Ionization Oscillations and Breathing Modes in EXB Plasmas

Andrei Smolyakov

University of Saskatchewan, Saskatoon CANADA

Acknowledgements:
O. Chapurin, University of Saskatchewan
G Hagelaar, LAPLACE & Université Paul Sabatier
Y. Raitses, Princeton University and PPPL

Online Low Temperature Plasma Seminar
July 6, 2021

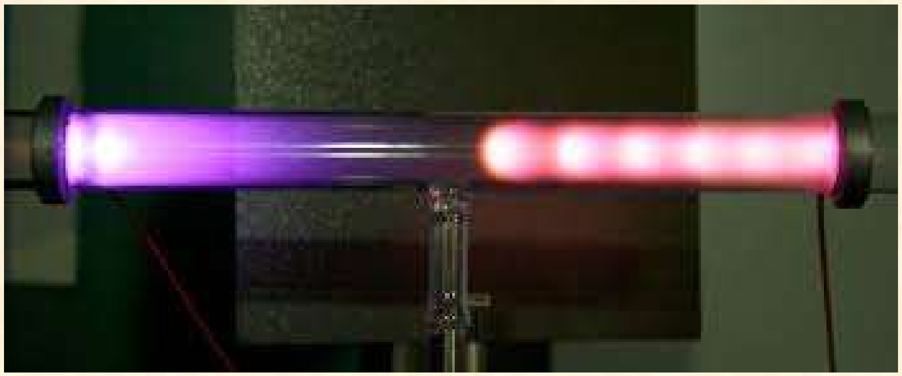
Outline

Introduction: ionization instabilities in low-temperature plasmas
Ionization instability in ExB plasmas
-- breathing mode in Hall thrusters and magnetrons
Full model simulations of the breathing mode
Reduced physics model for the breathing mode
Summary

Ionization instabilities are abundant in LTP

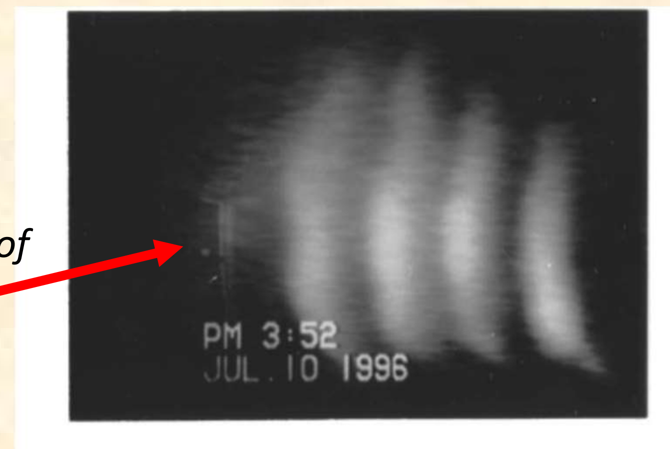
Striations, strata, …

Nedospasov A ,"Striations" *Sov. Phys. Usp.* **11** 174–187 (1968), 10.1070/PU1968v011n02ABEH003806



https://www.wikiwand.com/en/Ionization_instability

Ion sound waves and dust:
Ionization instability in dusty plasmas, N. D'Angelo, *Physics of Plasmas*(1997)
C. Thompson et al. *Physics of Plasmas*(1997)



