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Towards predictive modeling of ExB plasma discharges

Andrei Smolyakov
UNIVERSITY OF SASKATCHEWAN

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14. ABSTRACT

This research programme is devoted to the development of physics models and modelling tools toward an understanding of the behavior of large scale coherent structures and anomalous transport in ExB plasma relevant to the electric propulsion. We are using the reduced (simplified) theoretical models in combinations with fluid and kinetic simulations to address some specific problems inspired and suggested by experimental observations, primarily from the Hall thruster and Penning discharge experiments at Princeton Plasma Physics Laboratory. Specifically, we have developed the model for breathing modes including the effects of the external drive, have confirmed theoretically and experimentally the presence of gradientdrift driven modes in the Penning discharge, have theoretically demonstrated the modes transitions and saturation of the drift driven instabilities in Hall thrusters via the formation of large scale (spoke-like) structures and identified a novel mechanism of the anomalous electron transport in the region with low (or negligible axial electric field) such as the plume region.

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Toward predictive modeling of $\mathbf{E}\times\mathbf{B}$ plasma discharges

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Summary

This research programme is devoted to the development of physics models and modelling tools toward an understanding of the behavior of large scale coherent structures and anomalous transport in ExB plasma relevant to the electric propulsion. We are using the reduced (simplified) theoretical models in combinations with fluid and kinetic simulations to address some specific problems inspired and suggested by experimental observations, primarily from the Hall thruster and Penning discharge experiments at Princeton Plasma Physics Laboratory. Specifically, we have developed the model for breathing modes including the effects of the external drive, have confirmed theoretically and experimentally the presence of gradient-drift driven modes in the Penning discharge, have theoretically demonstrated the modes transitions and saturation of the drift driven instabilities in Hall thrusters via the formation of large scale (spoke-like) structures and identified a novel mechanism of the anomalous electron transport in the region with low (or negligible axial electric field) such as the plume region.

Outline

I. Fluid and hybrid modeling of the axial ionization modes and instabilities: Modeling and control of breathing mode by external voltage modulations, Refs. [4,6,9,14,16,17].

We have studied theoretically and experimentally the effects of the external modulations on the breathing mode. Stimulated by the experiments at the PPPL Hall thruster experiment laboratory, we have developed a 1D fluid model and adapted 1D hybrid (fluid electrons and kinetic ions) models [to describe and characterize axial profiles and ionization oscillations (breathing mode) in Hall thrusters [14,16]. The results from these two different models, fluid and hybrid, have been compared and shown to be reasonably close to each other, e.g. see Fig 1. We have performed a comparison of our results with experimental data [17]. A Ph.D. graduate student of the University of Saskatchewan (I. Romadanov) has visited Princeton Plasma Physics Laboratory for extended periods of time to perform experiments and then worked on a theoretical model and performed numerical simulations to interpret the experimental data. A Ph.D. graduate student of Princeton University (J. Simmonds) has visited the University of Saskatchewan to work with our group to learn the numerical simulations tools to interpret his experimental data on breathing mode and external modulations.

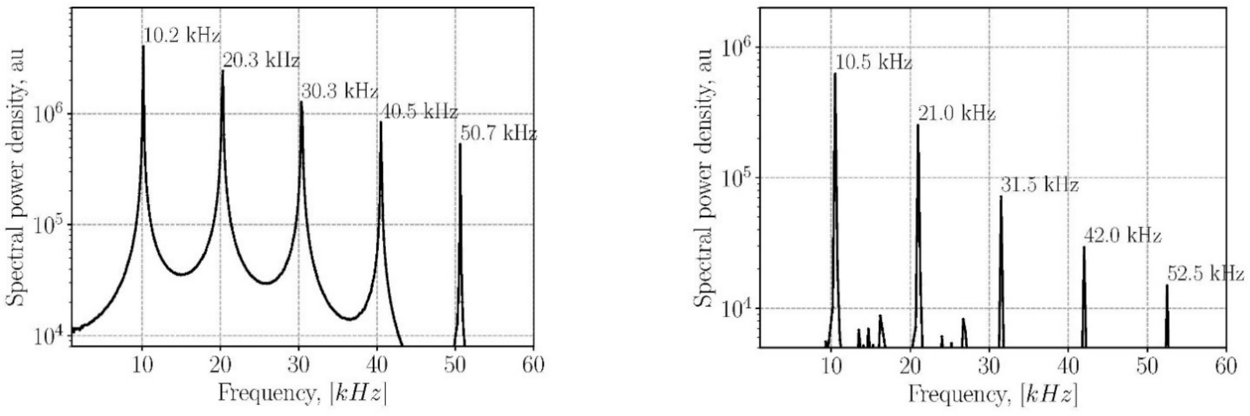

Fig. 1. Comparison of the frequency spectra of the total current breathing mode oscillations obtained from the fluid (left) and hybrid (right) models, from [16].

he comparison of the results of our theoretical and numerical model with the experimental data from

PPPL Hall thruster experiments have shown that the model qualitatively predicts many features and tendencies observed in the experiments, such as resonant behavior of the thruster response to external modulations at various frequencies,
nonlinear response to the amplitude of voltage modulations, and nonlinear locking of the current response to the external modulations. It was found that current and voltage efficiencies are clearly affected by simple harmonic voltage modulations and can be increased, but overall efficiency was not significantly modified by modulations, similar to the behavior in the experiment [4,17].

A new finding of our theoretical model was the identification of two distinct regimes of breathing mode: solo-regime when a single low-frequency mode is present, and another, two-mode regime when the low-frequency mode coexists with high-frequency oscillations. It is important that these two regimes are distinguished by the extent and position of the ionization zone, and exhibit quite different behavior of the ionization profiles. Based on this analysis we have proposed a reduced model that seems predicts well the scaling of the breathing mode frequency with the parameters of the neutral gas injection. A similar tendency was also obtained experimentally . Our results were presented at AIAA Propulsion and Energy Forum, Aug 2019, Indianapolis IN, [16,17] where they induced significant interest followed up by discussions with other experimental groups.

