The electron cyclotron drift instability: thruster studies and physical interpretations

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Acknowledgments

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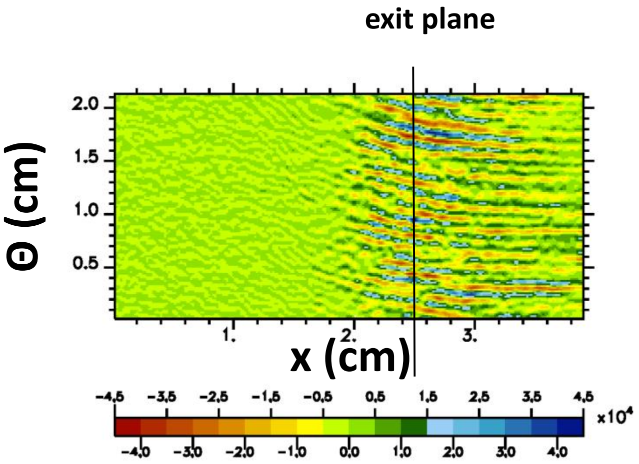
Topics

- why do we focus on the ECDI?
- what is the nature of this mode?
- how do we identify it experimentally?
- experimental results vs. theory and azimuthal-axial PIC
- experimental results vs. theory and azimuthal-radial PIC
- what transport mechanisms may be involved?
- any experimental evidence for the role of this mode in transport?

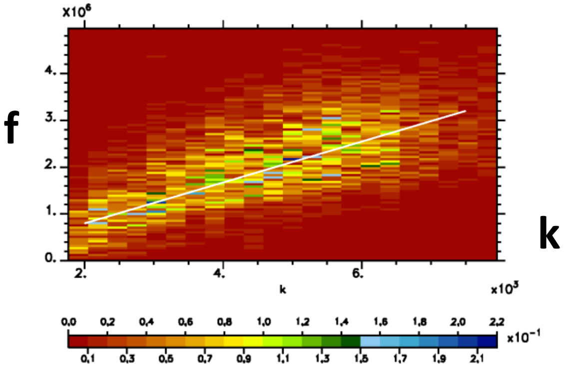
Why do we focus on the electron cyclotron drift instability?

A candidate identified for anomalous transport

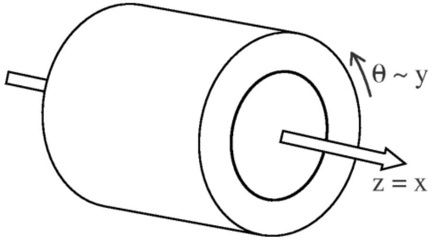
- 2004: self-consistent azimuthal-axial fully-kinetic PIC simulations by Adam, Héron and Laval[1]



electric field



potential



neglected: secondary electron emission, charge exchange collisions, multiple ionizations and recombination

key observations:

- short-scale azimuthal electric field at exit plane (drift-driven)
- linear, discrete dispersion relation; MHz frequencies, mm wavelengths
- significant level of fluctuating electric field – 25% of applied field

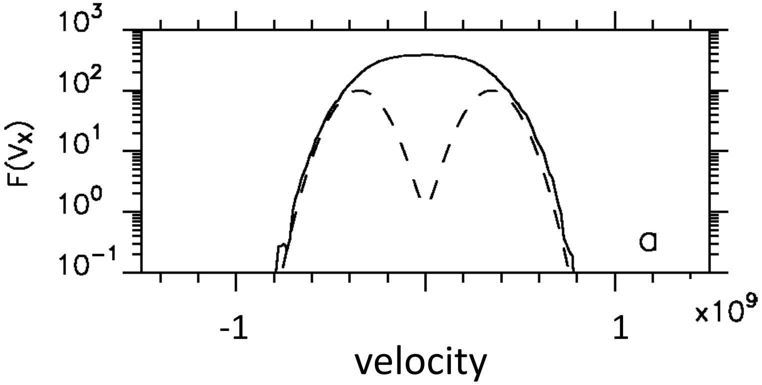
1. Adam, Héron and Laval, Phys. Plasmas 11, 295 (2004)

Simulations: role of mode in transport

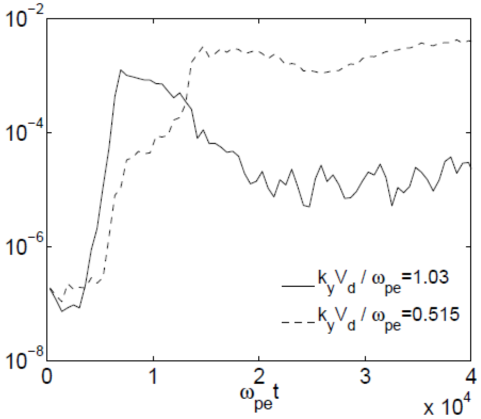
- The contribution of the mode to electron transport is visible in different ways

❶ **axial diffusion of electrons**

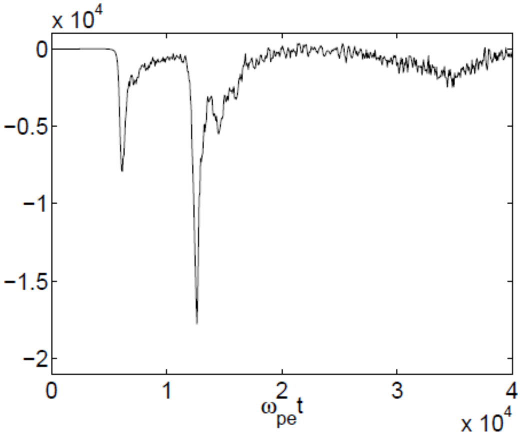
Adam, Héron and Laval, Phys. Plasmas 11, 295 (2004)



❷ **electron transport with development of unstable modes**



electrostatic energy



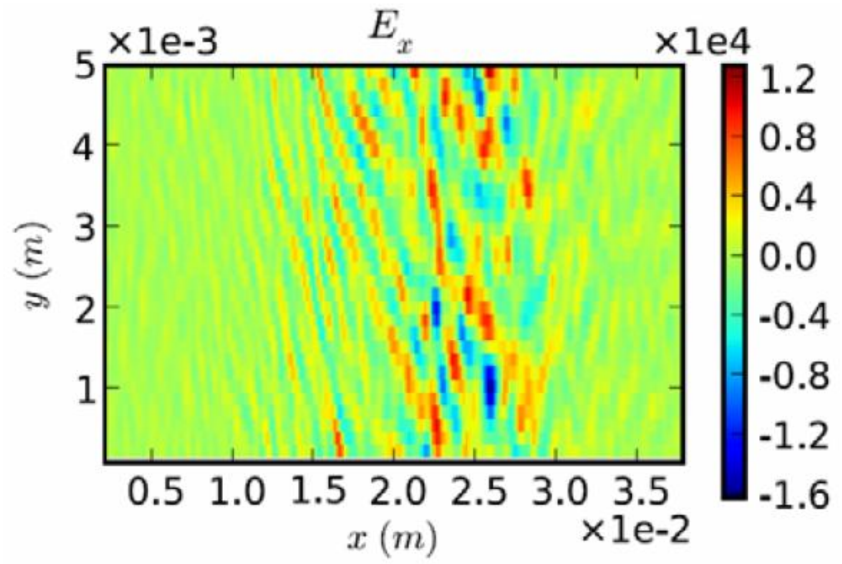
axial electron velocity (m/s)

PhD thesis, A. Ducrocq (2006)

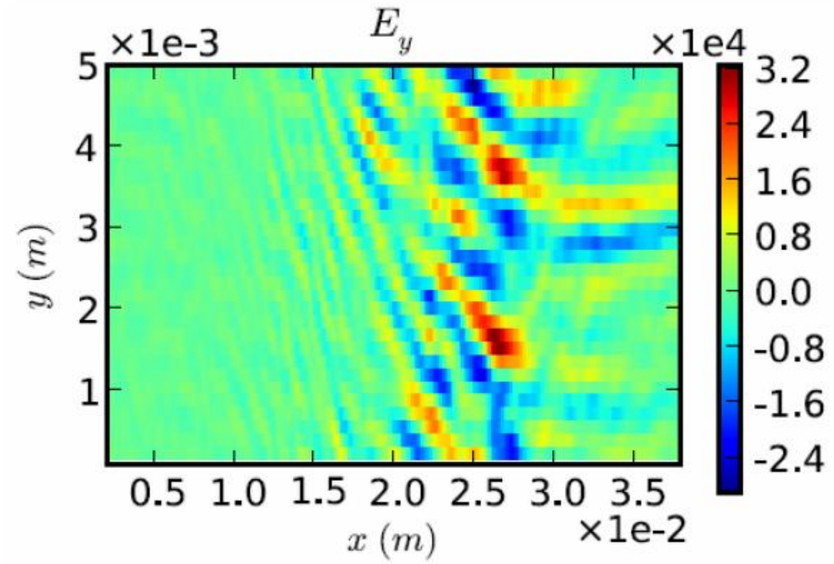
Simulations: role of mode in transport

❸

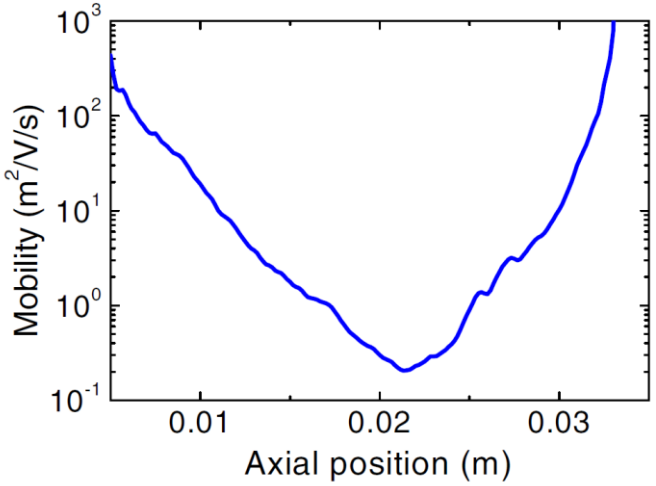
Adam et al., Plasma Phys. Control. Fusion 50, 124041 (2008)



axial component of mode E field



azimuthal component of mode E field



$$\mu_\perp \approx j_{\mathrm{ex}}/e n_{\mathrm{e}} E_x$$

- **fluid approximation**
- **averaging in the azimuthal direction**

Ex, Jx over 0.1 µs

Simulations: role of mode in transport

- first unambiguous evidence of link between electron current and a specific instability in thrusters

- successful description of thruster discharge, not requiring adjustable parameters
  - correct discharge current level and low frequency oscillations
  - correct localization of electric field and amplitude

- identification of driving mechanism involved in transport: fast electron drift, inherent to all thrusters

- results compatible with linear kinetic theory analysis
  - instability excited near cyclotron resonances

These original results were the driver for our experimental efforts to detect and fully characterize the instability

- recent PIC simulations also carried out by Coche and Garrigues[1] (2D) and Lafleur et al.[2] (1D)

1. **Coche and Garrigues, Phys. Plasmas 21, 023503 (2014)**
2. **Lafleur, Baalrud and Chabert, Phys. Plasmas 23, 023502 (2016)**

What is the nature of the mode?

