



Azimuthal and axial structures in 3D Particle-in-Cell simulation of $E \times B$ Penning discharge

M. Papahn Zadeh, A. Likhanskii, A. Smolyakov, M. Tyushev, N. S.
Chopra, I. Romadanov, Y. Raitses,

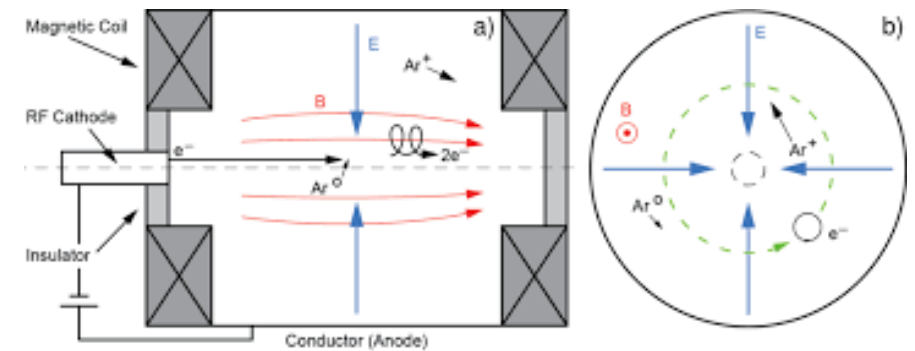
Department of Physics and Engineering Physics, University of Saskatchewan,
Saskatoon, Saskatchewan, Canada S7N 5E2

Princeton Plasma Physics Laboratory, Princeton, NJ, US

Email: mina.papahnzadeh@usask.ca

Overview

- Motivation
- 3D-PIC/MCC Simulation of Penning Discharge
- Results
- Summary(key findings)
- References



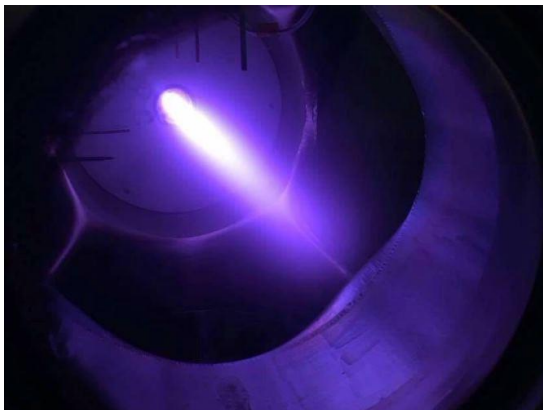
Schematic experimental setup of the penning discharge at PPPL in r-z geometry. (right) Cross section of Penning discharge in r- θ domain.

A. T. Powis et al. Phys. Plasmas 25, (2018).

Motivation



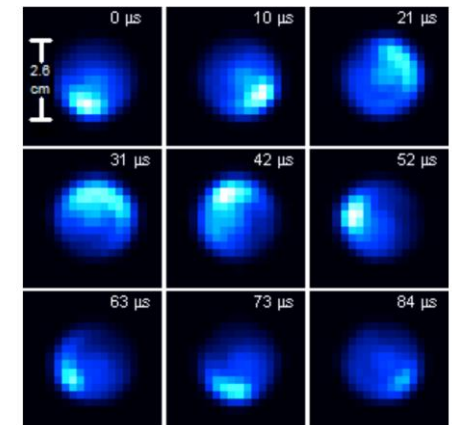
- The physics of magnetized plasmas and $E \times B$ devices is complex and very non-linear
- Electron beam-induced $E \times B$ plasmas have a wide range of application in plasma propulsion and material processing.
- This system exhibits a wide range of plasma instabilities[1,2], that may result in the formation of a long and short wavelength fluctuation in plasma density called Spoke, and spiral arms structures.
- Spoke may play an important role in the anomalous transport of electrons across the applied magnetic field, a source of reduced efficiency.



Penning discharge device, PPL

Gas Pressure: 0.1-10 mt
Xenon or Argon
Magnetic field: 10-150 G

Y. Raitses et al.



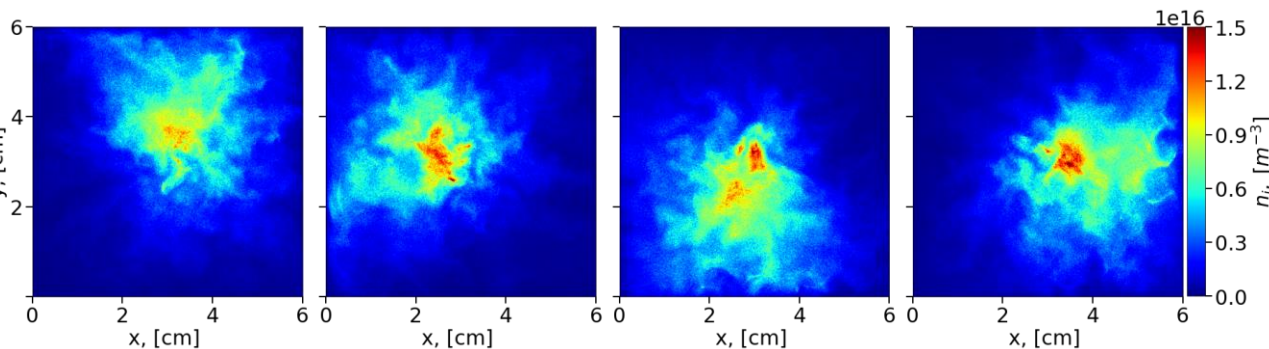
Motivation



- Numerical simulations can bring a better understanding of the phenomena
- Due to its highly non-linear, turbulent, and global nature, the spoke has continued to evade a clear theoretical understanding, there is discrepancy in the mechanism of them.
- Have performed realistic 2D simulations
 - Characterize and control these instabilities and oscillation for effective and reliable device performance