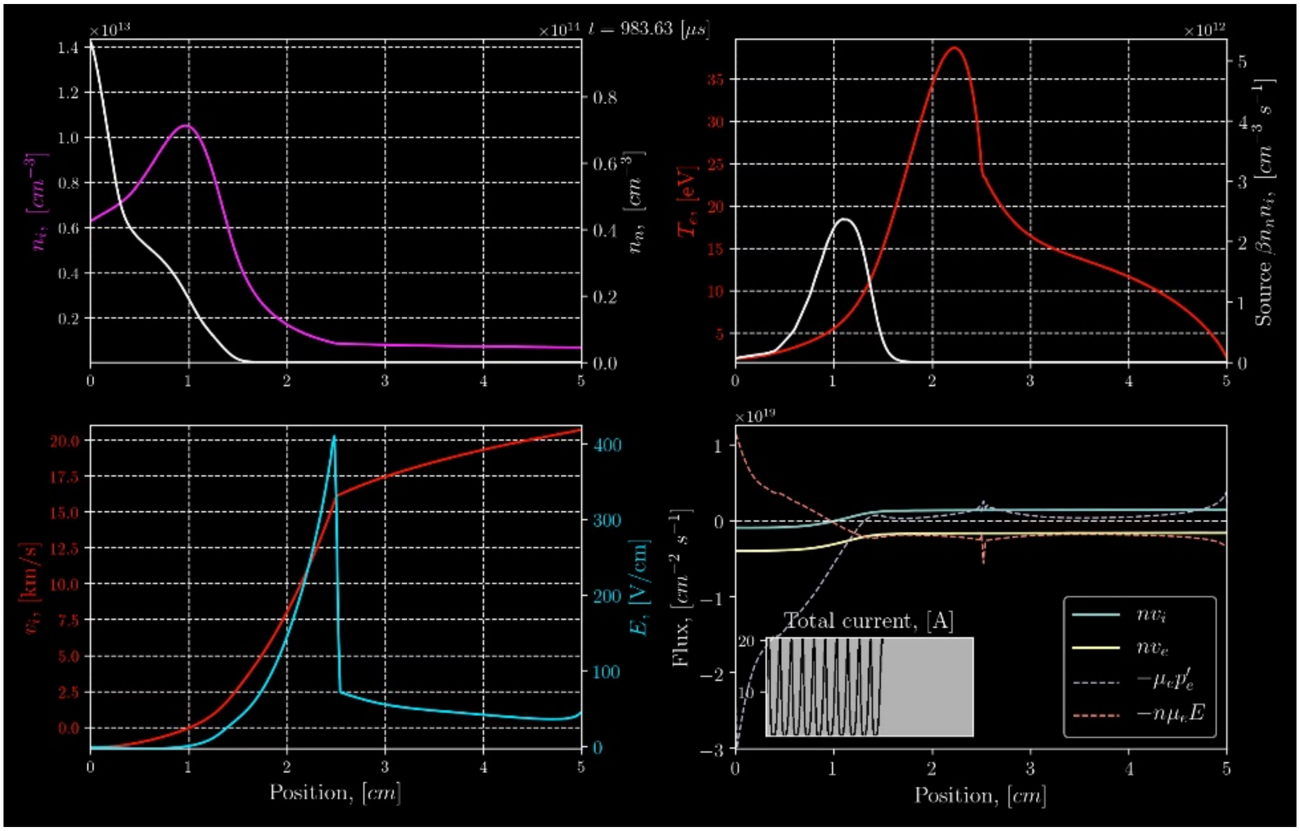

Fig. 2. Snapshots of the axial profiles of neutral, ion density, electric field, ion velocity and current time dependence (on the insert).

Our 1D time-dependent models (both fluid and hybrid) for the axial breathing mode demonstrate complex time-spatial evolution of the electric field fluctuations, electron diffusion, temperature and heat flux, Fig. 2. The time-averaged (e.g. such as the averaged profiles of the electric field and position of the acceleration zone) and integral (such as the total discharge current) characteristics of the discharge are the results of this complex spatial and temporal behavior which require further studies. One clear conclusion so far is that temporal variations of the axial gradients, such as density and electric field, will affect the excitation of the small scale azimuthal modes that in turn will lead to the variations of the anomalous mobility. Therefore the stationary models for the anomalous mobility with the fixed axial profile are not likely to be a good approximation.

The large scale azimuthal modes, such as spoke, are also depend on and can be driven by the axial gradients of plasma density and axial electric field (e.g. via the Simon-Hoh instability mechanism), that will occur in the axial mode oscillations such as breathing mode. This suggests the coupling of the axial (breathing mode) and the azimuthal (spoke) modes. We have demonstrated experimentally that the azimuthally rotating spoke mode can be suppressed by the external modulation of the anode potential at frequencies near the natural breathing mode [9]. These results show that there is an interaction between the azimuthal and axial modes.

II. Fluid modeling of large scale azimuthal (spoke-like) and axial structures, Refs. [3,5,15]

The theoretical model of gradient-drift modes that were developed previously as a part of the AFOSR supported research[1] was recently applied to the experiments on spoke instability in Penning discharge at PPPL. It was shown that experimental data are well correlated with the prediction of our analytical mode[1]. This model was also recently used by two other groups to explain their numerical results on spoke formation[2].We gave further studied coupling of the azimuthal (spoke-like) and axial structures in nonlinear reduced fluid model. We have studied the turbulent regimes of gradient-drift and lower-hybrid modes in neglect of ionization and assuming fixed axial plasma density gradient and electric field. The instabilities driven by combinations of the plasma density gradient,

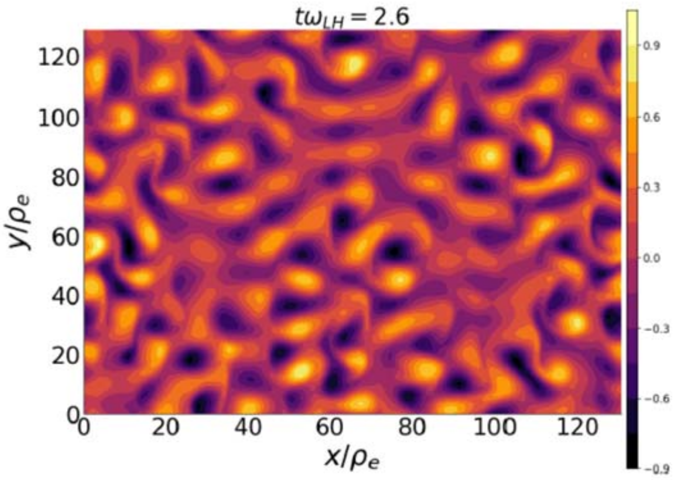

Fig. 3: Vorticity landscape in the azimuthal (vertical) and axial (horizontal) plane at the time of the transition from the linear to the nonlinear stage .

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[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 ExB discharges, Plasma Physics and Controlled Fusion **59**, 014041 (2017); Frias, A. Smolyakov, I. Kaganovich, and Y. Raitses, "Long wavelength gradient drift instability in Hall plasma devices. II. Applications," Physics of Plasmas **20**, 052108 (2013);   W. Frias, A. I. Smolyakov, I. D. Kaganovich, and Y. Raitses, "Long wavelength gradient drift instability in Hall plasma devices. I. Fluid theory," Physics of Plasmas **19**, 072112 (2012).

[2] R. Kawashima, K. Hara, and K. Komurasaki, "Numerical analysis of azimuthal rotating spokes in a crossed-field discharge plasma," Plasma Sources Science & Technology **27**, 035010 (2018).

J. P. Boeuf, "Micro instabilities and rotating spokes in the near-anode region of partially magnetized plasmas," Physics of Plasmas **26**, 072113 (2019).

ExB drift and ion flows in presence of the electron-neutral collisions were considered. Our nonlinear simulations have revealed the following phenomena and stages in the nonlinear evolution (i) the most unstable small scale gradient-drift waves are excited and grow exponentially in time; the mode structure in the linear to nonlinear transition is shown in Fig. 3; (ii) the large scale shear flows form due to the inverse cascade with subsequent development of vortices (similar to Kelvin-Helmholtz instability); the turbulence significantly enhances the axial electron conductivity; (iii) the anomalous electron current triggers the axial instability and axial modes grow; (iv) axial modes saturate into a high amplitude axial structures. The axial modes significantly change the density and electric field profiles, affecting the underlying gradient-drift instabilities. The latter mechanism underlines the coupling of the axial modes (breathing modes) with the azimuthal (spoke-like) modes.

