



AFRL-AFOSR-VA-TR-2023-0239

Mechanism(s) of the anomalous electron current and coherent structures in magnetized ExB discharges

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01/04/2023
Final Technical Report

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Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

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1. REPORT DATE 20230104	2. REPORT TYPE Final	3. DATES COVERED <table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: none;">START DATE 20211026</td> <td style="width: 50%; border: none;">END DATE 20221025</td> </tr> </table>		START DATE 20211026	END DATE 20221025
START DATE 20211026	END DATE 20221025				
4. TITLE AND SUBTITLE Mechanism(s) of the anomalous electron current and coherent structures in magnetized ExB discharges					
5a. CONTRACT NUMBER	5b. GRANT NUMBER FA9550-21-1-0031	5c. PROGRAM ELEMENT NUMBER 61102F			
5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER			
6. AUTHOR(S) Andrei Smolyakov					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF SASKATCHEWAN 105 ADMINISTRATION PL SUITE E 80 SASKATOON, SK S7N 5A2 CAN			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203		10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR RTA1	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-VA-TR-2023-0239		
12. DISTRIBUTION/AVAILABILITY STATEMENT A Distribution Unlimited: PB Public Release					
13. SUPPLEMENTARY NOTES					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 13		
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			
19a. NAME OF RESPONSIBLE PERSON MITAT BIRKAN			19b. PHONE NUMBER (Include area code) 426-7234		

Air Force Office of Scientific Research



Award number: FA9550-21-1-0031

Final Report

Reporting Periods: Jan 15, 2021 – Jan 14, 2023

Distribution A-Approved for Public Release

Space Propulsion and Power, Program Officer Dr. Mitat A. Birkan

Principal Investigator: Andrei Smolyakov, University of Saskatchewan

Mechanism(s) of the anomalous electron current and coherent structures in magnetized
ExB discharges

ABSTRACT

This research develops theoretical models and numerical simulations tools to explain, predict, and control coherent structures and related anomalous electron current in the ExB devices such as Hall thrusters, magnetrons and Penning discharges. Four inter-related topics are addressed in this period: axial large scale ionization modes (breathing modes) in Hall thrusters; azimuthal modes, instabilities, and transport related to the electron-cyclotron drift instabilities in Hall thrusters; azimuthal instabilities and structures in cylindrical Penning discharge; and transonic accelerating flows formed by the “Laval nozzle effect” in the devices with magnetic nozzle and geometric apertures devices.

Accomplishments

- Research Objectives:
 - Major goal of the project is to determine the causes of the anomalous electron transport in ExB devices relevant to electric propulsion, develop numerical models and tools for predicting and control of transport and coherent structures. The approach is based on theoretical analysis and numerical simulations together with numerical benchmarking and validation against experimental data from Princeton Plasma Physics Laboratory (Y. Raitses).
- Major accomplishments during this reporting period.
 - We have participated in the international activity in which groups from USA, France, Germany and Italy have performed the Particle-in-Cell (PIC) simulations of the radial-axial model of Hall thruster benchmark model therefore confirming the robustness and validity of the 2D EDIPIC code. The results of this benchmark were published in Plasma Sources Science and Technology, 30: 075002 (2021), by Villafana et al.
 - The theoretical models and associated numerical code were developed to simulate externally driven breathing modes in Hall thrusters. This model was used (by J. Simmonds) to interpret the experimental data at PPPL and JPL. University of Michigan (by B. Jorns) has expressed interest to compare our model against the experimental data. This work however did not proceed further due to difficulties working with dimensionless variables since the data with real discharge parameters were not available to us due to export control issues.
 - We have developed one-dimensional 2V continuous (Vlasov) code. The comparative studies with this code and PIC simulations revealed the role of noise in PIC simulations on Electron Cyclotron Drift Instability and Buneman instability. This study also revealed the excitation in the nonlinear regimes the backward waves -the wave propagating in the direction opposite to the driving beam.
 - We have developed a model for a cylindrical Penning discharge self-consistently supported by ionization due to the axial injection of electrons. With this model we have discovered two different regimes: one regime with pronounced $m = 1$ spoke activity, and the other regime with prevalent small-scale $m > 1$ spiral structures. The transition between two regimes is controlled by the energy input to the discharge. This finding is currently being investigated experimentally at PPPL. After our paper was published in Arxiv, we have been approached by the group from Seoul National University, who claim to have seen similar behavior in the experiment.
 - We have demonstrated that the transonic acceleration velocity profiles formed by the “Laval nozzle effect” such as in the magnetic nozzle and Hall thrusters are robustly stable and represent an attractor among many possible solutions. We have proposed a unifying theoretical framework opening up perspectives for hybrid electrostatic-magnetic acceleration and including the swirl acceleration.
- Dissemination of the results
 - The results of this research were disseminated in refereed journal publications and presented at Annual Gaseous Electronics Conferences in 2021 and 2022, International Electric Propulsion Conference in 2022, meetings of the Division of Plasma Physics of the American Physical Society in 2021 and 2022, and ExB Workshop in 2021. A.

Smolyakov has made presentations on electric and plasma propulsion to undergraduate students. Two undergraduate summer students have participated in this research in the reporting period.