The electron cyclotron drift instability (ECDI)

- previously studied in the context of:
    - theta-pinch machines for fusion
    - collisionless shocks (e.g. Earth's bow shock)

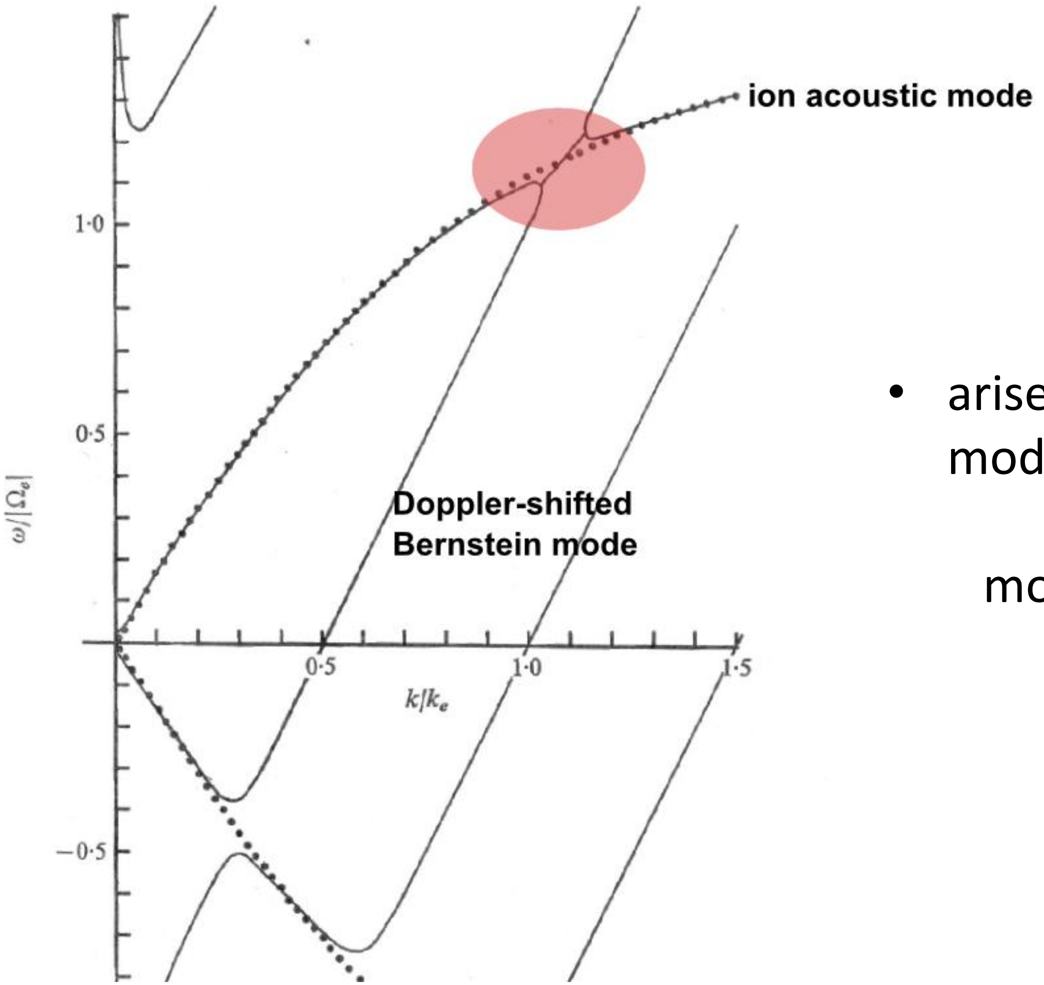
- the subject of a several theoretical and numerical studies dating back to the 1970s:

Gary and Sanderson, J. Plasma Physics, 4, 739 (1970)
Gary, J. Plasma Physics, 4, 753 (1970)
Forslund et al., PRL, 25, 1266 (1970); Forslund et al., PRL, 27, 1424 (1971);
Forslund et al, Phys. Fluids 15, 1303 (1972)
Wong, Phys. Fluids 13, 757 (1970)
Lampe et al, PRL 26, 1221 (1971); Lampe et al., Phys. Fluids 15, 662 (1972)
Lashmore-Davies, Phys. Fluids 14, 1481 (1970)

- more recent studies:

Muschietti and Lembège, Adv. Space Res. 37, 483 (2006)
Muschietti and Lembège, J. Geophys. Res.: Space Phys. 118, 2267 (2013)…

The electron cyclotron drift instability (ECDI)



- arises due to coupling between two mode types:
    - Bernstein and ion acoustic modes

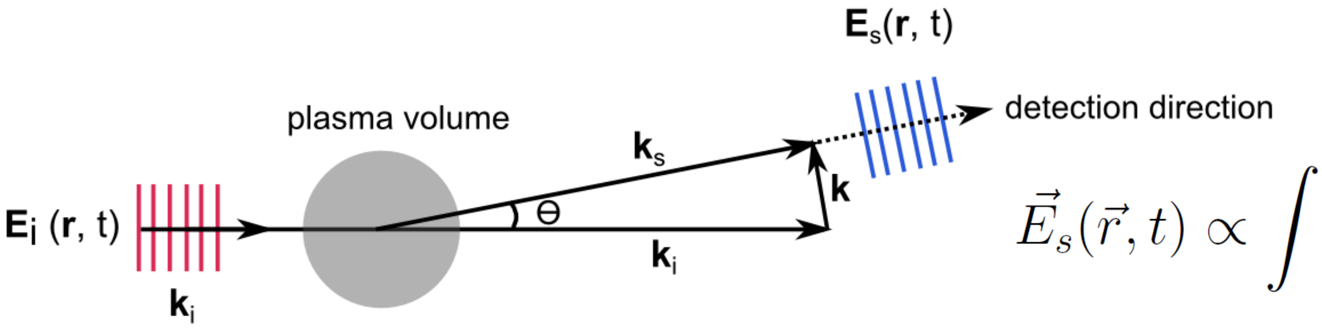
$$k_y V_d = n\omega_{ce}$$

S. P. Gary and J. J. Sanderson, J. Plasma Phys. 4, 739 (1970)

How do we identify the mode experimentally?

Coherent Thomson scattering

- length scales scanned > Debye length (in contrast to incoherent Thomson scattering)
  → correlated fluctuations become visible



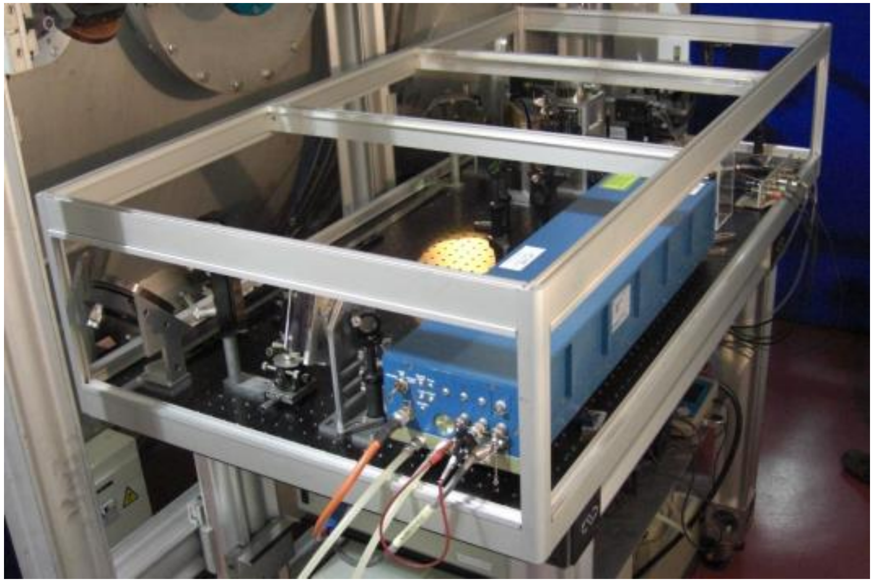
$$\vec{E}_s(\vec{r},t) \propto \int\!\!\int\!\!\int_V e^{-i\vec{k}.\vec{r}}\ \rho(\vec{r},t)\ d^3\vec{r}$$

- the diagnostic measures electron density fluctuations associated with the instability
- the observation wave vector **k** properties can be varied for sophisticated studies of the mode properties

Implementation

- a new scattering tool designed, constructed and tested: PRAXIS
- very high sensitivity, well-suited to characterizing turbulence in low density plasma environments

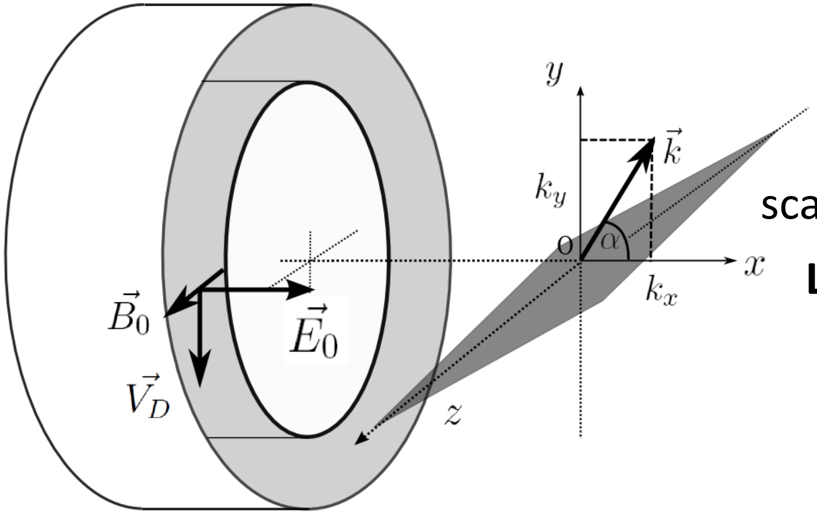
PIVOINE-2G national thruster facility (Orléans)



PRAXIS collective scattering bench

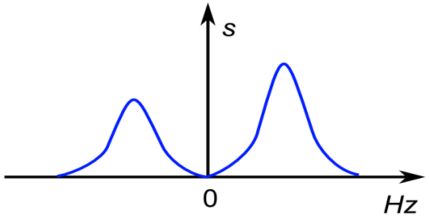
S. Tsikata, N. Lemoine, V. Pisarev and D. Grésillon. Phys. Plasmas 16, 033506 (2009)

Implementation



scales scanned: 0.4 – 2 mm

Larmor radius ~ 1 mm



time-varying scattered signal (two channels in quadrature) → raw FFT spectra → dynamic form factor

- high resolution (14 bit, 100 MHz)
- several points (> 6x10^6 points)

4 record types

norm. spectrum x $\frac{h\nu}{\eta P_p}\frac{\pi w^2}{\lambda^2 {r_0}^2}\frac{1}{n_0 l_s}$

