Low temperature Hall plasmas with ExB drift : turbulence, anomalous transport and structures

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Outline

- **Subject:**

- Hall plasmas with ExB drift of magnetized electrons and weakly magnetized ions; much different from fusion plasmas

- **Scientific Frontier, Challenges, Approaches and Tools**

- Physics questions: Origin and interactions of fluctuations, transport and structures, profiles self-organization

- **Importance and benefits**:

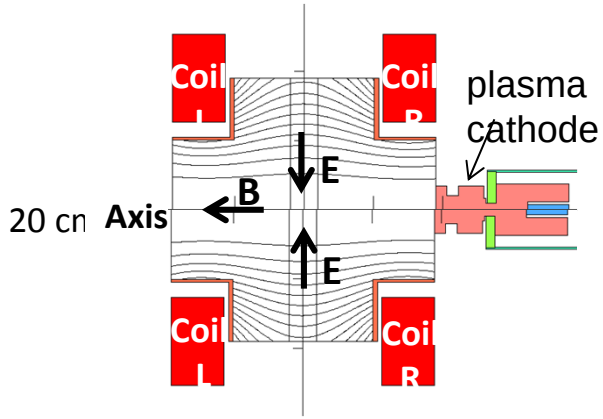
- Distinct area of basic plasma physics and plasma turbulence; poorly explored but within the reach of current analytical and numerical capabilities
- Critical for important technologies of electric propulsion and material processing (magnetrons)

Hall plasmas with $\mathbf{E}\times\mathbf{B}$ drift

- Magnetized electrons $\rho_e < L \qquad \omega < \omega_{ce}$
- Unmagnetized ions $\rho_i > L \qquad \omega > \omega_{ci}$

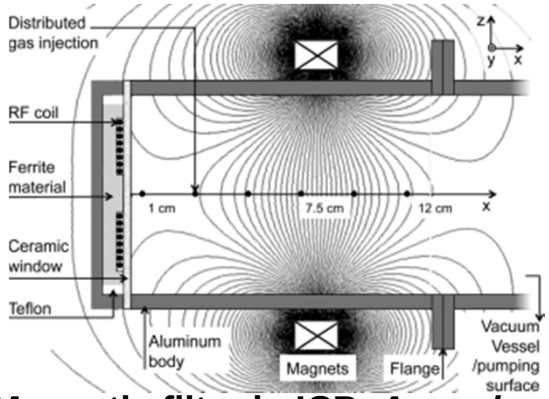
- Electrons are magnetically controlled, motion across the magnetic field is constrained due to small Larmor radius, $\mathbf{E}\times\mathbf{B}$ drift due stationary electric field perpendicular to the magnetic field, density and temperature gradients
- Ions are weakly affected by the magnetic field, not magnetized, controlled by the electric field, e.g. can be accelerated/extracted/segregated, etc

Common physics in devices of interest: Hall thrusters magnetrons, Penning sources, magnetic filters (e.g. for negative ion sources), FRC thrusters, ….

