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Fluid modeling of instabilities and structures in Hall plasmas relevant to electric propulsion

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14. ABSTRACT
This program studied the dominant mechanisms of the anomalous transport and formation of coherent structures in partially magnetized plasmas relevant to electric propulsion. The ultimate goal of this research is to develop physics based simulation capabilities for predictive design of new plasma propulsion systems. The advanced fluid model describing the instabilities, turbulence, and anomalous current has been developed and implemented in high performance numerical code. For the first time, the first principle fluid simulations have predicted the anomalous transport which is roughly consistent with experimental values and results of kinetic simulations. The inverse cascade toward larger scale structures was demonstrated showing formation of zonal flows, vorticies and streamers. It was shown that anomalous transport in these systems is dominated by large scale modes.

15. SUBJECT TERMS
Electric propulsion, Hall thruster, FRC, turbulence, nonlinear coherent structures, spokes, anomalous transport and current, numerical simulations, fluid models

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Fluid and kinetic modeling of instabilities and structures in Hall plasmas relevant to electric propulsion

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Executive Summary

This research aims to clarify the dominant mechanisms of the anomalous transport and formation of coherent structures in partially magnetized plasmas (magnetized electrons and unmagnetized ions) relevant to electric propulsion such as Hall thrusters driven by the electron ExB drift, FRC devices, Penning discharges and others. The ultimate goal of this research is to develop physics based simulation capabilities for predictive design of new plasma propulsion systems. The advanced fluid model describing the instabilities, turbulence, nonlinear saturation, and anomalous current in plasmas driven by ExB electron drift has been developed and implemented in high performance numerical code. The model includes the effects of finite electron temperature which allows physics based description of instabilities across wide range of wavelengths including the short wavelength modes and the transition to the ion sound instability. The model is 2D in the plane perpendicular to the magnetic field and includes collisional effects. The linear studies within this model have revealed multiple unstable modes, in particular, new short wavelength high frequency modes and the existence of unstable modes in the regions where the local criteria predict stability. The linear local dispersion relation solver has been developed to facilitate the analysis and interpretation of the experimental data and comparison with results of kinetic simulations. The nonlinear model has been implemented in the BOUT++ framework, and linear and nonlinear simulations have been performed. The linear simulations have been benchmarked against the linear eigen-value solution. The nonlinear simulations have demonstrated nonlinear saturation of the instabilities, anomalous transport and tendency toward the formation of large scale structures. For the first time, the first principle fluid simulations have predicted the anomalous transport which is roughly consistent with experimental values and results of kinetic simulations. The value of the effective Hall parameter found in nonlinear simulations is close to the experimental values observed in Penning discharge at PPPL and PIC kinetic simulations performed at PPPL. The nonlinear simulations show the correlated large scale structures in density, potential and anomalous current. The excitation of the large scale structures is explained as a result of nonlinear instability and energy cascade from small scales fluctuations that have the largest linear growth rates. The large scale axial modes (in the direction of the external electric field) have been identified in 2D fluid simulations. These modes have been explained as the axial resistive modes as confirmed by the analytical theory and 1D (axial) nonlinear simulations. It was shown that these mode are the crucial element of ionization mode instabilities resulting in the periodic axial structures with characteristics (frequency and wavelength)

similar to those of the breathing mode. Time-resolved measurements of the externally modulated breathing oscillations in a cylindrical Hall thruster have been performed in collaboration with PPPL. These experimental results have shown a possibility of enhanced thrust with external modulations as also confirmed by preliminary results of numerical simulations. Analytical studies of 3D effects (including the parallel electron dynamics along the magnetic field) have been performed showing the strong stabilization effects depending on the nature of the current closure conditions at the wall boundaries (along the magnetic field). These three results: experimental demonstration of the external control of the breathing modes, analytical studies of 3D effects, and preliminary numerical model, open the way for the external control and suppression of the large scale modes such as spokes.
The role of the kinetic effects, in particular Electron Cyclotron Drift (ECDI) has been clarified in our studies. A new 2D3V PIC code (2DPIC) was developed and benchmarked. In addition to fluid simulations, complementary kinetic Particle in Cell (PIC) simulations of ECDI have been performed in 1D3V and 2D3V geometries. Based on these results, it is conjectured that the ECDI may operate as an energy input for small scale modes which subsequently condensate into large scale structures (via the inverse energy cascade) providing dominant contribution to the anomalous transport. The energy cascade to the large scales is also instrumental in formation of spokes that affect the device operation and performance.

Most significant results

Plasma sources relevant to Hall, FRC, helicon thrusters and other electric propulsion systems operate with strongly non-equilibrium plasmas created by the applications of the external electric and magnetic fields, external heating and ionization by the RF power. These plasmas exhibit a variety of linear instabilities, interactions of different modes, turbulence and nonlinear self-organization. The experimental results from PPPL Penning discharge and Cylindrical Hall thruster are used as a starting point of this research outlining the range of phenomena and plasma parameters of the interest. We have developed an advanced two-fluid models for plasma description, perform analysis of linear instabilities, eigen-mode structure and conditions for the instabilities, and study nonlinear behavior with numerical simulations. The information from linear analysis is used to get insight on the nature and type of excited modes. The results of nonlinear simulations are further analyzed and characterized giving the predictions for anomalous transport and structure formation. These predictions are tested and validated against the experimental results and complementary of PIC kinetic simulations. The results and achievements within this programme are described below.

2. 1 Advanced fluid model. The nonlinear fluid model has been developed for description of the instabilities driven by density and magnetic field gradient and collisions in presence of the electron current due to the $\mathbf{E}\times\mathbf{B}$ drift. The model is based on the reduced electron dynamics for magnetized electrons in the low frequency approximation, $\omega < \omega_{ce}$ and full ion dynamics in neglect of the magnetic field. The model describes the Simon-Hoh, lower-hybrid and ion sound instabilities including the effects of the ion beam velocity [1]. The model also includes the transverse electron inertia and finite electron temperature effects (electron gyro-viscosity tensor) and thus incorporates the effects of finite electron Larmor radius. For small but finite values of the perpendicular wave-vector $k_\perp^2\rho_e^2 < 1$, the Larmor radius effects in this model are asymptotically exact (as compared to the full kinetic theory), and for large values, $k_\perp^2\rho_e^2 > 1$, our model provides the qualitatively correct Pade type approximation to the exact Bessel functions of the kinetic theory. Therefore, this advanced fluid model provides physically correct picture of electron dynamics in the whole range of the wavelengths, including the short wavelength limit, $k_\perp^2 \rho_e^2 > 1$. As a result, our model is able to describe the required transition to the ion sound instability in the limit $k_\perp^2 \rho_e^2 >> 1$ when the electrons become un-magnetized. Our model predicts the excitation of the ion-sound instabilities driven the electron drift current, density gradient and collisions, Fig. 1. Further extension of this mode includes the effect of pressure anisotropy [2].

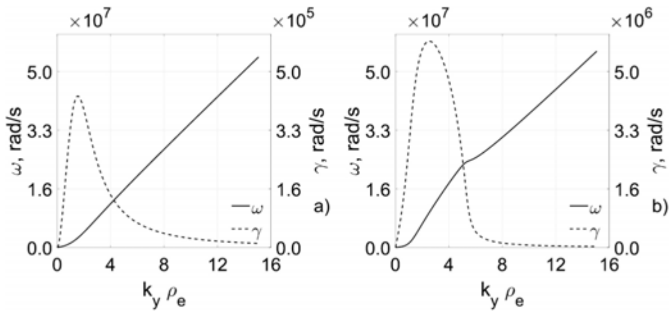


Fig. 1. Effect of the gyro-viscosity and conversion into the ion sound mode, note the almost linear dependence on the wave-vector corresponding to the ion sound dispersion, $\omega = k_y c_s$. (a) Destabilization of the ion-sound mode by density gradient and collisions; (b) Destabilization by density gradient, **E**×**B** drift and collisions.

