of operation

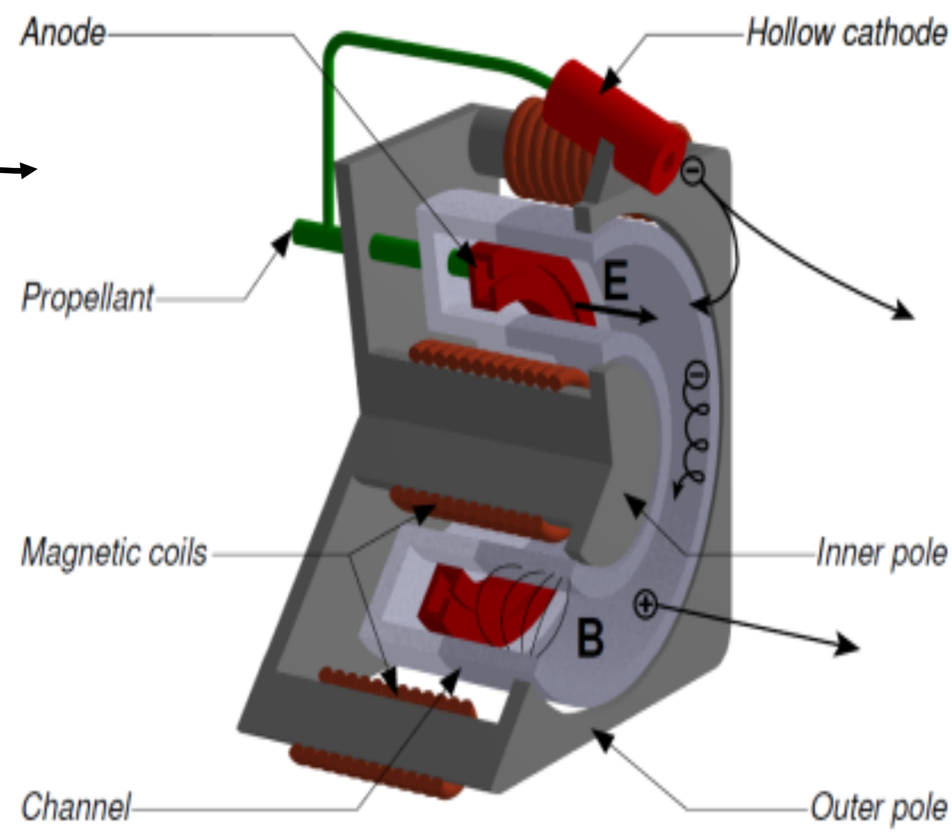




Electrons follow electric field and current flows between cathode and anode

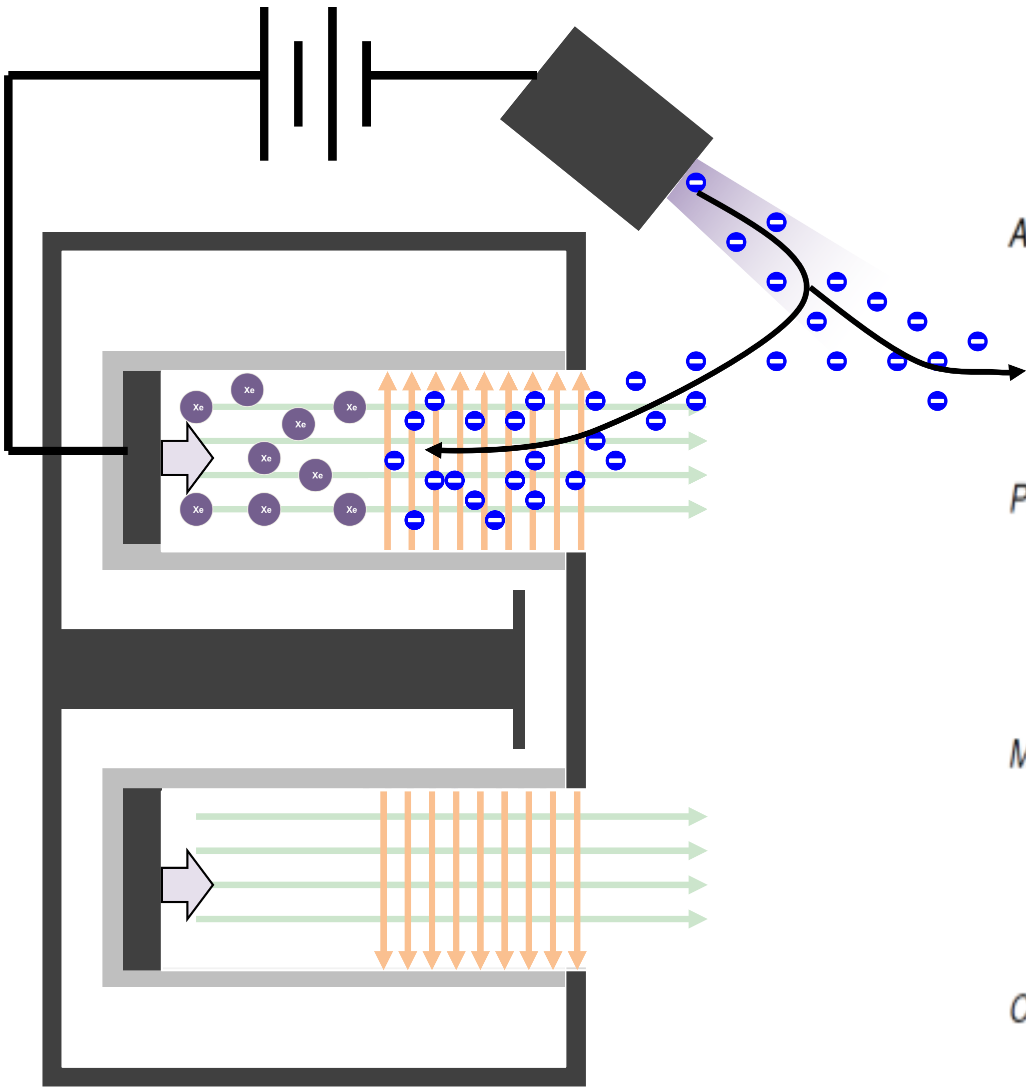
Hall thruster principle of operation

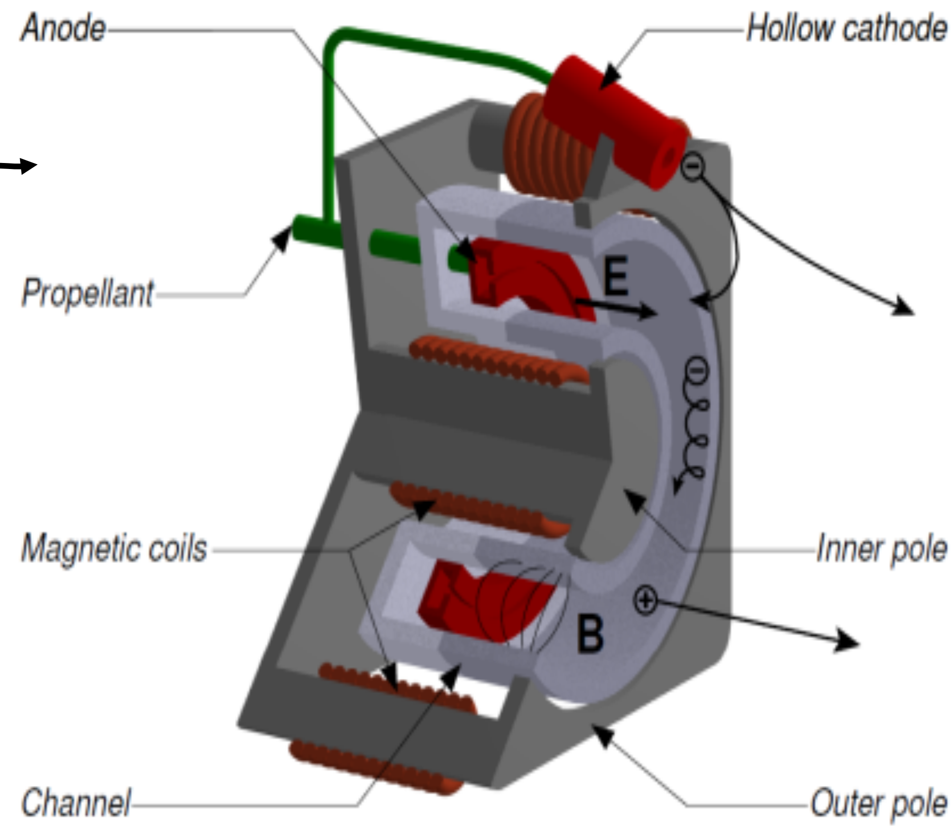




Magnetic field is applied in the radial direction. Electrons are trapped in $\mathbf{E} \times \mathbf{B}$ azimuthal drift: *Hall effect*

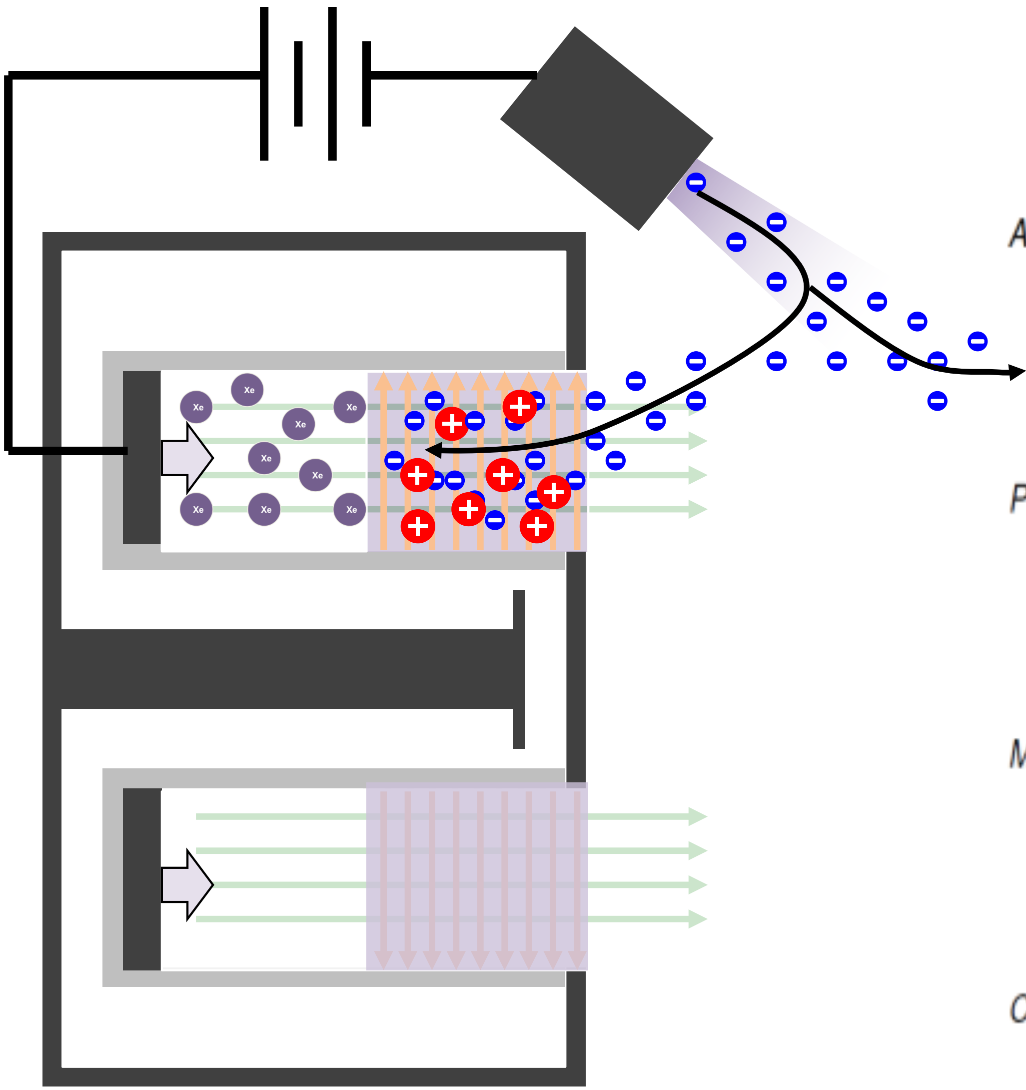
Hall thruster principle of operation

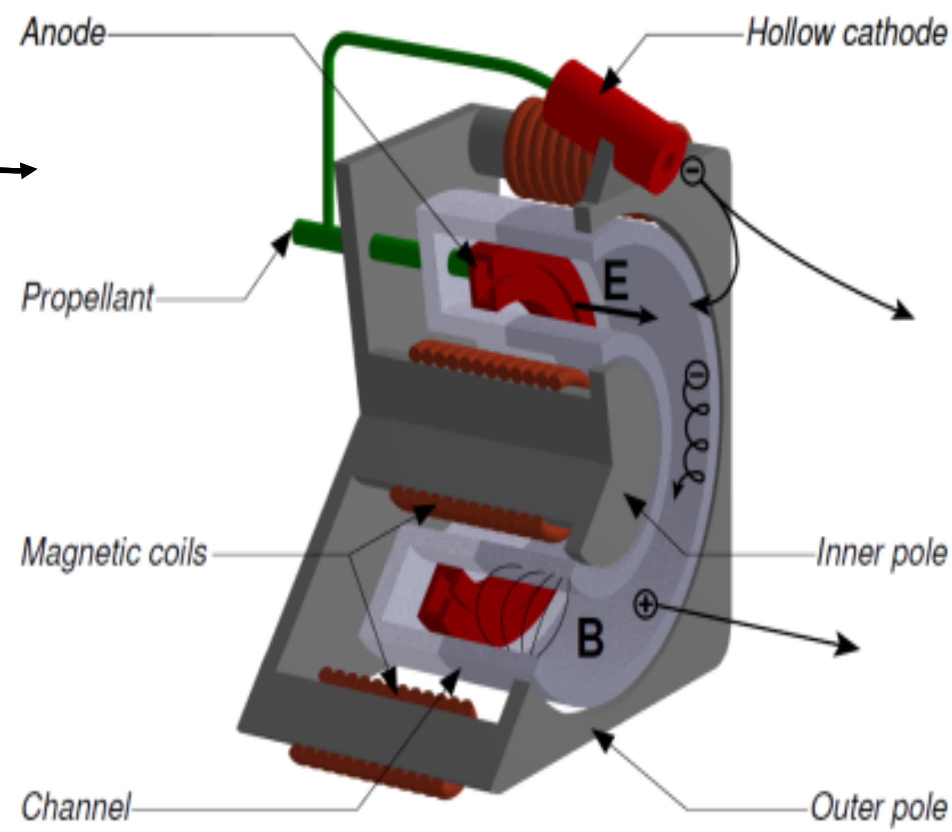




Neutral gas (xenon) flows through thruster anode.

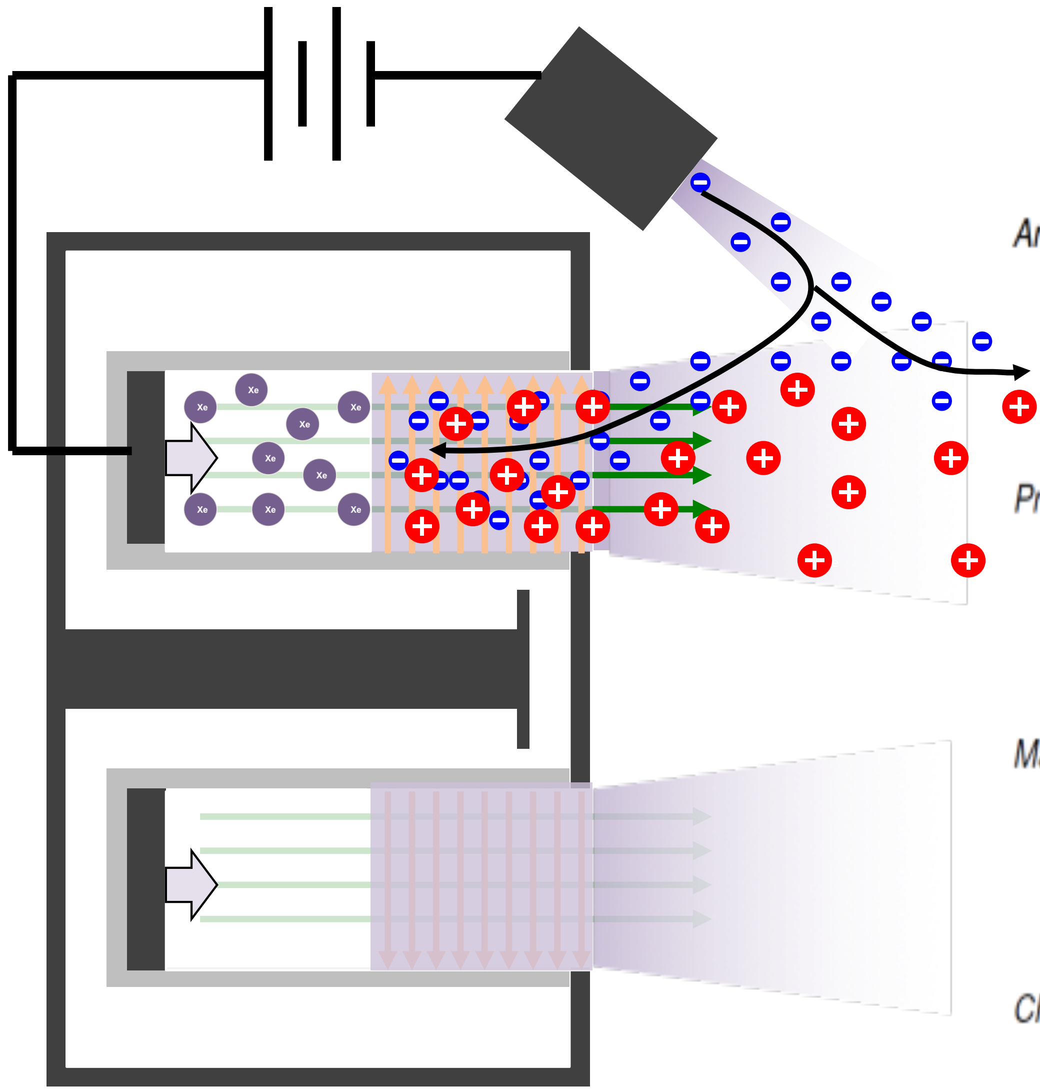
Hall thruster principle of operation

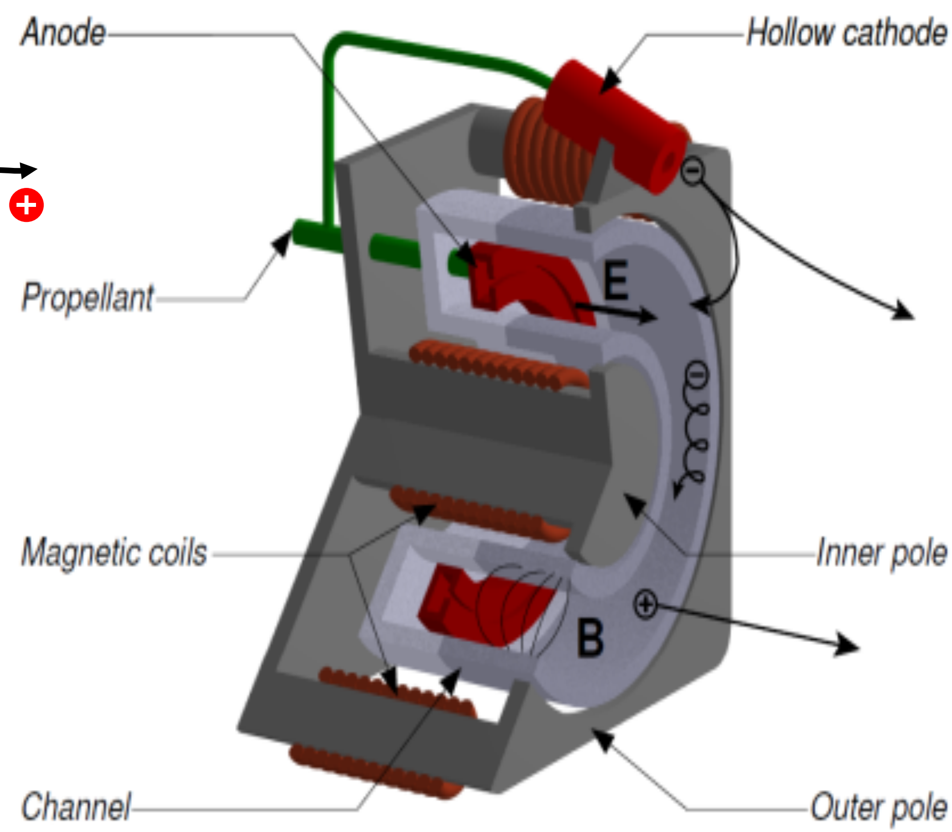




Electron azimuthal drift “buzz saw” ionizes neutral xenon. Plasma is created.

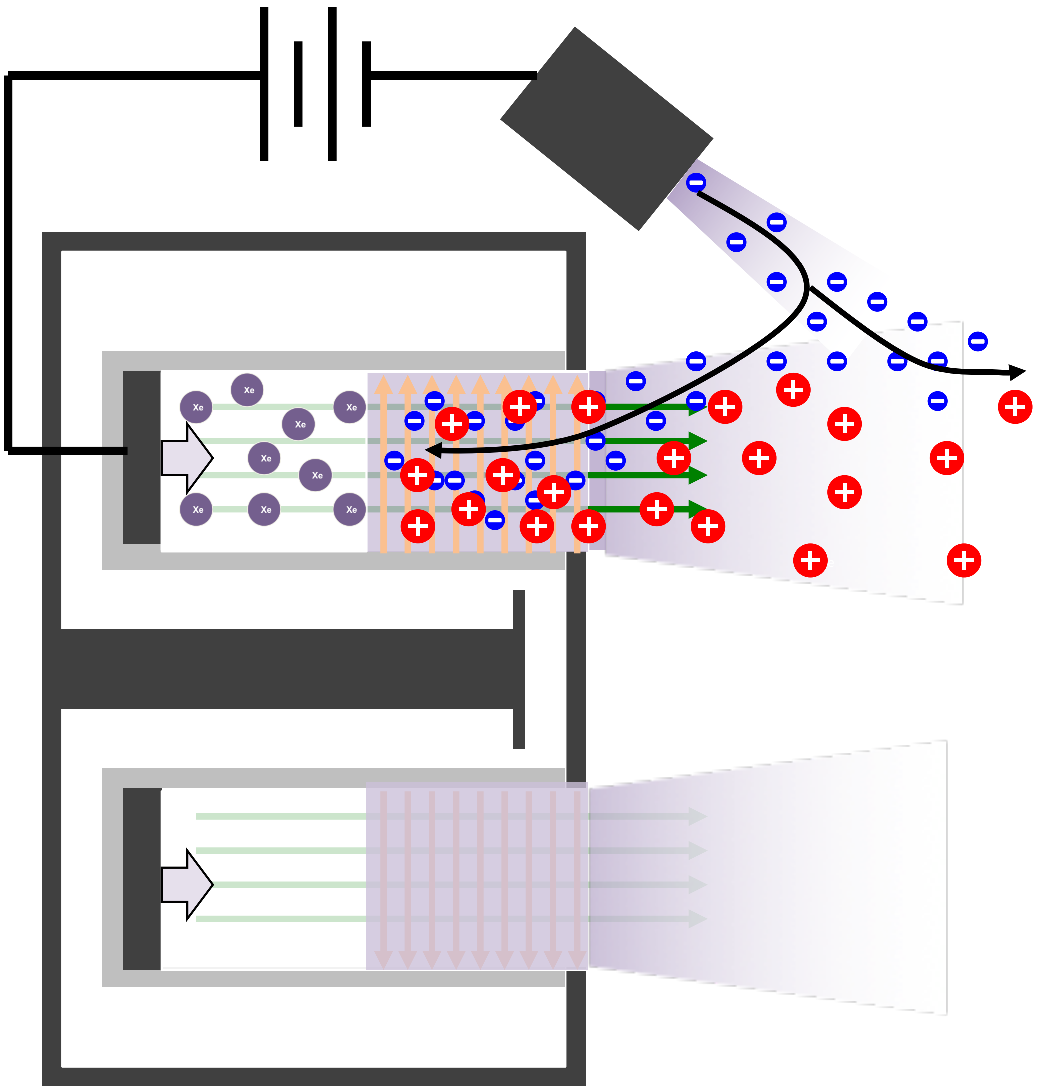
Hall thruster principle of operation

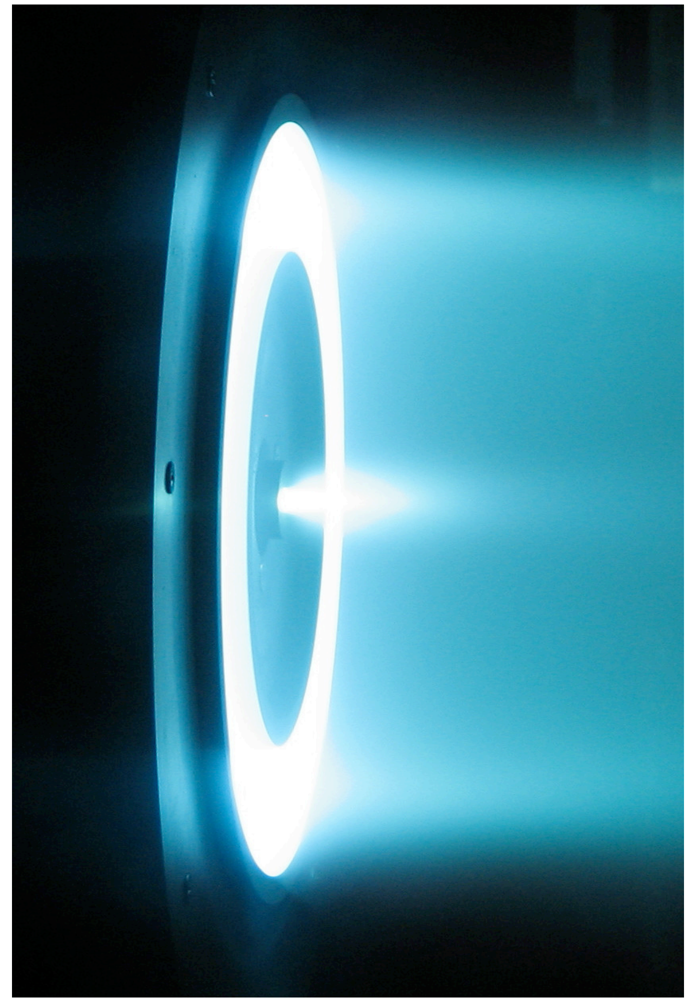




Ions are unmagnetized and therefore follow electric field lines directly.
Accelerated ions are neutralized by electrons in plume

