Physics of Partially Magnetized ExB Plasmas in the Laboratory and Space

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Low temperature, 10-50 eV partially magnetized plasmas
--naturally exist in ionosphere and solar plasma conditions
Created in laboratory and industry for material processing, film deposition (e.g. microelectronics), electric propulsion, …
Partially magnetized: moderate magnetic field exist naturally (e.g. ionosphere) or created externally so that the electrons are magnetized, but ions are not
ExB - electric field exists (in space conditions), or is applied/created externally to control ions: confine/extract/accelerate ions (e.g. propulsion) for useful applications.

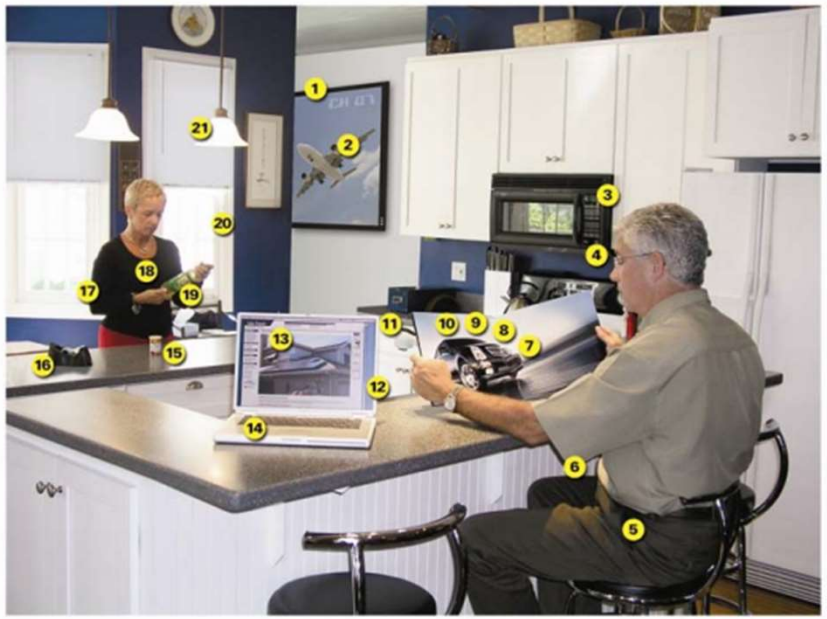
High temperature (>1 keV) plasmas: Tokamak, fusion, instabilities, turbulence and nonlinear waves, solitons, nonlinear physics, chaos, space physics, collisionless shock waves, …

1980s:
Department of Physics and Chemistry of Plasmas
Moscow Institute of Physics and Technology
Kurchatov Institute, Moscow, Soviet Union

Low temperature (~10s eV) plasmas:
Physics of gas discharges… dominated by collisions,
Plasma chemistry — (too complex …):
" ..a wide but shallow sea" L. Tsendin
Море широкое, но мелкое …
many applications, e.g. Plasma reactor for sulfur recovery from natural gas in Caspian see deposits

In the meantime:
LTPSE- Low Temperature Plasma Science and Engineering – Tremendous developments in scope and applications

LTPSE: ROBUST SCIENCE, SOCIETAL BENEFIT



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

- **Operating premise:**

  LTPSE has a history and future of robust, interdisciplinary science challenges whose resolution provides immediate and long term societal benefit.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Plasma 2010: **Low Temperature Plasma Science and Engineering**

M. Kushner, 2008, LTSP priorities and directions …

Low temperature plasmas are becoming collisionless, magnetic field and nonlinear dominated!

V.A. Godyak, PoP 2005 **Hot plasma effects in gas discharge plasma**

M.A. Lieberman; V.A. Godyak, TPS IEEE 1998, From Fermi acceleration to collisionless discharge heating

A. Smolyakov, V. Godyak, PoP 2003 Nonlinear effects in inductively coupled plasmas

.....

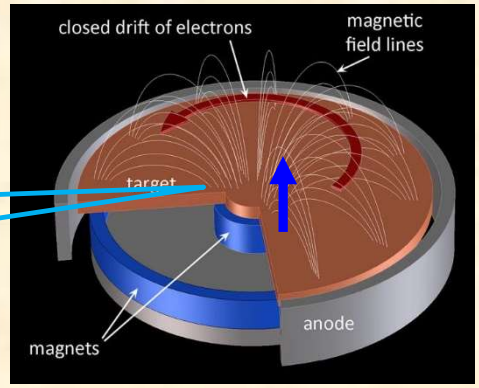
V. Kolobov and V Godyak, PoP 2019, Electron kinetics in low-temperature plasmas

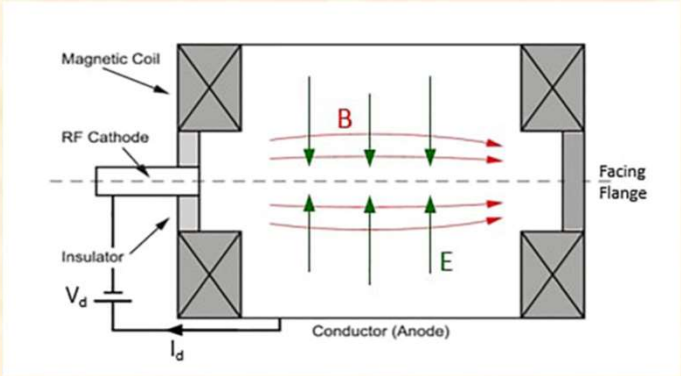
.. Experimental and theoretical advances reveal the importance of nonlinear and kinetic phenomena in low-temperature plasmas (LTPs)
… Illustrate common physics in space and laboratory plasma, collisionless and collisional plasmas, and low-pressure and high-pressure discharges
… Nonlocal electron kinetics and nonlocal electrodynamics in low-pressure rf plasmas resembling collisionless and nonlinear effects in space plasma and hot plasma effects in fusion science, terahertz technology, and plasmonics.

Common physics in laboratory, industrial material processing, electric propulsion and space plasmas.

Devices: magnetrons, Penning discharge, magnetic filters, Hall thrusters ,

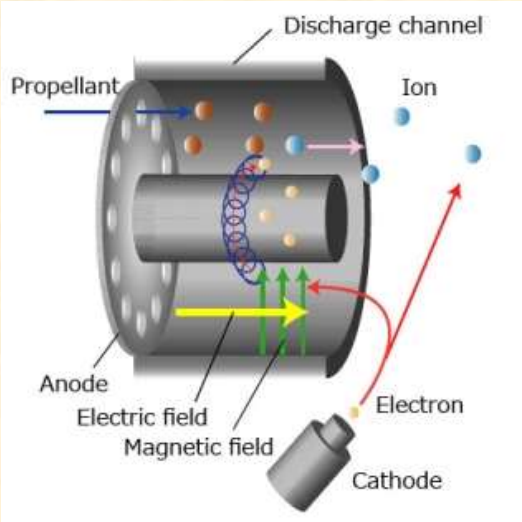
E electric field





Planar magnetron, A. Anders, J App Phys 2017

Hall thruster



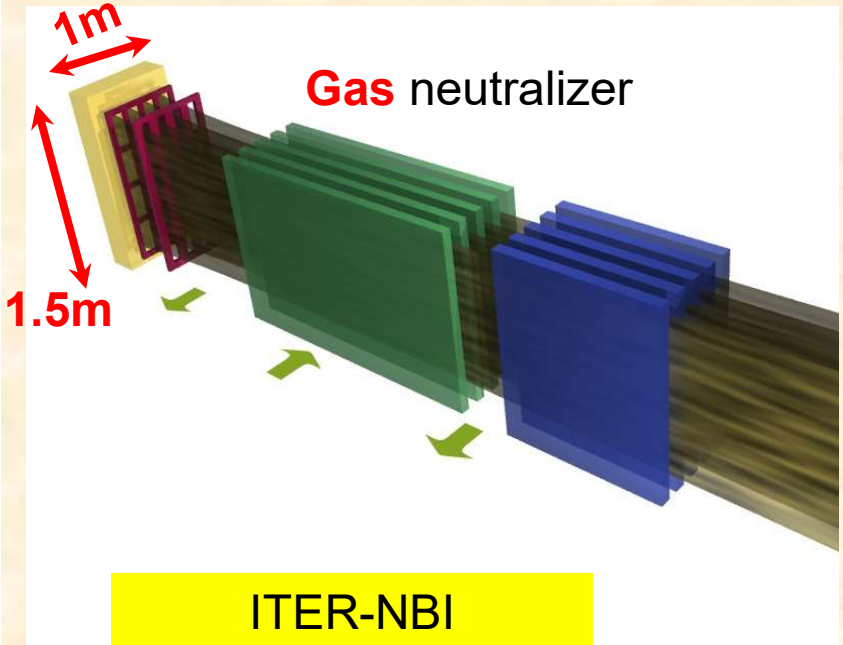
http://www.al.t.u-tokyo.ac.jp/hall_en.html

Cylindrical Penning discharge,

Y. Raitses PPPL,

From Rodrigues et all, PoP 2019

Magnetic filter for negative ion beam source



ITER-NBI

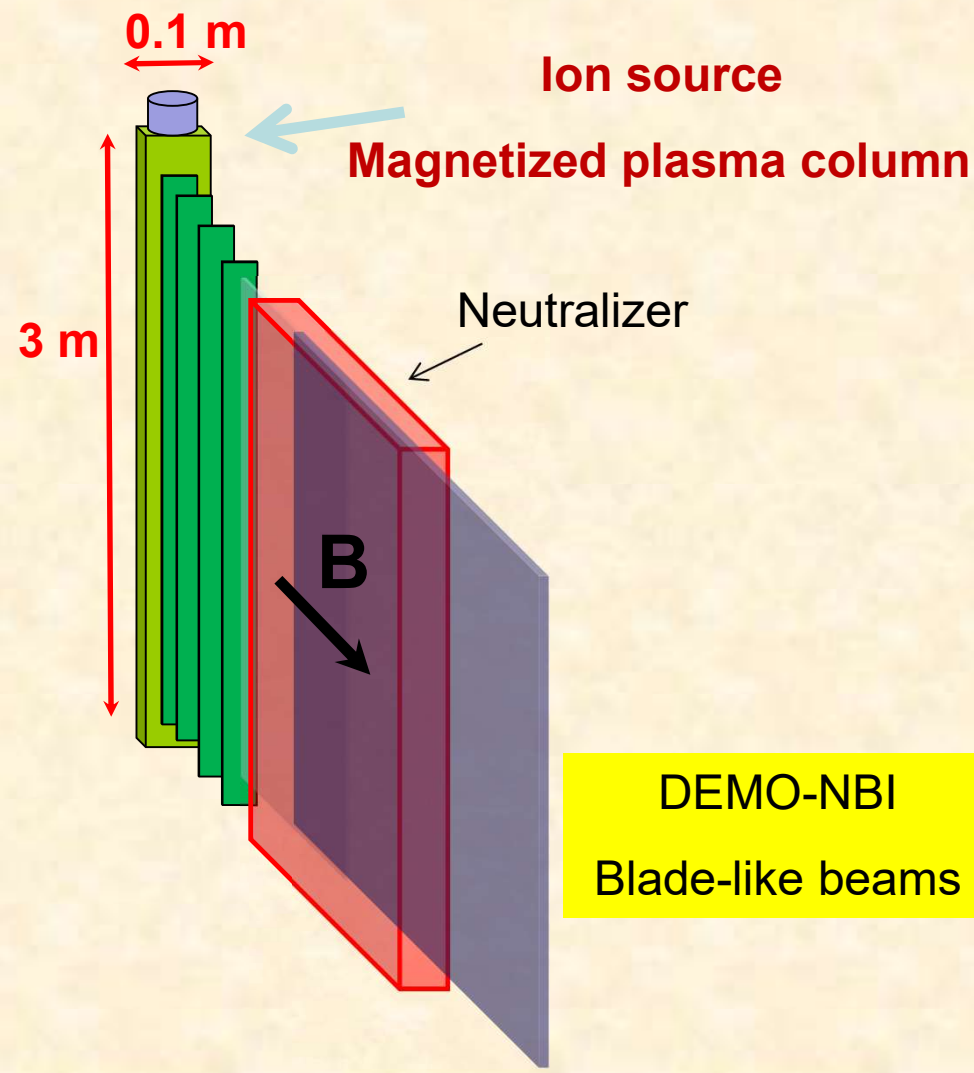
Square aspect ratio

Significant beam losses

Poor injector efficiency (< 25 %)

G Fubiani

Objectives: increase the injector efficiency



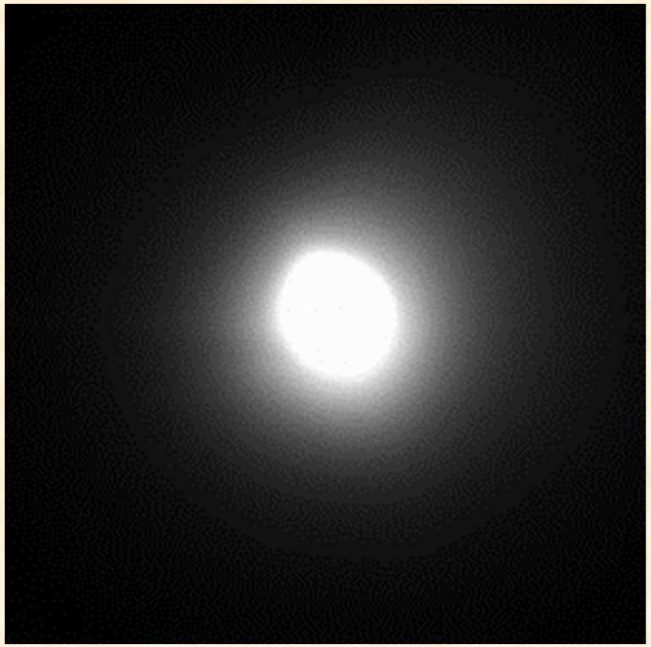
DEMO-NBI

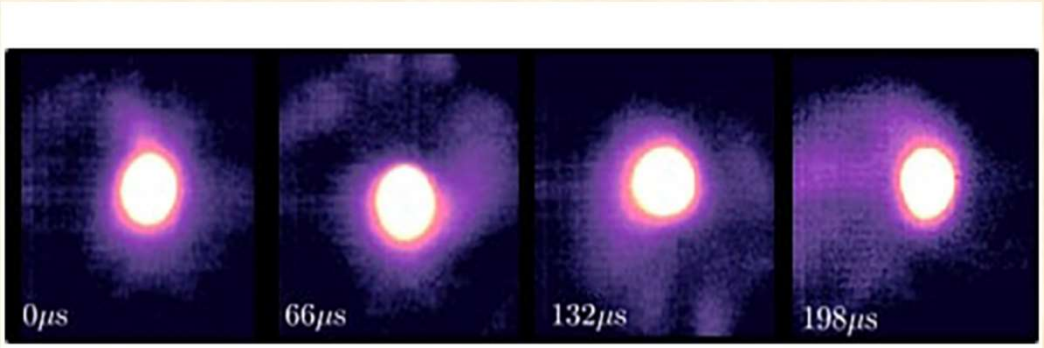
Blade-like beams

Physics of ExB plasmas addresses (among other problems):

