An overview of instabilities capable of inducing cross-field transport in low-temperature, partially magnetized discharges

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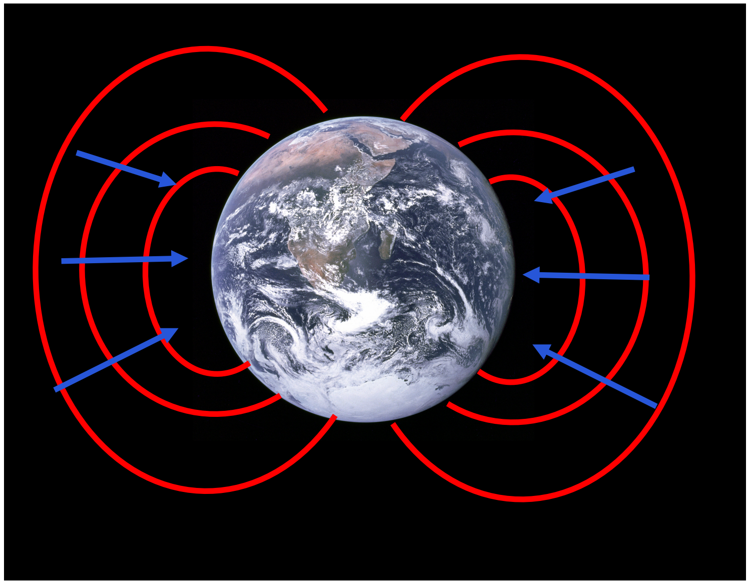
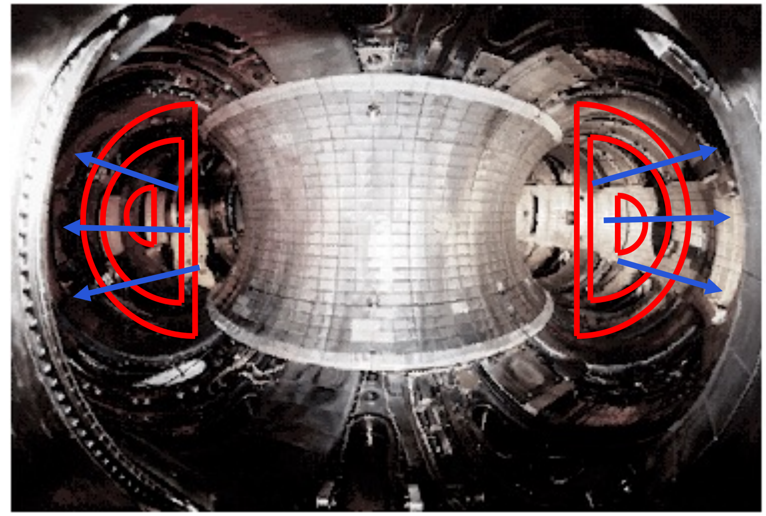
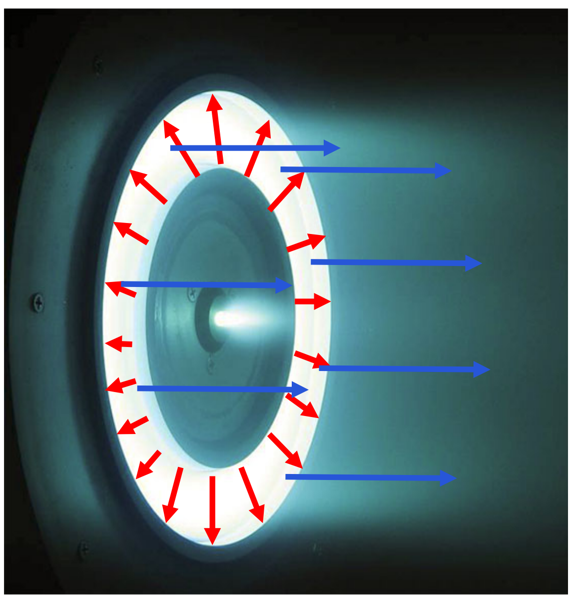
Key Points

- What is the problem of cross field transport in partially magnetized, low-temperature devices?
- How can instabilities contribute to this transport?
- How do we differentiate among the “zoo” of modes that exist in these devices?

Anomalous Cross-Field Transport Occurs in Many Plasma Systems







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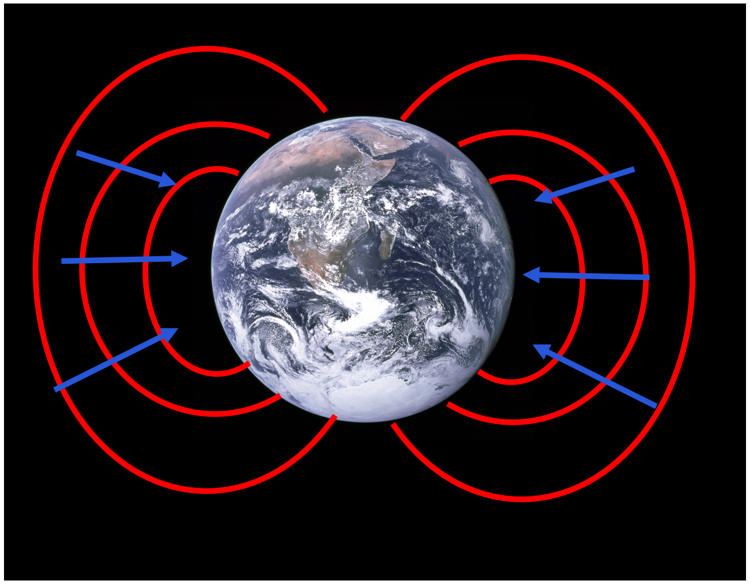

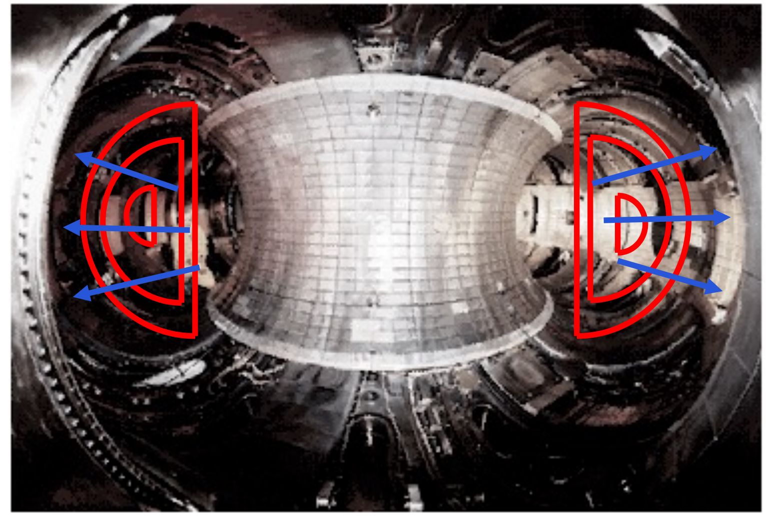

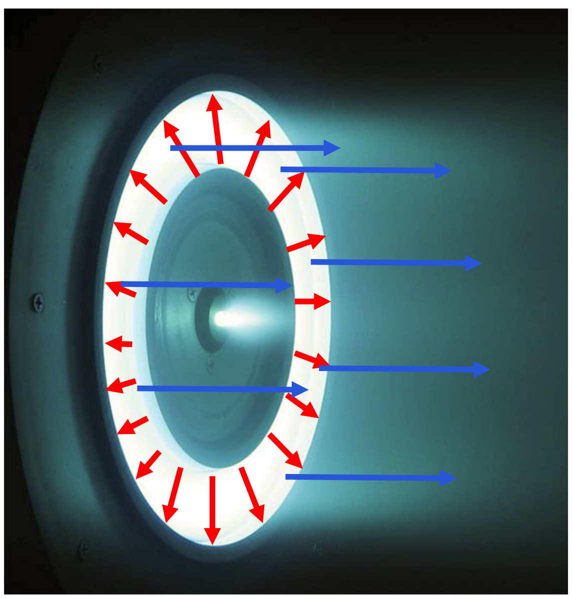

Problem of electron transport

- In many systems, electron current across confining magnetic field orders of magnitude higher than predicted from classical, i.e. collisional theory
- We do not know what drives this cross-field flow
- Precludes fully predictive modeling

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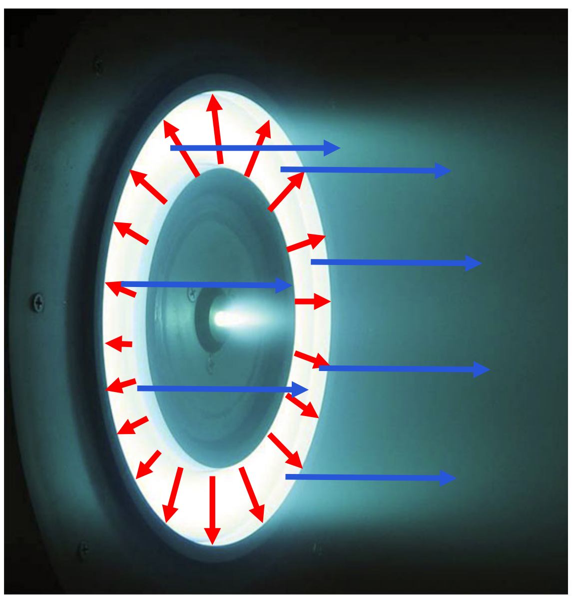
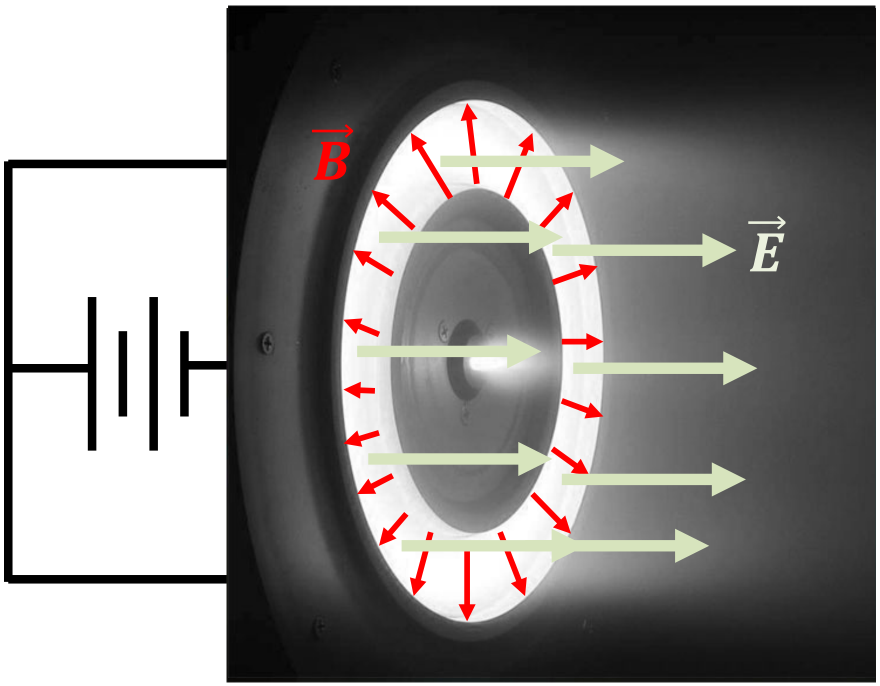
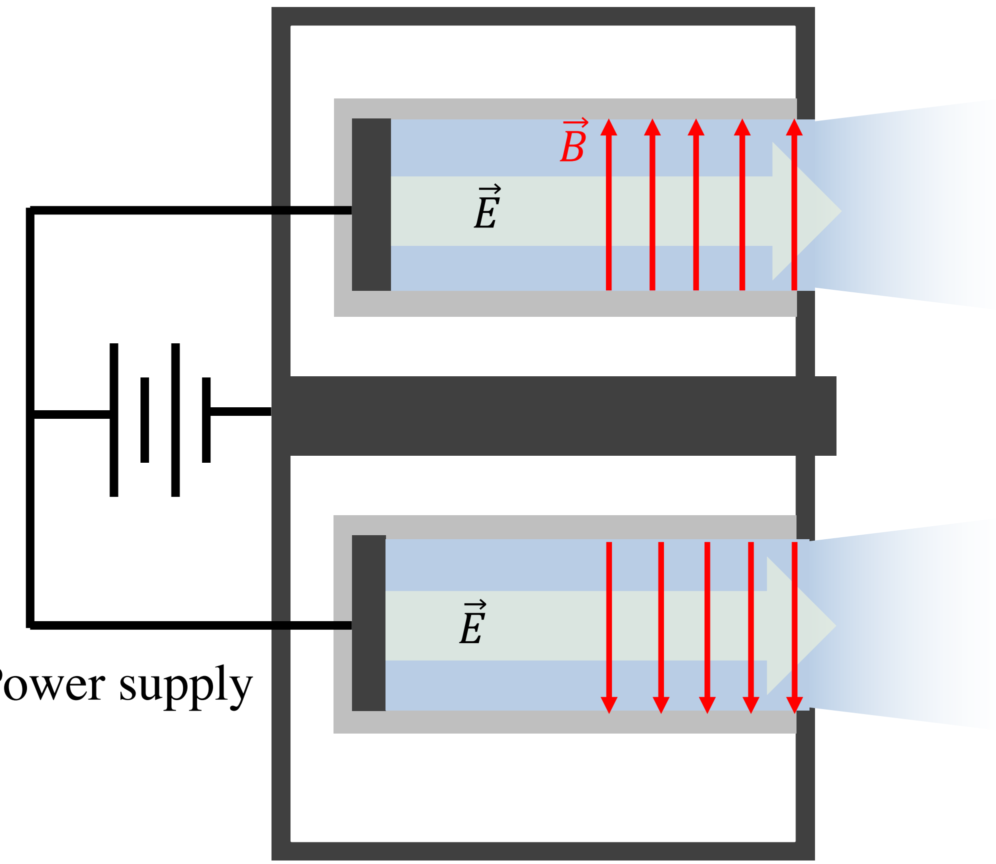


Plasma systems examined today

- Unmagnetized ions ($L_S \gg r_{ci}$)
- Low temperature electrons ($T_e < 70$eV)
- Examples:
  - Hall effect thrusters
  - Penning discharges
  - Some magnetic nozzles

Cross-field Transport in Partially Magnetized Plasmas



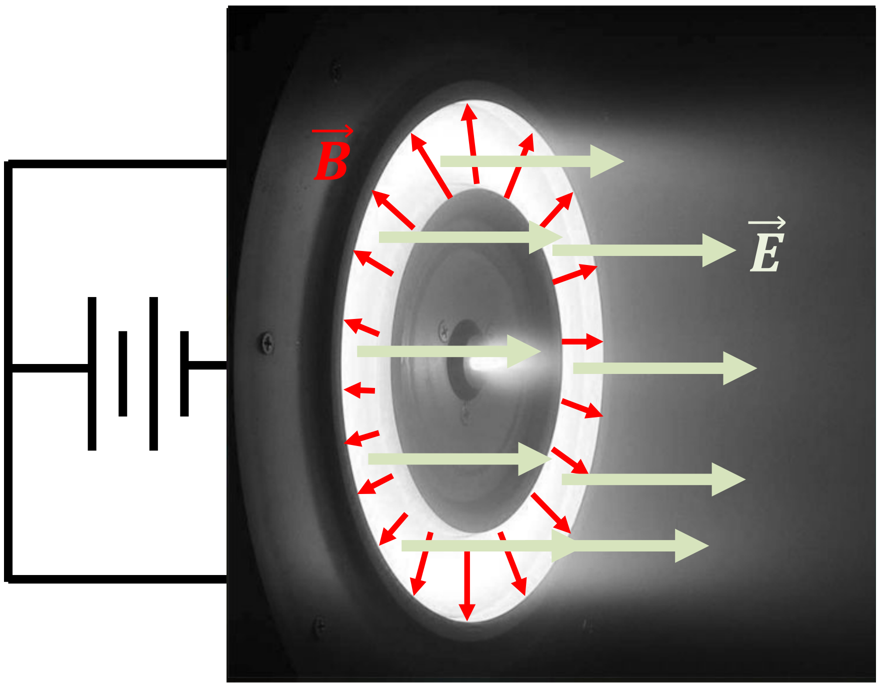


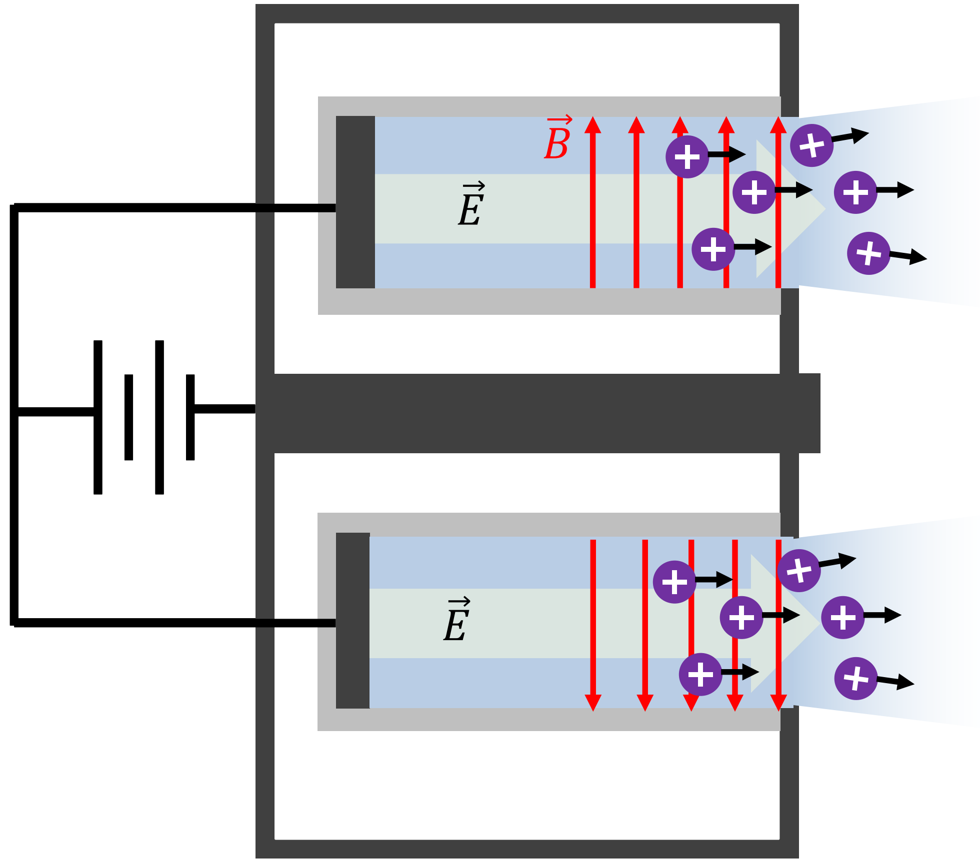
Cross-field Transport in Partially Magnetized Plasmas

Unmagnetized ions

$$\vec{V_i} = \frac{q}{m_i}\int \vec{E}\,dl$$

Ions follow the applied electric field



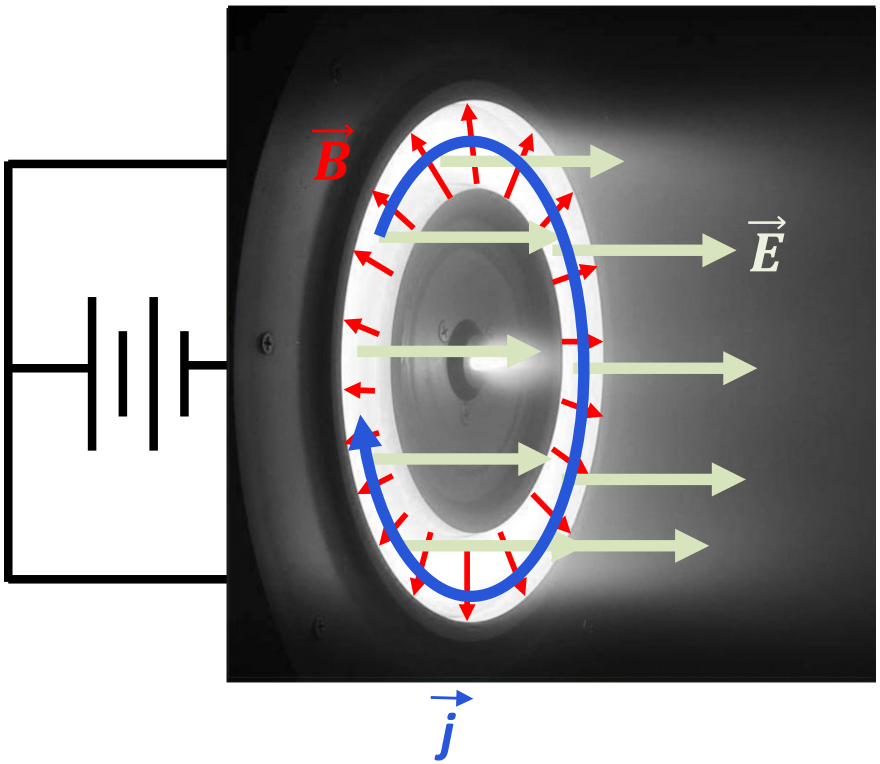


Cross-field Transport in Partially Magnetized Plasmas

Case 1: no electron collisions

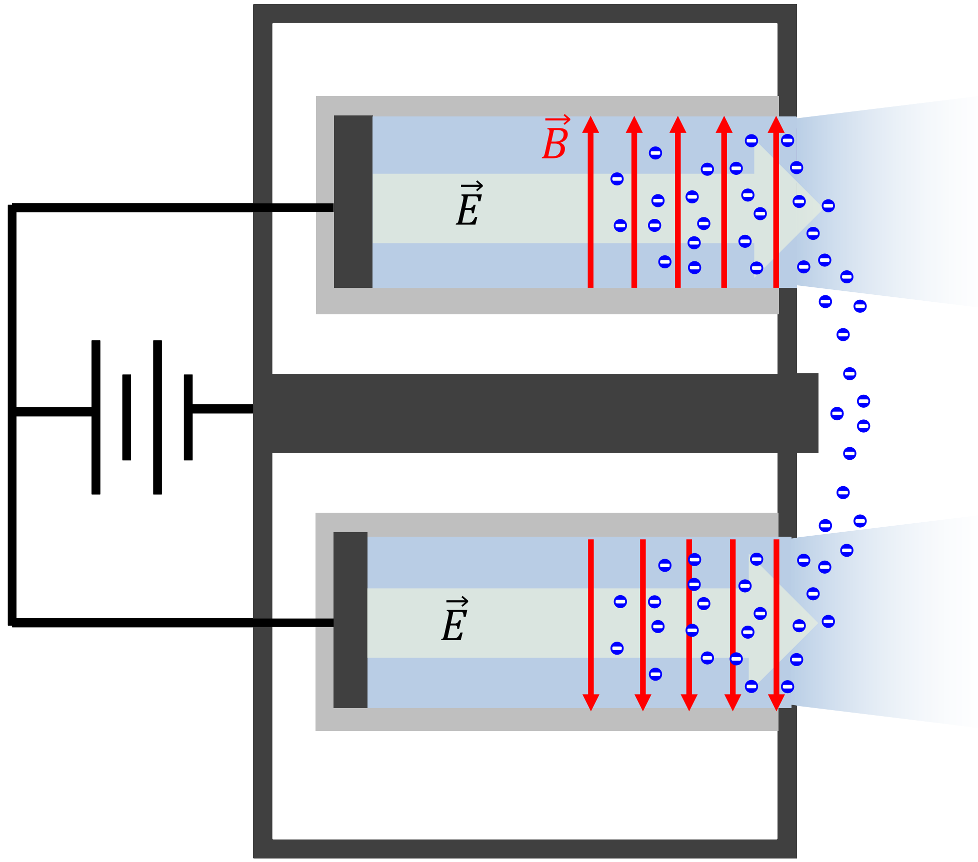
$$j_{\vec{E}\times\vec{B}} = -qn\,\frac{E}{B}$$