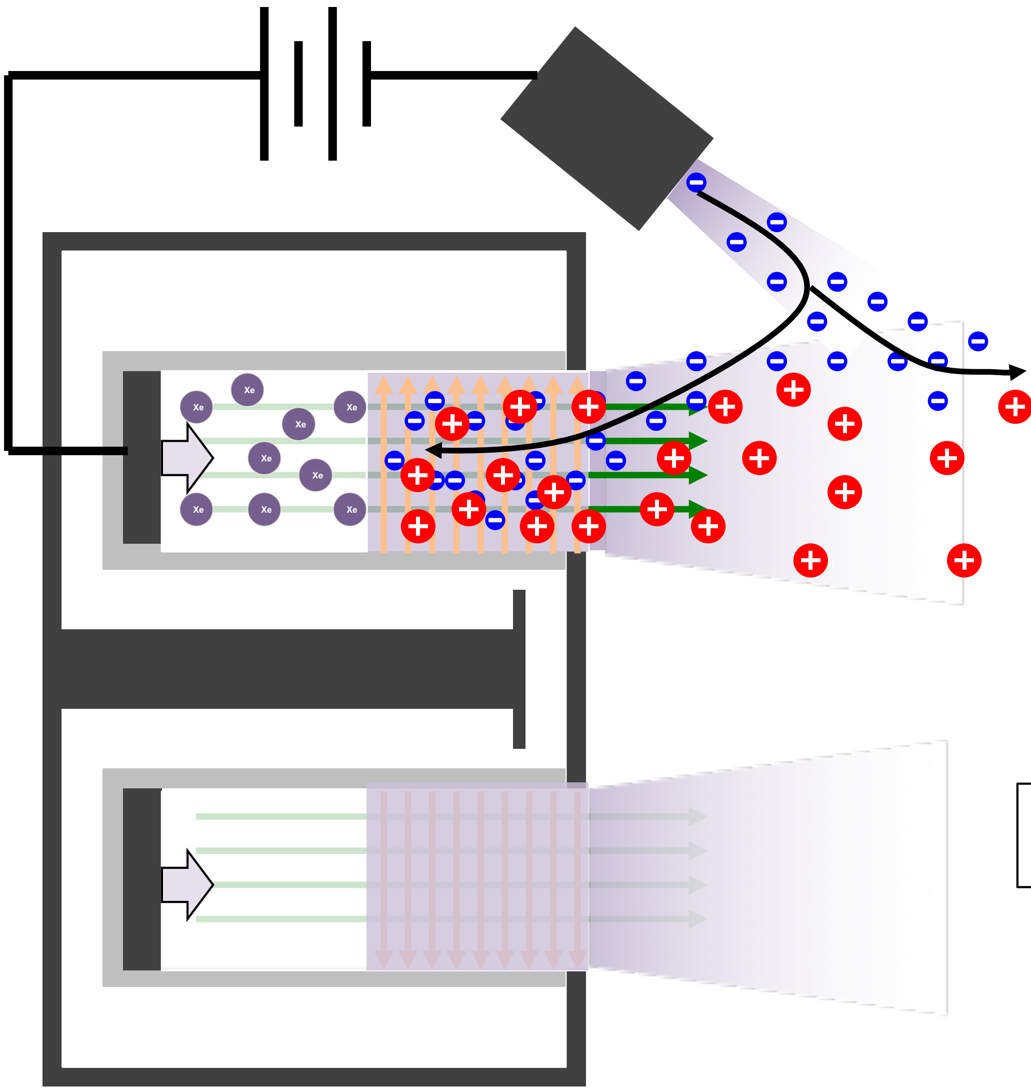
Hall thruster principle of operation





Hall thrusters work and currently fly on hundreds of spacecraft on orbit

Hall thruster principle of operation



High specific impulse

$$I_{sp} \propto \sqrt{V_D}$$ 1000-3000 s

High thrust density

$$\sum_s q_s n_s = 0$$ 30-500 mN

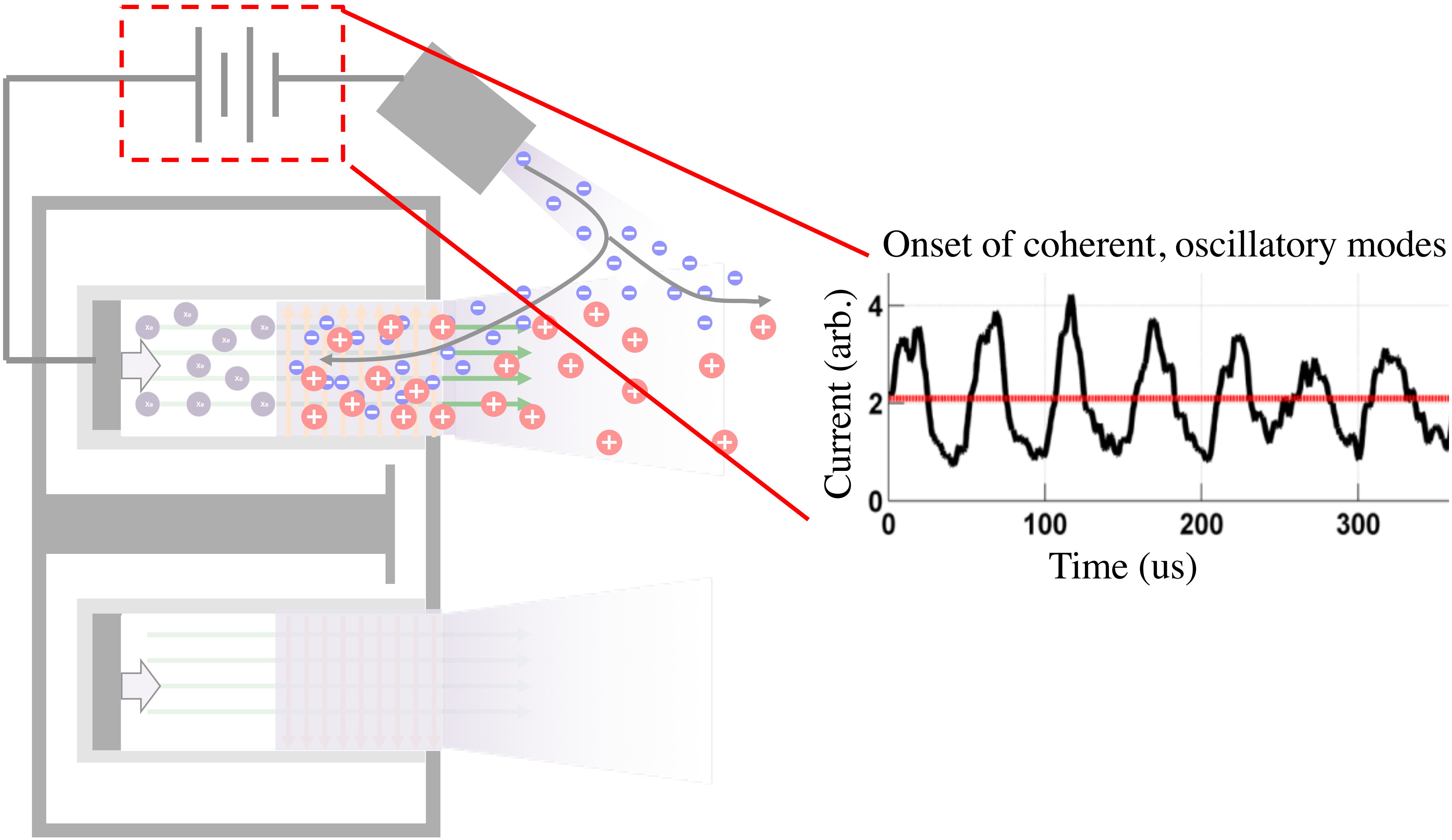
Simple PPU and control logic

1-13 kW

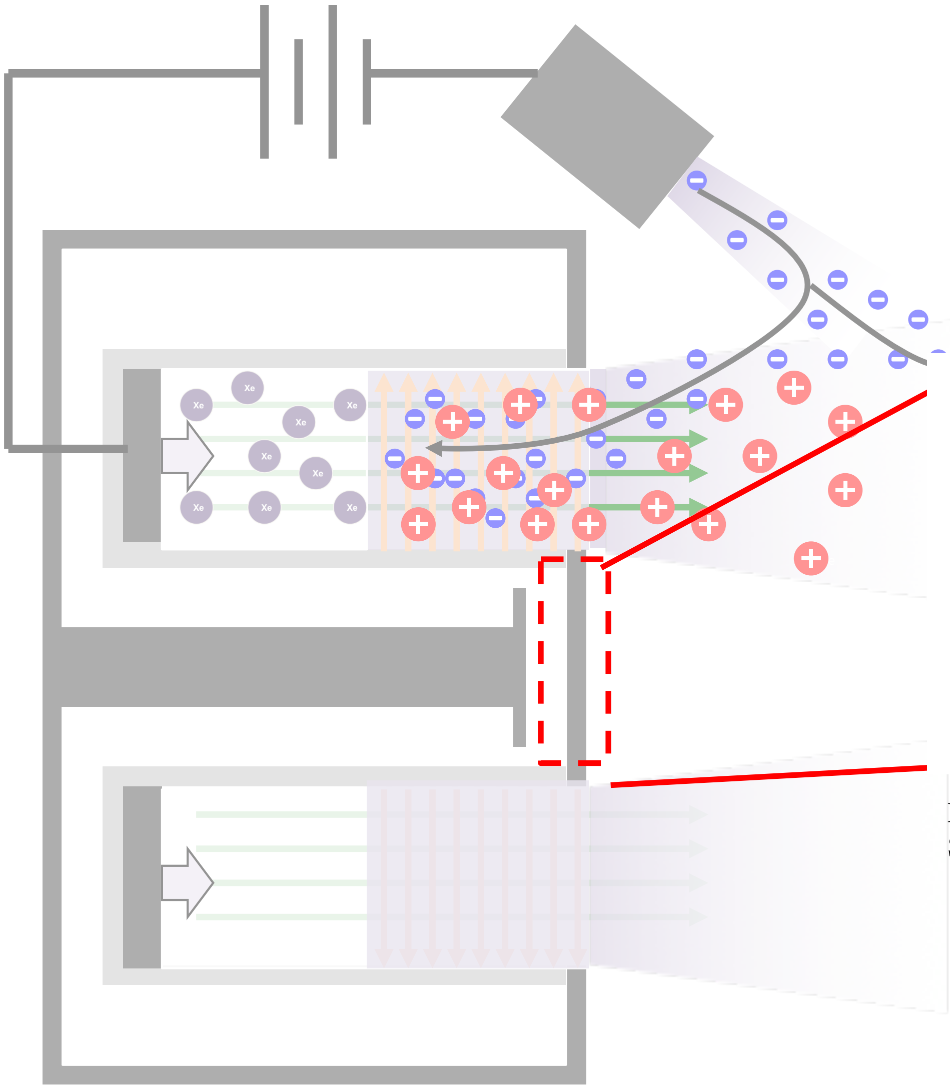
Hall thrusters work and currently fly on hundreds of spacecraft on orbit

However, there are key aspects of their operation that we do not understand

Anomalous Processes in Hall Thruster Operation



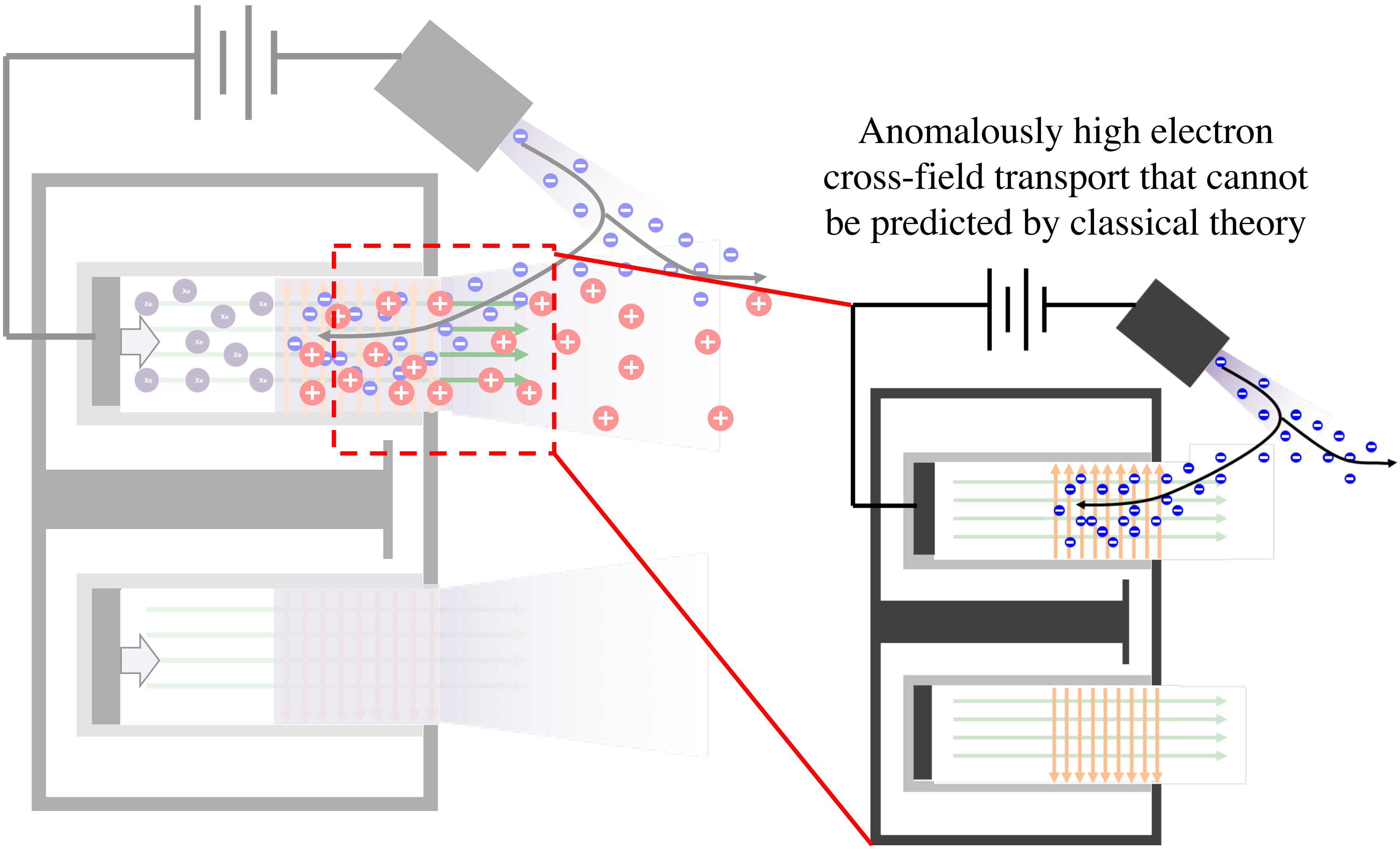
Anomalous Processes in Hall Thruster Operation



Unexplained erosion of downstream surfaces

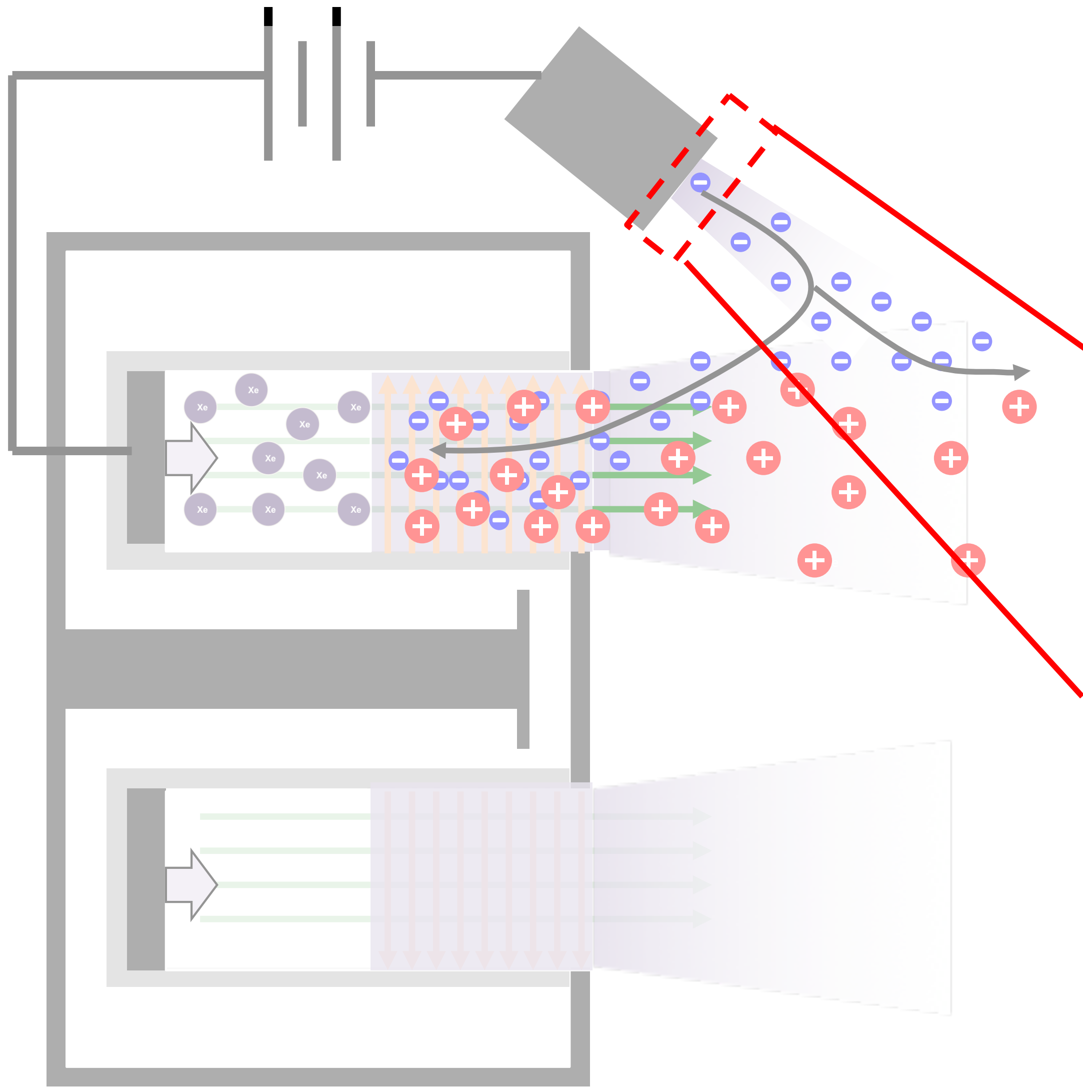
M. Sekerak et al. “Wear Testing of a Magnetically Shielded Hall Thruster at 2000 s Specific Impulse,” IEPC-2015-155.

Anomalous Processes in Hall Thruster Operation

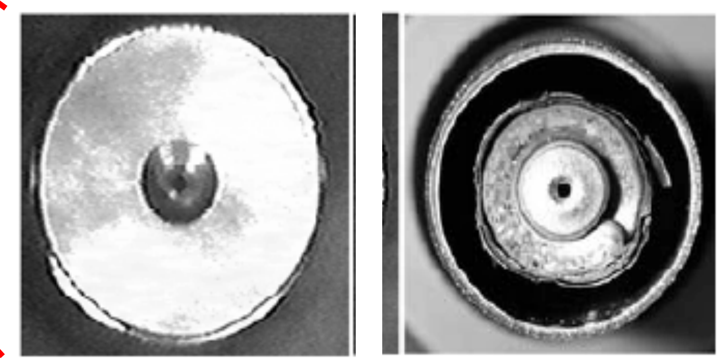


Anomalously high electron cross-field transport that cannot be predicted by classical theory

Anomalous Processes in Hall Thruster Operation



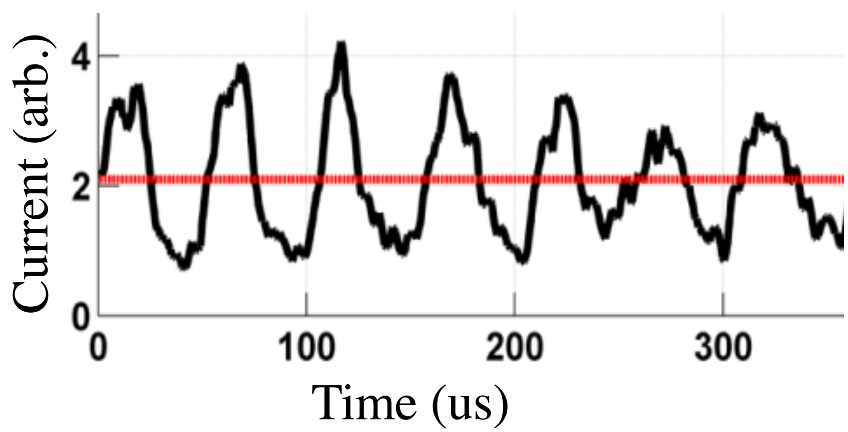
Unexplained erosion and electron transport in region of hollow cathode



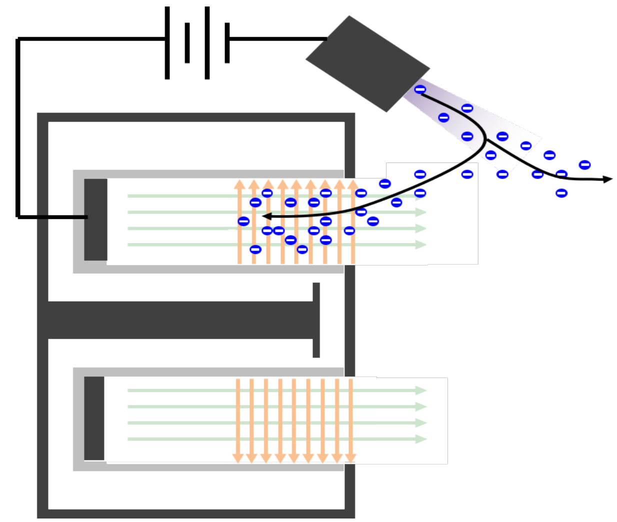
Sengupta, A., Brophy, J. R., and Goodfellow, K. D. AIAA 03-4558, July 2003.

Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

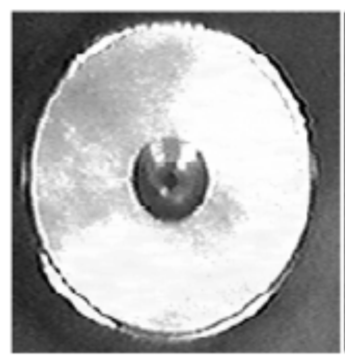


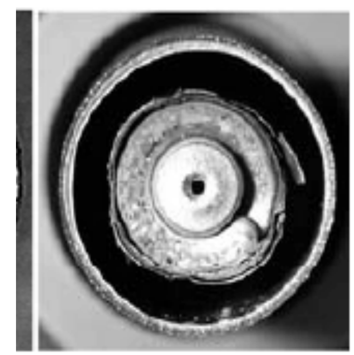
Cross-field transport



Thruster surface erosion

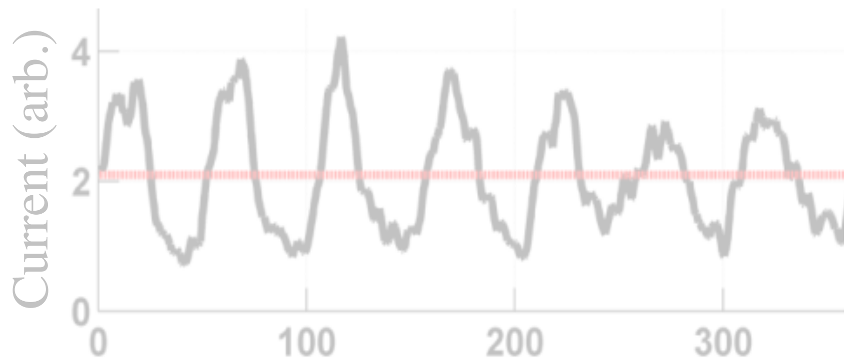
Cathode erosion and electron transport



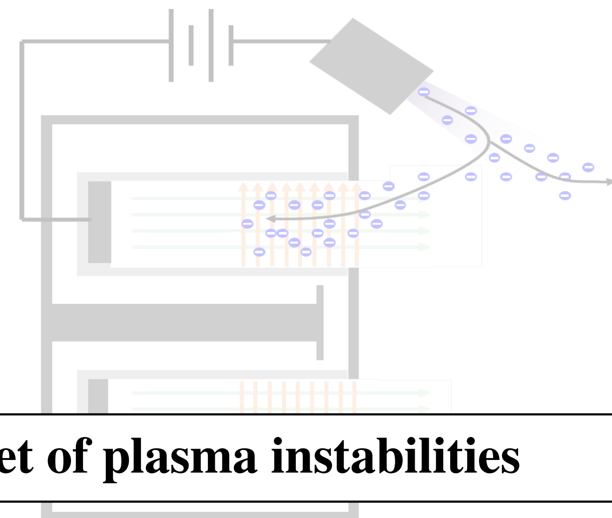


Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

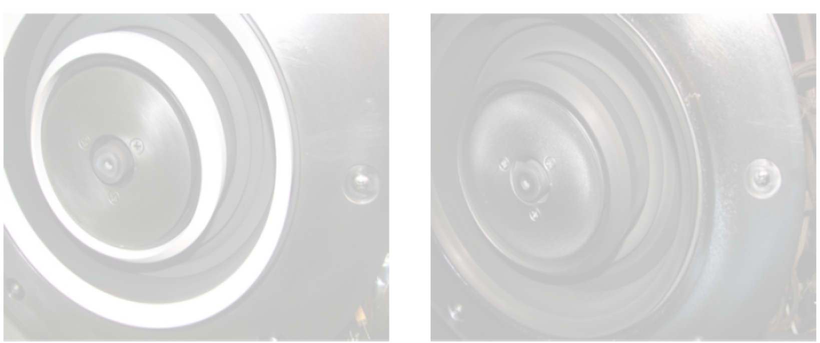


Cross-field transport

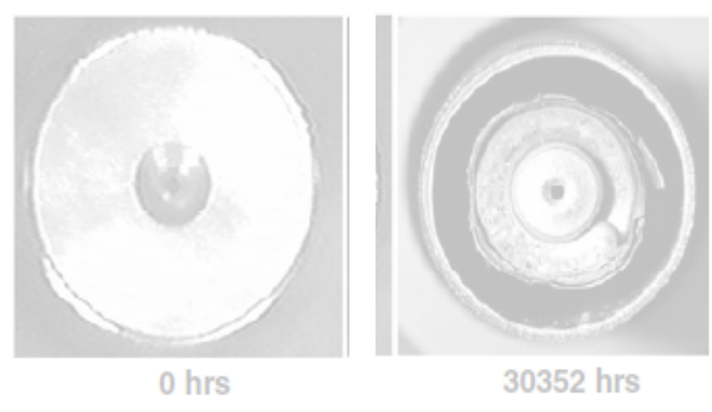


Each of these mechanisms is related to the onset of plasma instabilities

Thruster surface erosion

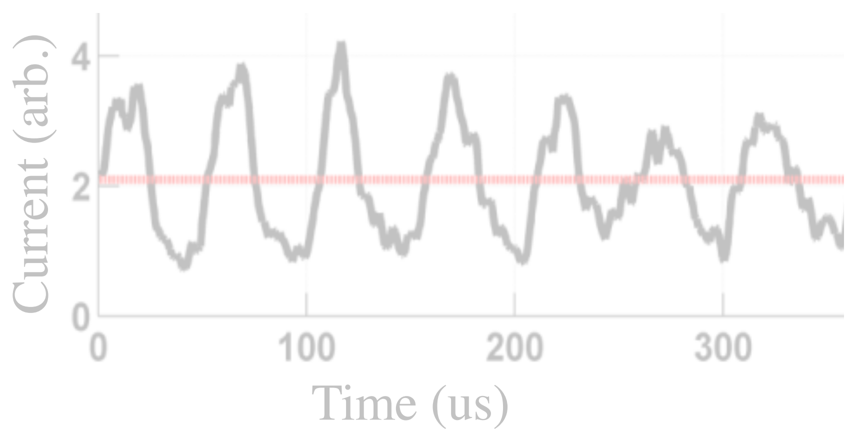


Cathode erosion and electron transport

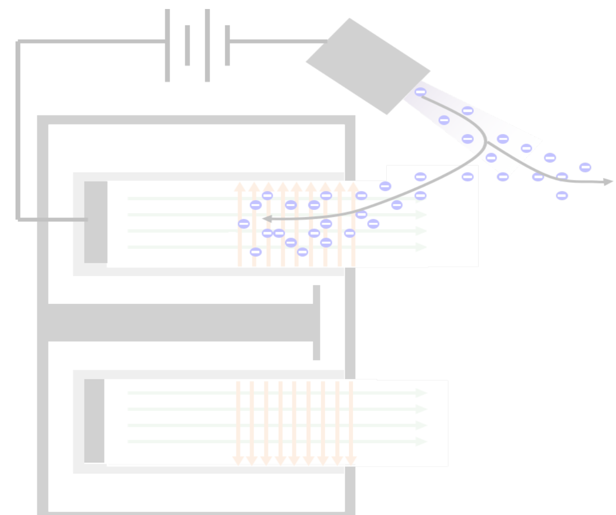


Anomalous Processes in Hall Thruster Operation

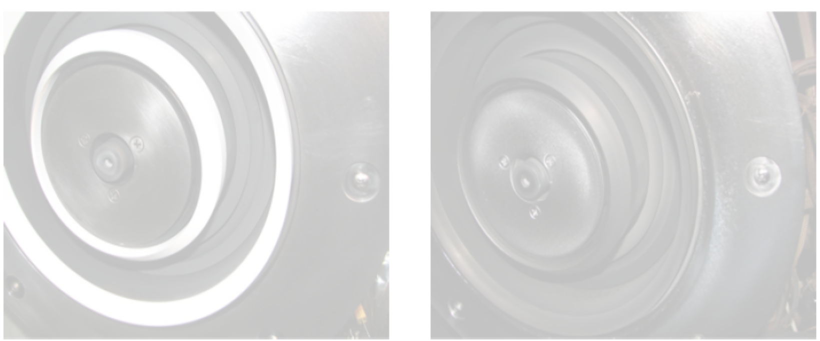
Onset of coherent, oscillatory modes



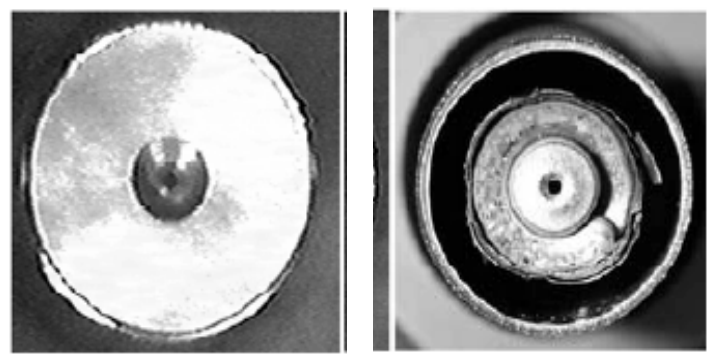
Cross-field transport



Thruster surface erosion



Cathode erosion and electron transport



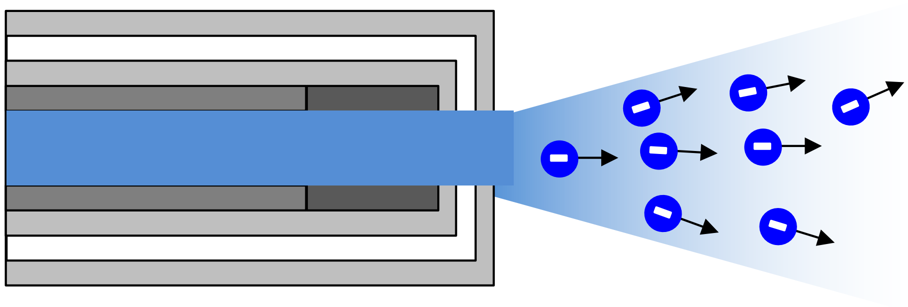
0 hrs   30352 hrs

Anomalous processes in the hollow cathode plume:

Cathode erosion

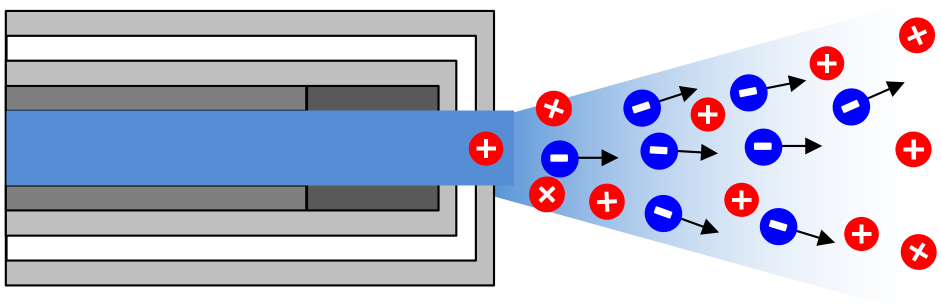
Non-classical electron resistivity

Anomalous ion heating leading to cathode erosion



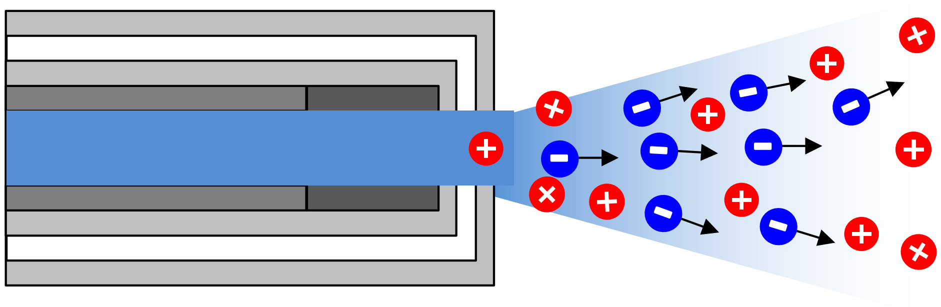
- Cathode is an electron source

Anomalous ion heating leading to cathode erosion



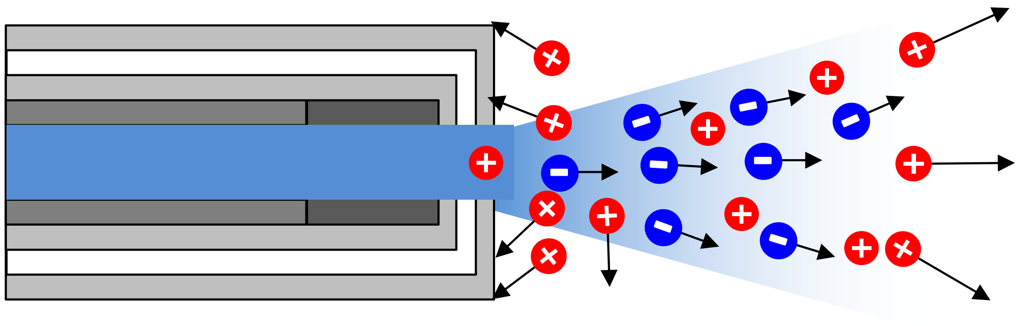
- Cathode is an electron source
- Plasma is quasineutral: electrons stream against background of ions

Anomalous ion heating leading to cathode erosion



- Cathode is an electron source
- Plasma is quasineutral: electrons stream against background of ions
- Classically, background ions should be low energy

Anomalous ion heating leading to cathode erosion



- Cathode is an electron source
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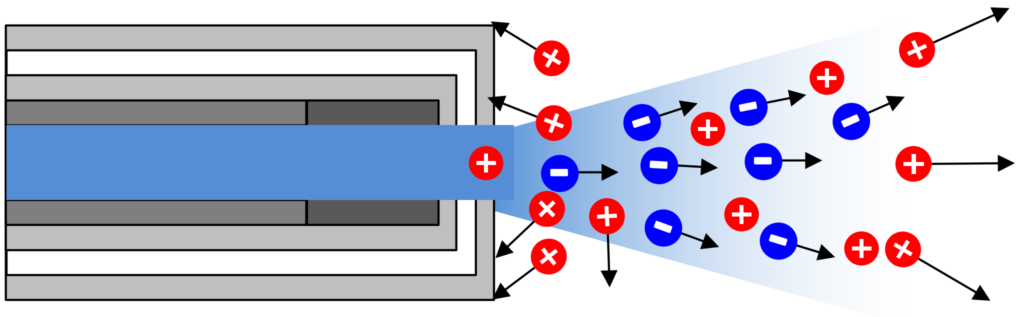
- However, *some unknown process* in plume accelerates ions to high and damage-causing energy

Anomalous ion heating leading to cathode erosion



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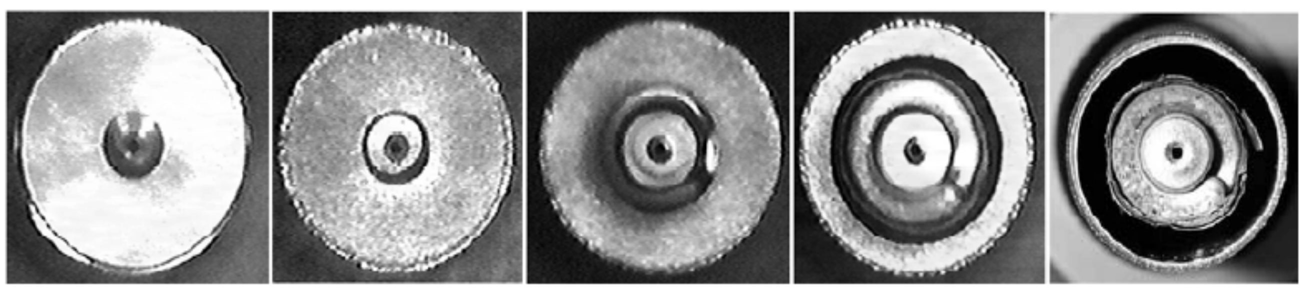
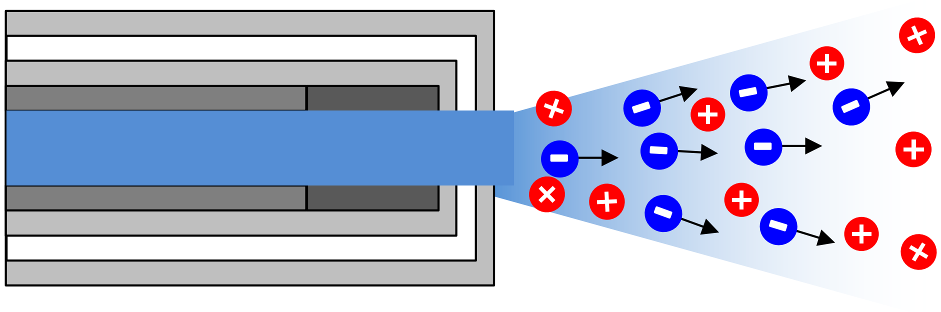
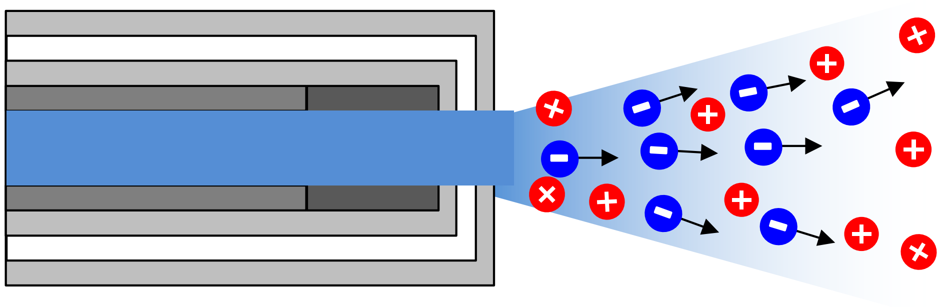


Fig. 2 Front view of the DHC keeper at various times during the 30,000 h ELT of a 30-cm ion thruster.

Anomalous electron resistivity

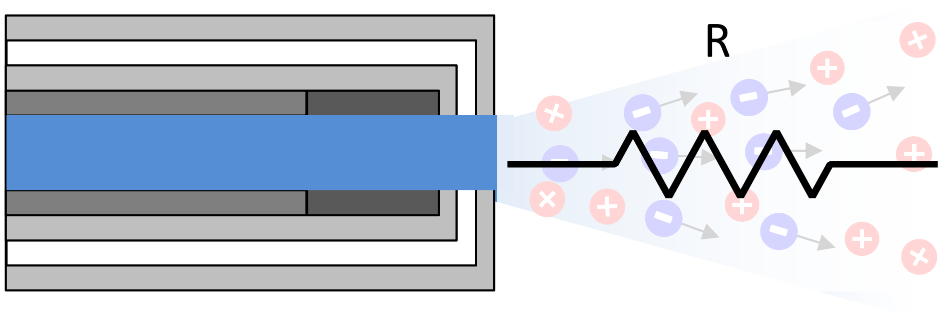


Anomalous electron resistivity



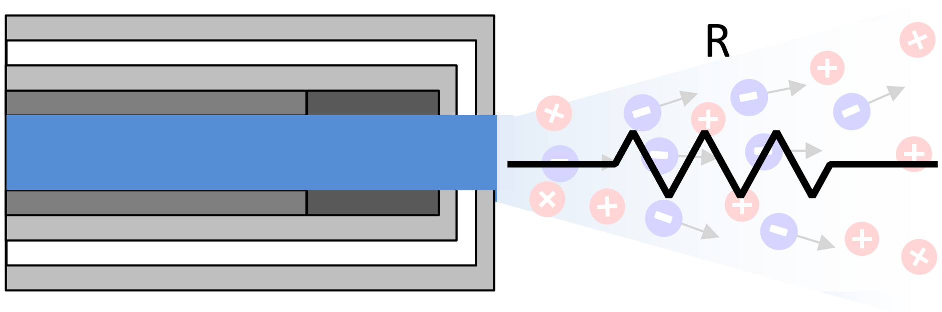
- Plasma current carried by electrons.

Anomalous electron resistivity



- Plasma current carried by electrons.
- Plasma has an inherent resistance which is classically due to collisions slowing down electron motion

Anomalous electron resistivity



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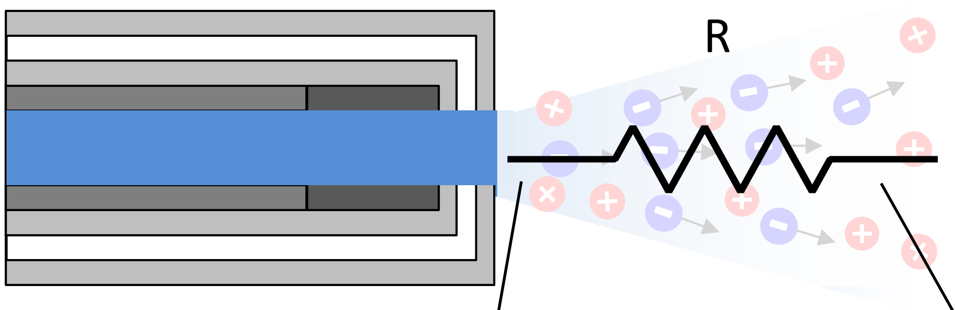
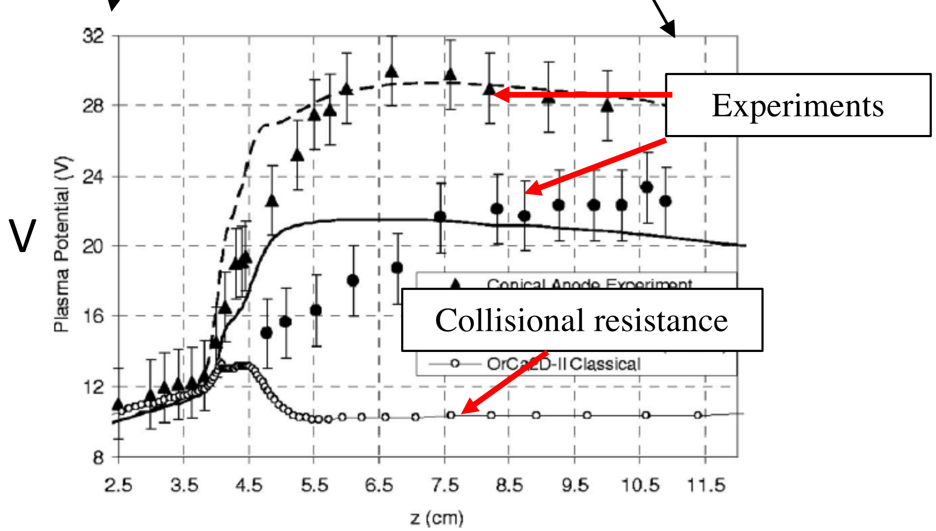
Anomalous electron resistivity

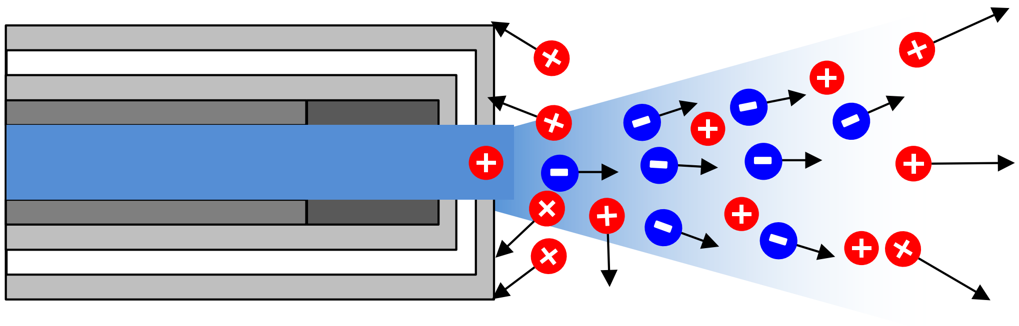


- Plasma current carried by electrons.
- Plasma has an inherent resistance which is classically due to collisions slowing down electron motion
- Some *unknown* mechanism provides additional drag on electrons: $R_{classical} << R_{experimental}$
- Plasma potentials higher in experiment than estimates based on classical, collisional theory

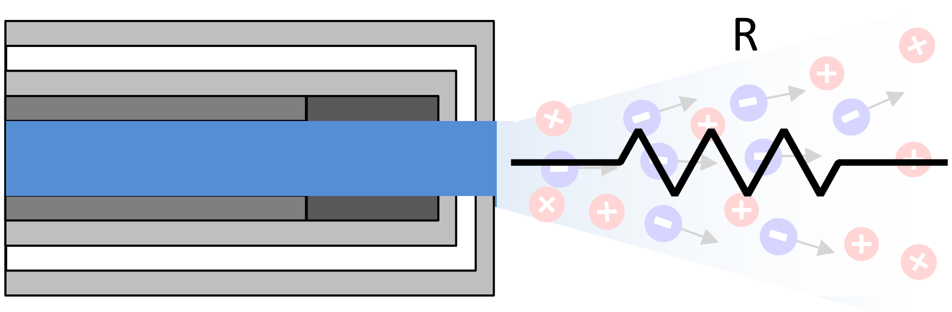


Mikellides, I., Katz, I., Goebel, D., Jameson, K. *JPP* 101, 063301 (2007)

Anomalous processes in hollow cathode

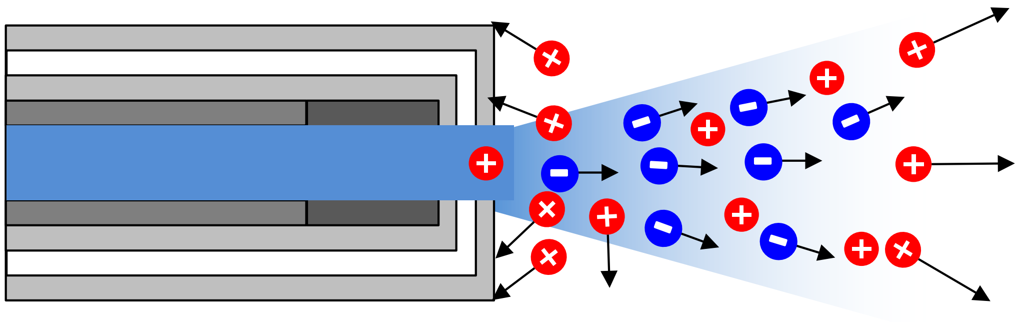


Unknown mechanism heats the ions



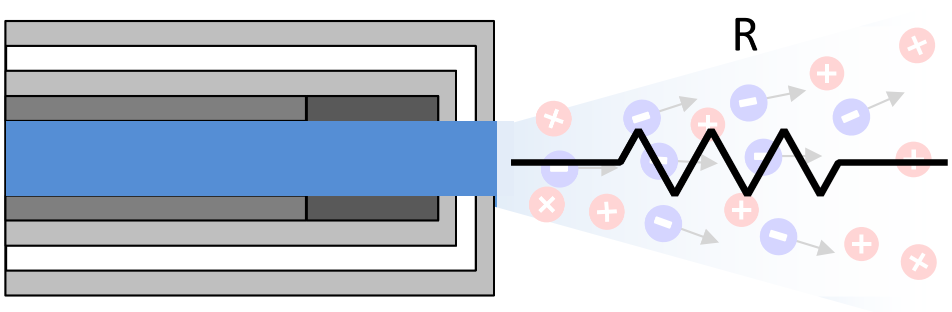
Unknown mechanism induces drag on electrons

Anomalous processes in hollow cathode



Unknown mechanism heats the ions

Hypothesis (2013): both mechanisms can be explained by the onset of ion acoustic turbulence in the cathode plume



Unknown mechanism induces drag on electrons

Ion Acoustic Turbulence

Ion --- Low frequency (1-5 MHz), electrostatic modes carried by ion motion

Acoustic --- Waves propagate with linear dispersion relation (frequency vs. wavenumber) at ion sound speed

Turbulence – Spectrum of incoherent modes excited concurrently in plume

Overview of Investigation into IAT Hypothesis (2013-2017)

- Start with a physical description of how IAT could lead to anomalous cathode plume effects
- Experimentally determine if described process actually occurs in cathode plume
- Incorporate findings into first-principles model to determine if anomalous effects can be explained self-consistently by IAT

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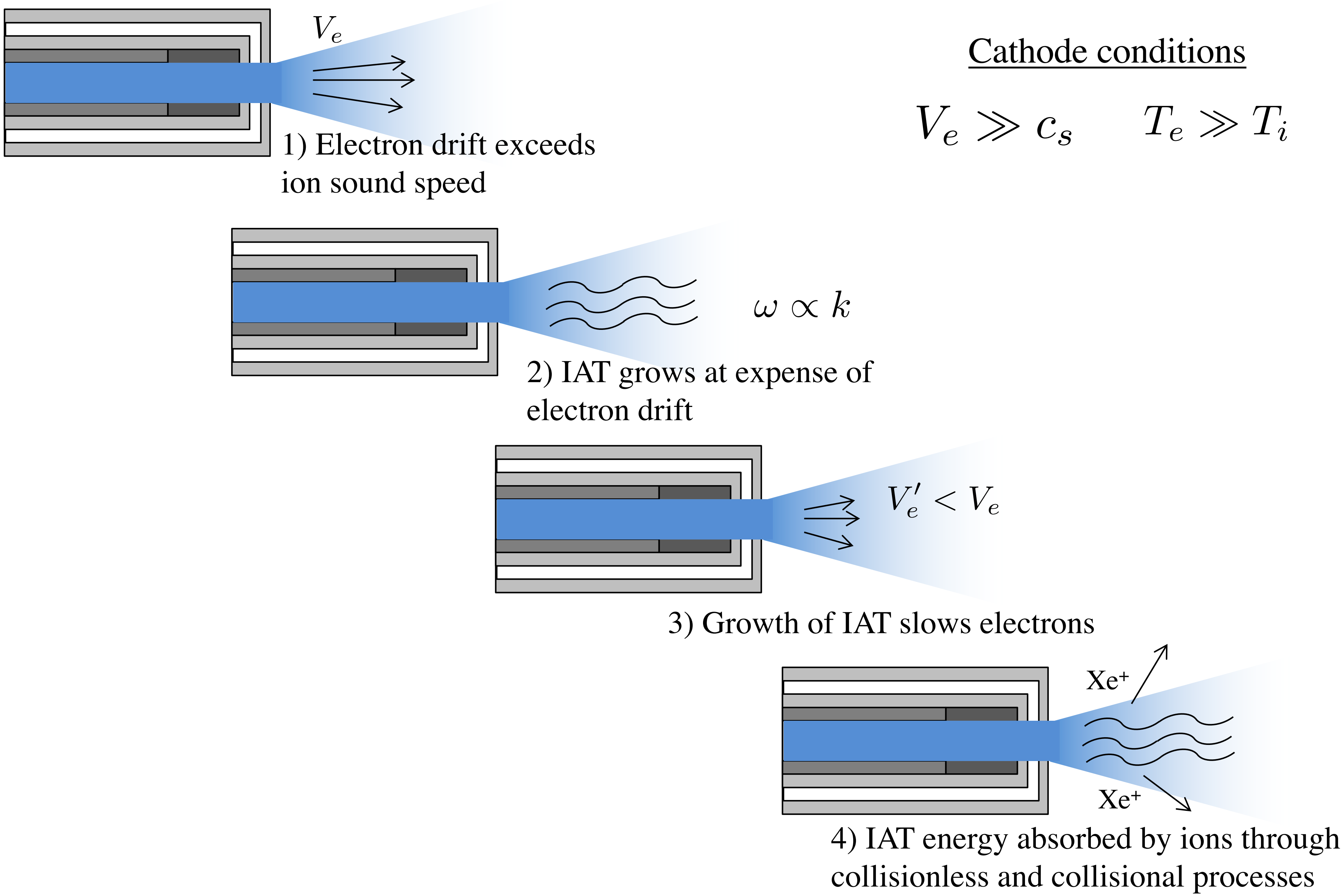
Ion Acoustic Turbulence (IAT) interaction with cathode plume



Cathode conditions

$$V_e \gg c_s \qquad T_e \gg T_i$$

Overview of Investigation into IAT Hypothesis (2013-2017)