- Range of unstable fluctuations of different frequencies and scale ubiquitously observed in Hall thrusters, magnetrons, and similar devices
- Electron transport across the magnetic field is anomalous.
- Large scale coherent structures (spoke)
- Fluctuations across different time and length scales, have dramatic effects on underlying regimes and performance of various devices (10 kHz-1 MHz and higher)
- Nature of fluctuations and transport is poorly understood, precludes first principle predictive modeling

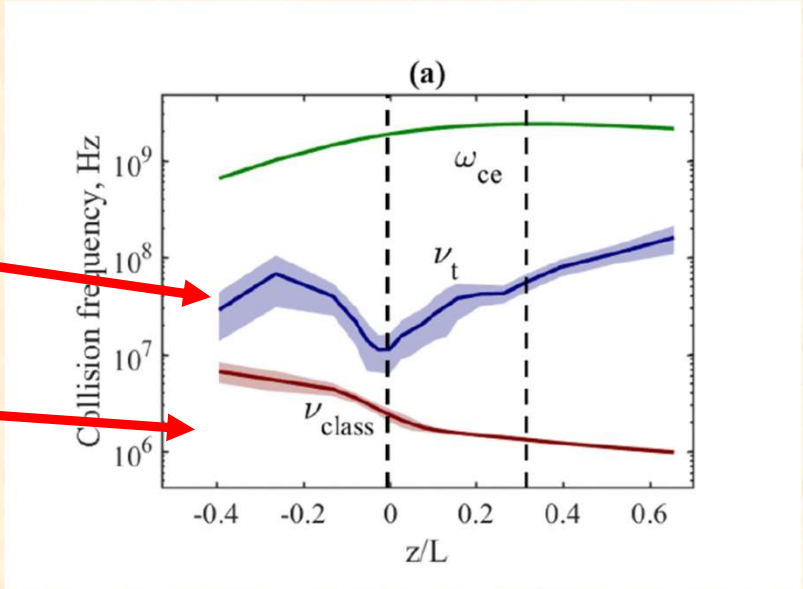
Rotating spoke in Penning discharge, Rodrigues et all, PoP 2019





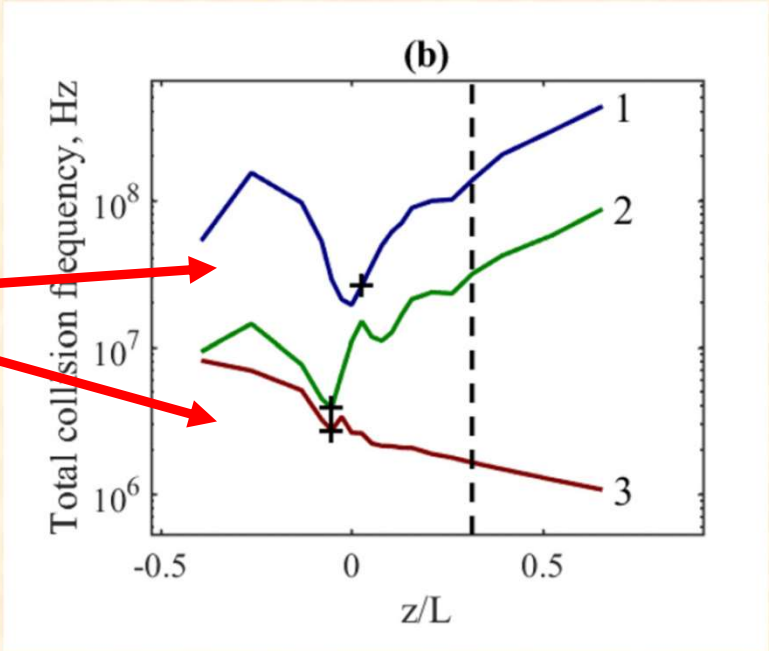
Experiments on mobility

Electron current is anomalous, orders of magnitude above the classical



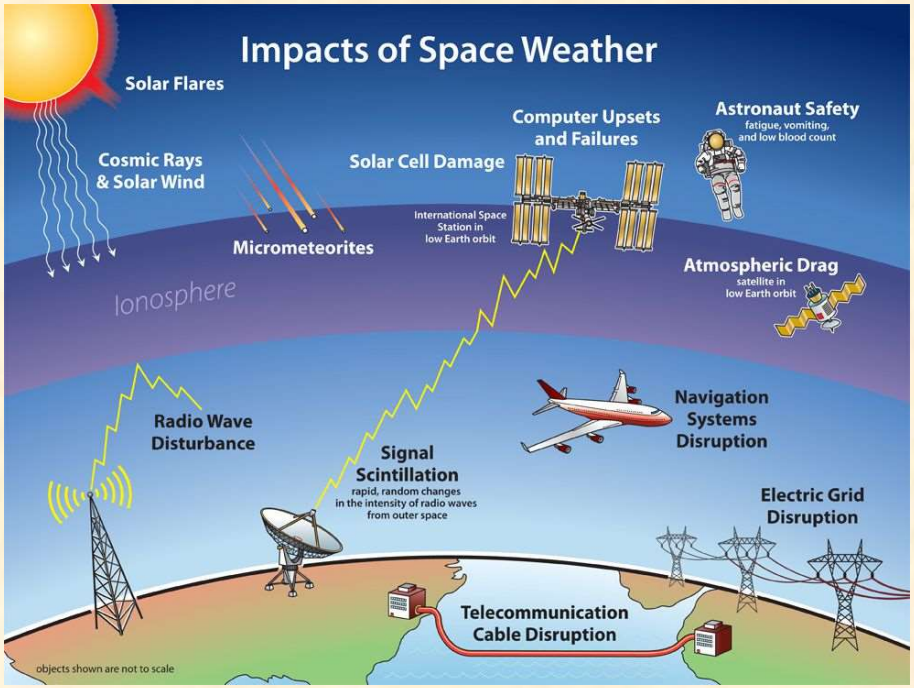
Effective (total) collision frequency in Hall thruster, E. Dale, B Jorns, PoP 2019

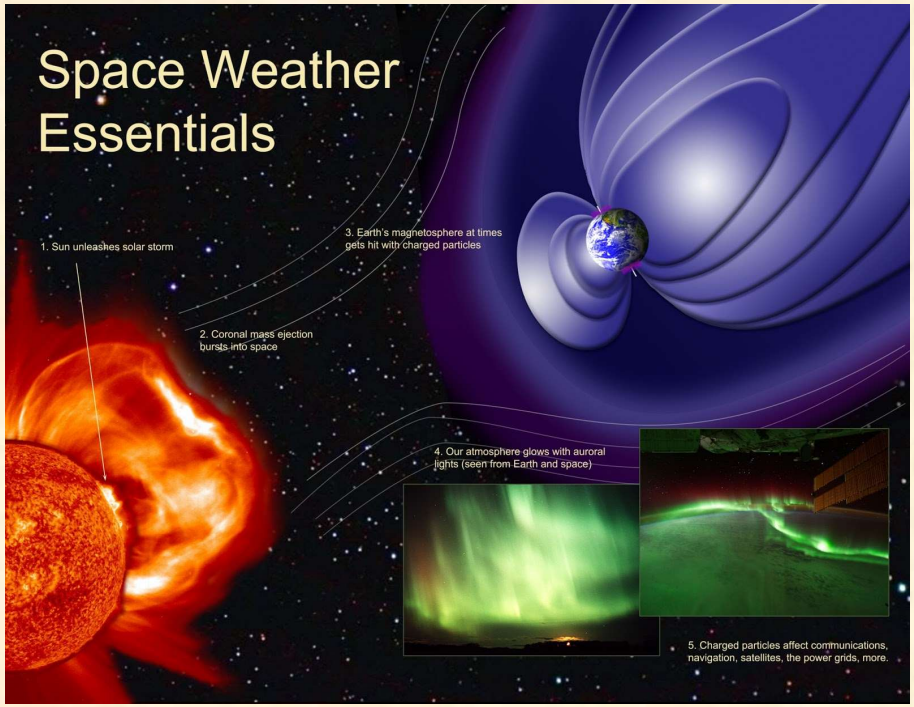
Anomalous electron current is modulated by the lower frequency (~10 kHz) breathing mode cycle



E. Dale, B Jorns, PoP 2019

Plasma fluctuations and structures (**irregularities**) in space weather





Space weather is a branch of space physics and aeronomy, or heliophysics, concerned with the time varying conditions within the Solar System, including the solar wind, emphasizing the space surrounding the Earth, including conditions in the magnetosphere, ionosphere, thermosphere, and exosphere. …
https://en.wikipedia.org/wiki/Space_weather

Ionosphere irregularities

Super Dual Auroral Radar Network (SuperDARN) Facility for studies of ionosphere irregularities (Coherent Radar Scattering), near Saskatoon SK

Photo credit: A Reimer, Ph D student, Department of Physics and Engineering Physics , University of Saskatchewan

Partially magnetized $\mathbf{E}\times\mathbf{B}$ plasmas (Hall plasmas)

- Configuration with perpendicular electric and magnetic fields, $\mathbf{E}_0 \perp \mathbf{B}_0$
- Magnetized electrons $\omega < \omega_{ce}$ $\rho_e < L$
- Un-magnetized ions $\rho_i > L$
- Magnetic filter: electrons are trapped; motion across the magnetic field is constrained, drifting $\mathbf{V}_\mathbf{E} = \mathbf{E}\times\mathbf{B}/B^2$
- **Ions are weakly affected by the magnetic field; controlled by the electric field; can be accelerated/ extracted, etc,…**

Problem

Fluctuations, structures and anomalous transport in ExB plasmas:

- Ubiquitously observed in many devices
- Multi-scale nonlinear problem: small scales are typically most unstable, can feed large scale structures; large scale structures modify the equilibrium and affect stability conditions for small scales: self-organization

Long wavelength modes dominantly contribute to the anomalous transport/current (e.g. large fraction of the current may go via spoke structure)

$$D \simeq \frac{(\Delta x)^2}{\tau} \sim \frac{\lambda^2}{\lambda} \sim \lambda$$

$$\tau \sim \gamma^{-1}$$

$$\gamma \sim kc_s \sim 1/\lambda$$

Approach, methods and tools

First principle physics (analytical) models

Analysis of linear eigen-modes and instabilities

Reduced analytical and nonlinear simulations models

Fluid and kinetic numerical simulations

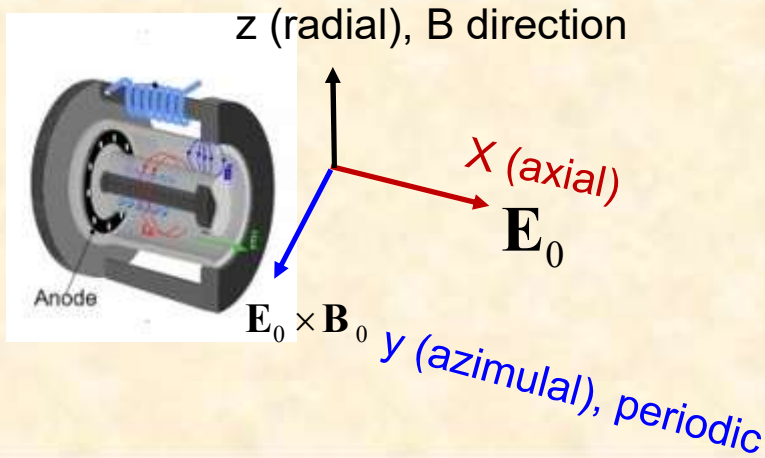
Verification, e.g. codes bechmarking and validation with experiments

2D reduced (azimuthal-axial) fluid turbulence code
2D kinetic (particle-in-cell) codes (azimuthal-axial, azimuthal-radial)
1D fluid and 1D hybrid (kinetic ions and neutrals) codes for ionization/breathing modes
1D Vlasov (direct-kinetic) turbulence code

Next:

- Eigen-modes and instabilities
  - Gradient-drift (Simon-Hoh) modes
  - Lower hybrid modes

  } Azimuthal modes along $\mathbf{E}_0 \times \mathbf{B}_0$
  - Resistive, axial (along the applied $\mathbf{E}_0$) modes
- Advanced fluid model and simulations
  - Inverse cascade, self-organization and coherent structures: zonal flows, vortices and streamers
  - Anomalous current
- Kinetic effects and simulations



Confined plasmas has gradients

→ Density, temperature, magnetic field are inhomogeneous
also electric field is a part of the equilibrium

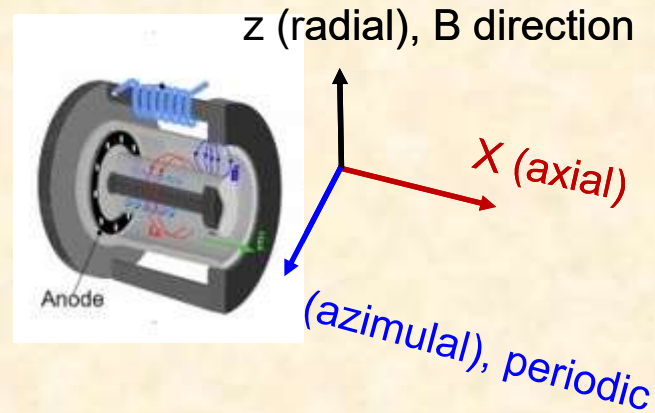
→ Gradients induce waves -- drift waves
and instabilities

→ Drift waves in partially magnetized plasma are
different from e.g. tokamak (fully magnetized)

Drift mode in partially magnetized plasma

- Gradient effects in electron dynamics

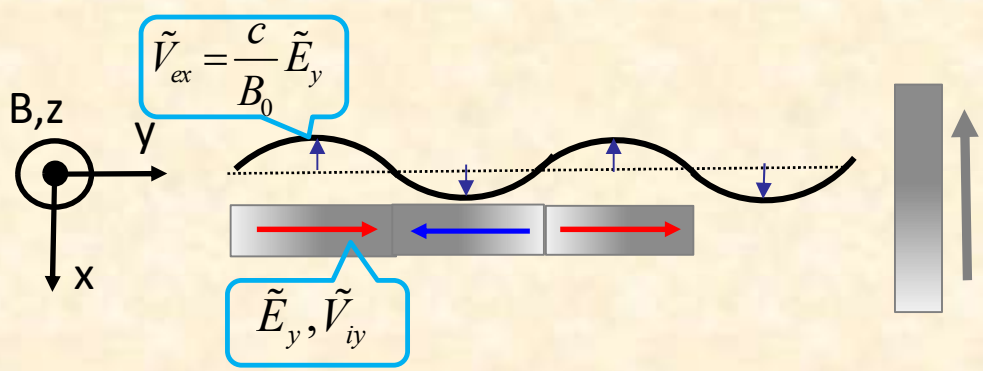
$$\frac{\partial}{\partial t}\tilde{n}+\tilde{V}_E\cdot\nabla n_0=\frac{\partial}{\partial t}\tilde{n}+\frac{c}{B_0}\tilde{E}_y\frac{\partial n_0}{\partial x}=0$$