Electrons caught in E ✖ B drift



$$j_{\vec{E}} = 0$$

No cross-field current



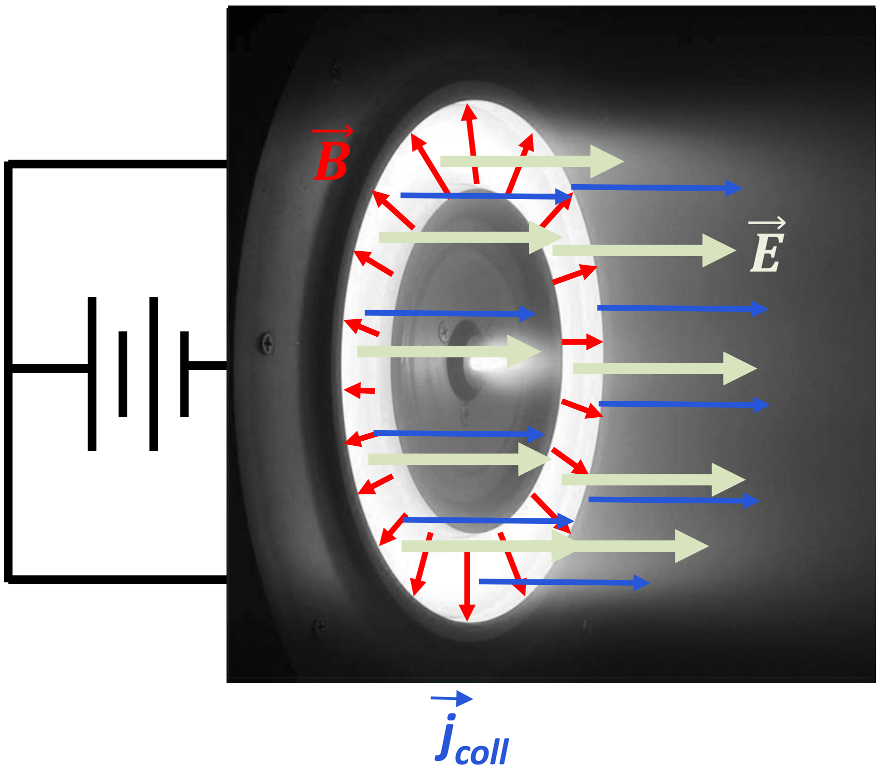
Cross-field Transport in Partially Magnetized Plasmas

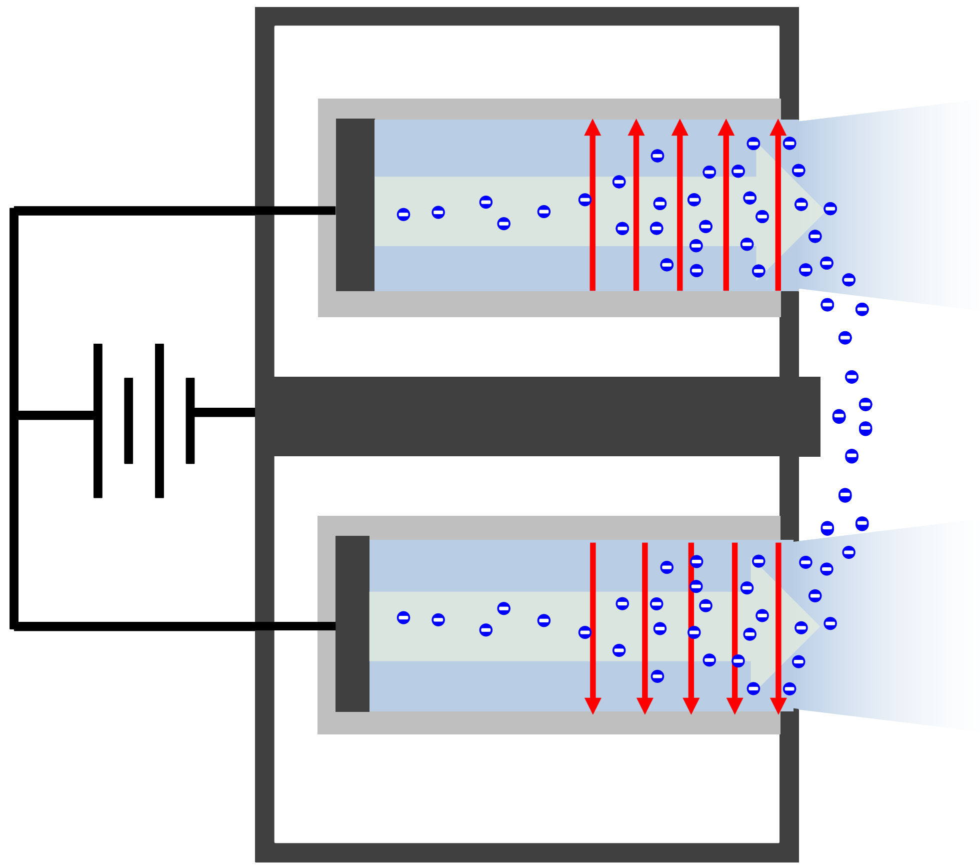
Case 2: Allow for classical electron collisions

$$\Omega_e = \frac{\text{cyclotron frequency}}{\text{collision frequency}}$$

$$j_{\vec{E}(coll.)} = E\frac{1}{\eta(1+\Omega_e^2)}$$

$$\eta = \text{resistivity}$$





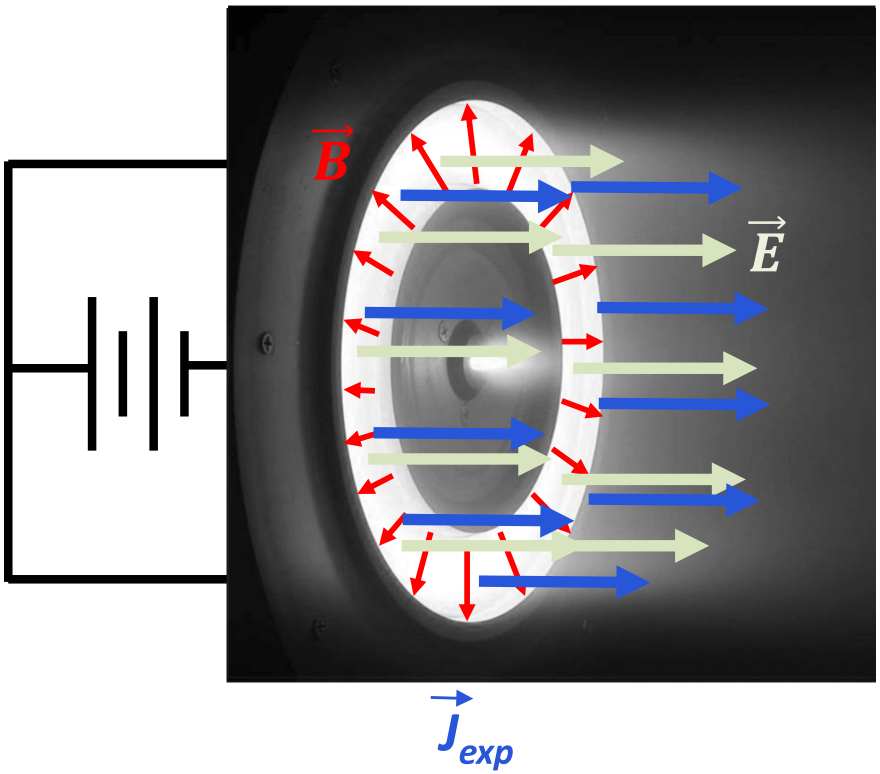
Collisions allow for some electron current to cross field lines

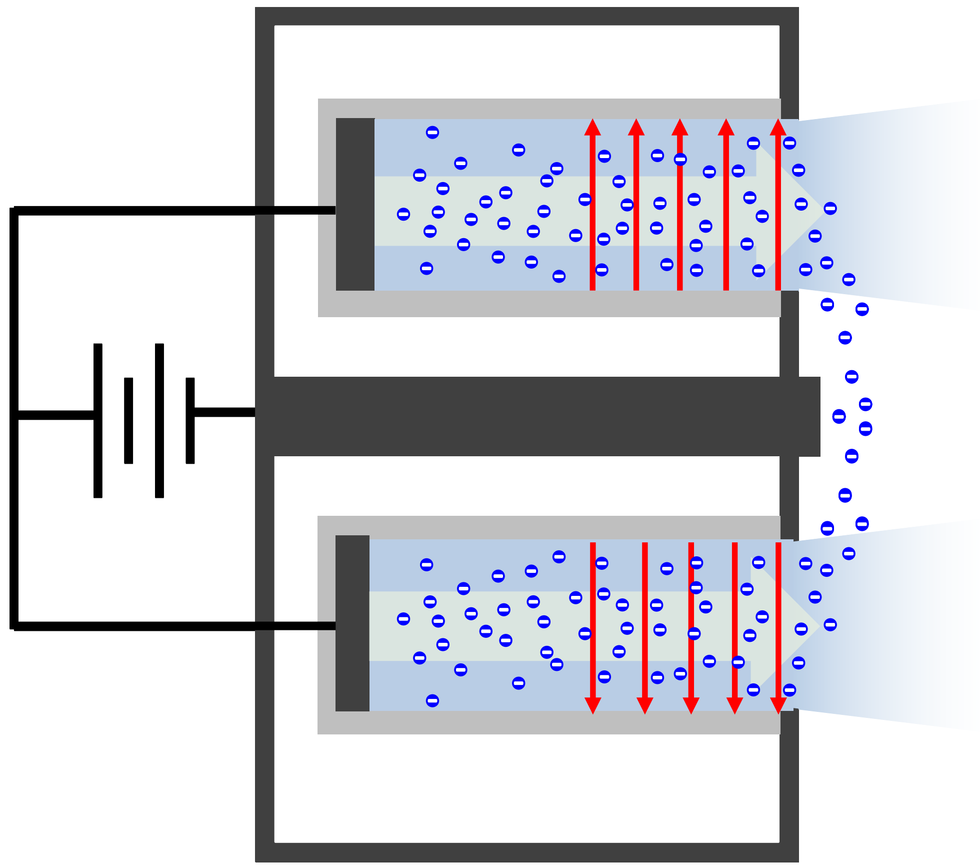
Cross-field Transport in Partially Magnetized Plasmas

Case 3: Experimental observations

$$j_{\vec{E}(\text{exp.})} \gg j_{\vec{E}(coll.)}$$

Experimental measurements show cross-field current orders of magnitude higher than transport induced by collisions





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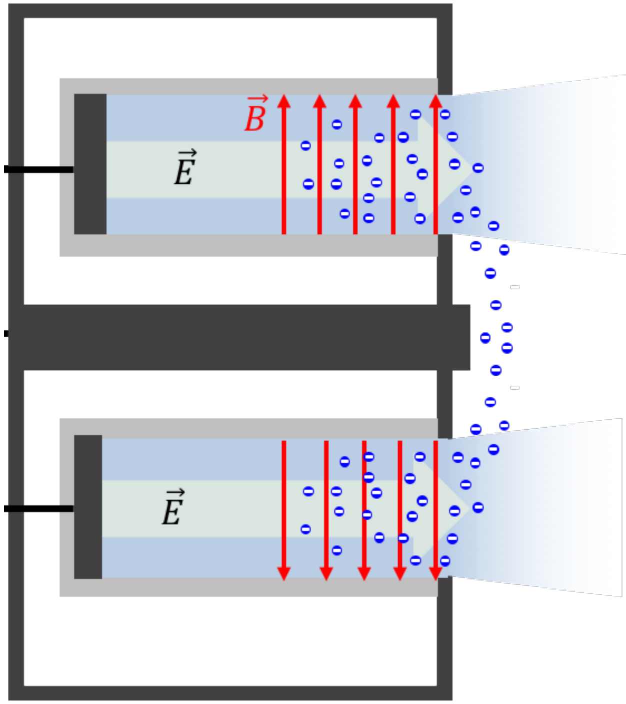

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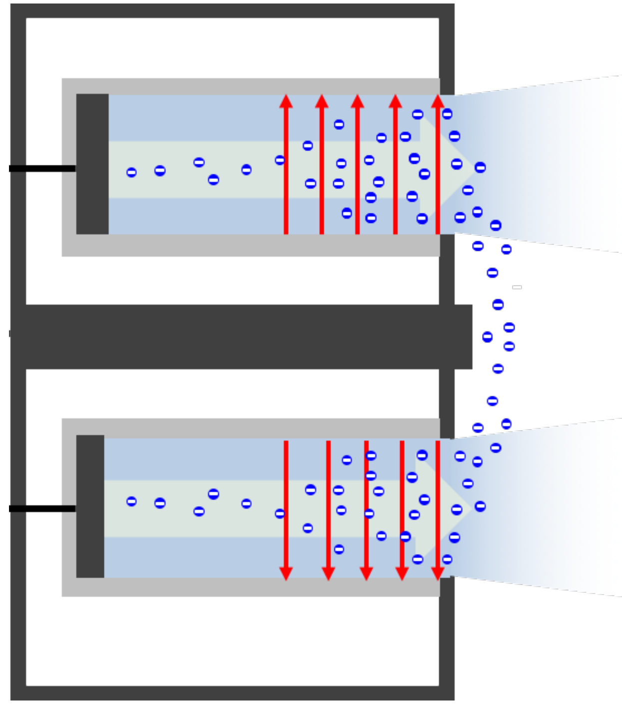
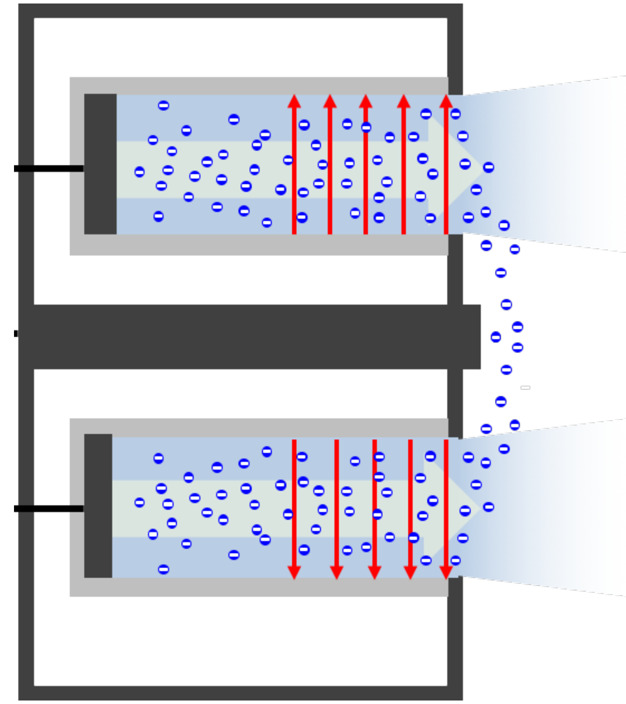


Classical transport from particle collisions



Experimentally-observed, anomalous transport

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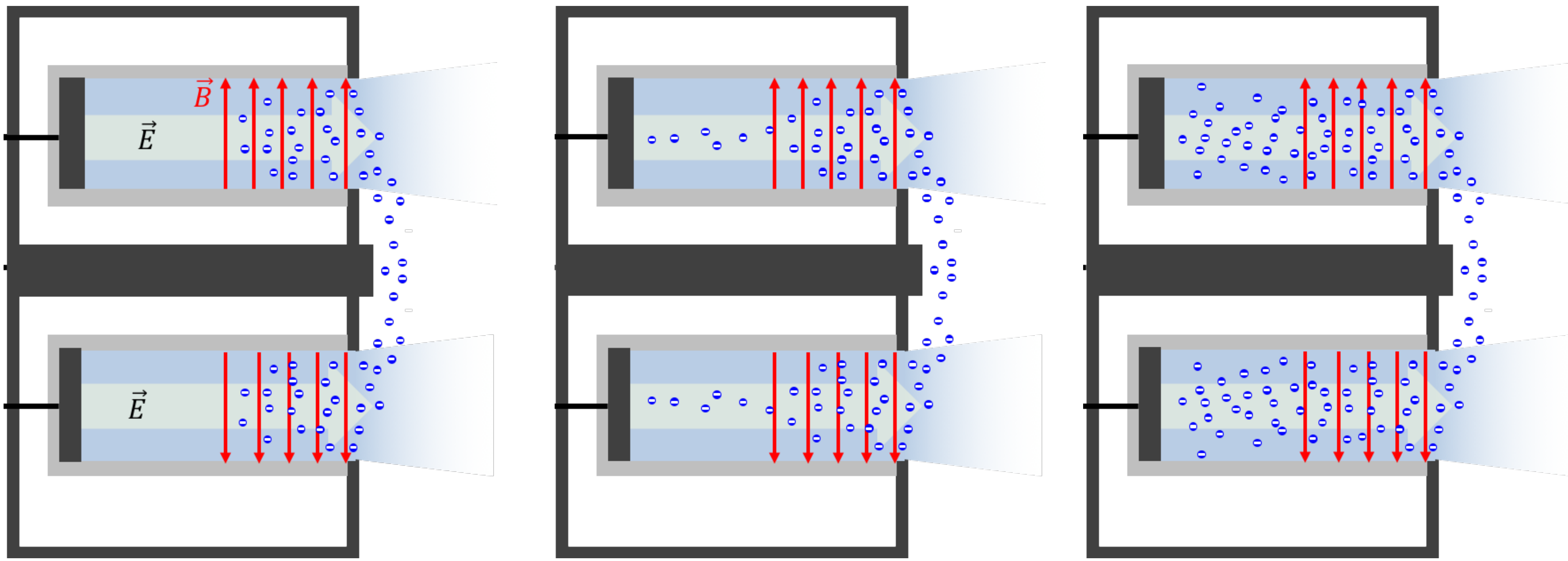

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Adversely impacts efficiency

Precludes predictive models

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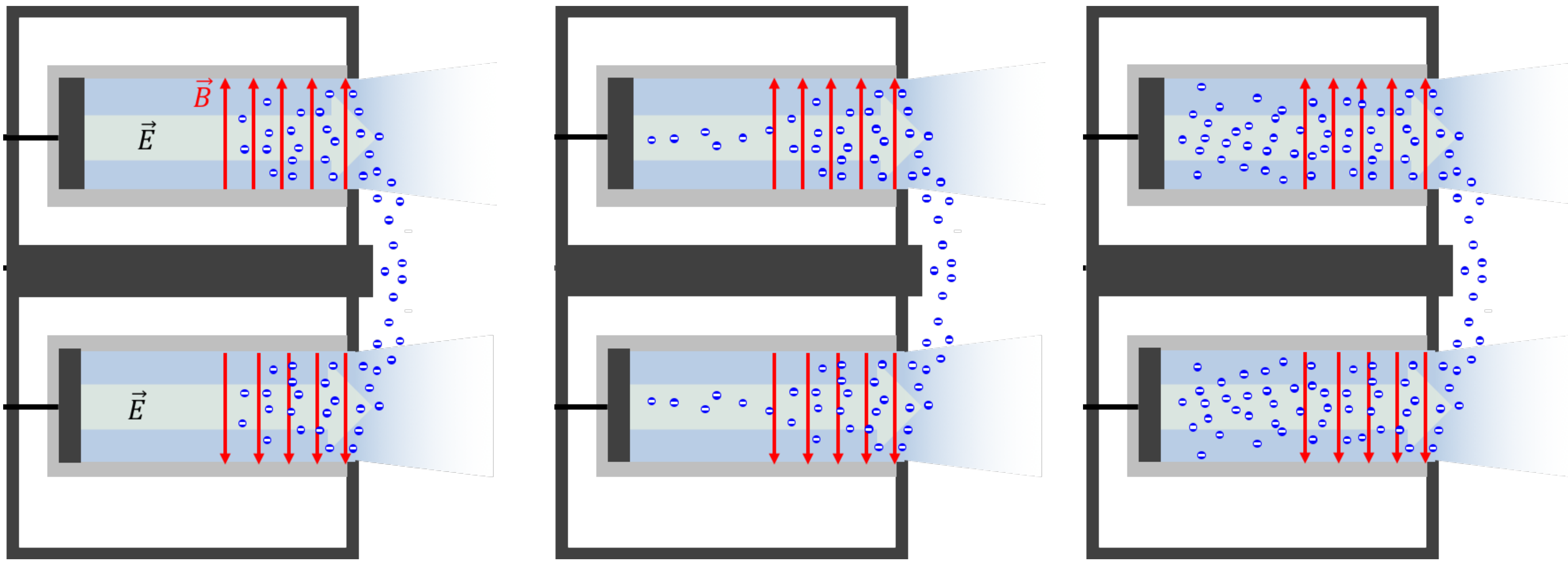

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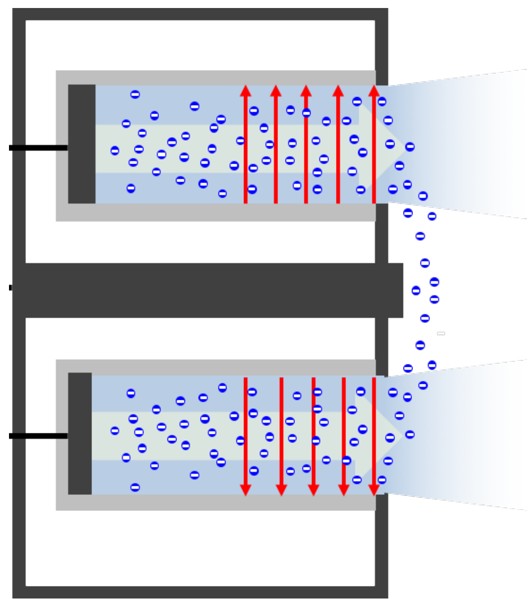
Cross-field Transport in Partially Magnetized Plasmas

What drives this cross-field transport?