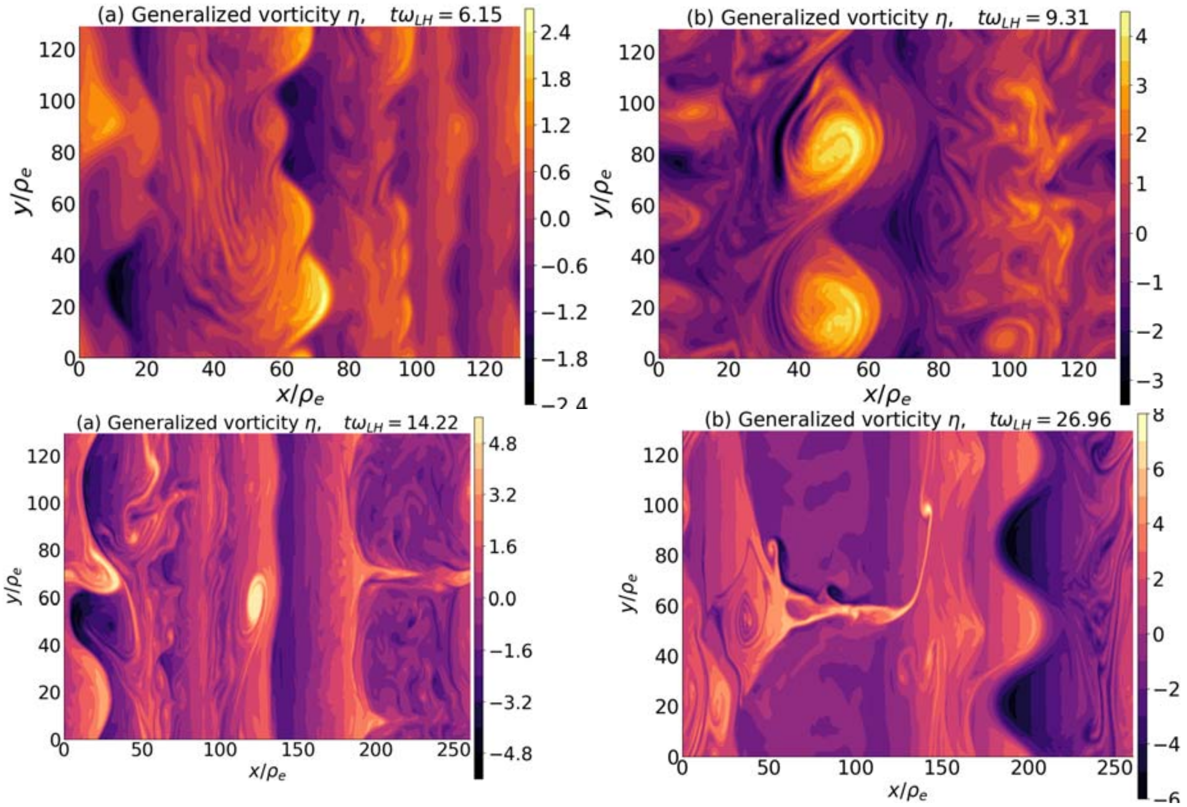

Fig. 4. Generatation of large scale shear flows, vortices, and streamers in the nonlinear stage. Compare with Fig. 3 at the end of the linear stage, x- axial direction, y -azimuthal.

The large scale structures (shear zonal flows and vortices) are produced via the inverse cascade of the energy flow from short-wavelength modes, Fig. 2. The turbulence self-organization in our simulations is further enhanced by coupling to the axial modes produced by linear and nonlinear mechanisms. This coupling is twofold: (i) the anomalous current produced by nonlinear interaction of azimuthal gradient-drift modes results in a strong drive of the axial instability, thus enhancing its growth; (ii) the axial modes modify the density and electric profiles, providing feedback on turbulent azimuthal modes. The ensuing turbulence

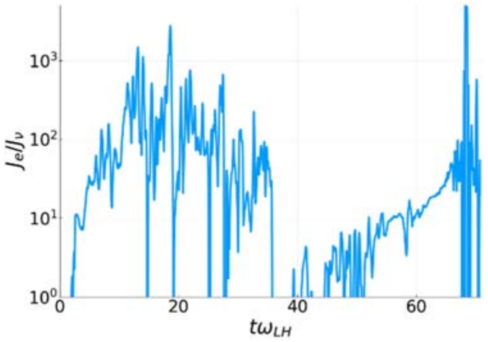

Fig 5: The axial anomalous current as a function of time, normalized to classical value.

demonstrates the complex interactions of large scale shear flows, vortices, and streamers that produce anomalous electron current orders of magnitude higher than the collisional current, with a typical Hall parameter of the order of 10-20. These results suggest that turbulent transport observed in $E \times B$ experiments and kinetic simulations can be explained as a result of turbulence driven by gradient-drift modes. A notable feature of the anomalous current in these conditions with large scale structures is its highly intermittent and blobby nature, as is shown in Fig. 4. Such anomalous current cannot credibly be parameterized by the enhanced transport coefficients, such as mobility, but rather requires avalanche-like approaches as in self-organized-criticality models with transport events at different scales. We also show the existence of quasi-stable axial streamers, that are axially elongated and azimuthally localized structures providing a large contribution to the axial anomalous current, as shown in Fig. 3. The model is now being extended into the third dimension with appropriate boundary conditions along the magnetic field

III. Mode transitions and anomalous transport in 2D full annular simulations of the ExB drift instability, Ref. [1].

Full 3D kinetic simulations are not accessible to us yet due to computer resources limitations. We therefore resort to a combination of 2D simulations to reveal the important physics. A particular emphasis is on the nonlinear evolution of turbulence and the development of large scale structures that are important for anomalous transport. To this end, we are extending our simulations to the cases with

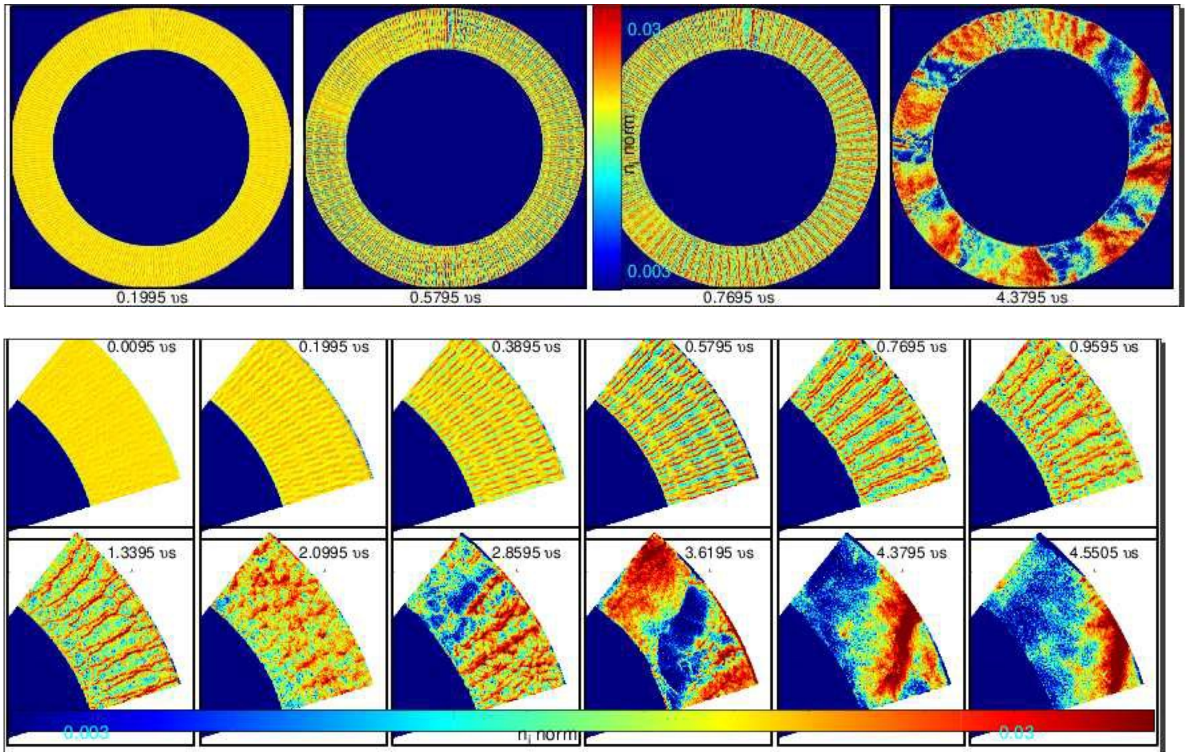

Fig.6. The top panel: the mode transitions in the ion density at various times, shown in the full cylinder. The bottom panel: the zoomed-in azimuthal segments from the same simulations. Transitions in azimuthal (density) structures as a result of the inverse cascade, the mode numbers decrease with time from n=284 in the linear stage to n=8 at saturation.

longer simulations boxes, up to the realistic values of 30 cm in circumference (in 2D azimuthal-radial simulations). Most of the previous simulations were done with 2-3 cm length in the periodic direction, with the justification that the most unstable linear modes have the wavelength of the order of 2-3 mm. Our earlier work has indicated that the size of the simulation box affects the maximum wavelength of the nonlinearly generated modes and that the longer wavelengths produce a larger contribution to anomalous mobility. To further investigate the role of the long-wavelength structures in the anomalous transport we performed azimuthal-radial simulations of the full annular channel of 10 cm in diameter, in 2D radial-azimuthal geometry with the radial magnetic field. The radially reflecting boundary conditions for particles were applied at the outer and inner radial boundaries, so there were no sheath effects in these simulations. The radial magnetic field and steady axial electric field were applied and the Poisson equation was solved in azimuthal and radial directions. Simulations were performed for three different species: Xenon, Argon, and Hydrogen to investigate mass scaling effects and also allow faster simulations of the nonlinear stage (keeping the simulation time reasonable), in case of Hydrogen. These simulations demonstrate the development of Electron-Drift-Instability from the linear high m =240 azimuthal mode in the beginning to the low m=3 modes in the final stage, as shown in Fig. 6.