Mechanism is due to temperature dependence of the ionization rate on temperature

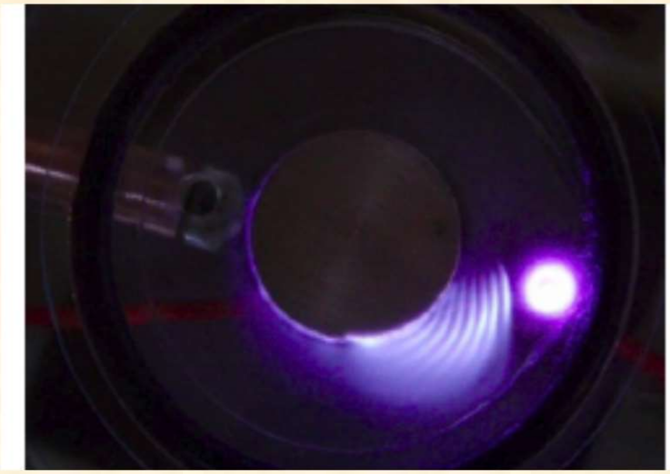
Non-Maxwellian effects are important: Electron kinetic effects: Striations in rare gas plasmas. V. I Kolobov 2006 J. Phys. D: Appl. Phys.39 R487

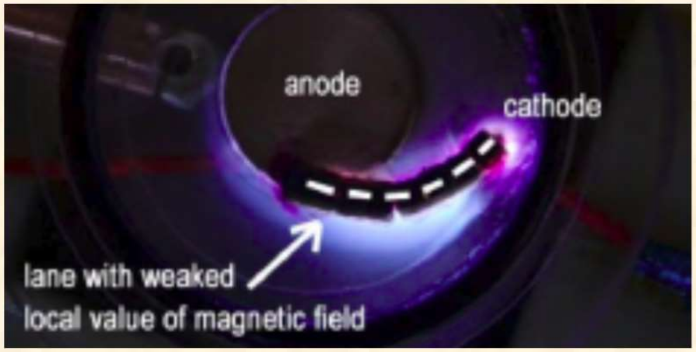
Ionization instabilities in plasmas with magnetic field, e.g. MHD generators

Electrothermal instability, Velikhov et al Atomic Energy Review, 14 (2), 325-385 (1976), , Kerrebrock et al 1960s

Analysis of the nature and growth of electrothermal waves
A H Nelson and M G Haines 1969 *Plasma Physics* **11** 811

Electrothermal instability .. discovered by E. Velikhov .. presented at the international MHD congress ..1962, announced the complete ruin of the dreams of … working on electric current production processes by direct energy conversion of a fluid. Acta Polytechnica 53(2):219–222, 2013 , J Petit et al



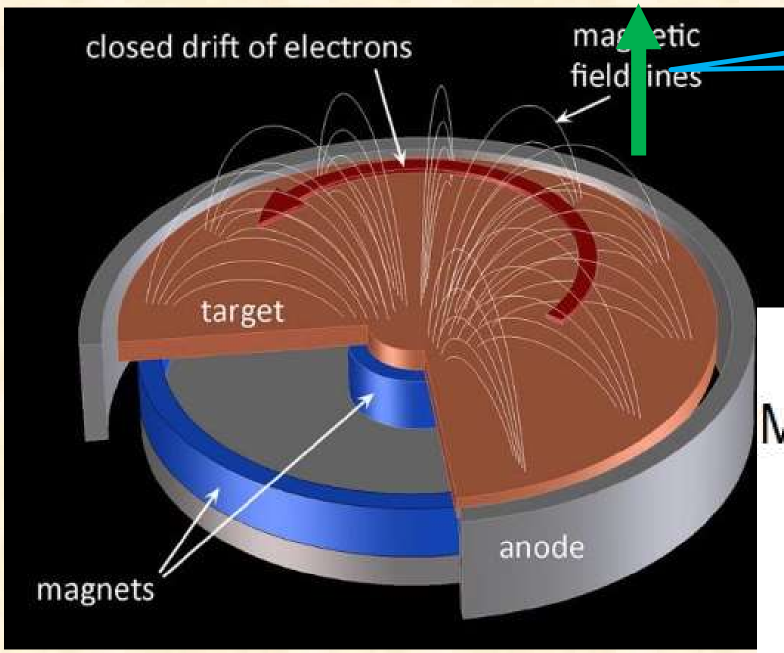


Ways to control this instability were found? May find some applications In MHD controlled ramjets , J Petit … 2013