2.2 Local analysis of linear instabilities and dispersion relation numerical tool. The local analysis of linear instabilities is a simple approach which provides a useful assessment of the relevance and importance of various instabilities for typical experimental conditions and facilitate the development of physical intuition. Based on our advanced fluid model that describes a range of instabilities for a wide range of the wave-vectors including the small scale modes $k_\perp^2 \rho_e^2 >> 1$, we have performed an extensive studies of the Simon-Hoh, lower-hybrid and ion-sound instabilities [1,3].

An unexpected role of two dimensional perturbations for Simon-Hoh mode has been revealed. Contrary to the previous belief that for the long wavelengths the Simon-Hoh is the low frequency mode with the eigen-mode frequency well below of the $\mathbf{E} \times \mathbf{B}$ frequency, $\omega_0 = k_\theta V_E$, it has been established that the growth rate is the non-monotonous function of the transverse wave vector in the radial (axial) direction, k_x, and the growth rate is maximal for highly anisotropic modes with $k_x \approx 2(\omega_0 \omega_*)^{1/2} / c_s >> k_\theta$, where k_θ is the azimuthal wave vectors, and $\omega_* = -k_\theta c T_e / e B_0 L_n$ is the electron drift frequency. For such modes, the growth rate and real part of the mode frequency become equal, $\omega = \omega_0 + i\omega_0$.

Our models has demonstrated that the Simon-Hoh and lower-hybrid modes are in fact a single continuous mode. The small scale modes are the most unstable, and for typical experimental plasma parameters the mode growth rate is maximal for the mode with $k_\perp^2 \rho_e^2 \approx 1$, the exact value depends on the values of the ω_0 and ω_* frequencies. It has been also found that the lower-hybrid mode can be destabilized by the density gradient and collisions even in absence of the $\mathbf{E} \times \mathbf{B}$ drift. Another important finding was the discovery of the destabilization mechanism due to the ion beam alone even in the neglect of the electron $\mathbf{E} \times \mathbf{B}$ current.

Our analysis of various destabilization mechanism noted above revealed that the parametric dependencies of the mode frequencies and growth rate are quite complex and quite sensitive to absolute and relative values of specific plasma parameters such as magnetic field, density gradient, electric field, electron temperature, ion beam velocity and neutral gas pressure. We have developed the interactive dispersion relation solver which can be conveniently used by researchers to assess the particular instabilities for specific plasma parameters in a given experiment. The tool is user friendly, includes several different analytical models and provides convenient interface, plotting and saving functions. This solver is available for free download [5].

2.3 Nonlocal analysis of linear instabilities. Most of the previous studies of gradient-drift modes were based on the local approximation. However, for plasmas with complex profiles of plasma density, magnetic and electric field, the local approximation breaks down and non-local analysis of the global modes has to be invoked taking into account the variations of plasma parameters. We have developed the linear spectral eigen-value code using Chebyshev polynomials to approximate the eigen-modes. Using this code, the properties of the global modes for realistic plasma parameters profiles (electric field, density and magnetic field) and the effects of cylindrical geometry for Penning discharge and Hall thruster were studied [3]. Nonlocal theory shows significant differences from the local model. This difference is especially important for the long wavelength modes which are expected to provide the dominant contributions to the anomalous transport. One of the important conclusions is the presence of unstable global modes in the regions where the local theory predicts stability, Fig. 2, and existence of localized unstable solutions in sheared flows, Fig.3.

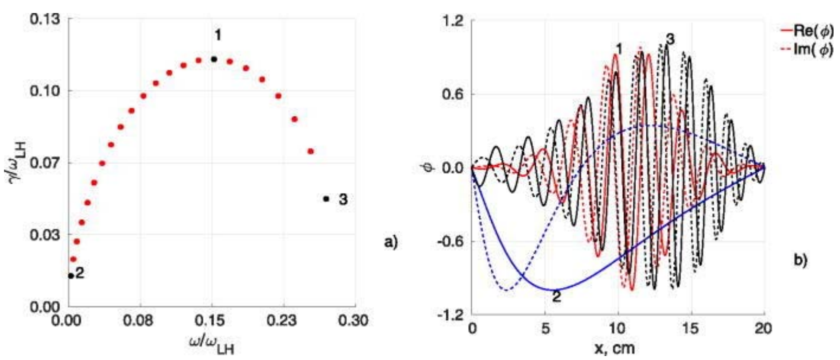


Fig. 2. (a) Full spectrum of unstable eigenvalues for the constant E × B shear profile; (b) multiple unstable eigen-functions; wavenumber $k_y = 20\ m^{-1}$: the eigen-function with the largest growth rate , $\omega = (0.15 + 0.11)\ \omega_{LH}\ s^{-1}$ (red); the ground state unstable eigen-function with $\omega = (0.002 + 0.014i)\cdot \omega_{LH}\ s^{-1}$ − 2 (blue); the eigenfunction with largest real frequency $\omega = (0.27 + 0.05i)\cdot \omega_{LH}\ s^{-1}$ − 3 (black).

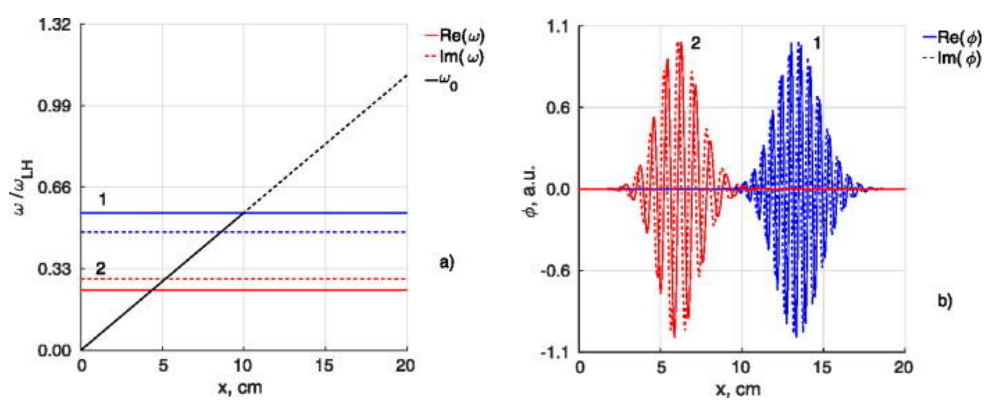


Fig. 3. The localized eigen-functions for the extended domain L= 20 cm, $k_y = 100\ m^{-1}$. The eigen-

function with the largest growth rate, $\omega = (0.56 + 0.48i) \cdot \omega_{LH}\ s^{-1} - 1$ (blue); $\omega = (0.24 + 0.29i) \cdot \omega_{LH}\ s^{-1} - 2$ (red).

2.4 Linear and nonlinear benchmarking of the numerical tools. Our nonlinear fluid model has been implemented in the BOUT++ fluid simulations framework which is based on finite difference schemes in magnetic field aligned coordinates and allows the 3D simulations in complex magnetic geometry. The linear differential operators along and perpendicular of the magnetic field as well as nonlinear Poisson bracket employed in BOUT++ have been extensively tested before, in particular, with the Method of Manufacturing Solutions. We have tested our numerical model in linear regime against the linear eigen-mode solvers which shows good agreement, see Fig 4..