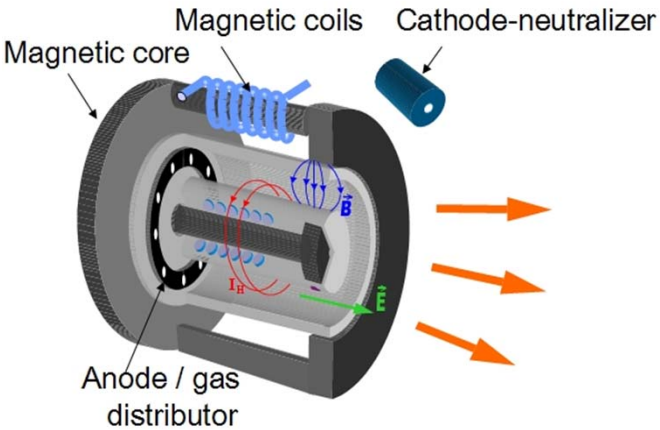


Penning set-up, Y. Raitses PPPL

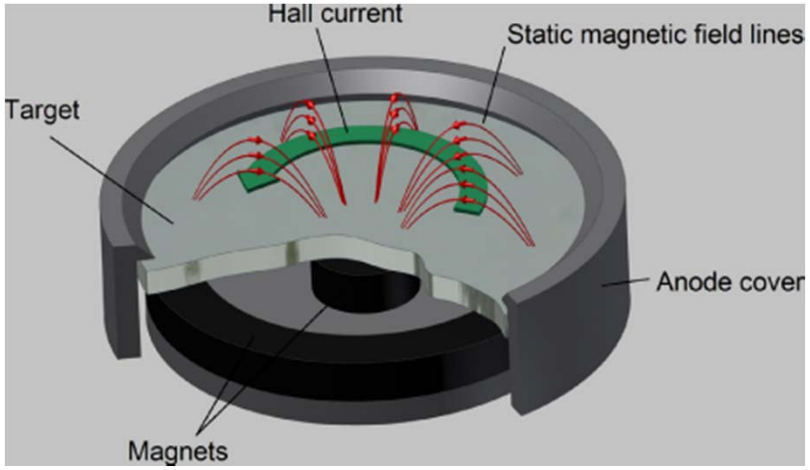
Cylindrical magnetron



•**Magnetic filter in ICP** ***Aanesland et al., Appl. Phys. Lett. 100 (2012), J.-P. Boeuf (ICOPS 2015)***



Y. Raitses et al., J Appl Phys 2000



•**Planar magnetron, J. Winter et al, J. D 2013**

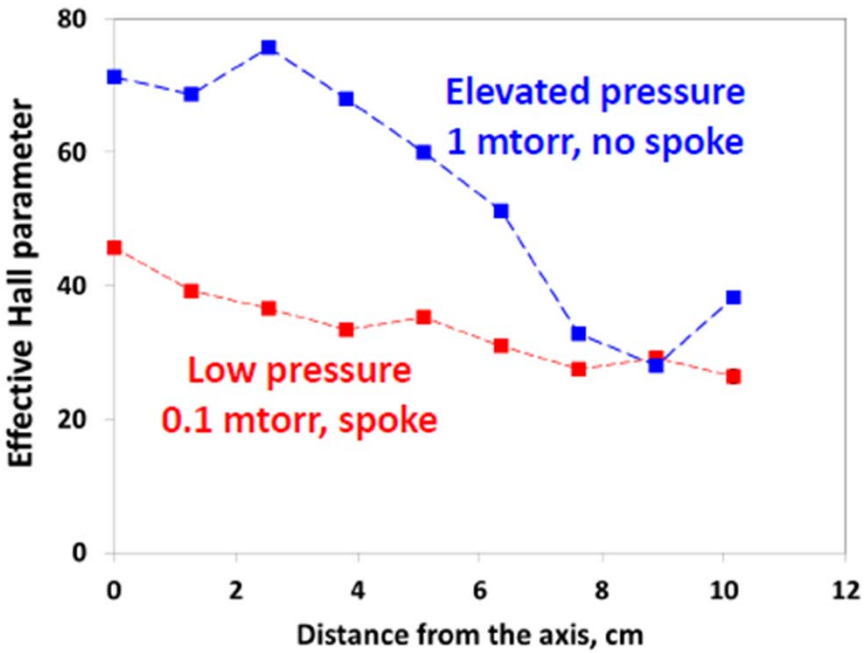
Empirically: What is happening?

- Range of unstable fluctuations of different frequencies ubiquitously present, 1 kHz to 10's MHz
- Self-organization into coherent structures (spoke) typically occur in Hall plasma devices
- Electron transport across the magnetic field is anomalous.
- Fluctuations across different time and length scales, structures and their interactions are not clear but have clear and dramatic effects on underlying regimes and performance of various devices

Specific issues (I): Anomalous transport and structures

- **The electron current is anomalous.**
- **Anomaly of electron cross-field transport, ν_{eff} / ν_m ~ 10-100**

We do not know the dominant modes that lead to transport!
We do not understand the mode behavior with seemingly small effect of neutral pressure