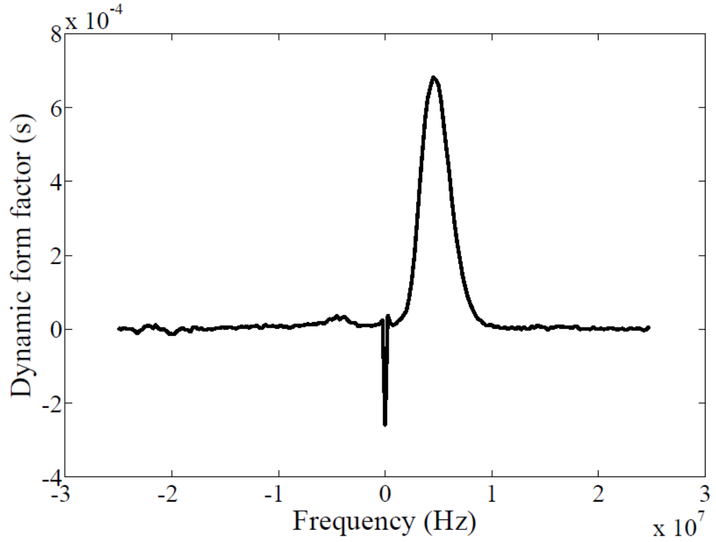
static form factor **S**(k)

absolute measure of intensity of density fluctuations

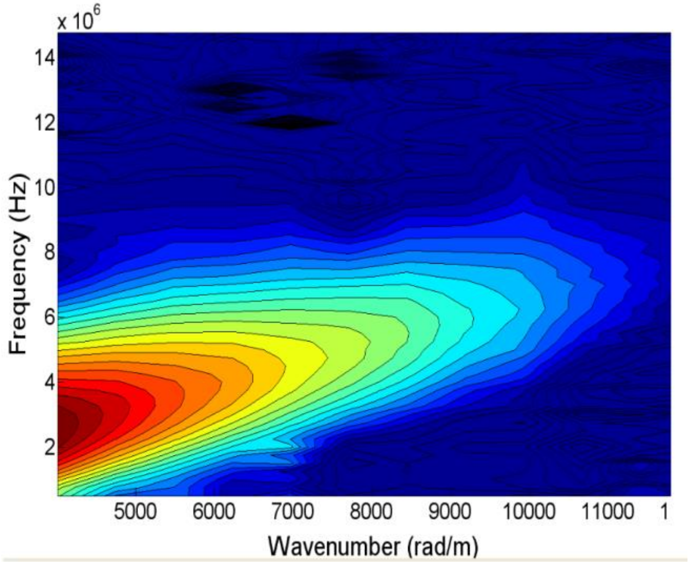
Results in the context of theory and simulations (azimuthal-axial)

Experiments: spectra and dispersion relations

- **mode identified experimentally: MHz frequencies, mm wavelengths:**
  result compatible with expectations from linear kinetic theory analysis and simulations
- **continuous dispersion relation**



symmetric mode peaks for azimuthal **k**



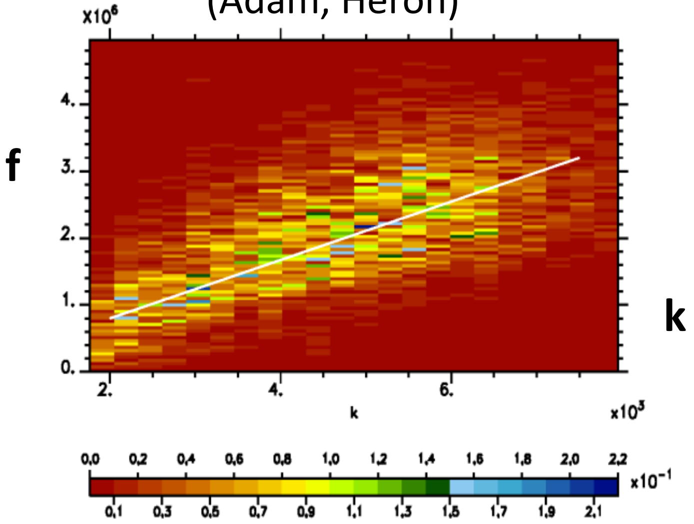
experimental dispersion relation, shown with dynamic form factors: linear and continuous

Experiments: spectra and dispersion relations

simulations

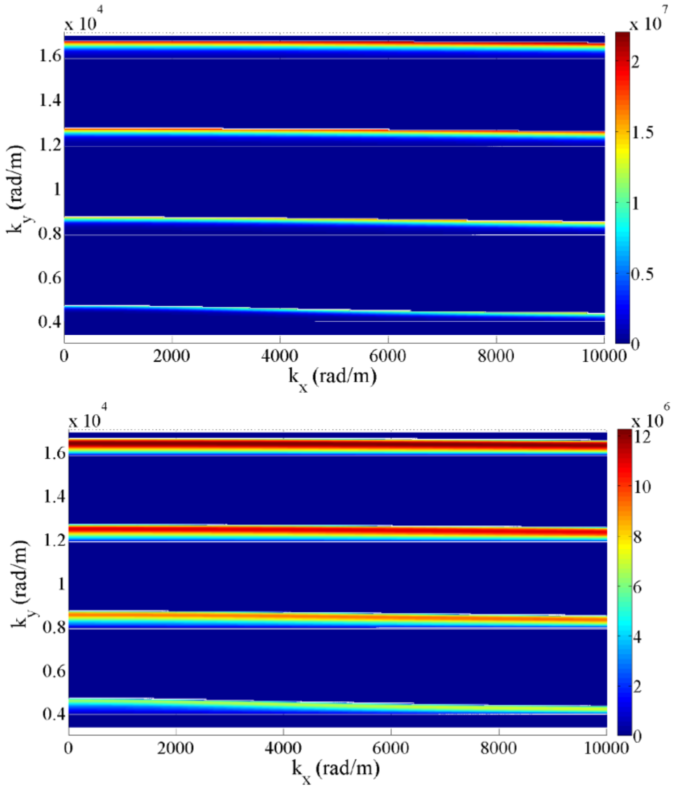
linear kinetic theory (2D)

numerical result
(Adam, Héron)



potential

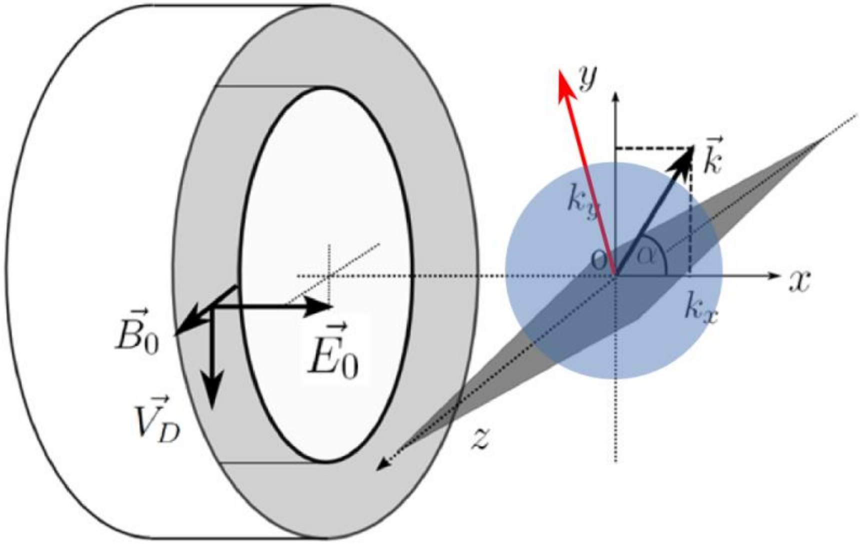
2D: frequency and growth rate



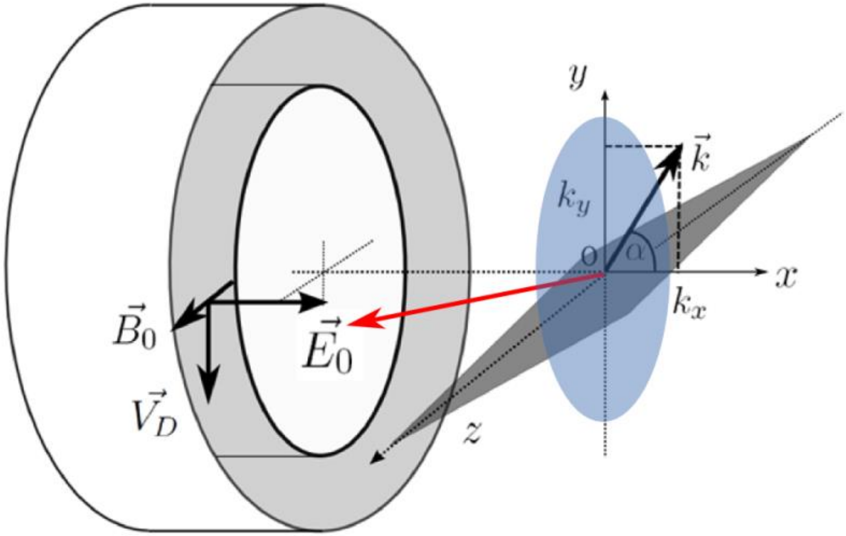
How do we reconcile the discrete nature of the numerical and theoretical dispersion relation with experimental data?

Experiments: mode directivity

- mode has components in all spatial directions: not purely azimuthal



(**E**x**B**, **E**) plane: 10° inclination; axial component

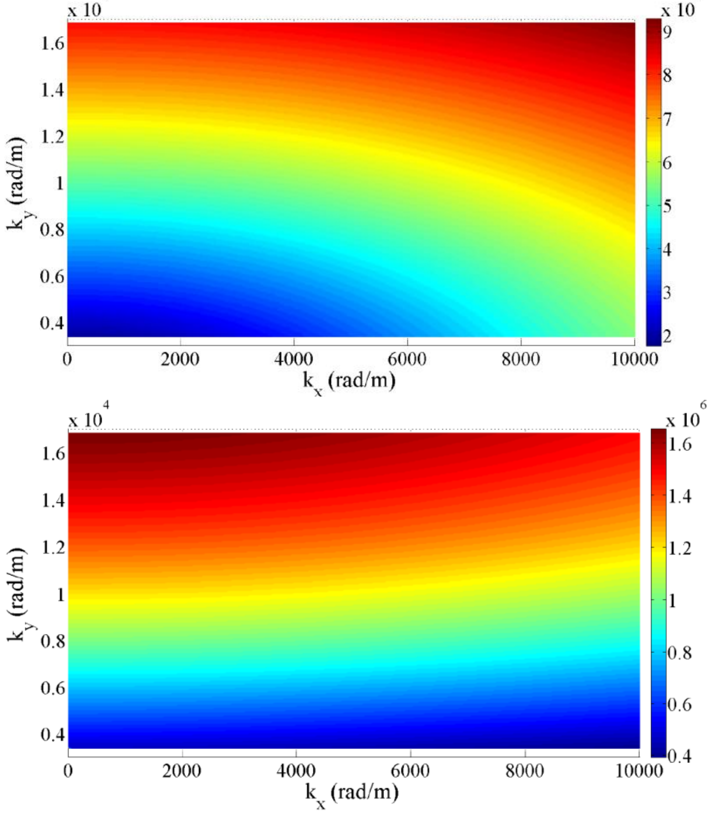


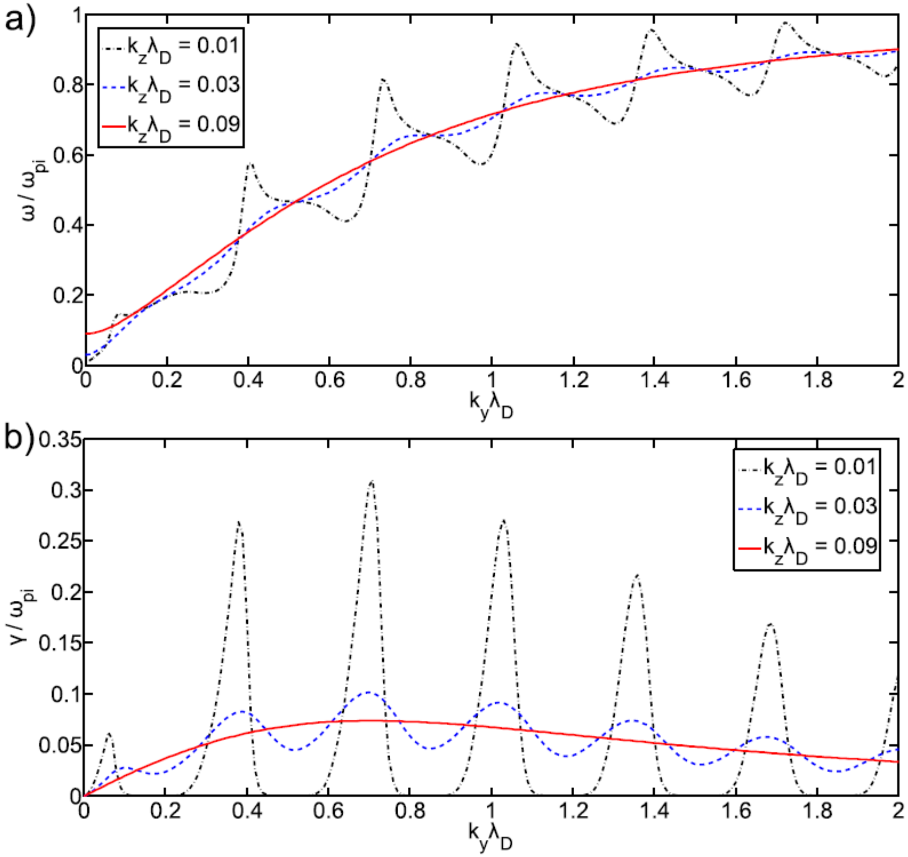
(**E**x**B**, **B**) plane: 5° inclination; radial component