- Unmagnetized ions

$$\frac{\partial\tilde{V}_y}{\partial t}=\frac{e}{m_i}\tilde{E}_y$$

- "Anti-drift mode" (Fridman, 1964)



$\nabla n_0 = n_0 / L_n$

$$\omega=-k_y\omega_{ci}L_n=\frac{k_y{}^2c_s{}^2}{\omega_*}$$

$$\omega_*=-\frac{k_ycT_e}{eB}\frac{n_0'}{n_0}$$

Gradient-drift/Simon-Hoh instability in ExB plasma

- Electron dynamics with $\mathbf{V} = c\mathbf{E}\times\mathbf{B}/B^2 = -cE_{0x}/B_0\hat{\mathbf{y}}$ electron flow
  Simon-Hoh instability: Negative compressibility/negative energy

aka Rayleigh-Taylor instability of the stratified density in the gravity field (heavy fluid on top)

$$\omega^2 = k_y{}^2\omega_{ci}V_{0y}L_n < 0$$

$$\gamma = k_y\sqrt{\frac{eE_{0x}L_n}{m}}$$

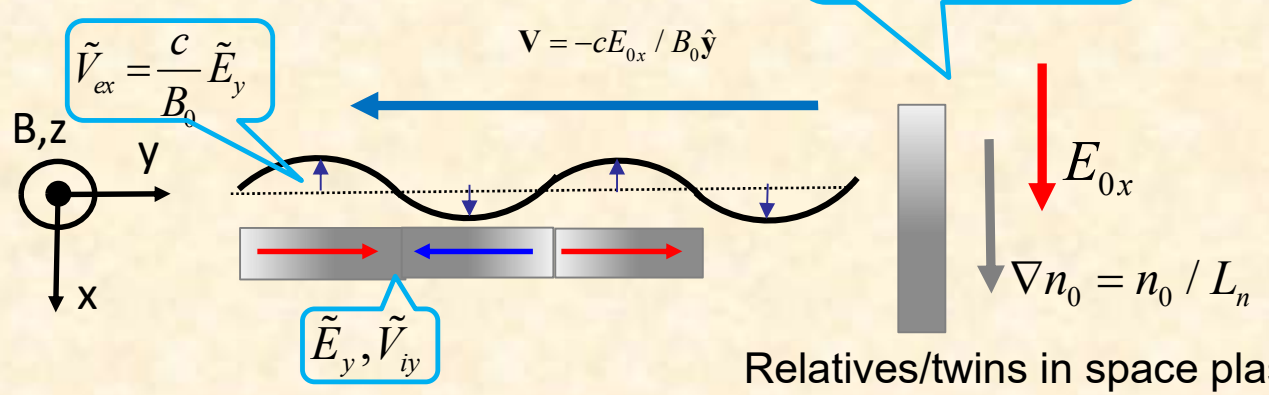
$$\frac{\partial p}{\partial n} = -eE_{0x}\left(\frac{1}{n_0}\frac{\partial n_0}{\partial x}\right)^{-1} = -eE_{0x}L_n < 0$$

Modified by magnetic field gradients

$$\nabla n \to \nabla\left(n/B^2\right)$$

$$E_{0x}\frac{\partial n_0}{\partial x} > 0$$

Unstable configuration

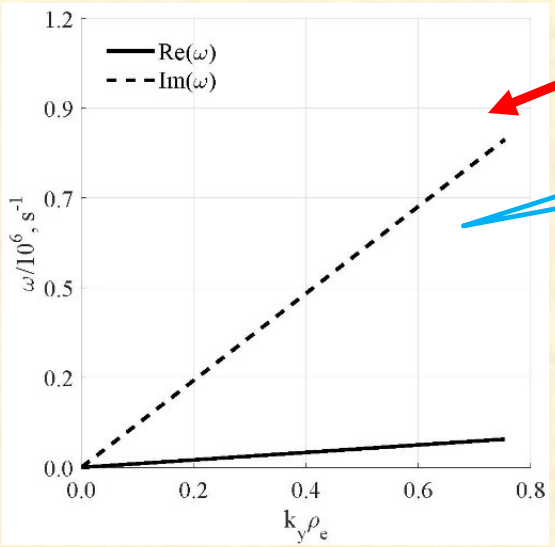


Simon, Hoh, …, 60s, Huba, .. Sakawa, 1992,
Morozov, Esipchuk, Tilinin, 60s, Cappelli, Ahedo, Kapulkin Raitses,..

Relatives/twins in space plasma: gradient-drift and Farley-Buneman instabilities

Inertia modification of the Simon-Hoh instability?

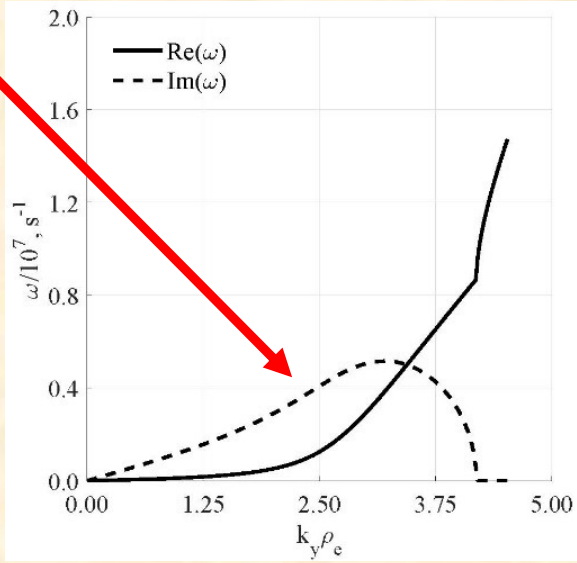
Electron inertia brings new mode (lower-hybrid) and provides the physics based cut-off at high wavelengths –lower-hybrid instability



Growth rates

Without inertia

With inertia

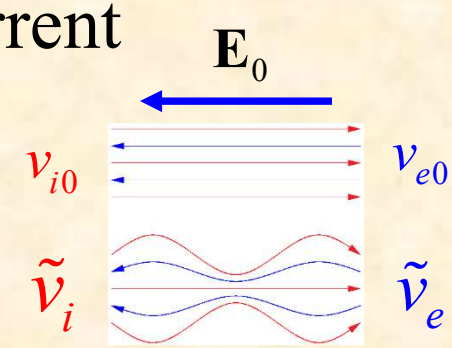


High frequency" ion sound: short wavelength extension of the lower-hybrid mode

$$\omega^2 = \omega_{LH}{}^2\left(1 + k_\perp{}^2\rho_e{}^2\right) \approx \omega_{LH}{}^2 k_\perp{}^2\rho_e{}^2 = k_\perp{}^2 c_s{}^2$$

Resistive current flow (axial) instability

Driven by the axial ion/electron current. Phase shift between the ion inertial (ballistic) and electron dissipative response. Electron anomalous current can serve the role of the dissipative current

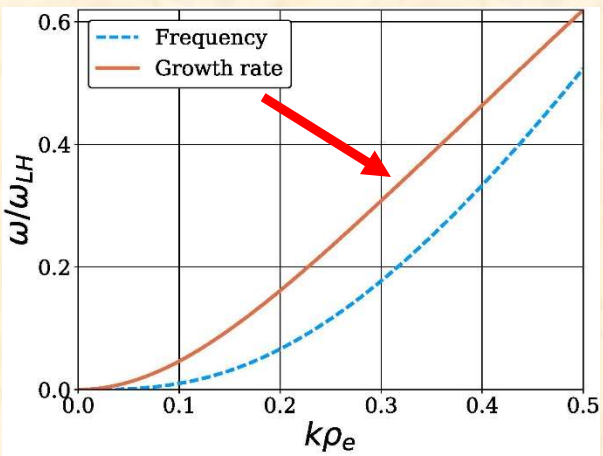


Inherent instability of the current flow due tp the phase shift between the dissipative response of the electron flow and ballistic (inertial) response of ions

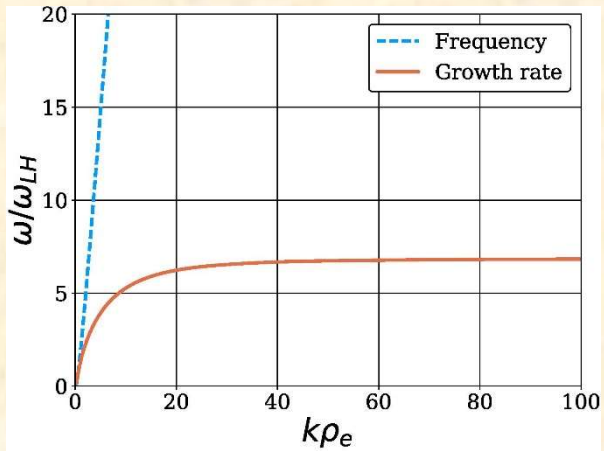
Chable, Rogier, 2005
Fernandez et al 2008
Koshkarov et al, 2017, 2018

Electron current: $\mathbf{J}_e = \sigma_\perp \mathbf{E}_0$
collisional and/or anomalous

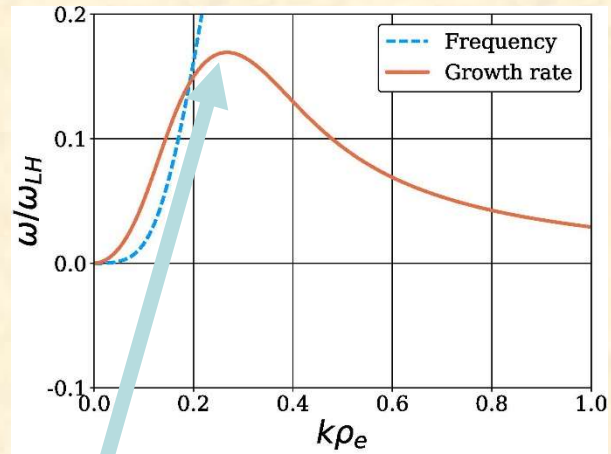
Electron inertia selects the most unstable mode



Growth rates: without inertia



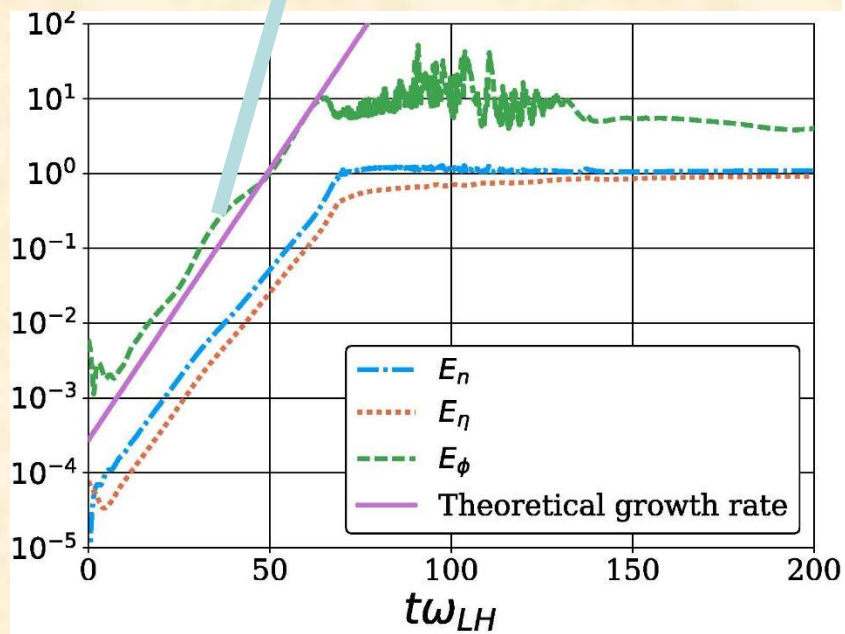
with diffusion but without inertia



with inertia

The mode is long-wavelength!

$$\gamma \simeq \nu \frac{k_x^{\,2} v_{0i}^{\,2}}{\omega_{LH}^{\,2}}$$



Linear growth and nonlinear saturation of axial resistive modes.

Koshkarov et al, Physics of Plasma 2017, 2018

Advanced fluid model for nonlinear simulations

- **Unmagnetized ions**
- **Reduced model for magnetized electrons, expansion in small**
  - **parameters** $\omega_{ce} > \left(\omega, \nu_e, k_\perp V_\perp\right)$
  - **Finite electron radius effects are included, good agreement with kinetic theory, Pade approximants for large** $k_\perp \rho_e \gg 1$
  - **Density gradient mode** $\omega = -\omega_{ci} k_y L_n$ **, destabilized by** $\mathbf{E} \times \mathbf{B}$ **flow (Simon-Hoh**
  - **Electron inertia and lower-hybrid modes**
  - **Resistive instabilities and ion flow destabilization**

Reduced nonlinear equations: $\omega_{ce}^{-1}\partial/\partial t << 1$

Density gradient, Simon-Hoh

Magnetic field gradient

Collisions

Electrons

$$\frac{\partial n}{\partial t} + \frac{c}{B}\{\phi, n\} + \mathbf{v}_E \cdot \nabla n_0 - 2n\mathbf{v}_E \cdot \nabla \ln B - 2n\mathbf{v}_{pe} \cdot \nabla \ln B + \frac{\nu c n_0}{B_0 \omega_{ce}} \nabla_\perp^2 \left(\phi - \frac{T_e}{e n_0} n\right)$$
$$+ \frac{n_0 c}{\omega_c B_0}\left(\frac{\partial}{\partial t} + \mathbf{v}_E \cdot \nabla\right) \nabla_\perp^2 \phi + \frac{c^2 T_e}{e B^2 \omega_{ce}} \nabla \cdot \{\nabla\phi, p\} = 0$$

inertia

Ion flow

Ions

$$\tilde{\mathbf{v}} = -\nabla\tilde{\chi}.$$

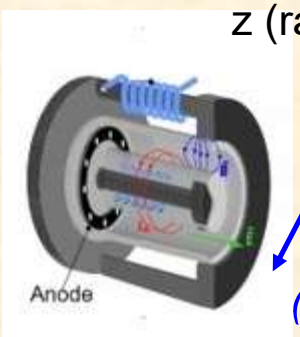
$$\frac{\partial}{\partial t}\nabla^2\tilde{\chi} = \nabla^2\left(\frac{e}{m_i}\phi + \frac{(\nabla\tilde{\chi})^2}{2}\right) - v_0 \frac{\partial}{\partial z}\nabla^2\tilde{\chi} - 2\frac{\partial v_0}{\partial z}\frac{\partial^2\tilde{\chi}}{\partial z^2} - \frac{\partial\tilde{\chi}}{\partial z}\frac{\partial^2 v_0}{\partial z^2}$$

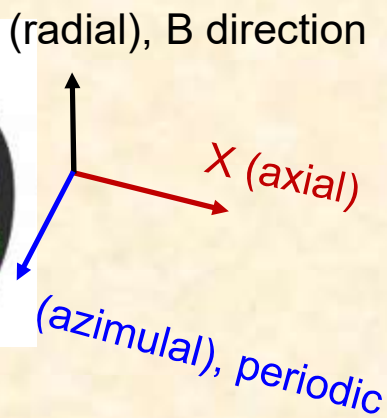
$$\left(\frac{\partial}{\partial t} + \mathbf{v}_0 \cdot \nabla\right)\tilde{n} - \nabla\tilde{\chi} \cdot \nabla n_0 + \tilde{n}\nabla \cdot \mathbf{v}_0 - n_0\nabla^2\tilde{\chi} - \nabla \cdot (\tilde{n}\nabla\tilde{\chi}) = 0.$$