- Our publication “Restructuring of rotating spokes in response to changes in the radial electric field and the neutral pressure of a cylindrical magnetron plasma,” by M. Sengupta, A. Smolyakov, and Y. Raitses, Journal of Applied Physics (2021), <https://aip.scitation.org/doi/full/10.1063/5.0049457> was highlighted in SciLight by AIP publishing, “The effect of electric field and other external controls on plasma spokes”, by Chris Patrick, <https://doi.org/10.1063/10.0005178>, and selected for a free open access.
- Our theoretical results on spoke formation have been further confirmed in simulations and magnetron experiments at Ruhr University, Bochum, as described in these preprints (to be published): “Formation mechanism of the rotating spoke in partially magnetized plasmas”, Liang Xu, Denis Eremin, **Andrei Smolyakov**, Dennis Krüger, Kevin Köhn, Ralf Peter Brinkmann, [arXiv:2202.07033](https://arxiv.org/abs/2202.07033) (2022); and “Electron dynamics in planar radio frequency magnetron plasmas: I. The mechanism of Hall heating and the μ -mode” Denis Eremin, Dennis Engel, Dennis Krüger, Sebastian Wilczek, Birk Berger, Moritz Oberberg, Christian Wölfel, **Andrei Smolyakov**, Jan Lunze, Peter Awakowicz, Julian Schulze, Ralf Peter Brinkmann, [arXiv:2211.04805](https://arxiv.org/abs/2211.04805) (2022).
- The PI as invited to give presentations on the results of this research at Gaseous Electronics Conference, Sendai Japan (Oct 4, 2022); Asia Pacific Physics Conference, APPEC15, (August 26 2022); the 1st Low-Temperature Plasma School, 13-17 June 2022, University of Minnesota, <https://bruggeman.umn.edu/2021USPlasmaSchool>; International Online Low Temperature Plasma Seminar, (July 6, 2021), Old Dominion University, <https://theory.pppl.gov/news/seminars.php?scid=17&n=oltp-seminar-series>; Michigan Institute for Plasma Science and Engineering (14 April 2021), Review and Research Seminar of Princeton Plasma Physics Laboratory, (Sep 28th 2021), University of California at San-Diego, Jacobs School of Engineering, Center for Energy Research (January 27 2021).

Impacts

Development of the principal discipline(s) of the project

Physics of plasma is a basic science discipline studying the behavior of an ionised gas such as that naturally present on the Sun, Earth's ionosphere, interplanetary and interstellar space. Plasma processing is pervasive in industrial applications for microelectronics manufacturing, material surface modification, waste treatment, light sources, and many other areas. Plasmas are used in electric propulsion devices for deep space missions and long-term station keeping. In nature and laboratories, plasmas are often immersed in the electric and magnetic fields making it unstable and turbulent. Turbulence is result of nonlinear wave interactions resulting in highly irregular and unpredictable behavior. Despite the progress, such as in aerodynamics and weather forecasting, the turbulence and

related anomalous (turbulent) transport is the great challenge of classical physics. Progress in many plasma applications, such as plasma processing and electric propulsion, has been hindered by difficulties caused by plasma turbulence. Long term objective of this research is to explain and predict the turbulent behavior and transport of magnetically confined plasmas for technological applications. Specifically, the goal is the development of physical models and numerical simulations to predict anomalous electron current and anomalous heating in turbulent plasma maintained by crossed electric and magnetic fields which are the basis of electric propulsion. Improved understanding of the turbulent plasma processes in these devices would satisfy critical needs of electric propulsion technologies and bring better performance and new opportunities for material processing. This research promotes deep knowledge of physics, analytical and critical analysis, and strong skills in high performance computations and large data set processing.

Describe the impact in this reporting period on the development of human resources

There were 5 graduate students and one postdoctoral fellow supported in part by this award in the reporting period. Two M.Sc. and one Ph.D. theses were defended in the reporting period on the research supported by this award. One more Ph.D. defence is scheduled to defend the thesis in January 2023. Two former M.Sc. students supported by this award now continue in the Ph.D. programs. One student, supported by the award and completed his Ph.D. in the reporting period is currently a postdoctoral fellow at Los Alamos National Laboratory. Another Ph.D. student who participated in the project via collaborations with Princeton Plasma Physics laboratory is now employed at Jet Propulsion Laboratory. Two of graduate students supported by this award are members of under-represented groups.

Describe the impact on teaching and educational experiences

The PI was invited to give a lecture at 1st Low-Temperature Plasma School, 13-17 June 2022, University of Minnesota, <https://bruggeman.umn.edu/2021USPlasmaSchool>. Some results of this research were incorporated in the plasma physics courses taught by PI.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

The numerical code for simulations of breathing mode and externally driven Hall thrusters was made available to Princeton Plasma Physics Laboratory and subsequently (via J. Simmonds) to Jet Propulsion Laboratory and was used to predict and interpret the experimental data. EDIPIC and EDIPIC-2D codes that were originally developed by D Sydorenko, PhD student and Postdoctoral fellow formerly supported by AFOSR grants were licensed by Princeton Plasma Physics Laboratory as GNU General Public License v3 for public use, <https://github.com/PrincetonUniversity/EDIPIC> and <https://github.com/PrincetonUniversity/EDIPIC-2D>.

Changes

Changes in approach

There were no changes in the approach.

Problems or delays

Covid pandemic and related restrictions have significant adverse effects on the personnel. Research projects for some graduate students had to be re-assigned and restructured resulting in delays on some topics.

Expenditures Impacts

Covid pandemic, related restrictions and delays have caused additional expenditures for student stipends due to longer times in the programs.

Technical Updates

Here we provide abstracts of selected publications with additional details and illustrations.