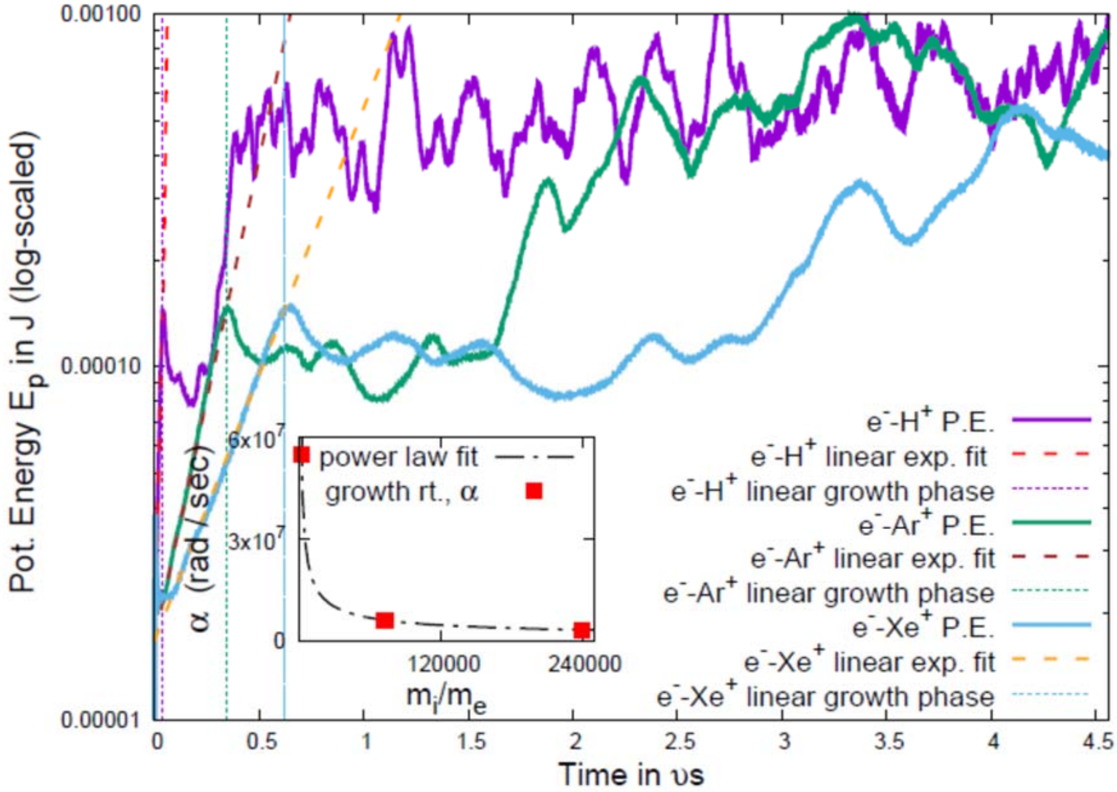

Fig. 7. The energy saturation for simulations with different species. Note that transitions in energy for Argon and Xe species. These transitions correspond to the mode transitions in Fig 6 and accompanied transitions in mobility, Fig. 8.

The distinct transitions in the mode structure, from m=240 to m=80, and again to the lower modes, are evident in the mode energy, shown in Fig.7, for three different species. Note that mode transitions occur well after a distinct linear stage, and thus, the transitions are nonlinear. The mode transitions are accompanied by the enhanced values of the anomalous current, i.e. the anomalous mobility is increased as the dominant modes shift into the longer wavelengths, Fig. 8. The simulations for Hydrogen reach the final stage quickly, while the transitions for Argon and Xenon are slower.

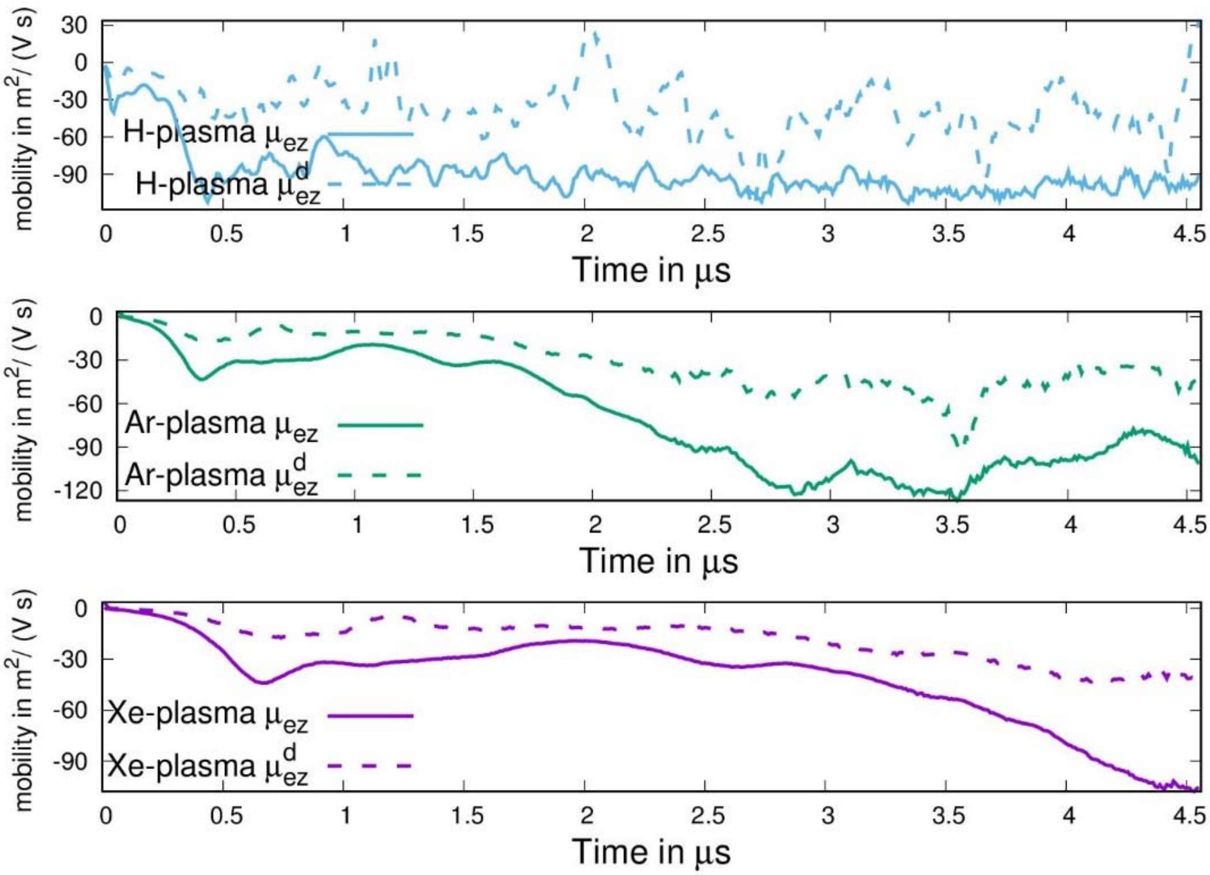

Fig. 8. Evolution of the anomalous mobility with time. The mobility increases are well-correlated with the mode transitions shown in Fig 6 and 7. From [1].

IV. Neutral pressure effects on the gradient drift instabilities

We have investigated the role of neutral pressure on the linear and nonlinear development of gradient-drift instabilities in kinetic (Particle-in-Cell) simulations of the cylindrical magnetron configuration, Fig 1 and 2. The coaxial geometry with an axial magnetic field is considered. The potential difference of 100 V is applied between the inner cathode and outer anode electrodes. The electrons are emitted from the cathode with a fixed current. The discharge is supported by the MCC ionization from the uniform background of neutrals. The radial distribution of the density and the potential are established self-consistently. These conditions correspond to the excitation of Simon-Hoh type and lower-hybrid instabilities. We have considered the role of elastic electron-neutral collisions on the instabilities. The analytical theory predicts that elastic electron-neutral collisions allow the shorter wavelengths to be excited while reducing the growth rates. This is what has been seen in our simulations: in the presence of the elastic collisions we see the short-wavelength structures that are absent without collisions. The linear growth rates observed in these simulations are consistent with predictions of the linear theory. Another observation is that changing the neutral pressure from 40 mTorr to 1 mTorr results in the excitation of the lower azimuthal mode m=1-2 vs m=8-9 seen for high pressure, see Figs 9 and 10. This work is in progress, and we continue to investigate the effects of pressure on the anomalous transport.