What anomalous force drives the transport?

Bohm Diffusion

Wall Interactions



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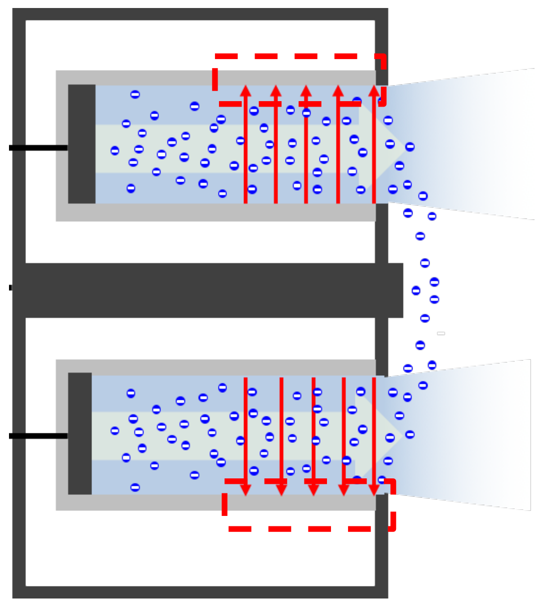

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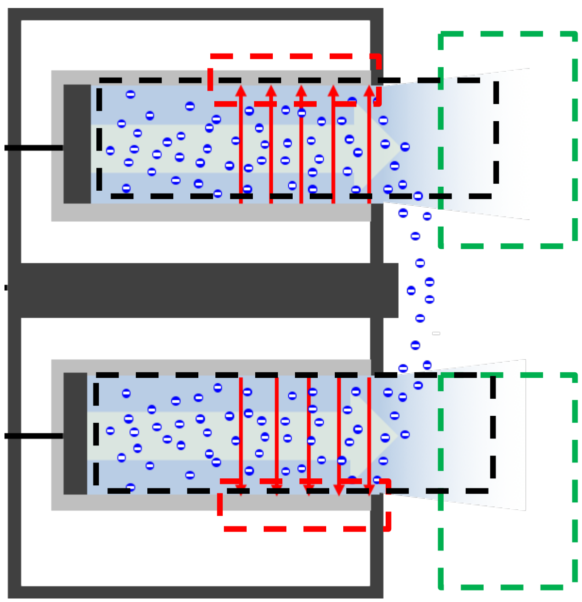

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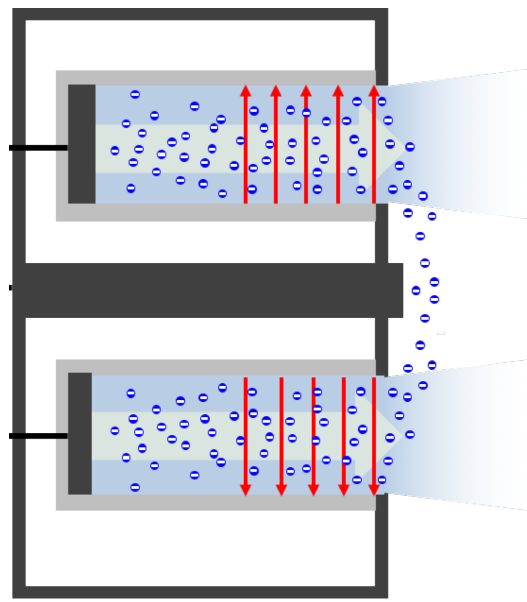
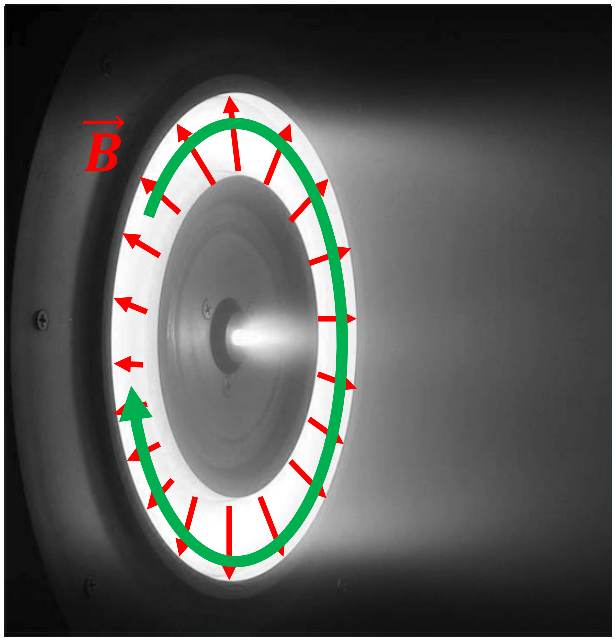


Instabilities

How can oscillations drive transport?



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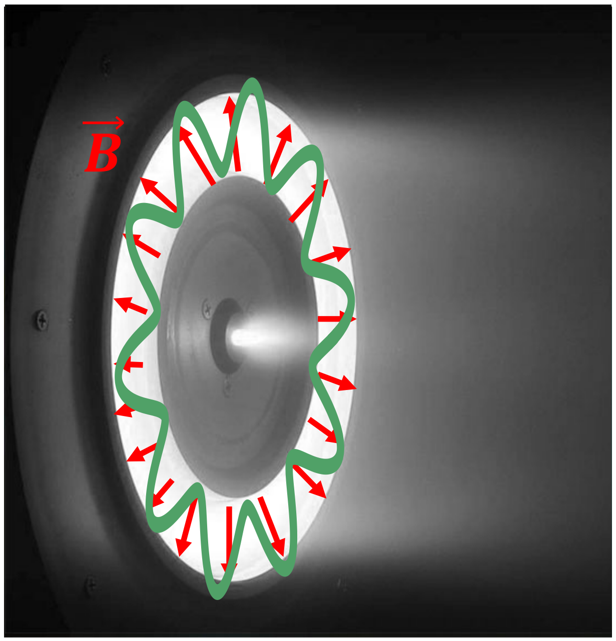

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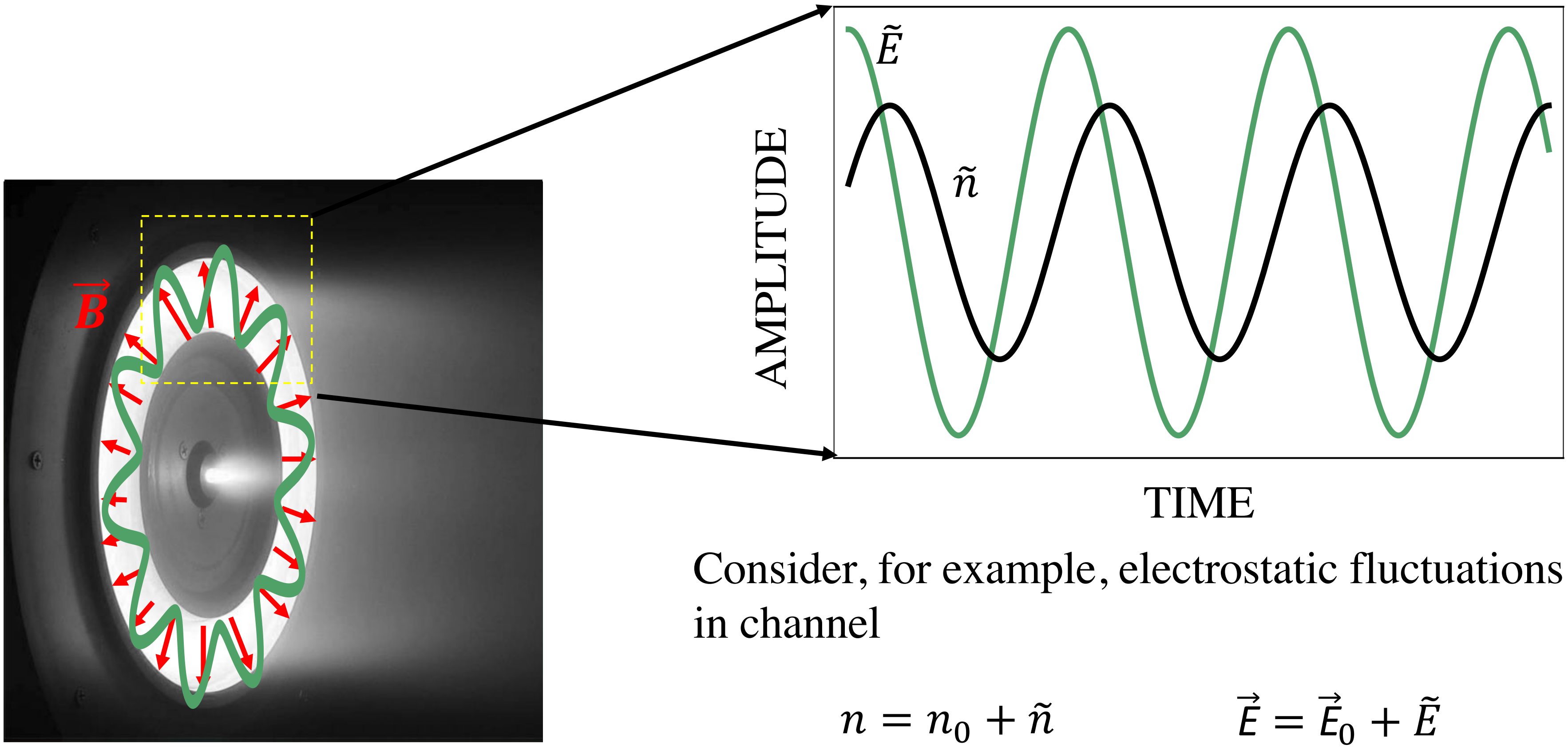

Consider, for example, electrostatic fluctuations in channel

$$n = n_0 + \tilde{n} \qquad \vec{E} = \vec{E}_0 + \tilde{E}$$

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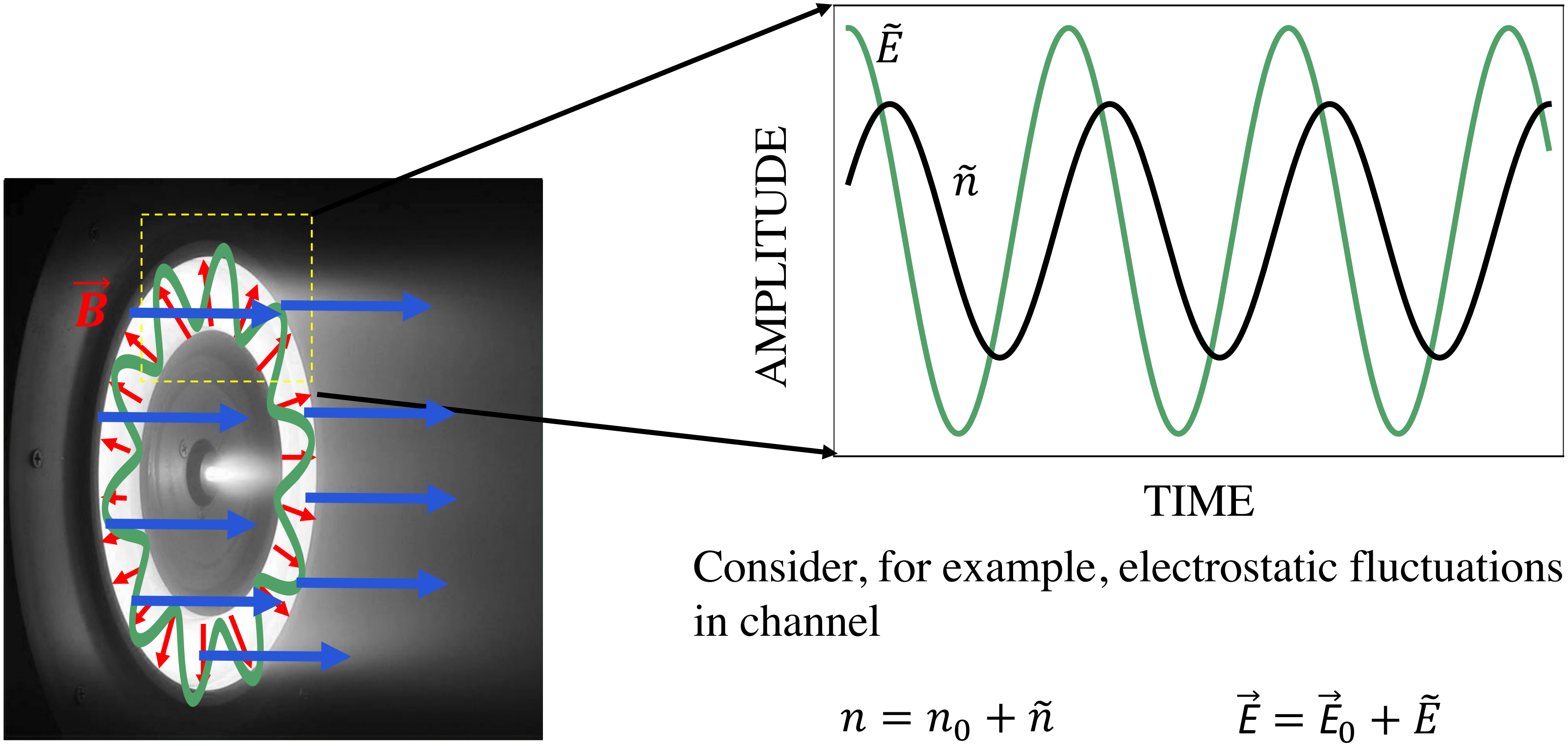

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Ohm's Law in limit of $\Omega_e \gg 1$

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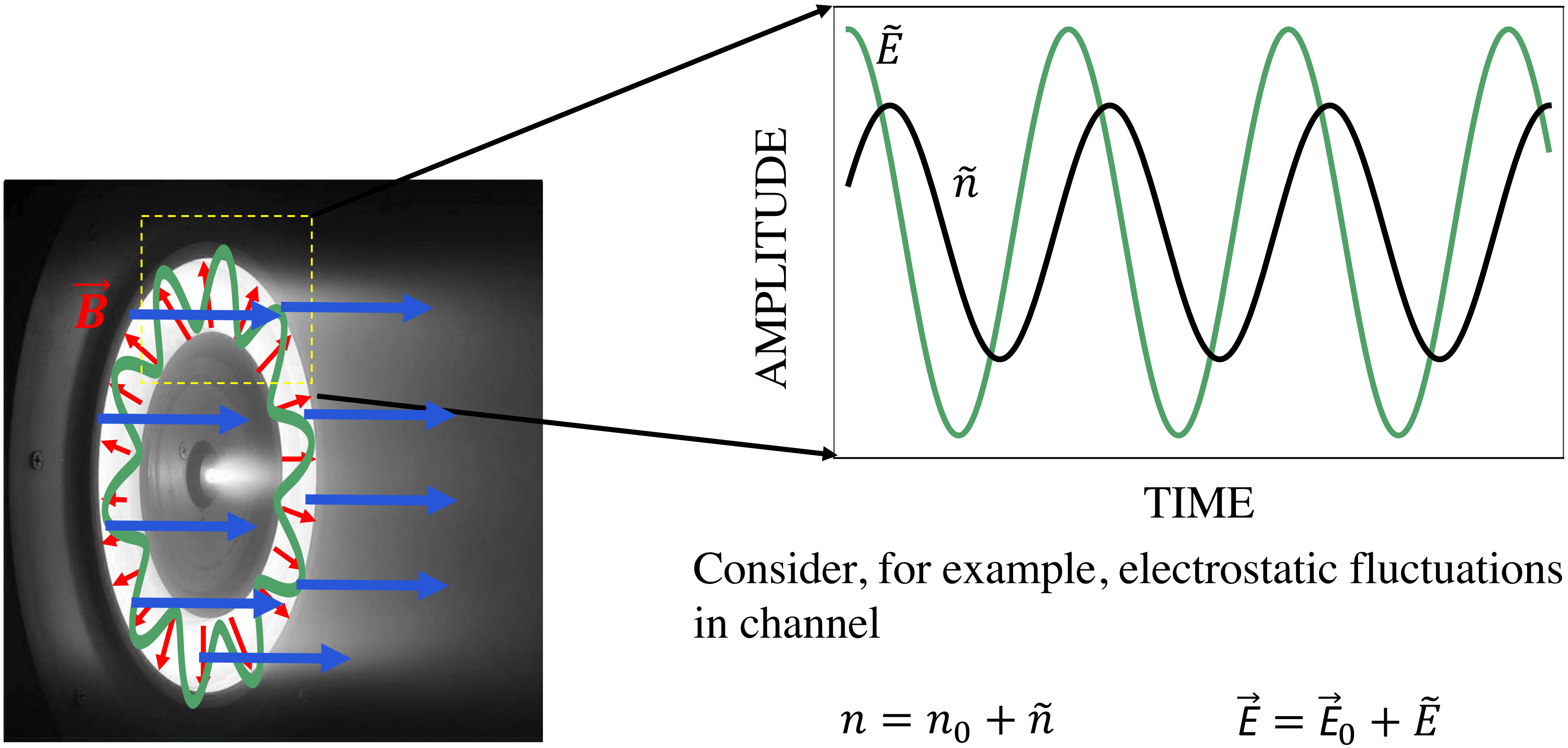

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Fluctuations in electric field and density in Hall direction can lead to cross-field transport

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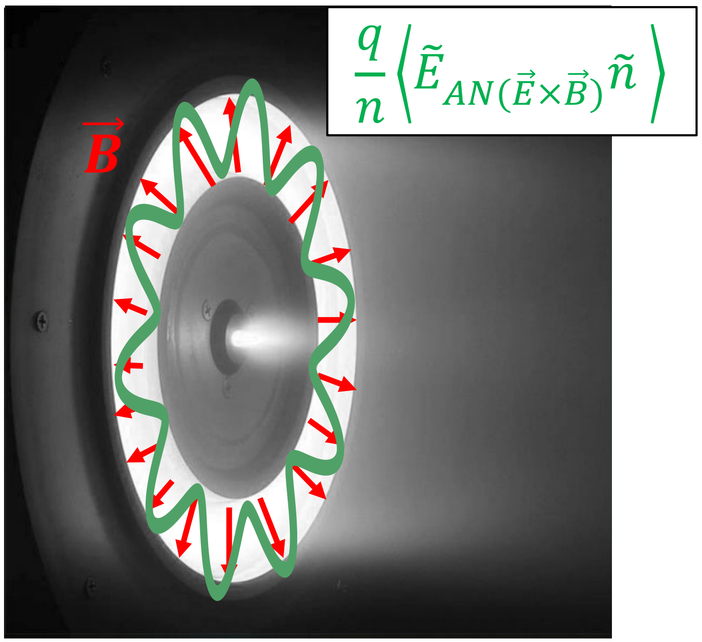

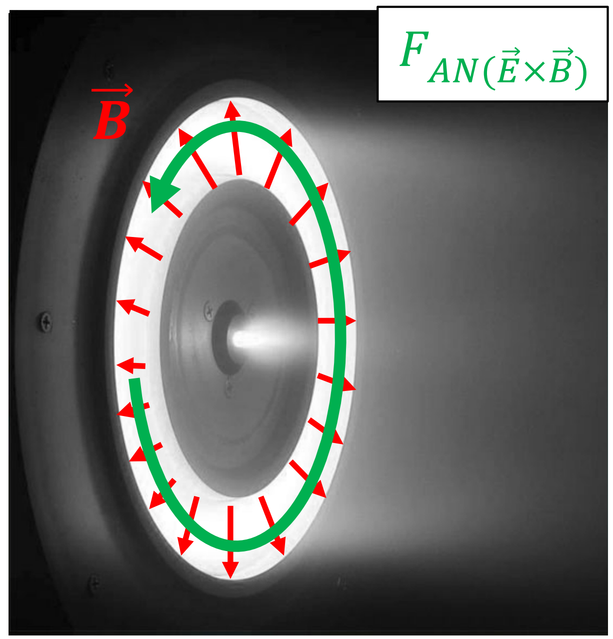

Physical interpretation: Electric field from oscillation **in Hall direction** provides anomalous "force" necessary to drive cross-field current

$$j_{\vec{E}} = \frac{q}{B}\left\langle \tilde{E}_{AN(\vec{E}\times\vec{B})}\tilde{n}\right\rangle \qquad j_{\vec{E}} = n\frac{F_{AN(\vec{E}\times\vec{B})}}{B}$$

How can oscillations drive transport?