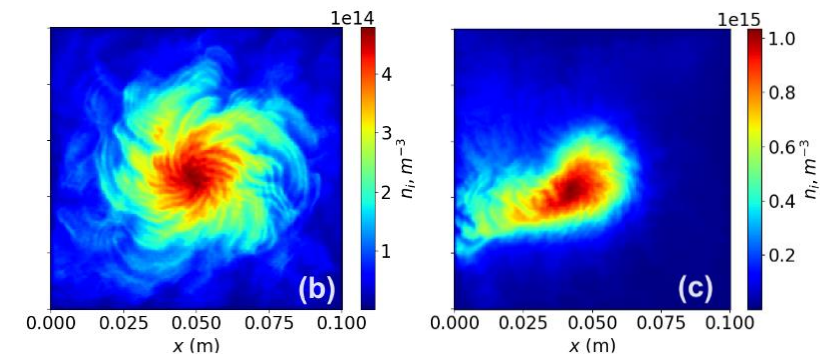
Find the answer to these questions

- What is the driving mechanism behind the formation of these rotating structures
- How does the transition happen between different length scale, Spiral arms to Spoke



Spoke rotation, 40 mTorr Argon gas Background

M. Tyushev, M.
Papahn Zadeh et al.
POP, (2023, 2025).



B=50 G

B=100

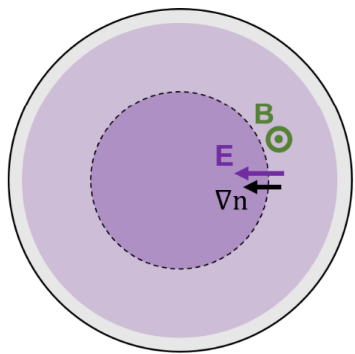
Azimuthal $m > 1$, Spiral arm structures and $m = 1$ Spoke 0.44 mTorr Argon gas Background

Heuristic Description of Spoke formation

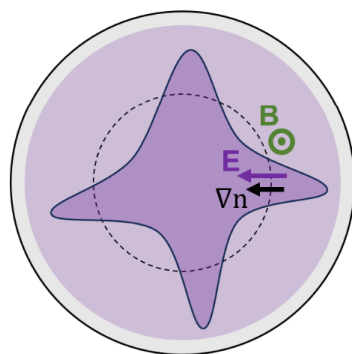


- Gradient drift instability of partial magnetized plasma

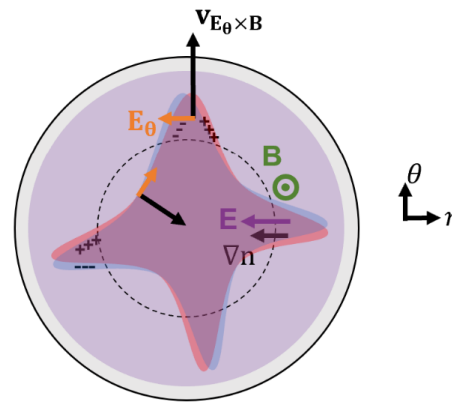
I. Equilibrium



II. Perturbation



III. $E_r \times B \rightarrow$ charge separation \rightarrow
 $E_\theta \times B \rightarrow$ instability



Sakawa et al, Phys,Fluid (1993)

A I Smolyakov et al Plasma Phys. Control. Fusion (2017)

$$k_\perp^2 \lambda_D^2 + \frac{\omega_* + k_\perp^2 \rho_e^2 (\omega - \omega_0 + i\nu_{en})}{\omega - \omega_0 + k_\perp^2 \rho_e^2 (\omega - \omega_0 + i\nu_{en})} - \frac{k_\perp^2 c_s^2}{\omega(\omega + i\nu_{in})} = 0.$$