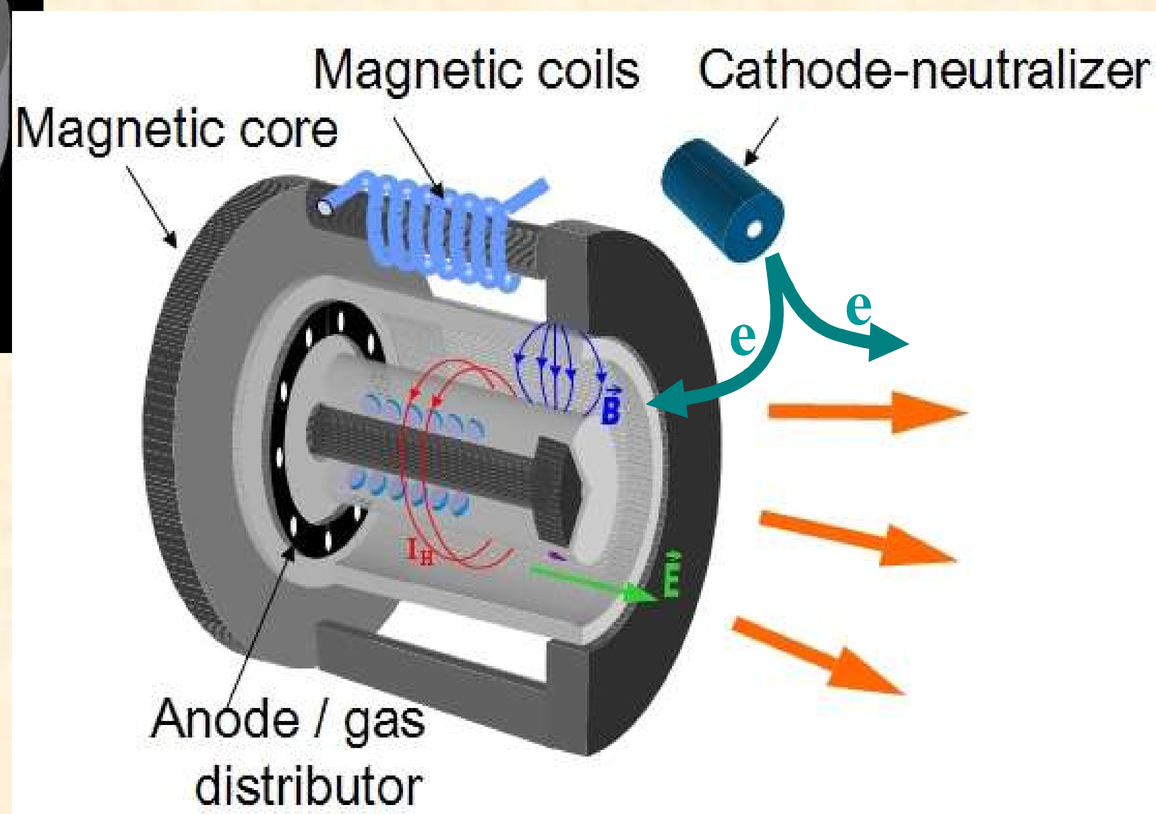
Partially magnetized ExB devices for industrial applications and electric propulsion