- Start with a physical description of how IAT could lead to anomalous cathode plume effects

- Experimentally determine if described process actually occurs in cathode plume

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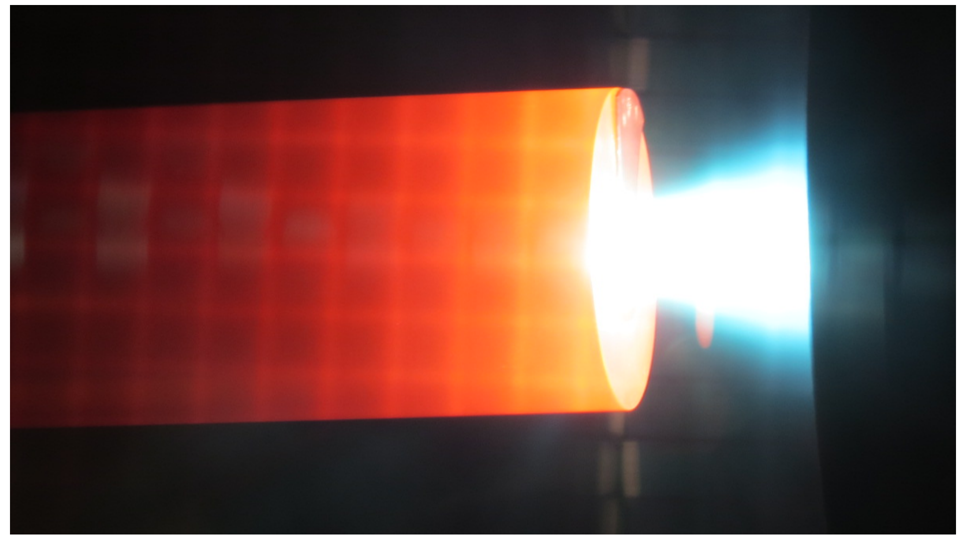
Experimental investigation into role of IAT

Diagnostic suite for cathode testing

Cathode firing



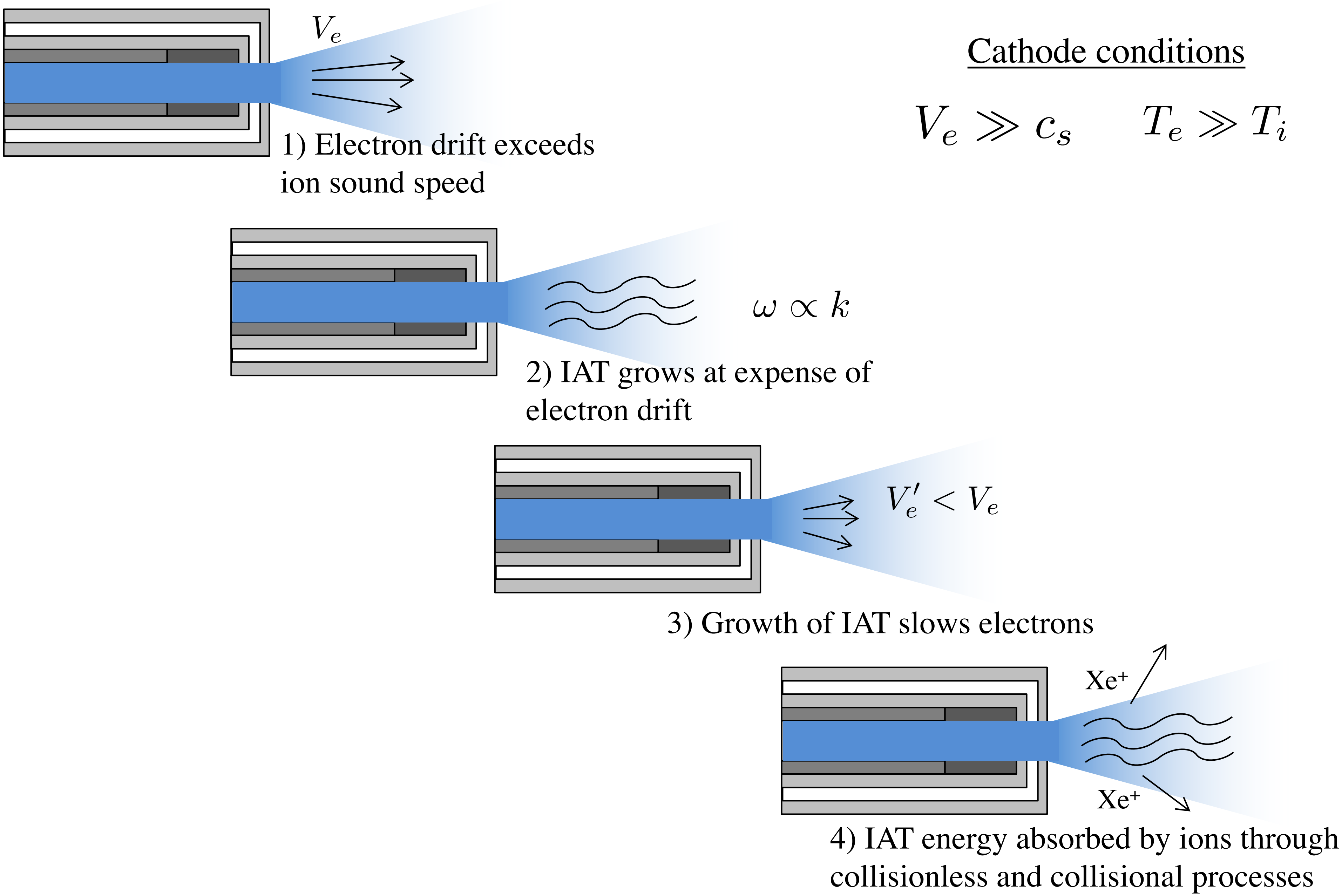
Diagnostics	
RPA	Ion energy
Single Langmuir probe	n_e, T_e
I_{sat} probe array	Wave dispersion
Laser Induced Fluorescence (LIF)	T_i and ion drift velocity

100-A LaB_6 Hollow Cathode	
Discharge Current	20 – 180 A
Flow rate	5, 8, 10, 12, 15, 20 sccm
Gas	Xe
Applied Magnetic Field	**None**
P_B	1-4 × 10^{-4} T

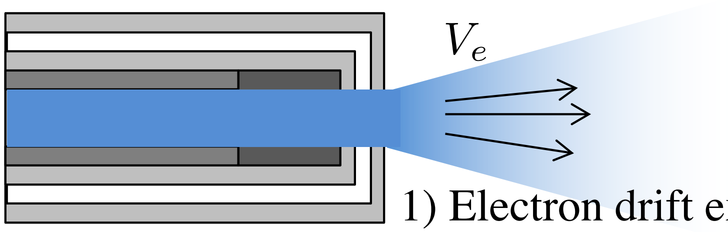
Experimental investigation into role of IAT

Cathode conditions

$$V_e \gg c_s \qquad T_e \gg T_i$$



Experimental investigation into role of IAT

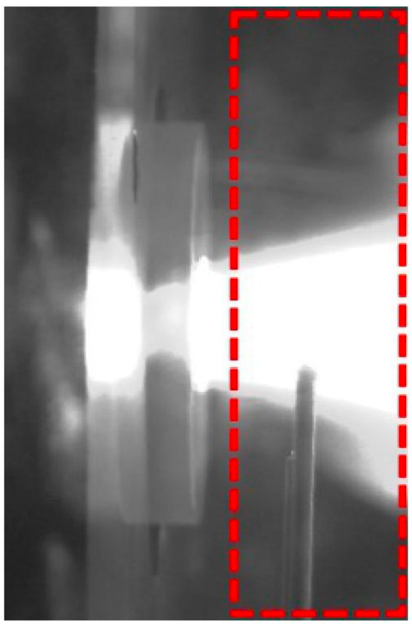


1) Electron drift exceeds ion sound speed

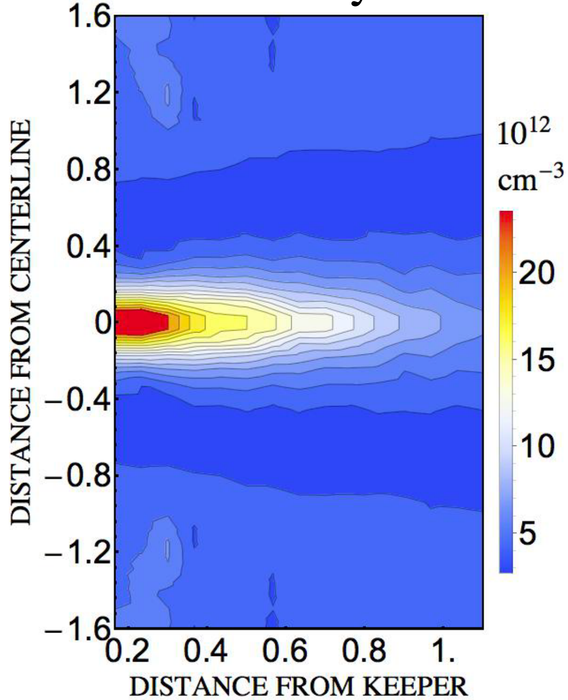
Cathode conditions

$V_e \gg c_s$ ✓ $\qquad T_e \gg T_i$ ✓

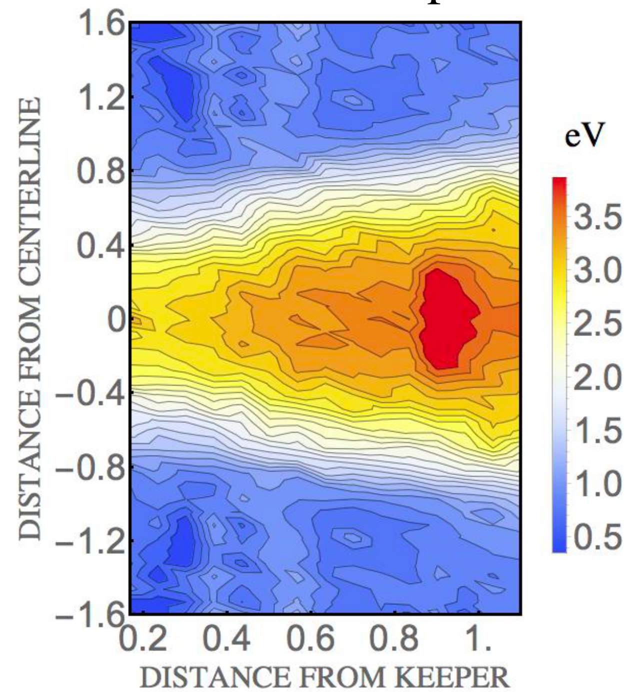
Photo



Density



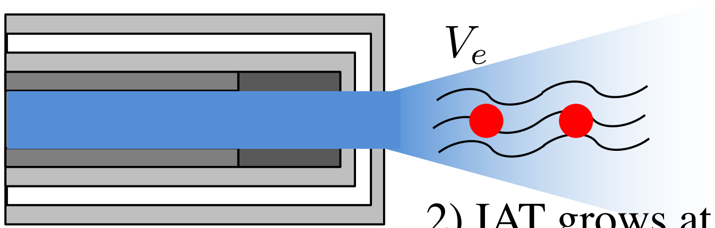
Electron temp.



140 A and 15 sccm xenon

B. Jorns, D. Goebel, and I. Mikellides. AIAA-2014-3826.

Experimental investigation into role of IAT

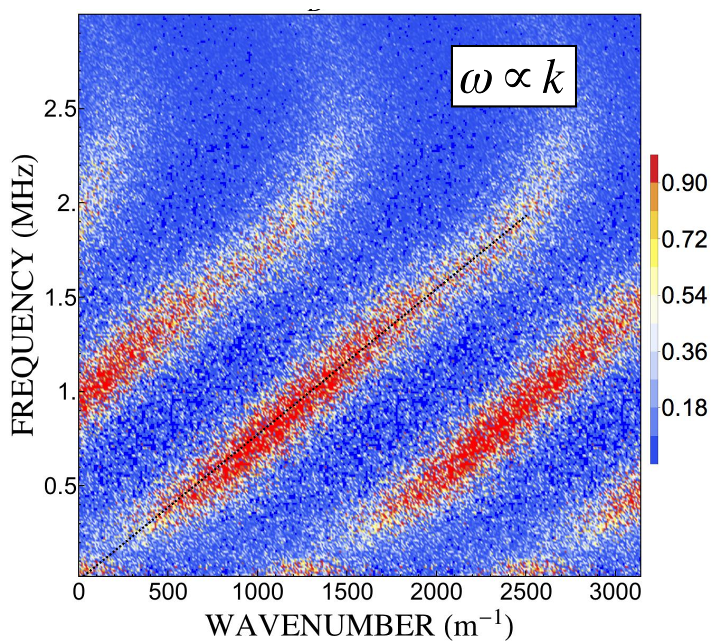


2) IAT grows at expense of electron drift

Quasi-linear theory

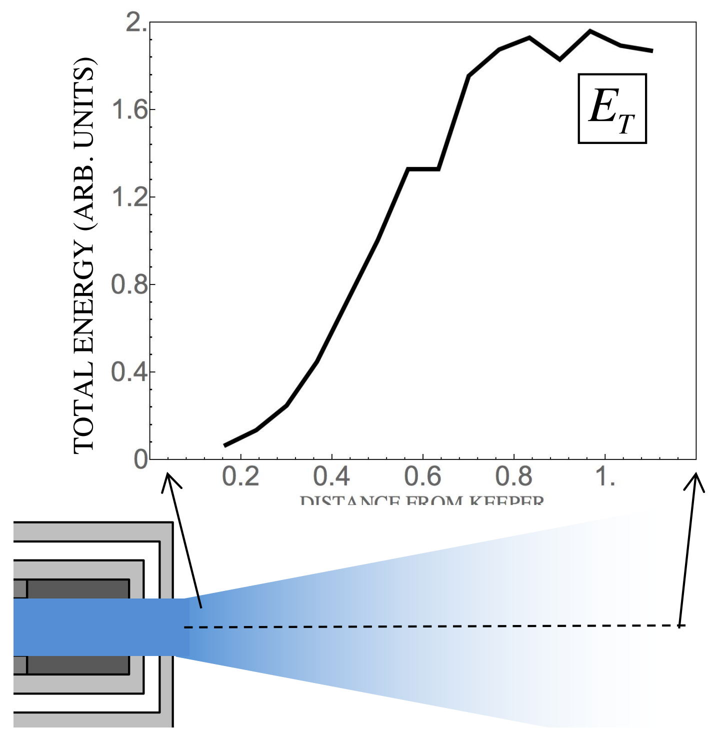
1) $\omega \propto k$ ✓ 2) $\frac{dE_T}{dt} \propto V_e E_T$ ✓

1) Measurement of dispersion relation in plume



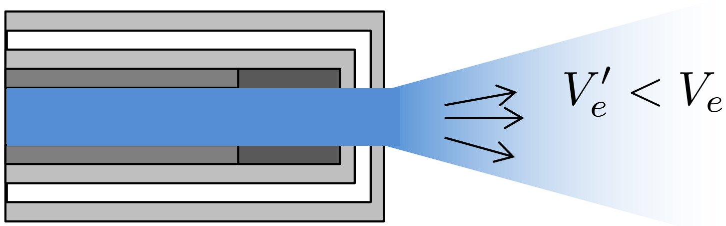
B. Jorns, I. Mikellides, and D. Goebel. Physical Review E 90, 063106. (2014).

2) Evolution of IAT energy in plume



B. Jorns, D. Goebel, and I. Mikellides. 50th AIAA JPC. AIAA-2014-3826.

Experimental investigation into role of IAT



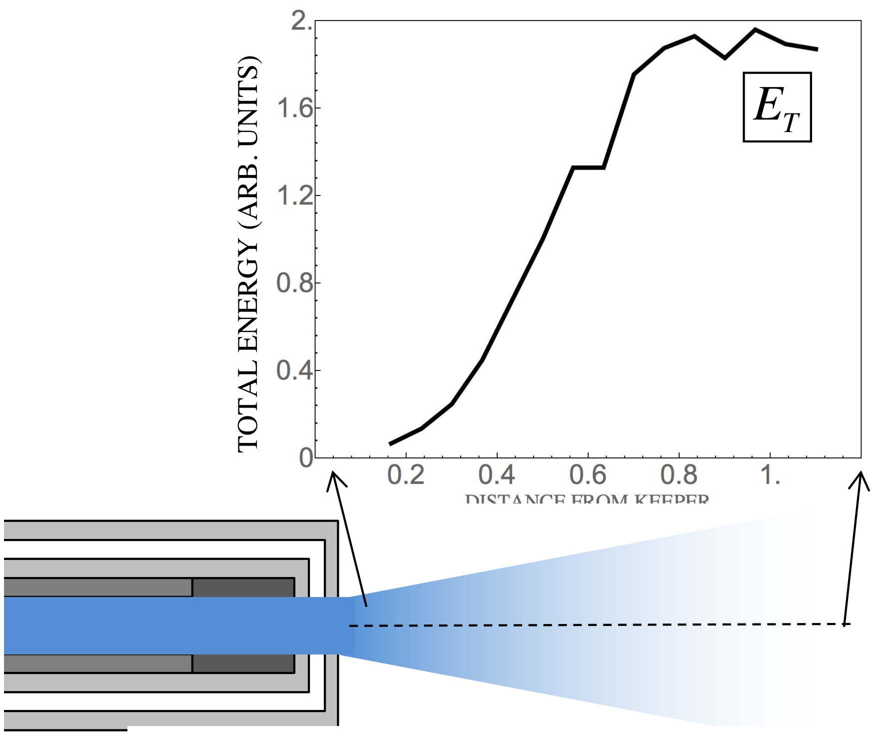
3) Growth of IAT slows electrons

Quasi-linear theory

✓

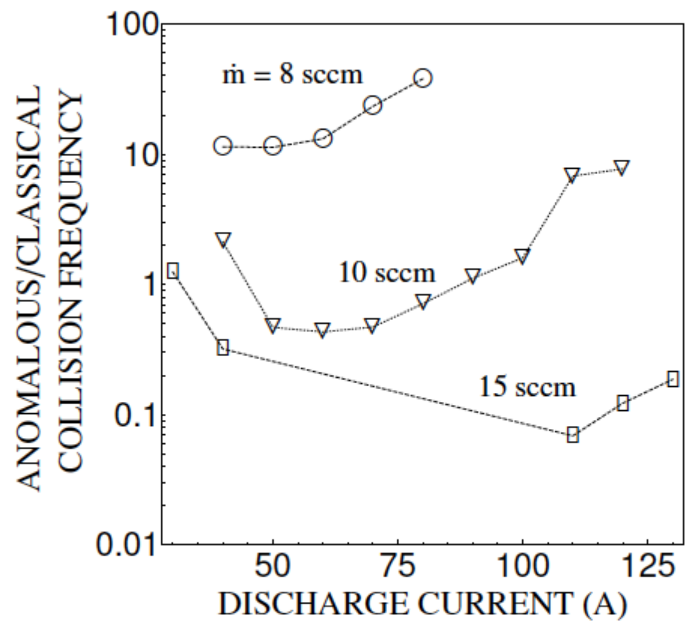
1) $\nu_{IAT} \propto E_T$ 2) $\nu_{IAT} > \nu_{classical}$

1) Use measured energy to infer effective collision frequency



B. Jorns, D. Goebel, and I. Mikellides. 50th AIAA JPC. AIAA-2014-3826.

2) Compare IAT driven collision frequency to classical collisions



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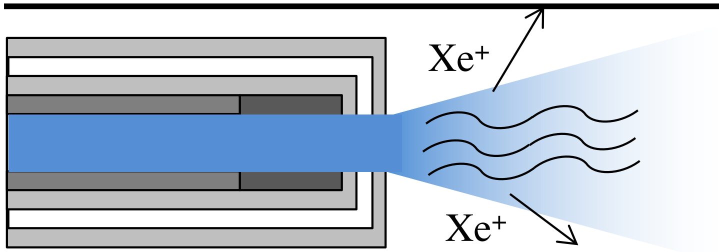
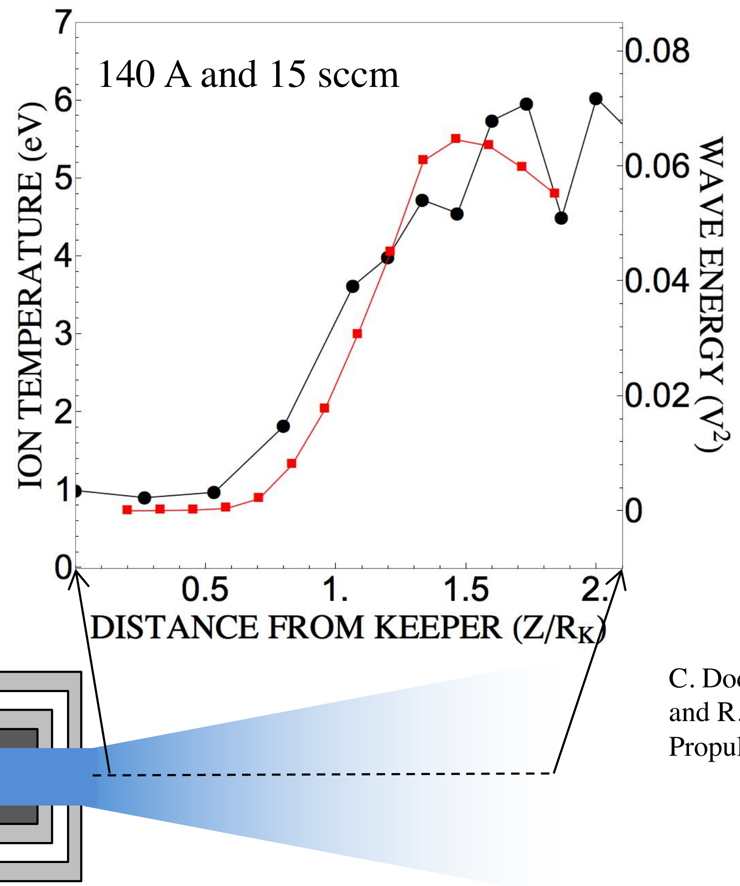


4) IAT energy absorbed by ions through collisionless and collisional processes

Quasi-linear theory

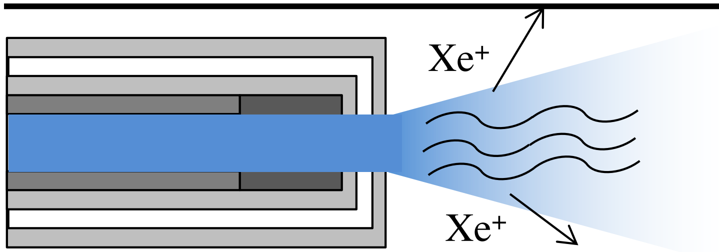
$$\Delta T_i \propto E_T$$

Measured **wave energy** and **ion temperature** as functions of position



C. Dodson, D. Perez-Grande, B. Jorns, D. M. Goebel, and R. E. Wirz, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016. AIAA 2016-4838.

Experimental investigation into role of IAT



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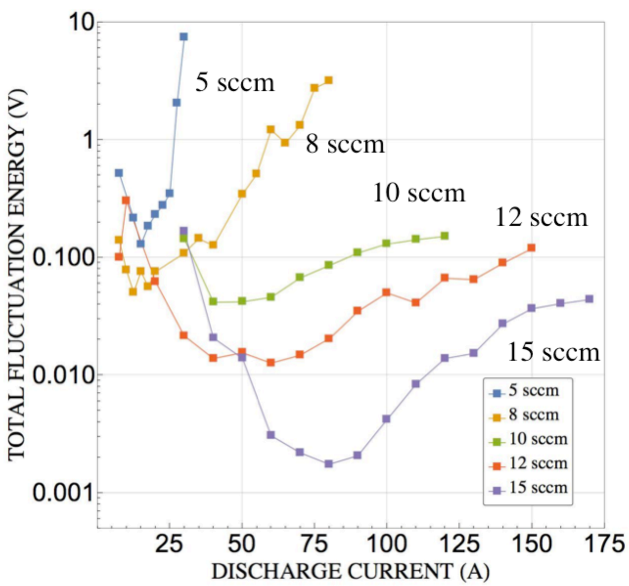
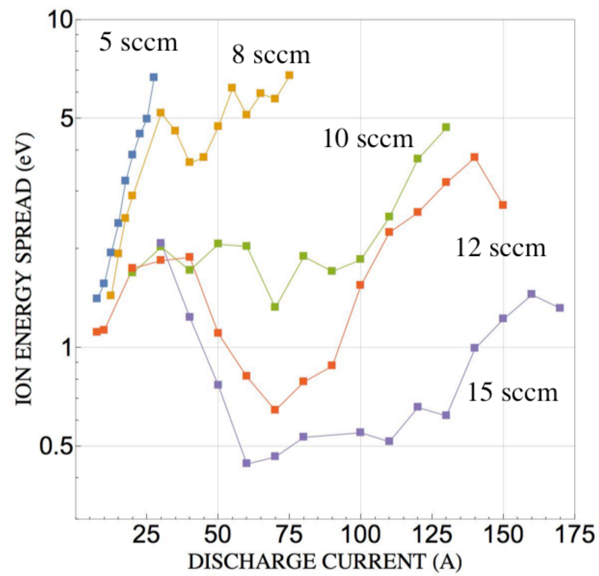
$$\Delta T_i \propto E_T \quad ✓$$