I. **Fluid and hybrid simulations of the ionization instabilities in Hall thruster, Chapurin et al, J. Appl. Phys. 132, 053301 (2022); doi: 10.1063/5.0094269**

Low-frequency axial oscillations in the range of 5–50 kHz stand out as a pervasive feature observed in many types of Hall thrusters. While it is widely recognized that the ionization effects play the central role in this mode, as manifested via the large-scale oscillations of neutral and plasma density, the exact mechanism(s) of the instabilities remain unclear. To gain further insight into the physics of the breathing mode and evaluate the role of kinetic effects, a one-dimensional time-dependent full nonlinear low-frequency model describing neutral atoms, ions, and electrons is developed in full fluid formulation and compared to the hybrid model in which the ions and neutrals are kinetic. Both models are quasi-neutral and share the same electron fluid equations that include the electron diffusion, mobility across the magnetic field, and the electron energy evolution. The ionization models are also similar in both approaches. The predictions of fluid and hybrid simulations are compared for different test cases. Two main regimes are identified in both models: one with pure low-frequency behavior and the other one, where the low-frequency oscillations coexist with high-frequency oscillations in the range of 100–200 kHz, with the characteristic time scale of the ion channel fly-by time, 100–200 kHz. The other test case demonstrates the effect of a finite temperature of injected neutral atoms, which has a substantial suppression effect on the oscillation amplitude

II. **On the mechanism of ionization oscillations in Hall thrusters, Chapurin et al., J. Appl. Phys. 129, 233307 (2021); doi: 10.1063/5.0049105**

Low-frequency ionization oscillations involving plasma and neutral density (breathing modes) are the most violent perturbations in Hall thrusters for electric propulsion. Because of its simplicity, the zero-dimensional (0D) predator–prey model of two nonlinearly coupled ordinary differential equations for plasma and neutral density has often been used for the characterization of such oscillations and scaling estimates. We investigate the properties of its continuum analog, the one-dimensional (1D) system of two nonlinearly coupled equations in partial derivatives (PDEs) for plasma and neutral density. This is a more general model, of which the standard 0D predator–prey model is a special limit case. We show that the 1D model is stable and does not show any oscillations for the boundary conditions relevant to Hall

thrusters and the uniform ion velocity. We then propose a reduced 1D model based on two coupled PDEs for plasma and neutral densities that is unstable and exhibit oscillations if the ion velocity profile with the near-the-anode back-flow (toward the anode) region is used. Comparisons of the reduced model with the predictions of the full model that takes into account the self-consistent plasma response show that the main properties of the breathing mode are well captured. In particular, it is shown that the frequency of the breathing mode oscillations is weakly dependent on the final ion velocity but shows a strong correlation with the width of the ion back-flow region

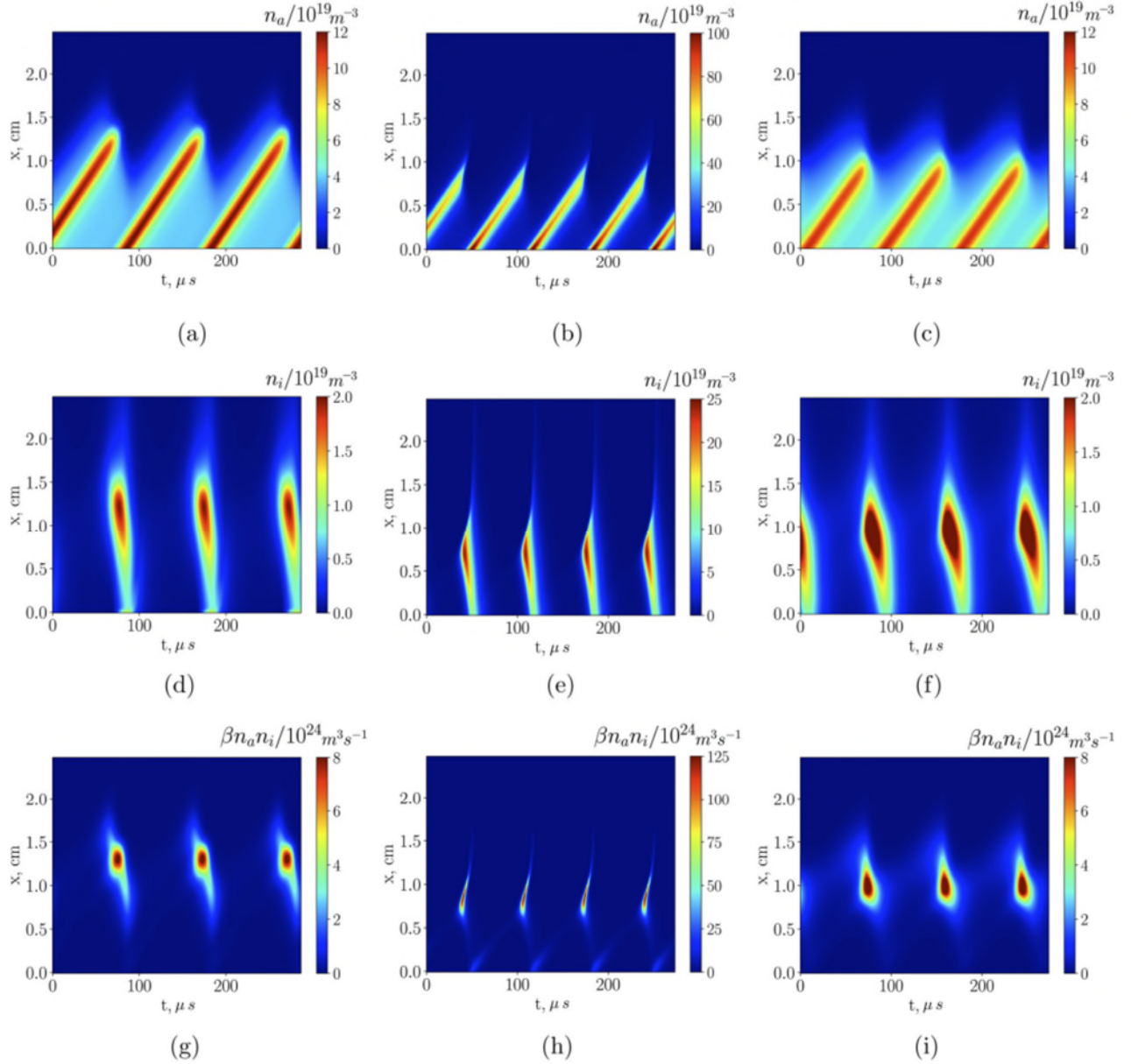


Figure 1. Comparison of the full fluid model (left column), the reduced model (middle column), and the reduced model (right column) with lower values of β for neutral density (a)–(c), ion density (d)–(f), and ionization source (g)–(i).