Magnetrons, Hall thrusters, and other magnetic filters …

E electric field



Planar magnetron, A. Anders, J App Phys 2017

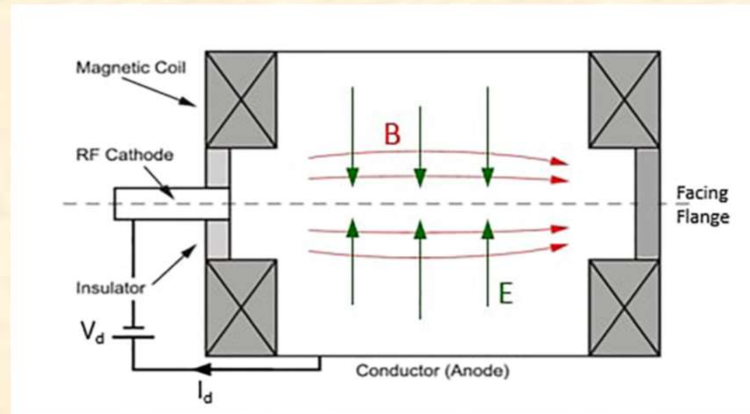


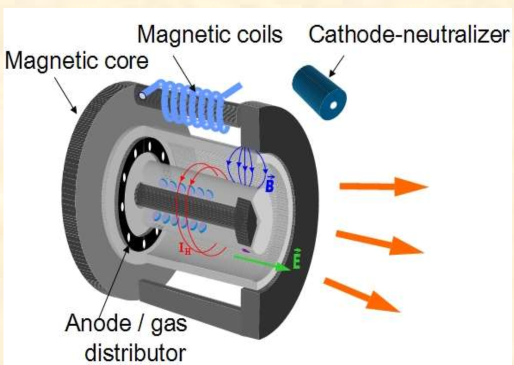
Hall thruster

Magnetic filter --ExB configuration:
Electric field accelerates unmagnetized ions, the magnetic field impedes the electron flow across B