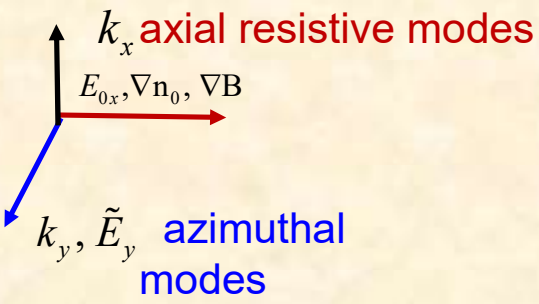
2D: azimuthal-axial, includes ion flow

Smolyakov et al.,
Plasma Physics and Controlled Fusion, 2016

Self-organization in partially magnetized ExB plasma







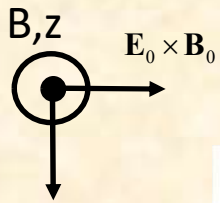
Axial E_{0x} and $\nabla n_0, \nabla B$ gradients drive $k_y, \tilde{E}_y$ azimuthal modes

azimuthal modes drive axial anomalous $\langle \tilde{n}\tilde{E}_y \rangle / B_0$ transport σ_{anom}

axial resistive modes are excited due to anomalous σ_{anom} and create large scale axial electric field and density gradients

This coupling has been demonstrated in reduced simulations

Turbulence, transport and structures in nonlinear fluid simulations driven by $\mathbf{E}_0$ and ∇n



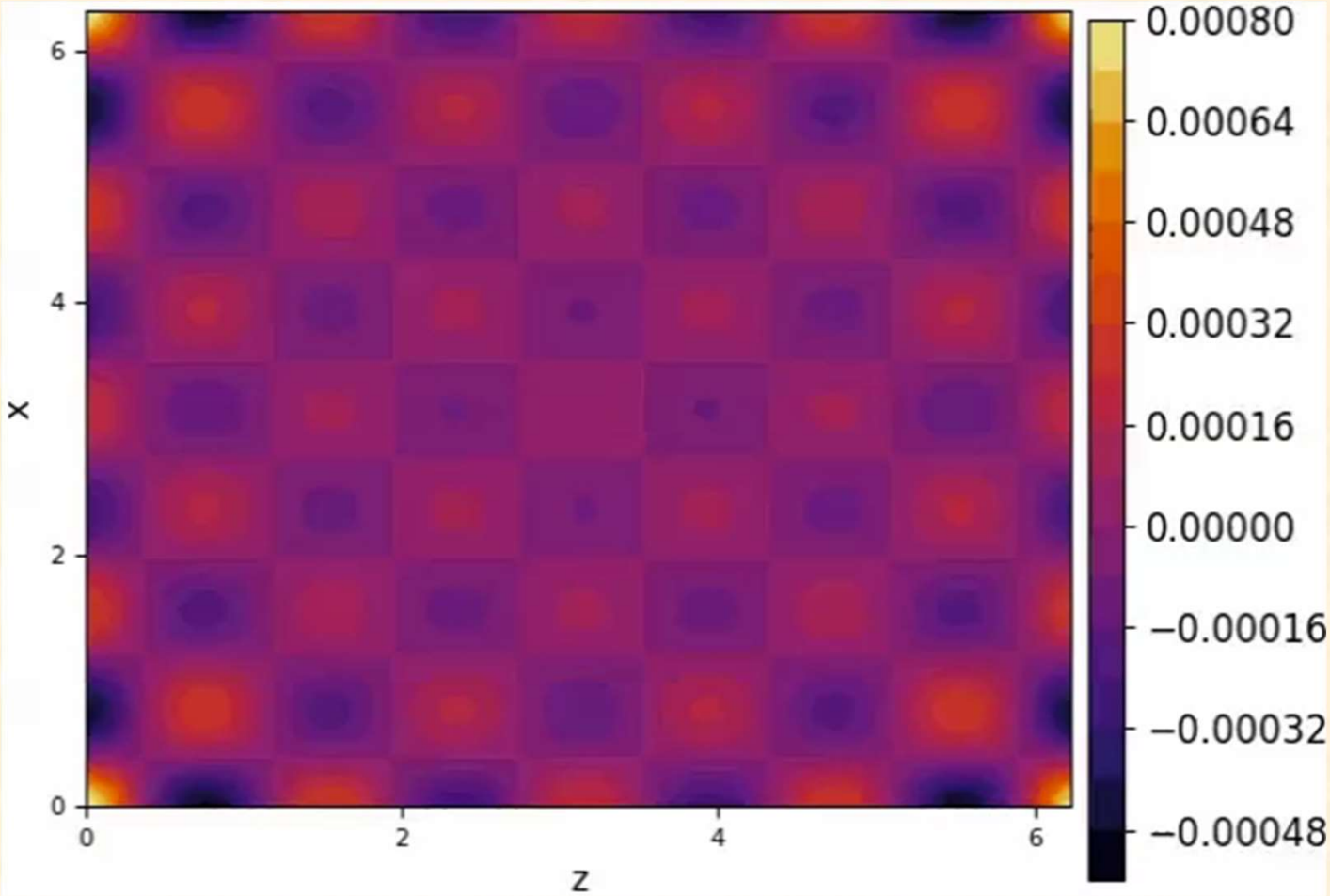
(azimuthal modes

(axial modes)

azimuthal direction, $\mathbf{E}_0 \times \mathbf{B}_0$, $\tilde{E}_y$

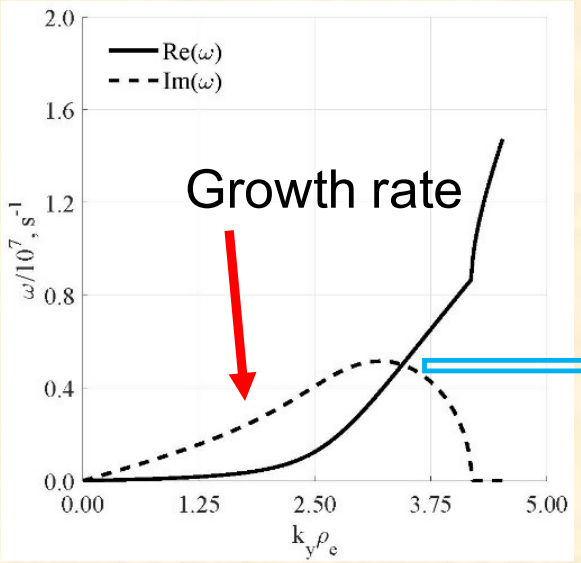
axial direction

$\mathbf{E}_0$ ∇n

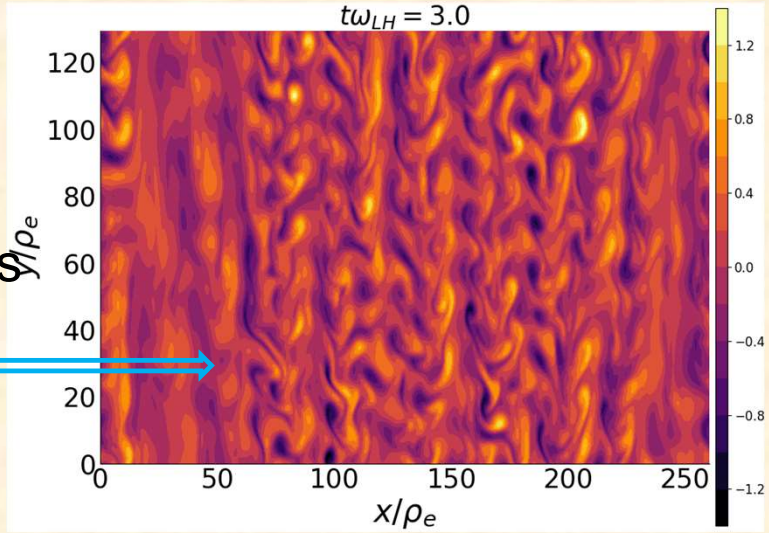


Koshkarov, USask PhD thesis, PRL 2019

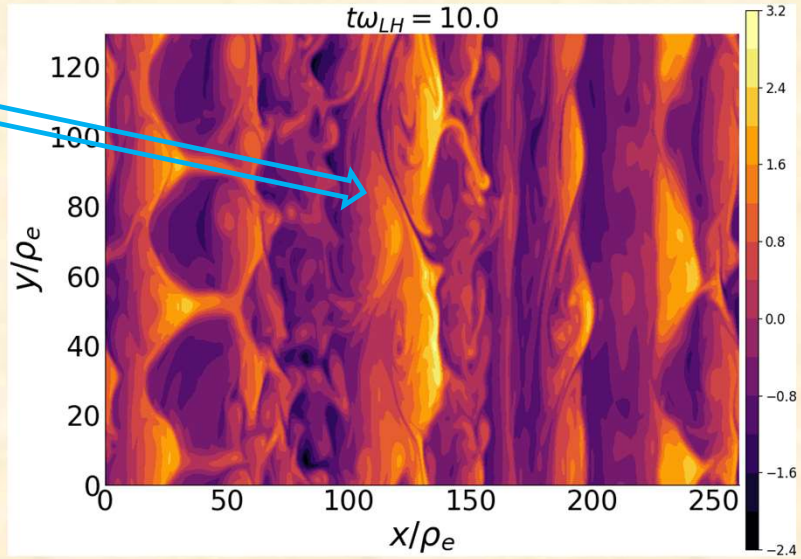
Energy cascades from high k (most unstable) to low k (box size) modes: inverse cascade



Most unstable small scale modes



Large scale structures in saturated state

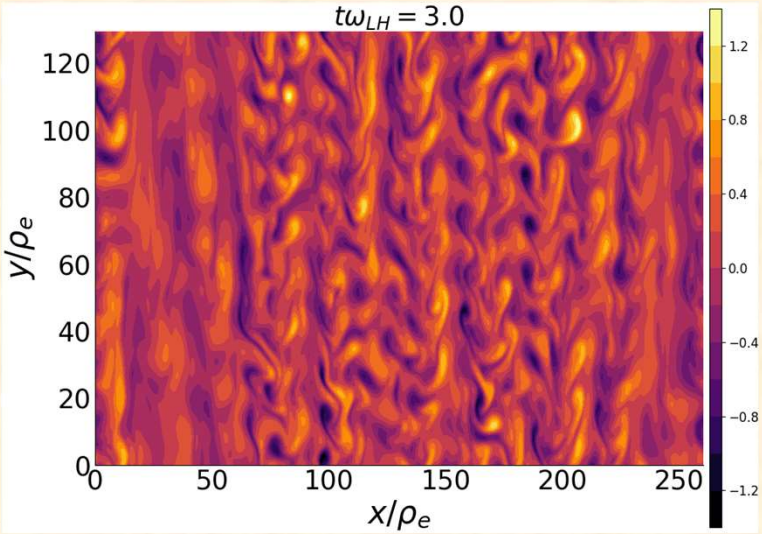


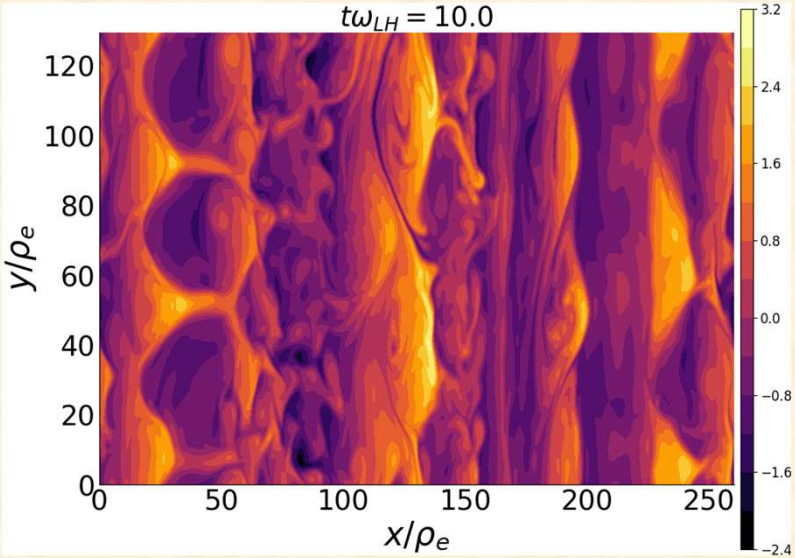
Inverse cascade is a signature of 2D systems:
Nonlinear terms from electron inertia

$$\mathbf{V}_e = \ldots + \frac{\mathbf{B}}{\omega_{ce} B} \times \left(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla + \mathbf{V}_{pe} \cdot \nabla \right) \mathbf{V}$$

Nonlinear excitation of long-wavelength modes in Hall plasma, Lakhin, Ilgisonis, Smolyakov PoP 2016

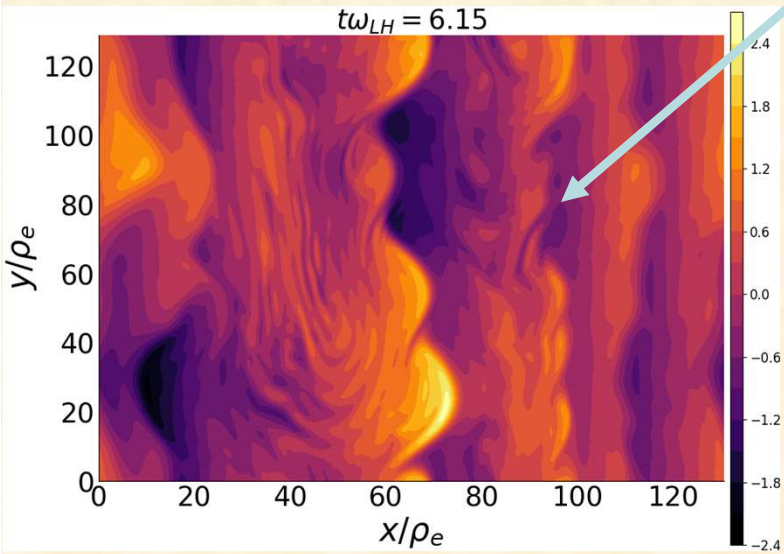
Inverse cascade -> zonal flows and vortex structures