There are many types of oscillations in Hall thrusters:

What plasma modes are present in the accelerator that can provide this force?

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PHYSICS OF PLASMAS VOLUME 8, NUMBER 4 APRIL 2001

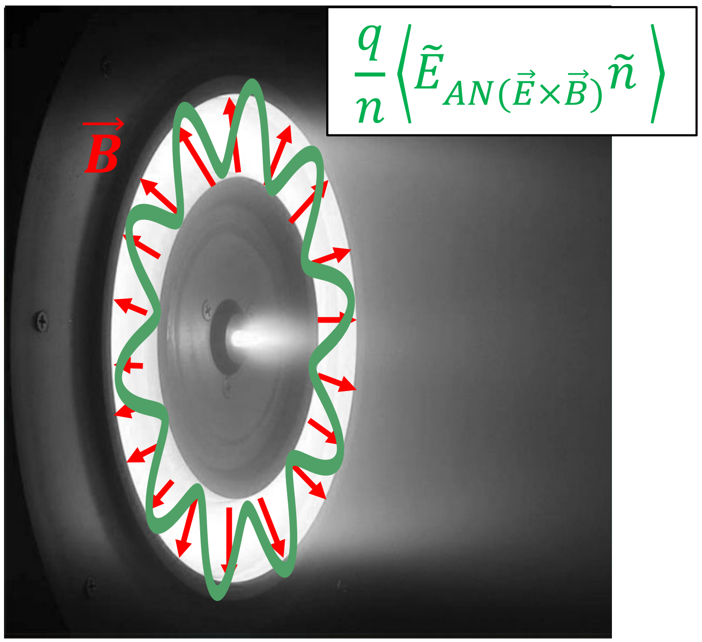
Plasma oscillations in Hall thrusters

E. Y. Choueiri
Electric Propulsion and Plasma Dynamics Laboratory, Princeton University, Princeton, New Jersey 08540

(Received 27 September 2000; accepted 14 November 2000)

The nature of oscillations in the 1 kHz–60 MHz frequency range that have been observed during operation of Hall thrusters is quantitatively discussed. Contours of various plasma parameters measured inside the accelerating channel of a typical Hall thruster are used to evaluate the various stability criteria and dispersion relations of oscillations that are suspected to occur. A band by band up-to-date overview of the oscillations is carried out with a description of their observed behavior and a discussion of their nature and dependencies through comparison of the calculated contours to reported observations. The discussion encompasses the excitation of low frequency azimuthal drift waves that can form a rotating spoke, axially propagating ''transit-time'' oscillations, azimuthal drift waves, ionization instability-type waves, and wave emission peculiar to weakly ionized inhomogeneous plasmas in crossed electric and magnetic fields. [DOI: 10.1063/1.1354644]

Many possible instabilities with component in Hall direction



- Efforts have focused on identifying modes and their relative contributions to cross-field transport:
  - Resistive drift-waves
  - Spoke modes
  - Modified Simon-Hoh instability
  - Electron cyclotron drift instability (ECDI)
  - Ion acoustic-like modes
  - . . .
- Some to most of these instabilities actually exist in Hall effect thrusters and many are active areas of research

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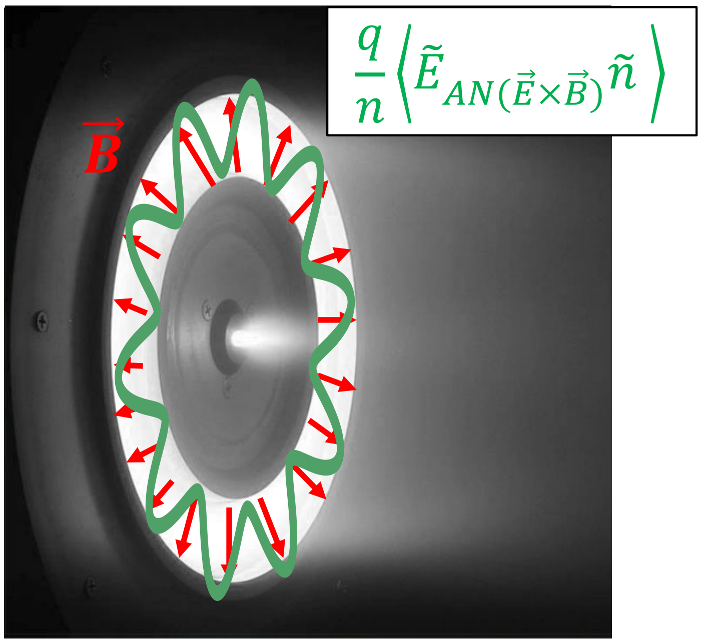

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How do we evaluate which modes are "important" and dominate cross-field transport?

Criteria to evaluate whether an instability drives the cross-field transport

1. Is there evidence that this type of mode should exist in the plasma?

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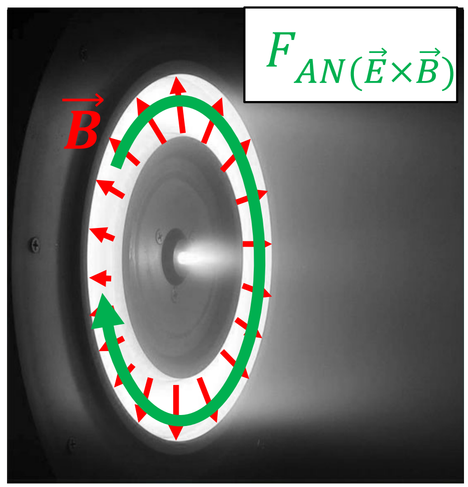
4. Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

Applying criteria to two popular modes for Hall thrusters

Bohm Diffusion

Wall Interactions

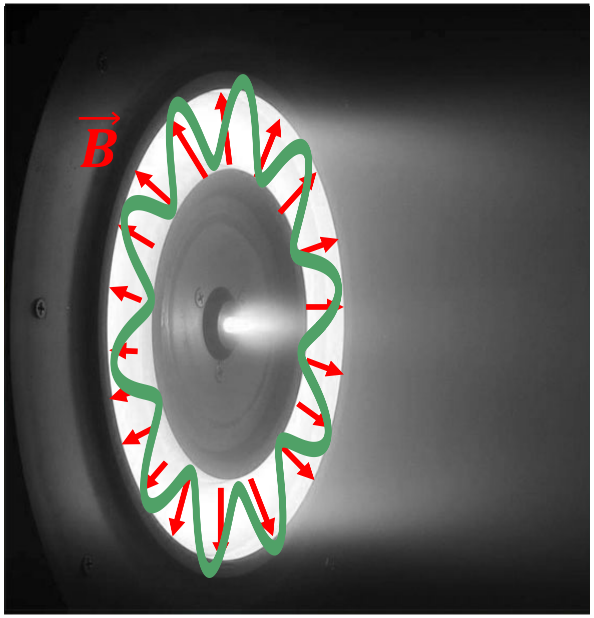


Instabilities

Large-scale fluctuations

Micro fluctuations

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters



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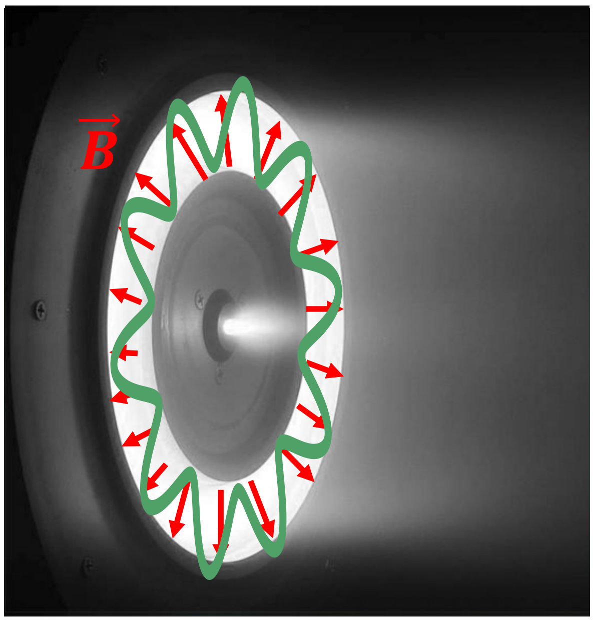

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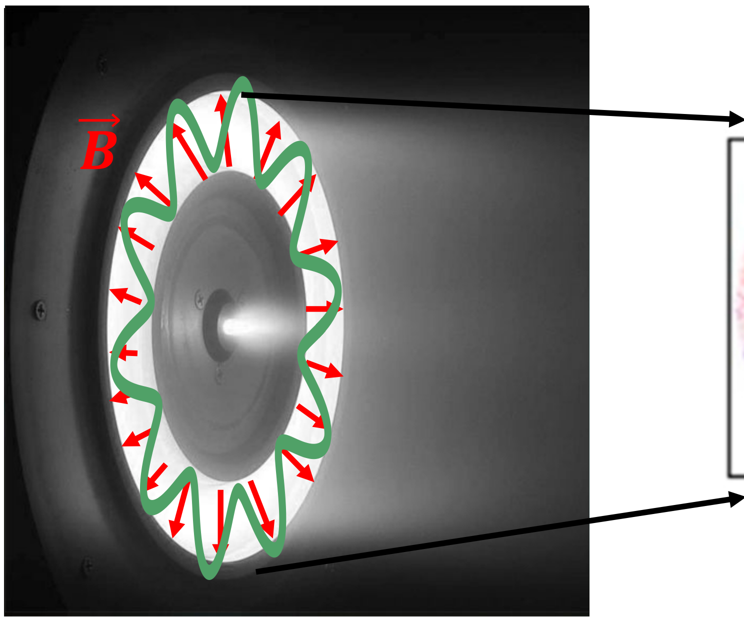
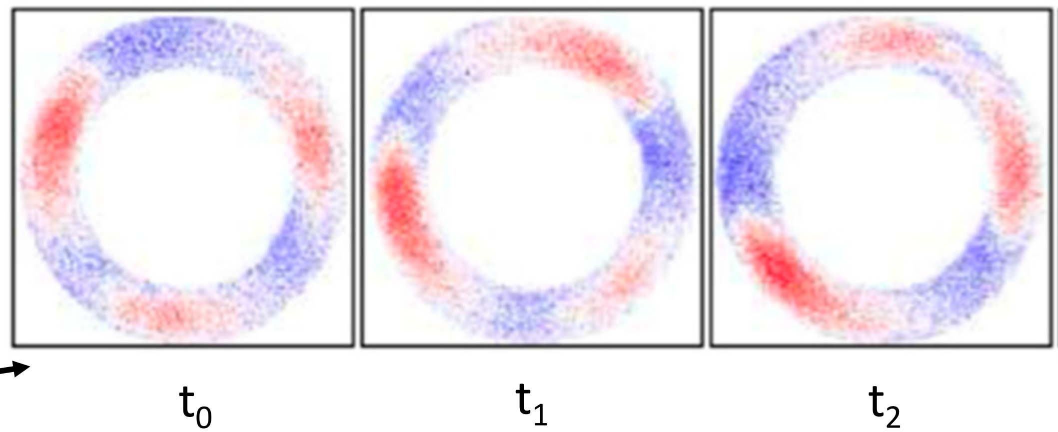


Images from high-speed video of light intensity fluctuations in Hall thruster*



Rotating $m \geq 1$ modes at 20-50 kHz

*M. McDonald, C. Bellant, A. S. Brandon, and A. Gallimore, "Measurement of cross-field electron current in a Hall thruster due to rotating spoke instabilities," AIAA Paper No. 2011-5810, 2011.

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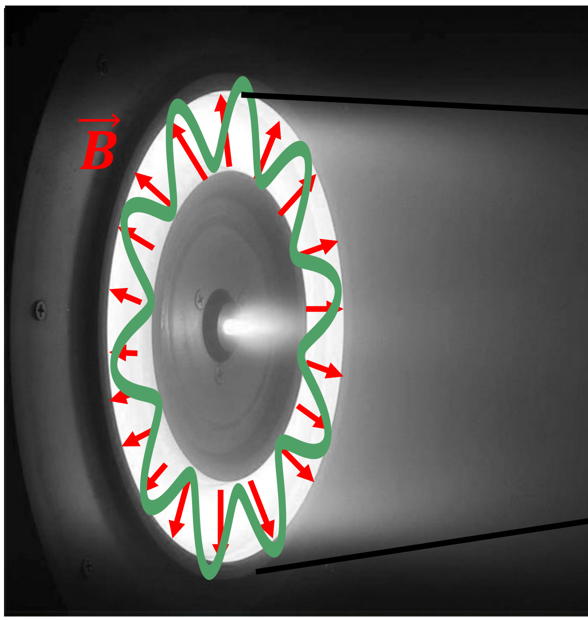
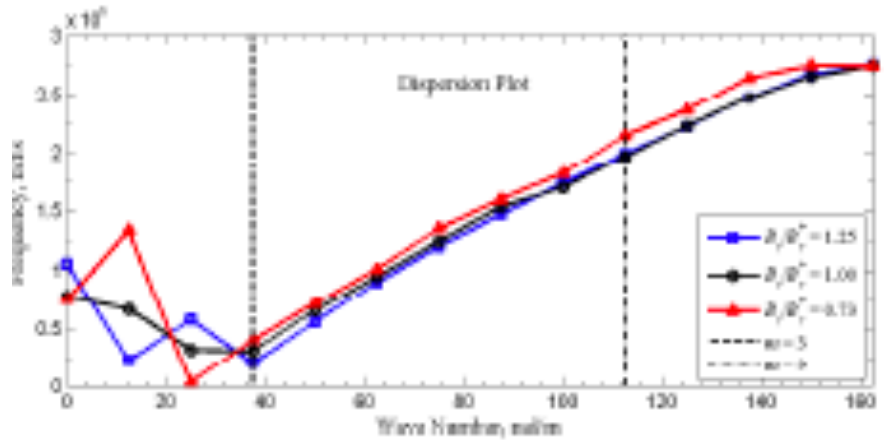


Dispersion relation in the azimuthal direction for the propagating modes*



*M. Sekerak. Ph.D Thesis. University of Michigan. 2013.

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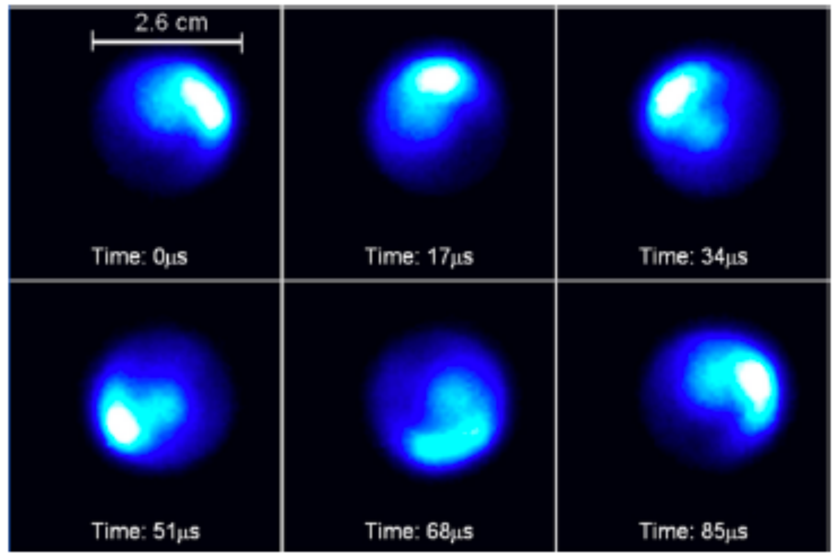
Images from high-speed video of light intensity fluctuations in Cylindrical Hall thruster*



Rotating $m = 1$ modes at 20-50 kHz

*C. L. Ellison, Y. Raitses, and N. J. Fisch, "Cross-field electron transport induced by a rotating spoke in a cylindrical Hall thruster," Phys. Plasmas 19, 013503 (2012).

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

1. Is there evidence that this mode should exist in the plasma?

Other probing studies

- C. S. Janes and R. S. Lowder, "Anomalous electron diffusion and ion acceleration in a low density plasma," Phys. Fluids 9, 1115 (1966).
- E. Chesta, M. Lam, N. B. Meezan, D. Schmidt, and M. A. Cappelli, "A characterization of plasma fluctuations within a Hall discharge," IEEE Trans. Plasma Sci. 29, 582 (2001).
- A. W. Smith and M. A. Cappelli, "Time and space-correlated plasma potential measurements in the near field of a coaxial Hall plasma discharge," Phys. Plasmas 16, 073504 (2009).

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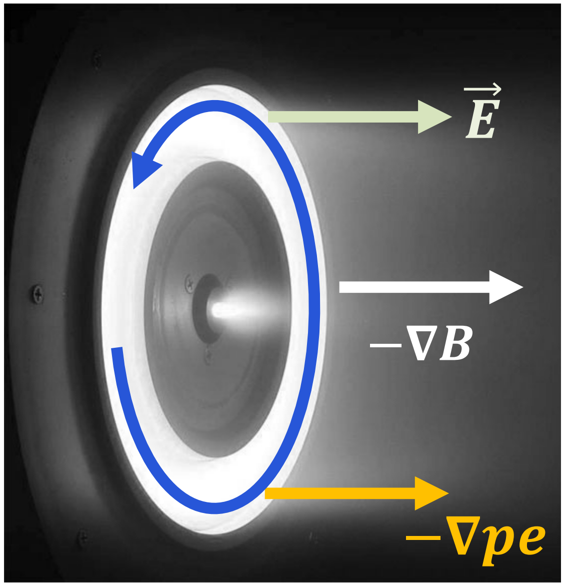
What is the mode?



- Gradients in plasma act as free source of energy driving stabilizing electron drift in Hall direction

- A number of modes can result, but the nature of the mode in the thruster is still unclear

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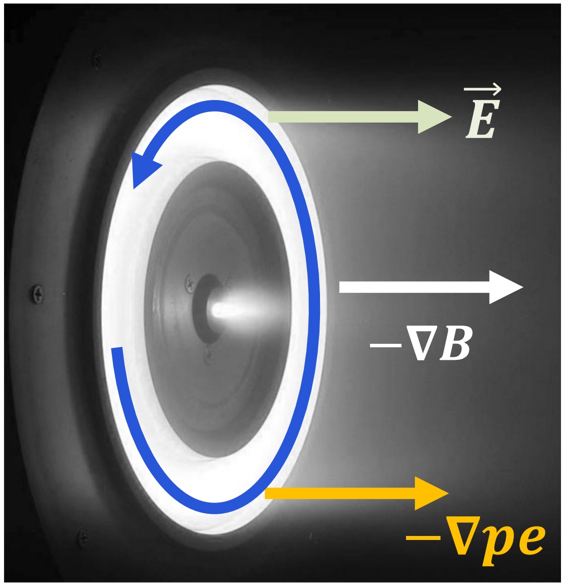

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Some potential candidates

- Modified Simon-Hoh instability*
- Ionization related mode**
- Energy transfer from kinetically-driven short wave length oscillations***

*W. Frias, A. I. Smolyakov, I. D. Kaganovich, and Y. Raitses, "Long wavelength gradient drift instability in Hall plasma devices. I. Fluid theory," Phys. Plasmas 19, 072112 (2012).

**D. Escobar and E. Ahedo. "Low frequency azimuthal stability of the ionization region of the Hall thruster discharge. I. Local analysis." Phys. Plasmas 21, 043505 (2014)

***S. Janhunen, A. Smolyakov, and O. Chapurin. "Non-linear structures and anomalous transport in partially magnetized plasma driven by the transverse current."

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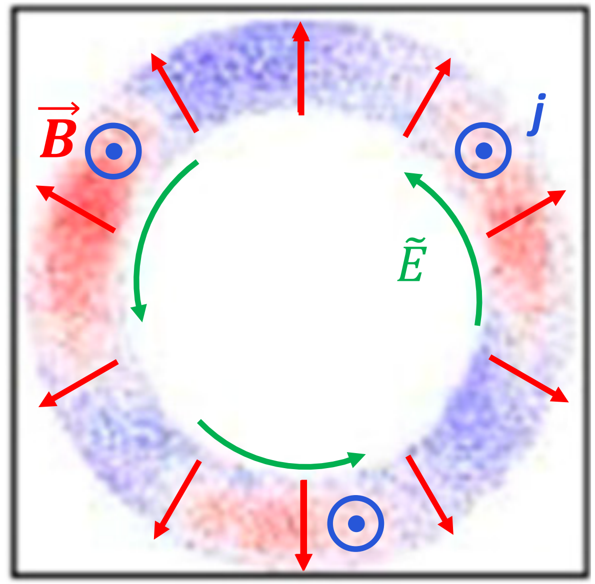
- A number of modes can result, but the nature of the mode in the thruster is still unclear

How does it move electrons?