Measured wave energy at single point

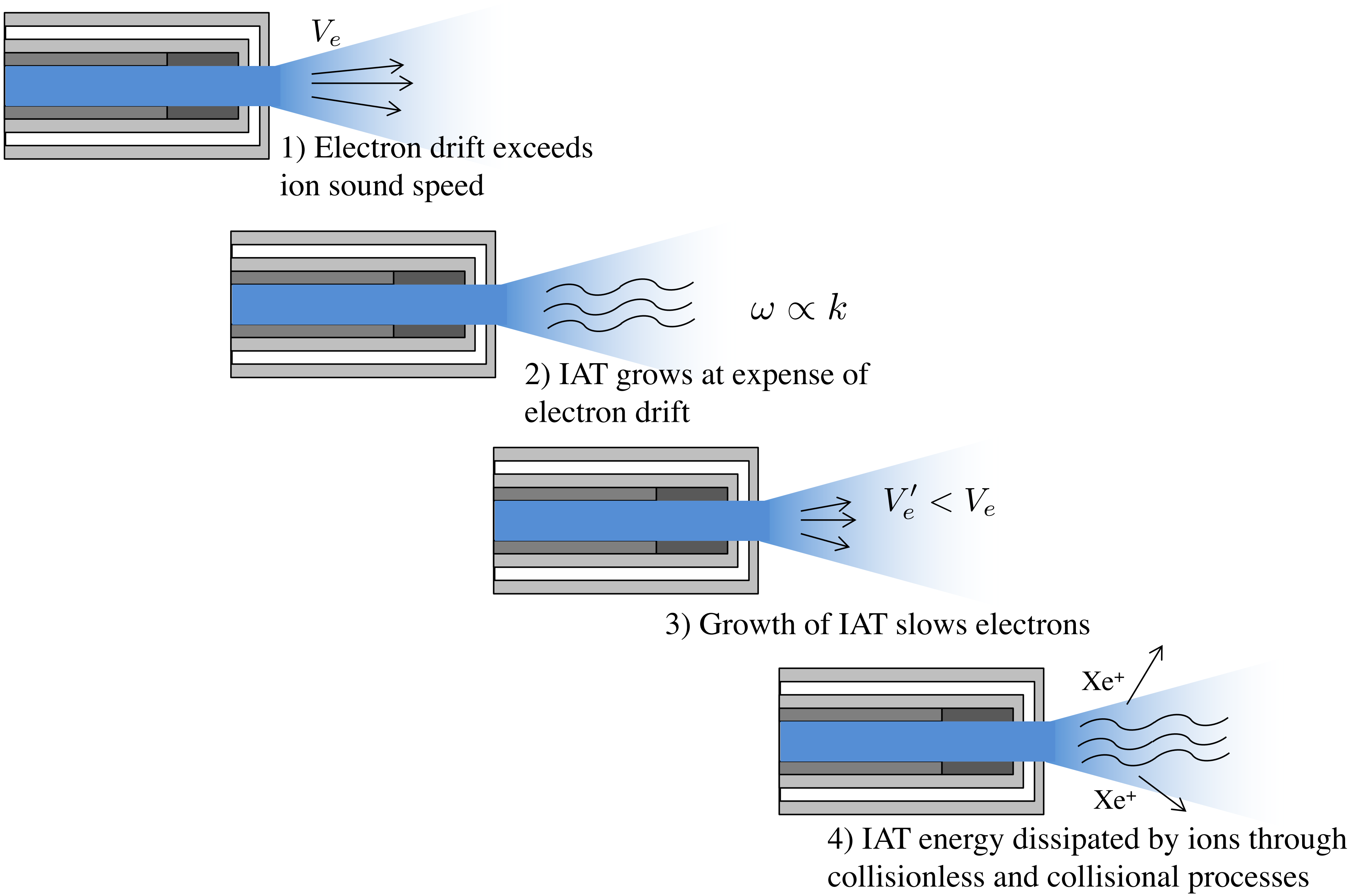


Measured ion energy at single point



Correlational and causal relationship between IAT and energetic ions persists over wide parameter space

Experimental investigation into role of IAT



Overview of Investigation into IAT Hypothesis (2013-2017)

- Start with a physical description of how IAT could lead to anomalous cathode plume effects
- Experimentally determine if described process actually occurs in cathode plume
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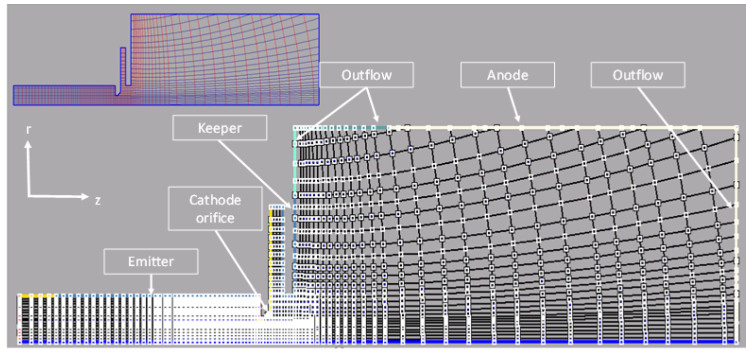
Modeling impact of IAT on plasma properties

Simulation



Governing equations

Continuity
$$\frac{dn_s}{dt} + n_s \nabla \cdot \mathbf{V}_s = 0,$$

Momentum
$$m_s n_s \frac{d\mathbf{V}_s}{dt} + \nabla \cdot \mathbf{p}_s - e_s n_s (\mathbf{E} + \mathbf{V}_s \times \mathbf{B}) = \mathbf{F}_s, \quad + F_{s(AN)}(E_T)$$

Energy
$$\frac{3}{2}\frac{dp_s}{dt} + \frac{3}{2} p_s \nabla \cdot \mathbf{V}_s + \mathbf{p}_s : \nabla \mathbf{V}_s + \nabla \cdot \mathbf{q}_s = W_s. \quad + W_{s(AN)}(E_T)$$

Wave energy
$$\frac{\partial E_T}{\partial t} + \vec{v}_g \cdot \nabla E_T = \omega_0 E_T \left[\zeta_e - \zeta_i - \frac{\nu_i}{\omega_0} \right]$$

"Drag"

"Heating"

Derived from quasilinear theory

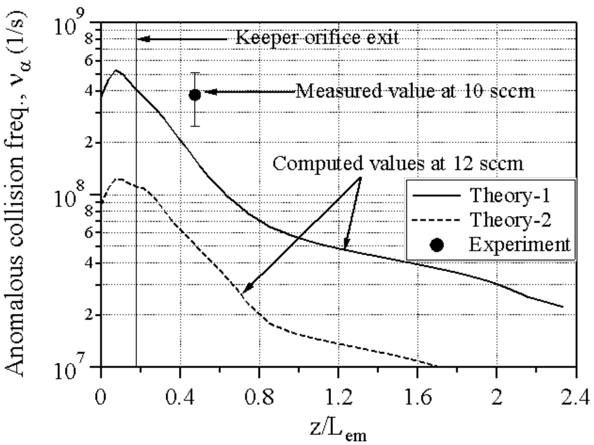
B. Jorns, A. Lopez Ortega, and I. G. Mikellides, 52nd AIAA Joint Propulsion, 2016. AIAA 2016-4626.

A. Lopez Ortega, B. Jorns, and I. Mikellides, Journal of Propulsion and Power Submitted (2017).

Validating IAT-based terms on plasma properties

Drag

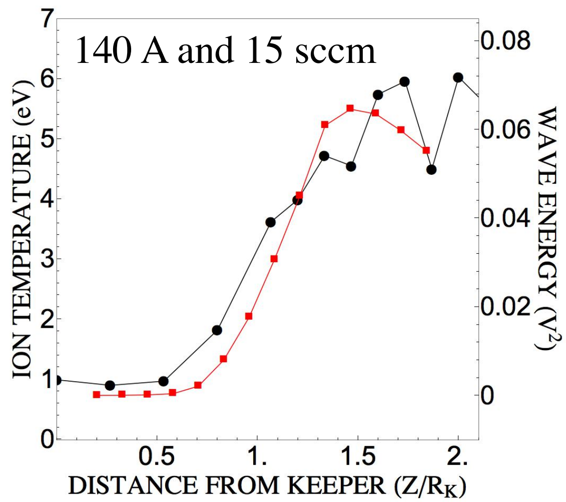
$F_{s(AN)}(E_T)$



I. Mikellides, D. Goebel, B. Jorns , J. Polk, and P. Guerrero. IEEE Transactions on Plasma Science 43 (1). 173-184 (2015).

Heating

$W_{s(AN)}(E_T)$



C. Dodson, D. Perez-Grande, B. Jorns, D. M. Goebel, and R. E. Wirz, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016. AIAA 2016-4838.

Wave energy

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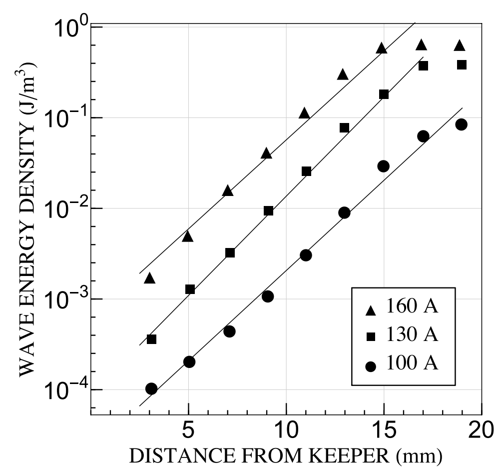
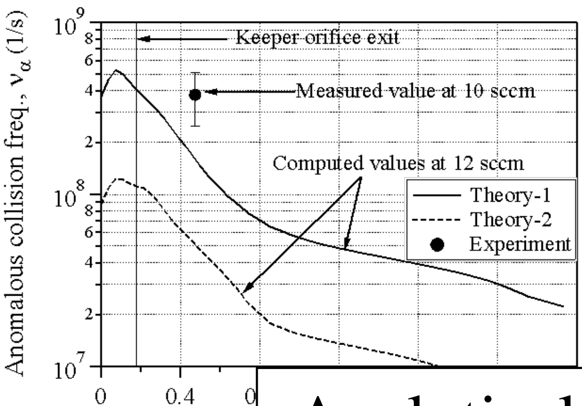


B. Jorns et al. Physical Review E. **Submitted**

Validating IAT-based terms on plasma properties

Drag

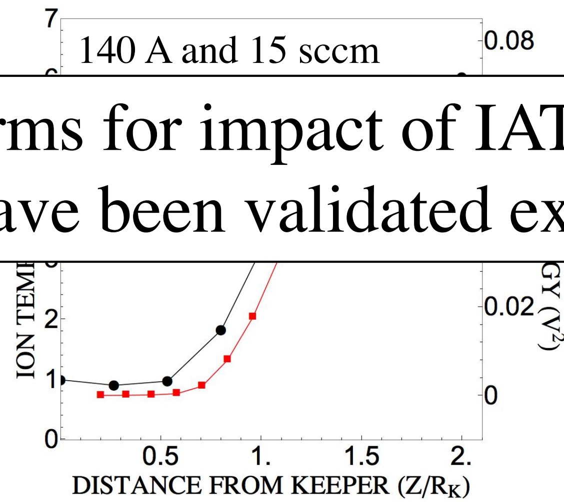
$F_{s(AN)}(E_T)$



I. Mikellides, D. Go… Guerrero. IEEE Tra… (1). 173-184 (2015)

Heating

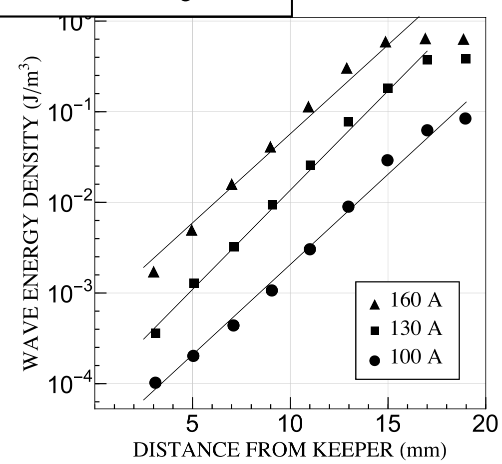
$W_{s(AN)}(E_T)$



C. Dodson, D. Perez-Grande, B. Jorns, D. M. Goebel, and R. E. Wirz, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016. AIAA 2016-4838.

Wave energy

$E_T \left[\zeta_e - \zeta_i - \frac{\nu_i}{\omega_0}\right]$

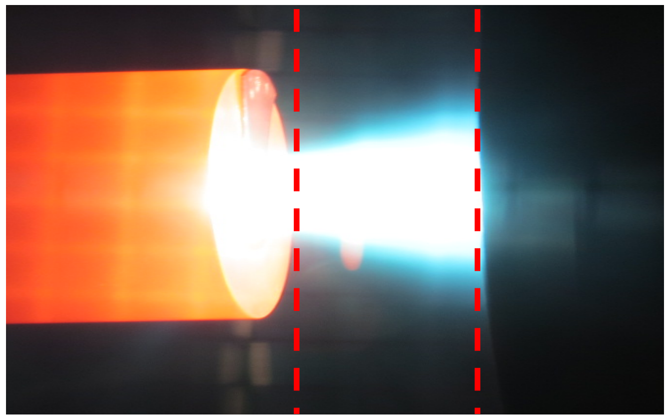


B. Jorns et al. Physical Review E. **Submitted**

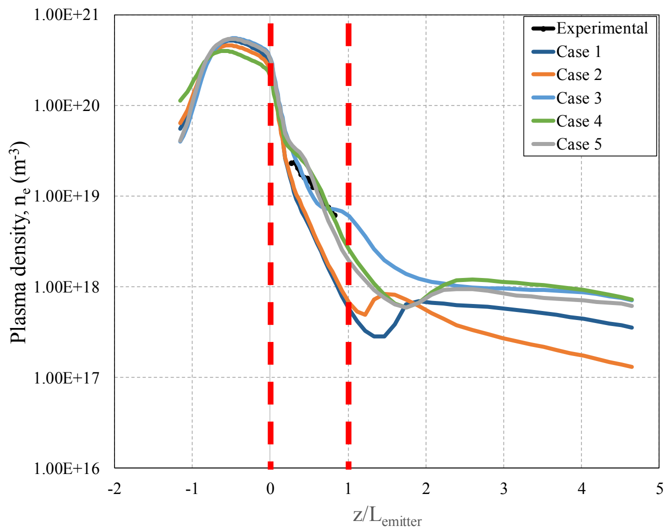
Analytical terms for impact of IAT on governing equations have been validated experimentally

Self-consistent predictive model that includes anomalous effects

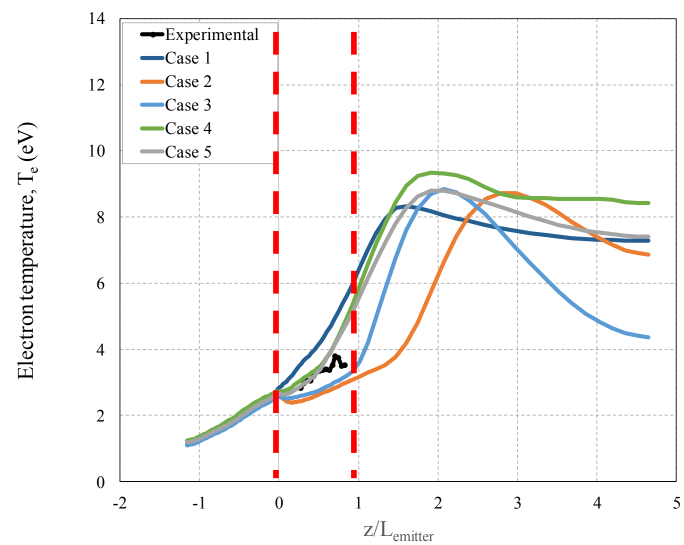
140 A and 10 sccm



Density on centerline



Temperature on centerline



A. Lopez Ortega, B. Jorns, and I. Mikellides. Journal or Propulsion and Power. *Submitted*

Overview of Investigation into IAT Hypothesis (2013-2017)

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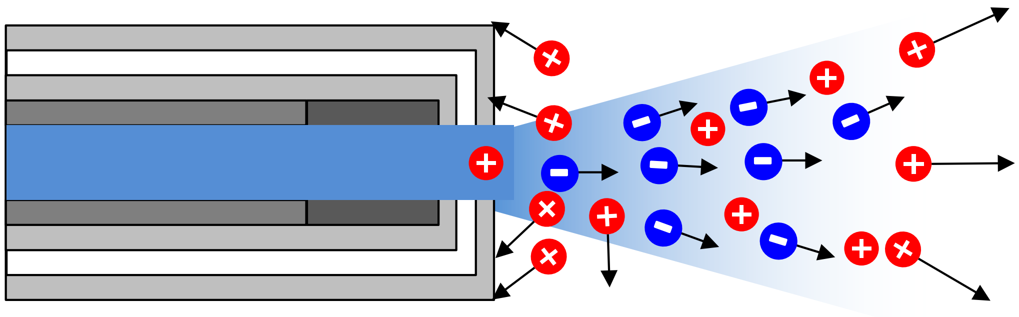
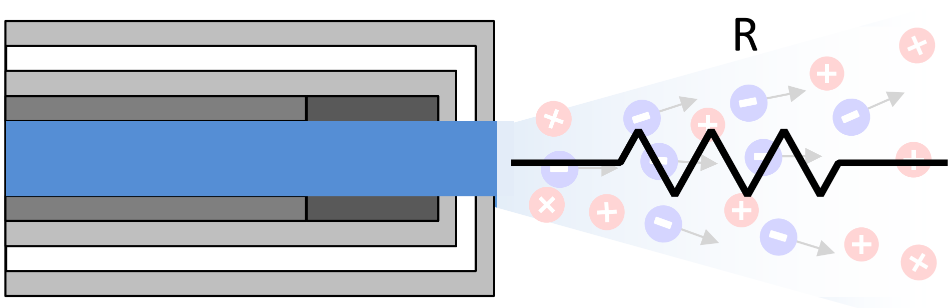
Anomalous processes in hollow cathode



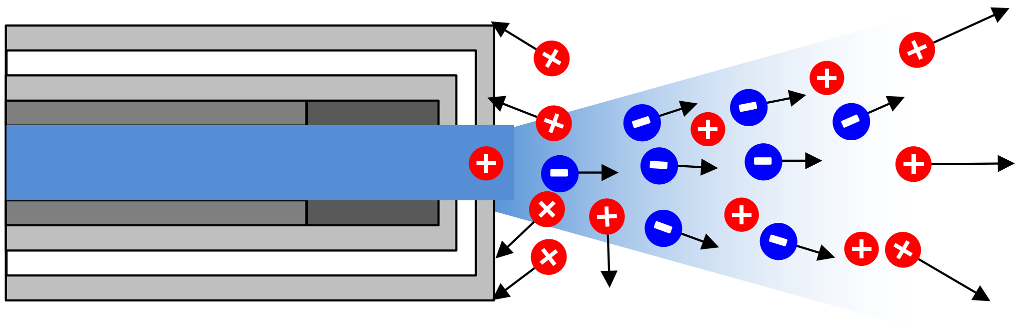
Unknown mechanism heats the ions

Hypothesis (2013): both mechanisms can be explained by the onset of ion acoustic turbulence in the cathode plume



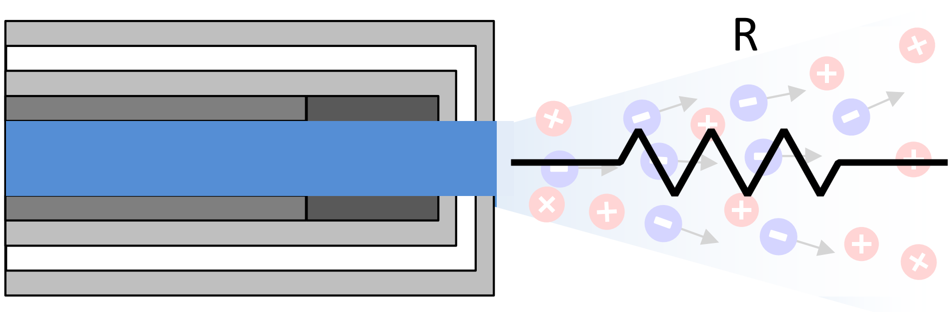
Unknown mechanism induces drag on electrons

Anomalous processes in hollow cathode



Unknown mechanism heats the ions

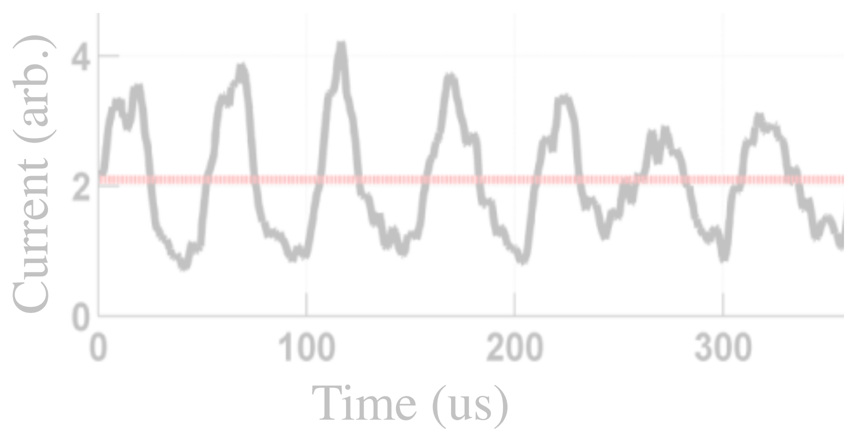
Validated theory (2017): both mechanisms can be explained by the onset of ion acoustic turbulence in the cathode plume



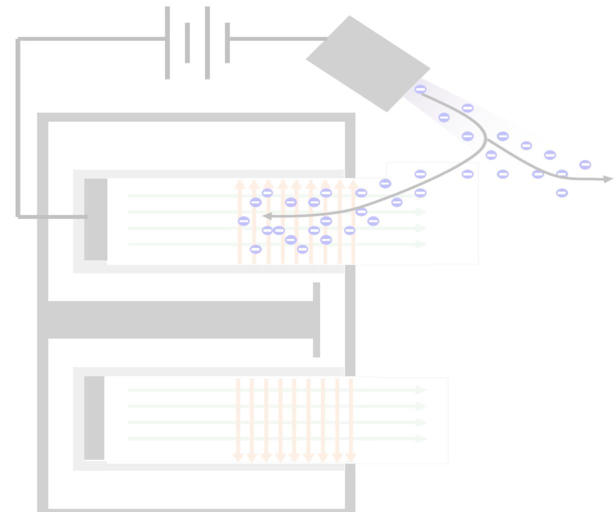
Unknown mechanism induces drag on electrons

Anomalous Processes in Hall Thruster Operation

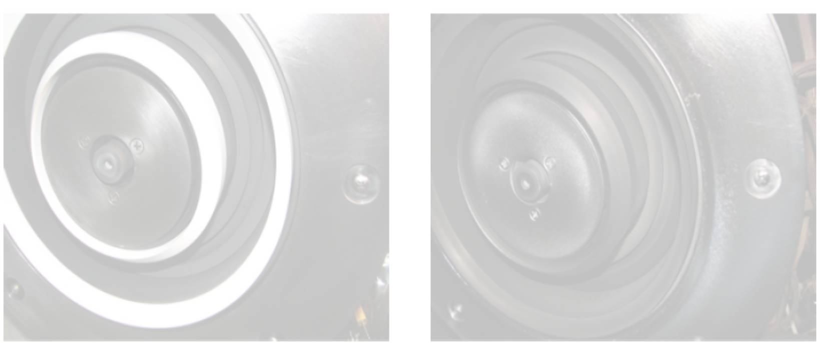
Onset of coherent, oscillatory modes



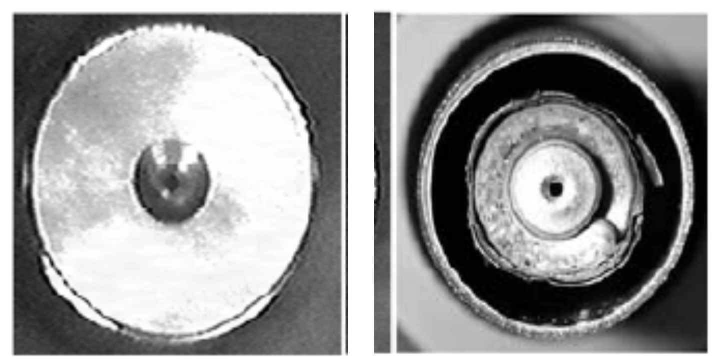
Cross-field transport



Thruster surface erosion



Cathode erosion and electron transport

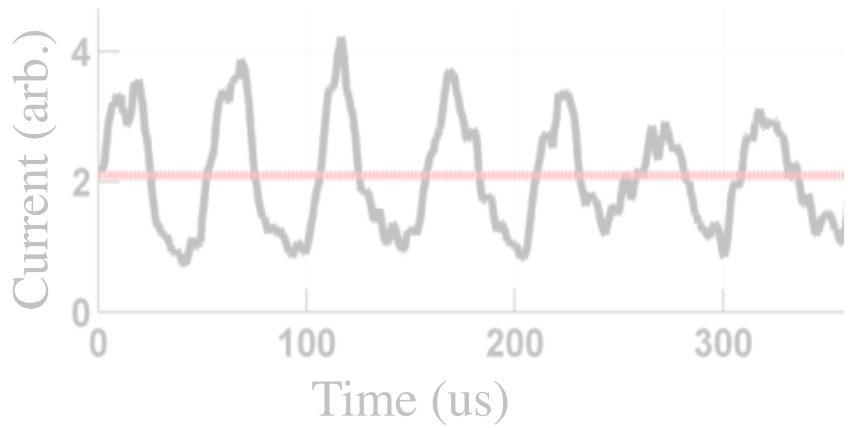


0 hrs

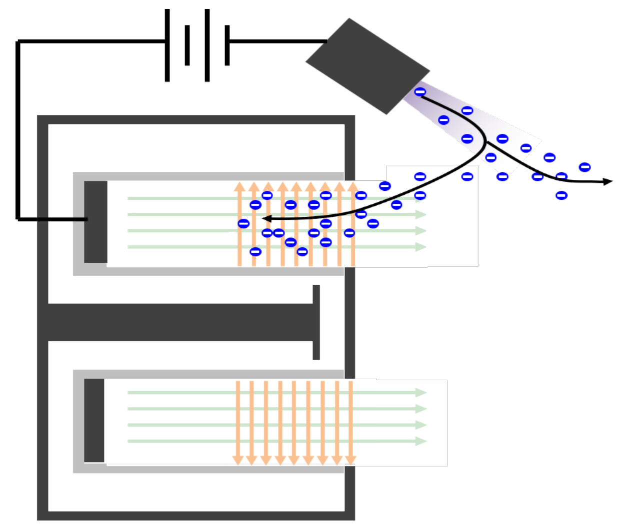
30352 hrs

Anomalous Processes in Hall Thruster Operation

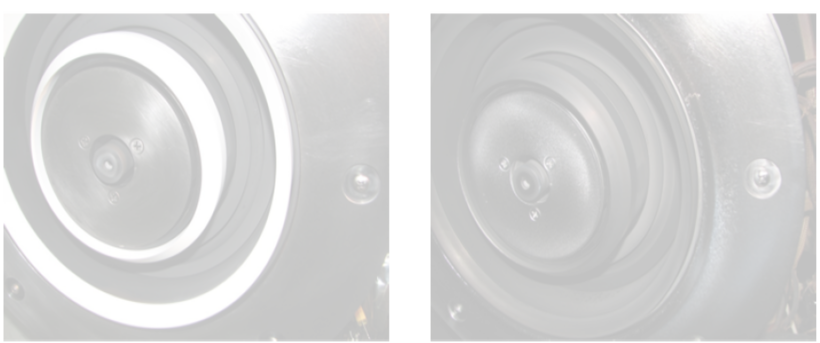
Onset of coherent, oscillatory modes



Cross-field transport



Thruster surface erosion



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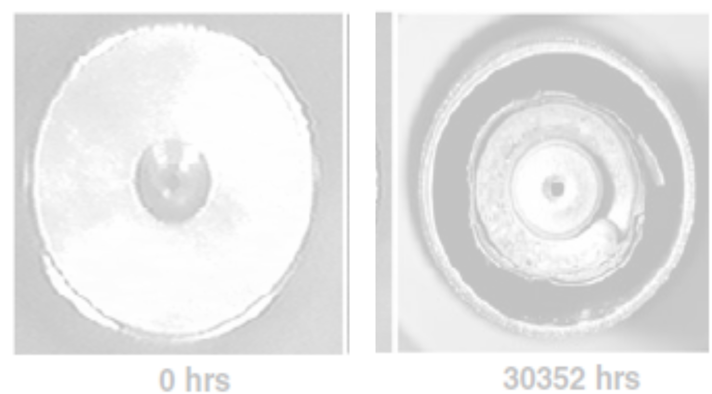
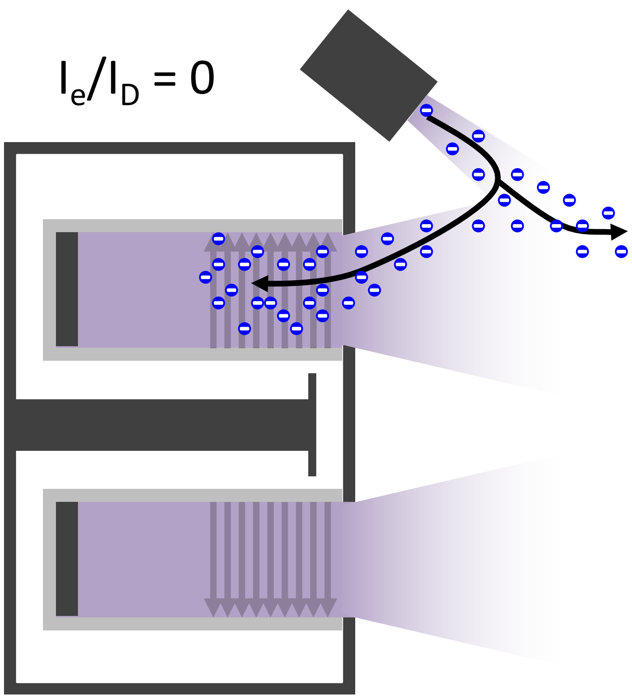