III. Restructuring of rotating spokes in response to changes in the radial electric field and the neutral pressure of a cylindrical magnetron plasma. Sengupta et al., J. Appl. Phys. 129, 223302 (2021); doi: 10.1063/5.0049457

Nonlinear plasma structures in the partially magnetized ExB plasma of a cylindrical magnetron are investigated using 2D3V particle-in-cell Monte Carlo collision simulations. In the early phase of the discharge, plasma gradients and radial electric fields excite a lower hybrid type instability that forms long wavelength rotating density spokes. As the discharge grows in density by ionization and the cathode gets shielded by the formation of an ion sheath, radial electric fields diminish in the quasineutral region of the discharge. This induces a transition of the spokes into short-scale spoke-on-spoke modes. The short wavelength structures can be reversed back into a long spiral spoke by lowering the neutral pressure, which revives the radial electric fields via a turbulent plasma expansion. Plasma phenomena connected to the rotating spoke include the anomalous radial transport and loss of electrons through the spoke, azimuthal dragging of ions by the spoke's field, plasma temperature modulations by the spoke structure, and formation of electron vortices around equipotential islands, in some cases with opposing rotations to the underlying ExB drift. Electron scattering from non-ionizing collisions with neutrals also has a minor influence on the instability.

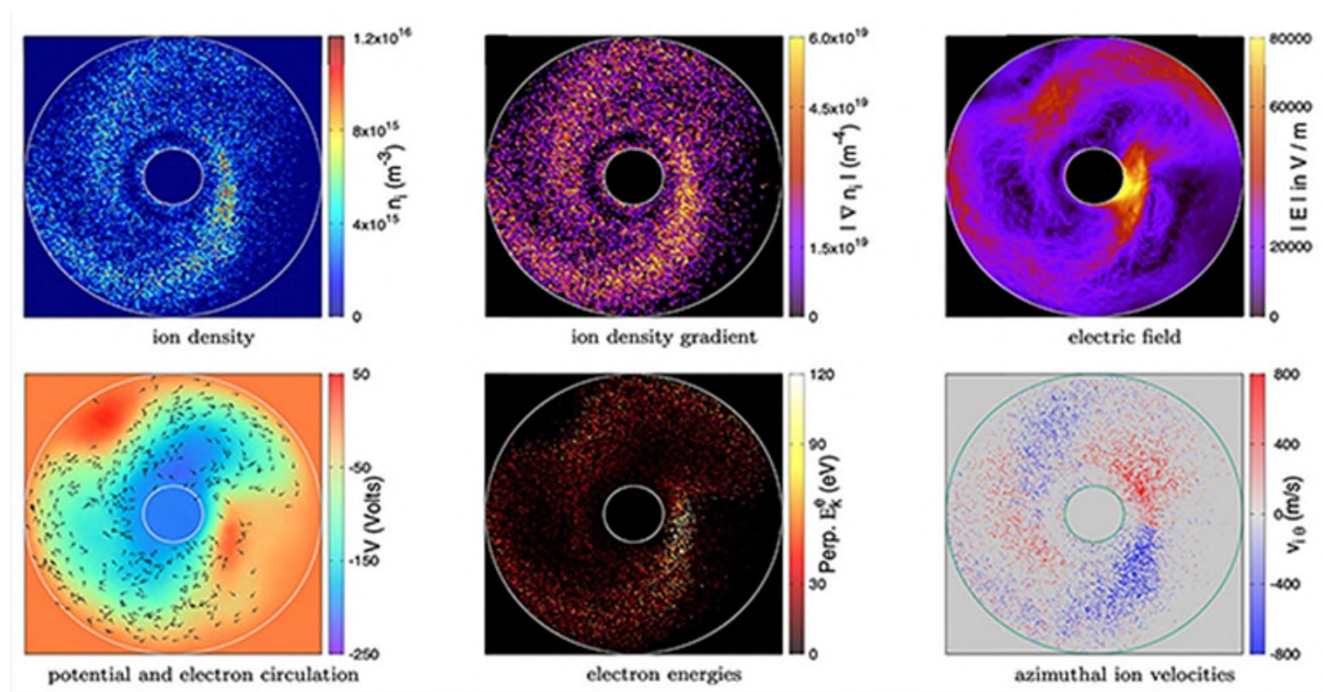


Figure 2. Rotating spoke through different diagnostic lenses.