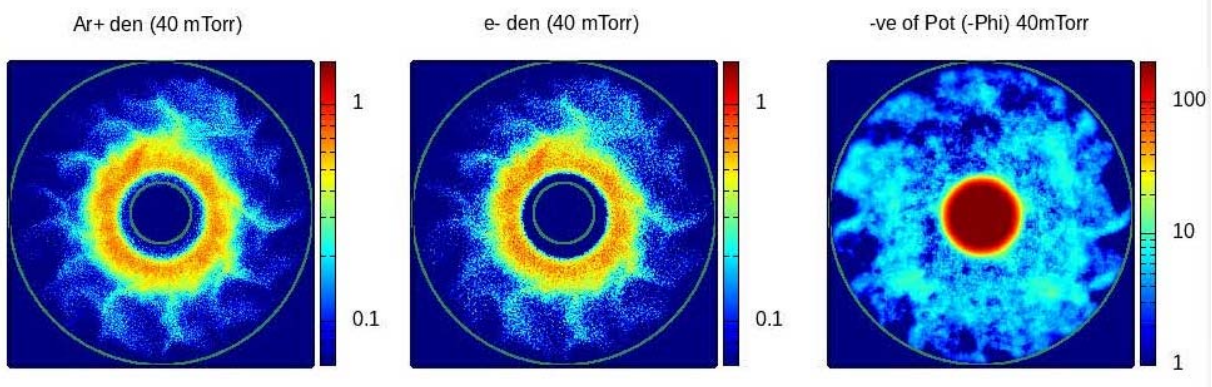

Fig. 9. Azimuthal structures in the ion (left), electron (center) densities, and potential (right) due to the gradient modes at 40 mTorr.

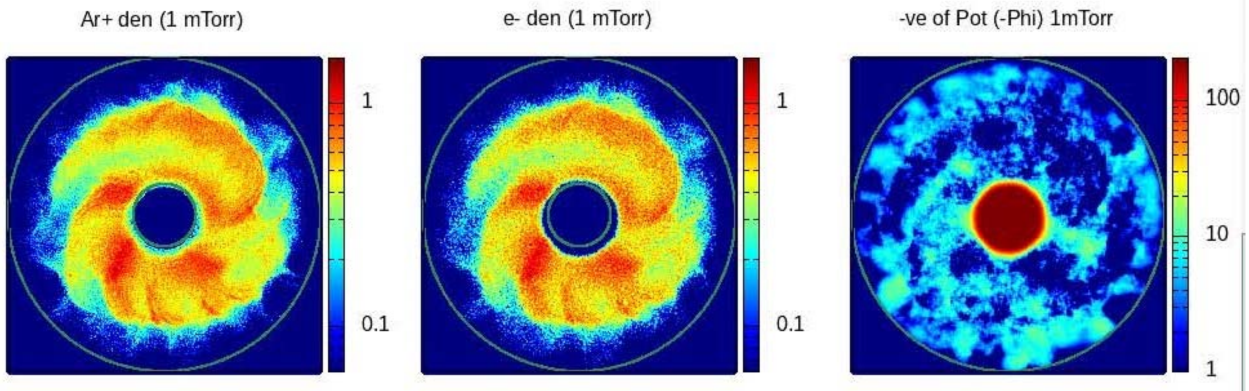

Fig. 10. Modification of the azimuthal mode structure when the neutral pressure is changed from 40 mTorr (in Fig. 9) to 1 mTorr, the ion (left), electron (center) densities, and potential (right) are shown.

V. Kinetic (Particle-In-Cell) simulations of the Electron-Drift Instability, Refs. [1,2,7]

In our group, we have developed the 2D3V Particle-in-Cell kinetic code that we have used to discover several novel phenomena that were not reported in previous studies. We have studied the nonlinear excitation of the robust instability driven by a strong electric field, which is known as Electron-Cyclotron-Drift Instability (ECDI) or as the Electron Drift Instability (EDI) [12]. This instability has attracted a lot of attention recently as a possible source of oscillations in the region of the strong magnetic field (such as the acceleration zone of Hall thruster).

We have demonstrated for the first time that in the nonlinear stage, the initial small scale instability generates the secondary long-wavelength modes. Such long-wavelength modes are absent as the linear instability but appear as a result of the energy cascade from linear unstable small scale modes. The process of the inverse cascade (energy transfer from small to large scale, contrary to the direct cascade from large to small scale as in fluid 3D turbulence) results in large scale structures which provide dominant contributions to the anomalous transport, as it has been demonstrated in our simulations. In our 2D azimuthal-radial simulations of the Hall thruster [7], we have also demonstrated the importance of the electron motion along the magnetic field resulting in the excitation of the so-called Modified Two Stream Instability. One of the consequences of this instability is strong electron heating along the magnetic field and formation of radially interspersed large scale axial jets of the electron current. Our previous finding of inverse cascade dynamics in the 1D case has also been confirmed in 2D radial-azimuthal simulations [7]. Our studies have also confirmed that ECDI instabilities largely are driven by the cyclotron type resonances and no transition to the regime of unmagnetized ion-sound instability occurs, contrary to some claims in previous work by other groups. We note that the assumption of fully unmagnetized ion-sound instability in Hall thrusters was used in some modeling efforts[3]. Recent experimental measurements of fluctuations in Hall thrusters show the presence of the cyclotron resonances peaks in the acceleration region and near-field plume[4]. These measurements also indicate that low-frequency modes appear through nonlinear generation, as it has been proposed in our earlier work and demonstrated in nonlinear simulations.

Our 2D3V code was a major contributor to the recent international benchmark study of the magnetized plasma test case which was participated by 8 groups from France, Germany, the USA, and Canada. This study demonstrated excellent consistency of our results with the results from other groups [2].

V.a. Long-wavelength structures in 2D azimuthal-axial PIC simulations of The Electron-Drift Instability

These studies are aimed to clarify the role of the Electron Drift Instability on electron transport. We have performed azimuthal-axial simulations with realistic profiles of the magnetic field and axially applied potential difference. Plasma ionization was modeled by the source with a given spatial profile. In these simulations, we compare two cases: the simulations in 2 cm and 8 cm wide box in the azimuthal (periodic) directions. We observe quasicoherent modes propagating azimuthally (x-direction) and extended axially (y-direction), Fig. 11. These primary modes are identified as nonlinearly saturated states of the Electron Drift Instability.

In narrow box simulations, we observe global intense low-frequency oscillations of the current, electric field, temperature, and density. In wider box simulations, these oscillations disappear. An

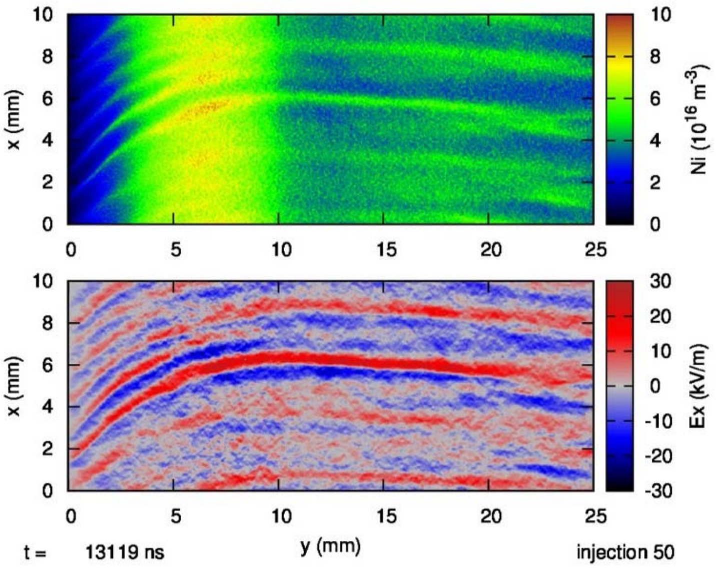

Fig. 11. The azimuthally propagating (x-direction) and seen on the density and azimuthal electric field

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[3] I.G. Mikellides, B. Jorns, I. Katz, A. Lopez Ortega, Hall2De Simulations with a First-principles Electron Transport Model Based on the Electron Cyclotron Drift Instability, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, American Institute of Aeronautics and Astronautics https://doi.org/10.2514/6.2016-4618, 2016.