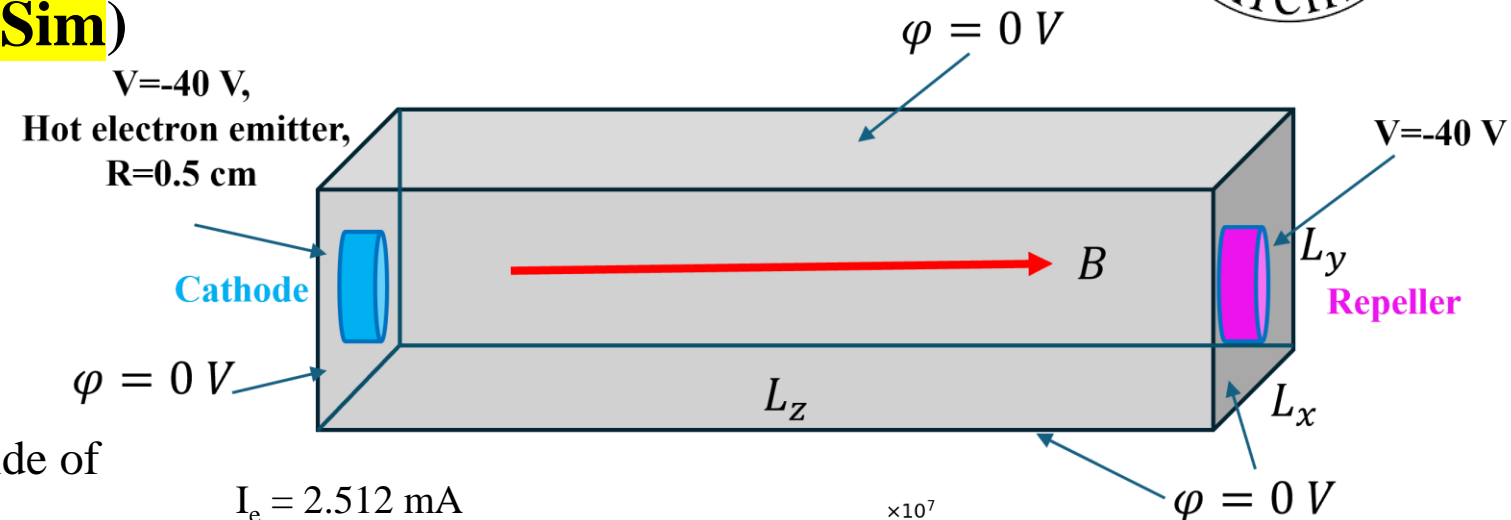
Instability condition

$$\vec{E} \cdot \vec{\nabla} n > 0$$

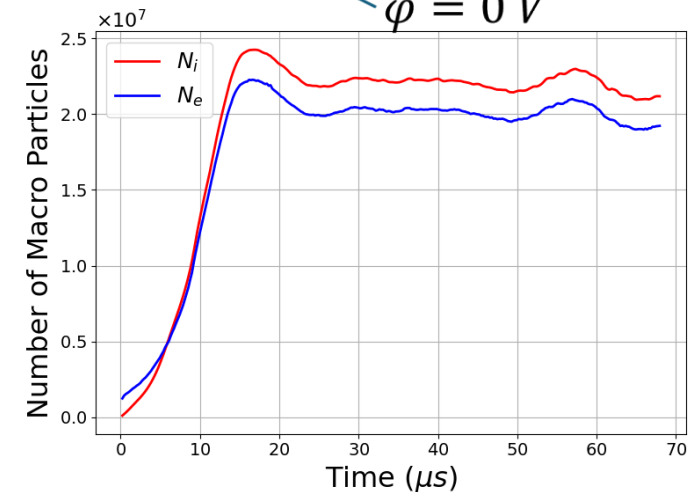
3D-PIC/ MCC Simulation of Penning Discharge

Simulation Setup (Reflex Configuration) (VSim)

- Uniform Cartesian grid
- Axial magnetic field
- Conducting Dirichlet B.C (4 walls)
- Cathode/Repeller $V=-40$ V
- Axial e-Beam initiates and sustains discharge
- Electron emitter is a circular region at the left side of domain
- Monte Carlo Collisions (MCC)
(Electron-Neutral Ionization & Electron-Neutral Elastic, and Excitation Collisions, Ion-Neutral Elastic, and Charge Exchange Collision)
- Background neutral Argon gas density is uniform and constant



$I_e = 2.512$ mA
 $m_e \langle v_b \rangle^2 = 0.028$ eV
 Beam temperature $T_b = 0.057$ eV
 $B = 50$ G
 $R_{inj} = 0.5$ cm
 $P_{Argon} = 0.62$ mT
 Mesh = $105 \times 105 \times 250$
 $L_x = L_y = 2.1$ cm, $L_z = 5$ cm
 $\Delta t = 4.5 \times 10^{-11}$ s