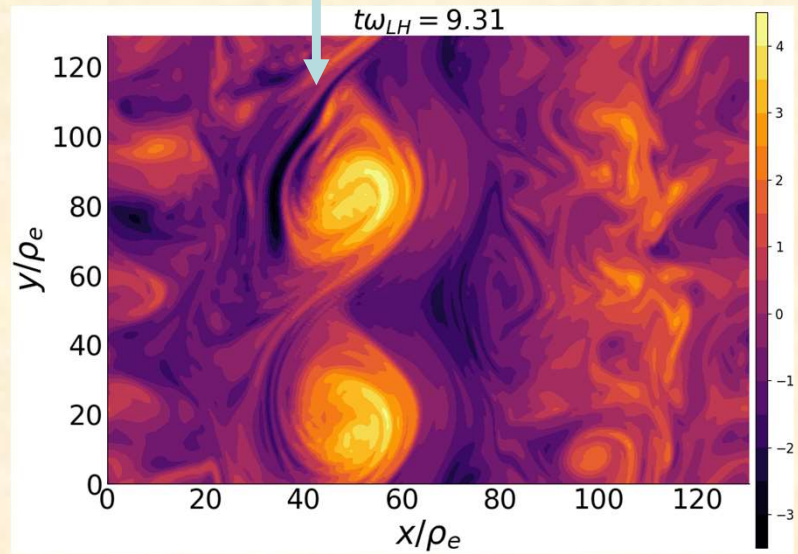


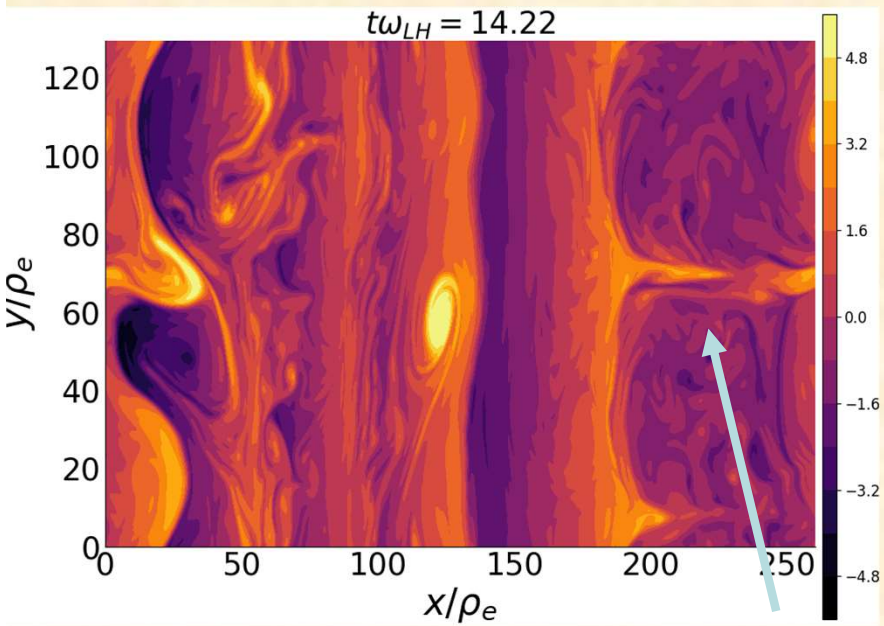


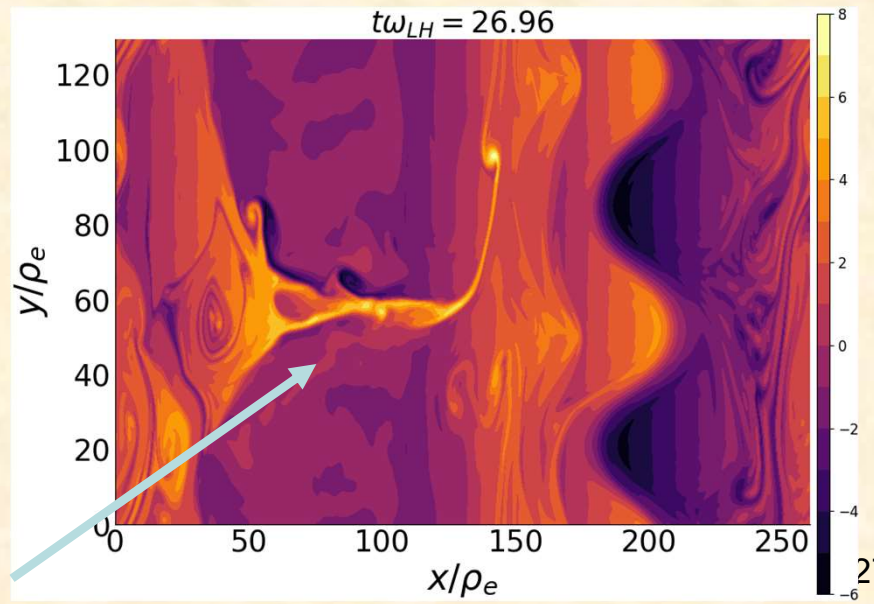
Zonal flows and Great Red Spot on Jupiter

Self-organization: zonal flows, vortices and streamers



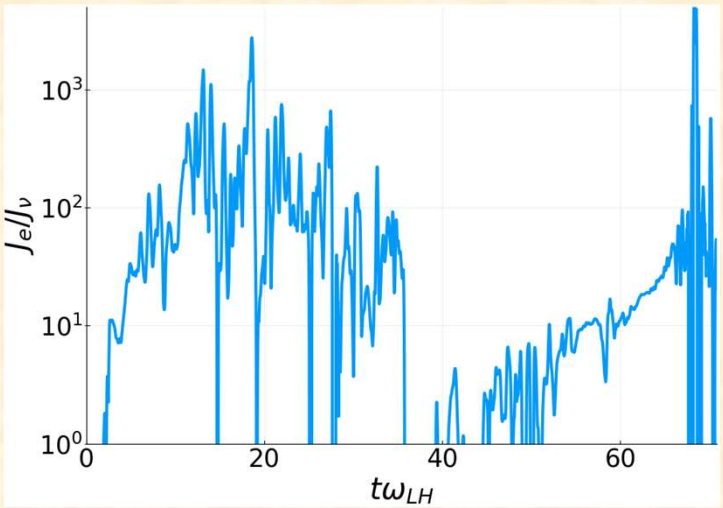






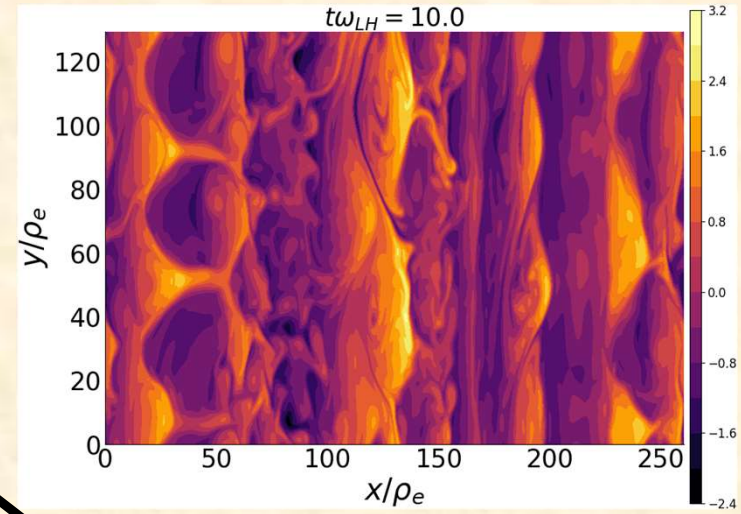
streamers

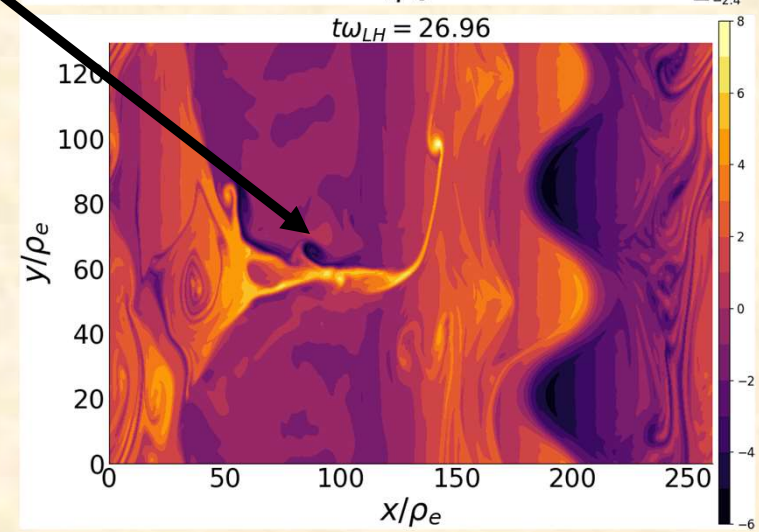
- First principle self-consistent demonstration of the anomalous conductivity in fluid simulations
- Inverse cascade, self-organization and formation of large scale structures from small scale turbulence



Zonal flow and vorticies

Streamer





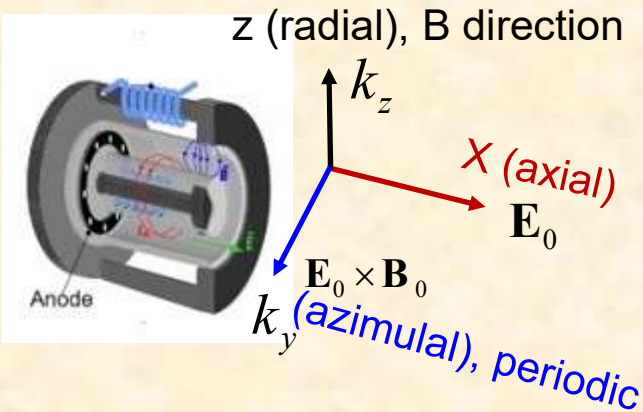
- Large anomalous current: effective Hall parameter ~27-50;
- Highly intermittent: not diffusive process (of many small events); rather like sequence of relatively rare but large transport events)
- Self-organized criticality (avalanche occurs near the critical state)
- Does parameterization of anomalous current by mobility apply here?

Kinetic effects and Instabilities in ExB discharges

- **Electron Cyclotron Drift Instability (ECDI):** ⟹ Strong electric field. **Cyclotron resonance driven (collisionless). No density, magnetic field and other gradients are required,** k_y along $\mathbf{E}_0 \times \mathbf{B}_0$

- **Electron Drift Instability (EDI)** ⟹ Strong electric field. ECDI modified by **nonlinear and other effects**, e.g. turbulence broadening, ion sound, etc k_y along $\mathbf{E}_0 \times \mathbf{B}_0$

- **Modified Two Stream Instability (MTSI)** ⟹ Strong electric field. Electron motion along the magnetic field is included + Doppler shift along $\mathbf{E}_0 \times \mathbf{B}_0$, k_y and k_z



Magnetized electrons $\mathbf{E}_0 \times \mathbf{B}_0$ beam streaming with respect to unmagnetized (stationary) ion – aka two-stream instability

Electron Cyclotron Drift, Modified Two-Stream Instabilities and Buneman (magnetized plasma) instabilities

In cold plasmas

Buneman, 1962

$$1-\frac{\omega_{pi}^{2}}{\omega^{2}}-\frac{\omega_{pe}^{2}}{\left(\omega-k_{y}V_{E}\right)^{2}-\omega_{ce}^{2}}-\frac{k_{z}^{2}}{k^{2}}\frac{\omega_{pe}^{2}}{\left(\omega-k_{y}V_{E}\right)^{2}}=0$$

Buneman Modified two-stream

With warm electrons, sequence of resonances, m=1,2,3..

$$\omega-k_{y}v_{0}-m\omega_{ce}\approx 0$$

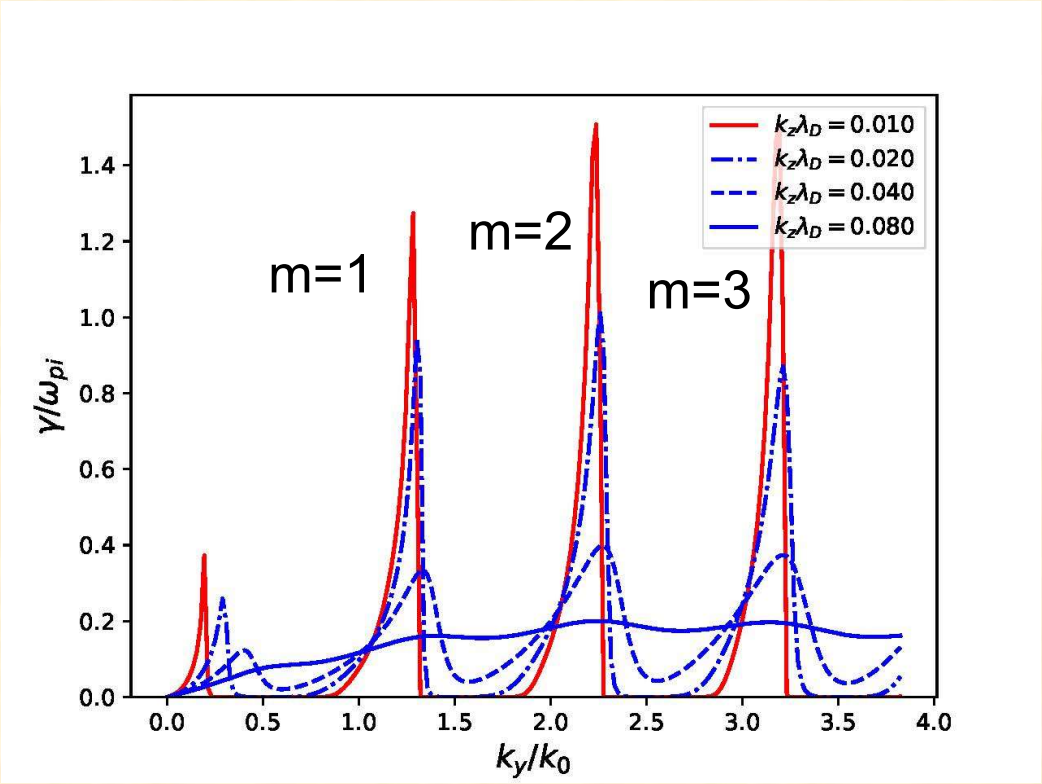
$$1+K_{i}+K_{e}=0 \qquad K_{i}=-\frac{\omega_{pi}^{2}}{\omega^{2}}$$

$$K_{e}=\frac{1}{k^{2}\lambda_{D}^{2}}\left[1+\frac{\omega-k_{y}v_{0}}{\sqrt{2}k_{z}v_{Te}}\sum_{m=-\infty}^{\infty}I_{m}\left(k_{\perp}^{2}\rho_{e}^{2}\right)\exp\left(k_{\perp}^{2}\rho_{e}^{2}\right)Z\left(\frac{\omega-k_{y}v_{0}-m\omega_{ce}}{\sqrt{2}k_{z}v_{Te}}\right)\right]$$

Electron cyclotron drift instability

$\omega - k_y v_{ExB} = m\omega_{ce}$ m=1,2, 3.. resonances

$\omega \ll k_y v_{ExB} \sim m\omega_{ce}$



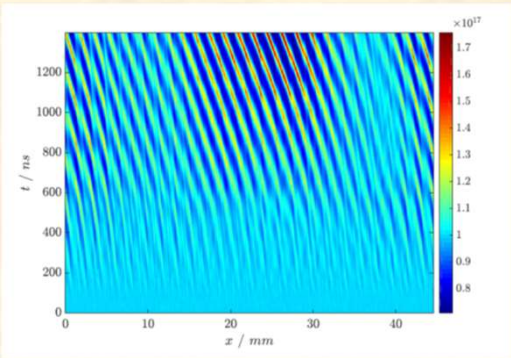
ECDI in ExB discharges, Hall thrusters and magnetron applications

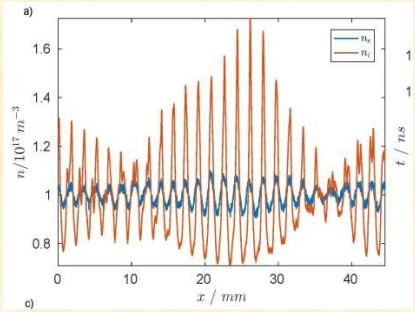
- PIC simulations: Adam, Heron 2004, 2006,…, 2013; Ducroq 2006
- Tsikata- 2009, 2011, 2015…Collective light scattering measurements, Magnetron -2015
- Lafleur, Baalrud… 2016, 2017; quasilinear estimates
- Katz, Mikellides 2015 – applied to HT
- Lafleur 2017, Croes 2017 – R-θ PIC simulations
- Boeuf 2013, 2015, 2017 –review in J Appl Phys
- Charoy et al 2019
- ….