IV. Azimuthal structures and turbulent transport in Penning discharge, Tyushev et al, arXiv:2210.16887 (2022)

Azimuthal structures in cylindrical Penning discharge are studied with 2D3V radial-azimuthal PIC/MCC model with the axial magnetic field. The discharge is self-consistently supported by ionization due to the axial injection of electrons. It is shown that the steady-state discharge can be supported in two different regimes with different type of observed azimuthal structures. The transition between the regimes is controlled by the mechanism of the energy input to the discharge. In the first

regime (low energy of the injected electrons), with the pronounced $m = 1$ spoke activity, the power input is dominated by the energy absorption due to the radial current and self-consistent electric field. In the other regime (higher energy of the injected electrons), with prevalent small-scale $m > 1$ spiral structures, and the lower values of the anomalous transport, the total energy deposited to the discharge is lower and is mostly due to the direct input of the kinetic energy from the axial electron beam. We show that the large ($m=1$) spoke and small-scale structures occur as a result of Simon-Hoh and lower hybrid instabilities driven by the electric field, density gradient, and collisions. We show that the spoke frequency follows the equilibrium ion rotation frequency

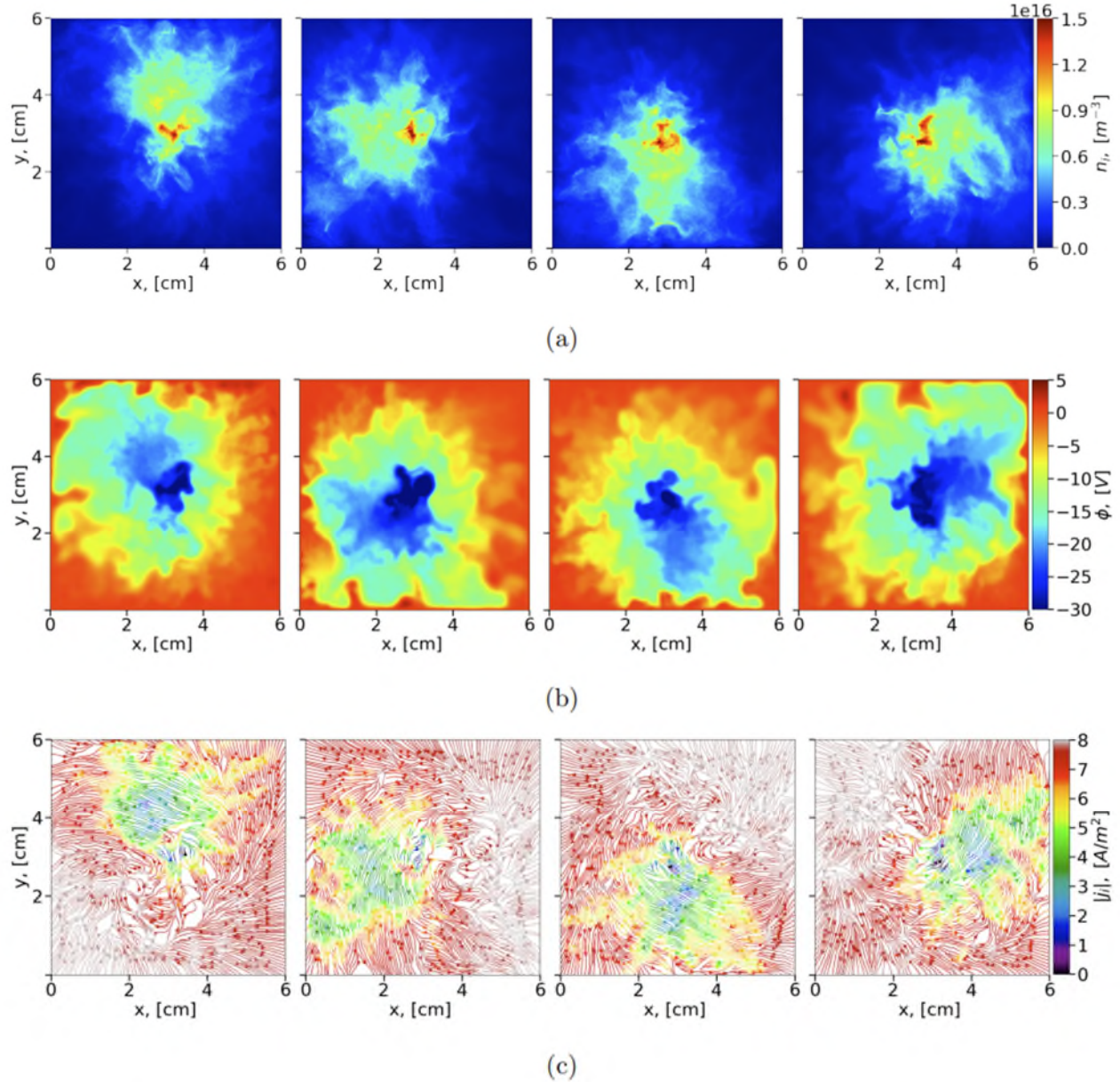


Figure 3: Snapshots at different times, from left to right $t = 73, 79, 83, 88 \mu\text{s}$, demonstrating spoke rotation: a) the ion density; b) the potential; c) the ion current amplitude shown by the color and streamlines plotted on a uniform grid