Azimuthal $m = 8$ rotating structures

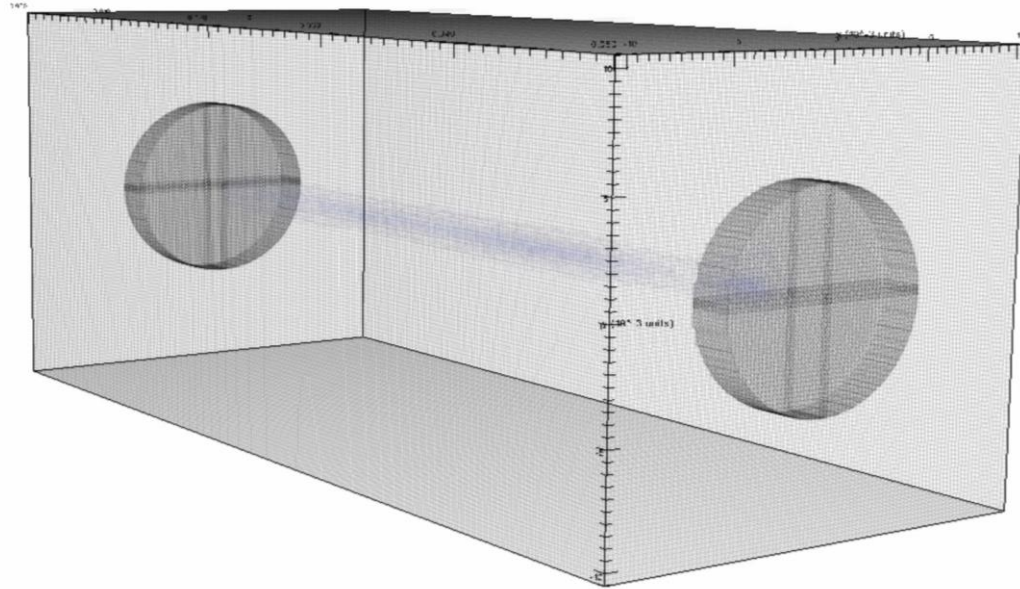


Mesh:
Var: globalGridGlobal

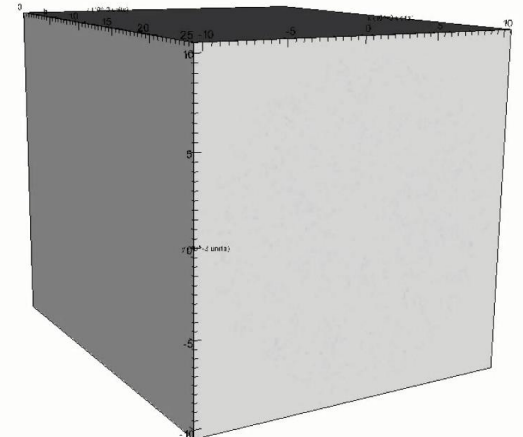
Mesh:
Var: cylinder1MappedPolysData

Mesh:
Var: cylinder0MappedPolysData

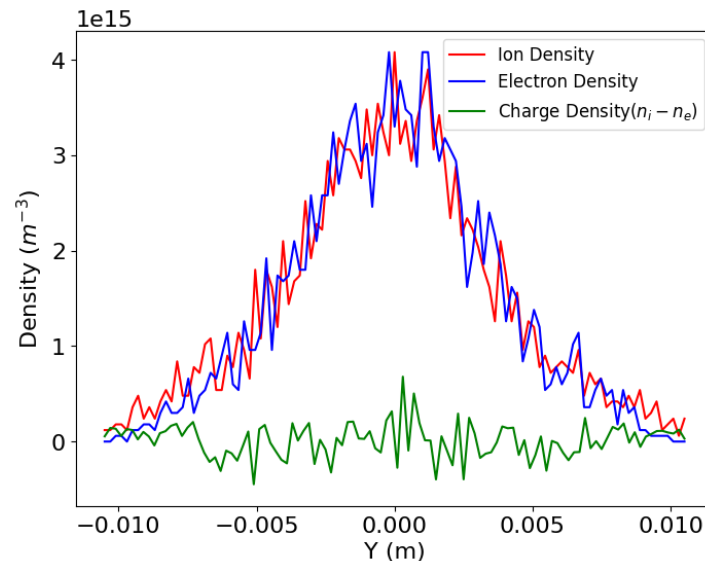
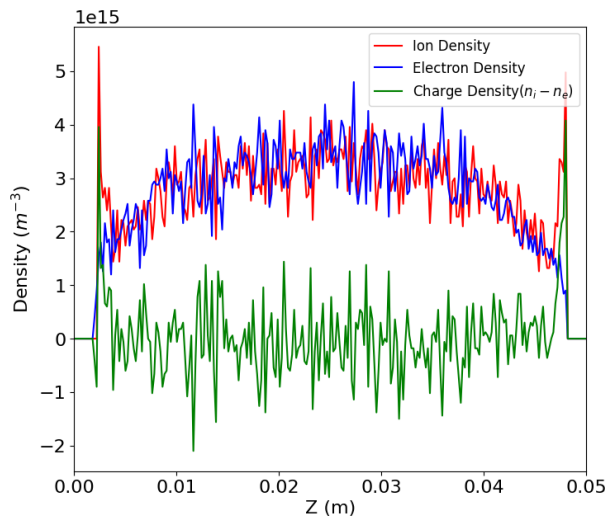
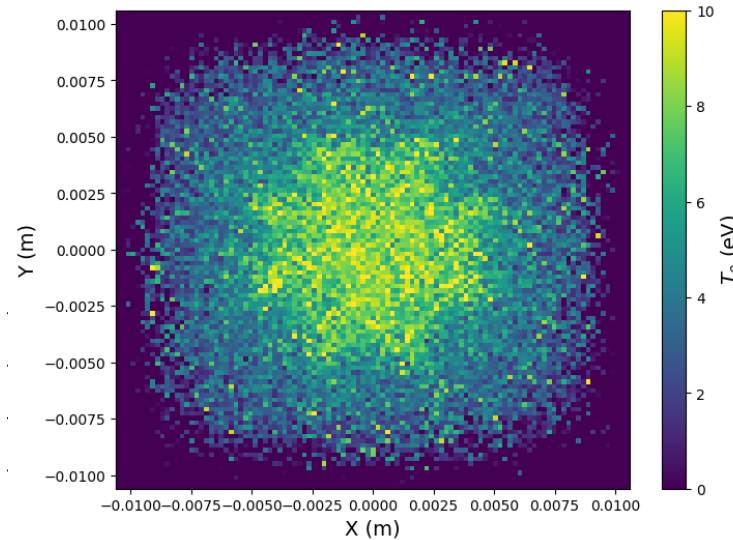
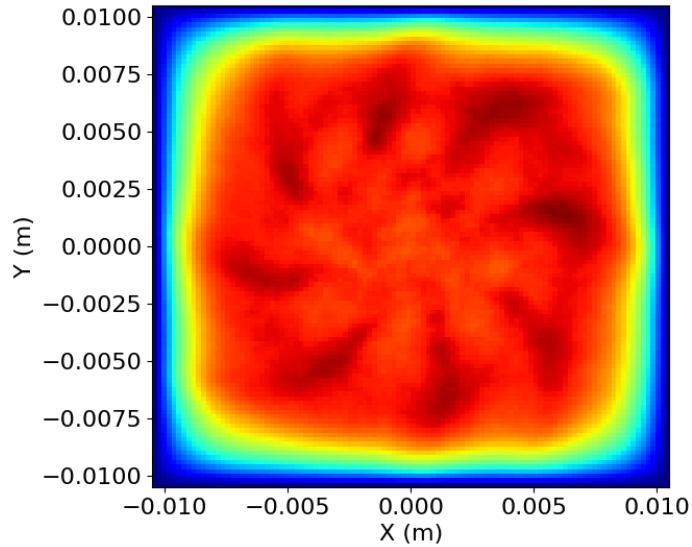
Pseudocolor
Var: ionsDensity
5.500e+15
4.125e+15
2.750e+15
1.375e+15
0.000
Max: 1.560e+15
Min: 0.000