The Problem of Anomalous Electron Transport

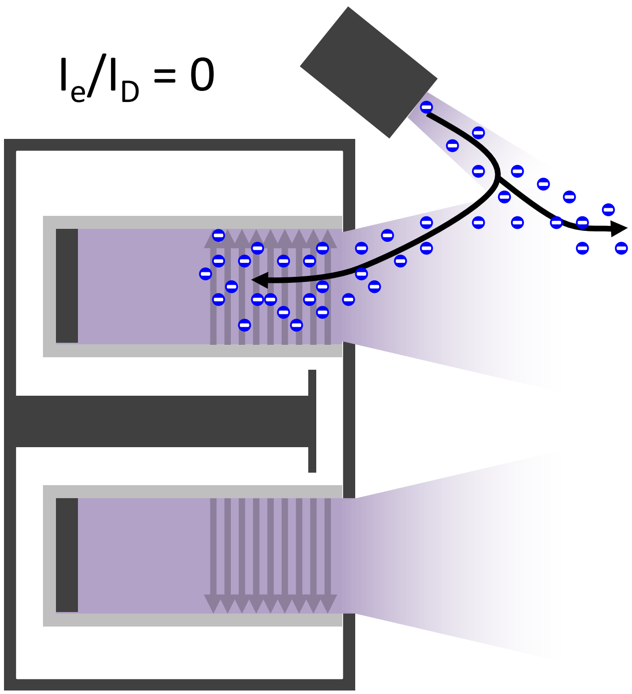
Anomalous electron transport in Hall thruster



Ideal (collisionless)

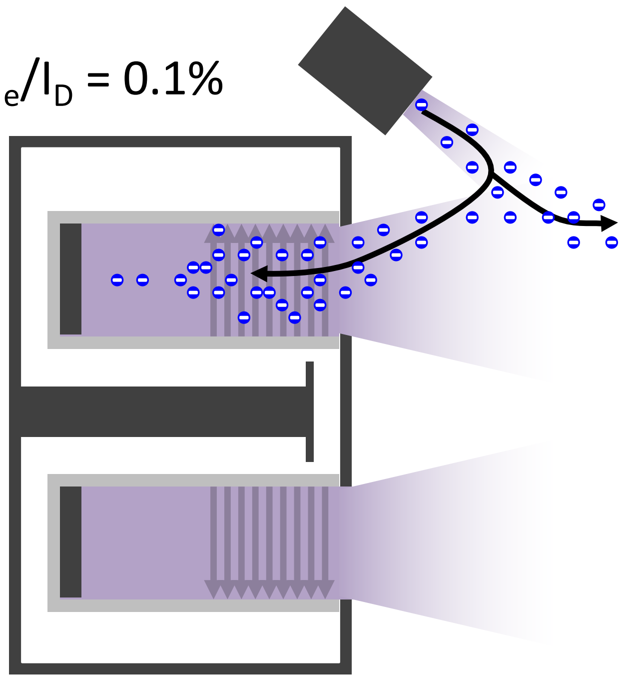
Anomalous electron transport in Hall thruster

$I_e/I_D = 0$



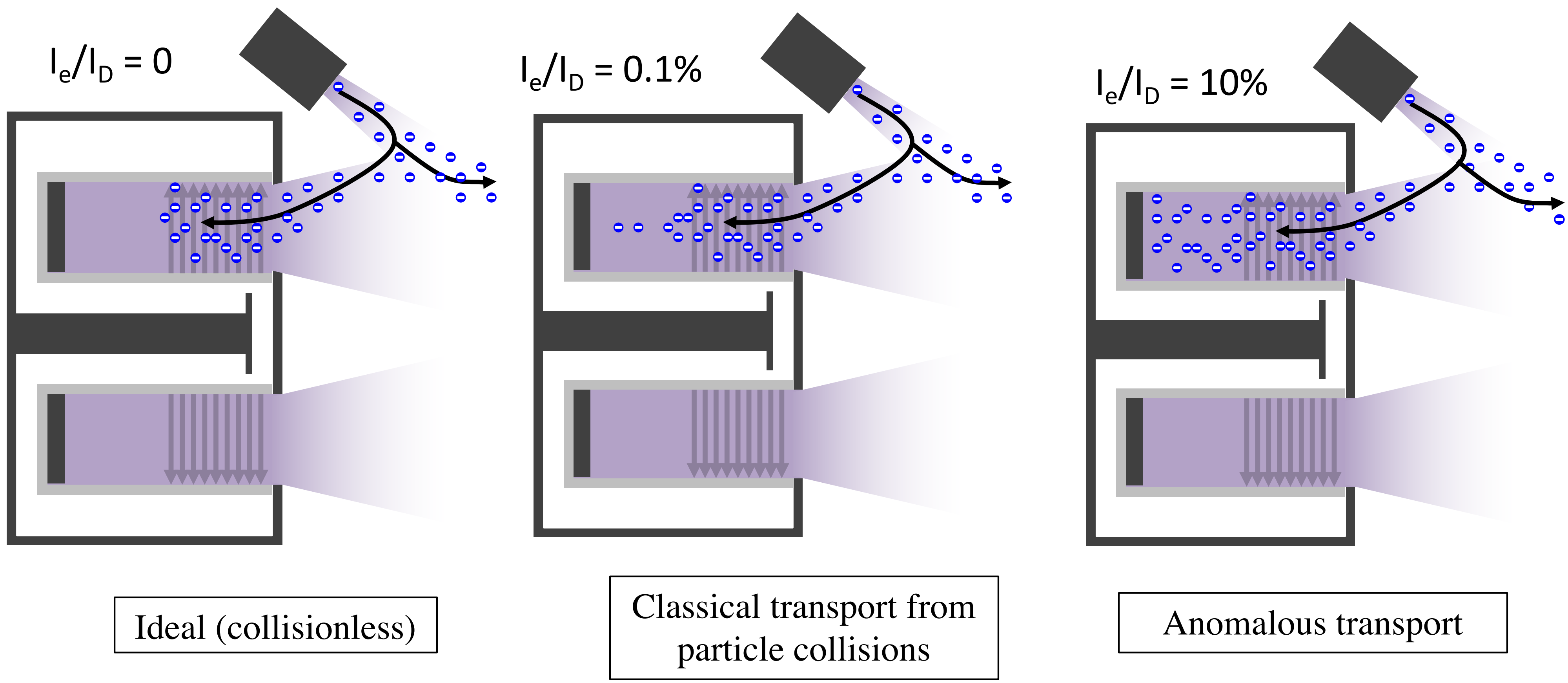
Ideal (collisionless)

$I_e/I_D = 0.1\%$

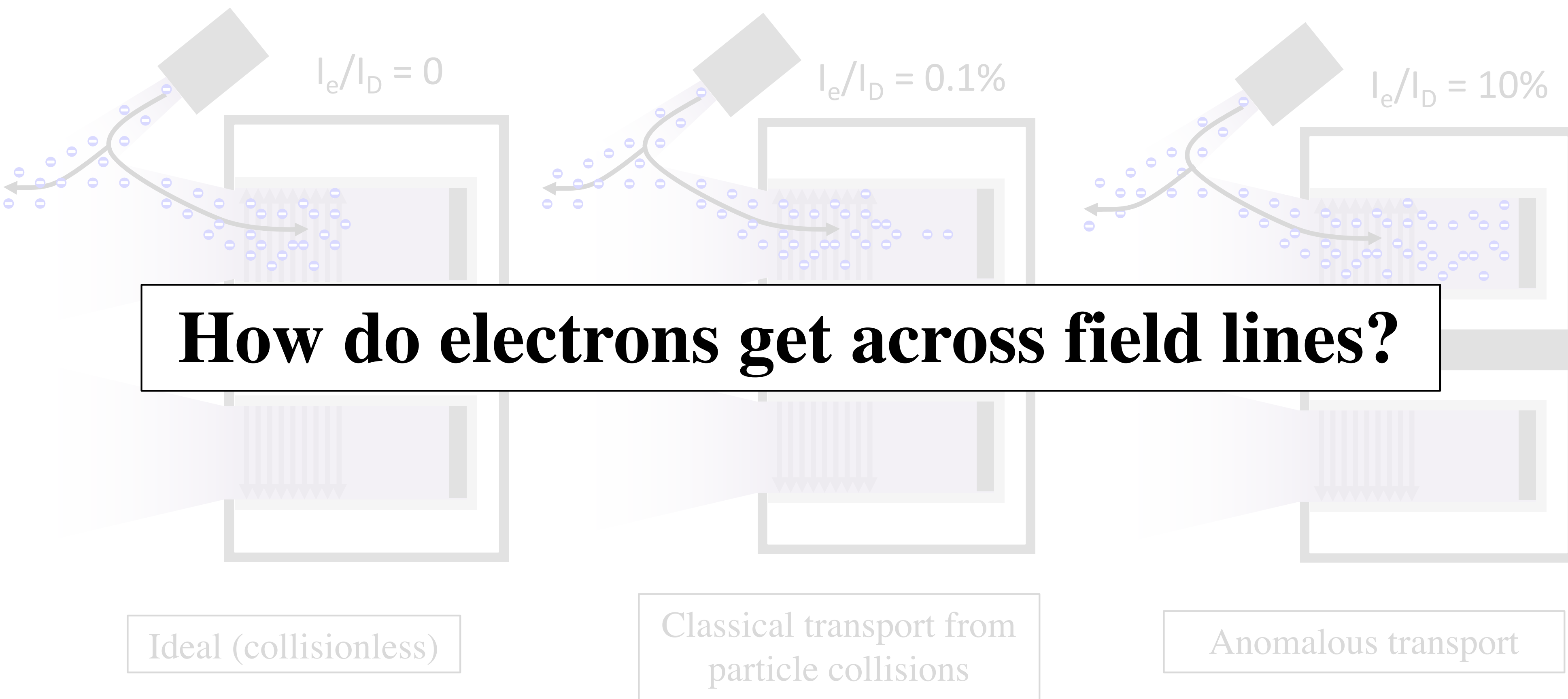


Classical transport from particle collisions

Anomalous electron transport in Hall thruster

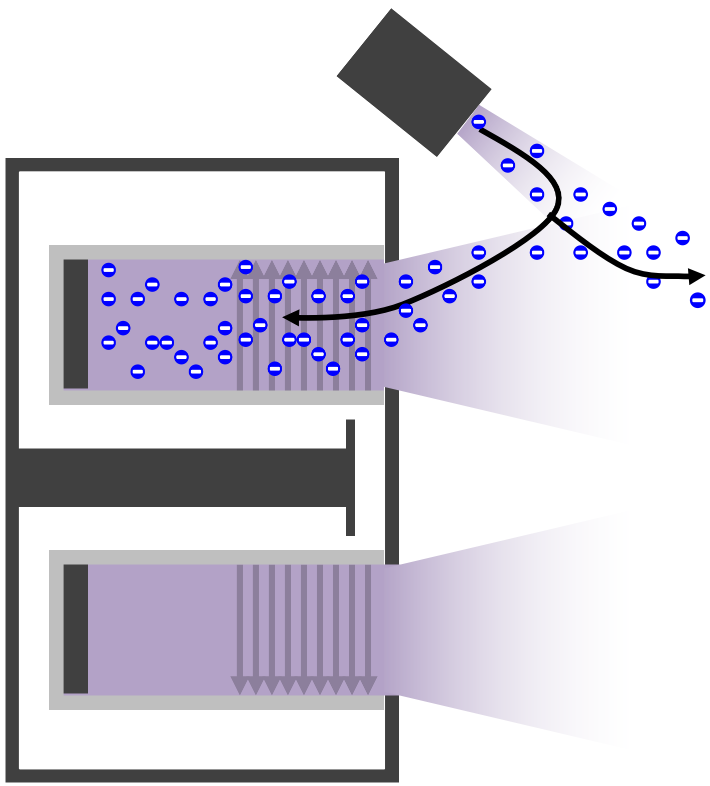


Anomalous electron transport in Hall thruster



How do electrons get across field lines?

Anomalous electron transport in Hall thruster

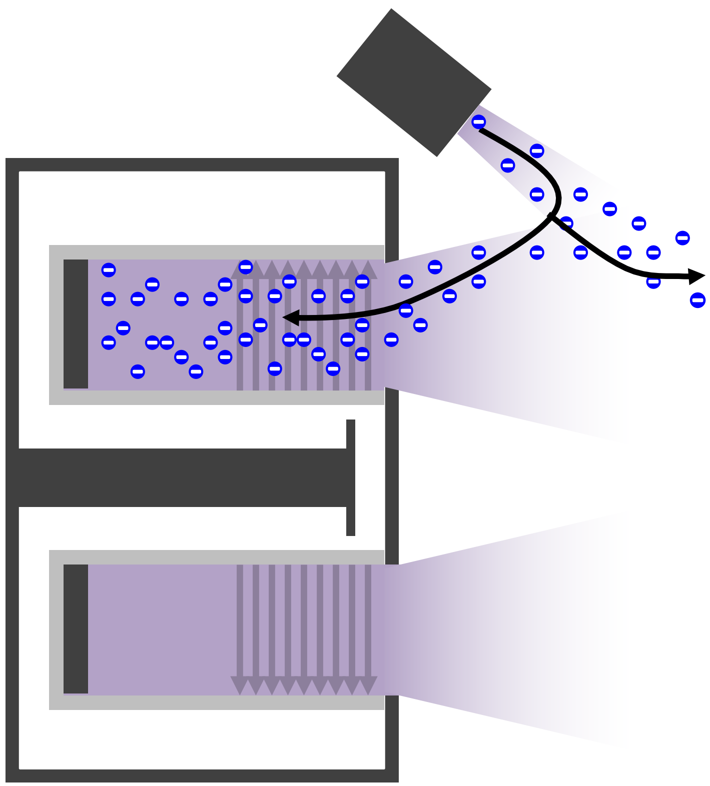


- In magnetized plasmas, electron transport across field lines is driven **by collisions**

$$I_{ez} \propto E_{0z}\nu_{eff}$$

- Classical collision frequency in Hall thruster is too low to allow observed electron transport
- Models account for transport as an effective collision frequency

Anomalous electron transport in Hall thruster



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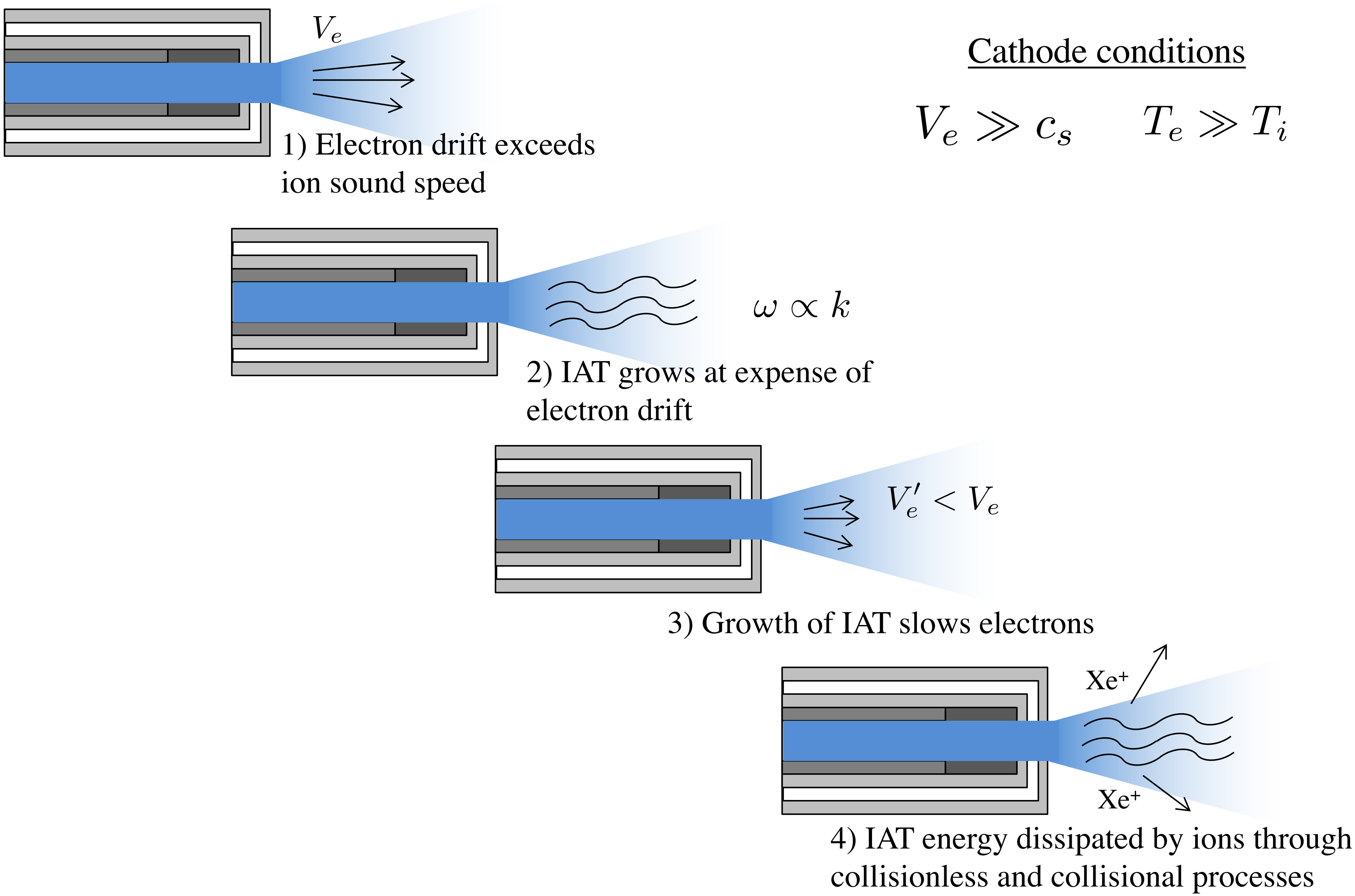
- Models account for transport as an effective collision frequency

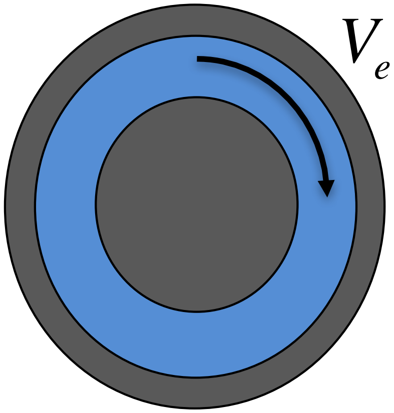
Problem of anomalous electron transport ➡ Problem of anomalous collision frequency

- **Problem of anomalous electron collision frequency is 50 years old.**
  - Recent advances in diagnostics and theory have enabled new progress on problem.
  - Popular theory that has emerged in analog to hollow cathode processes: acoustic-like turbulence may drive the collision frequency

Ion Acoustic Turbulence (IAT) interaction with cathode plume

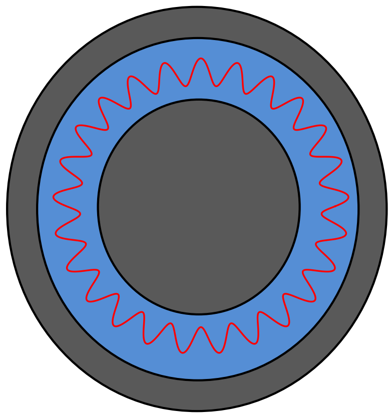


Mechanism for effective collision frequency in Hall thrusters

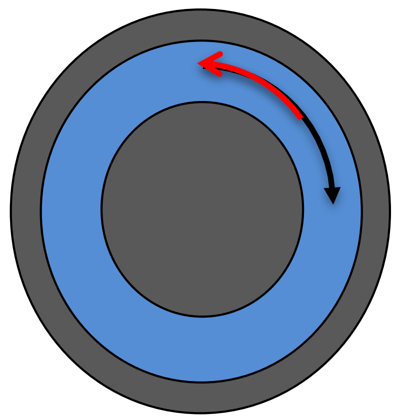


$$V_e = \vec{E} \times \vec{B}$$

1) Strong E × B drift between electrons and ions

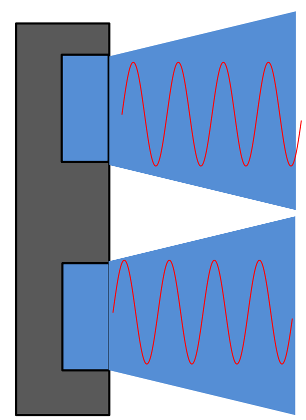


2) Azimuthal wave driven unstable by drift through inverse cyclotron or Landau damping



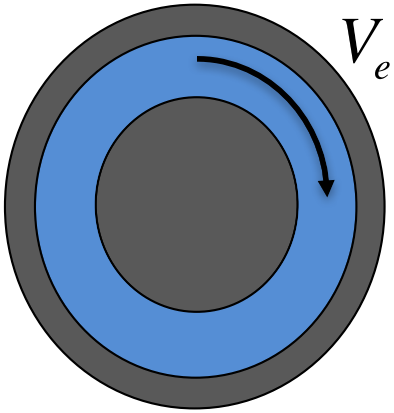
$$V'_e < V_e$$

3) Electrons slowed in E × B direction by wave growth leads to effective collision frequency



4) Wave convected out of channel by ion axial drift

Mechanism for effective collision frequency in Hall thrusters



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Mechanism for effective collision frequency in Hall thrusters

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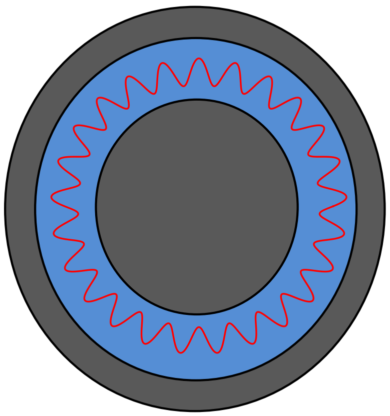

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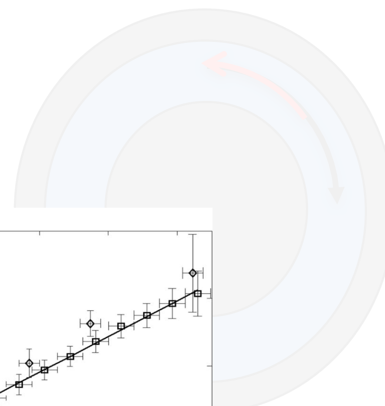
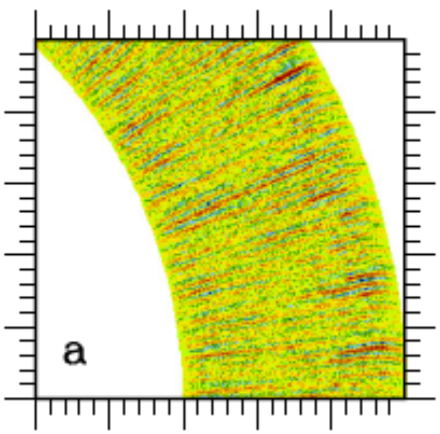
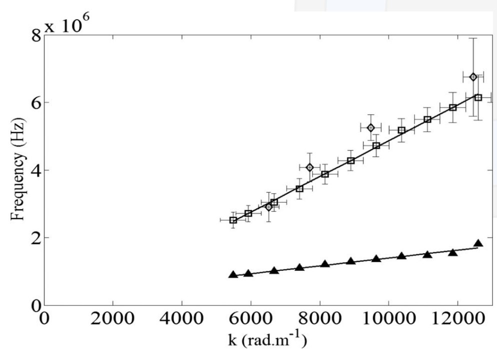


$V'_e < V_e$

3) Electrons slowed in E × B direction by wave growth leads to effective collision frequency





4) Wave convected out of channel by ion axial drift

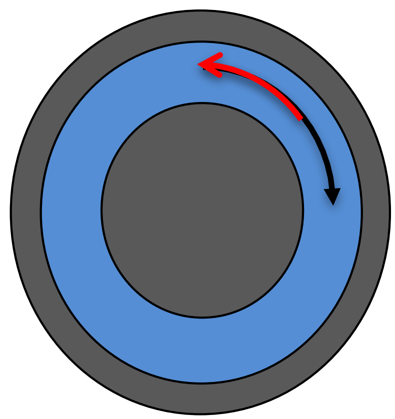
Tsikata, S., Lemoine, N., Pisarev, V., and Grésillon, D. M. *Physics of Plasmas*. Vol. 16., No. 3. 2009.