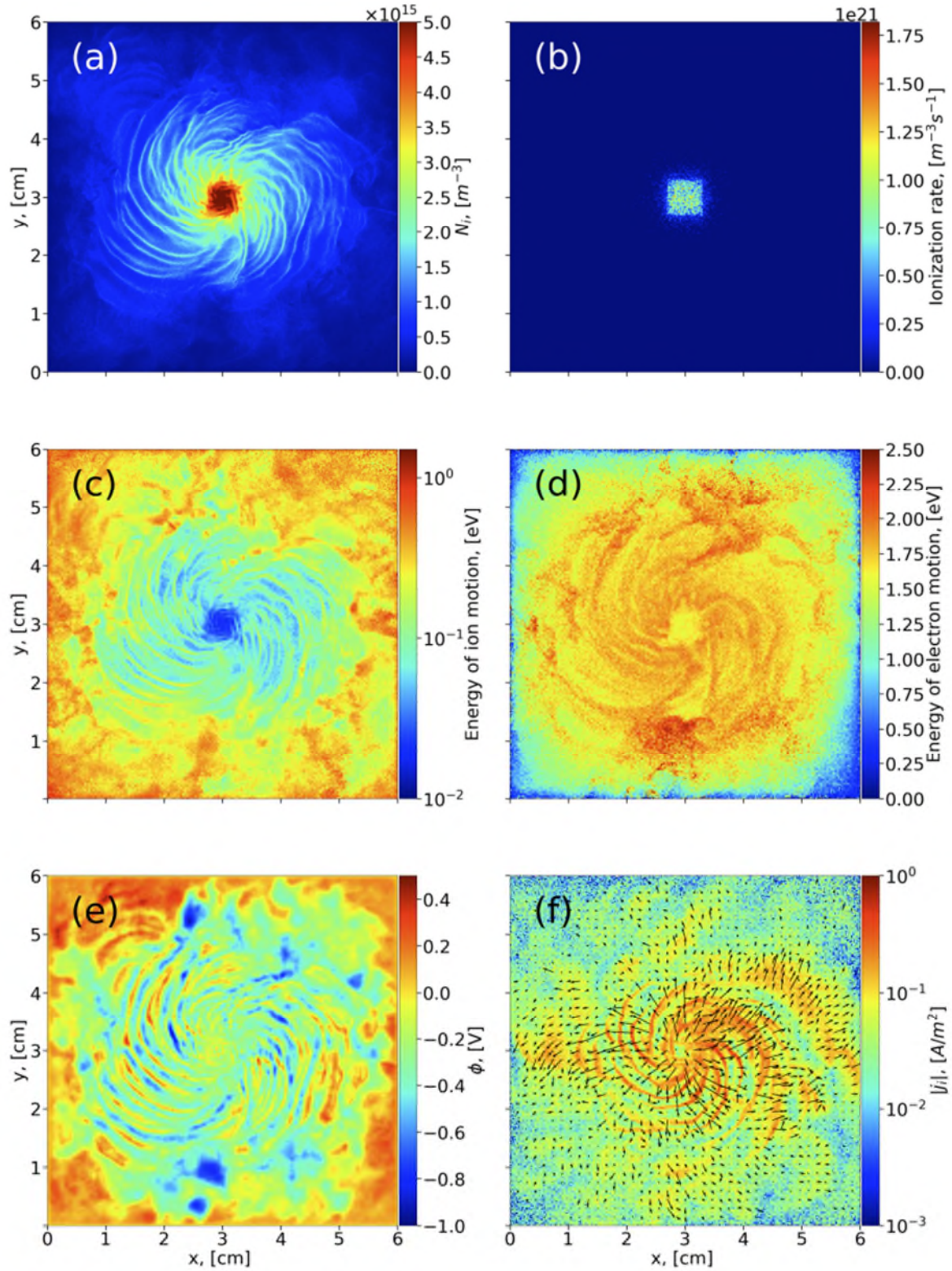


Figure 4: Snapshots of plasma parameters in the small-scale regime, injection energy 30 eV: a) ion concentration; b) ionization rate; c) ion energy; d) electron energy; e) potential; and f) absolute value of the ion current density with the direction vectors.

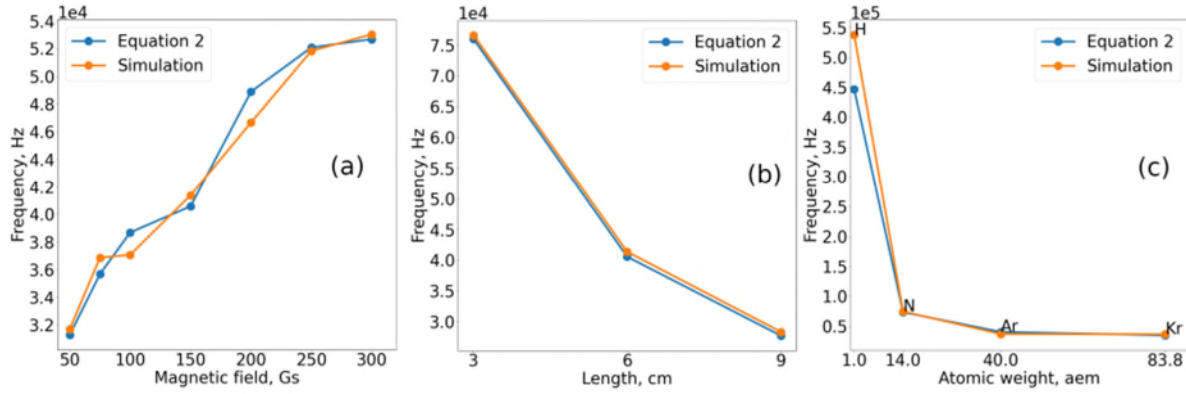


Figure 5: Comparison of the spoke rotation frequency in simulations with theoretical formula as a function of a) magnetic field; b) size, and c) atomic element

V. Ion kinetic effects and instabilities in the plasma flow in the magnetic mirror, Jimenez et al, Phys. Plasmas 29, 112117 (2022); <https://doi.org/10.1063/5.0120727>

Kinetic effects in plasma flow due to a finite ion temperature and ion reflections in a converging–diverging magnetic nozzle are investigated with collisionless quasineutral hybrid simulations with kinetic ions and isothermal Boltzmann electrons. It is shown that in the cold ions limit, the velocity profile of the particles agrees well with the analytical theory, predicting the formation of the global accelerating potential due to the magnetic mirror with the maximum of the magnetic field and resulting in the transonic ion velocity profile. The global transonic ion velocity profile is also obtained for warm ions with isotropic and anisotropic distributions. Partial ion reflections are observed due to a combined effect of the magnetic mirror and time-dependent fluctuations of the potential as a result of the wave breaking and instabilities in the regions when the fluid solutions become multi-valued. Despite partial reflections, the flow of the passing ions still follows the global accelerating profile defined by the magnetic field. In simulations with reflecting boundary condition imitating the plasma source and allowing the transitions between trapped and passing ions, the global nature of the transonic accelerating solution is revealed as a constrain on the plasma exhaust velocity that ultimately defines plasma density in the source region.