pseudocolor
n: ionsDensity
1.400e+16
1.050e+16
7.000e+15
3.500e+15
0.000
ax: 3.000e+14
n: 0.000



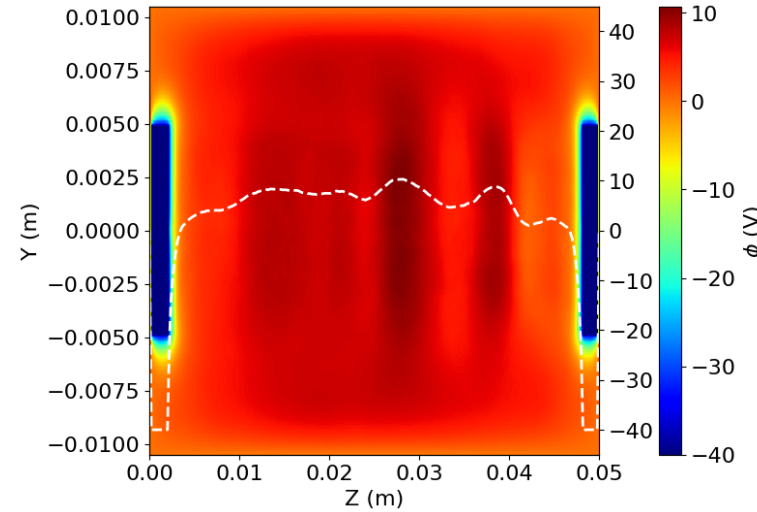
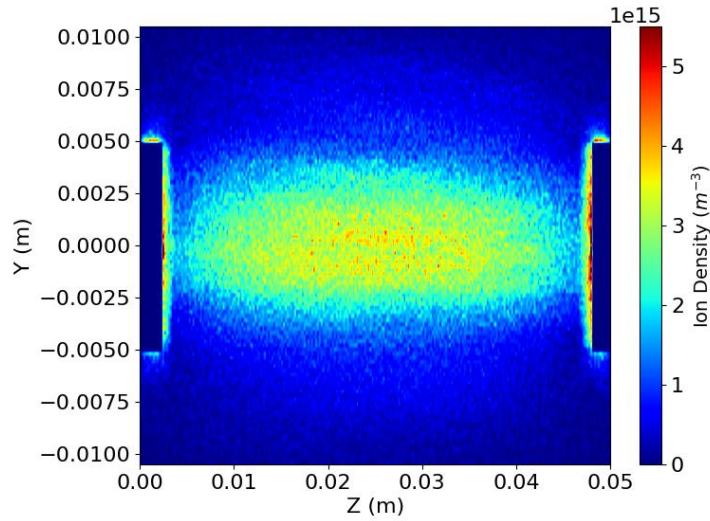
General characteristics of the azimuthal fluctuations



Observation:

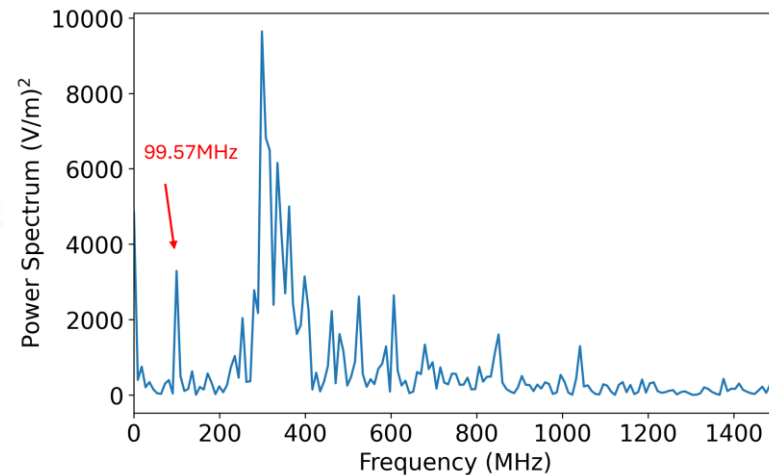
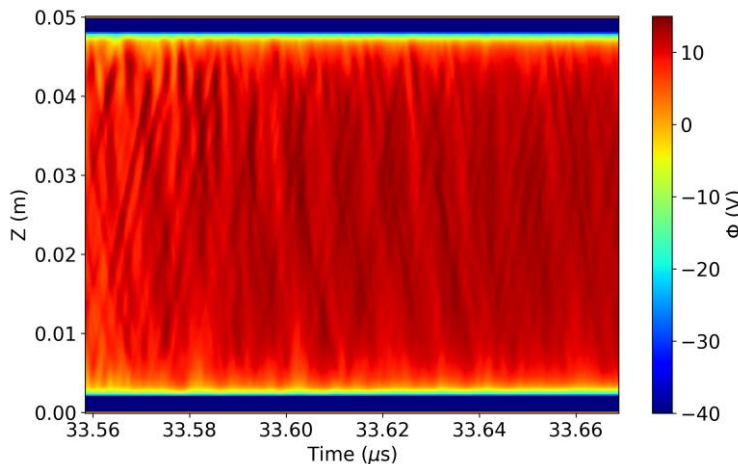
- The cross-sectional view of electron and ion densities demonstrates plasma quasi-neutrality.
- $m = 8$ counterclockwise-rotating structures visible in plasma density, electron temperature, and particle fluxes, and potential.
- Regime with largely positive radial electric field when SH instability criteria are not satisfied.