Mechanism for effective collision frequency in Hall thrusters

$$V_e = \vec{E} \times \vec{B}$$

1) Strong E × B drift between electrons and ions

2) Azimuthal wave driven unstable by drift through inverse cyclotron or Landau damping



$$V'_e < V_e$$

3) Electrons slowed in E × B direction by wave growth leads to effective collision frequency

4) Wave convected out of channel by ion axial drift

QL model for collision frequency as a function of wave action

$$\boxed{\nu_{AN} = \left[\frac{e}{n_{e0}}\right]\left(\frac{\pi}{8}\right)^{1/2}\left(\frac{1}{m_i m_e}\right)^{1/2} k^2 N}$$

Mechanism for effective collision frequency in Hall thrusters

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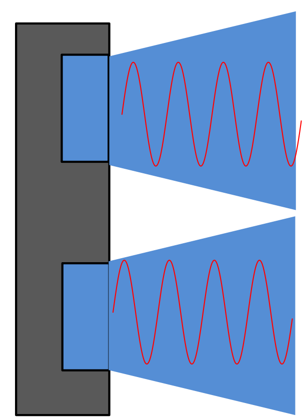
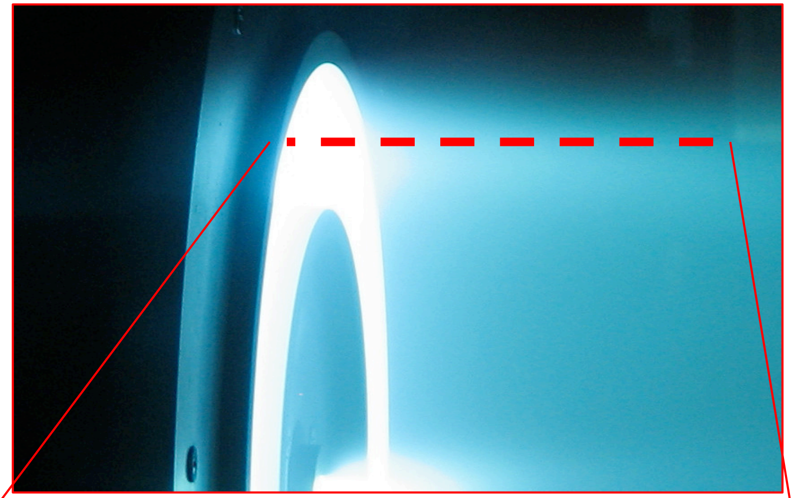


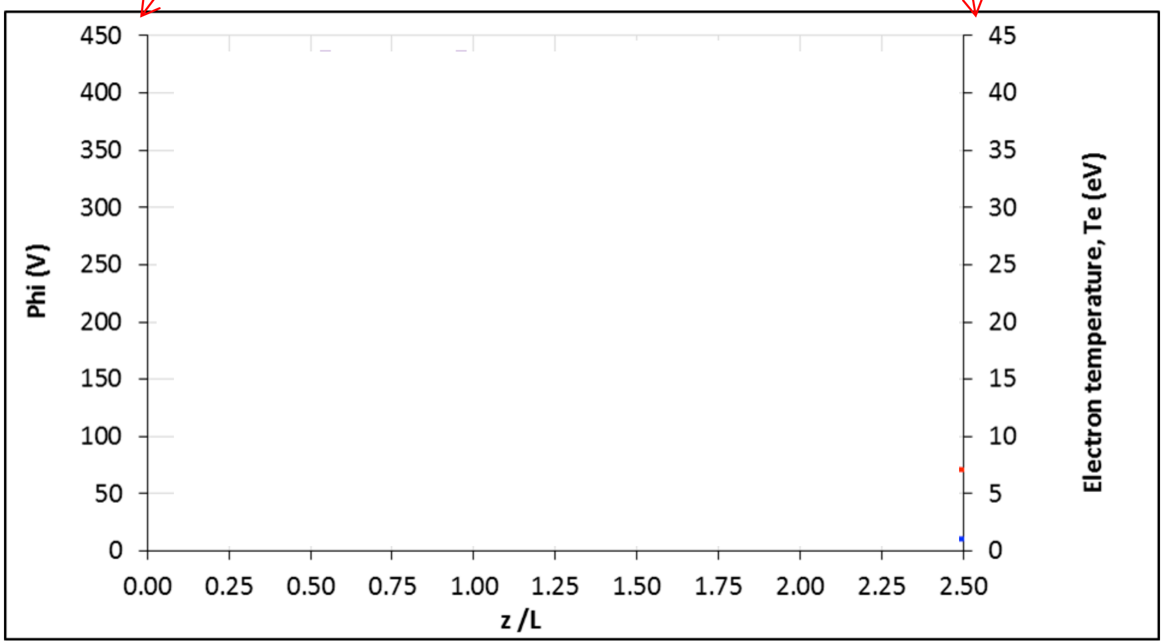
4) Wave convected out of channel by ion axial drift

Convective model for wave energy

$$\boxed{\frac{\partial N_k}{\partial t} + \frac{\partial}{\partial \vec{r}} \cdot \left[\frac{\partial \omega}{\partial \vec{k}} N_k \right] - \frac{\partial}{\partial \vec{k}} \cdot \left[\frac{\partial \omega}{\partial \vec{r}} N_k \right] = 2\gamma_k N_k}$$

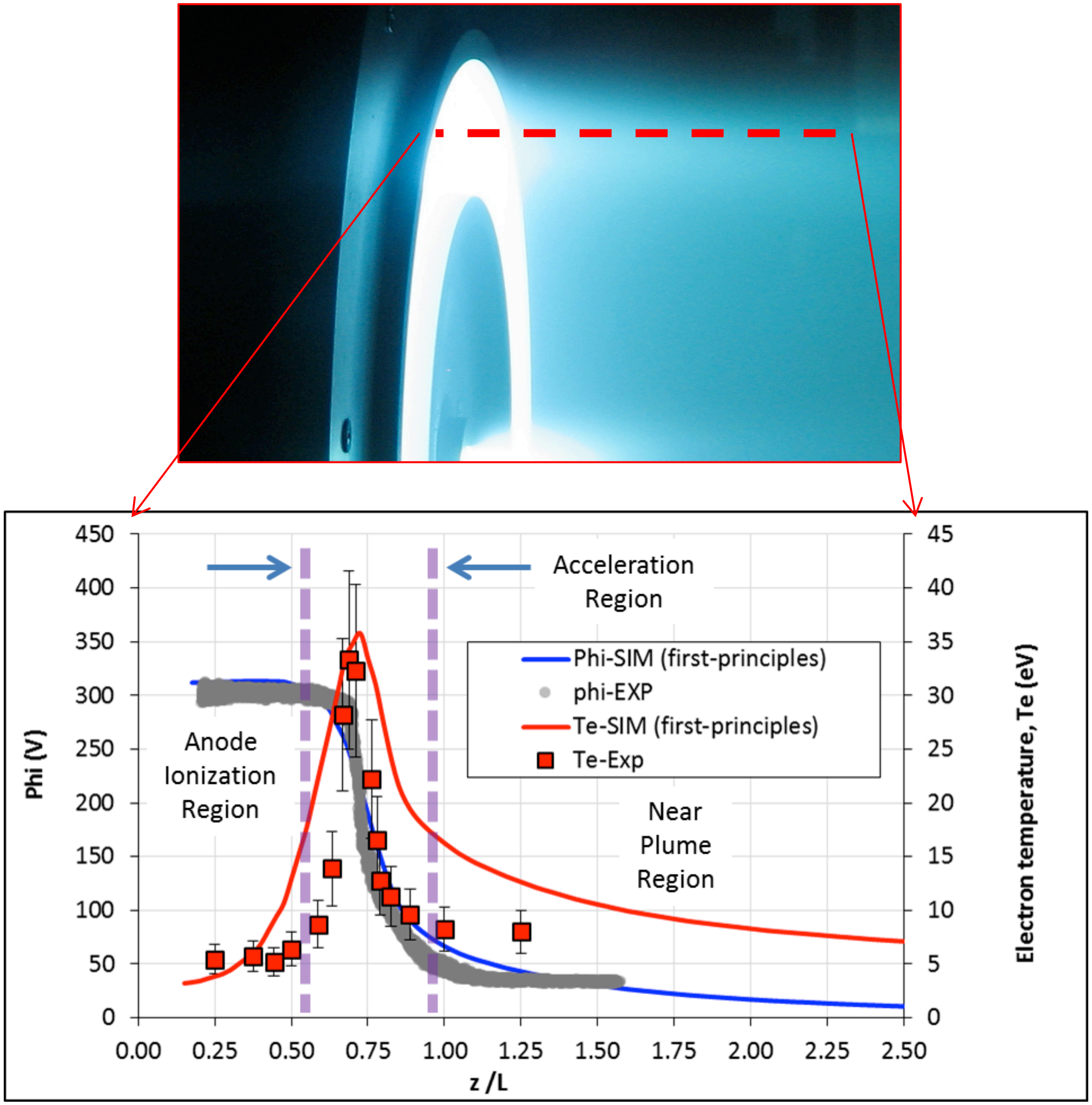
Results from model for collision frequency





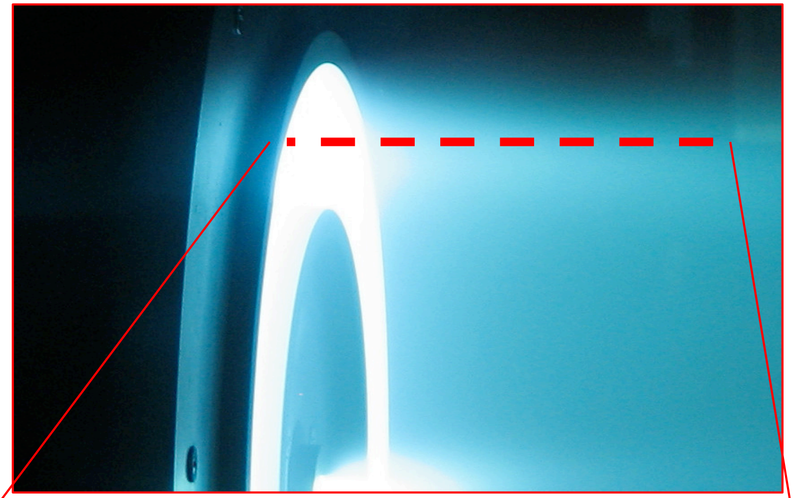
I. Katz, I. Mikellides, B. Jorns, and A. Lopez-Ortega. 34th IEPC. Kobe, Japan. IEPC-2015-402.

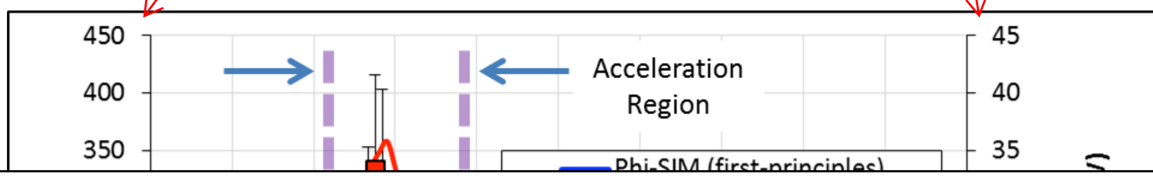
Results from model for collision frequency



I. Katz, I. Mikellides, B. Jorns, and A. Lopez-Ortega. 34th IEPC. Kobe, Japan. IEPC-2015-402.

Results from model for collision frequency





However there are still many open questions about the process

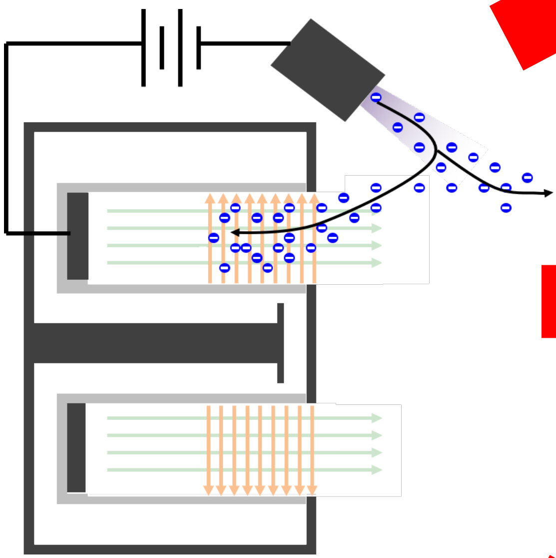
Is the turbulence actually dominant?

Does it propagate in the way we think it should?

What is the correct way to model its interaction with the electrons?

I. Katz, I. Mikellides, B. Jorns, and A. Lopez-Ortega. 34th IEPC. Kobe, Japan. IEPC-2015-402.

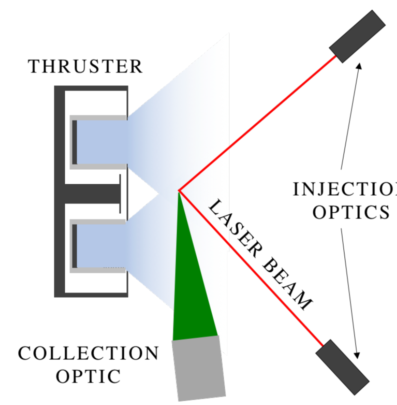
On-going work into examining role of turbulence in cross-field transport



Re-evaluating theory for effective collision frequency

$$\nu_{AN} = \left[\frac{e}{n_{e0}}\right]\left(\frac{\pi}{8}\right)^{1/2}\left(\frac{1}{m_i m_e}\right)^{1/2} k^2 N$$

Developing new experimental tools to characterize turbulence growth

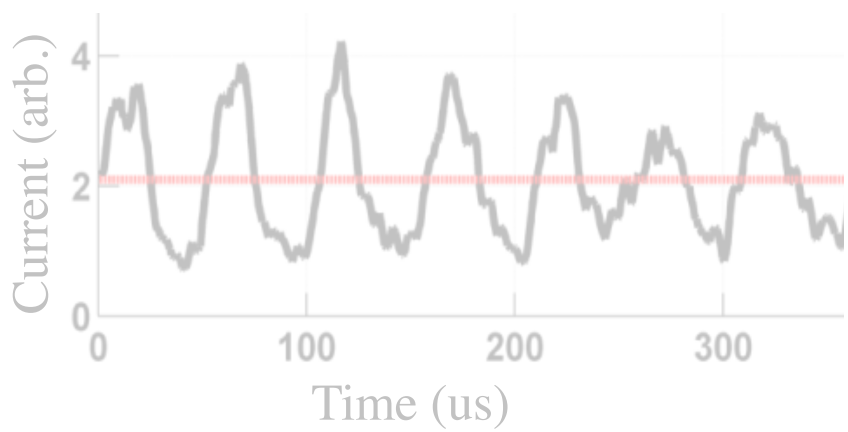


Re-examining governing hierarchy for turbulent energy in simulations

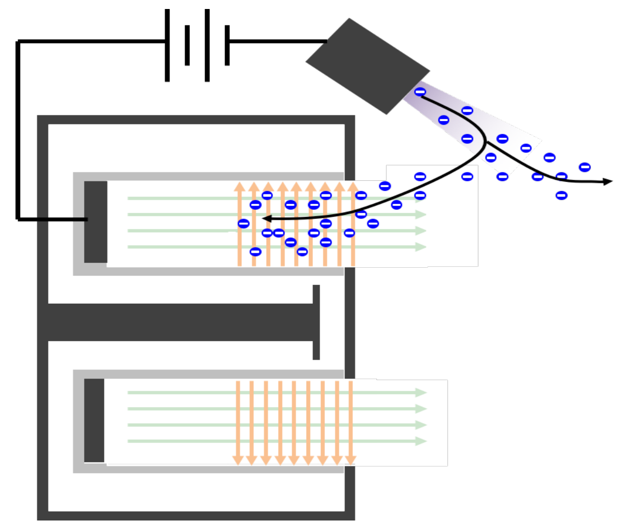
$$\frac{\partial N_{\vec{k}}}{\partial t} + \nabla \cdot \left(N_{\vec{k}} \vec{v}_g\right) - \nabla_{\vec{k}} \cdot \left(N_{\vec{k}} \nabla \omega_r\right) = N_{\vec{k}} \left[2\omega_i + \mathcal{C}\left(N_{\vec{k}}\right)\right]$$