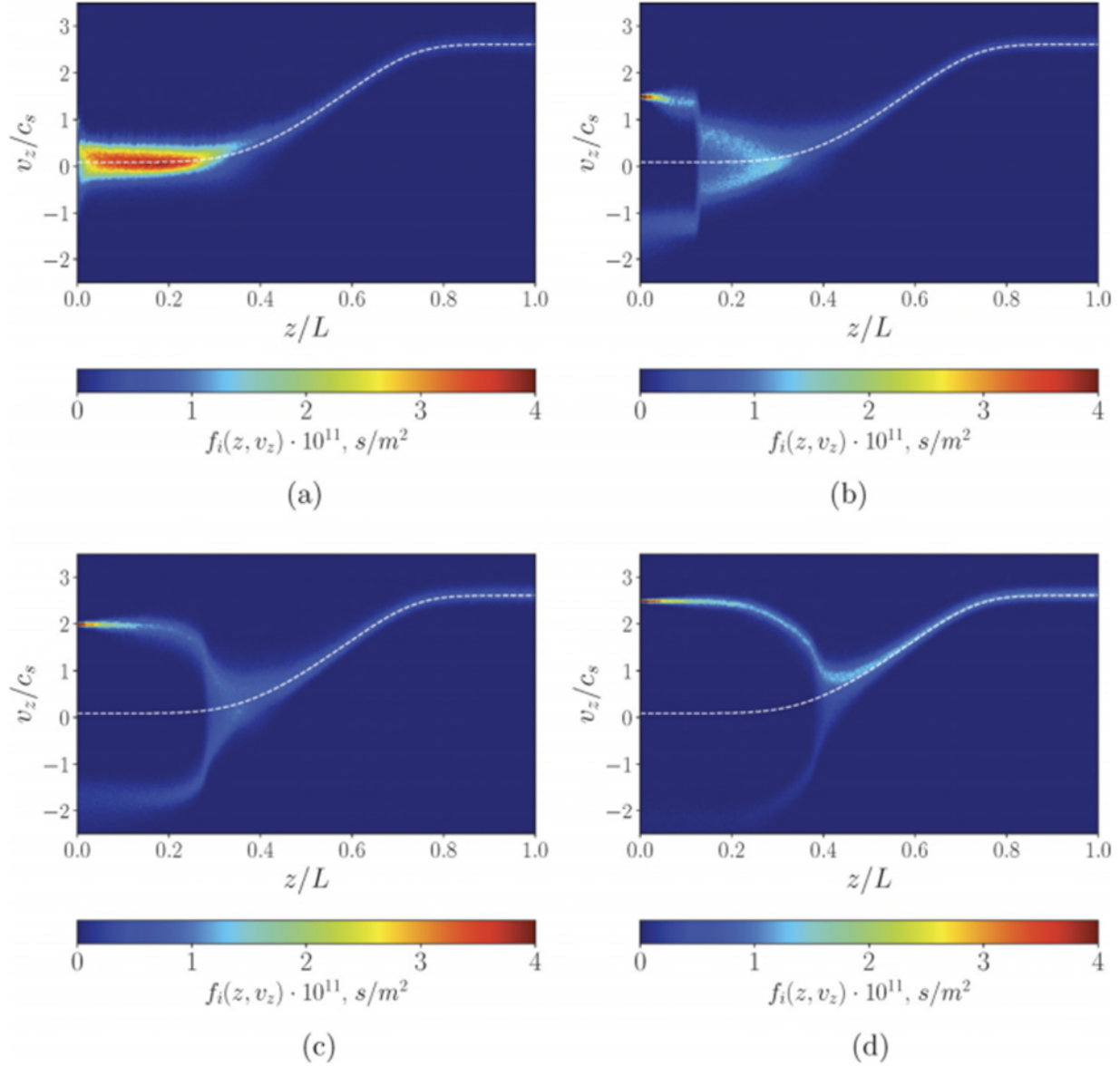


Figure 6. Ion distribution function in $(z-v_z)$ - space for monoenergetic injection with different injection velocities at $z=0$. The stable transonic accelerating profile from the fluid theory is shown by the white dashed line. The injection with different velocity at $z=0$ results in “stalling” the flow and eventual transition to a unique transonic accelerating velocity profile.

VI. Facility effects: Instabilities in the magnetic mirror with neutral backflow and charge-exchange interactions, by Chapurin et al, in preparation

In this study, quasi-two-dimensional (paraxial) computational model has been developed to study the effects on neutral backflow from the recycling walls of the chamber on the accelerated plasma flow in the magnetic nozzle configurations. The model includes the emitting (source) wall, quasineutral flow/acceleration region with diverging magnetic field, and recycling/absorbing wall. The model is implemented in a hybrid quasineutral code with the drift-kinetic ions and fluid electrons. Neutral atoms emitted by recycling wall are fully kinetic with ionization, charge-exchange collisions

simulated with the direct simulation Monte Carlo approach and radial losses represented by the geometrical effects due to finite radius and radial spreading of the neutral beam. The ion interactions with the wall includes reflections, desorption of cold atoms at the wall temperature, and warm atoms from molecular desorption and further ionization and dissociation (the so-called Franck-Condon atoms of 1 eV - 4 eV). Reflection and desorption phenomena are modeled empirically with coefficients available in the literature. In absence of recycling wall, the model well reproduces plasma acceleration in the magnetic nozzle. It is shown that the fraction of slow atoms with short mean free path have the most significant effect creating the dense plasma layer near the wall. The layer modifies the plasma potential (generally reducing it) near the wall. For some parameters, large scale perturbations are detected in this region due to the ion-ion streaming instabilities leading to strong modification of plasma acceleration. It is suggested that this instability is a reason for plasma facility effects on operation of electric propulsion devices in laboratory conditions.