General characteristics of the axial fluctuations



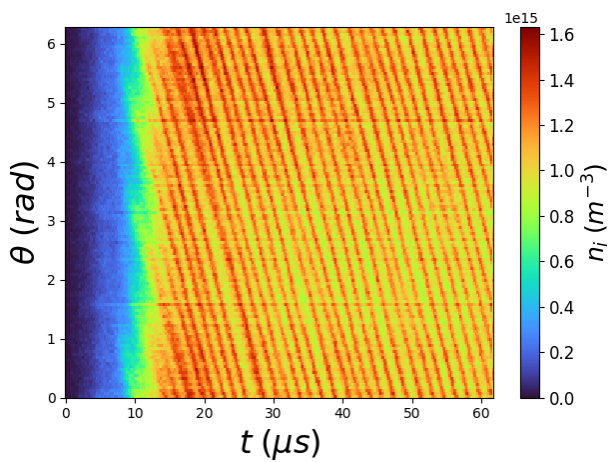
Observation:

- The axial fluctuations that are weakly correlated with the azimuthal modes.
- The electron temperature is anisotropic.
- Existence of the forward and backward waves propagating $v_{beam} = 3.75 \times 10^6 m/s$
- The axial oscillations are caused by the plasma-beam instabilities.

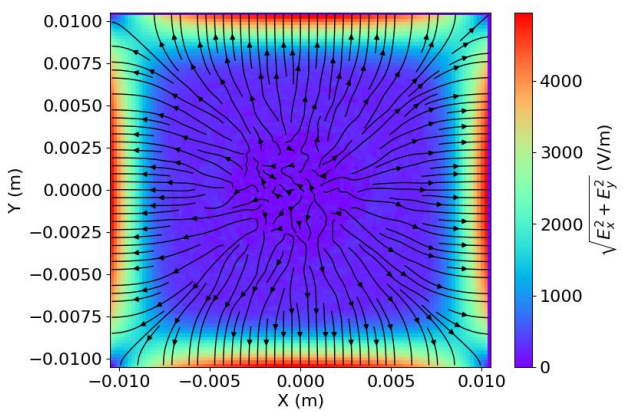
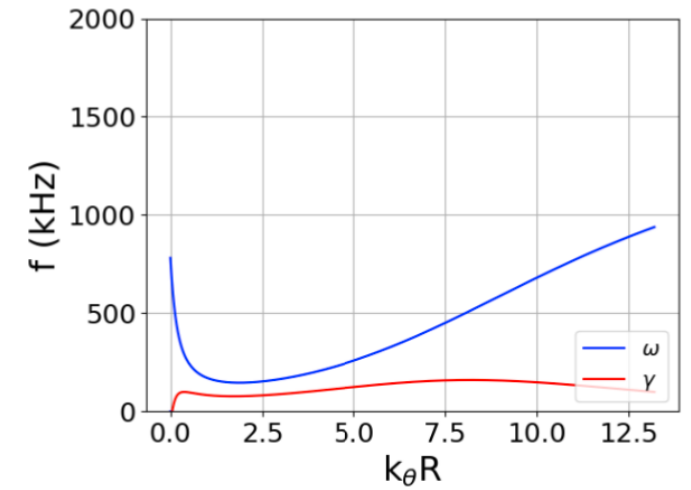
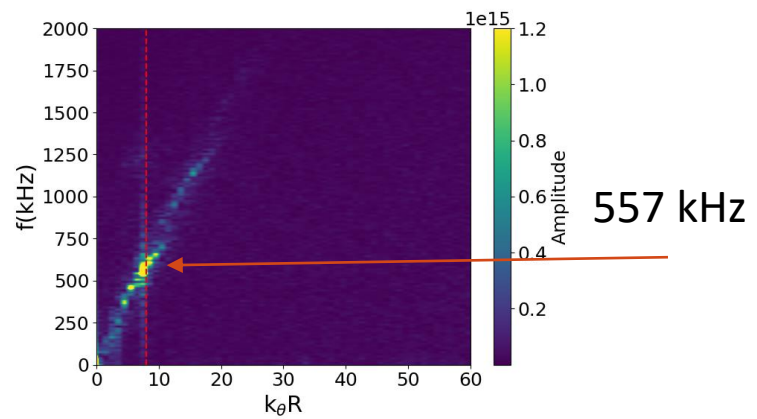