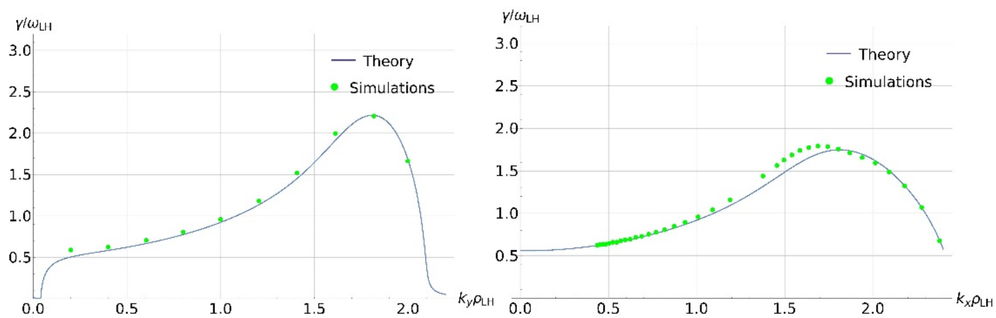


Fig 4. Linear benchmark of BOUT++ simulations against the theoretical eigen-value solutions.

In nonlinear regime, we have tested our simulations for saturation starting from different initial conditions and grid convergence. It has been shown that the final saturated state is independent of the initial state and is well convergent for different grid resolutions and values of the hyperviscosity coefficients [1]. To test the fidelity of the finite difference nonlinear simulations, we have been developing a high resolution pseudo-spectral code for a double periodic region. The identical system of nonlinear equations has been simulated with finite difference BOUT++ and a pseudo-spectral code. The comparison of the result has been encouraging, Fig. and ongoing now. Pseudo-spectral methods have been successful in modeling of incompressible fluids. However, straightforward application of this approach to more general hyperbolic problems which tend to develop shock wave type solutions may lead to stability problems due to Gibbs phenomenon and spectral blocking. We are now employing smooth filters which allow the pseudo-spectral method to be stable for almost singular solutions.

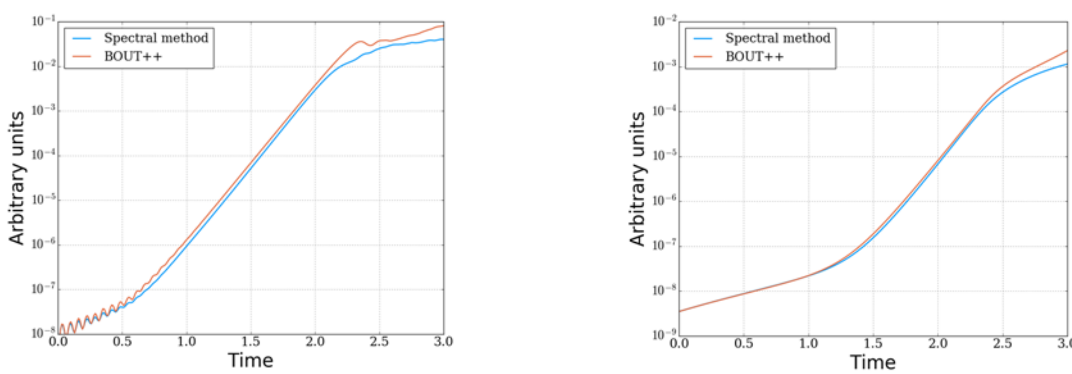


Fig. 5. Comparison of density a) and potential fluctuations b) in nonlinear simulations with BOUT++ and pseudo-spectral code.

2.5 Nonlinear fluid simulations: Anomalous electron current and structures. In our nonlinear simulations, the saturation of turbulence and formation of the coherent structures have been demonstrated [1]. It is shown that the instability reaches the saturation in nonlinear regime at a level which is independent of the initial state. For the first time, significant anomalous current due to turbulent fluctuations has been found in the first principle nonlinear simulation model. The anomalous (turbulent) current is strongly intermittent and the structures observed in the current density are correlated with density and potential structures. The density and current structures are reminiscent of experimentally observed structures (spokes) in Hall thrusters and magnetrons and the values of the anomalous Hall parameter are consistent with experiments in Penning discharge and PIC simulations [5].

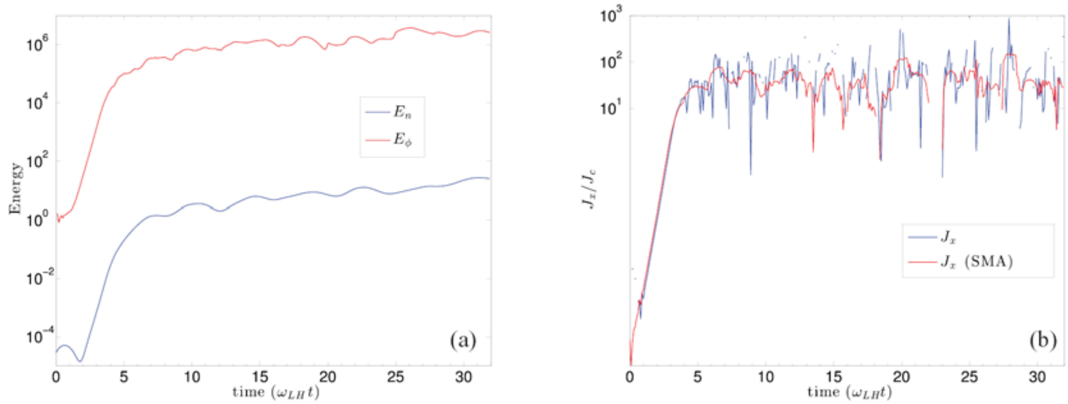


Fig. 6. The time evolution of the density and potential energy integrals (a); the time dependence of the anomalous current (in units of the classical collisional current) (b).

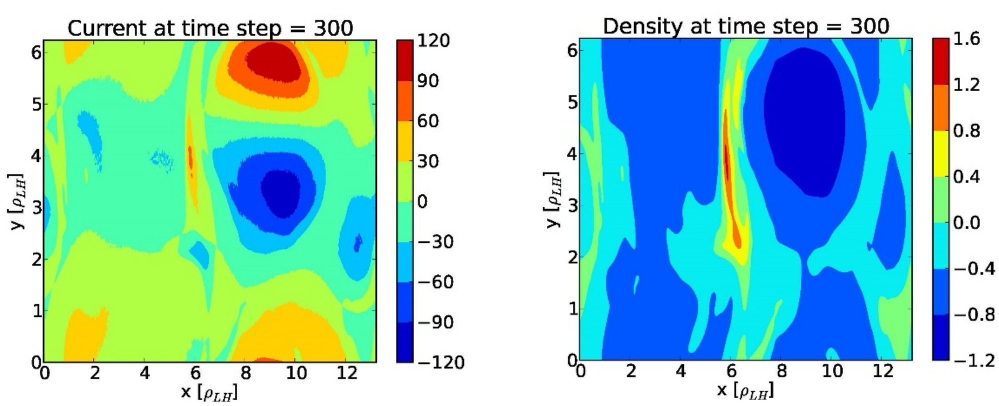


Fig. 7a. Large scale structures in density (right) and electric current (left), From Ref. 1