Electric field perturbations in Hall direction in phase with density fluctuations lead to cross field transport

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

3. Is there evidence that this mode is sufficiently strong to drive observed cross-field electron transport?

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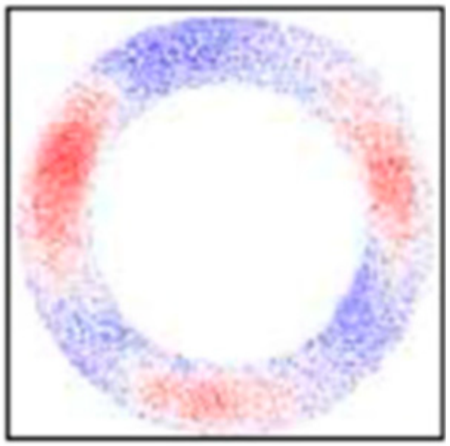

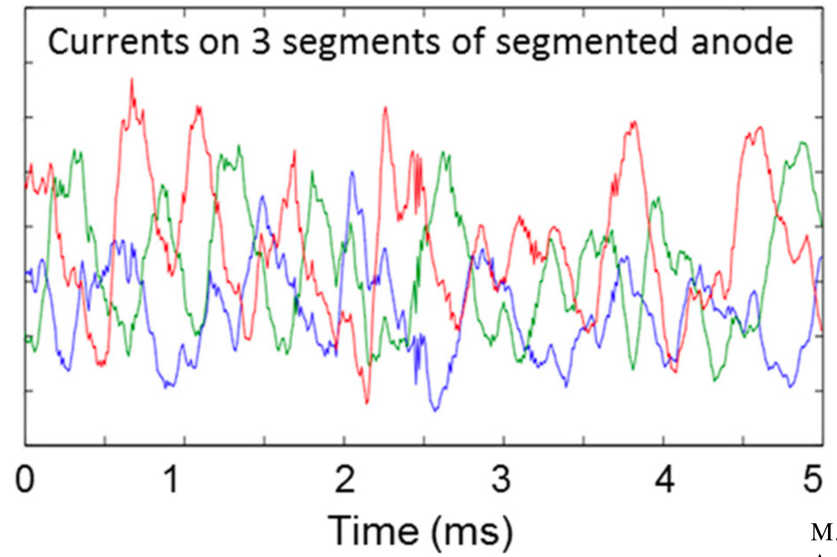

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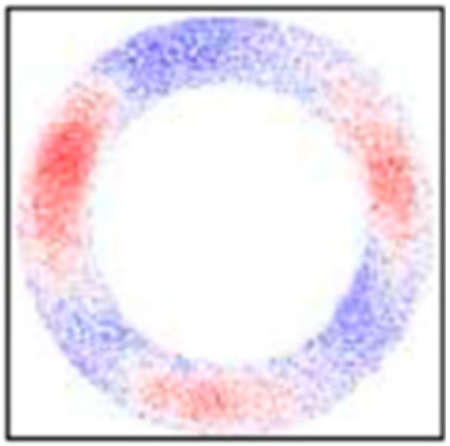

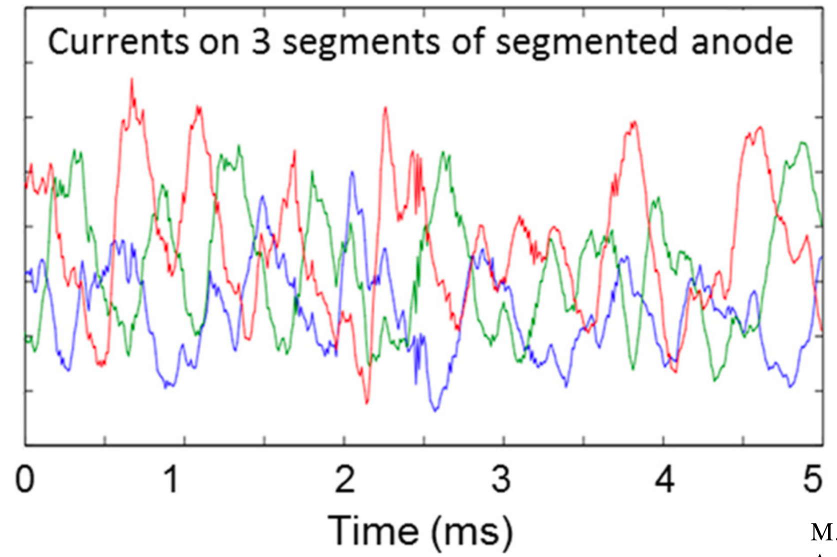

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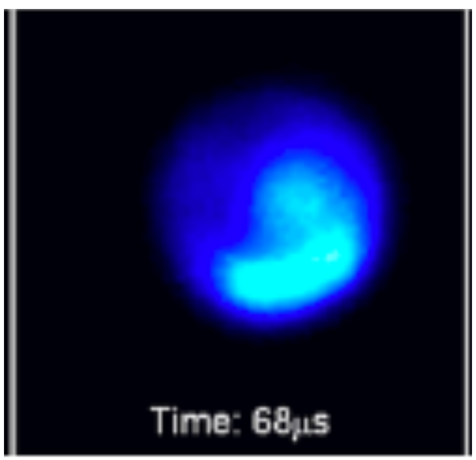

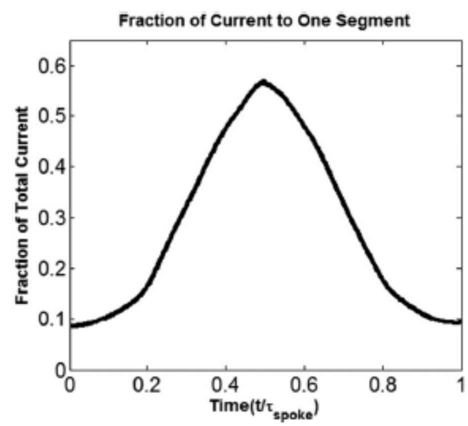

C. L. Ellison, Y. Raitses, and N. J. Fisch, Phys. Plasmas 19, 013503 (2012).

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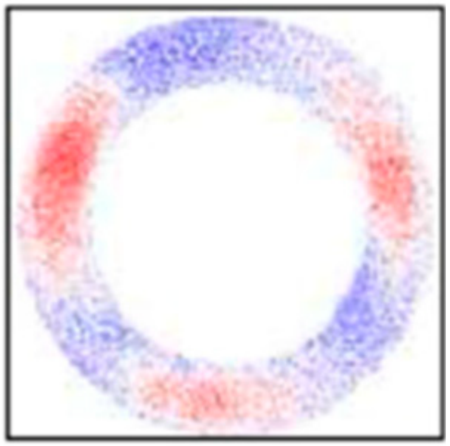

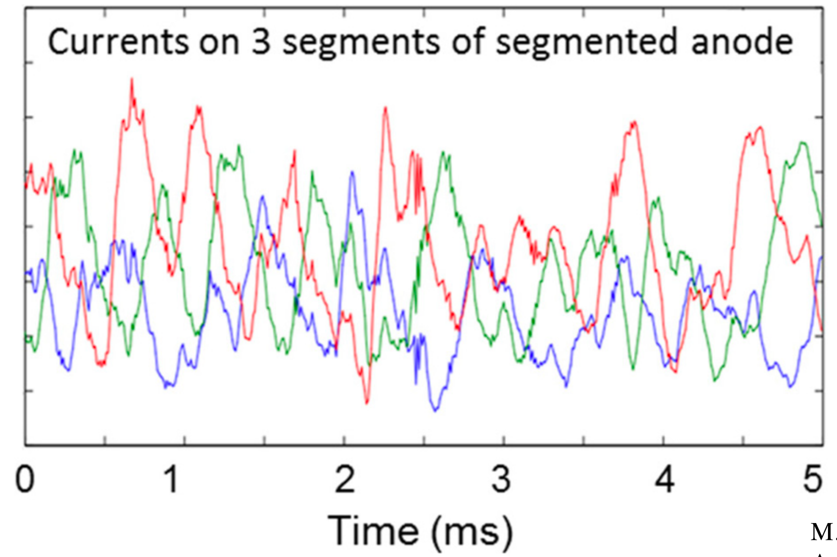

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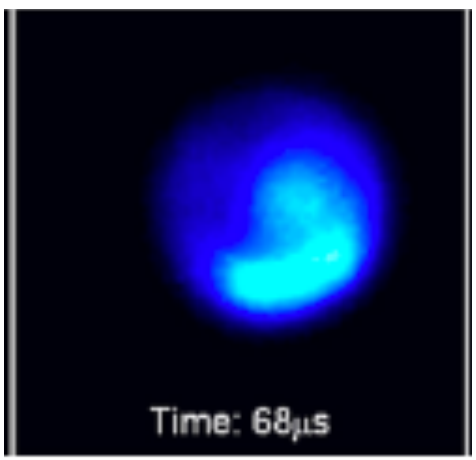

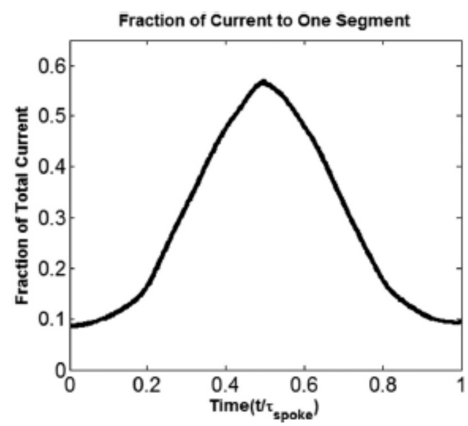

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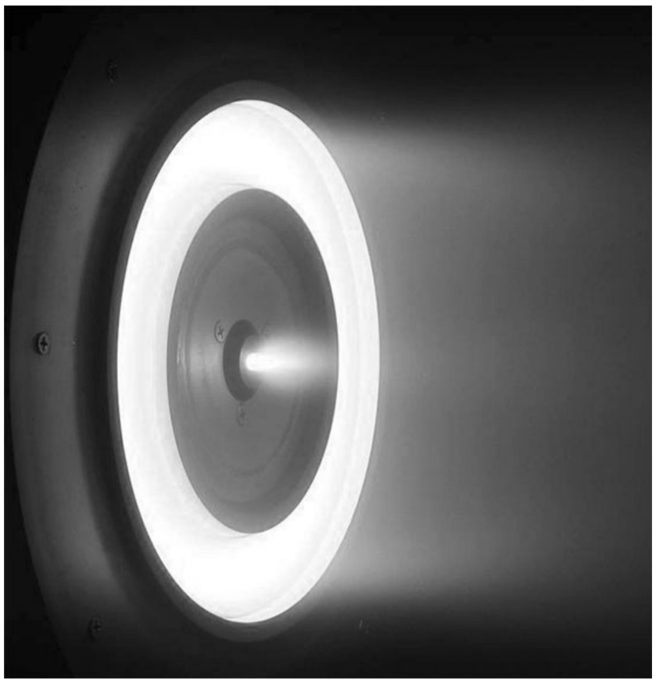
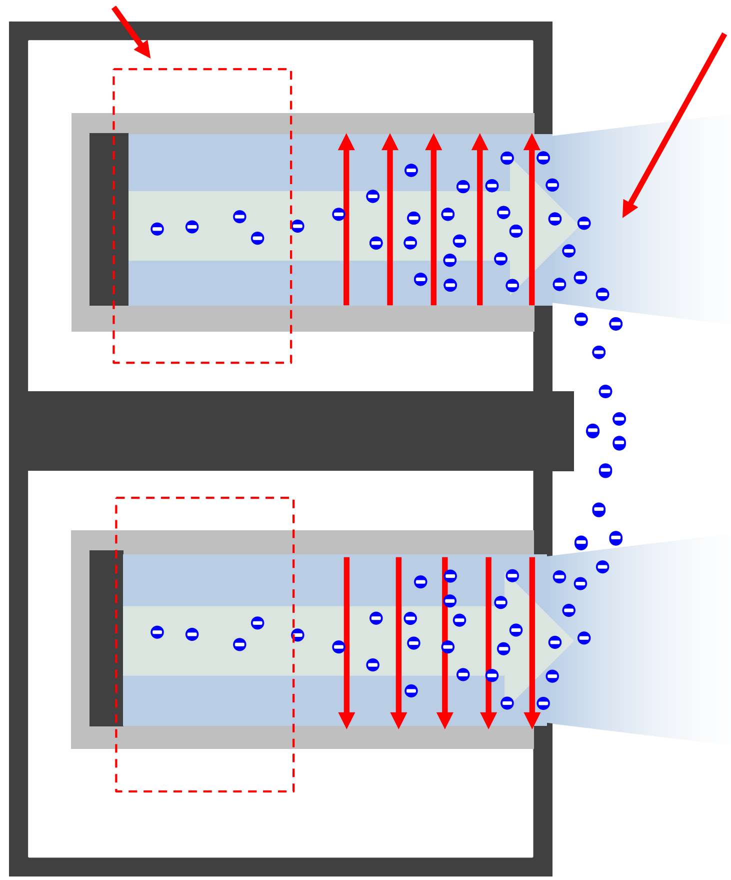
Both studies showed 50% of electron current is conducted by spoke across field lines,
but there are caveats

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

3. Is there evidence that this mode is sufficiently strong to drive observed cross-field electron transport?





Some experimental evidence suggests spoke only exists near anode, but majority of anomalous diffusion is needed downstream

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

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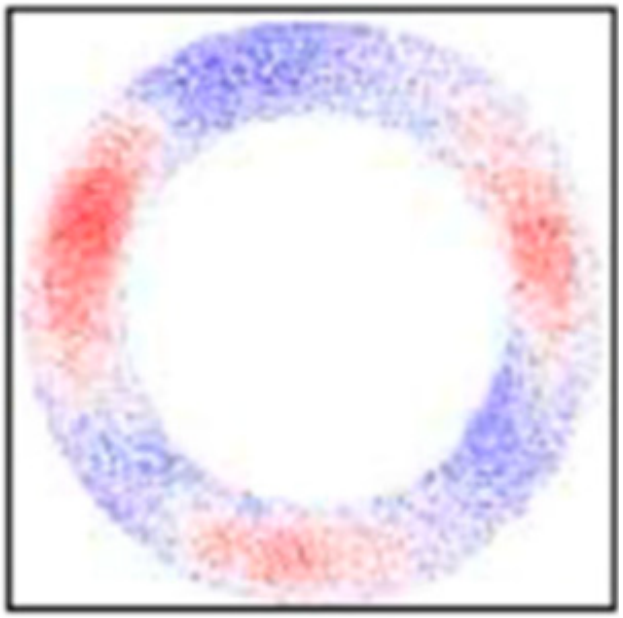
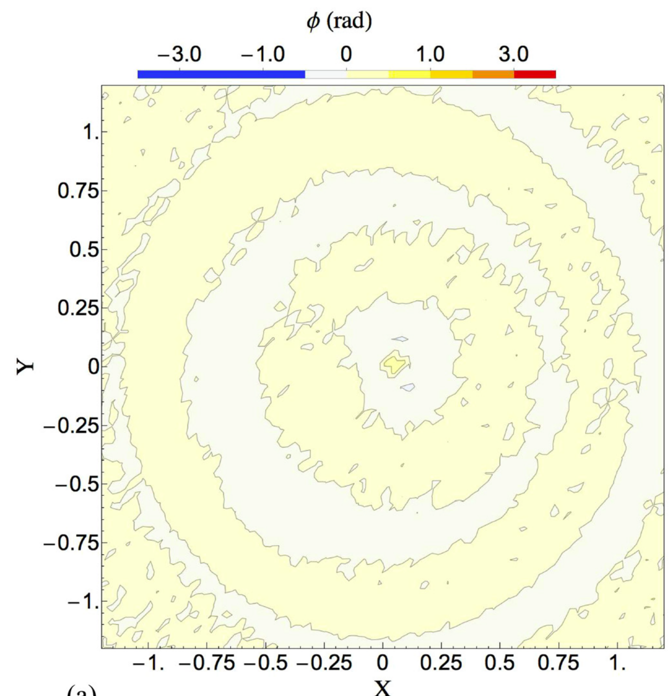
Traditional 6-kW thruster*



Magnetically shielded 6-kW thruster**



(a)

Spoke doesn't exist in all thrusters, but yet they operate in the same way

*M. McDonald, C. Bellant, A. S. Brandon, and A. Gallimore, AIAA2011-5810, 2011.

**B. Jorns and R. Hofer. "Plasma Oscillations in a 6-kW Magnetically Shielded Hall Thruster," Physics of Plasmas 21 , 053512 (2014);

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

4. Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

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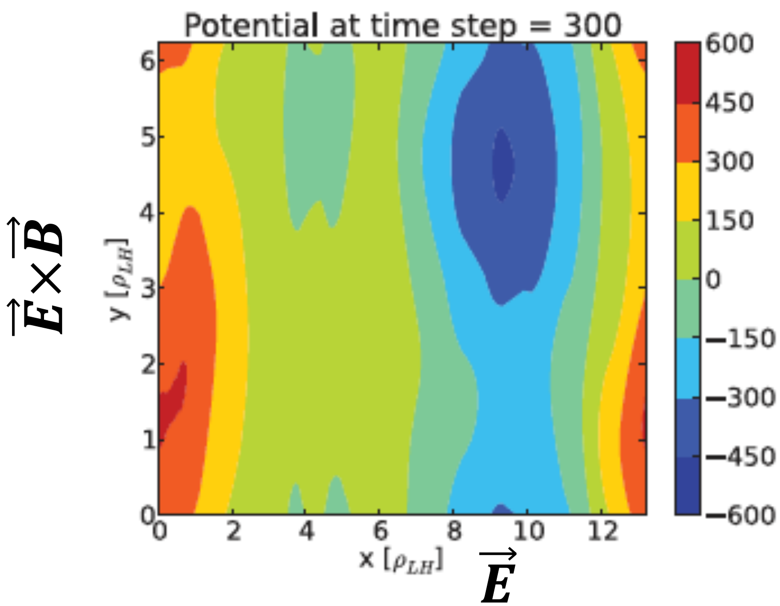
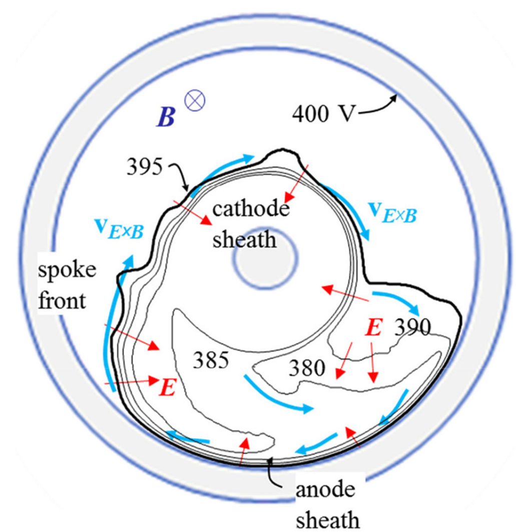
Nonlinear fluid simulations*



2D Particle-in-Cell**



*A. Smolyakov et al, "Fluid theory and simulations of instabilities, turbulent transport and coherent structures in partially-magnetized plasmas of ExB discharges," Plasma Phys. Control. Fusion 59 (2017) 014041.

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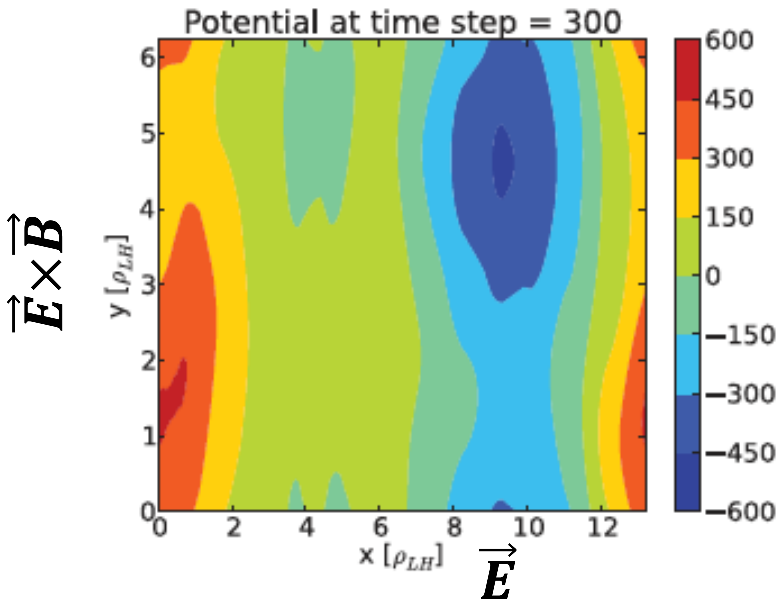

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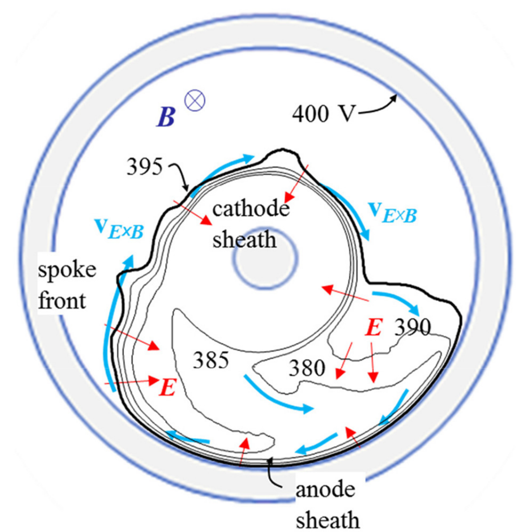

Simulations to date show that modes can onset and contribute to cross-field transport

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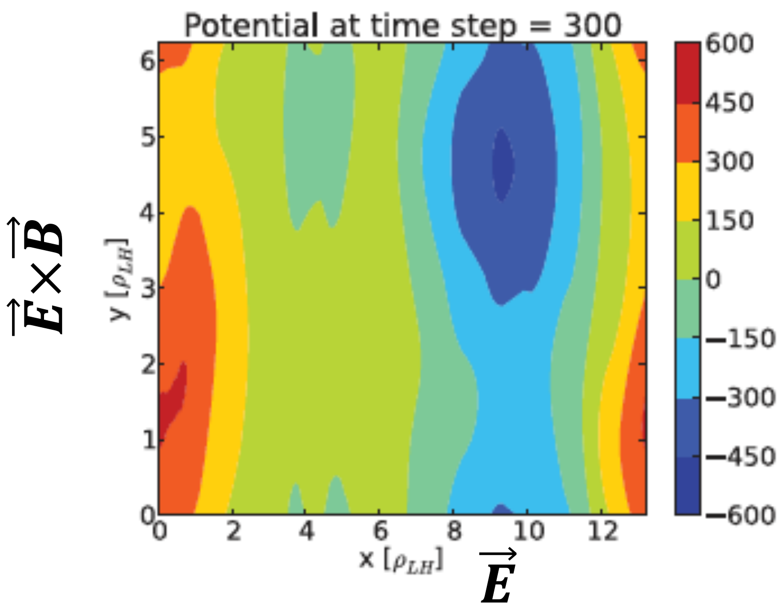

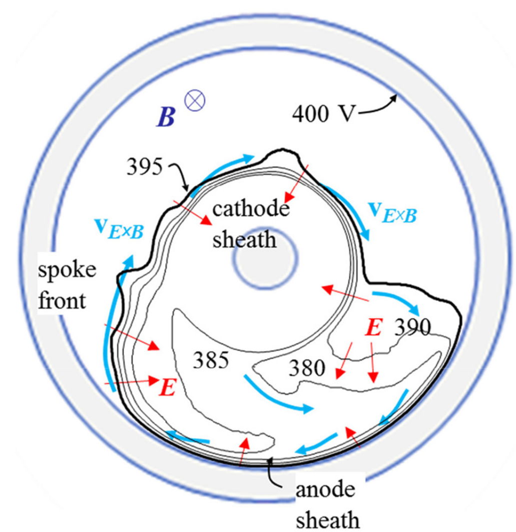

Simulations to date show that modes can onset and contribute to cross-field transport

- Not clear if cross-field current is "enough"
- ". . .the mechanism for spoke formation is still not clear"*
- Models do not yet have fidelity for capturing actual thruster geometry

*A. Smolyakov et al, "Fluid theory and simulations of instabilities, turbulent transport and coherent structures in partially-magnetized plasmas of ExB discharges," Plasma Phys. Control. Fusion 59 (2017) 014041.