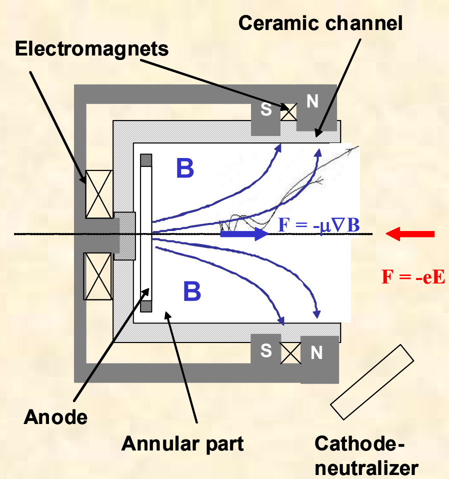
Cylindrical Penning discharge,

Y. Raitses PPPL,Rodrigues et all, PoP 2019



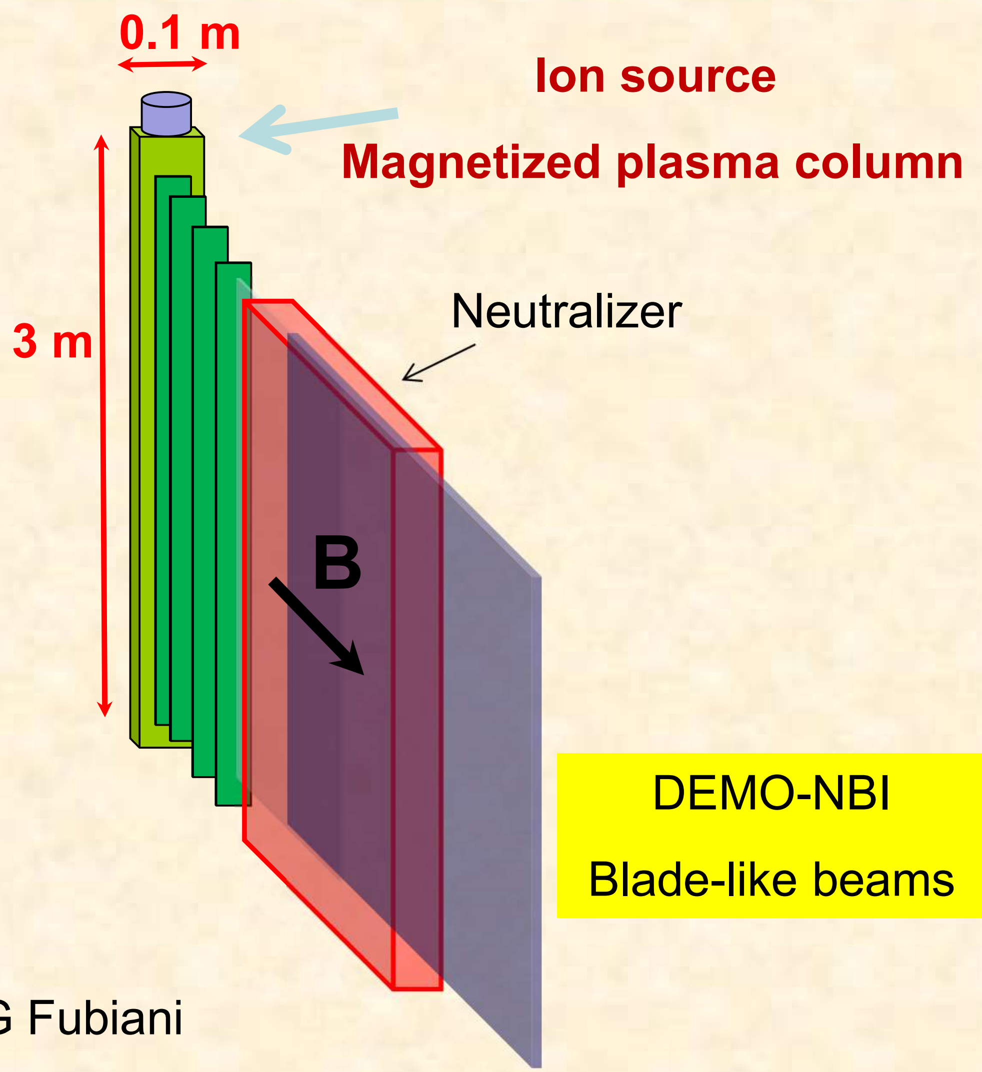


Annular thruster



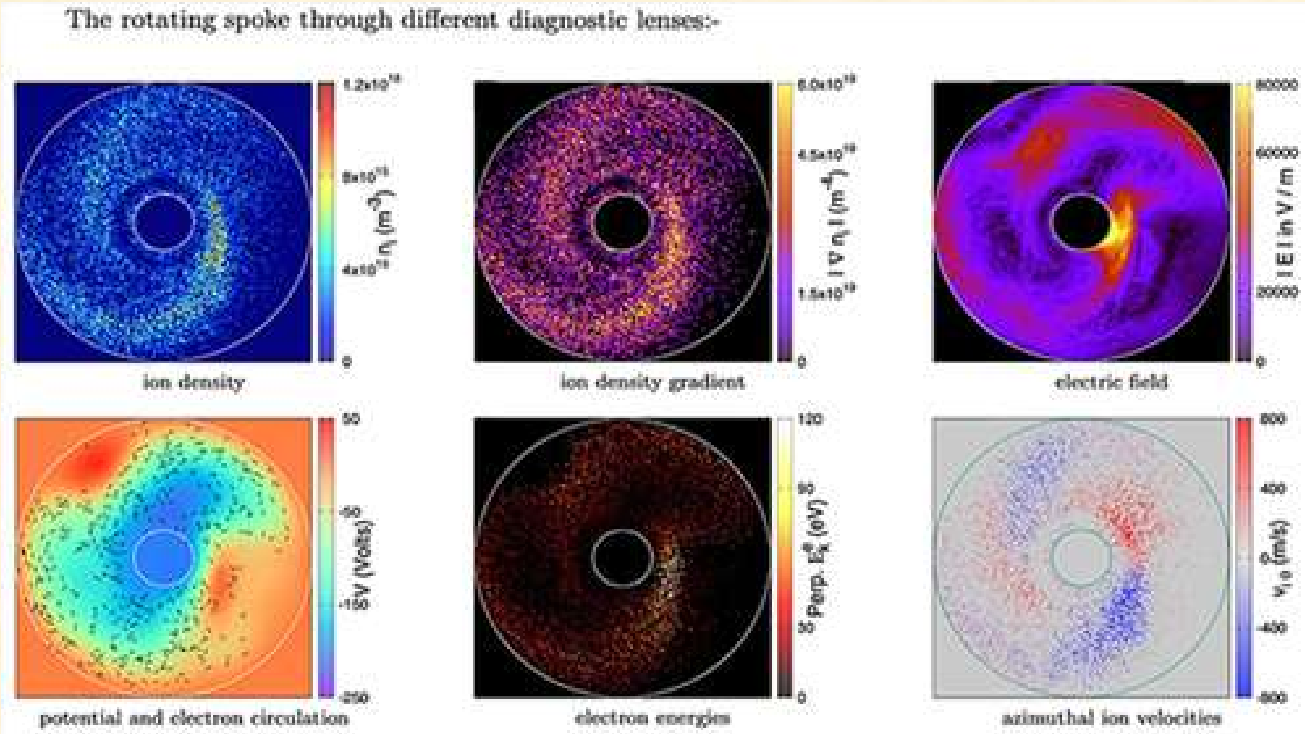
Cylindrical Hall Thuster, HTX PPPL,
Y. Raitses