Coherent modes in 1D and 2D simulations

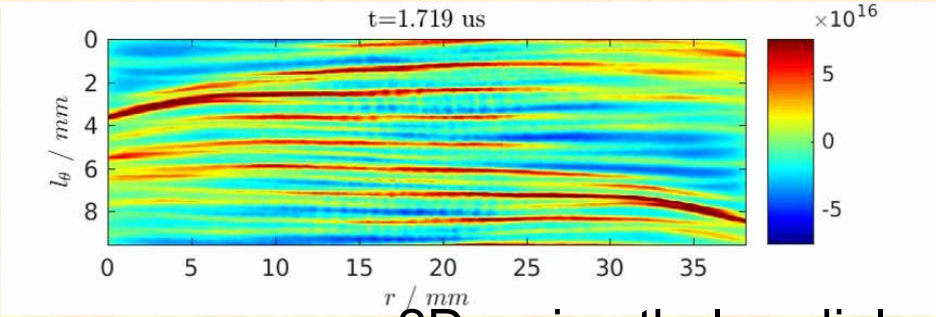
Lafleur et al. 2016, Boeuf .. 2017, Janhunen et al, Phys Plasmas 2018a,b; Zintel… 2019, Charoy et 2019, Taccogna 2019

Long wavelength condensation

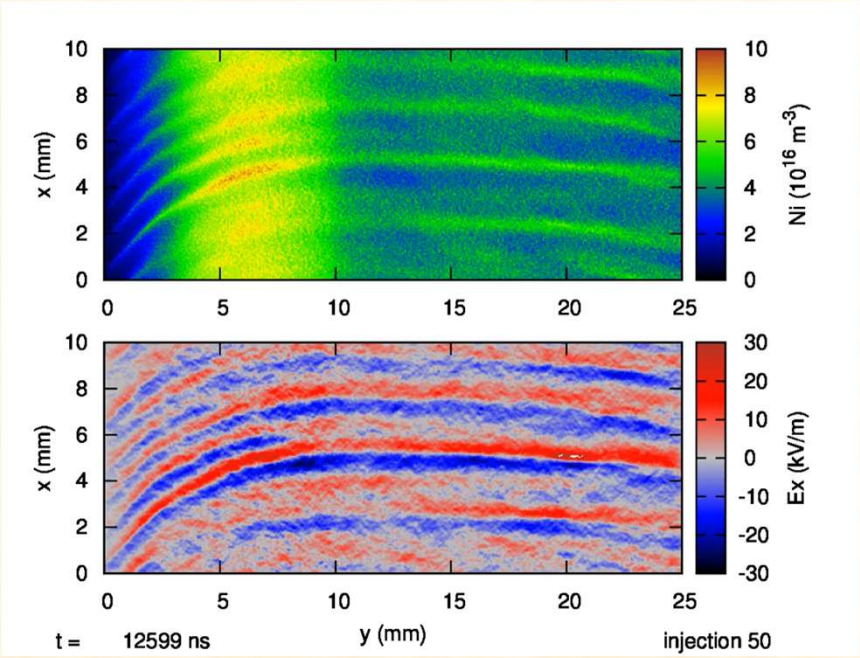




1D azimuthal



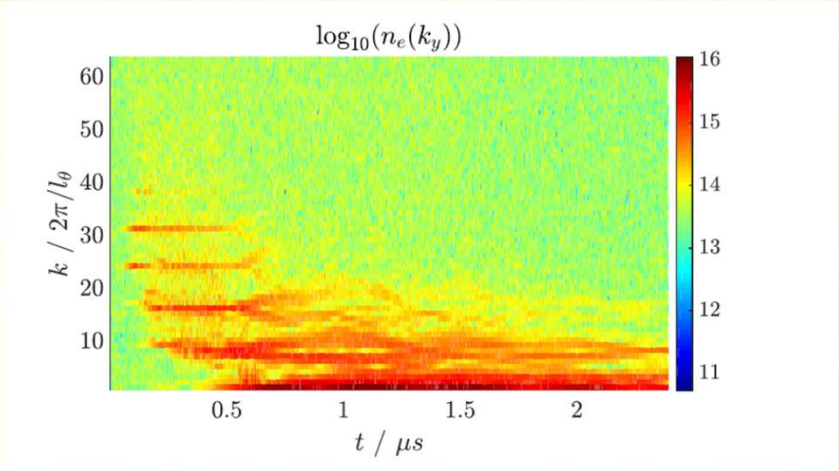
2D: azimuthal -radial

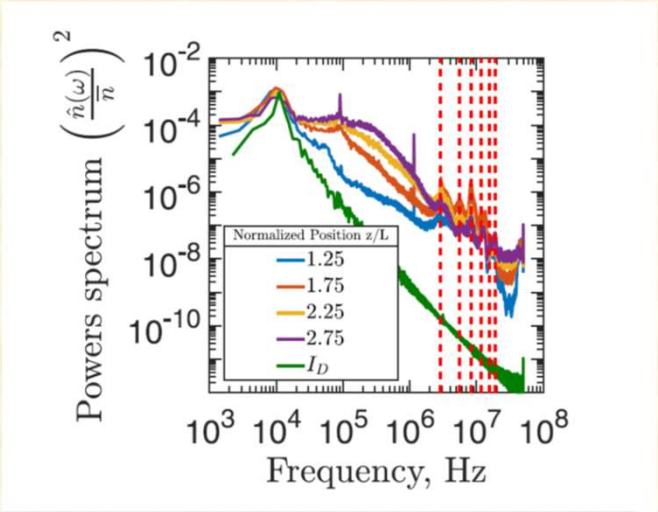


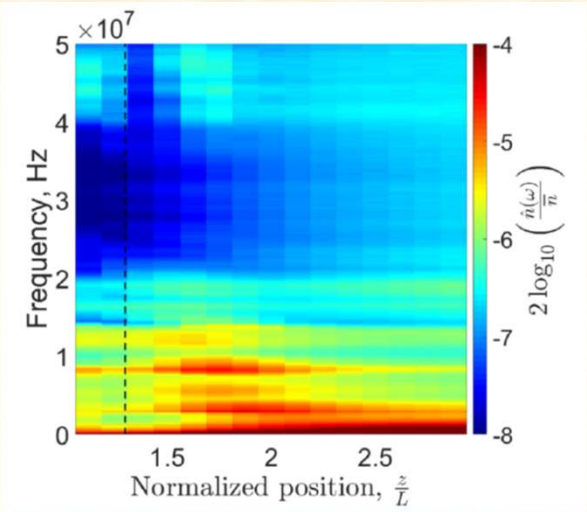
2D: azimuthal -axial

Cyclotron resonances and inverse cascade to longer wavelengths

Resonances and condensation toward the long wavelength
S Janhunen, Smolyakov et al. 2018

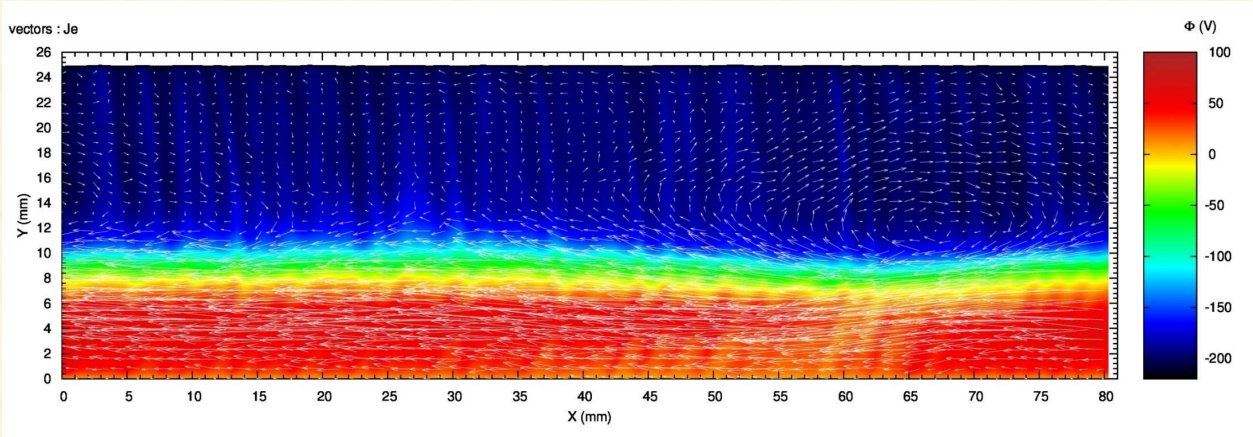






Resonances and long wavelength condensation in experiment
Z Brown, B Jorns, PoP 2019

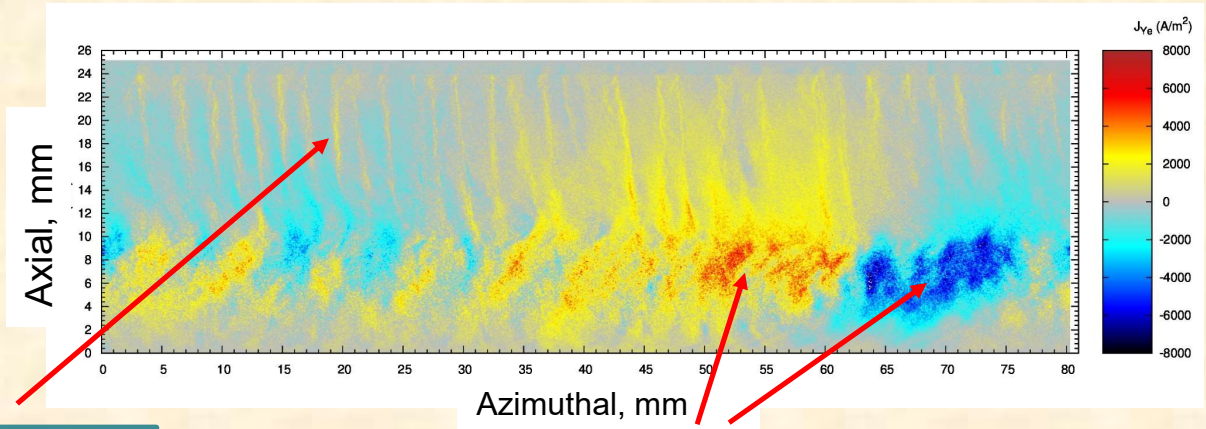
Inverse cascade: Current streamers and current vorticies in large box simulations



Electron current forms a vortex (or two) in the transport region (almost zero electric field)

Sydorenko, Smolyakov, Tavasolli 2021

Coherent structures in current!