J. DATLOV et al (1968)

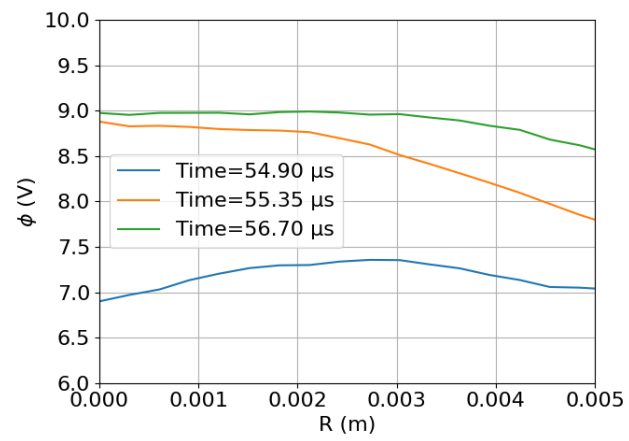
General characteristics of the azimuthal fluctuations



2D Fourier spectrum of the azimuthal profile of ion density

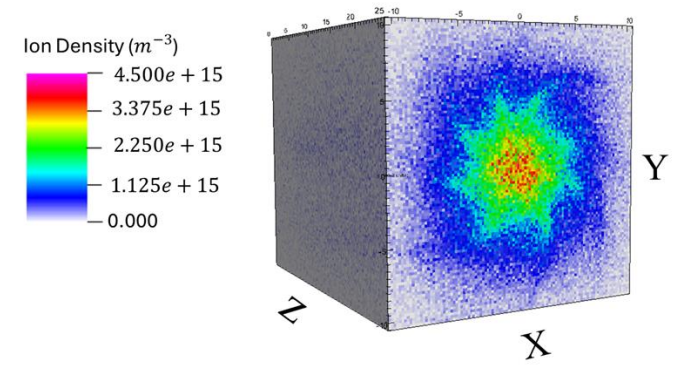


Time average of 2D xy-plane view of the electric field at $t = 24.95\mu s - 60.75\mu s$

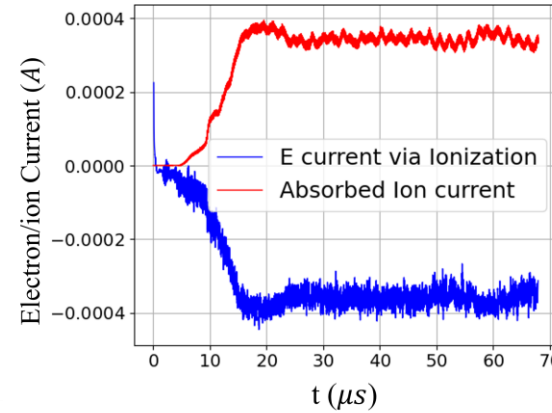
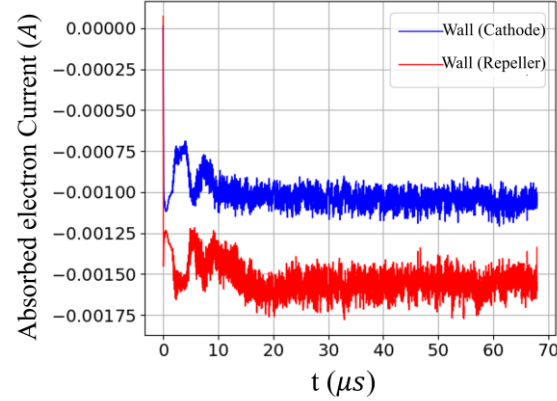
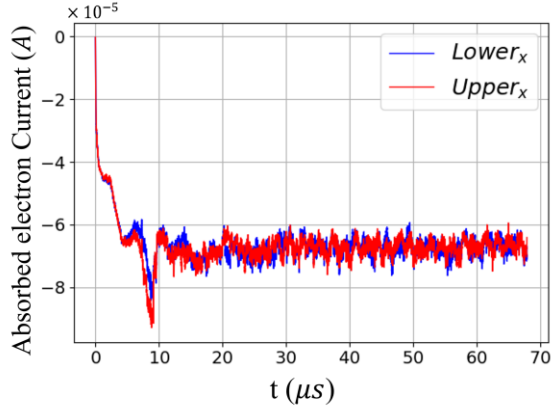


Azimuthally averaged radial profile of the potential

$$k_{\perp}^2 \lambda_D^2 + \frac{\omega_* + k_{\perp}^2 \rho_e^2 (\omega - \omega_0 + i\nu_{en})}{\omega - \omega_0 + k_{\perp}^2 \rho_e^2 (\omega - \omega_0 + i\nu_{en})} - \frac{k_{\perp}^2 c_s^2}{\omega(\omega + i\nu_{in})} = 0.$$



Particle Balance

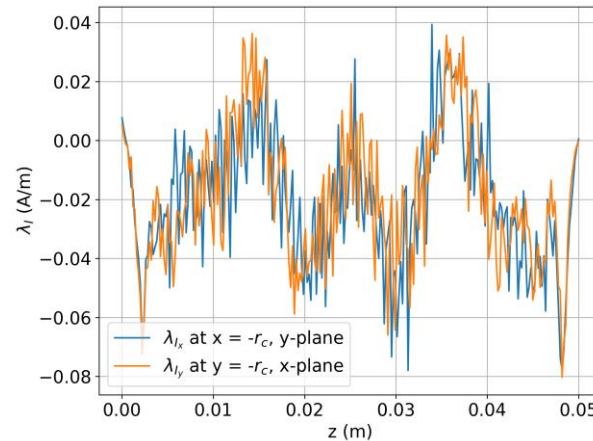
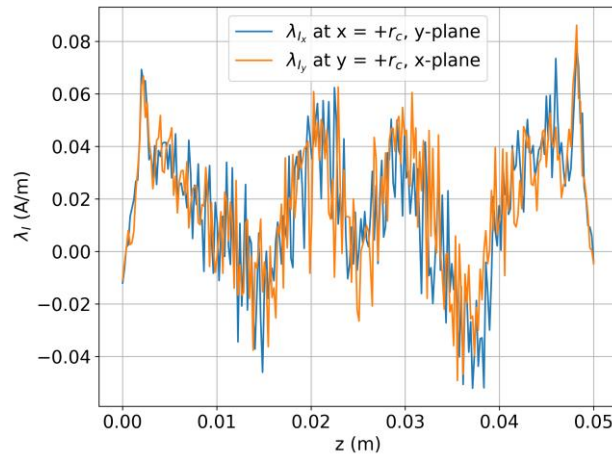