Experiments: mode directivity

- inclusion of a **radial** component to the mode smooths the resonances

3D: frequency and growth rate
(inclusion of radial wave vector)





S. Tsikata (2009)

Cavalier et al. Phys. Plasmas 20, 082107 (2013)

Experiments: density fluctuation rate

- a determination of the density fluctuation rate is possible, using the flexibility of the diagnostic wavevector investigations

$$\langle \tilde{n}^2 \rangle = \frac{n_0}{(2\pi)^3} \int S(\vec{k})\, dk^3$$

density fluctuation level

based on careful determinations made during experiments,

$$\langle \tilde{n}^2 \rangle \approx \underbrace{\frac{S_0 n_0}{(2\pi)^3} \int_0^{\infty} dk\, e^{-kb}}_{\substack{\text{from exponential} \\ \text{dependence of S(k) on k}}} \underbrace{\int_0^{2\pi} d\alpha\, k e^{-\frac{(\alpha-\mu_\alpha)^2}{2\sigma_\alpha{}^2}}}_{\substack{\text{from the Gaussian form of} \\ \text{S(k) observed in the } (ExB,\ E) \\ \text{plane}}} \underbrace{k\Delta\beta}_{\substack{\text{a mean peak width } (\Delta\beta \sim \\ \text{0.15 rad) of S(k) in the} \\ (ExB,\ B) \text{ plane}}}$$

- a local plasma density of 3 x 10^{17} m^{-3} gives a density fluctuation rate associated with this instability of **1%**

S. Tsikata et. al, Phys. Plasmas 17, 112110 (2010)

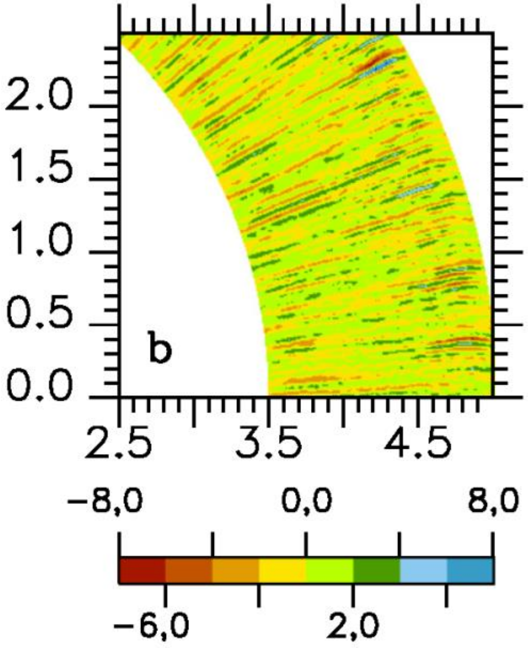
Results in the context of theory and simulations (azimuthal-radial)

Simulations: azimuthal-radial observations

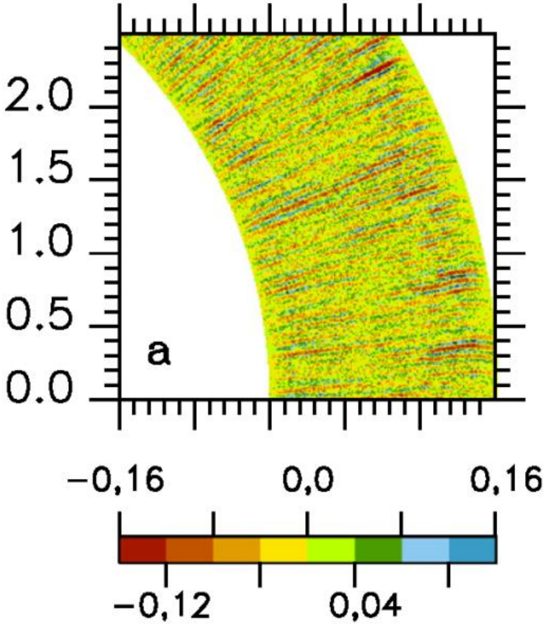
- recent 2D simulations, <u>azimuthal-radial geometry</u>

  Héron and Adam, Phys. Plasmas 20, 082313 (2013)

  - rBr constant, radially uniform E field



potential fluctuations



ion density fluctuations

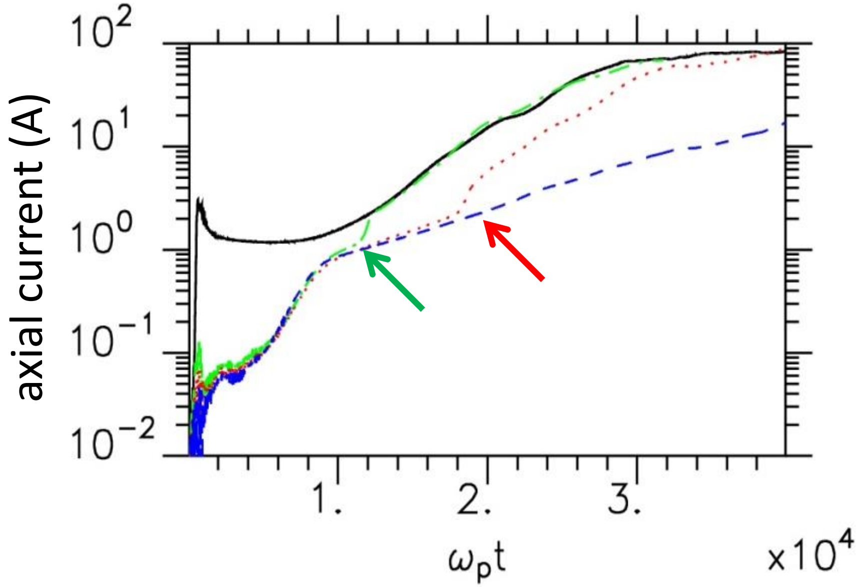
- sheath modulation
- mode influence on ion dynamics
- axial convection + azimuthal motion: possible explanation for erosion pattern?

compatible with our experimental analyses on standing waves (2010)

Simulations: azimuthal-radial observations

- azimuthal-radial simulations reveal an additional contribution of the instability beyond « direct » wave particle interaction

ε*: **20** – **30** – **50** – **1000** eV (high → low emissivity wall material)



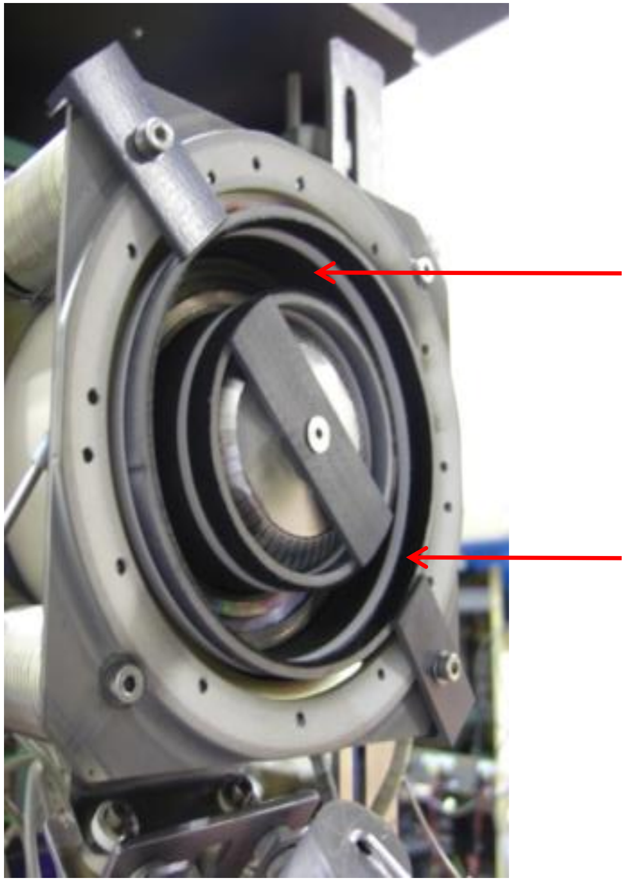
$\omega_p t$ = 10000 → 0.3 µs

- start of simulation: transport dominated by ExB mode heating, independent of emissivity
- jumps in current: beam-plasma instability due to interaction between ExB mode and wall-emitted electrons

expected: higher emissivity, higher electron current

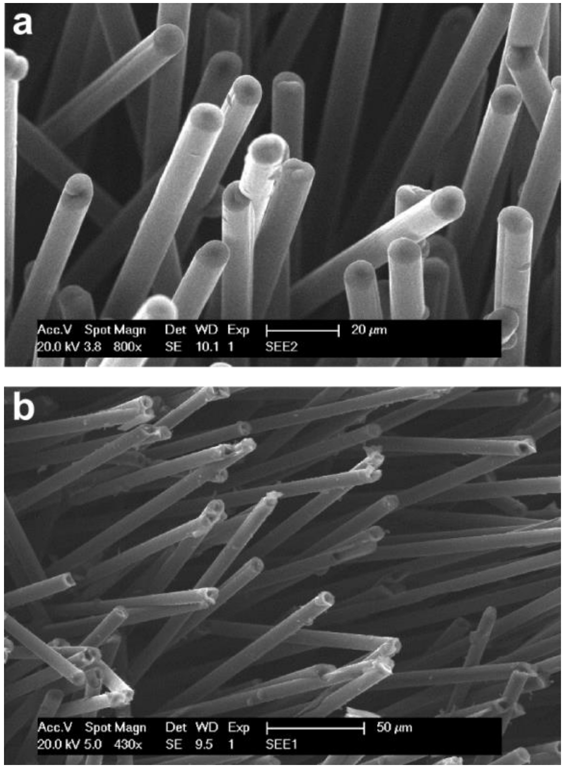
Experiments

- actually, the real outcome is somewhat counterintuitive!