Magnetic filter for negative ion beam source



G Fubiani

Physics of ionization instabilities coupled with gradient-drift mode instabilities in ExB plasma is more complicated



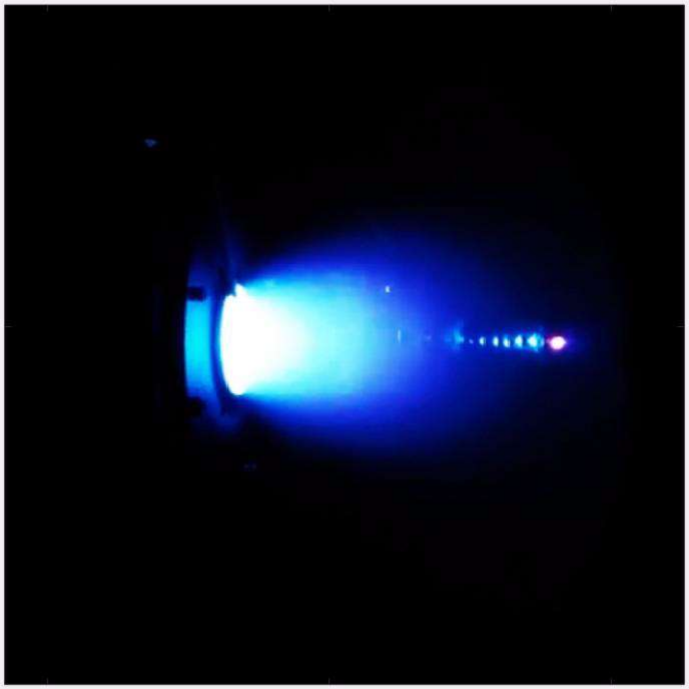
Restructuring of rotating spokes in response to changes in the radial electric field and the neutral pressure of a cylindrical magnetron plasma.
M.Sengupta, A. Smolyakov, and Y. Raitses, Journal of Applied Physics 129, 223302 (2021);

Instabilities at the ionization fronts heat electrons thereby enhancing the instability further
--Alfven critical ionization phenomena