[4] Z. Brown, B.A. Jorns, Spatial Evolution of Plasma Waves in the Near-field of a Magnetically Shielded Hall Thruster, 2018 Joint Propulsion Conference, American Institute of Aeronautics and Astronautics 2018.

important finding, however, is the generation of long-wavelength structures in plasma density and anomalous current as shown in Fig. 12. Note the vortex structure of the axial current, with alternating positive and negative directions. This observation could be a critical result showing that the large scale structures produced by secondary (nonlinear) instabilities (inverse cascade) are a substantial component of the anomalous transport, similar to the results of our fluid simulations.

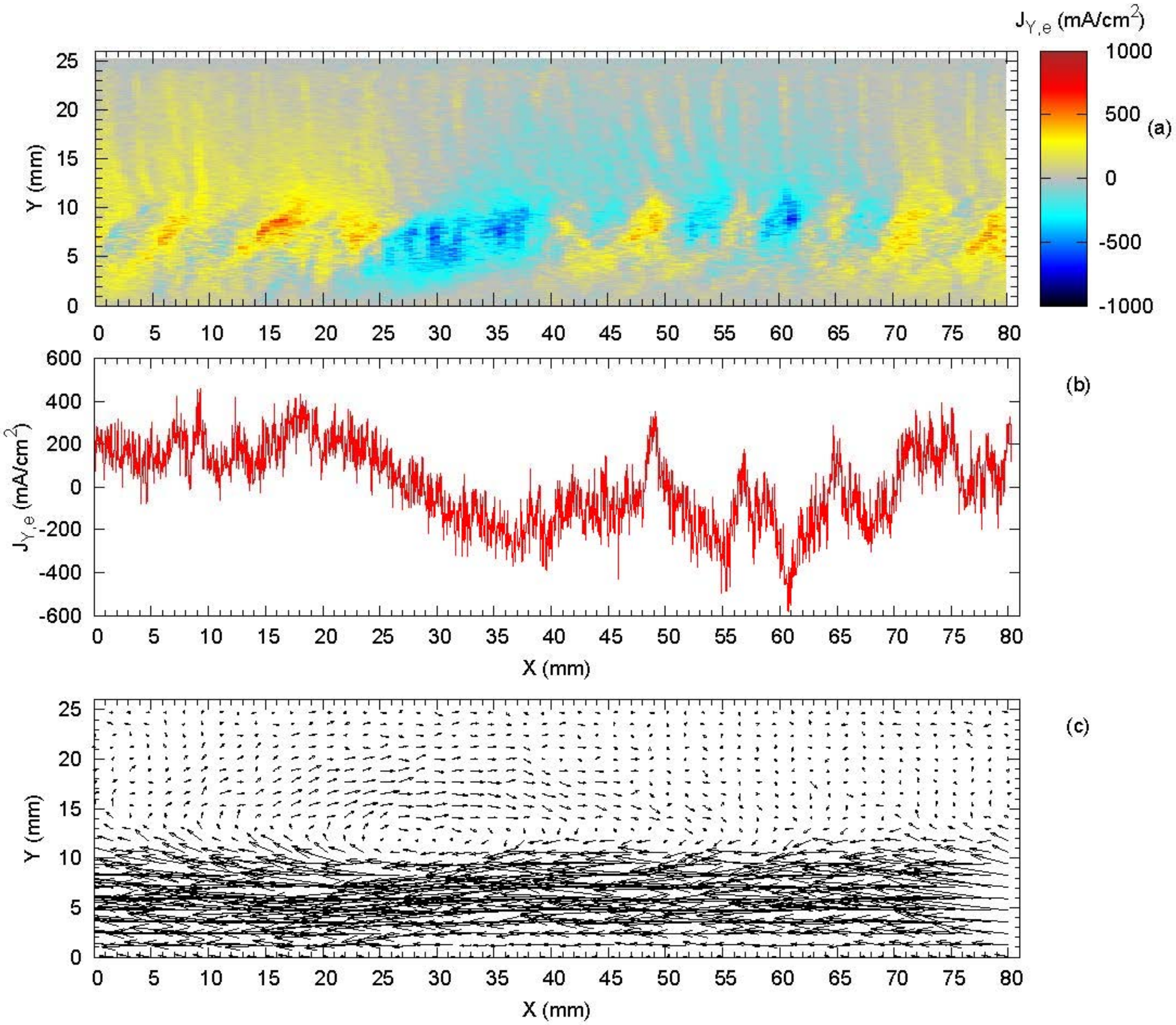

Fig. 12. The long-wavelength current vortex structures with alternating directions of the axial current as observed in simulations of the wider system; (a) contour plots of the current density, (b) the averaged value of the axial current, (c) the vector plot of the current density.

V.b. New mechanism of anomalous electron current due to azimuthally propagating nonlinear coherent structures.

In our most recent studies of the nonlinear Electron-Cyclotron-Drift instability in 2D azimuthal-axial geometry, we have identified a new mechanism of anomalous electron current driven by a traveling coherent (periodic) wave. Our recent work shows that the azimuthally propagating coherent structures extend axially to the injection region (near cathode). Such structures are most pronounced in the potential and ion density perturbations. One of the important results, not reported earlier in the literature, is that the electron current occurs in the form of narrow channel-like structures (in the axial direction), see Fig. 13. The position of the current structures (current streamers) is unequivocally correlated with the structures in the potential, compare Figs. 13 and 14. It is important to note that the axial electric field is essentially absent in this region. Therefore the electron transport in this region cannot be parameterized as the anomalous conductivity (mobility), nor by the anomalous collision frequency. Another important result is that the identified electron transport mechanism is sensitive to the temperature of electrons injected at the cathode side. Our results show the three-fold decrease of the electron current when the injected temperature is changed from $T_e = 0.1$ eV to $T_e = 10$ eV, Fig. 15. These effects may be related to the cathode effects observed experimentally. Further investigations of these processes are in progress.

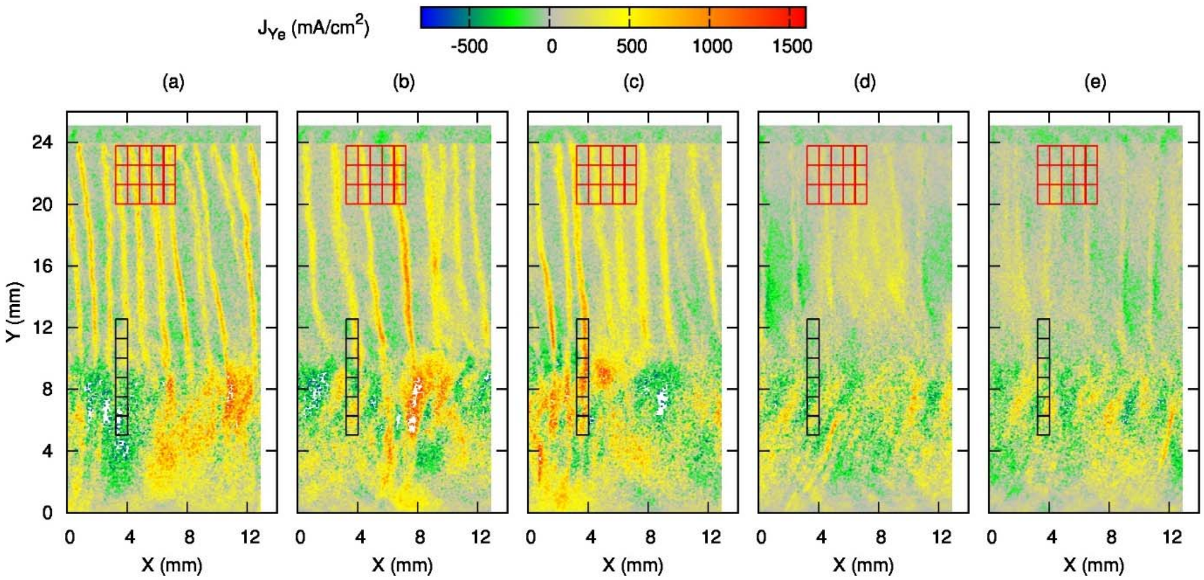

Fig. 13. Axial current streamers of the electron current. The streamers are well correlated with potential structures shown in Fig. 7. There is virtually zero current between the streamers (see color bar above). The streamers are well pronounced for low injected temperature, $T_{e,in} = 0{,}1-2$ eV. Streamers disappear and current is reduced for higher temperature, $T_{e,in} = 4-10$ eV. Here, the vertical axis is in the axial direction, the horizontal axis is in the azimuthal direction; (a)--$T_{e,in} = 0.1$ eV, (b)--$T_{e,in} = 1$ eV, (c)--$T_{e,in} = 2$ eV, (d)--$T_{e,in} = 4$ eV, (e)--$T_{e,in} = 10$ eV.