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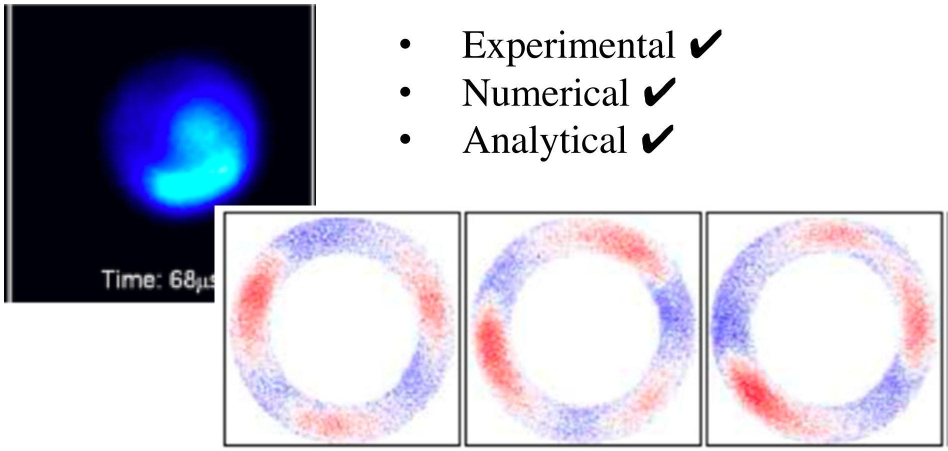
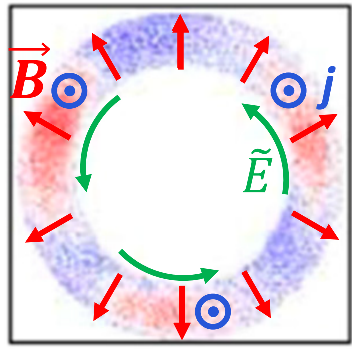
Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

Is there evidence that this mode should exist in the system?



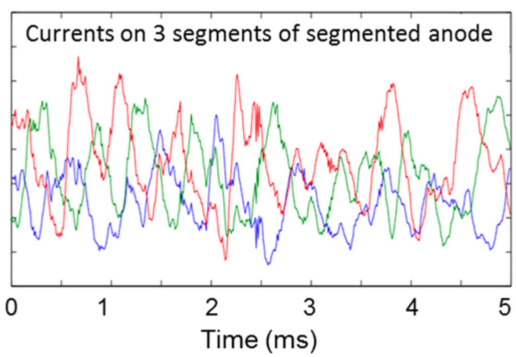
- Experimental ✔
- Numerical ✔
- Analytical ✔

Is there a first-principles explanation for this mode and how it impacts electron transport?



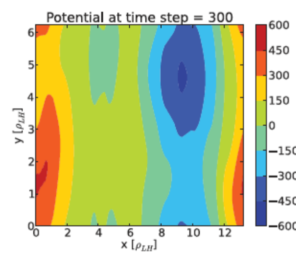
- Energy source from gradients ✔
- Transport due to electric field perturbations in Hall direction ✔

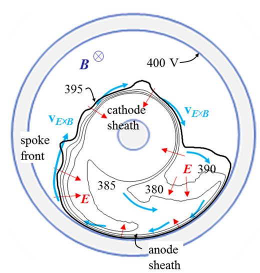
Is there evidence that this mode is sufficiently strong to drive observed cross-field electron transport?



- Direct measurements of cross-field current from this mode ✔
- However, current is not necessarily in right place (?)
- Mode not ubiquitous (?)

Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?





- Multiple hierarchies being explored that predict some level of transport ✔
- Models are still simplified geometries (?)
- Not clear if this is dominant effect (?)

Case Study 1: Long-wavelength, azimuthal structures in Hall thrusters

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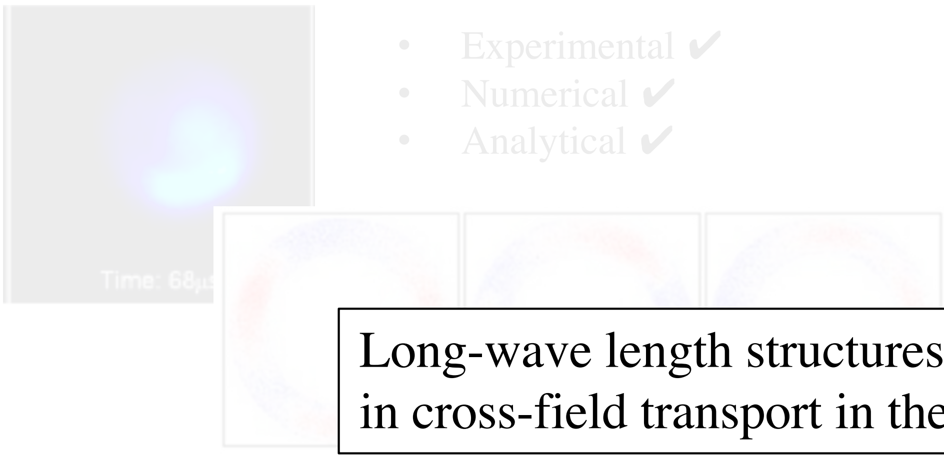

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Is there a first-principles explanation for this mode and how it impacts electron transport?

- Energy source from gradients ✔
- Transport due to electric field ...rbations in Hall direction ✔

Long-wave length structures may play an important role in cross-field transport in these devices

Is there evidence that this mo... drive observed cross-field elec...

On-going area of research

...on transport be modeled self-... ...ed transport dominant?

- Direct measurements of cross-field current from this mode ✔
- However, current is not necessarily in right place (?)
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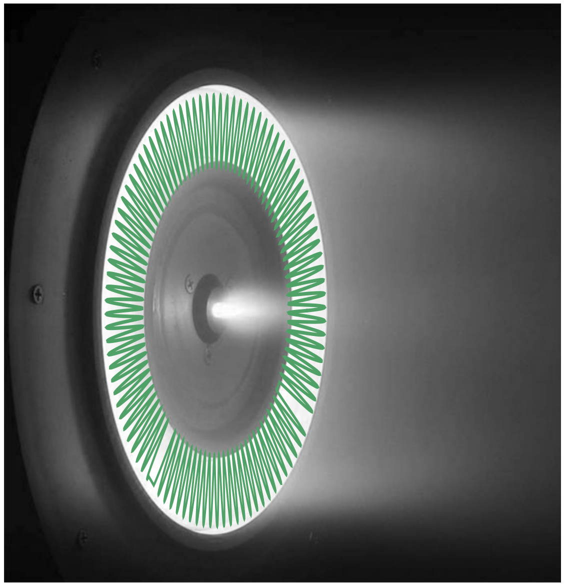
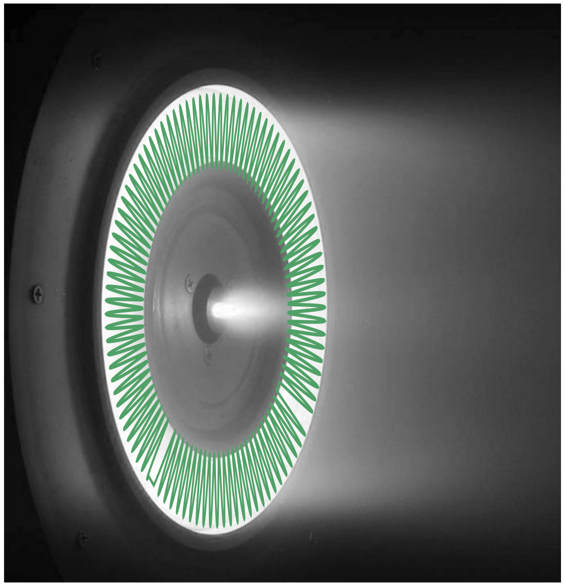
Case Study 2: Micro-scale instabilities in plasma



Case Study 2: Micro-scale instabilities in plasma

1. Is there evidence that this type of mode should exist in the plasma?



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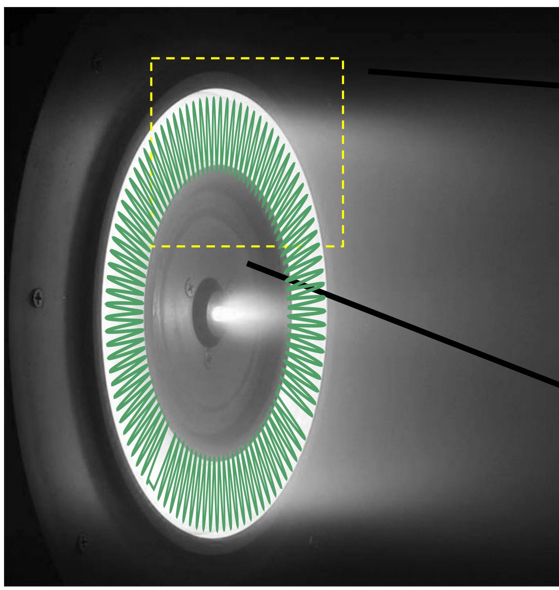
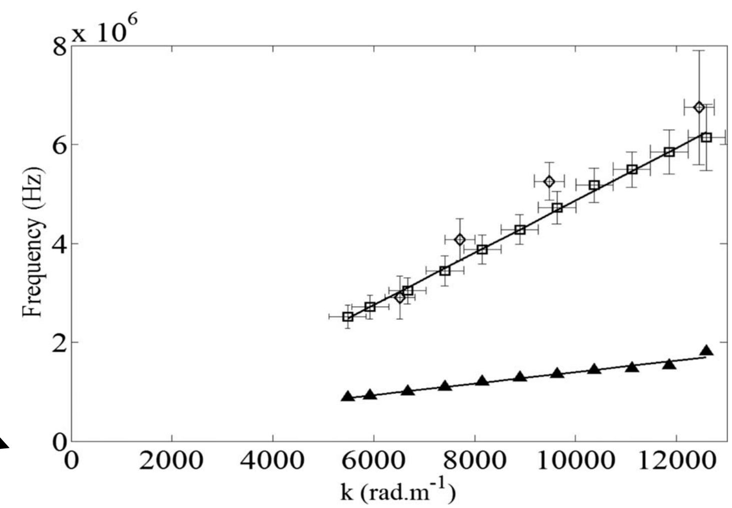


Experimental dispersion relation of small-scale oscillations in Hall direction



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

- Wavelengths < 1 mm
- Dispersion is acoustic-like
- Modes are incoherent

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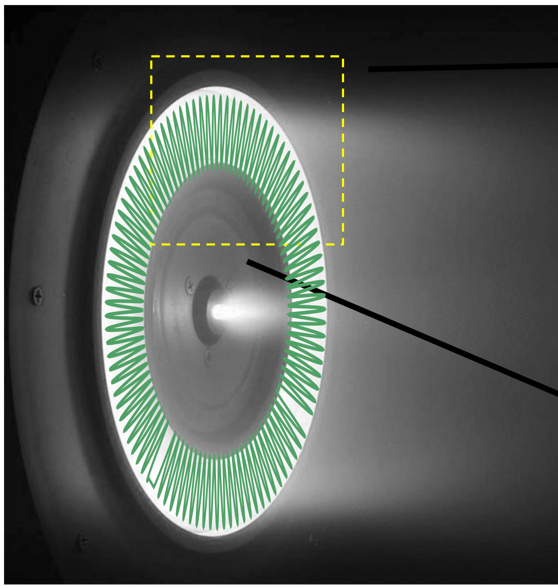
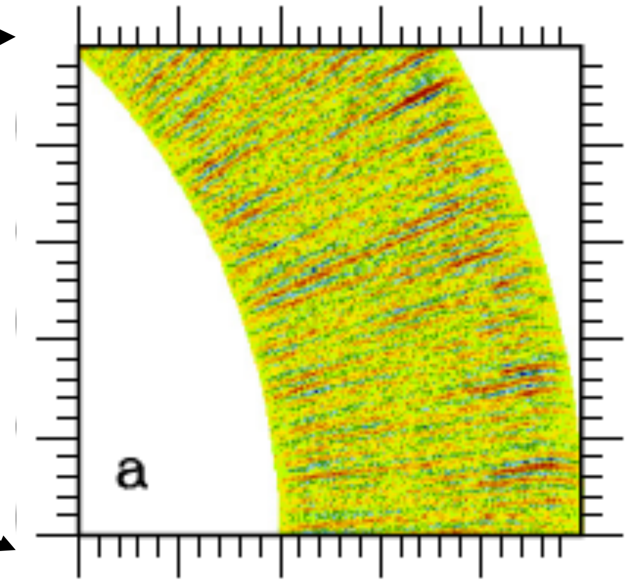


Density fluctuations from PIC, 2D model



* A. Héron and J. C. Adam, "Anomalous conductivity in Hall thrusters: Effects of the non-linear coupling of the electron-cyclotron drift instability with secondary electron emission of the walls."Physics of Plasmas 20 , 082313 (2013);

<u>Sampling of other numerical models showing instability</u>

- J. C. Adam , A. Héron , and G. Laval, Physics of Plasmas 11 , 295 (2004)
- A. Ducrocq , J. C. Adam , A. Héron , and G. Laval, Physics of Plasmas 13 , 102111 (2006);
- J.P. Boeuf. Frontiers in Physics, Vol. 2, No. 74, (2014)
- T. Lafleur , , S. D. Baalrud , and P. Chabert, Physics of Plasmas 23 , 053502 (2016);
- V Croes et al. Plasma Sources Sci. Technol. 26 (2017)

Case Study 2: Micro-scale instabilities in plasma

2. Is there a first-principles explanation for this mode and how it impacts electron transport?

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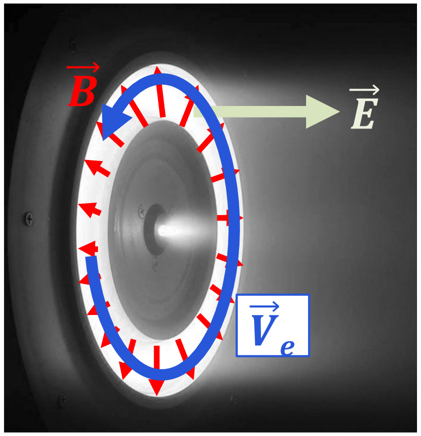
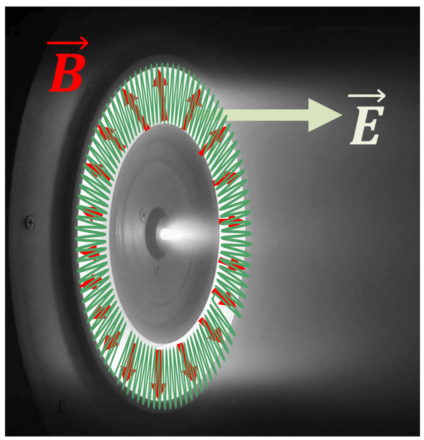
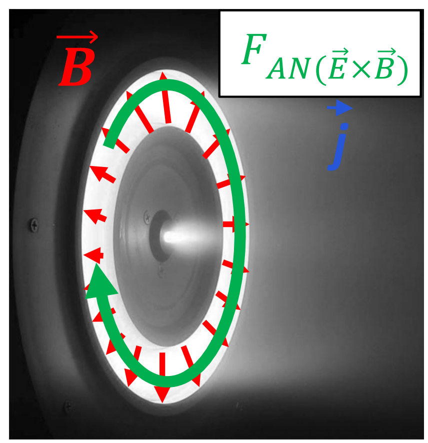


1) Strong E × B drift between electrons and ions

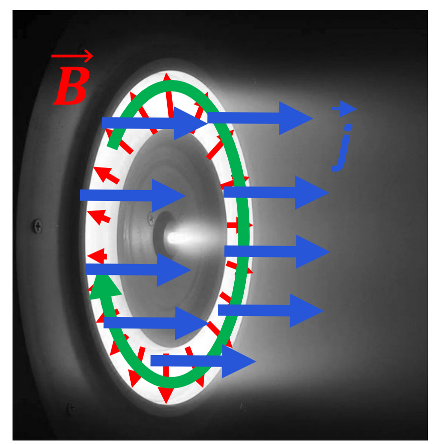


2) Azimuthal electron cyclotron drive instability (ECDI) driven unstable by drift through inverse cyclotron or Landau damping

3) Electrons slowed in E × B direction by wave growth leads to effective drag in Hall direction



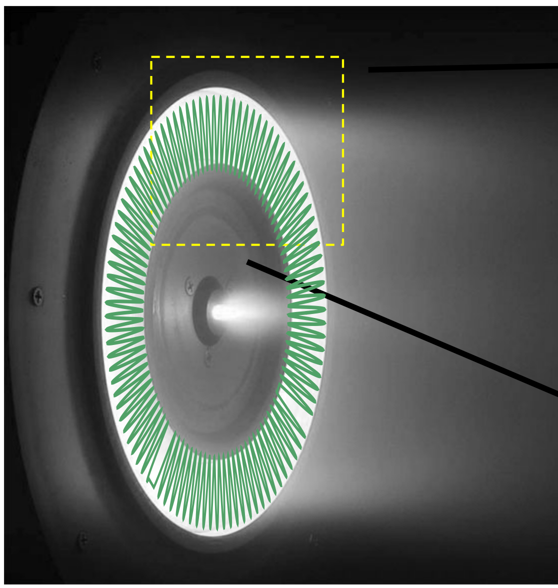
4) Effective drag due to onset of waves gives rise to cross-field electron current



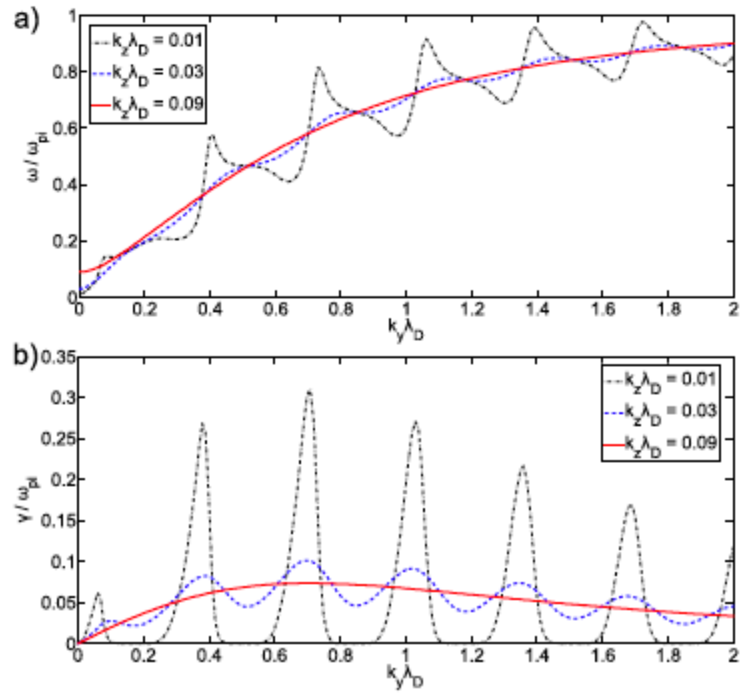
Case Study 2: Micro-scale instabilities in plasma

2. Is there a first-principles explanation for this mode and how it impacts electron transport?

Positive growth from linear dispersion relation



Linear dispersion relation for electron cyclotron drift instability*



* J. Cavalier et al, "Hall thruster plasma fluctuations identified as the E × B electron drift instability: Modeling and fitting on experimental data," Physics of Plasmas (1994-present) 20 , 082107 (2013);