BNSiO2 chamber

carbon velvet (8 mm wide)



- Experiments performed with carbon velvet[1] material to eliminate electron emission at the exit plane

[1] **Raitses et al., J. Appl. Phys. 99, 036103 (2006)**

Experiments

- suppressing emission at the exit plane alters the discharge:

  - E field shifted into channel
  - mode follows E field into region of higher azimuthal drift
  - anomalous mobility inside the channel should **increase**, even when a large contribution of the wall emission has been suppressed
  - higher electron currents observed

- the changes introduced in fact favor transport via the ECDI

This is at odds with azimuthal-radial simulations because the axial electric field in such simulations is imposed, and does not develop self-consistently

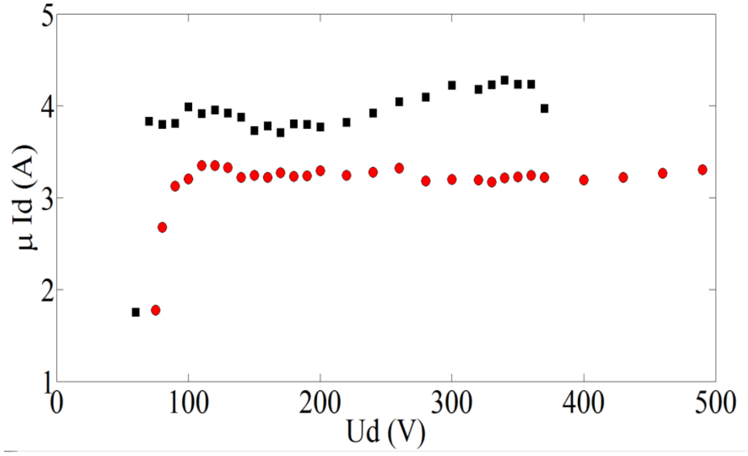
- This is evidence that even advanced simulations in 2D may fail to capture important features of the ECDI, whose action is **in three dimensions**

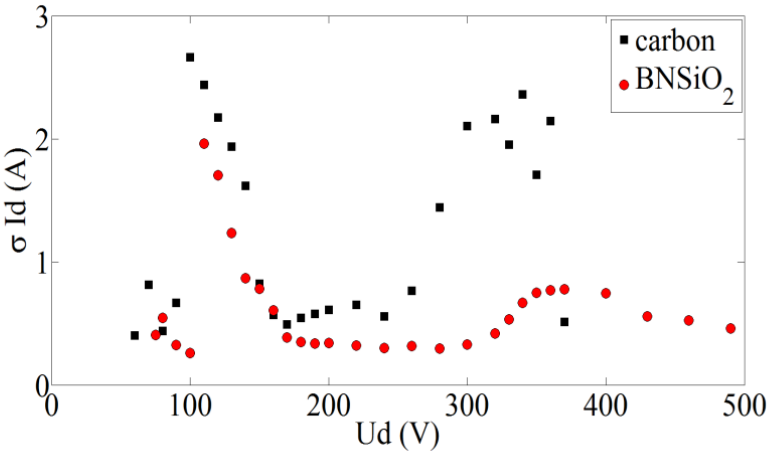
Tsikata, Héron, Honoré - Phys. Plasmas 24, 053519 (2017)

Experiments

Current characteristics: amplitude and discharge current

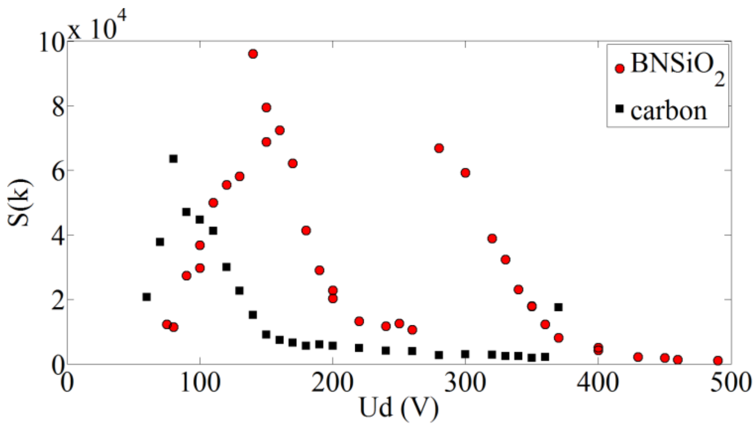
3.5 mg/s

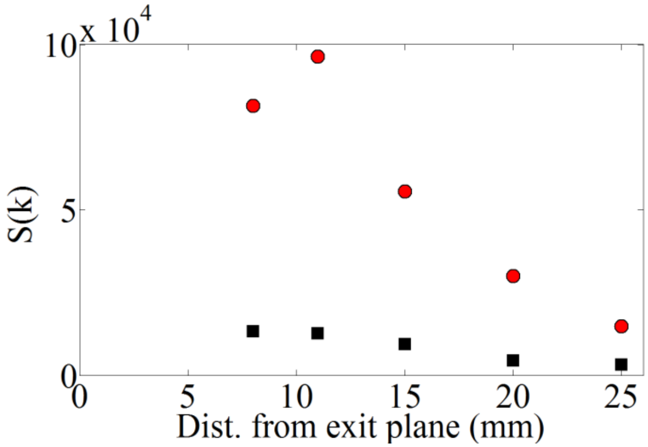




ECDI fluctuations

150 V





Tsikata, Héron, Honoré - Phys. Plasmas 24, 053519 (2017)

Which transport mechanisms may be involved?

Theory/transport mechanism

- transport may occur in a manner analogous to ion heating by a lower hybrid wave
  C. F. F. Karney, Phys. Fluids 21, 1584 (1978)

  provided resonance condition between the wave and particle (ion) is met, energy transfer from the wave can occur

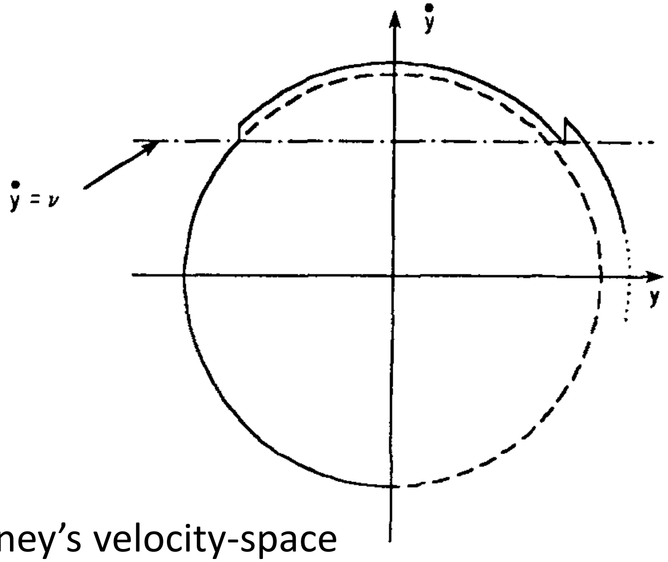
$$\omega = \vec{k} \cdot \vec{v}$$

- the net effect is a deviation in particle trajectories and stochastic particle motion

- this mechanism was evaluated for the the Hall thruster context

A. Ducrocq, PhD thesis, Ecole Polytechnique (2006)

- how is this condition satisfied?

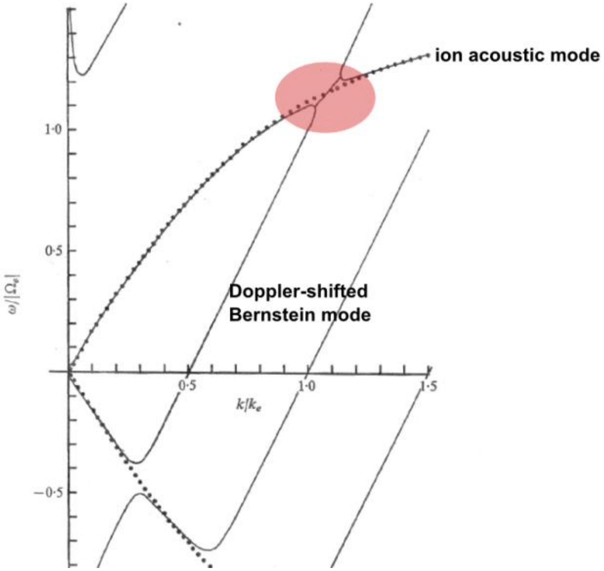


Karney's velocity-space diagram for wave-particle interaction

Theory/transport mechanism

- the drift velocity plays two roles with regards to this instability:

❶ drives the mode



❷ makes possible the meeting of the Karney resonance condition for heating

wave frequency in the electron reference frame: $\omega_d = \omega - \boxed{k_y V_d}$

for energy transfer: $\omega_d \; >> \; \omega_{ce}$

eg. for $\boldsymbol{\omega}$ = 5 MHz (31 x 10^6 rad/s), $\boldsymbol{k_y}$ = 4000 rad/m, $\boldsymbol{V_d}$ = 7 x 10^5 m/s,
$\boldsymbol{\omega_d}$ ~ **2.8 x 10^9 rad/s,** while $\boldsymbol{\omega_{ce}}$ = **2.6 x 10^9 rad/s**

Theory/transport mechanism

- based on Karney considerations, **A. Ducrocq, PhD thesis, Ecole Polytechnique (2006)**

$$\left(\frac{E_f}{E_0}\right) \approx \frac{1}{4}\frac{k_y}{k}\left(\frac{\omega_{ce}}{k_y V_d}\right)^{1/3}$$

stochasticity threshold for transport

$$V_x = \sqrt{\frac{\pi}{2}}\left(\frac{V_d}{v_{the}}\right)^3\left(\frac{E_f}{E_0}\right)^2 v_{the}\frac{1}{\sqrt{2\sqrt{b}}}$$

$$b = {k_y}^2{v_{the}}^2/{\omega_{ce}}^2$$

axial electron velocity,
dependent on amplitude of fluctuating field

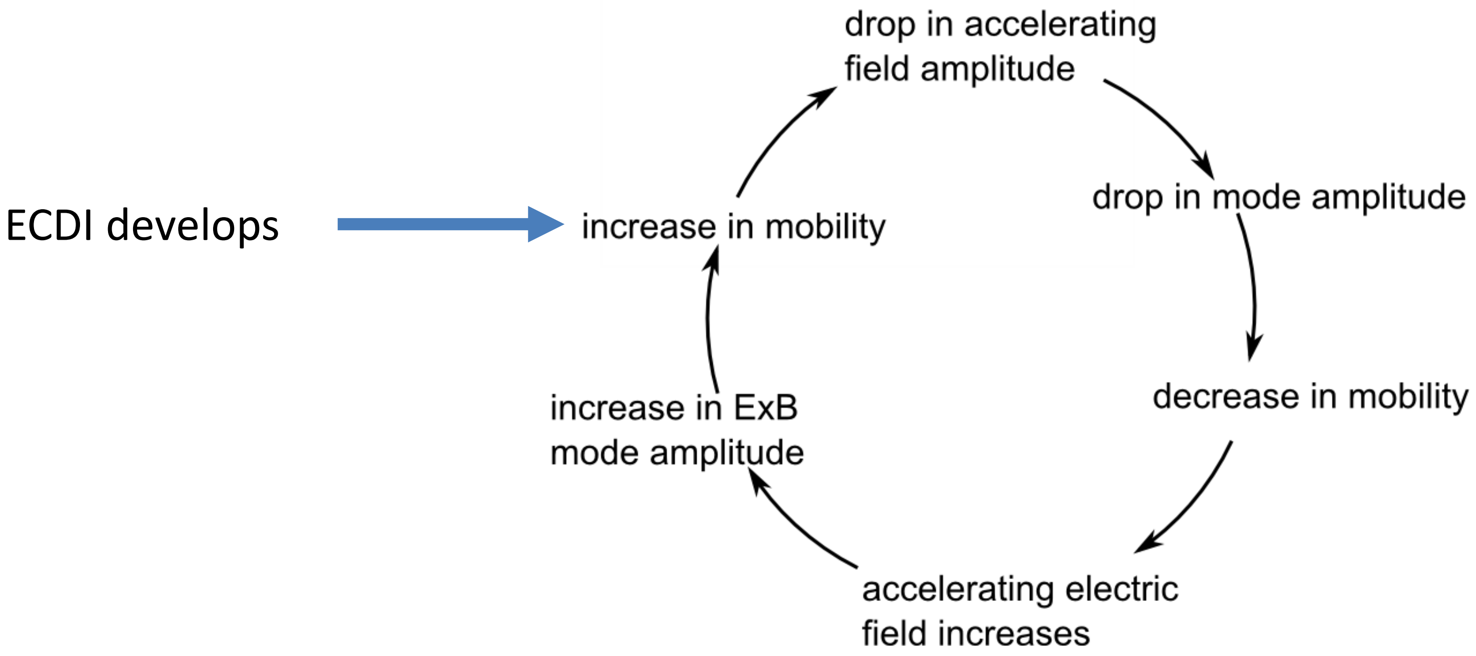
- a fluctuating field amplitude can be estimated from the measured density fluctuations

$$\frac{\tilde{n}}{n_0} = \frac{e\tilde{\phi}}{k_B T_e}$$

- axial velocity of ~ 4 km/s for E_f/E_0 = 0.25 is on the same order as that which is seen to develop in PIC simulations

Something to keep in mind

- from collective scattering measurements: saturated mode amplitude
- yet the system is a dynamic one!