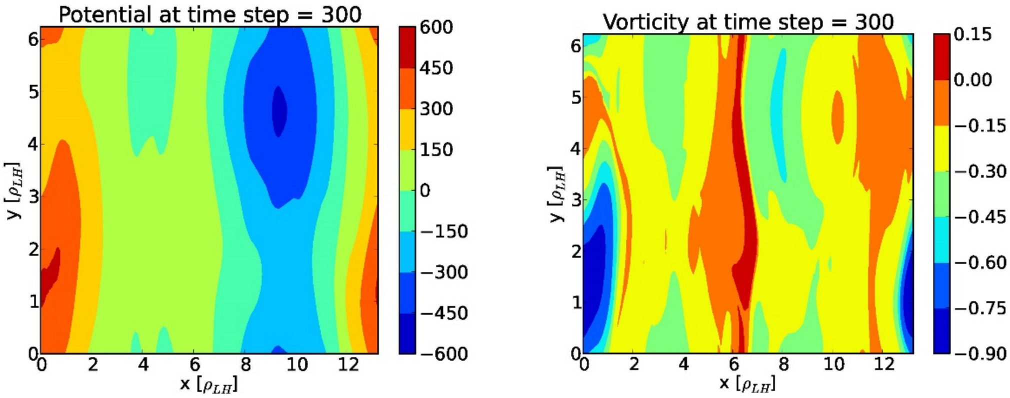


Fig. 7b. Large scale structures in potential (left) and vorticity(right), From Ref. 1

2.6 Coherent modes. Coexistence of large small scales. Energy cascade into large length scale modes. Using the approach of the modulational instability, we have considered the condensation of small scale lower-hybrid frequency modes into the long wavelength structures. It is shown that the bath of small scale modes is unstable with respect to the secondary instability of the large scale quasi-mode perturbations. The large scale structures are not linear unstable eigen-modes but the nonlinearly driven modes supported by the nonlinear energy transfer from small scale modes. It is suggested that the large scale slow coherent modes observed in a number of Hall plasma devices may be explained as a result of such secondary instabilities [4]. The secondary instability resulting in the excitation of the long wavelength envelope is shown in nonlinear kinetic simulations, Fig. 8.

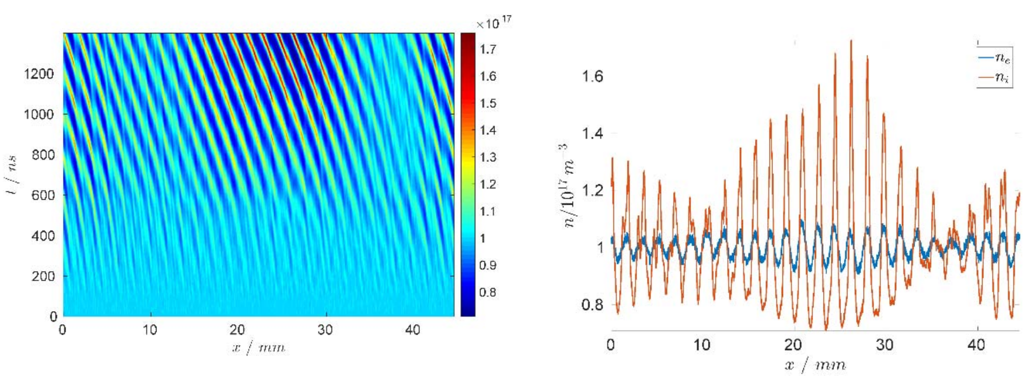


Fig. 8. Coherent density structure generated by ExB instability (left). Nonlinear modulational instability resulting in inverse cascade and energy transfer to long wavelengths (right) in nonlinear kinetic simulations. From Ref. 7.

Coexistence of large and small scale modes is shown in nonlinear 2D fluid simulations (Fig.9).

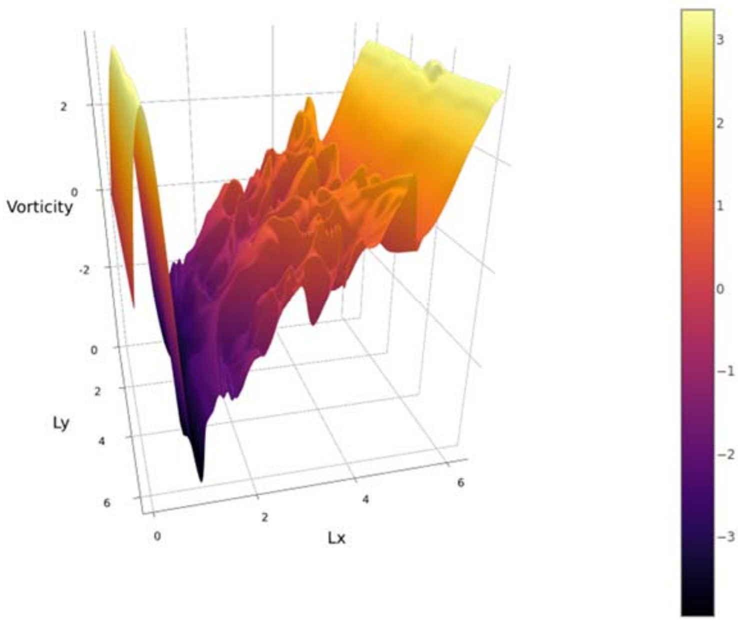


Fig. 9. The dimensionless amplitude of the vorticity from 2D nonlinear simulations. The small scale modes exist on the background of large axial mode, Lx is axial direction, and Ly is azimuthal direction of the Hall thruster.

2.7 Resistive instability of the axial modes and structures. The resistive axial modes occur as a result of the axial current flow instability due to phase shift and positive feedback between the dissipative electron response and ballistic (inertial) response of ions. We have developed a full nonlinear model for such modes taking into account the electron inertia effects. The electron inertia is important to limit the modes growth at small scales and thus selects the value of the wavelength for the most unstable modes. The axial flow instability has relatively low growth rate compared to azimuthal modes (of higher frequencies) which are driven by collisions and density gradientsWe detected this mode also in 2D simulations which show coexistence of large scale and small fluctuations, Fig 9. The significance of axial modes however is in the high amplitude of the saturated states. The mode saturation occurs due to ion dynamics resulting in appearance of highly nonlinear quasi-coherent structures resembling the cnoidal waves, Fig. 10.

It has been suggested that that this instability play a crucial role for breathing modes oscillations. We have included the ionization effects into the axial mode theory and performed nonlinear simulations. The obtained structures closely resemble the breathing modes, Fig 11 and Fig 14. It is worth noting that our model does not include the effects of the electron temperature.

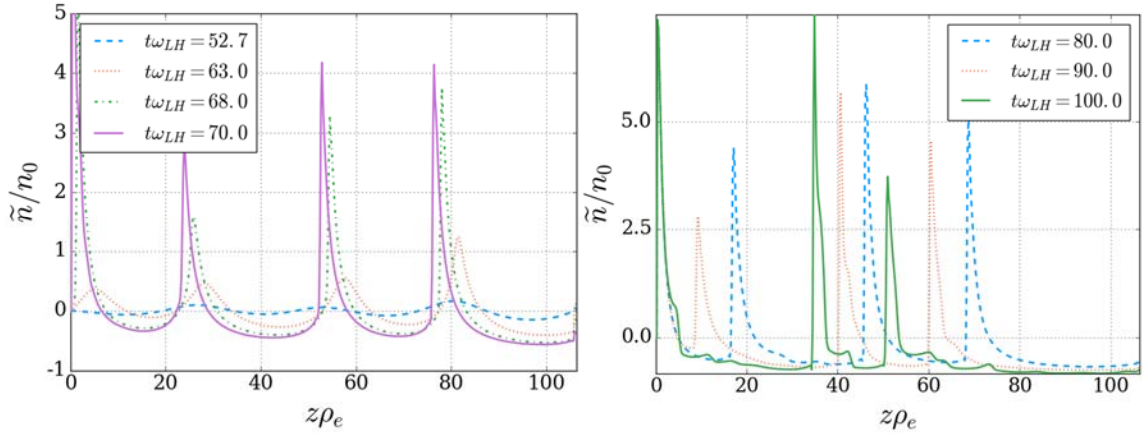


Fig. 10. Nonlinear development and axial motion of large scale (axial) modes (plasma density); compare with Fig 8. Here, z is the axial direction of the Hall thruster, From Ref.6.