Raitses, PPPL IEPC 307

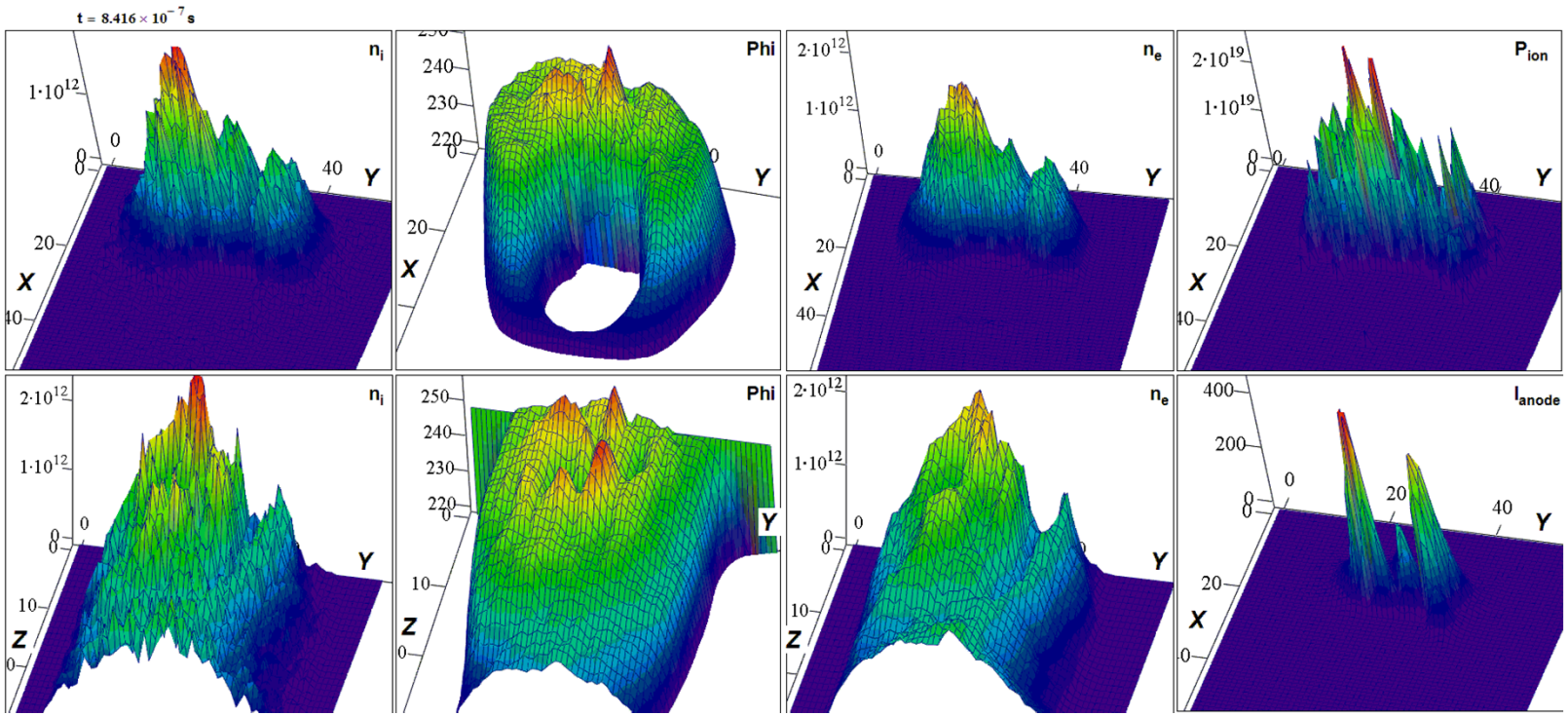
Spoke-secondary (nonlinear) instability or primary mode?

Specific issues (II): Instabilities
Basic Plasma Physics Challenge

- Plasma instabilities present in Hall ExB plasmas
  - Ion sound waves
  - Anti-drift modes
  - Gradient-drift (density, temperature, magnetic field) modes and **low hybrid instabilities**
    - **These are not drift modes such as in a tokamak!, ITG etc**
    - But previously studied for pulsed systems (theta –pinch) in 70's; cf e.g. Davidson, Krall, NF 1977
- What are the dominant modes in present experiments/conditions? saturation? Transport?