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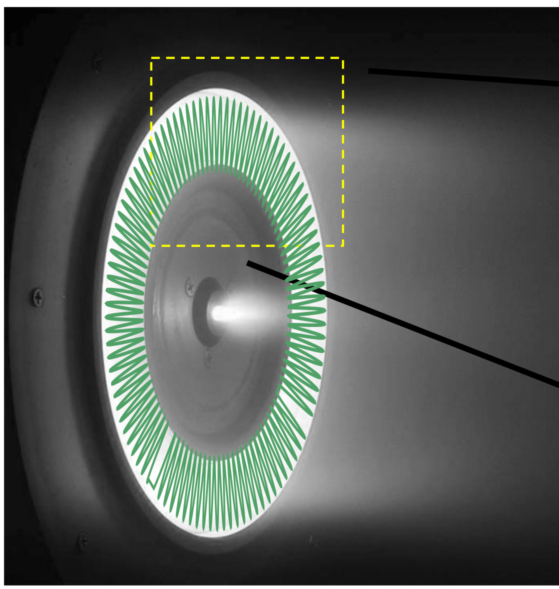
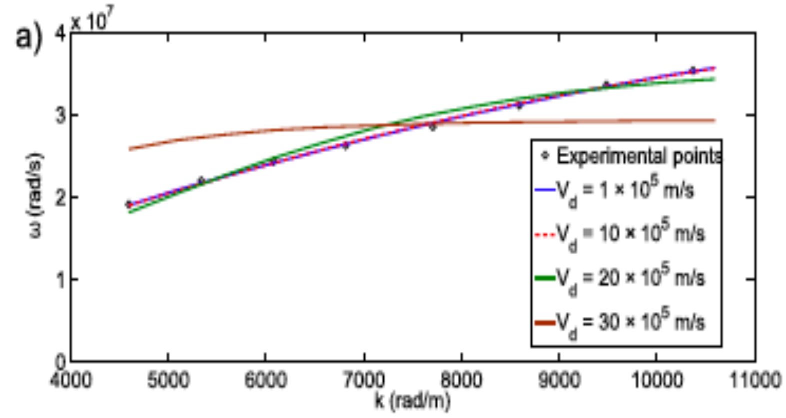


Linear dispersion vs. experimental data in E x B direction*



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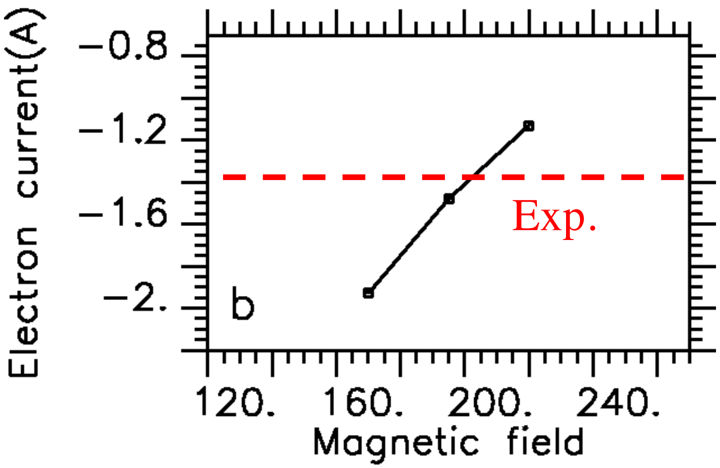
Numerical evidence from Z-θ PIC code of thruster



• J. C. Adam , A. Héron , and G. Laval, Physics of Plasmas 11 , 295 (2004)

- PIC numerical codes seem to indicate instability can drive most of transport
- Caveat: codes do not capture all experimental properties of observed waves

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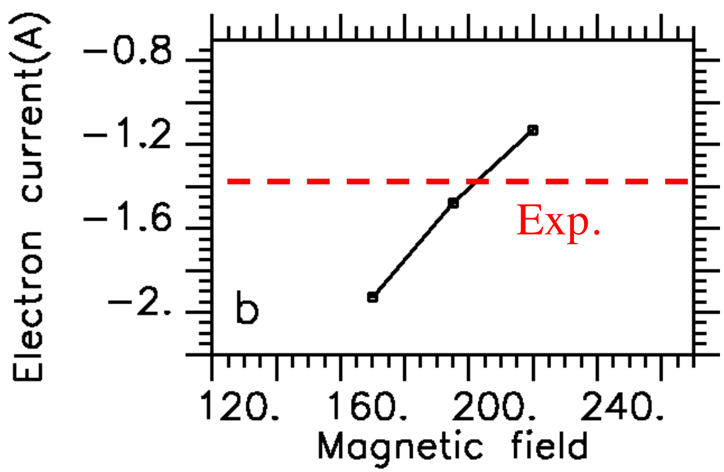

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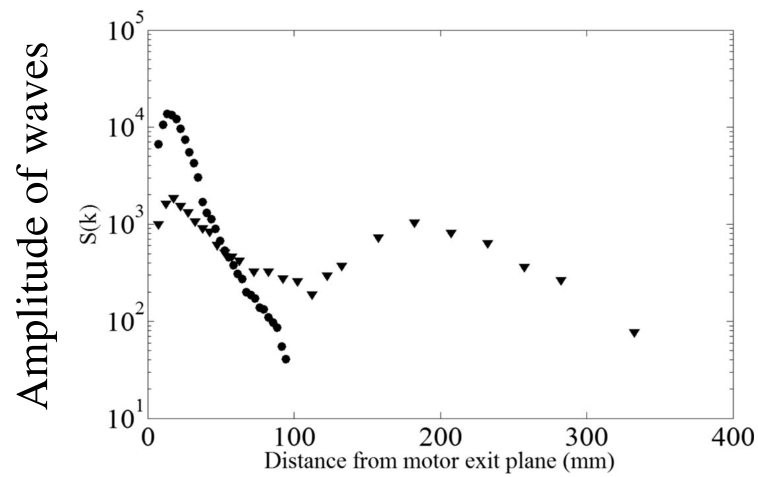
Experimental evidence



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- PIC numerical codes seem to indicate instability can drive most of transport
- Caveat: codes do not capture all experimental properties of observed waves

- Experimental measurements show spatial dependence of wave energy that is commensurate with electron mobility
- No direct measurements yet of cross-field electron current from these modes.

Case Study 2: Micro-scale instabilities in plasma

4. Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

Case Study 2: Micro-scale instabilities in plasma

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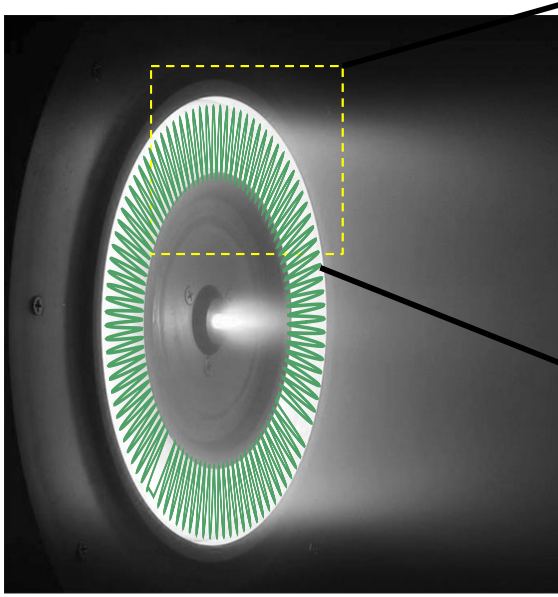
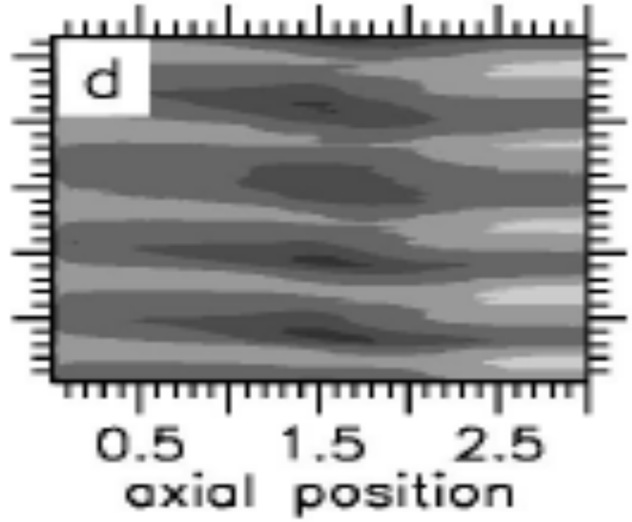


Density from Z-θ PIC simulation



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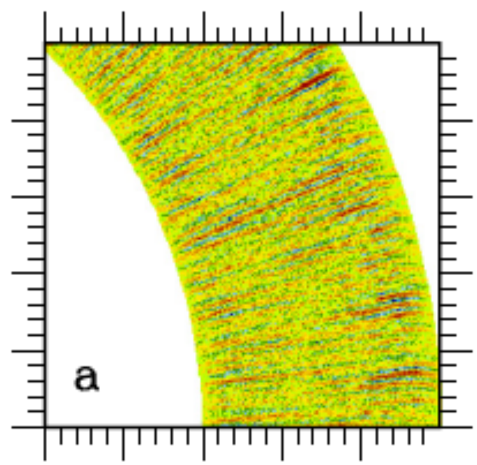
Density fluctuations from PIC, 2D model



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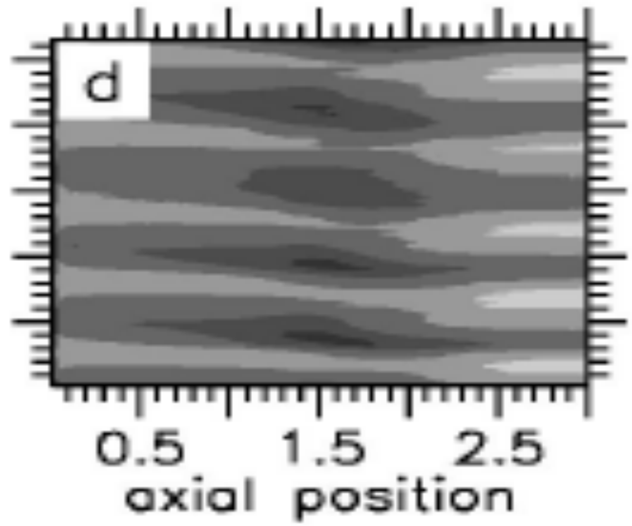

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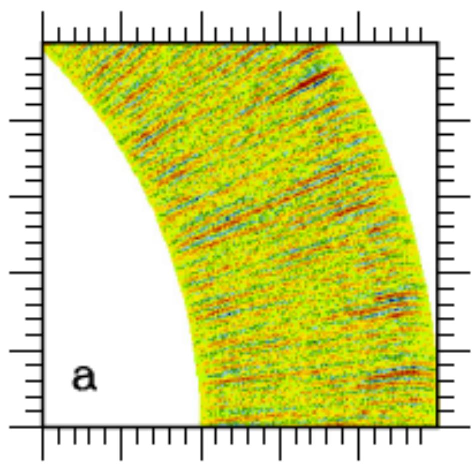

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- Models clearly capture onset of the instability and can lead to realistic estimates for cross-field transport
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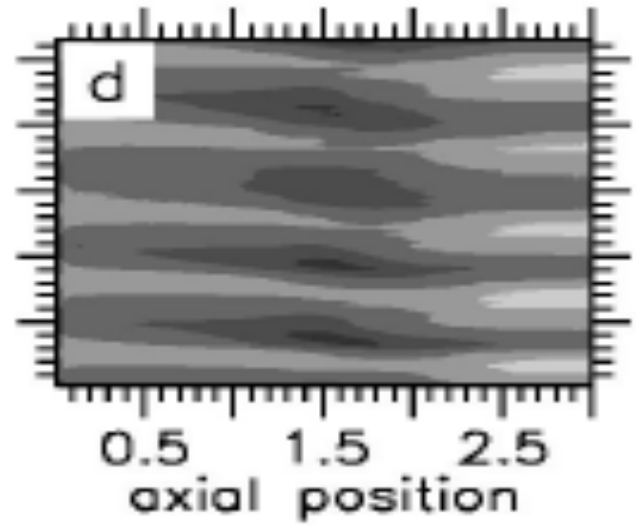
- Computational limits place bounds on geometries and operating conditions simulated

Case Study 2: Micro-scale instabilities in plasma

4. Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

Density from Z-θ PIC simulation



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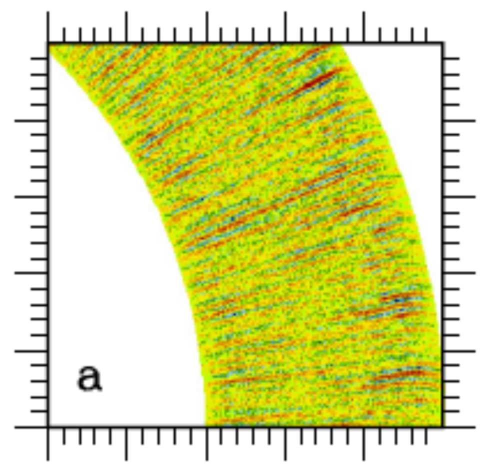

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Alternative approach: Fluid model

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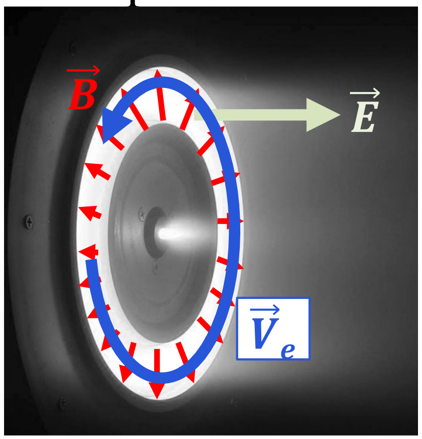
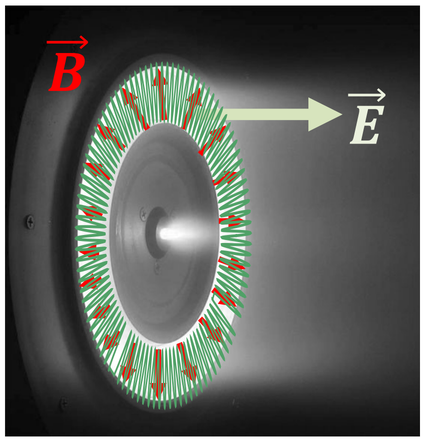
How do you model a kinetic, small-scale effect like ECDI with a fluid-hierarchy?

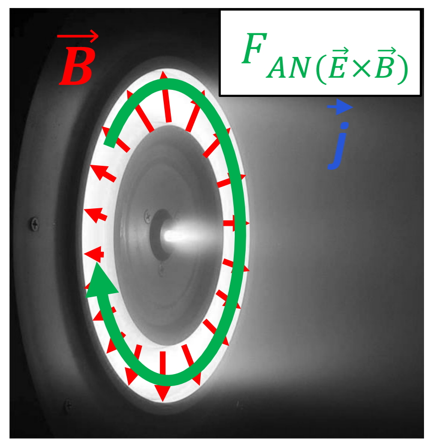


1) Strong E × B drift between electrons and ions

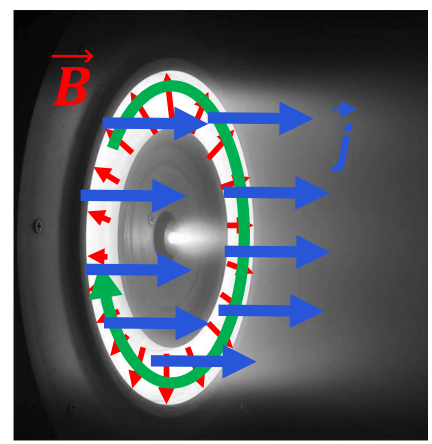


2) Azimuthal wave driven unstable by drift through inverse cyclotron or Landau damping

3) Electrons slowed in E × B direction by wave growth leads to effective drag in Hall direction



4) Effective drag due to onset of waves gives rise to cross-field electron current



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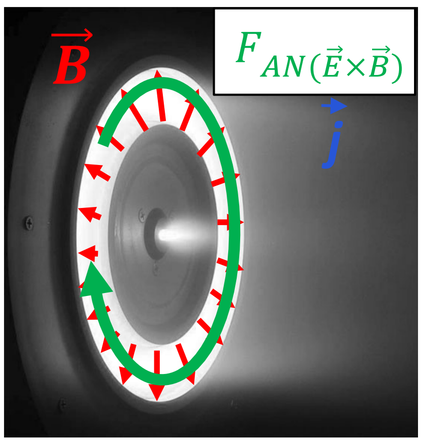

$$j_{\vec{E}} = \frac{1}{(1+\Omega_e^2)}\left[\frac{E}{\eta} + \Omega_e^2 n \frac{F_{AN(\vec{E}\times\vec{B})}}{B}\right]$$

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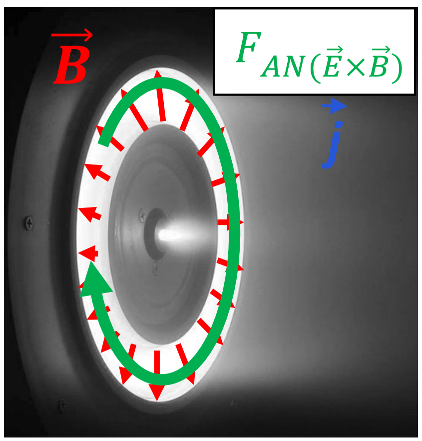

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NUCLEAR FUSION 17 6 (1977)

Review Paper

ANOMALOUS TRANSPORT IN HIGH-TEMPERATURE PLASMAS WITH APPLICATIONS TO SOLENOIDAL FUSION SYSTEMS

R.C. DAVIDSON*
Department of Physics and Astronomy,
University of Maryland,
College Park,
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N.A. KRALL
Laboratory for Applied Plasma Studies,
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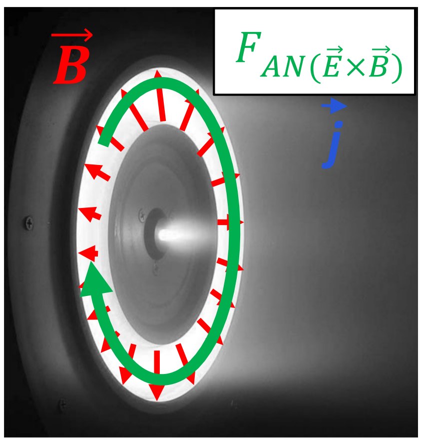
- Quasilinear theory
- Saturation closure
- Hybrid codes



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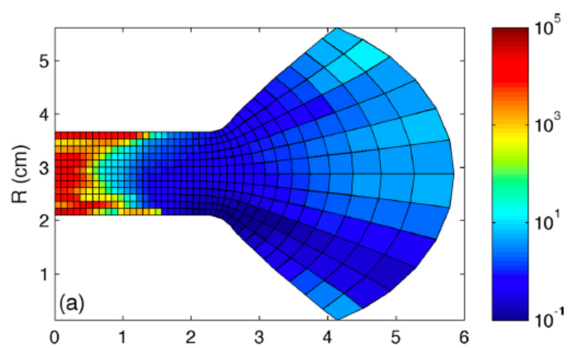
Entropy argument for closure



M. Cappelli et al. Physics of Plasmas 22 , 114505 (2015)

Full QL theory

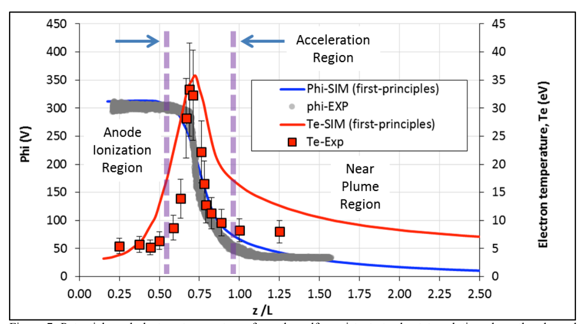
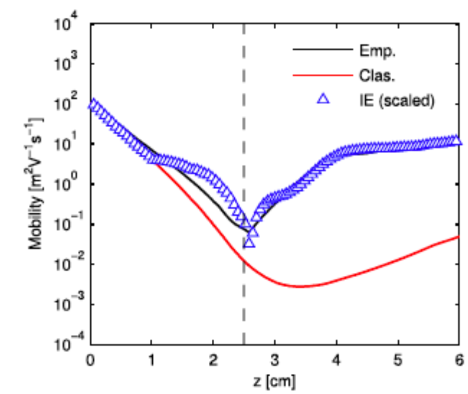


Figure 7. Potentials and electron temperatures from the self-consistent steady-state solution along the channel centerline compared with laboratory measurements on the H6US thruster

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

QL theory with saturation



T. Lafleur , , S. D. Baalrud , and P. Chabert. Physics of Plasmas 23 , 053503 (2016);

Case Study 2: Micro-scale instabilities in plasma

4. Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

Fluid approach

How do you model a kinetic effect like ECDI with a fluid-hierarchy?

Quasilinear theory

Saturation closure

Hybrid codes

No closure attempt has self-consistently captured the cross-field transport yet

There are many open questions about the validity of using fluid approximations and closures to model kinetic effects

Entropy argument for …

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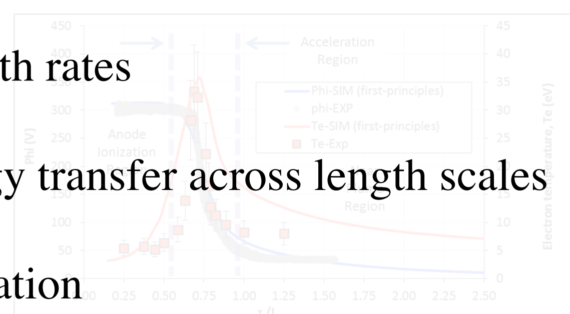
M. Cappelli et al. Physics of Plasmas 22 , 114505 (2015)



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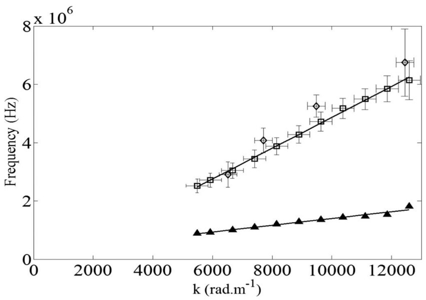
T. Lafleur , , S. D. Baalrud , and P. Chabert. Physics of Plasmas 23 , 053503 (2016);

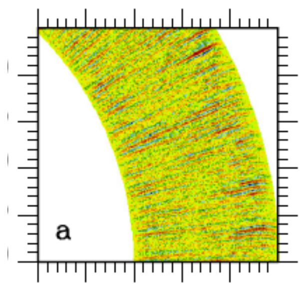
- Growth rates
- Energy transfer across length scales
- Saturation
- Non-thermalized plasmas

Case Study 2: Micro-scale instabilities in plasma

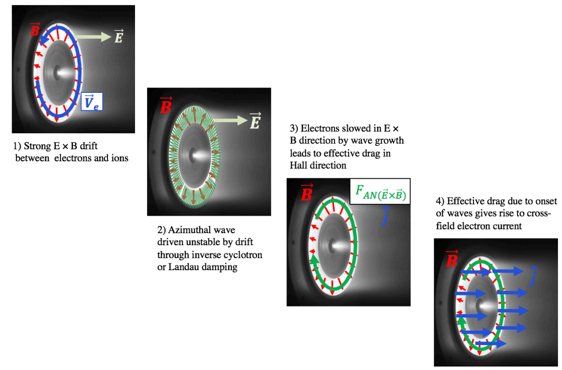
Is there evidence that this mode should exist in the system?