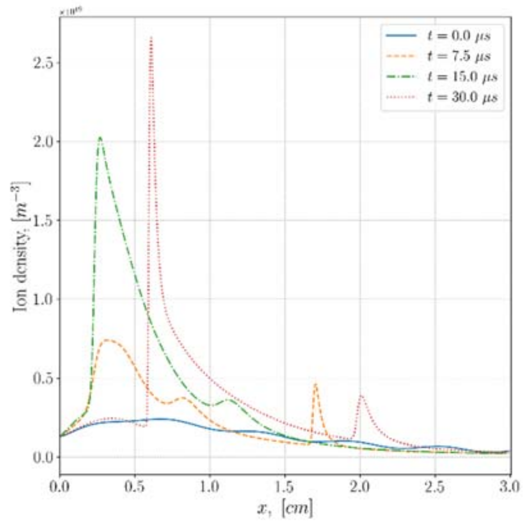


Figure 11. Axial propagation of the ion density structures in the model with ionization effects**.**

The ion beam can be another source of the axial modes. Such modes are related to the lower-hybrid instability driven by the ion flow in a finite length system. Similar instability mechanism was also identified for ion sound waves in unmagnetized plasmas. We have studied the linear and nonlinear stages of this instability and found that the instability results in stationary axial structures. It is interesting that the profiles of the perturbed potential in stationary state is not monotonous, Fig 12, and demonstrate the near anode region with the ion backflow.

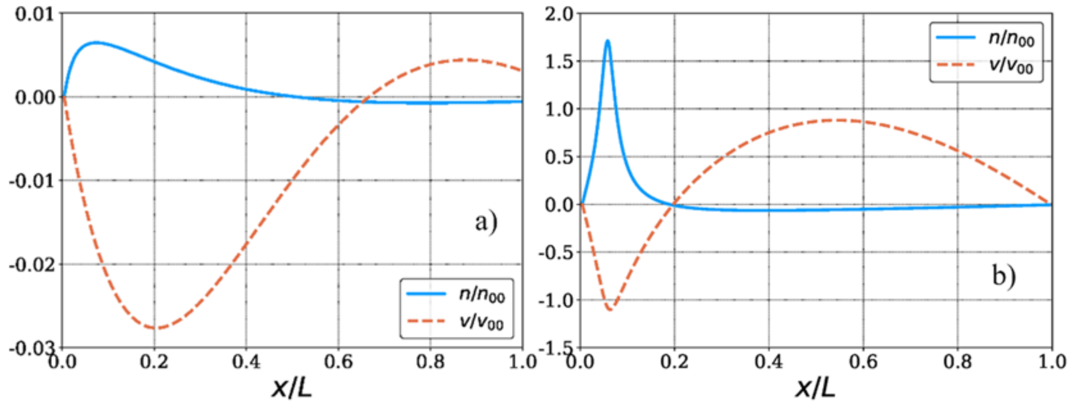


Figure 12. (a) Eigen-functions of density and ion velocity perturbations. (b) Stationary profiles of density and ion velocity.

2.7 Ionization instabilities and neutral pressure effects. We are developing the theory of gradient driven modes taking into account the ionization effects. It is shown that ionization effect result in the shift of the unstable modes to the long wavelengths, thus consistent with the range of spoke instabilities.

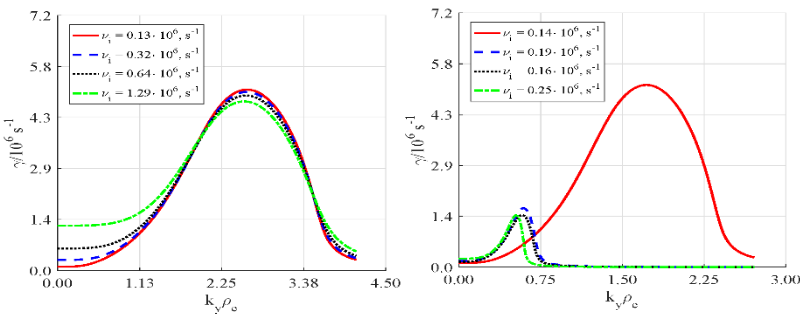


Fig 13. Growth rate of gradient-driven mode as a function of the wave-vector for different ionization frequencies (corresponding to different neutral pressure): direct effect of neutral pressure (left), effect of neutral pressure and temperature reduction are included (right).

We have included the ionization effects into the axial mode theory. The obtained structures closely resemble breathing modes, Fig 11 and Fig 14.

Fig. 14a: Nonlinear development of axial modes taking into account the ionization effects, at time t=198 ms

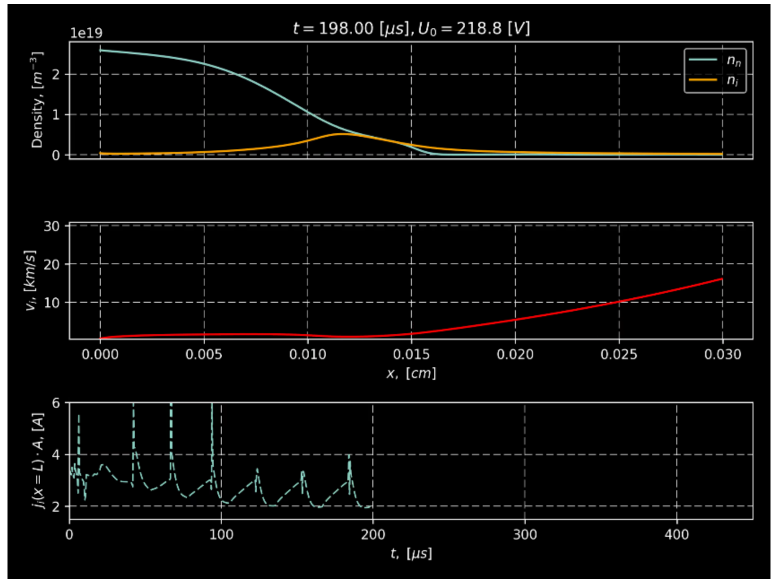


Fig. 14b: Nonlinear development of axial modes taking into account the ionization effects, at time t=204 ms.