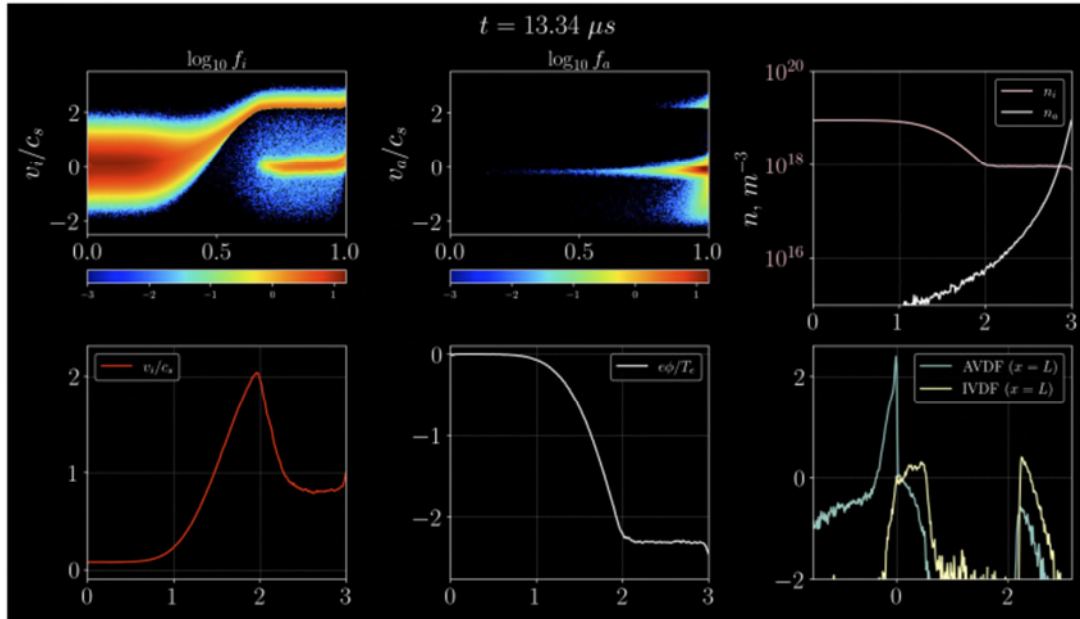


Figure 7. Single video frame from supplementary video files demonstrating spatial profiles of the main plasma parameters with warm Franck-Condon atoms. The phase space of the accelerated beam of charged ions is shown in upper left panel. Note a large fraction of ions reflected by the magnetic mirror force and the low energy ion beams formed by charge-exchange with neutral back flow emanating from the right-side recycling wall. The neutral beam is shown in the upper middle panel. The ion velocity is shown in the left bottom panel, and the accelerating potential profile is in the middle bottom panel.

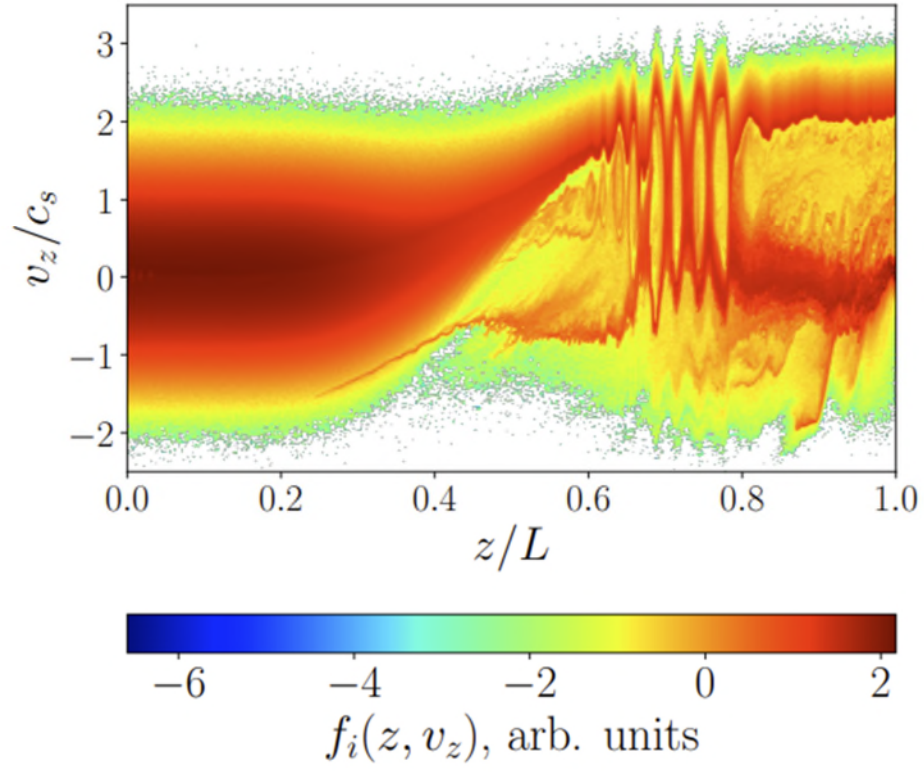


Figure 8: Instantaneous plot of velocity distribution function for ions (z, v_z) -space (shown in logarithmic scale), case for low fraction of Franck-Condon atoms, resulting in ion-ion streaming instability.