ECDI develops

increase in mobility

drop in accelerating field amplitude

drop in mode amplitude

decrease in mobility

accelerating electric field increases

increase in ExB mode amplitude

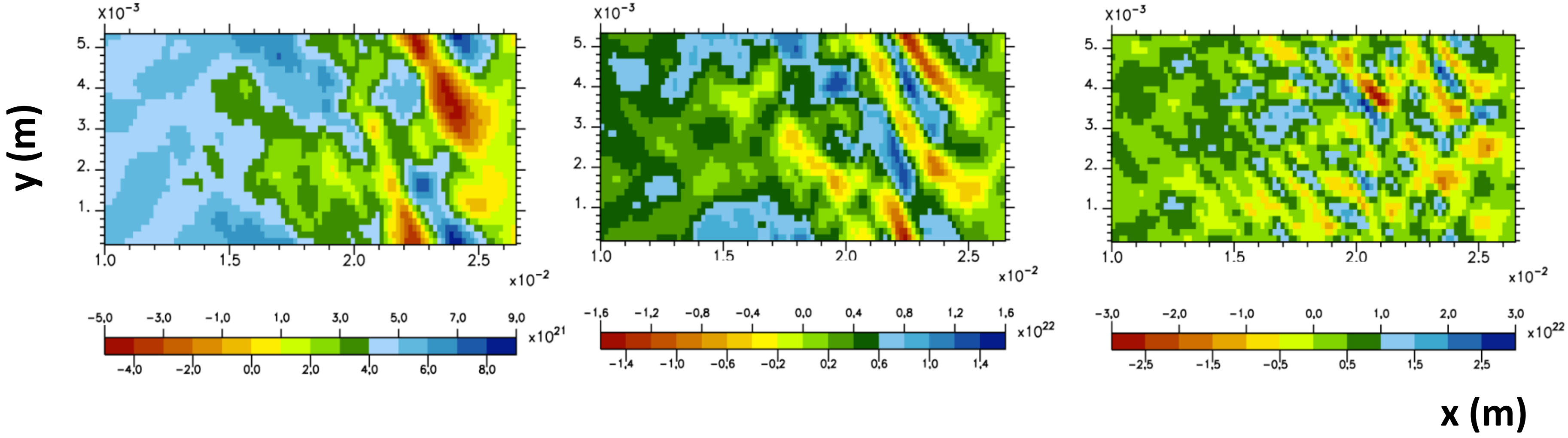
- other plasma parameters evolve in response to both the electric field and the ECDI
- **recent focus: developing a new diagnostic for electron properties, anisotropy**

Simulations: role of mode in transport

- structure of current evolves spatially and temporally due to the presence of the ECDI
- simplistic evaluations of the mobility due to the ECDI may be inadequate

Adam and Héron (2008)

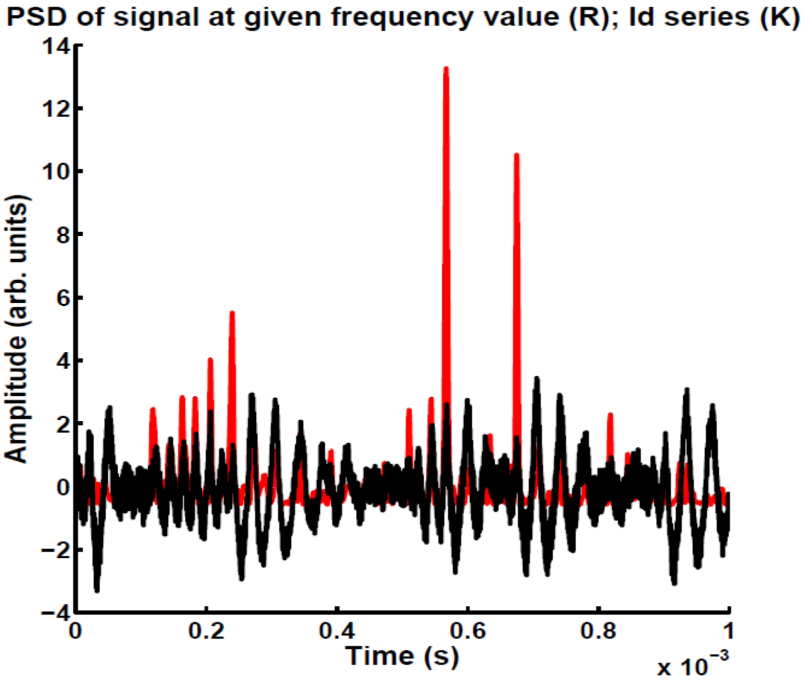
Current j_x determined averaging over at different times: 10, 1, 0.1 μs

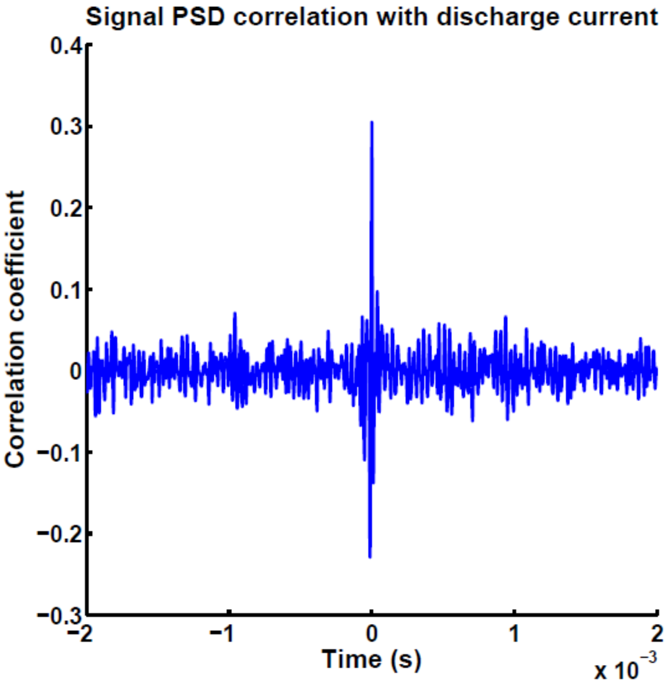


Experimental evidence for role of the ECDI in transport?

Experiments: role of mode in transport

- a clear correlation exists between the discharge current fluctuations and the experimental measurements of the ECDI fluctuations

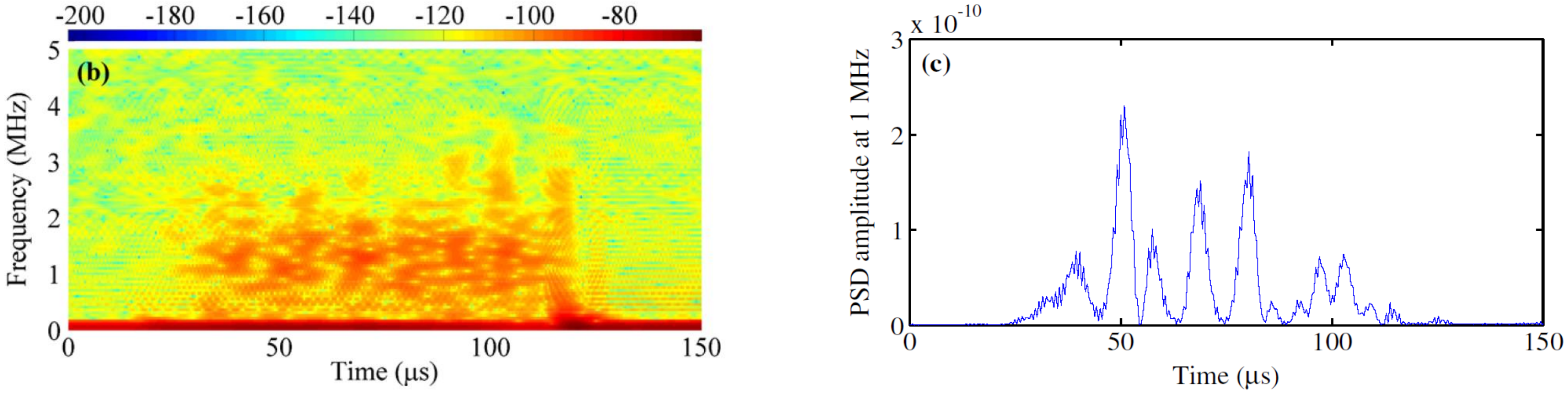


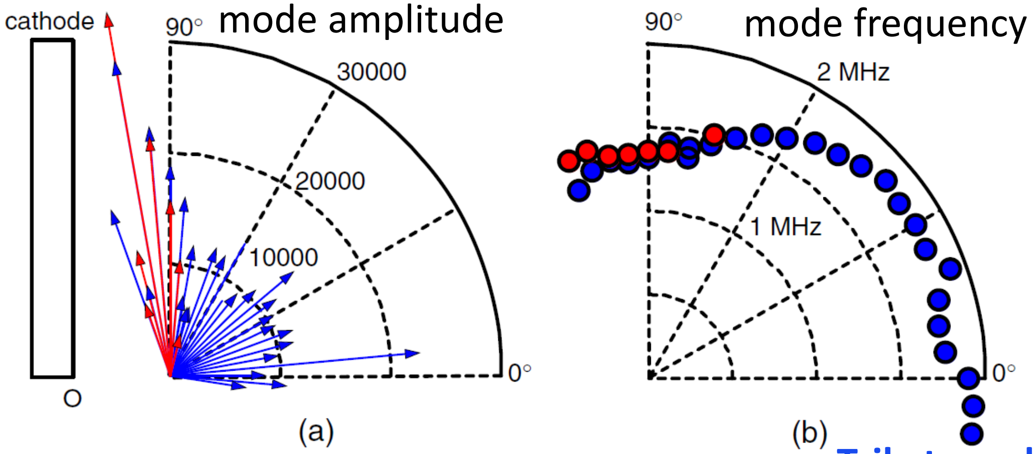


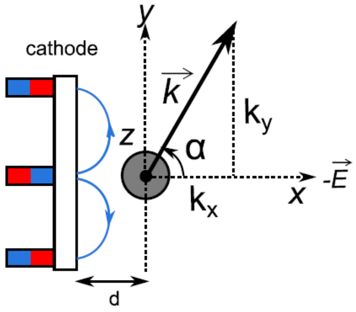
- discharge current signal lags behind ECDI fluctuations in such regimes
- fluctuations in ExB region followed by fluctuations at anode?