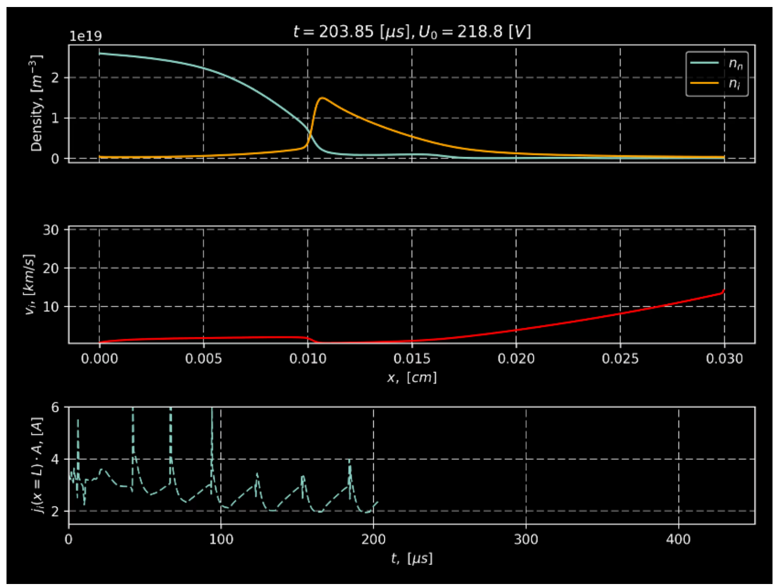
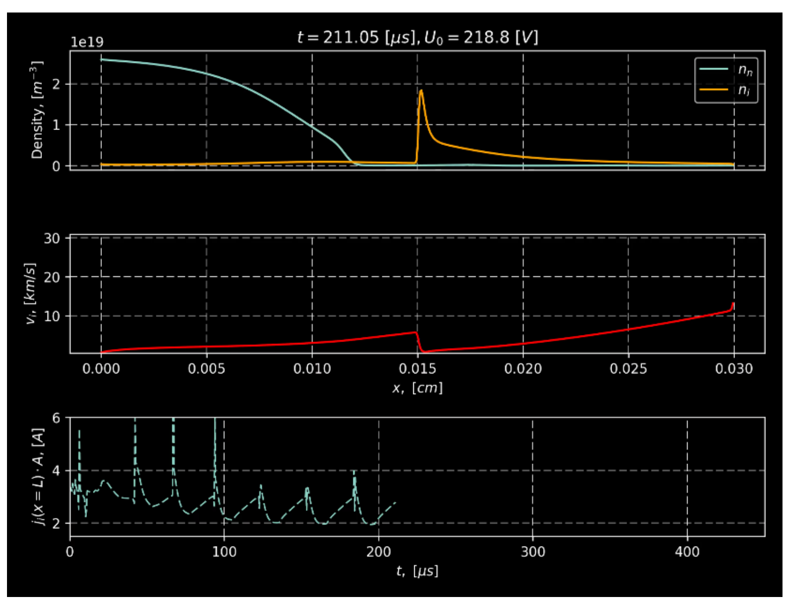


Fig. 14c: Nonlinear development of axial modes taking into account the ionization effects, at time t=211 ms.



Please also see the imbedded video showing the density, neutral density and current oscillations in our model.

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2.8 Kinetic effects and electron-cyclotron resonances: Electron-Cyclotron-Drift-Instability. The electron-cyclotron instabilityhas attracted an interest in view of its possible role in driving the instabilities of $\boldsymbol{E} \times \boldsymbol{B}$ plasma discharged. It has been suggested that this instability simply becomes the ion sound mode. We have studied this mode with the combination of the analytical theory and kinetic simulations, Ref. 7. Our results indicated that at moderately short wavelength $\boldsymbol{k_\perp^2 \rho_e^2 \geq 1}$, the eigen-modes of partially magnetized plasma indeed become similar to the ion-sound mode, e.g. as is shown in Fig. 15. However, in case of the kinetic modes strongly driven by $\boldsymbol{E} \times \boldsymbol{B}$ electron-cyclotron resonances, the situation is more complex. Our 1D PIC kinetic simulations show that initially there are multiple unstable electron-cyclotron harmonics which are excited according to the linear theory, as shown in Fig 15.

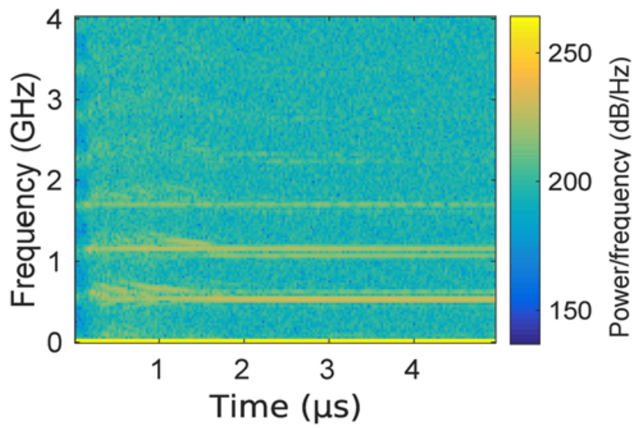

Figure 15. Development of multiple unstable cyclotron modes of the $E \times B$ instability as a function of time. Amplitude of higher harmonics reduces with time.

At a later stage, the nonlinear interactions result in robust reorganization with a single dominant mode selected by the resonance condition $k_0 v_E = \omega_{ce} \gg \omega$. This mode remains strongly coherent well into the nonlinear stage. This primary cyclotron resonance is a source of the energy that cascades further down to the ion-sound and lower hybrid modes. Our simulations demonstrate the energy accumulation at longer wavelengths. The inverse cascade is also evident in the appearance of secondary longer wavelength envelope on the background of the small-scale mode with the dominant wavelength $\lambda = 2\pi/k_0$, as in Fig 8. We have also performed 2D simulations corresponding to the $r-\theta$ plane of the Hall thruster. The magnetic field is in the radial (r) direction, while θ is the periodic azimuthal direction. For the 2D case, our simulations are: initial temperature is 10 eV, we have 2048 cells in r for 5.385 cm and 512 in theta for l_θ of 1.35 cm, 800 particles per cell. The dielectric walls are at $r = 0$ $r = 40$ mm so the sheath is formed at both walls. We show the evolution of the perturbed ion density in Figure 16. The pictures show the evolution of the ion density fluctuations: first we see the saturation of the linear modes, then a fast non-linear cascade to low-k through strong modulation particularly close to the sheath boundary, and subsequent ballistic release of fluctuations into the sheath region so at the fluctuations penetrate the sheath. The spatial Fourier content is still dominated by the fundamental cyclotron harmonic as in 1D case and the features of the cascade to long wavelength modes are strongly evident.