Specific issues (III): Multiscale dynamics

- Large scale structure coexist with high frequency modes. Significant fraction of the total current (50% and more) may occur within a single coherent low frequency structure .
- The mutual interaction, saturation mechanisms and contribution to the anomalous transport have to be understood



Matyash et al., IEPC 2013

Specific issues (IV):

- **Ionization, collisional and neutral dynamics effects**
  - Global (large scale and slow) phenomena, e.g. electric field (density) profiles are strongly affected by neutral pressure however ionization and collision frequencies are too low to affect the anomalous mobility directly?
- **Sheath , secondary emission and energetic/anisotropic components**
  - strong anisotropy of the electron distribution function affects the ionization balance
  - partial magnetization of the ion motion may form several distinct groups of ions with different energies due to charge-exchange collisions

Where do we want to go?

- **Enabling Physics**
  - **Understanding of anomalous transport and structure self-organization in typical Hall plasma device**
  - **Numerical tools capable of predictive modeling**
- **Impact and applications I**
  - Another incarnation of the wave turbulence and anomalous transport problem
  - Very different from Magnetic Fusion Plasmas!
  - Poorly explored!
  - Many MFE specific tools (eg, gyrokinetic codes) are not directly applicable **but** general expertize provides advantage and creates opportunities

- Impact and applications II

-Modern Hall plasma devices: the technology that works today:

By now over 250 Hall thrusters (kW class) on various space missions

Magnetron sputtering is commonly used process, enhanced performance regimes with High Power Impulse Magnetron Sputtering (HIMPS)

– **But scaling laws are unknown for power/size/erosion/ deep space conditions/Neutral pressure/facility effects rescaling**

Hall plasma transport maturity is not at par with e.g. understanding of ion transport in a tokamak, ITG modes, etc

– **Physics based anomalous transport model would enable predictive design of the next generation devices: high power for interplanetary missions, low power for cubesats, etc**

Approaches:

- Experimental input
- Integrated Particle-in-Cell simulations
- Fluid simulations of turbulence and structures with advanced nonlinear fluid models and platforms:
  - Advanced physics: reduced models-FLR effects, gyroviscosity, kinetic closures for kinetic effects, e.g. Landau damping
  - Computational: Parallelized High Performance simulations, 3D magnetic field geometry, eg. BOUT++
- Program wide benchmarking and validations (different codes and groups); Cyclon type effort

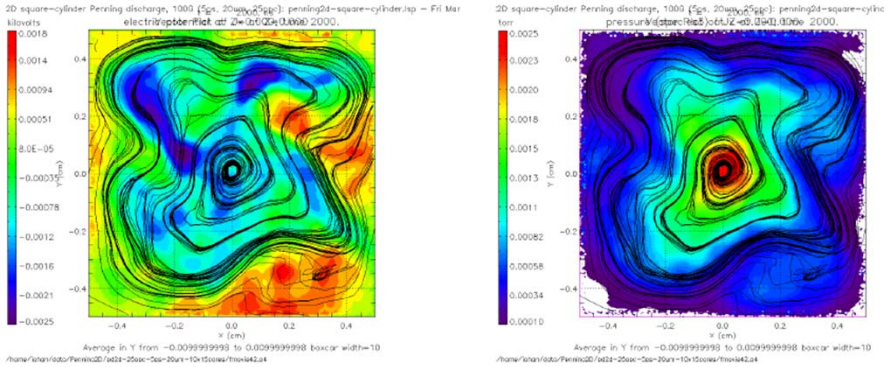
PARTICLE-IN-CELL CODES CAN RESOLVE COMPLEX MICRO PHYSICS AND COMPLEX GEOMETRY

3D PPPL-LSP code: electromagnetic and electrostatic modules.

We implemented anisotropic electron-atom scattering, ionization, and excitation as well as electron-ion and electron-electron collisions, electron induced emission, external circuit.

New Electrostatic PETSc Solvers

Relatively small dimensions make full device simulations feasible



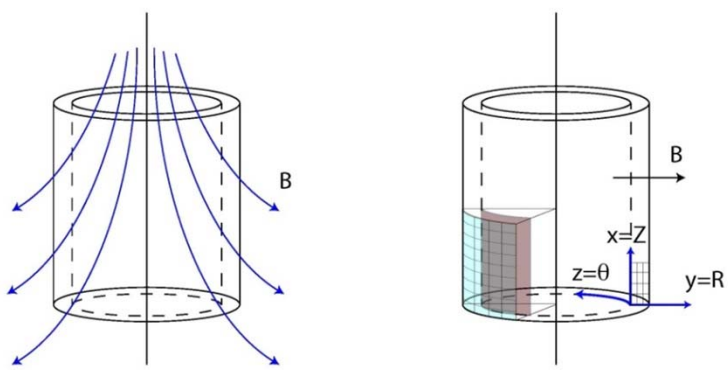
Spiral arm structure of radial current

J. Carlsson, IEPC 2015

Nonlinear fluid simulations

- are cheaper and faster; provide good physics insight
- BOUT++ was modified and set up for nonlinear fluid simulations of Hall plasmas