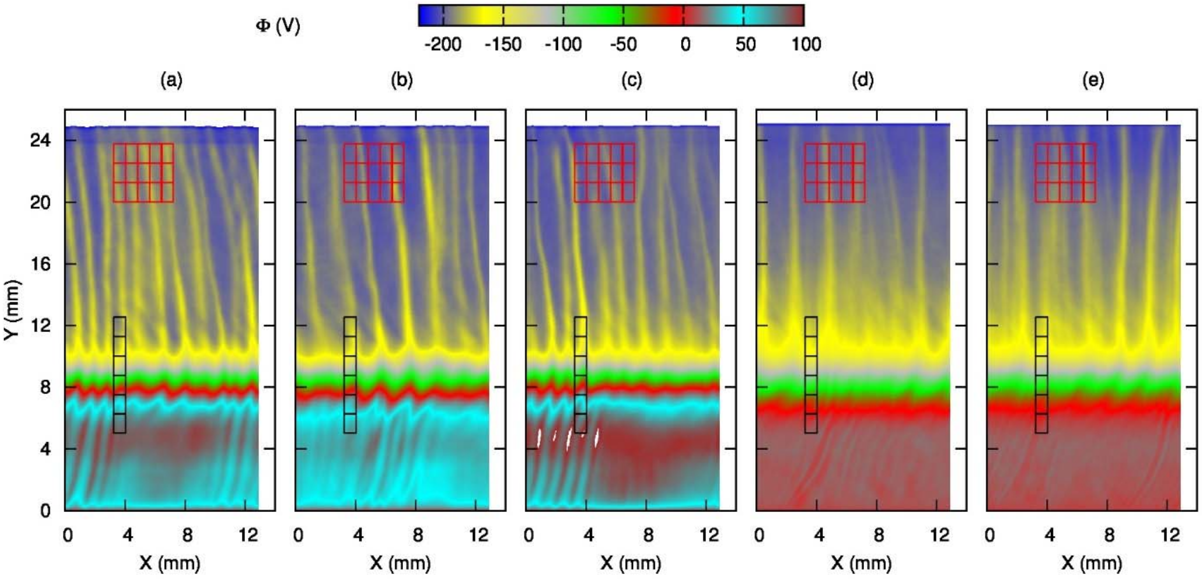

Fig. 14. Azimuthally propagating potential structures for different temperatures of the injected electrons. Here, the vertical axis is in the axial direction, the horizontal axis is in the azimuthal; (a)-- $T_{e,in} = 0.1\,\text{eV}$, (b)--$T_{e,in} = 1\,\text{eV}$, (c)--$T_{e,in} = 2\,\text{eV}$, (d)--$T_{e,in} = 4\,\text{eV}$, (e)--$T_{e,in} = 10\,\text{eV}$.

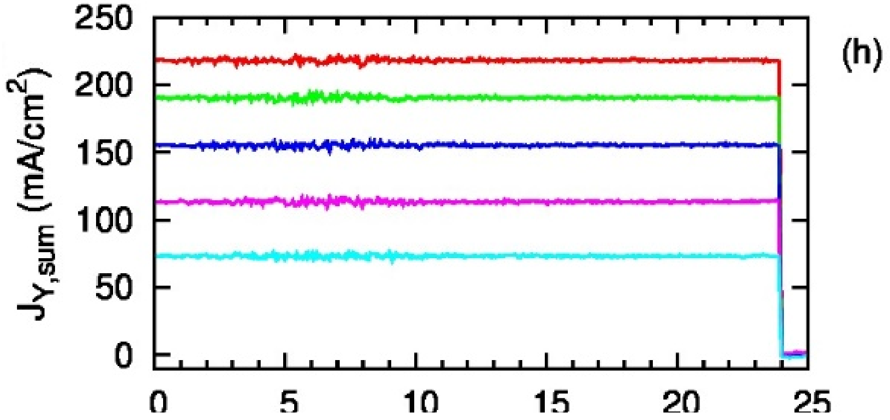

Fig.15. The total discharge current for different temperature of injected electrons. The current is azimuthally averaged. The current is constant in axial direction as expected from charge conservation; red-- 0.1 eV, green--1 eV, blue-- 2 eV, magenta--4 eV, cyan-- 10 eV.

VI. 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 the electric propulsion system. This work has been performed in close collaborations with PPPL (Y. Raitses and I Kaganovich) that included the graduate students' exchange.

Our focus is on the understanding of underlying physics principles and using the reduced models to characterize the phenomena important for the operation of electric propulsion and related devices. Here are our main results:

- The 1D fluid and hybrid (fluid electrons and kinetic ions and neutrals) models for simulations of axial instabilities (such as breathing mode) have been developed and implemented numerically and used to simulate the experiments with externally driven breathing mode.
  --The work in progress
- Our nonlinear fluid model and simulations have provided the first-principles calculations of the anomalous electron current from turbulent fluctuations driven by gradient-drift modes and demonstrated the structure formation via the inverse cascade.
- The transitions to the lower azimuthal modes and a concomitant increase of the anomalous transport was demonstrated in full radius radial-azimuthal simulations.
  The role of neutral pressure and elastic collisions was shown in 2D radial-azimuthal simulations of the cylindrical magnetron configuration. --The work in progress
- The formation of the wavelength axial current vortices and streamers was shown in 2D azimuthal-axial PIC simulations.
  A novel mechanism of the anomalous current driven by the coherent wave and operating in the region of a weak electric field was identified. --The work in progress

VIII. Additional Information

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

O Chapurin, Ph.D. Student
O Koshkarov, Ph.D. Student (completed 02. 2018)
I Romadanov, Ph.D. Student (completed 01.2019)
A. Tavassoli, Ph.D. Student
M. P. Zadeh, M.Sc. student
T. Zintel, M.Sc student
M. Jimenez, MSc. Student
V. Morin, M.Sc. Student (Completed 09.2018)
D. Sydorenko, Research Associate (03.2017-09.2019)
S Janhunen, Postdoctoral Fellow (08.2016-03.2018)
M. Sengupta, Postdoctoral Fellow (08.2018-)
Xu Liang, Postdoctoral Fellow (01.2018-08.2018)

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The large scale simulations for this project were performed on the Compute Canada computer clusters, which is the national (Canada) platform for supercomputing resources. These resources were provided to A. Smolyakov based on the results of national (Canadian) competition for the high-performance computing resources. Resources provided by Compute Canada:
2018-2019 Compute Canada Resource Allocation Competition – award of **$168,573**.
2019-2020 Compute Canada Resource Allocation Competition - award of **$104,990**.

Invited Conference and workshop presentations

Invited talk: Plasma metamaterials, International Workshop of Microplasmas 2019 (IWM-10) Kyoto, Japan, May 20-24, 2019

Invited talk: Effects of large scale structures on anomalous transport in PIC simulations of Electron Cyclotron Drift Instability in Hall thrusters,   36th International Electric Propulsion Conference University of Vienna, Austria, 2019.

Invited talk: Electron cyclotron drift instability in EXB plasmas, Workshop on EXB Plasmas, Princeton University, NJ USA, Nov 1-2 , 2018.

Invited seminar: Low frequency phenomena in Hall thrusters, Paul Sabatier University, Toulouse, France, Mar 28th, 2018.

The results obtained in this project were published in following Refereed Journals

[1] M. Sengupta, A. Smolyakov. Mode transitions in nonlinear evolution of the electron drift instability in a 2D annular E × B system, Phys. Plasmas 27, 022309 (2020); https://doi.org/10.1063/1.5139035.