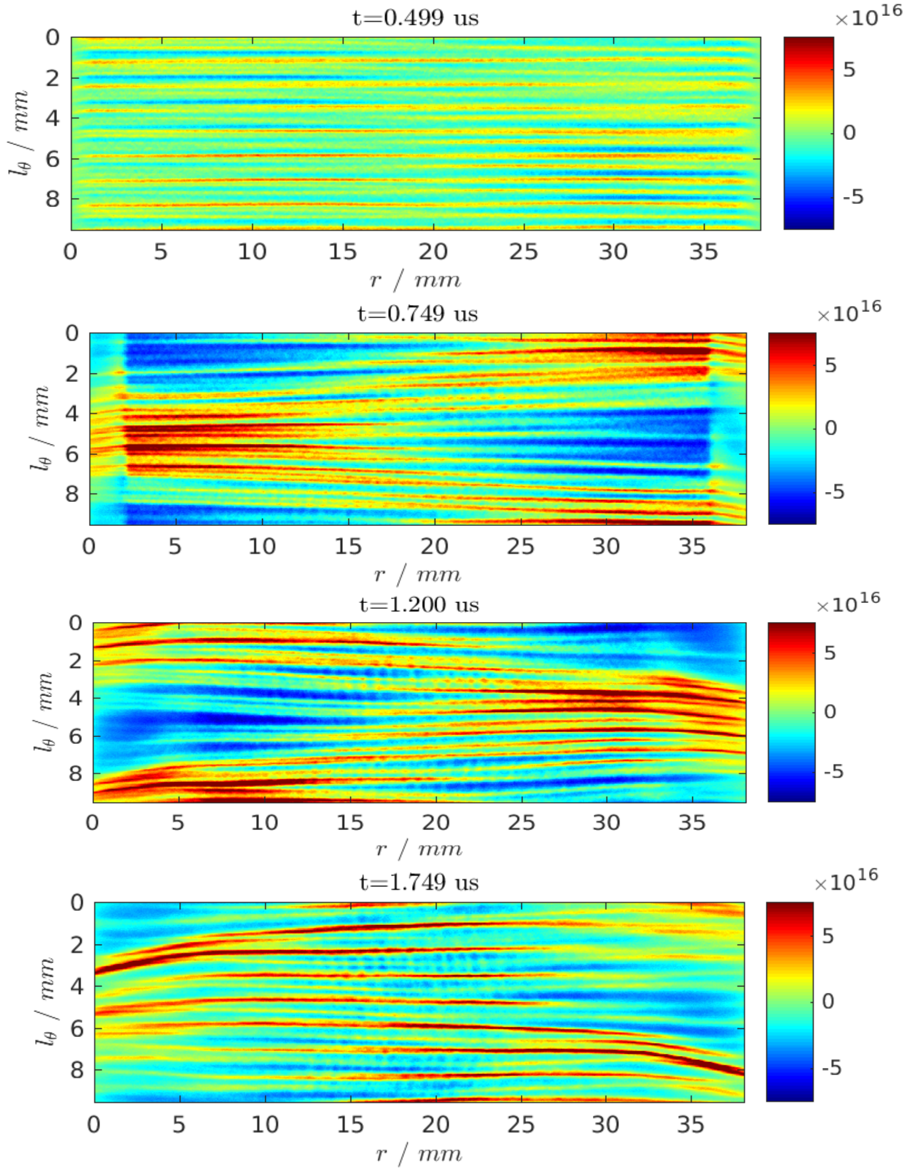

Figure 16. Snapshots of ion density fluctuations in the simulation over four distinct regimes of non-linear evolution. First, modes saturate and assume an amplitude-modulated form, then a strong cascade to low-k occurs. After this, the perturbations penetrate the sheath regions.

2.9 Non-linear response of Hall thruster plasma to modulation of the discharge voltage and feedback control. Our PhD student I Romadanov has performed a set of experiments with external modulations and feedback control of cylindrical Hall thruster. For cylindrical Hall thrusters, naturally occurred breathing oscillations have a characteristic frequency of 13 kHz. The external modulation of the anode potential was applied to make this mode coherent. To determine the driving frequency, a set of natural frequencies was defined from the Fourier transform of the discharge current and the ion current in the plume. By varying driving frequency in the range of 5-20 kHz and monitoring the power spectra of the currents, we found that the coupling of the driving frequency to the intrinsic breathing mode is at frequency of this mode 13 kHz rather than at the driving frequency. More than that, with the increase of the driving voltage, there is a non-linear response of the discharge current and the ion current as well as a shift of the breathing mode to lower frequencies. We are now in the process of simulating these recent results with out theoretical model.

Conclusions and Outlook

The group at the University of Saskatchewan (U of S, A. Smolyakov) has been conducting theoretical and numerical studies of nonlinear phenomena and structures in plasmas relevant to electric propulsion system. This work has been performed in close collaboration with PPPL (Y. Raitses and I Kaganovich). The PhD student from the University of Saskatchewan (I. Romadanov) has visited PPPL for several 2-4 months periods to perform the experiments. This work has stimulated improvement of the theoretical model that has been developed at U of S to explain and predict the experimental data. The fluid model has been implemented numerically within the high performance computational framework. Our nonlinear fluid model and simulations have provided the first principles calculations of the anomalous electron current from turbulent fluctuations and demonstrated the structure formation. In the course of these studies the potential role of the cyclotron instabilities has been identified, which was not in our initial plans. To evaluate the role of such kinetic effects, we have developed a new high performance 2D3V PIC code. Our 1D and 2D PIC simulations demonstrate strongly nonlinear waves driven by the fundamental cyclotron resonance as well as features of the cascade toward longer wavelength. Our most recent results indicate that these instabilities play the central role in ionization driven mode thus potentially revealing their roles in explanation of the neutral pressure effects. Preliminary theoretical studies with our model show that we might be able to predict the behavior of ionization modes (breathing modes and spokes) observed in experiments at PPPL (I Romadanov). Therefore, we might be in the position to control/suppress the excitation of large scale modes/spokes which would be among our next most immediate objectives.

The results obtained in our group have advanced us to the leadership positions in the electric propulsion plasma community as evidenced by a number of publications and invited talks at most prestigious conferences. A. Smolyakov has been invited to prepare the white paper on the physics and transport in partially magnetized plasmas (for Frontiers of Plasma Science Workshop, U.S. Department of Energy). A. Smolyakov is a co-chair (with J.P. Boeuf) of the ExB plasma Workshop that was held in 2017 (Tolouse, France), the next workshop is planned for 2018 at PPPL.

Additional Information

The large scale simulations were performed on the Compute Canada computer clusters, which is the national (Canada) platform of supercomputing resources. These resources were provided to A. Smolyakov free of charge based on the national (Canadian) allocation of the high performance computing resources. A new application was submitted to Compute Canada for 2017 Resource Allocation Competition to perform high performance parallel nonlinear simulations of partially magnetized plasmas relevant to electric propulsion systems.

Graduate students, Postdoctoral Fellows and Research Associates in part supported by the AFOSR grant.

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Invited Conference and workshop presentations

A.Smolyakov, Turbulence, anomalous transport and structures in low temperature Hall plasmas with ExB drift, Invited talk, Frontiers of Plasma Science Workshop, U.S. Department of Energy, Office of Fusion Energy Sciences, Town Hall Meeting: June 30 - July 1, 2015.

A.Smolyakov, Instabilities and transport in Hall thrusters, Invited talk, Electron transport workshop, NASA Jet Propulsion Laboratory, Sept. 8-9 2015, Pasadena, CA.

I. Romadanov, Structure of the nonlocal gradient-drift modes, Electron transport workshop, **July 24** 2017, Salt Lake City

A.Smolyakov, Turbulence and Structures related to low-hybrid and ion-sound instabilities in Hall thrusters, Invited talk, International Conference on Plasma Science, 19-23 June 2016, Banff, Alberta.

A.Smolyakov, Instabilities and anomalous transport in Hall plasmas, Invited talk, European Physics

Society Plasma Physics and Controlled Fusion Conference 2016, Leuven Belgium, 4-8 July, 2016.

A.Smolyakov. Instabilities and transport in Hall plasmas with ExB drift, Invited talk, 58th Annual Meeting of the APS Division of Plasma Physics, Oct 31–Nov 4 2016; San Jose, California

A.Smolyakov. Fluid simulations of turbulence and transport in plasmas with ExB drift, Invited talk, IMPULSE Workshop, Dec 1st, 2016, Universite Paul Sabatier, Toulouse, France

A.Smolyakov. Fluid and kinetic modeling of transport and structures in ExB plasma devicest, Invited **talk**, ExB plasmas Workshop, June 2017, Toulouse, France

Refereed Journal Publications

1. A I Smolyakov, O Chapurin, W Frias, O Koshkarov, I Romadanov, T Tang, M Umansky, Y Raitses, I D Kaganovich and V P Lakhin.Fluid theory and simulations of instabilities: Turbulent transport and coherent structures in partially-magnetized plasmas of E×B discharges, Plasma Phys. Control. Fusion **59** 014041 (2017), http://dx.doi.org/10.1088/0741-3335/59/1/014041

2. On the electron drift velocity in plasma devices with ExB drift, Chapurin, O.; Smolyakov, A. JOURNAL OF APPLIED PHYSICS **119** , 243306 (2016)

3. I. Romadanov, A. Smolyakov, Y.Raitses, I. Kaganovich, T. Tian, and S. Ryzhkov, Structure of nonlocal gradient-drift instabilities in Hall E × B discharges, Physics of Plasmas **23**, 122111 (2016); http://doi.org/10.1063/1.4971816

4. V. P. Lakhin, V. I. Ilgisonis, A. I. Smolyakov and E. A. Sorokina. Nonlinear excitation of long-wavelength modes in Hall plasmas, Phys. Plasmas **23**, 102304 (2016); http://dx.doi.org/10.1063/1.4964724.