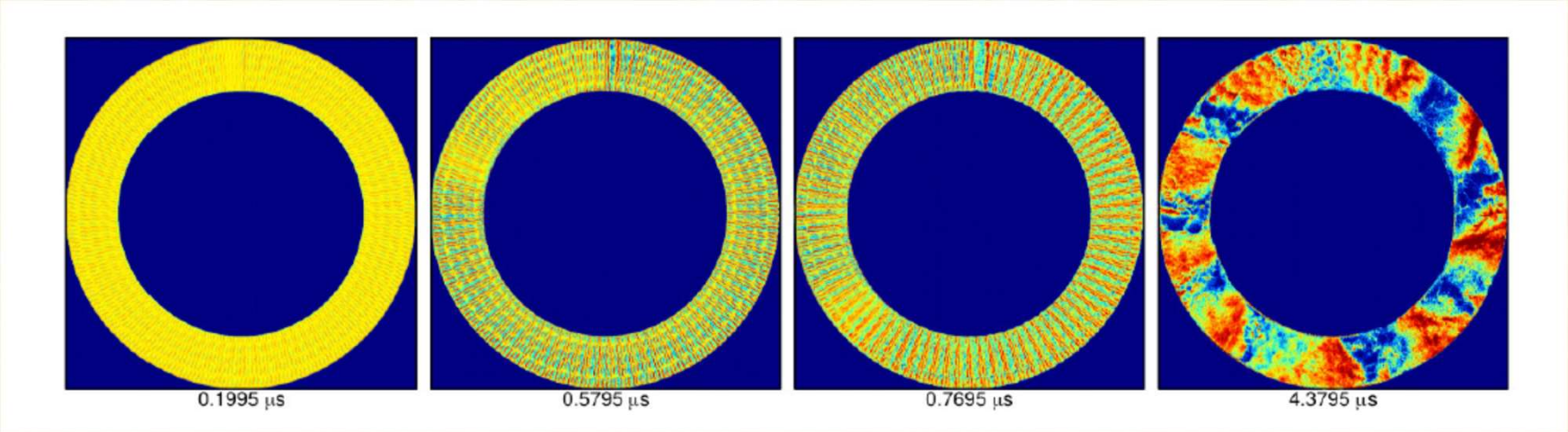


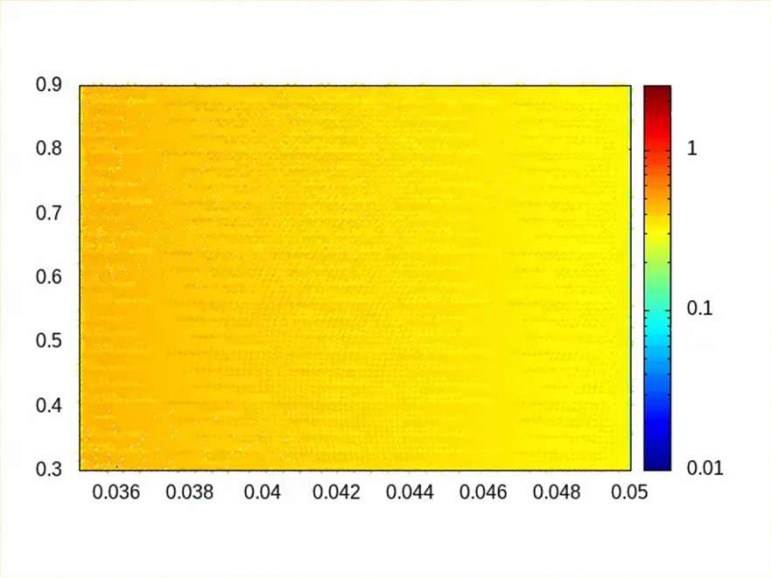
Current streamers

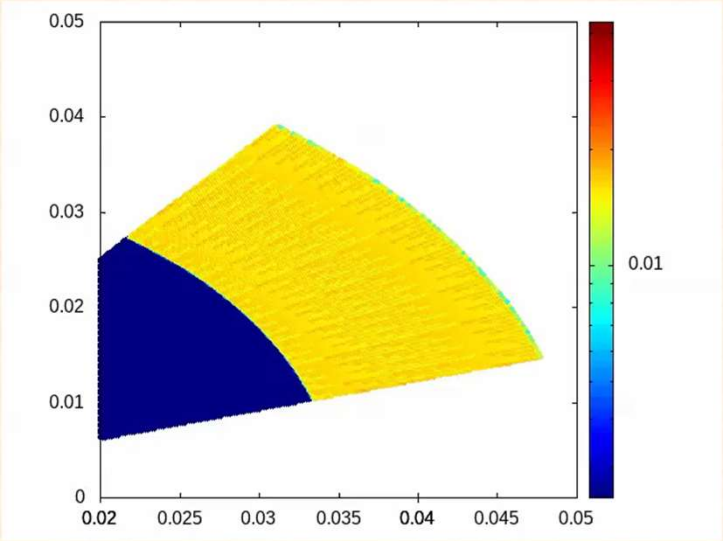
Current vortex

Mode transitions towards longer wavelengths in 2D azimuthal-radial simulations

10cmx10 cm

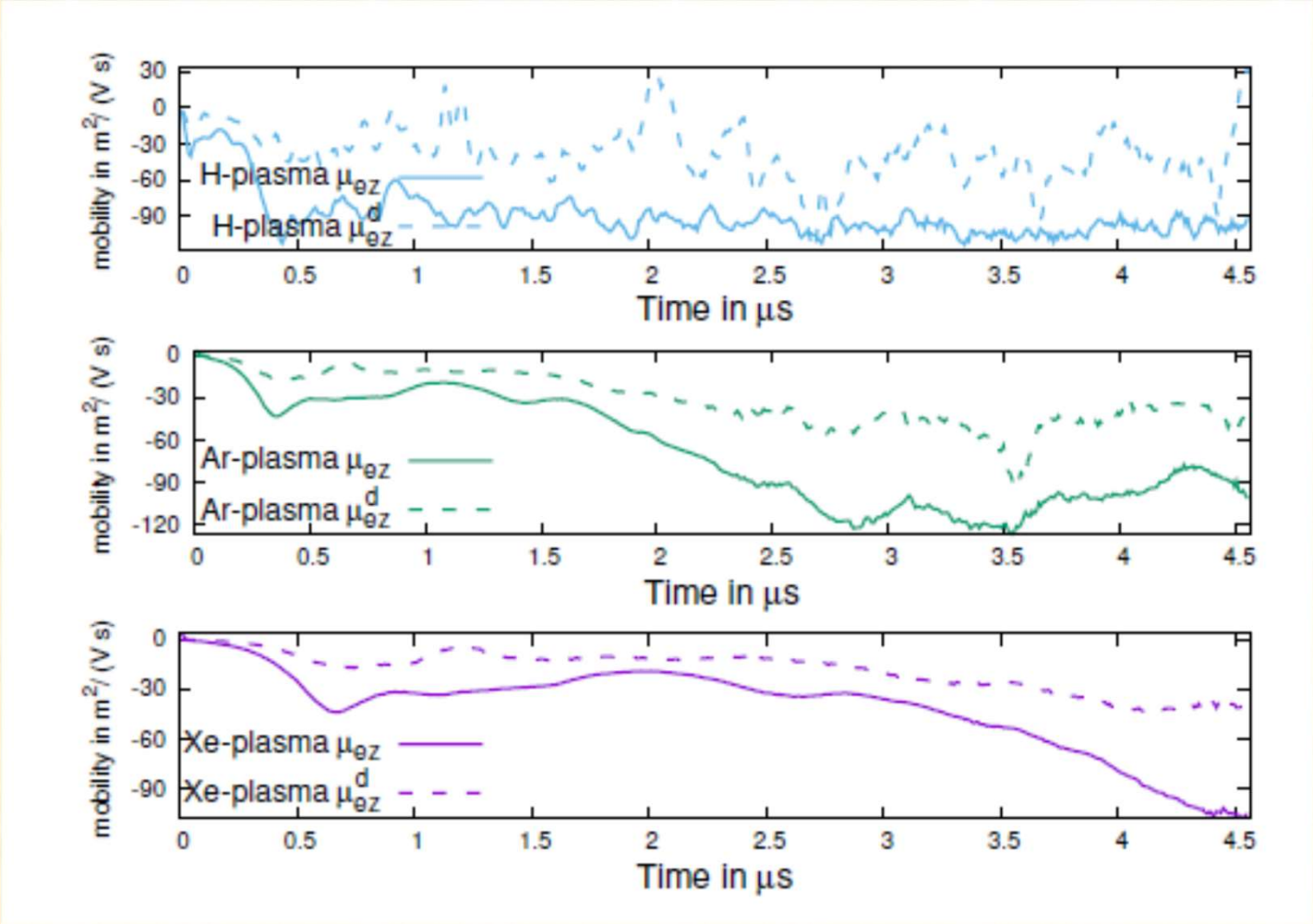






Sengupta, Smolyakov, Physics of Plasma 2019

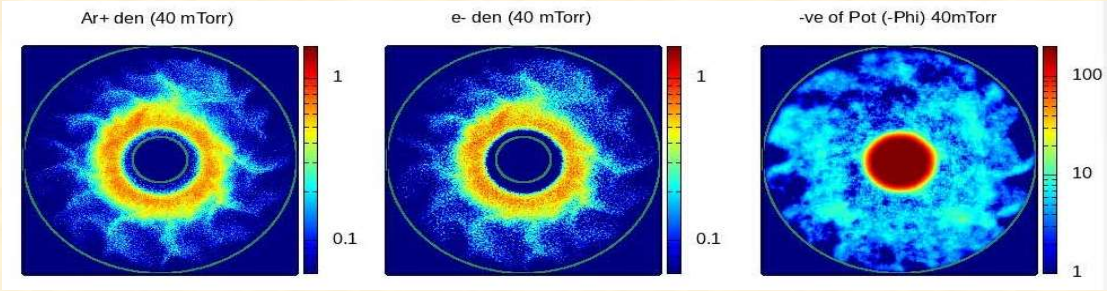
Transitions in anomalous mobility are synchronous with wavelengths transitions



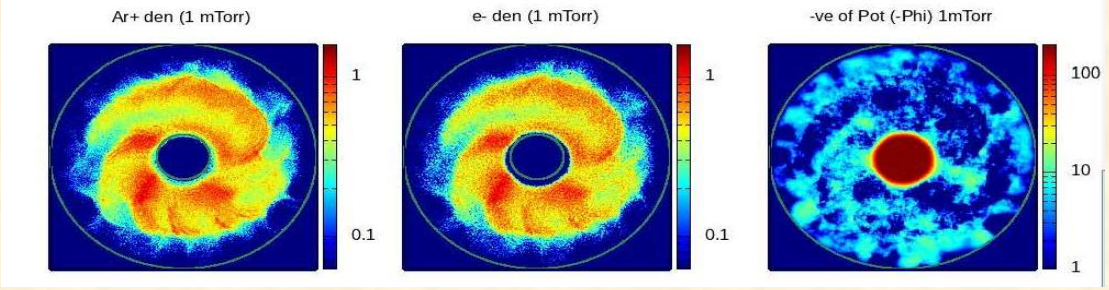
m=256 → time → m=8

Structures modifications with neutral pressure in Penning discharge

High pressure



Low pressure



Lower pressure facilitates the development of large scale structure (spoke)

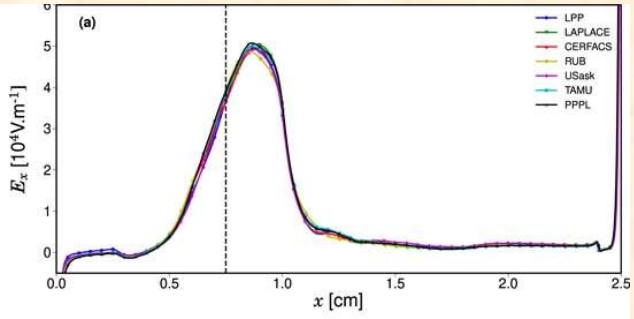
Sengupta, Smolyakov, Raitses 2021

Verification and benchmarking

ECDI structures and transport in 2D axial-azimuthal simulations:
PIC Codes benchmark, Charoy et al. PSST 2019

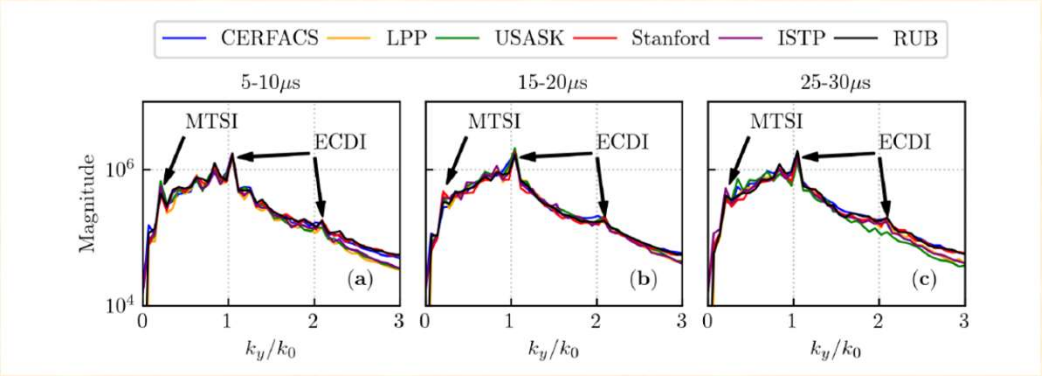
LPP, Ecole Polytechnique
LAPLACE, U Toulouse
CERFACS*
Ruhr University Bochum
U Saskatchewan
Texas AM University
PPPL, Princeton

*Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique



ECDI and MTSI in 2D radial-azimuthal simulations benchmark,
Villafana et al 2021

Fluctuations spectra

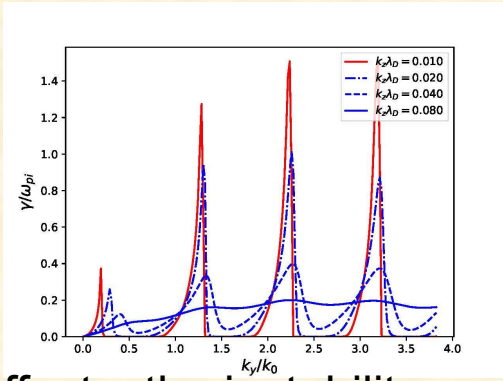


Different and independent codes, same physics and conditions

Physics issues and unsolved problems in nonlinear behavior of ECDI

Linear and nonlinear transition to the ion sound like mode?

For a finite k_z the resonance overlap due to thermal -> transition to unmagnetized ion sound instability driven by v_{ExB} beam (Gary, Sanderson 1970s)



Collisions and nonlinear broadening may provide similar effects, the instability proceeds and saturate as unmagnetized ion-sound, Lampe .., 1970 ?

Quasilinear approach, Lafleur et al, 2016-2020?

Does it occur and under what conditions? 2D and 3D effects?

Is quasilinear theory of unmagnetized ion sound applicable for ECDI?

In other words, does weak magnetic field affect ion-sound turbulence?

An old debate: Lampe .., 1970 s- instability proceeds as an ion-sound

Forslund, Biskamp, et 1970s magnetic field is crucial for saturation and heating

How does a finite B affect anomalous resistivity?

Max Planck and LANL study, 1970s, Lindman 1985, B is important!

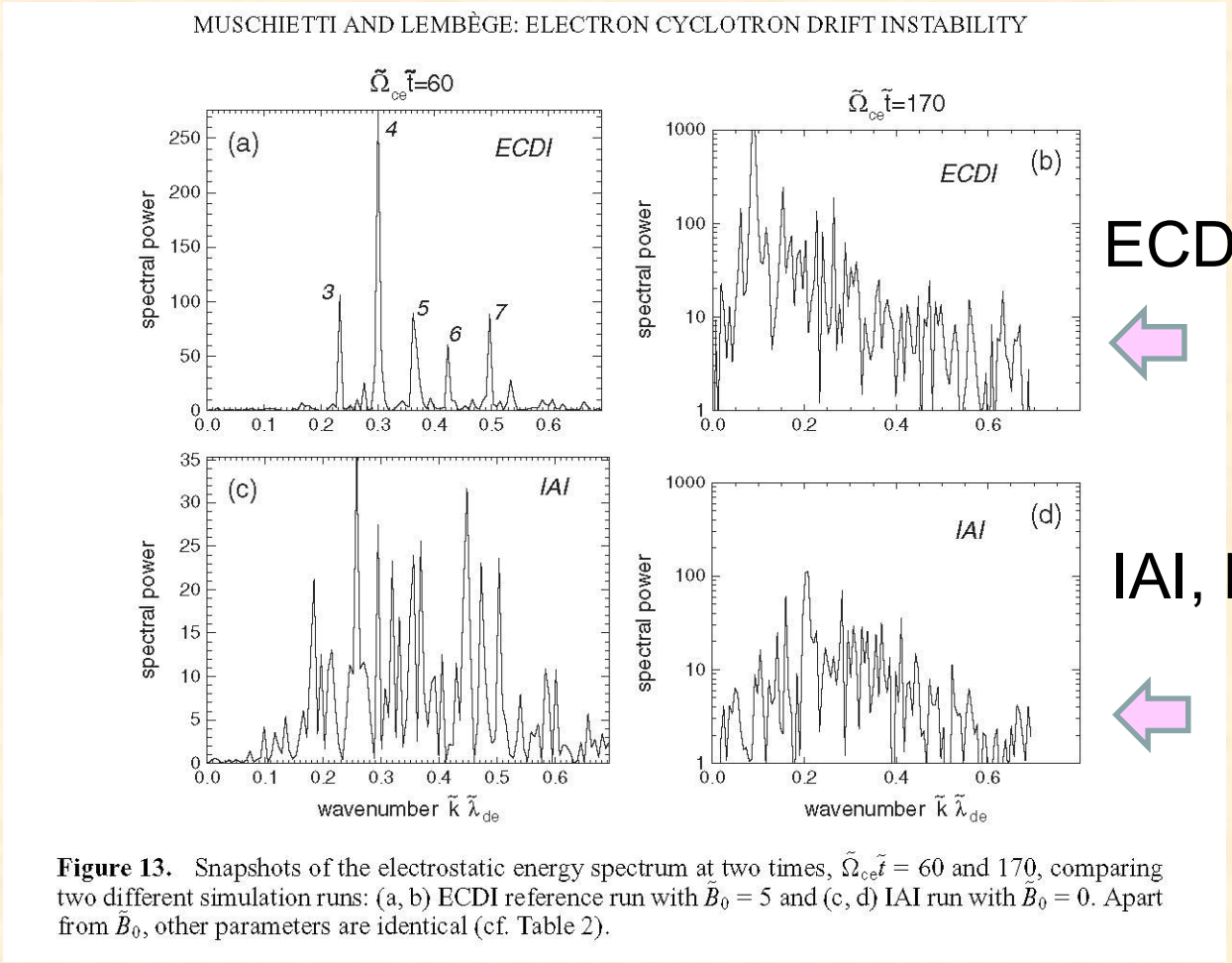
Direct comparison Muschietti and Lembege, JGR 2013

Role of particle noise in PIC simulations of ECDI and associated anomalous transport?