[2] T. Charoy, J.P. Boeuf, A. Bourdon, J.A. Carlsson, P. Chabert, B. Cuenot, D. Eremin, L. Garrigues, K. Hara, I.D. Kaganovich, A.T. Powis, A. Smolyakov, D. Sydorenko, A. Tavant, O. Vermorel, W. Villafana. 2D axial-azimuthal Particle-In-Cell benchmark for low-temperature partially magnetized plasmas. 2019 *Plasma Sources Sci. Technol.* in press https://doi.org/10.1088/1361-6595/ab46c5

[3] O. Koshkarov, A. Smolyakov, Y.Raitses, I. Kaganovich. Self-Organization, Structures, and Anomalous Transport in Turbulent Partially Magnetized Plasmas with Crossed Electric and Magnetic Fields, Physical Review Letters 122, 185001 (2019).

[4] I. Romadanov, Y. Raitses and A. Smolyakov, Hall thruster operation with externally driven breathing mode oscillations. Plasma Sources Sci. Technol. 27 (2018) 094006 (12pp) https://doi.org/10.1088/1361-6595/aadf06.

[5] O. Koshkarov, A. I. Smolyakov, A. Kapulkin, Y. Raitses and I. Kaganovich. Nonlinear structures of lower-hybrid waves driven by the ion beam. Physics of Plasmas 25, 061209 (2018); doi: 10.1063/1.5024237

[6] I. Romadanov, Y. Raitses, A. Diallo, I. D. Kaganovich, and A. Smolyakov, On limitations of laser-induced fluorescence diagnostics for xenon ion velocity distribution function measurements in

Hall thrusters, Physics of Plasmas 25, 033501 (2018).

[7] Salomon Janhunen, Andrei Smolyakov, Dmytro Sydorenko, Marilyn Jimenez, Igor Kaganovich, and Yevgeny Raitses, Evolution of the electron cyclotron drift instability in two-dimensions. Physics of Plasmas 25, 082308 (2018); doi: 10.1063/1.5033896

[8] E. Rodriguez, V. Skoutnev, Y. Raitses, A. Powis, I. Kaganovich, A. Smolyakov, Boundary-induced effect on the spoke-like activity in E x B plasma, Physics of Plasmas 26 (2019) 053503.

[9] I. Romadanov, Y. Raitses, A. Smolyakov, Control of Coherent Structures via External Drive of the Breathing Mode, Plasma Physics Reports, 45 (2019) 134-146.

[10] A. T. Powis, J.A. Carlsson, I.D. Kaganovich, Y. Raitses, A. Smolyakov Scaling of spoke rotation frequency within a Penning discharge, Physics of Plasmas 25, 072110 (2018) https://doi.org/10.1063/1.5038733.

[11] A. Smolyakov, and N. Sternberg, Plasmon resonances, anomalous transparency, and reflectionless absorption in overdense plasmas, Physics of Plasmas 25, 031904 (2018); doi: 10.1063/1.5023140

[12] Jean-Pierre Boeuf, and Andrei Smolyakov, Preface to Special Topic: Modern issues and applications of E× B plasmas, Physics of Plasmas 25, 061001 (2018); doi: 10.1063/1.5040848

[13] V. Morin, A.I. Smolyakov, Modification of the Simon-Hoh Instability by the sheath effects in partially magnetized E × B plasmas, Physics of Plasmas 25, 084505 (2018); doi: 10.1063/1.5044649

Invited Full conference papers

[14] O. Chapurin, A. Smolyakov, G. Hagelaar, J.P. Boeuf, Y. Raitses. Fluid and hybrid simulations of the ionization instabilities in Hall thruster, 36th International Electric Propulsion Conference University of Vienna, Austria, 2019, IEPC-2019-762, http://electricrocket.org/2019/762.pdf

[15] O. Koshkarov, A. Smolyakov, Y. Raitses, I. Kaganovich. Anomalous transport in reduced fuid modeling of E × B plasmas, 36th International Electric Propulsion Conference University of Vienna, Austria, 2019, IEPC-2019-545, http://electricrocket.org/2019/545.pdf

[16] A. Smolyakov, O.Chapurin, I. Romadanov, Y. Raitses, I. Kaganovich. Theory and Modelling of Axial Mode Oscillations in Hall Thruster, AIAA Propulsion and Energy Forum 2019, August 2019, Indianapolis, IN, AIAA 2019-4080, https://doi.org/10.2514/6.2019-4080

[17] Y. Raitses, I. Romadanov , J. Simmonds, A.Smolyakov, I. Kaganovich. Hall thruster with externally driven oscillations, AIAA Propulsion and Energy Forum 2019, August 2019, Indianapolis, IN, AIAA 2019-4078, https://doi.org/10.2514/6.2019-4078

Contributed papers in published conference proceedings and abstracts

Sengupta, A. Smolyakov, Plasma instabilities in ExB plasma devices. 61st Annual Meeting of the APS Division of Plasma Physics, Volume 64, Number 11, 2019, TP10.00099, http://absimage.aps.org/image/DPP19/MWS_DPP19-2019-001913.pdf

A. Sabo, A. Smolyakov, P. Yushmanov, S.Putvinski, Plasma flow in the magnetic nozzle. 61st Annual Meeting of the APS Division of Plasma Physics, Volume 64, Number 11, 2019, PP10.00038, http://absimage.aps.org/image/DPP19/MWS_DPP19-2019-001398.pdf

Y. Raitses, J. Simmonds, O. Chapurin, A. Smolyakov, I. Kaganovich, Driving Low Frequency Oscillations in Hall Thrusters, 61st Annual Meeting of the APS Division of Plasma Physics, Volume 64, Number 11, 2019, JO8.00002, http://absimage.aps.org/image/DPP19/MWS_DPP19-2019-001000.pdf

M. Jimenez, A. Smolyakov, O. Chapurin, T. Zintel, Two--dimensional simulations of Electron Cyclotron Drift instability, 61st Annual Meeting of the APS Division of Plasma Physics, Volume 64, Number 11, 2019, NP10.00106, http://absimage.aps.org/image/DPP19/MWS_DPP19-2019-001654.pdf

O. Chapurin, I. Romadanov, A. Smolyakov, Y. Raitses, I. Kaganovich, Axial Ionization Modes in Hall Thruster, 72nd Annual Gaseous Electronics Conference, Volume 64, Number 10, 2019, FT1.00021, http://absimage.aps.org/image/GEC19/MWS_GEC19-2019-000263.pdf

A.Smolyakov, I. Romadanov, O. Chapurin, Y. Raitses, G.Hagelaar, J.P.Boeuf Global characteristics of plasma acceleration across the magnetic field: sonic point regularization and global profiles, 60th Annual Meeting of the APS Division of Plasma Physics, Portlend, OR, Nov 2018. Volume 63, Number 11, BAPS.2018.DPP.JP11.116

A. Powis, J.Carlsson, I. Kaganovich, Y. Raitses, A. Smolyakov, E.Rodriguez. Scaling of Spoke Rotation Frequency within a Penning Discharge. 60th Annual Meeting of the APS Division of Plasma Physics, Portlend, OR, Nov 2018. Volume 63, Number 11, BAPS.2018.DPP.JP11.108

S.Sadouni, G.Hagelaar, A. Smolyakov. Fluid modeling and linear analysis of instabilities in ExB discharge plasmas in Hall Thrusters. 71st Annual Gaseous Electronics Conference, Portlend, OR, Nov 2018.. Volume 63, Number 10, BAPS.2018.GEC.LW1.13

J.P.Boeuf, A. Smolyakov, G.Hagelaar, K. Hara. Benchmark test cases for low temperature magnetized plasma modeling. 71st Annual Gaseous Electronics Conference, Portlend, OR, Nov 2018. Volume 63, Number 10, BAPS.2018.GEC.GT1.80.

E. Rodriguez, Y. Raitses, A.Powis, I. Kaganovich, A. Smolyakov, Effect of the magnetic field on rotating spoke in ExB discharge, 71st Annual Gaseous Electronics Conference, Portlend, OR, Nov 2018. Volume 63, Number 10, BAPS.2018.GEC.LW1.12