Hall thruster schematic and computational grid



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Benchmarks

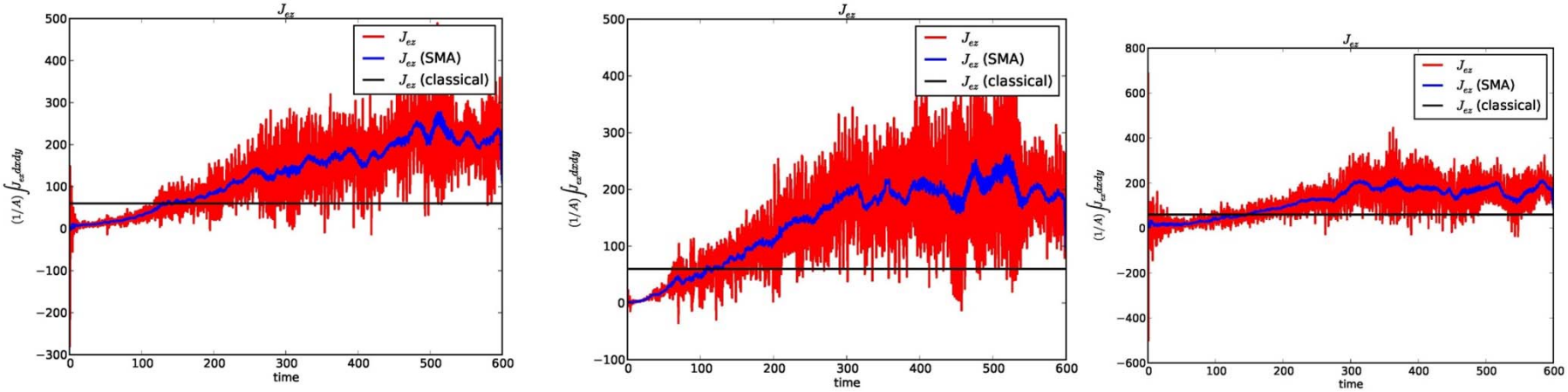
- Consistency with local theory of instabilities
- Linear eigen-value solutions: local and global
- Consistency with linear initial value simulations
- Consistency with kinetic simulations under similar conditions
- Nonlinear saturation of instabilities
- Turbulence spectra and transport

BOUT++ (LLNL and York U, UK)

- High performance platform for fluid and plasma simulations in vector form in 3D curvilinear magnetic field geometry
- Open magnetic field line configurations are included, allows sheath boundary conditions
- Designed and tested with reduced plasma fluid models applications in mind (e.g. Poisson brackets for nonlinear terms, Arakawa type schemes)
- Initial value, finite-difference and Fourier
- Widely used for edge tokamak plasmas

B. D. Dudson, M. V. Umansky, X. Q. Xu, P. B. Snyder and H. R. Wilson Computer Physics Communications 2009; BOUT++: A framework for parallel plasma fluid simulations

Turbulent electron current in BOUT++ simulations



Low hybrid ExB instability driven by weak collisions (Litvak, Fisch PoP 2001

Turbulent current is due to azimuthal fluctuations
Turbulent current is highly intermittent even after spatial average

In Summary

- **Scientific Frontier: Hall plasmas with ExB drift**
- **Challenge: Origin and interactions of fluctuations, transport and structures**
- **Methods and tools: Experiments motivated development of theory, dedicated Particle-in-Cell and fluid simulations**
- **Importance and benefits:**
  - **Poorly explored (but within the reach of current analytical and numerical capabilities) area of basic plasma physics and plasma turbulence**
  - **Critical for important technologies of electric propulsion and material processing (magnetrons)**