Anomalous Processes in Hall Thruster Operation

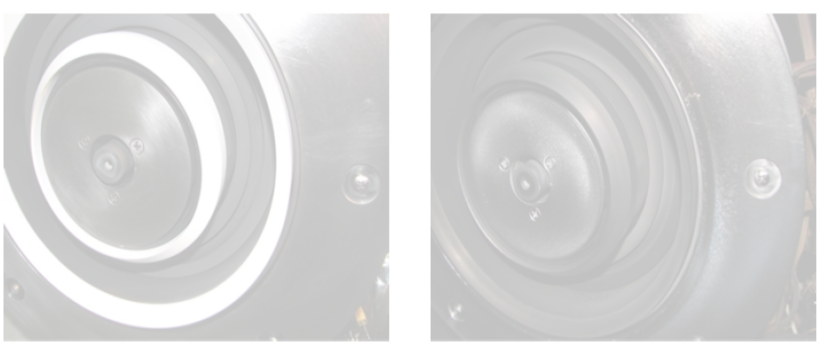
Onset of coherent, oscillatory modes



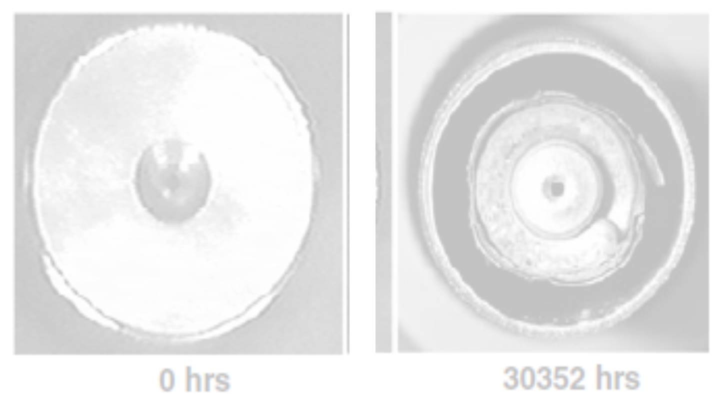
Cross-field transport



Thruster surface erosion

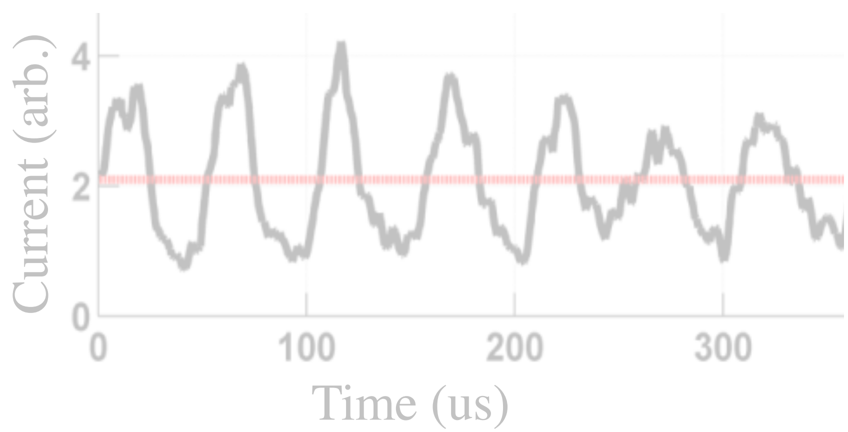


Cathode erosion and electron transport

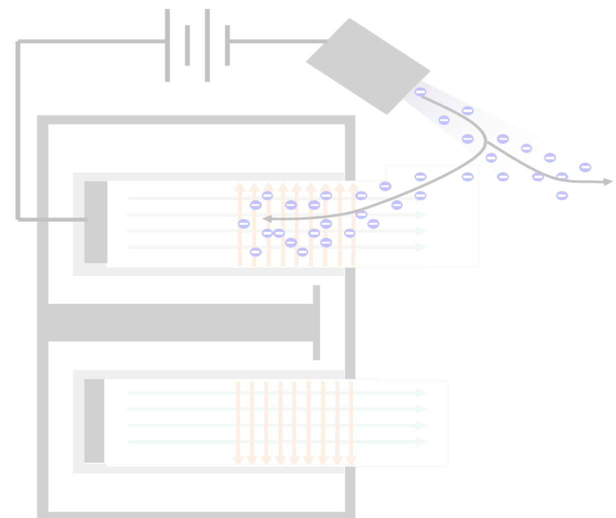


Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

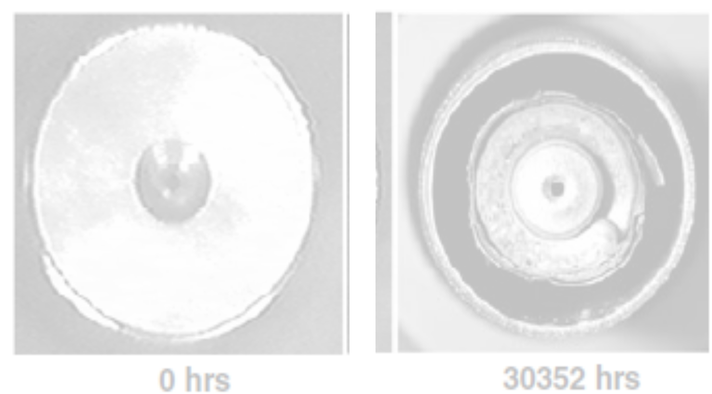


Cross-field transport



Thruster surface erosion

Cathode erosion and electron transport



The Problem of Magnetic Pole Erosion in Hall Thrusters

Iron poles of the Hall thruster are sputtered

0 hr

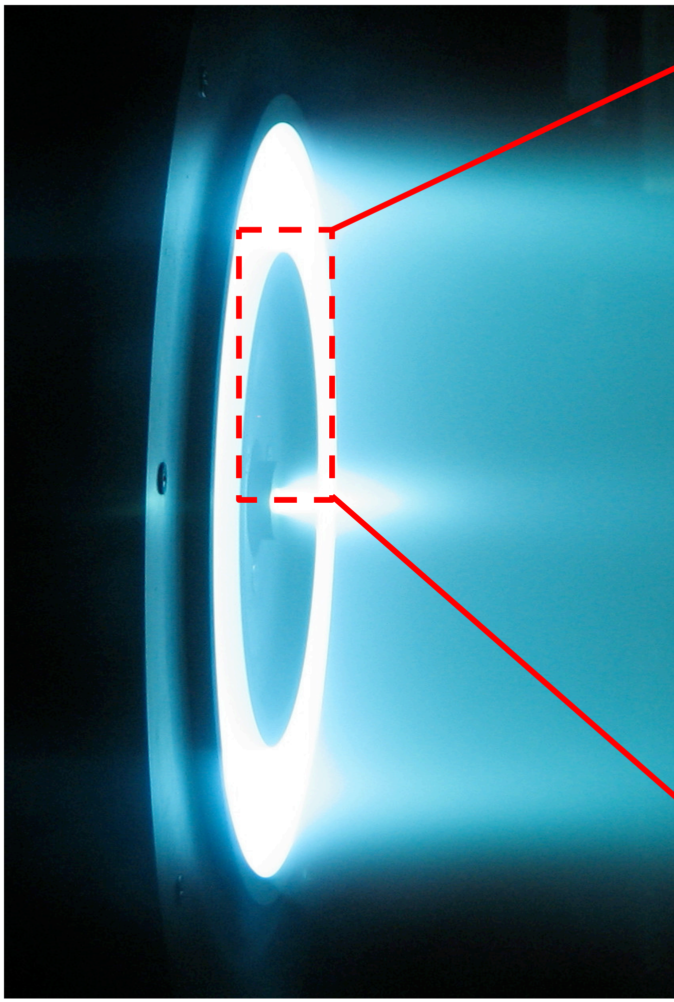
150 hr

M. Sekerak et al. "Wear Testing of a Magnetically Shielded Hall Thruster at 2000 s Specific Impulse," IEPC-2015-155.

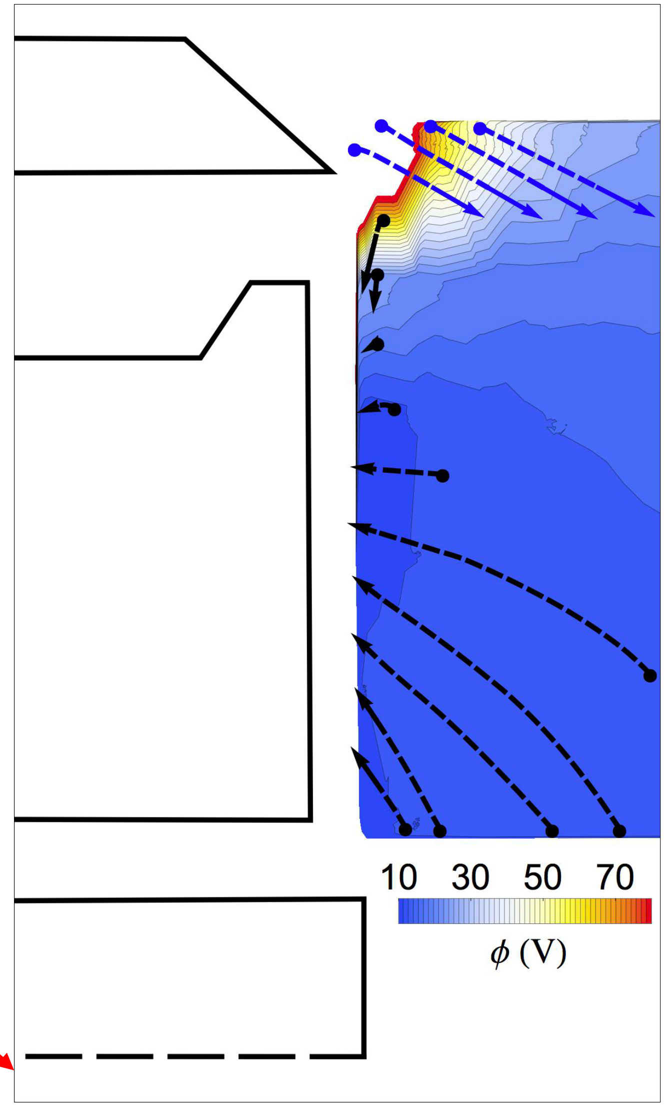
6-kW Hall effect thruster at JPL

Measurements show ion trajectories intersect pole pieces

6-kW Hall effect thruster at JPL



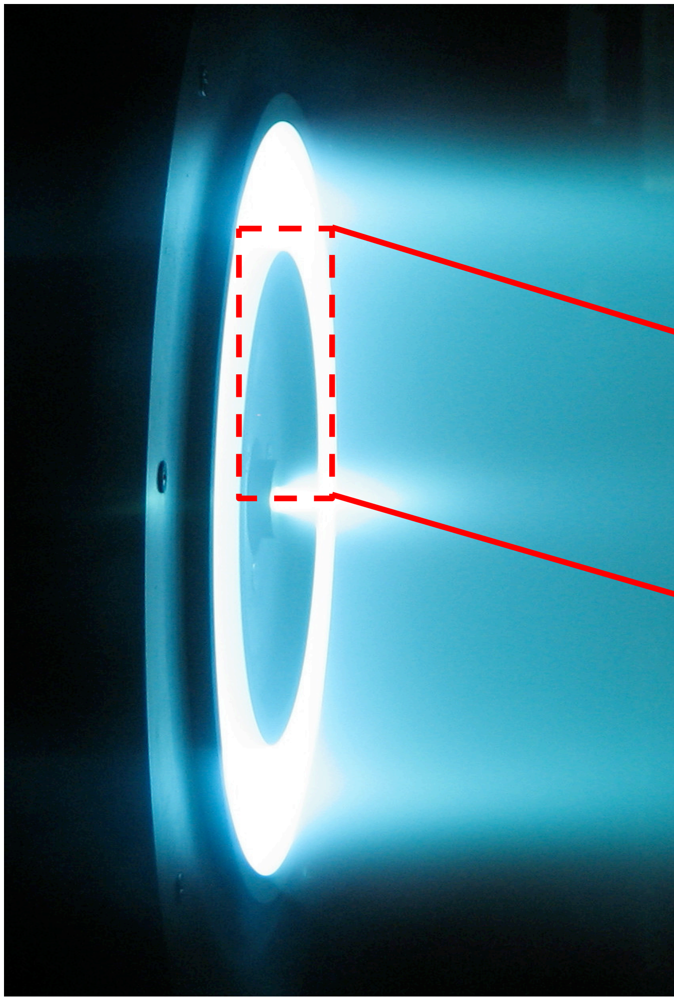
Measured ion trajectories



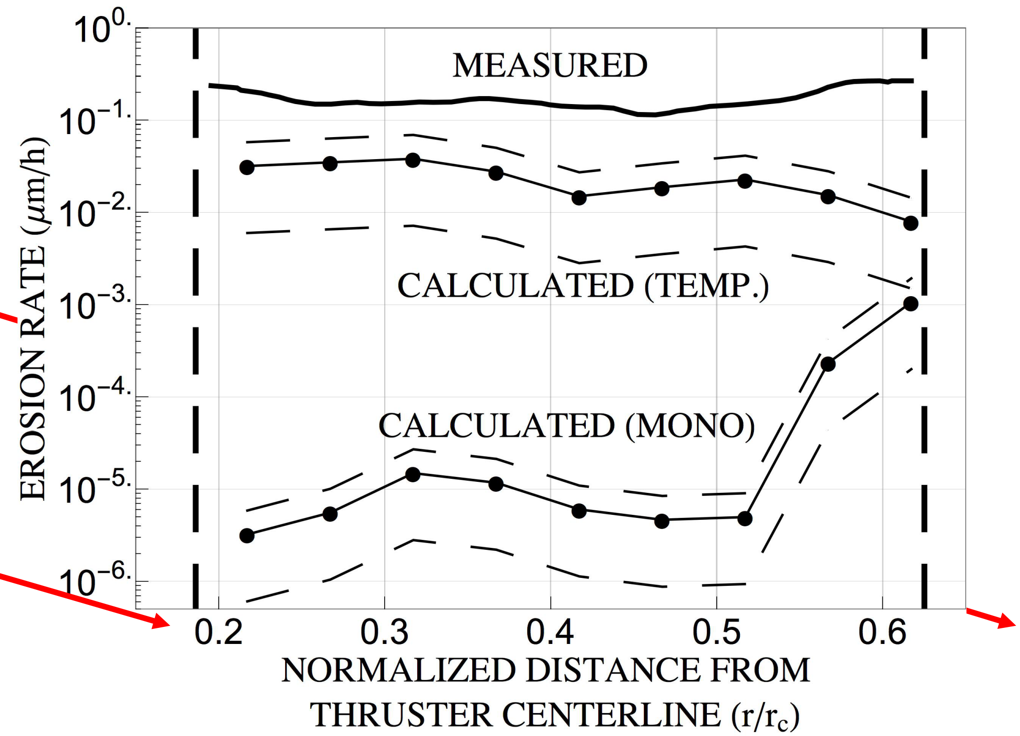
B. Jorns et al. AIAA-2016-4839

Measurements show ion trajectories intersect pole pieces

6-kW Hall effect thruster at JPL



Ion kinetic energy too low to explain measured erosion rate



B. Jorns et al. AIAA-2016-4839

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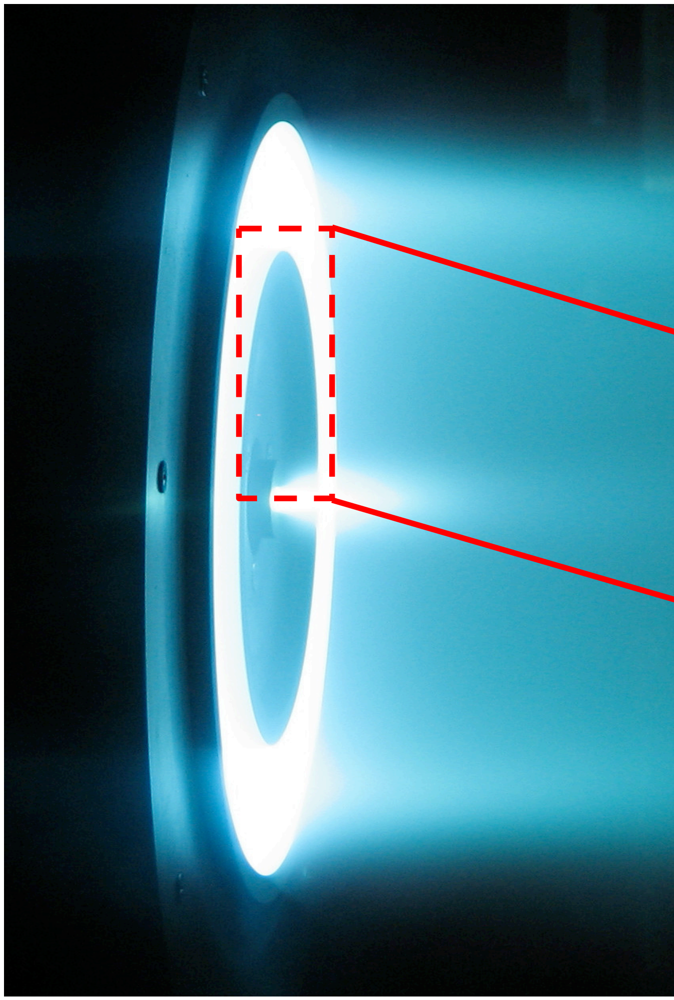
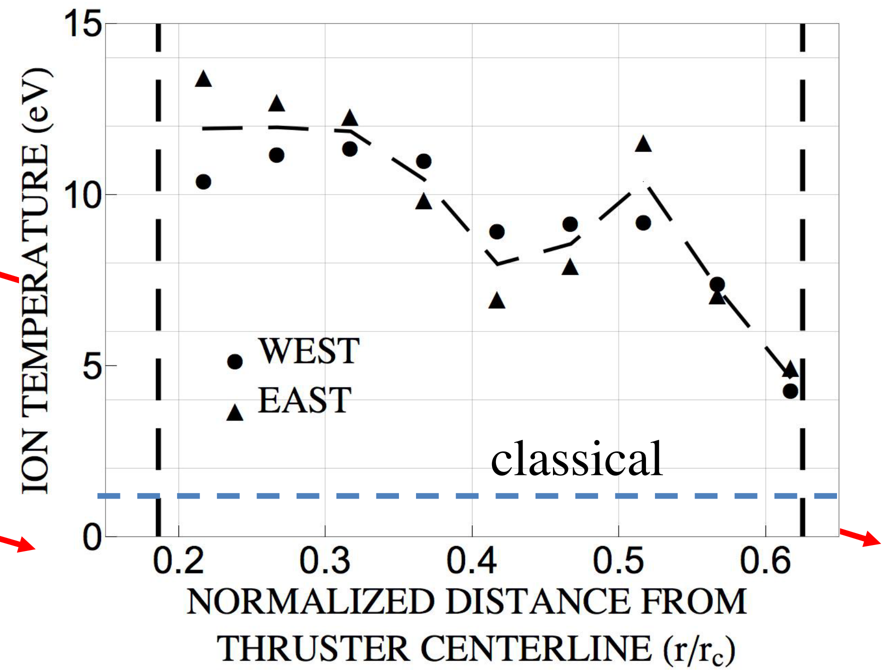
6-kW Hall effect thruster at JPL



Ion temperatures are anomalously high and can explain most of the erosion

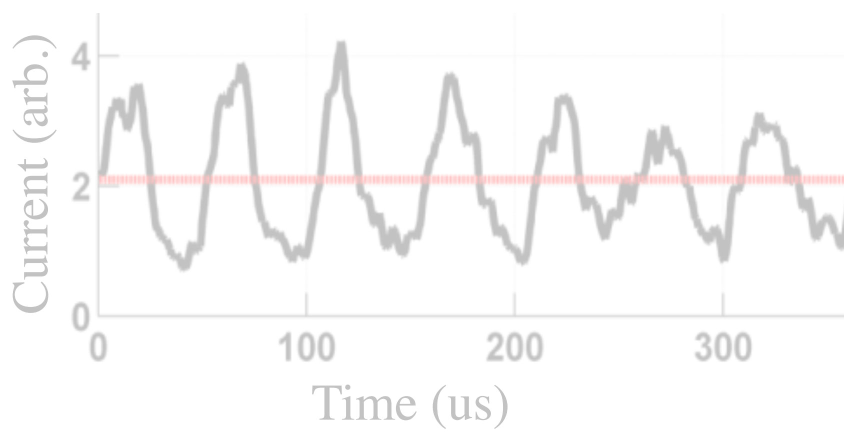


B. Jorns et al. AIAA-2016-4839

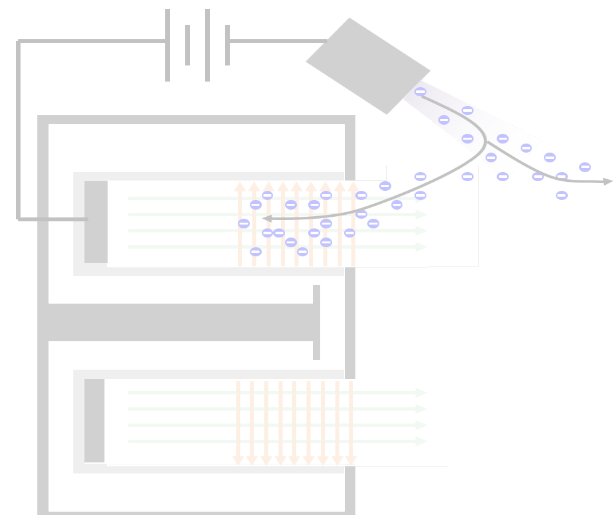
Ion heating in this region is non-classical and is possibly driven by turbulent heating or low-frequency ionization modes

Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

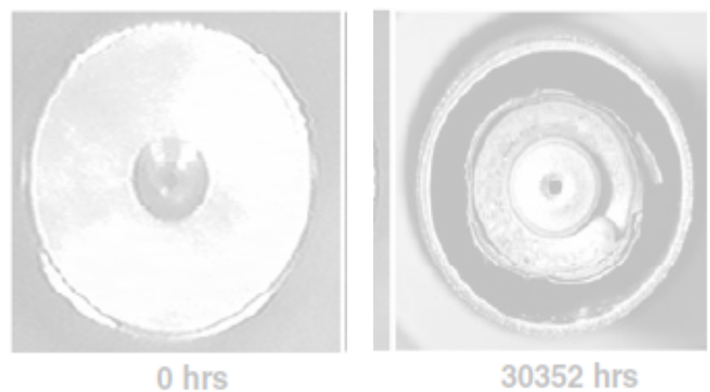


Cross-field transport



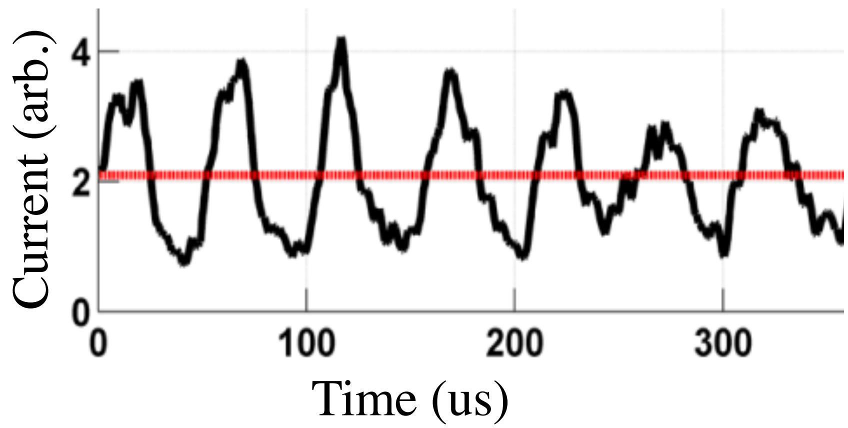
Thruster surface erosion

Cathode erosion and electron transport

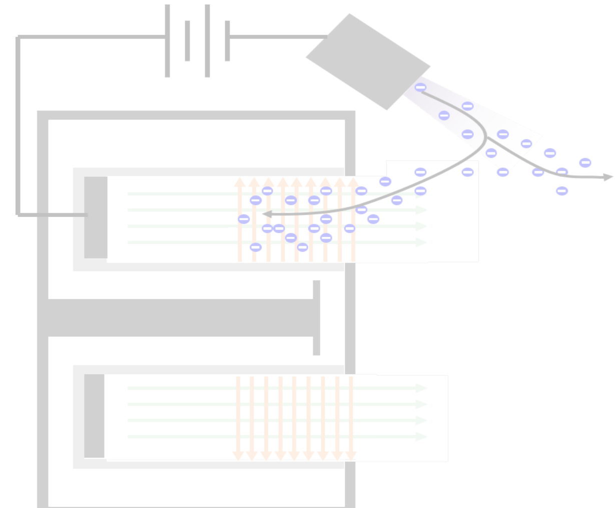


Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes



Cross-field transport



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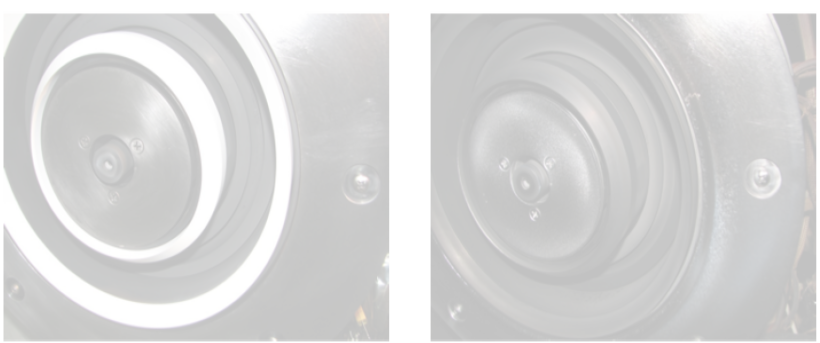
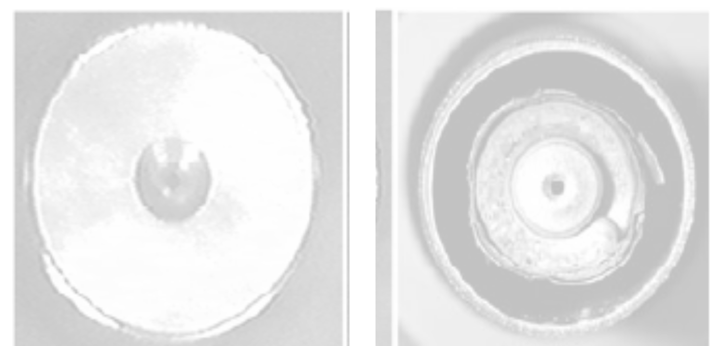
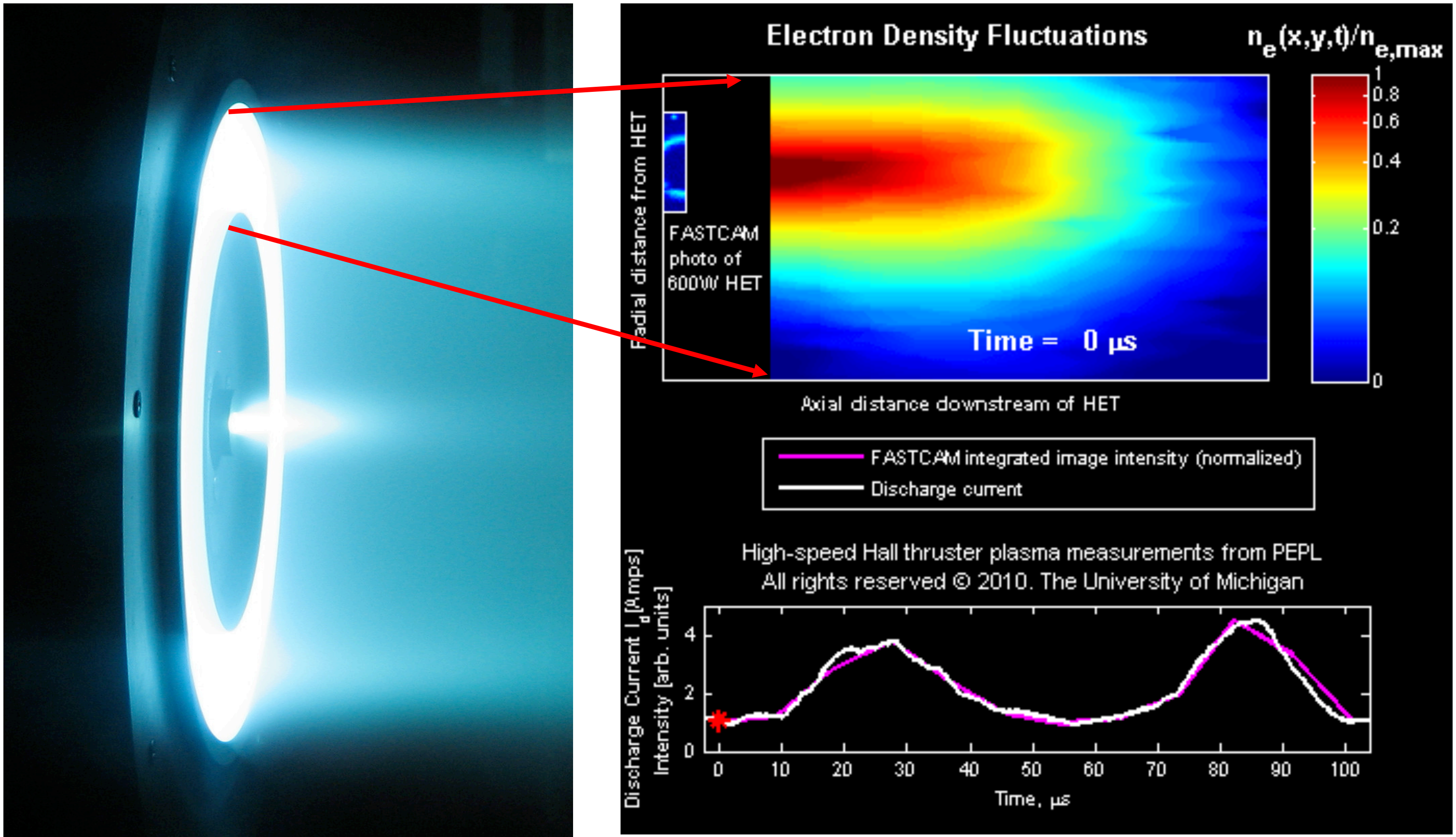


Cathode erosion and electron transport



The Problem of Hall Thruster Stability

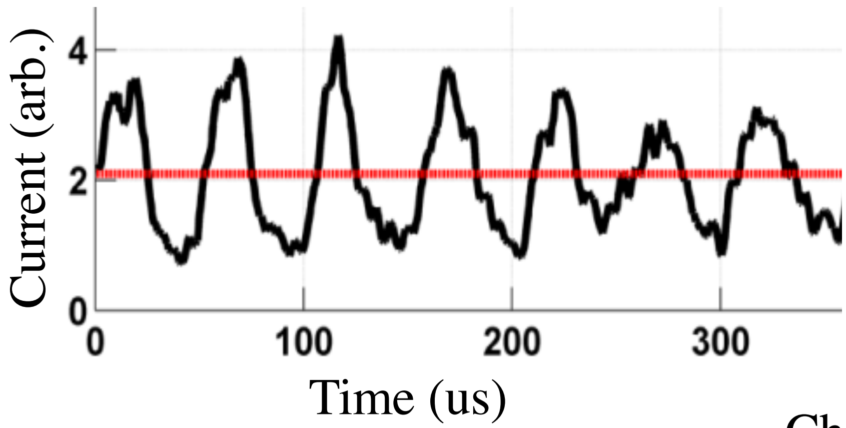
Global Hall thruster stability (breathing mode)



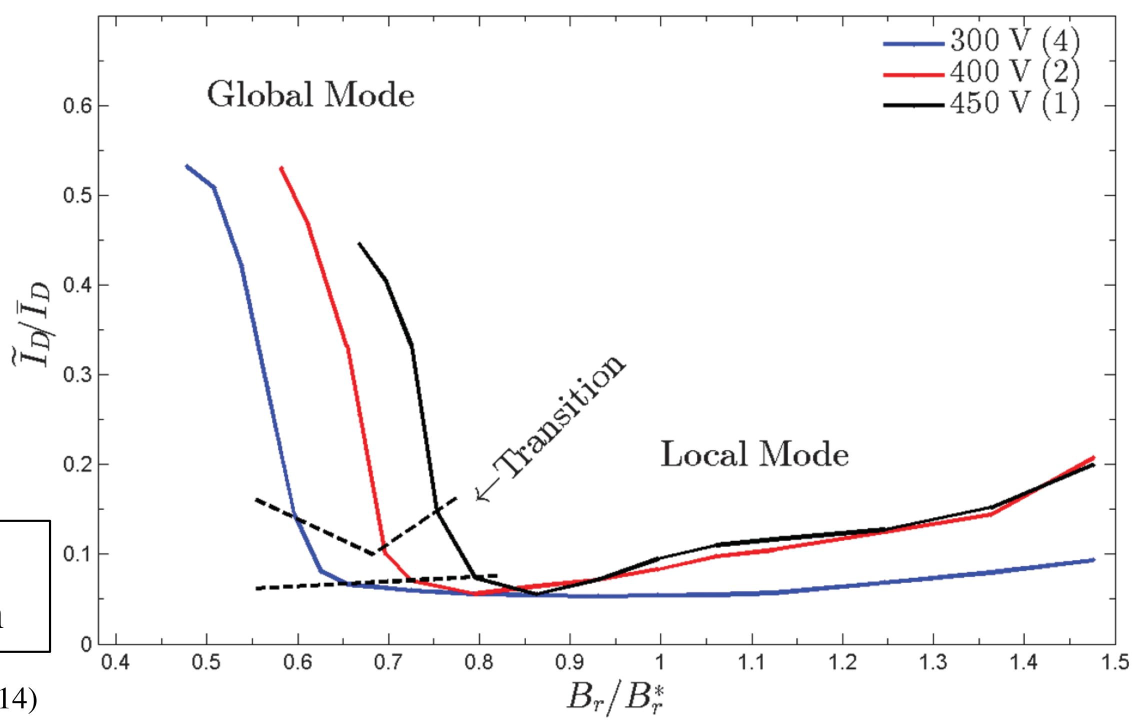
R. Lobbia, R. B., "A Time-resolved Investigation of the Hall Thruster Breathing Mode," Ph.D. Dissertation, University of Michigan, 2010.

Coherent large scale oscillations in plume and discharge current occur on the 10-100 kHz scale

Global Hall thruster stability (breathing mode)



Change in current oscillations with magnetic field



M. Sekerak et al. *Journal of Propulsion and Power*. Vol. 32, No. 4 (2016)

The stability of the thruster depends strongly on operating condition

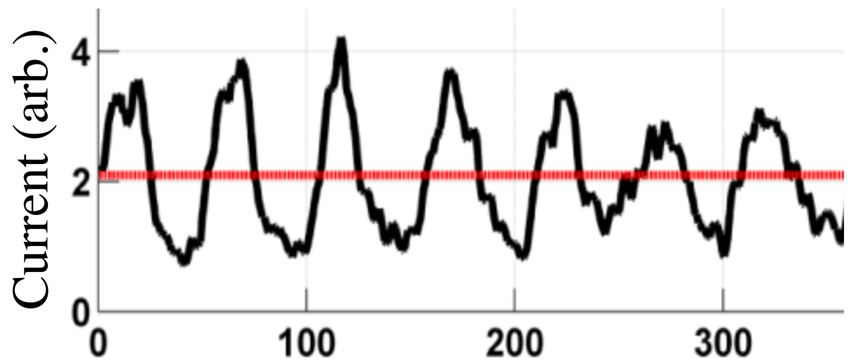
There has been some work on explaining these trends with numerical work*

We are actively investigation a first-principles description of this oscillation

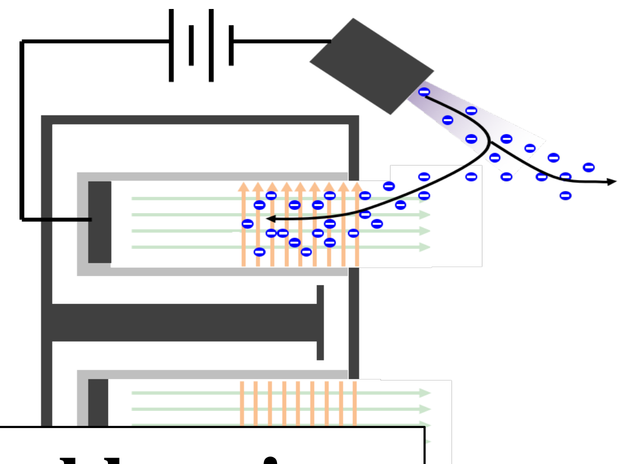
*K. Hara et al. Journal of Applied Physics. 115, 203304 (2014)

Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes



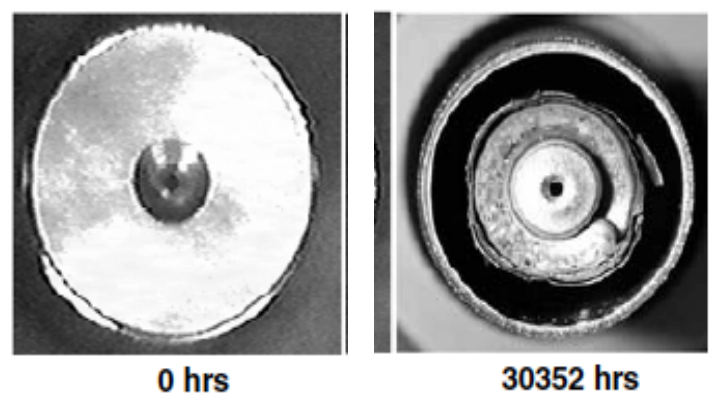
Cross-field transport



Instabilities can cause problems!

Thruster surface erosion

Cathode erosion and electron transport



Summary

- Electric propulsion is a key enabling technology for commercialization and exploration of space

- Hall thrusters are particularly attractive form of EP

- Although Hall thrusters are currently flown, there are key aspects of operation that we do not understand. *This poses a challenge for qualifying this technology for more ambitious missions*. Anomalous aspects of operation include
  - Stability
  - Erosion of thruster face
  - Cross-field transport
  - Cathode erosion and resistivity

- In all cases, plasma instabilities play a role (if the anomalous effects were classical, we would have predicted them already!)

- Previous and on-going work seeks to understand these instabilities from first-principles in such a way as to model and potentially mitigate the anomalous processes

Acknowledgement of collaborators

JPL

Dr. Dan Goebel
Dr. Ioannis Mikellides,
Dr. Alejandro Lopez Ortega
Dr. Richard Hofer
Dr. Ira Katz
Dr. Mike Sekerak

UCLA

Mr. Christopher Dodson
Prof. Richard Wirz

Mr. Marcel Georgin, PEPL
Mr. Ethan Dale, PEPL
Mr. Zach Brown, PEPL
Mr. Matthew Byrne, PEPL