Observation:

$$I^e = I_C^e + I_R^e + 4I_S^e = 2.858 \text{ mA.}$$

$$I^i = I_C^i + I_R^i + 4I_S^i = 0.343 \text{ mA.}$$

$$I^e - I^i = 2.51 \text{ mA,}$$



linear density (along the z-direction) of the radial current taken from the simulations, giving the total radial current of 3.66 mA

Summary (Key findings)

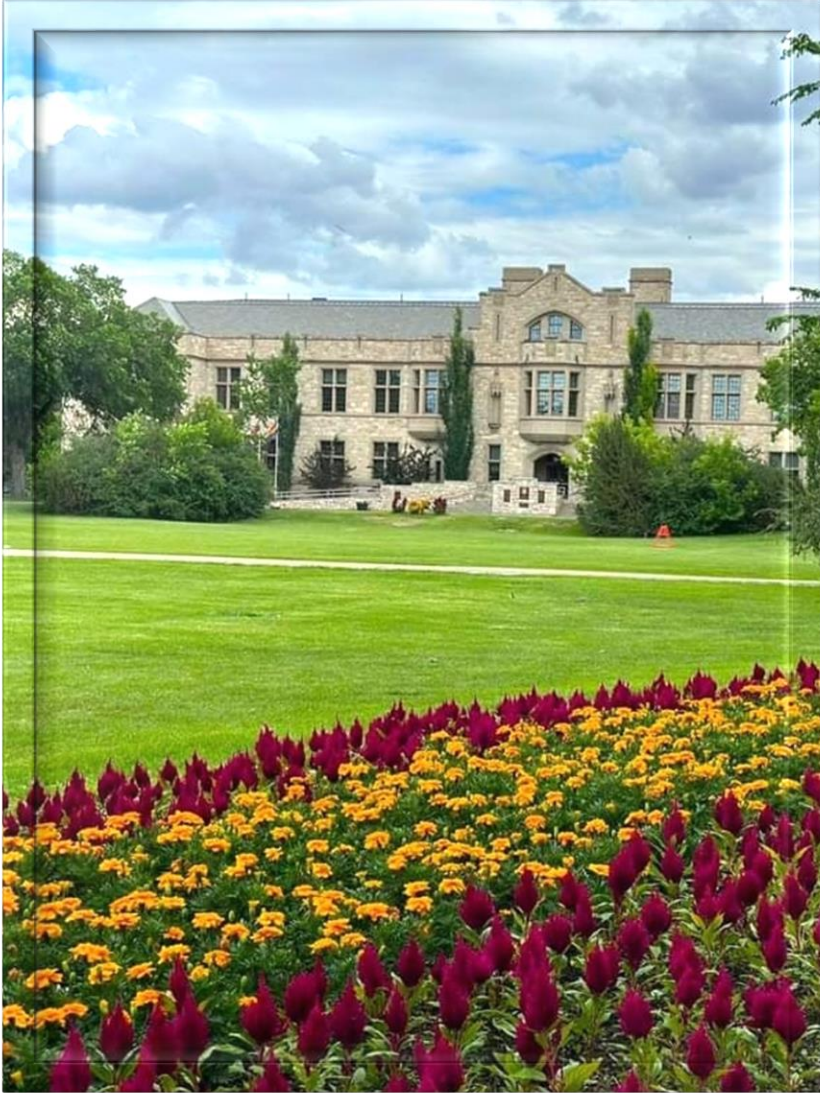


- 3D simulation reveals additional instability mechanisms beyond Simon-Hoh theory.
- Plasma potential at center is positive relative to chamber walls.
- Azimuthal structures linked to dissipative gradient-drift instability.
- Azimuthal modes rotate as a whole without axial shear.
- Axial oscillations are driven by plasma-beam instabilities, with forward and backward wave propagation.
- Axial and azimuthal oscillations in 3D are weakly correlated, indicating complex plasma dynamics.
- Electron transport modulated, producing a standing wave pattern in radial electron flux.
- Mitigation of Spoke formation can be achieved by adjusting electric field → Switching from inward to outward.
- **Future work:** In the future, I am going to complete my investigation regarding the source of predicted instabilities, in 3D simulation.

References



- [1] A.T. Powis, et al. *Physics of Plasmas* 25, 072110 (2018).
- [2] A. Likhanskii, 75th Annual Gaseous Electronics Conference, Oct 3–7, 2022; Japan, FT1.00003.
- [3] M. Tyushev, M. Papahn Zadeh, et al. *Phys. Plasmas* 30, 033506 (2023).
- [4] R. Lucken, et al. *Plasma Sources Science and Technology* 29.6 (2020): 065014
- [5] L.Garrigues and et al. *XXXV ICPIG, July 9-14, 2023, Egmond aan Zee, The Netherlands*



Thank you for your attention