5. Johan Carlsson, Igor Kaganovich, Yevgeny Raitses, Andrew Powis, Andrei Smolyakov, Ivan Romadanov , Particle-in-cell simulation of anomalous transport in a Penning discharge, submitted to Physics of Plasmas.

6. O. Koshkarov, A. I. Smolyakov, I. V. Romadanov, O. Chapurin, M. V. Umansky, Y. Raitses,and I. D. Kaganovich, Axial current flow instability and nonlinear structures in dissipative two-fluid plasmas. Accepted in Physics of Plasmas, 2017.

7. S. Janhunen, A. Smolyakov, O. Chapurin, D. Sydorenko, I. Kaganovich, and Y. Raitses, Non-linear structures and anomalous transport in partially magnetized plasma driven by the transverse current, Accepted in Physics of Plasma, 2017.

8. P. Svarnas, I. Romadanov, A. Diallo, Y. Raitses. Velocity distribution functions of Xe I and Xe II in ambipolar plasma flow using a single tunable diode laser, submitted to IEEE Transcations on Plasma Science

Technical Reports

1. I. Romadanov, A. Smolyakov, W.Frias, O. Chapurin, O.Koshkarov, Dispersion Relation Tool for generalized lower-hybrid mode with, density gradient, equilibrium ExB drift, collisions and finite electron Larmor radius, arXiv:1610.00218, https://bitbucket.org/ivr509/hall-plasmas-discharge-solver/downloads
2. A. Smolyakov, Y Raitses, I.Kaganovich, J.P. Boeuf, K. Matyash, R. Schneider, F. Taccogna, M. Cappelli, Turbulence, anomalous transport and structures in low temperature Hall plasmas with ExB drift, Invited White Paper, for Frontiers of Plasma Science, Panel 2: Plasma Turbulence and Transport, Department of Energy, Office of Fusion Energy Sciences, http://www.orau.gov/plasmawkshps2015/whitepapers/general-Smolyakov_Andrei.pdf

Invited Full conference papers

3. I. Romadanov, P. Svarnas, A. Diallo, Y. Raitses, A. Smolyakov. Parametric studies of velocity distribution functions for Xenon ions and neutrals in cylindrical Hall thruster with laser-induced fluorescence. 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Paper AIAA-2016-4622, 5 pages
4. Yevgeny Raitses, Igor Kaganovich, and Andrei Smolyakov. Effects of the Gas Pressure on Low Frequency Oscillations in E×B Discharges, 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4 – 10, 2015, IEPC-2015-307 /ISTS-2015-b-307, 6 pages.
10. Alexander V. Khrabrov, Igor D. Kaganovich, Yevgeny Raitses, Dmytro Sydorenko, and Andrei Smolyakov. Excitation of Ion Acoustic Waves in Plasmas with Electron Emission from Walls. 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4 – 10, 2015, IEPC-2015-340 /ISTS-2015-b-340, 6 pages.

11. W. Frias Pombo, A. I. Smolyakov, I. Romadanov, Y. Raitses, I. D. Kaganovich, and Maxim V. Umansky. Small scale fluctuations and anomalous electron current in Hall plasmas, 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4 – 10, 2015IEPC-2015-370/ISTS-2015-b-370, 10 pages.

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14. A. Smolyakov, O. Koshkarov, I. Romadanov, S. Janhunen, O. Chapurin, Y. Raitses, I. Kaganovich, D. Sydorenko. Fluid and Kinetic Modelling of Instabilities and Transport in ExB

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Contributed Papers in published Conference Proceedings and Abstracts

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2. SMOLYAKOV, I. ROMADANOV, W. FRIAS, J. CARLSSON, I. KAGANOVICH, Y. RAITSES. Small scale instabilities and anomalous electron current in Hall plasmas, 57th Annual Meeting of the APS Division of Plasma Physics, Volume 60, Number 19, November 16–20, 2015; Savannah, Georgia, Abstract ID: BAPS.2015.DPP.CP12.105, http://meetings.aps.org/Meeting/DPP15/Session/CP12.105

3. JOHAN CARLSSON, IGOR D. KAGANOVICH, ALEXANDER V. KHRABROV, YEVGENY RAITSES, ANDREI SMOLYAKOV. Two- and three-dimensional particle-in-cell simulations of ExB discharges. Annual Meeting of the APS Division of Plasma Physics, Volume 60, Number 19, November 16–20, 2015; Savannah, Georgia, Abstract ID: BAPS.2015.DPP.JP12.149, http://meetings.aps.org/Meeting/DPP15/Session/JP12.149

4. O. Chapurin; A. Smolyakov. On electron drift current in hall plasma devices with inhomogeneous and anisotropic plasmas. 2016 IEEE International Conference on Plasma Science (ICOPS). Year: 2016, DOI: 10.1109/PLASMA.2016.7533994

5. O. Koshkarov; W. Frias Pombo; A. I. Smolyakov; Y. Raitses; I. D. Kaganovich; M. V. Umansky. Nonlinear simulations and anomalous transport in hall thruster plasma 2016 IEEE International Conference on Plasma Science (ICOPS). Year: 2016, DOI: 10.1109/PLASMA.2016.7534020

6. A. Smolyakov; A. Koshkarov; I. Romadanov; A. Chapurin; M. Umansky; Y. Raitses; I. Kaganovich. Turbulence and structures related to lower-hybrid and ion-sound instabilities in Hall thrusters. 2016 IEEE International Conference on Plasma Science (ICOPS). Year: 2016, DOI: 10.1109/PLASMA.2016.7533972

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14. A. SMOLYAKOV, O. KOSHKAROV, W FRIAS, I. ROMADANOV, O. CHAPURIN, , M. UMANSKY, Y. RAITSES, I. KAGANOVICH, Instabilities in Hall E xB discharges with complex magnetic field configurations. 69th Annual Gaseous Electronics Conference, Bulletin of the American Physical Society, 69th Volume 61, Number 9, MW6.00054, 2016 http://meetings.aps.org/link/BAPS.2016.GEC.MW6.54.

15. A. SMOLYAKOV, Instabilities and transport in Hall plasmas with ExB drift, 58th Annual Meeting of the APS Division of Plasma Physics, Volume 61, Number 18, http://meetings.aps.org/link/BAPS.2016.DPP.GI3.3.

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18. A. SMOLYAKOV, O. CHAPURIN, M. JIMENEZ, S. JANHUNEN, O. KOSHKAROV, XU LIANG, V. MORIN, I. ROMADANOV, D. SYDORENKO, I. KAGANOVICH, Y. RAITSES. Instabilities and transport in ExB plasma discharges, 59th Annual Meeting of the APS Division of Plasma Physics, October 23–27, 2017; Milwaukee, Wisconsin, UP11.00048.

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