Large and small-scale structures

- recent magnetron study: low-frequency modulation of ECDI observable in HiPIMS regime
- small and large-scale structures coexist, and measurements show higher ECDI amplitude in spoke; transport by ECDI favored by spoke?



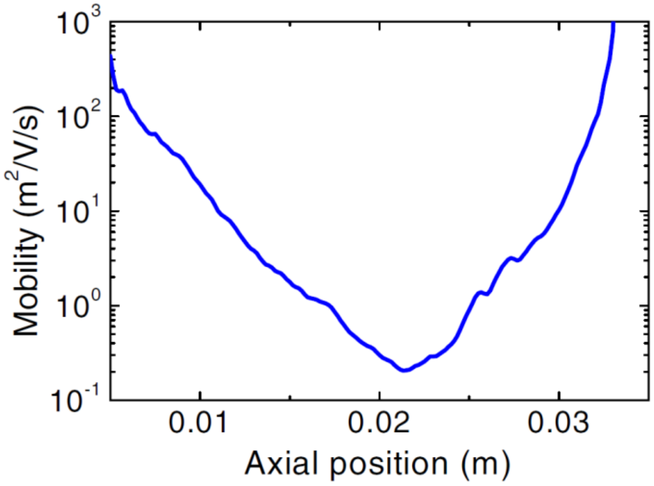




Tsikata and Minea, Phys. Rev. Lett. 114, 185001 (2015)

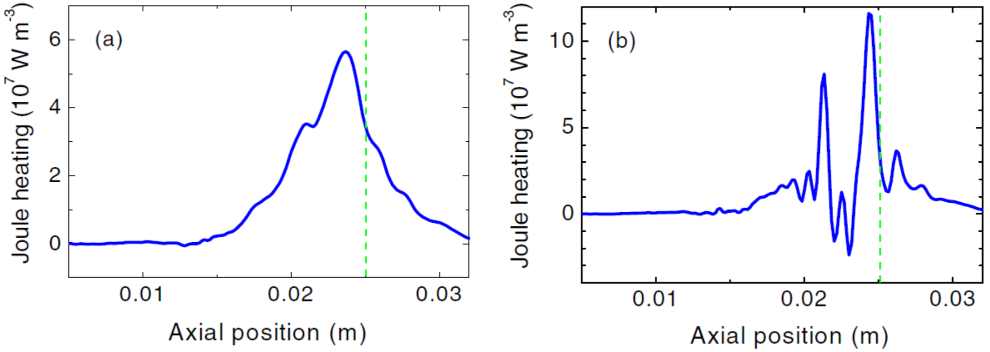
Addendum

Simulations: role of mode in transport



$$\mu_\perp \approx j_{\mathrm{ex}}/en_\mathrm{e}E_x$$

Adam et al., Plasma Phys. Control. Fusion 50, 124041 (2008)

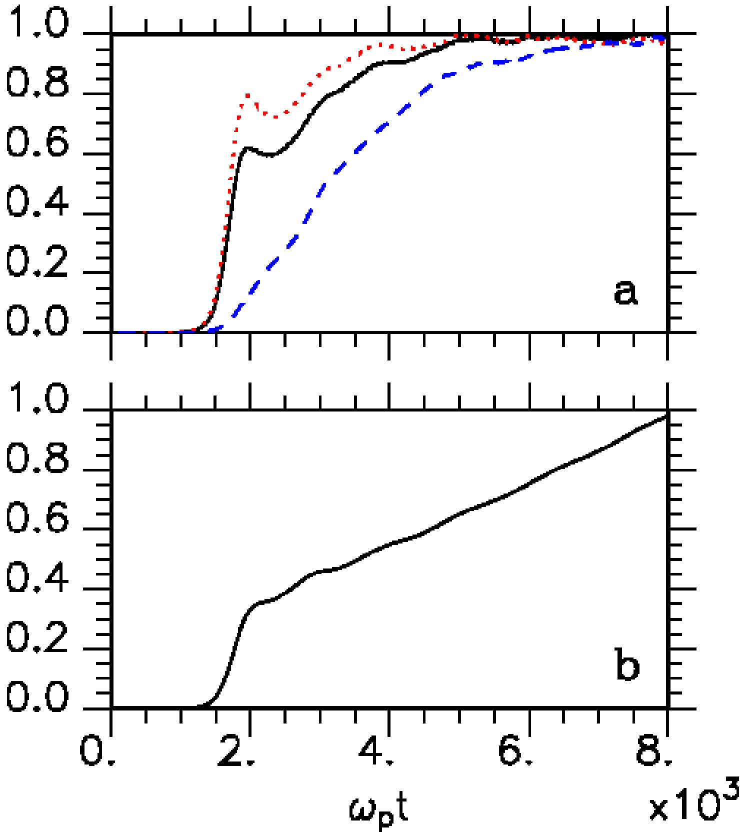


- **fluid approximation**
- **averaging in the azimuthal direction**

  Ex, Jx over 0.1 µs

Simulations

- evidence that heating due to mode is correlated with current: azimuthal-radial simulations



work by radial field

work by azimuthal field

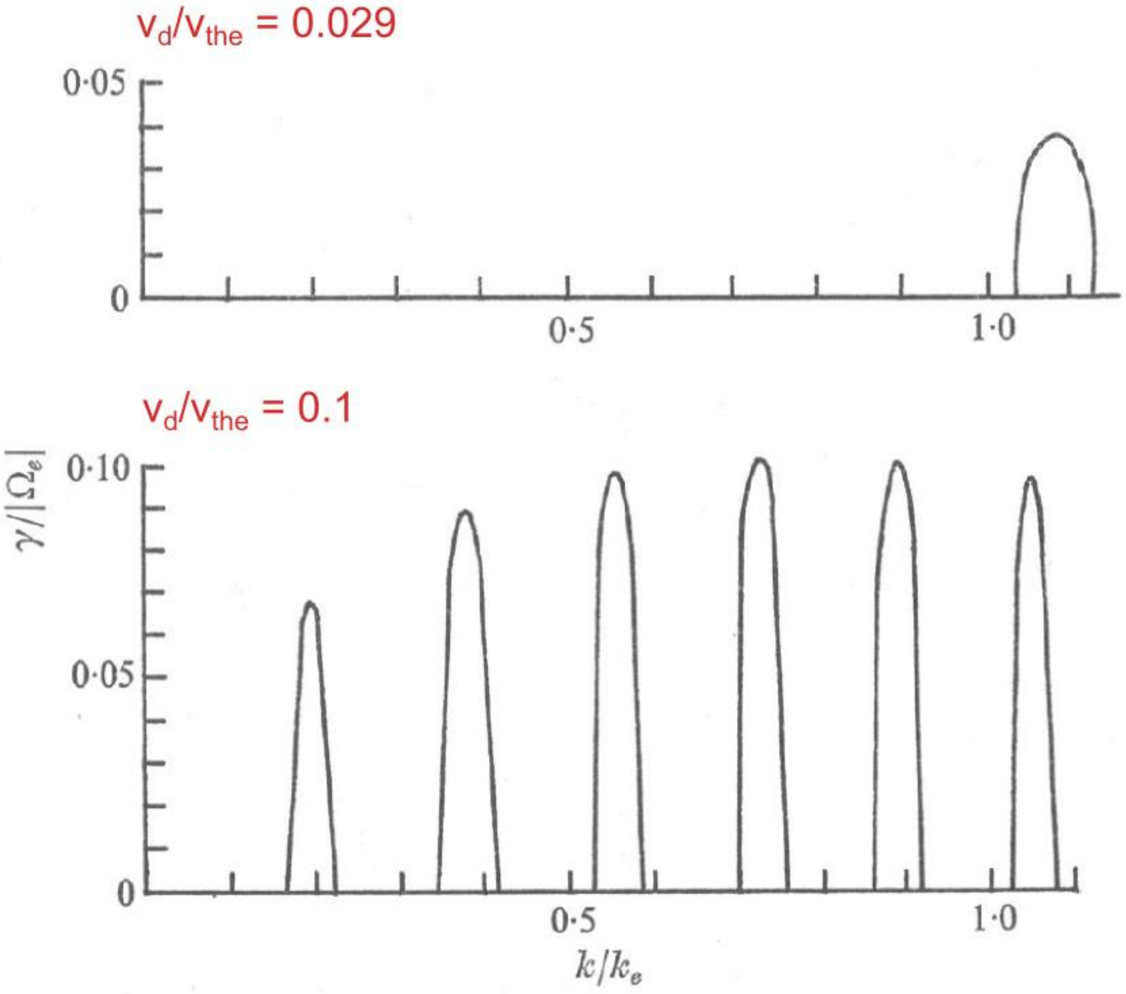
axial current density

electrostatic energy

- the evolution of system energy and current occurs on identical time scales to those of the instability

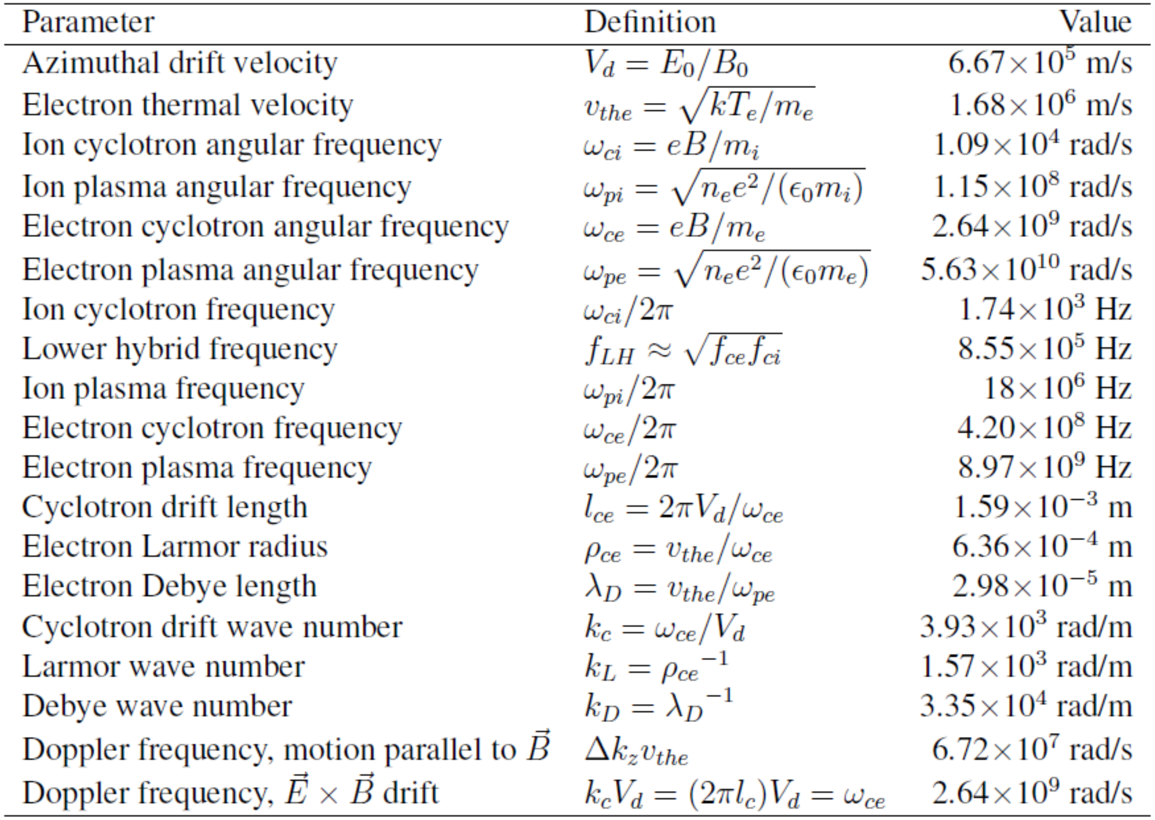
Héron and Adam, Phys. Plasmas 20, 082313 (2013)