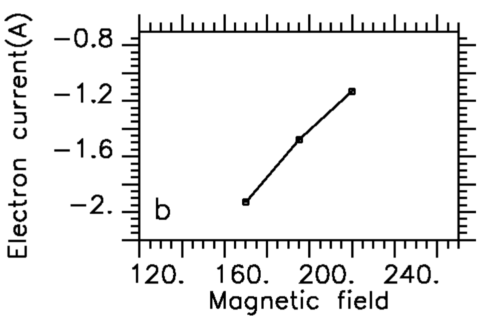
- Experimental ✔
- Numerical ✔
- Analytical ✔



Is there a first-principles explanation for this mode and how it impacts electron transport?



Is there evidence that this mode is sufficiently strong to drive observed cross-field electron transport?



- Numerical simulations suggest that it can be a dominant mode ✔
- Limited direct experimental evidence of electron transport (?)

Can the impact of this mode on transport be modeled self-consistently and is the modeled transport dominant?

- Multiple hierarchies being explored that predict some level of transport ✔
- PIC models do not have the computational power (?)
- Open question as to how to approximate effect in fluid models (?)

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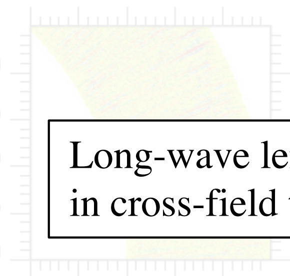
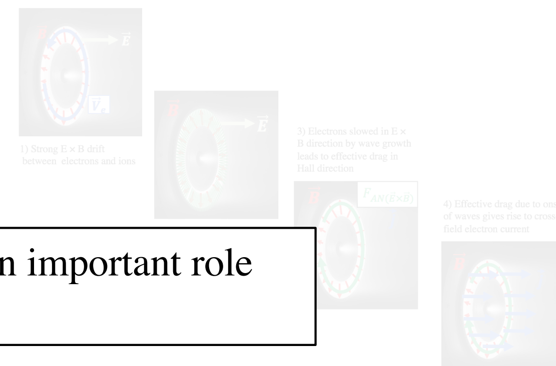
Is there evidence that this mode should exist in the system?

- Experimental ✔
- Numerical ✔
- Analytical ✔



Is there a physical explanation for how this mode grows and impacts electron transport?



Long-wave length structures may play an important role in cross-field transport in these devices

Is there evidence that this mo… drive observed cross-field electron transport?

On-going area of research

… on transport be modeled self-consistently and is the modeled transport dominant?

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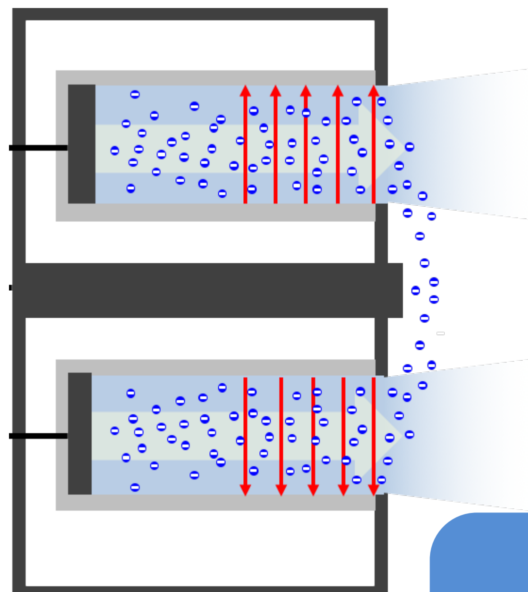
Recap

- There is probably some anomalous force in the Hall direction driving enhanced cross-field transport
- Plasma instabilities with components in the Hall the direction can contribute to this anomalous force
- There are many known instabilities in Hall thrusters. It is important to have criteria to differentiate and evaluate their importance for contributing to the cross-field transport
- Measured against these criteria, two promising and popular candidates are **large scale, near-coherent** fluctuations and **microturbulence**.

The actual physical system is more complex

Bohm Diffusion

Wall Interactions

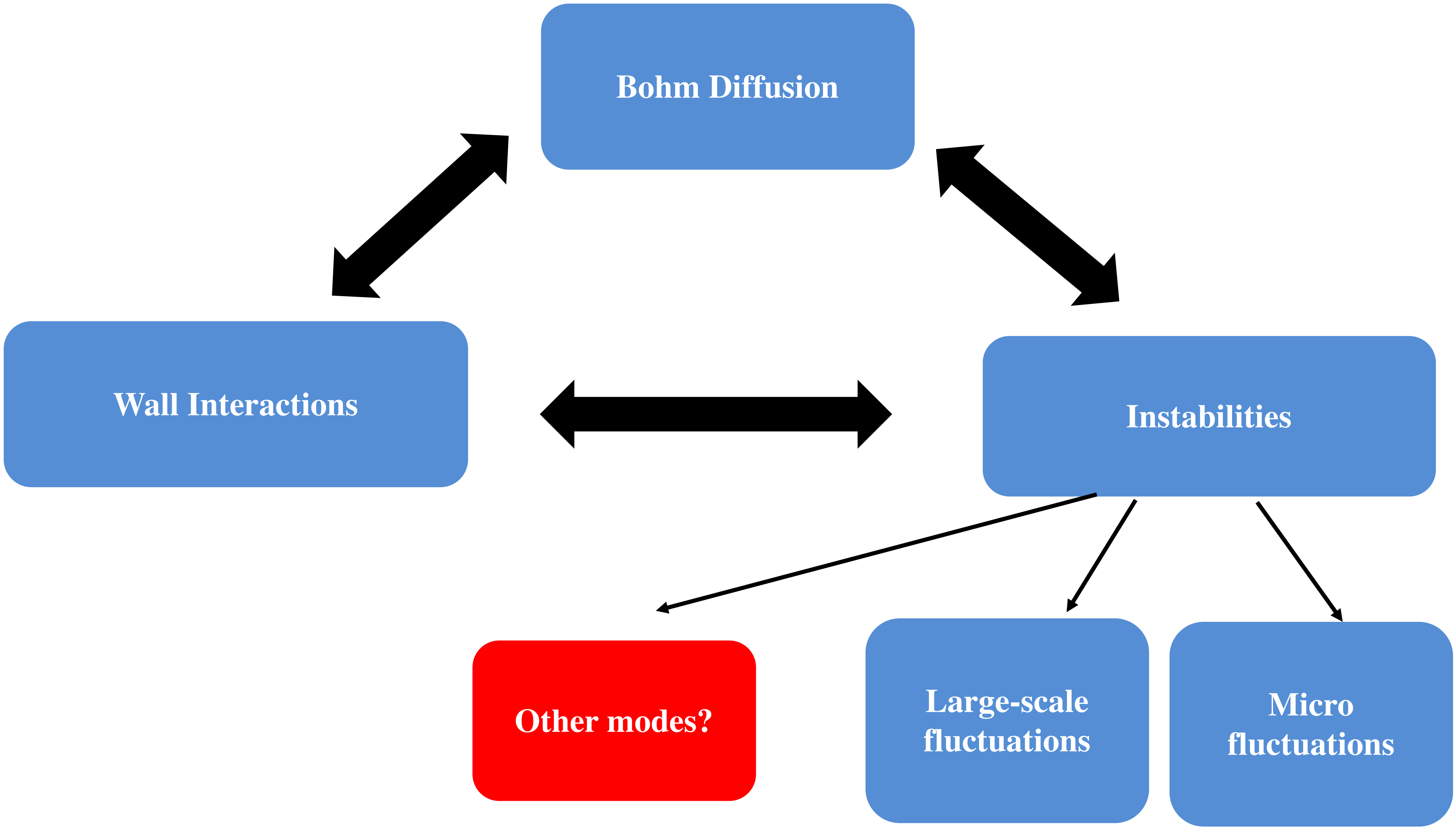


Instabilities

Large-scale fluctuations

Micro fluctuations

The actual physical system is more complex



Moving Forward

- **Need to continue to explore first-principles formulations and numerical efforts in parallel**
  - Computational speed and fidelity of PIC
  - Incorporating (where appropriate) kinetic effects into fluid codes
  - Understanding how disparate effects interact and convolve

- **Need to develop experimental tools and diagnostics to better characterize instabilities and their impact on transport**

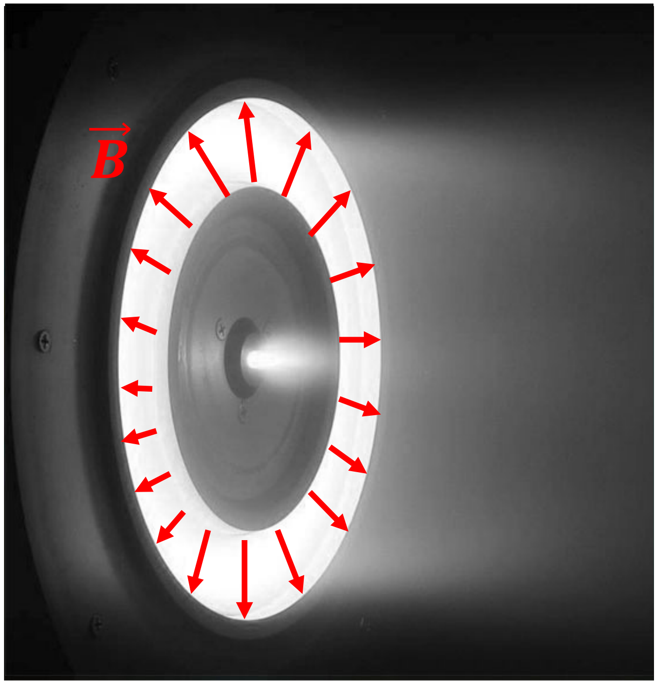
- **Need to continue to develop tools to identify instabilities in the thruster that may contribute to transport (next talk)**

Need for additional forcing terms to drive cross-field transport

Classical (collisional) Ohm's Law

$$\eta \vec{j} = \vec{E} - \frac{1}{qn} \vec{j} \times \vec{B}$$

η = resistivity



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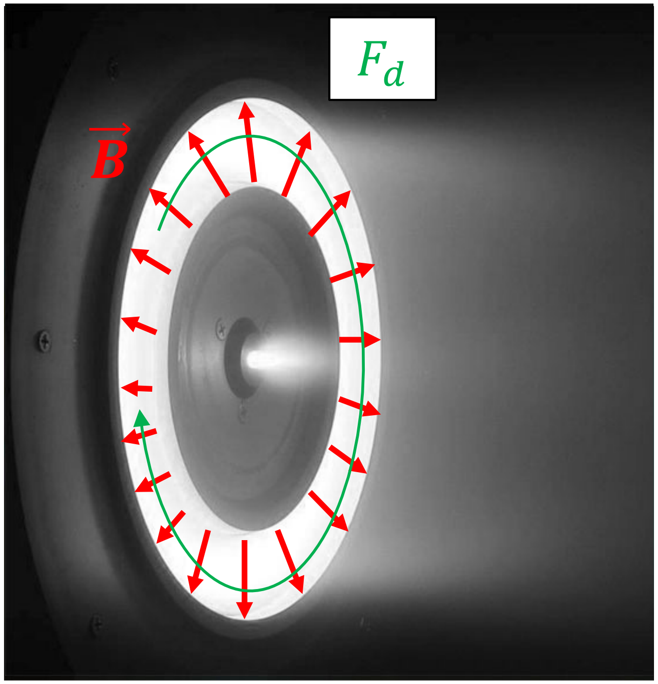
Resistive drag term "$\vec{F}_d$" against E ✖ B drift allows electrons to cross field lines



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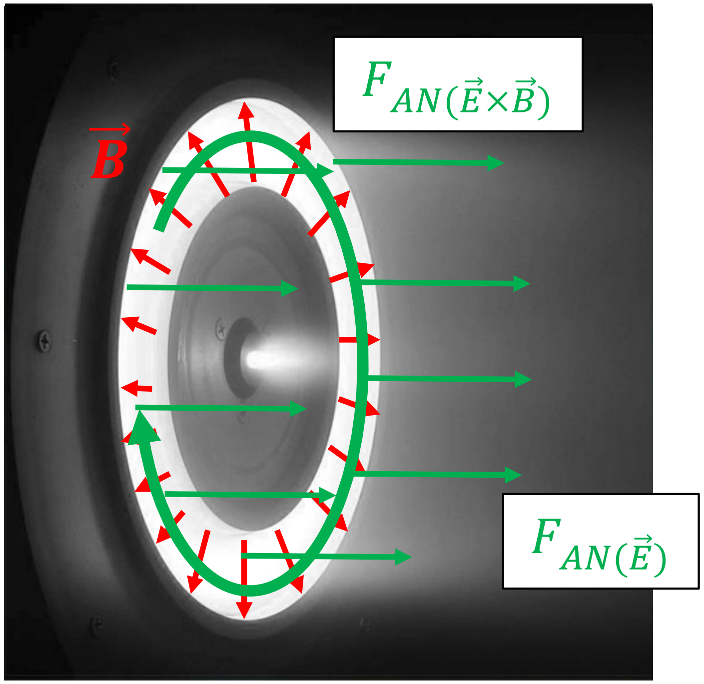
What if there are other forcing terms?

$$-\frac{1}{q}\vec{F}_{AN} + \eta\vec{j} = \vec{E} - \frac{1}{qn}\vec{j}\times\vec{B}$$



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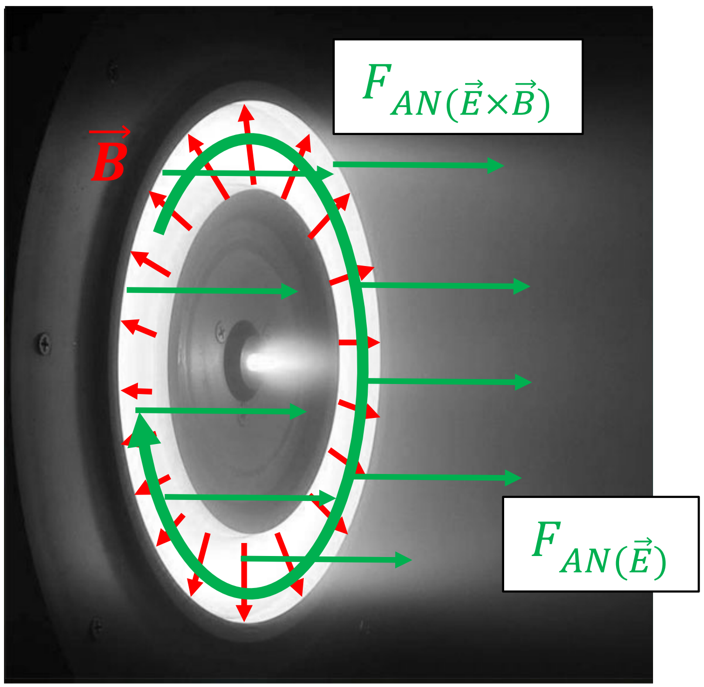

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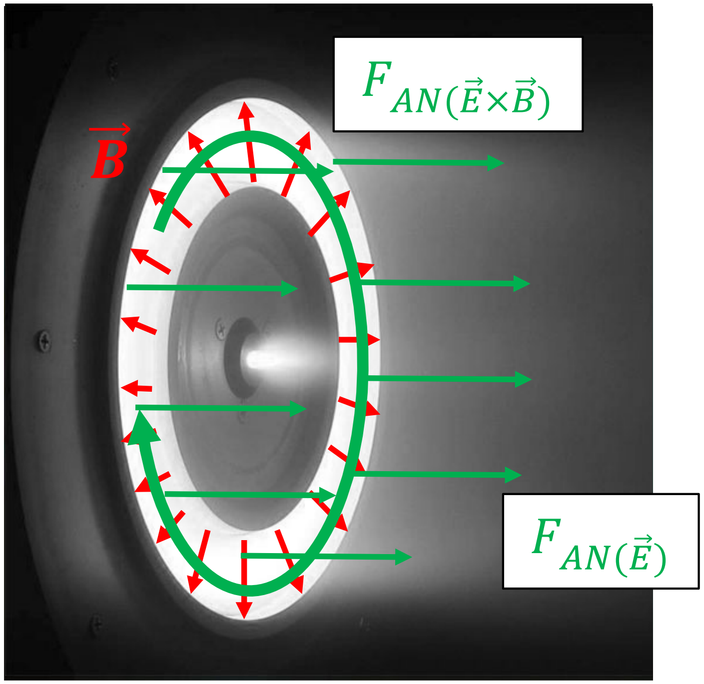
Classical

Anomalous



Additional force term can provide cross-field current

Cross-field Transport in Partially Magnetized Plasmas

Electric field is very strong in Hall accelerator and classical Hall parameter is high ($\Omega_e \gg 1$)

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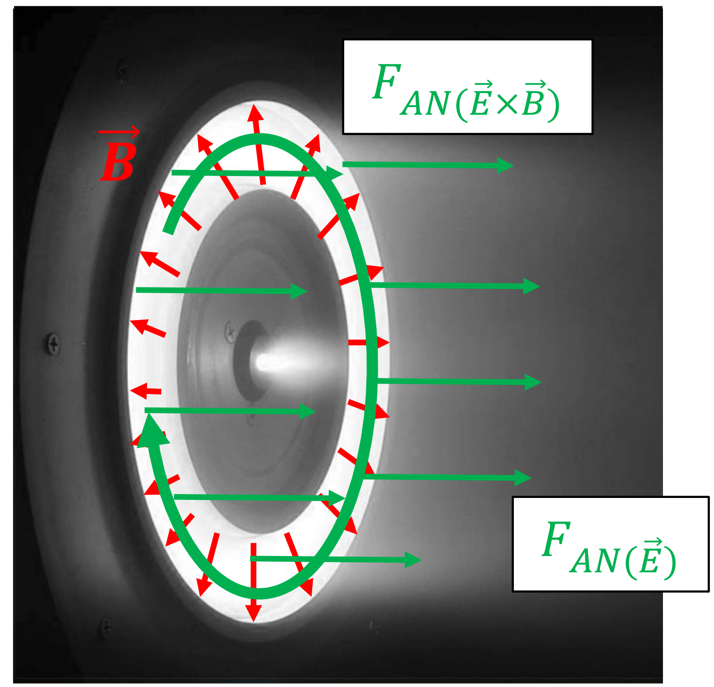

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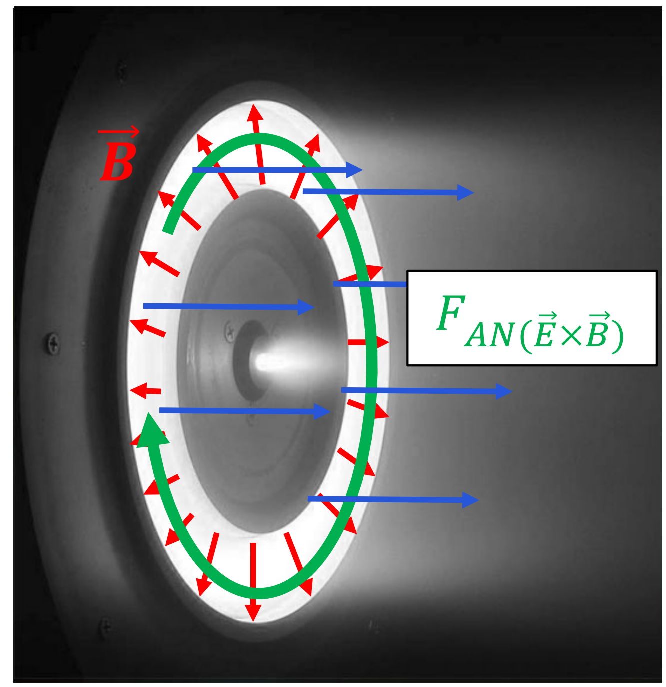
Cross-field current largely driven by force acting in the Hall direction



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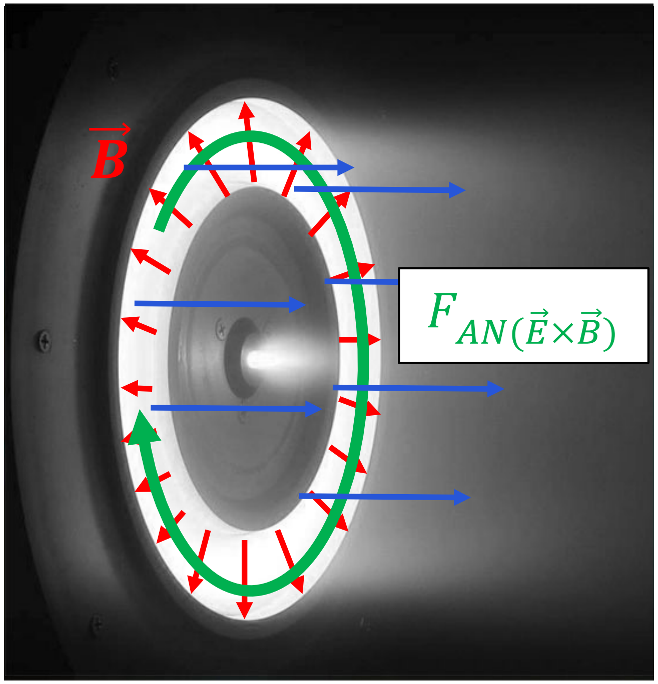

What can provide this additional force?