Strong heating and absence of saturation in PIC simulations of ECDI?

Direct comparison Muschietti and Lembege, JGR 2013

Identical parameters except B: ECDI shows much stronger spectral power



ECDI

IAI, B=0

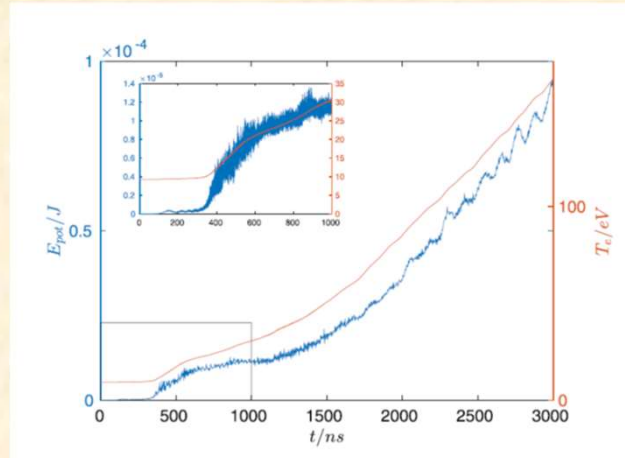
Figure 13. Snapshots of the electrostatic energy spectrum at two times, $\tilde{\Omega}_{ce}\tilde{t}$ = 60 and 170, comparing two different simulation runs: (a, b) ECDI reference run with $\tilde{B}_0$ = 5 and (c, d) IAI run with $\tilde{B}_0$ = 0. Apart from $\tilde{B}_0$, other parameters are identical (cf. Table 2).

Strong heating and absence of saturation in PIC simulations of ECDI. Universal property of existing simulations so far?

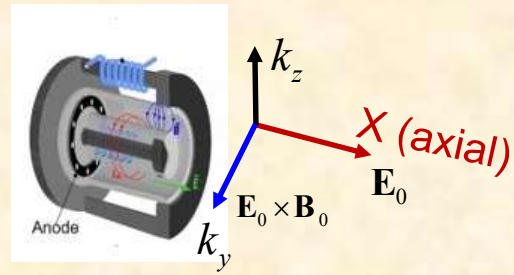
Often is “cured” with particles replacement,
“virtual length” model- particles are refreshed
(from cold distribution) after they travel a fixed distance

Particle replacement=effective collisions

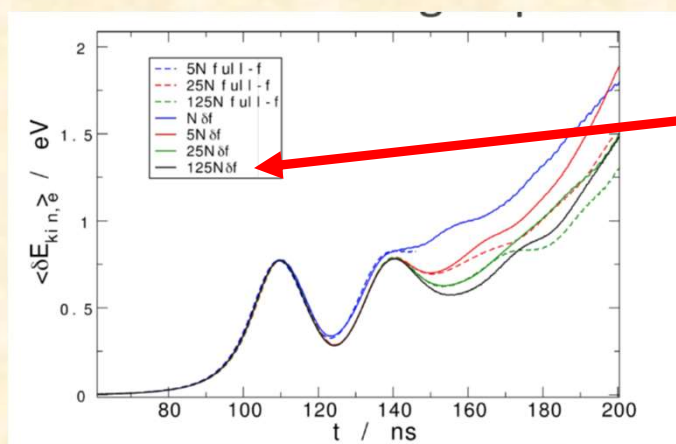
In simulations without replacement
Janhunen et al, PoP 2018, T>500 eV
No saturation in energy of fluctuations either



Axial transport = heating
Spurious transport=spurious heating



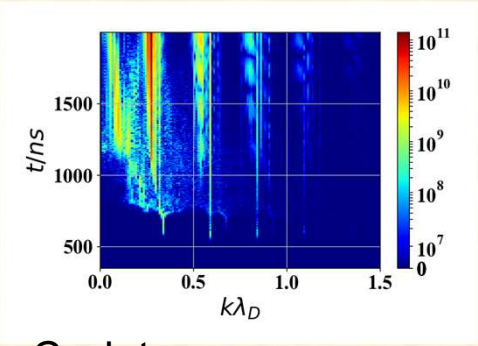
Spurious particle heating and transport in full and delta-f PIC simulations



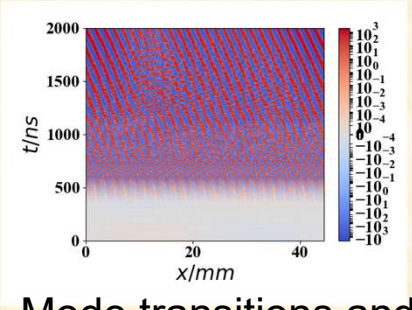
N=10 000, 1.25M particles per cell
Ridiculous for practical simulations

Janhunen, Smolyakov, GEC APS 2020

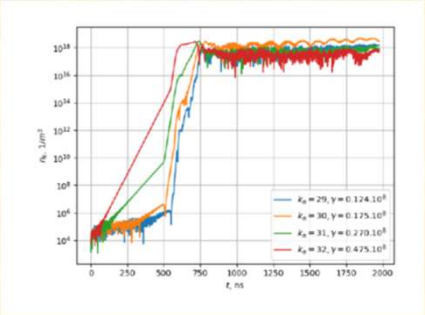
Direct Vlasov simulations of ECDI (one-dimensional)



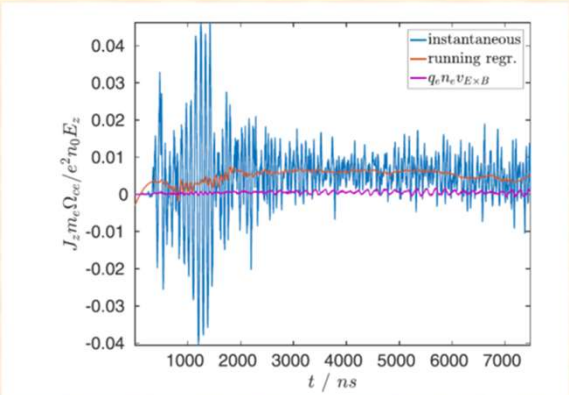
Cyclotron resonances



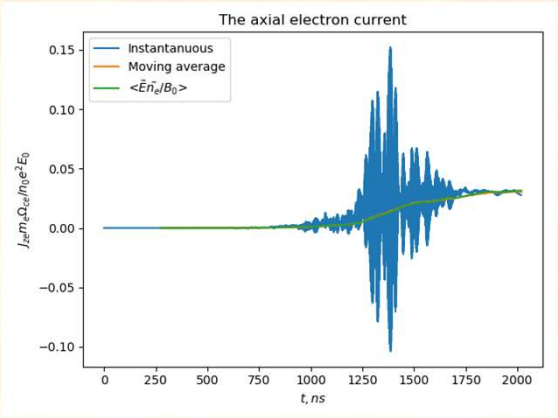
Mode transitions and inverse cascade



Energy saturation! due to the electron trapping



PIC (no particles replacement)
Janhunen POP 2018



Vlasov

Major differences:
Energy saturates in Vlasov

$< \tilde{E}_\theta \tilde{n} / B >$ transport is different

……..

Tavasolli, Smolyakov 2021

Particle noise effects is a difficult problem for ECDI

Discrete particle noise in particle-in-cell simulations of plasma microturbulence

Cite as: Phys. Plasmas **12**, 122305 (2005); https://doi.org/10.1063/1.2118729
Submitted: 03 August 2005 . Accepted: 21 September 2005 . Published Online: 12 December 2005

W. M. Nevins, G. W. Hammett, A. M. Dimits, W. Dorland, and D. E. Shumaker

Jenko, 2002] and Ref. [Lin, 2004; Lin, 2004a; Lin, 2005]. However, we will demonstrate that both the late-time decay of the ETG turbulence and the steady-state heat transport observed in our PG3EQ simulations and, by inference, in the GTC simulations reported in Ref. [Lin, 2004; Lin, 2004a; Lin, 2005] are a consequence of discrete particle noise. Hence, the PG3EQ simulations reported here and the GTC simulations reported in Ref. [Lin, 2004; Lin, 2004a; Lin, 2005] have nothing to say about steady-state heat transport associated with ETG turbulence in experimental plasmas.

ETG is an electron scale ρ_e microinstability, ECDI is on a shorter scale and can be even more difficult with weak magnetic field

$$\frac{\lambda_D^{\ 2}}{\rho_e^{\ 2}} = \frac{\omega_{ce}^{\ 2}}{\omega_{pe}^{\ 2}} < 1$$

From EPOCH manual. EPOCH is another PIC code widely used in space physics community

Noise disasters in tokamak simulation.

- PIC simulations predicted lower levels of transport in tokamaks than Eulerian simulations.
- Seemed to be converged with particle number (but weren't!). (See Hammett et. al., 2006)
- It was the diffusion due to noise that killed them.
- Lessons:
  - Understand how much noise is in the system and its effect.
  - Convergence scans necessary but liable to misinterpretation.

Ben F McMillan,
Centre for Fusion, Space and Astrophysics, Physics Department, University of Warwick, UK
Acknowledgements to the EPOCH team.

In summary

Turbulence in ExB disharges coexist at small and large scales
Experimental evidences of small scale fluctuations (and large scale) exist
Small scales are most unstable, subsequently feed large scales (inverse cascade)
Plasma and magnetic field gradients, ExB drift, and collisions are the drives.
Respectively: gradient-drift, lower hybrid instabilities, ECDI, ion-sound. First principle anomalous transport has been demonstrated in reduced fluid model simulations.
Relative importance of the driving factors varies between different regions (near-anode, acceleration zone, plume and near-cathode), mutual coupling in realistic conditions is still unclear

ECDI/EDI: Relatively easy to obtain in PIC numerical codes, many groups…
Has been well demonstrated in 1D (azimuthal) and 2D (azimuthal-axial, azimuthal-radial) simulations, 3D are rare and not conclusive but needed
Role of gradients and mutual coupling?
PIC noise effects on transport and heating? Saturation mechanisms?

Conversion of simulation results into practical predictions is still difficult.
Coordinated efforts: codes testing and benchmarking; suite of test cases based on analytical insights, codes verification metrics, codes validation (agreement with experiment) metrics
Development of experimental diagnostics and test bed experimental devices

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There is more on ExB plasma physics, eg, plasma-material Interactions, magnetic nozzle acceleration, .. see

Physics of Plasmas

Physics of E × B discharges relevant to plasma propulsion and similar technologies

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COLLECTIONS

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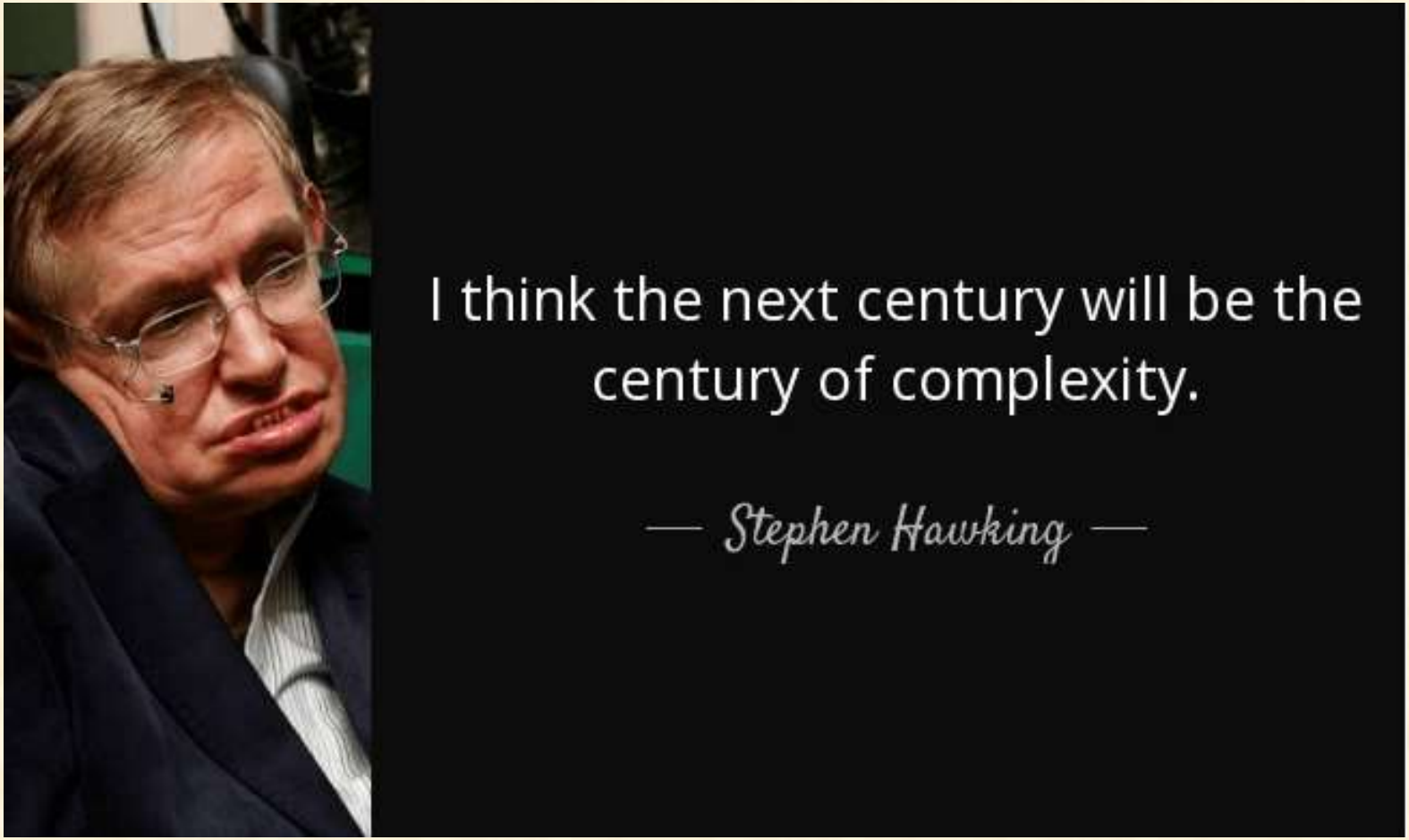
We know many elements of complex physics of ExB plasma.
Integration is still difficult


I think the next century will be the century of complexity.
— Stephen Hawking —

I think the next [21st] century will be the century of complexity. We have already discovered the basic laws that govern matter and understand all the normal situations. We don't know how the laws fit together, and what happens under extreme conditions. But I expect we will find a complete unified theory sometime this century. The is no limit to the complexity that we can build using those basic laws.

Stephen Hawking

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Thank you for your attention!