Instability generation



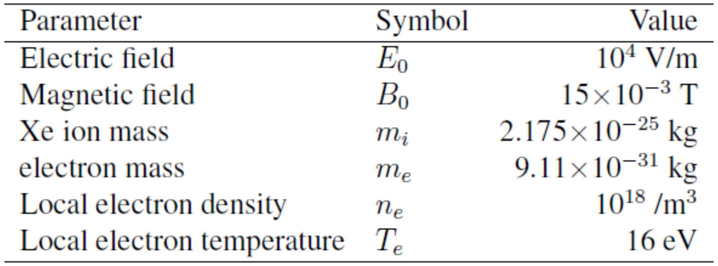
S. P. Gary and J. J. Sanderson, J. Plasma Phys. 4, 739 (1970)

Useful parameters relevant to presented data



Parameter	Definition	Value
Azimuthal drift velocity	$V_d = E_0/B_0$	6.67×10^5 m/s
Electron thermal velocity	$v_{the} = \sqrt{kT_e/m_e}$	1.68×10^6 m/s
Ion cyclotron angular frequency	$\omega_{ci} = eB/m_i$	1.09×10^4 rad/s
Ion plasma angular frequency	$\omega_{pi} = \sqrt{n_e e^2/(\epsilon_0 m_i)}$	1.15×10^8 rad/s
Electron cyclotron angular frequency	$\omega_{ce} = eB/m_e$	2.64×10^9 rad/s
Electron plasma angular frequency	$\omega_{pe} = \sqrt{n_e e^2/(\epsilon_0 m_e)}$	5.63×10^{10} rad/s
Ion cyclotron frequency	$\omega_{ci}/2\pi$	1.74×10^3 Hz
Lower hybrid frequency	$f_{LH} \approx \sqrt{f_{ce} f_{ci}}$	8.55×10^5 Hz
Ion plasma frequency	$\omega_{pi}/2\pi$	18×10^6 Hz
Electron cyclotron frequency	$\omega_{ce}/2\pi$	4.20×10^8 Hz
Electron plasma frequency	$\omega_{pe}/2\pi$	8.97×10^9 Hz
Cyclotron drift length	$l_{ce} = 2\pi V_d/\omega_{ce}$	1.59×10^{-3} m
Electron Larmor radius	$\rho_{ce} = v_{the}/\omega_{ce}$	6.36×10^{-4} m
Electron Debye length	$\lambda_D = v_{the}/\omega_{pe}$	2.98×10^{-5} m
Cyclotron drift wave number	$k_c = \omega_{ce}/V_d$	3.93×10^3 rad/m
Larmor wave number	$k_L = \rho_{ce}{}^{-1}$	1.57×10^3 rad/m
Debye wave number	$k_D = \lambda_D{}^{-1}$	3.35×10^4 rad/m
Doppler frequency, motion parallel to $\vec{B}$	$\Delta k_z v_{the}$	6.72×10^7 rad/s
Doppler frequency, $\vec{E}\times\vec{B}$ drift	$k_c V_d = (2\pi l_c) V_d = \omega_{ce}$	2.64×10^9 rad/s

Table 3.2: Characteristic plasma frequency and length scales



Parameter	Symbol	Value
Electric field	E_0	10^4 V/m
Magnetic field	B_0	15×10^{-3} T
Xe ion mass	m_i	2.175×10^{-25} kg
electron mass	m_e	9.11×10^{-31} kg
Local electron density	n_e	10^{18} /m^3
Local electron temperature	T_e	16 eV

Table 3.1: Thruster and plasma parameters

Simulations: parametric studies (1)

- E (V/m) as a function of wavenumber and axial location

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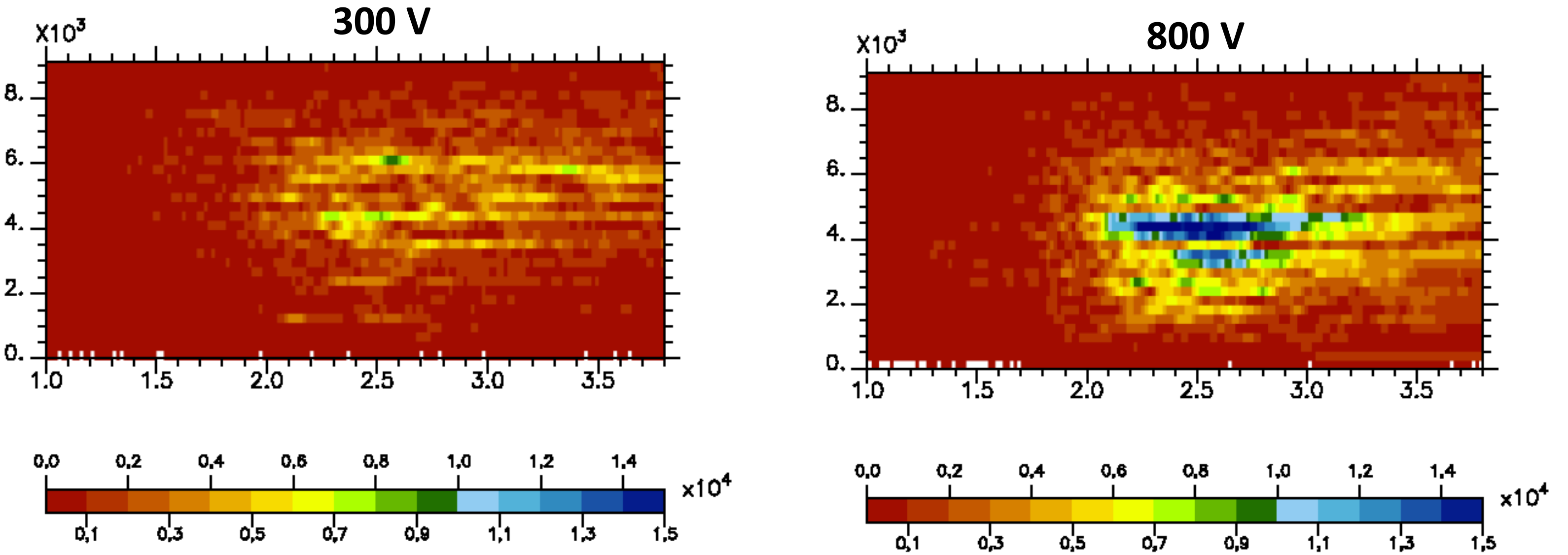
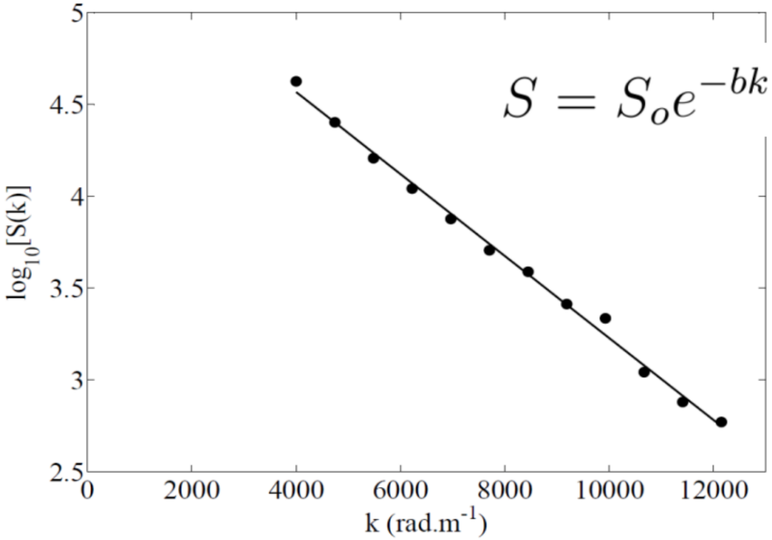


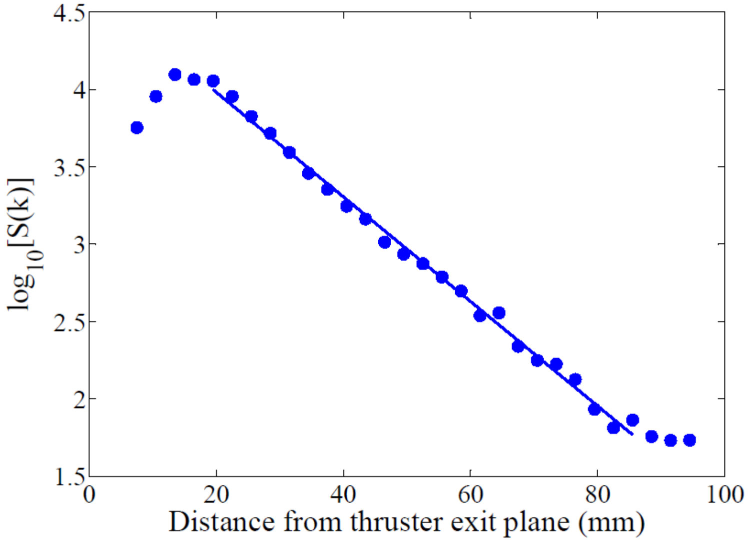
- increased axial localization of instability at higher Ud

- increased wavenumber localization

Experiments: fluctuation localization



exponential distribution of amplitude with scale



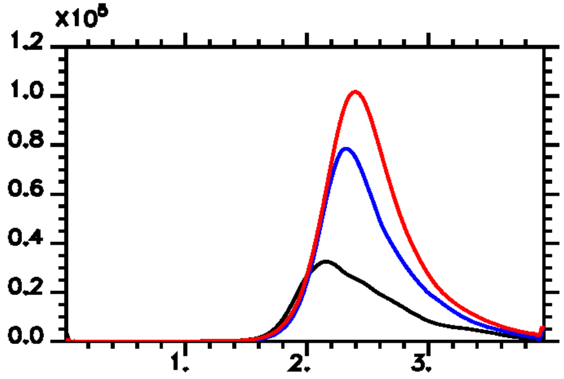
exponential variation of amplitude with distance

- mode convected far outside exit plane region

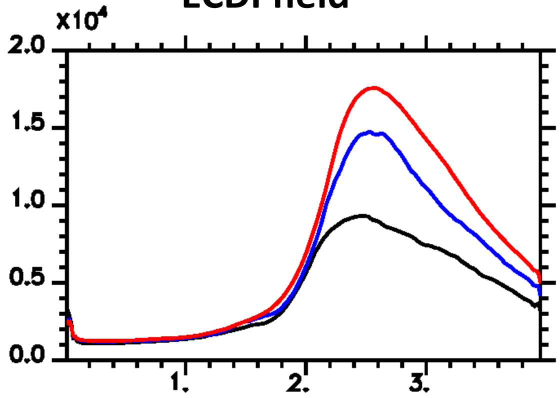
Simulations: parametric studies (2)

- relationship between accelerating E, fluctuating E – azimuthal-axial simulations

accelerating E



ECDI field



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300 – 600 – 800 V

electron density