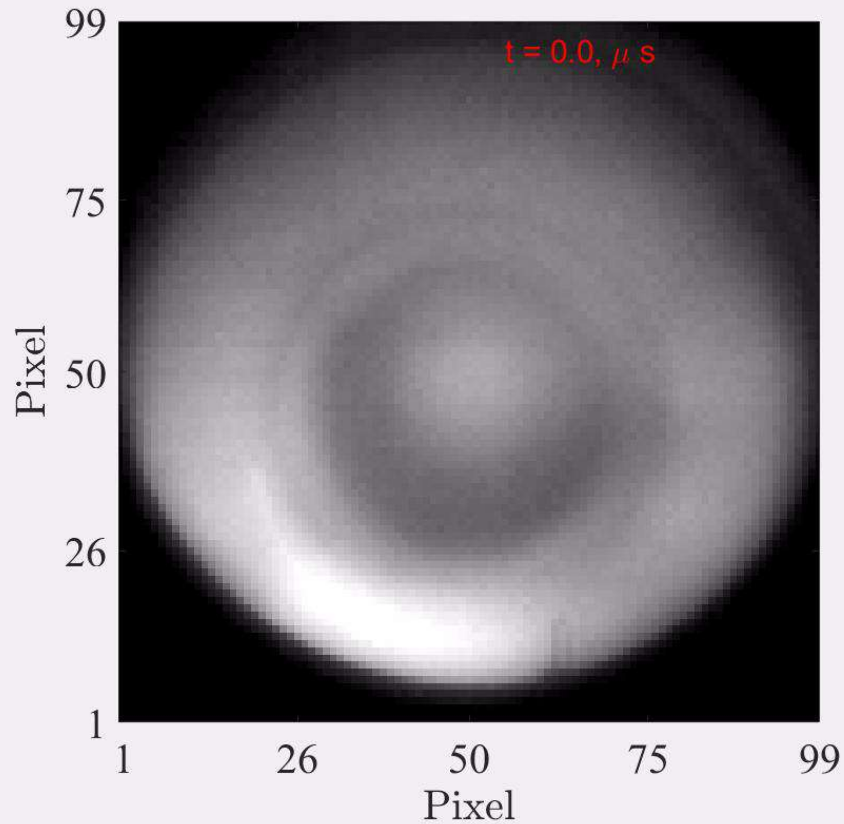
Breathing mode – axial ionization instability in Hall thrusters is ubiquitous

-- large m=0 oscillations of density

-- large oscillations of the electric current

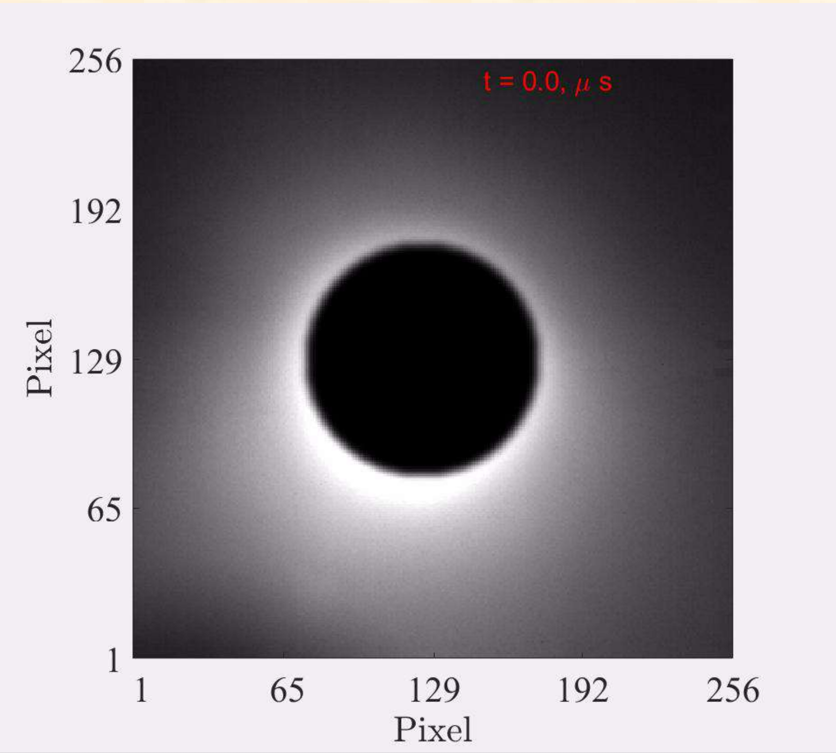


Cylindrical Hall Thruster (CHT) PPPL in operation, I Romadanov et al

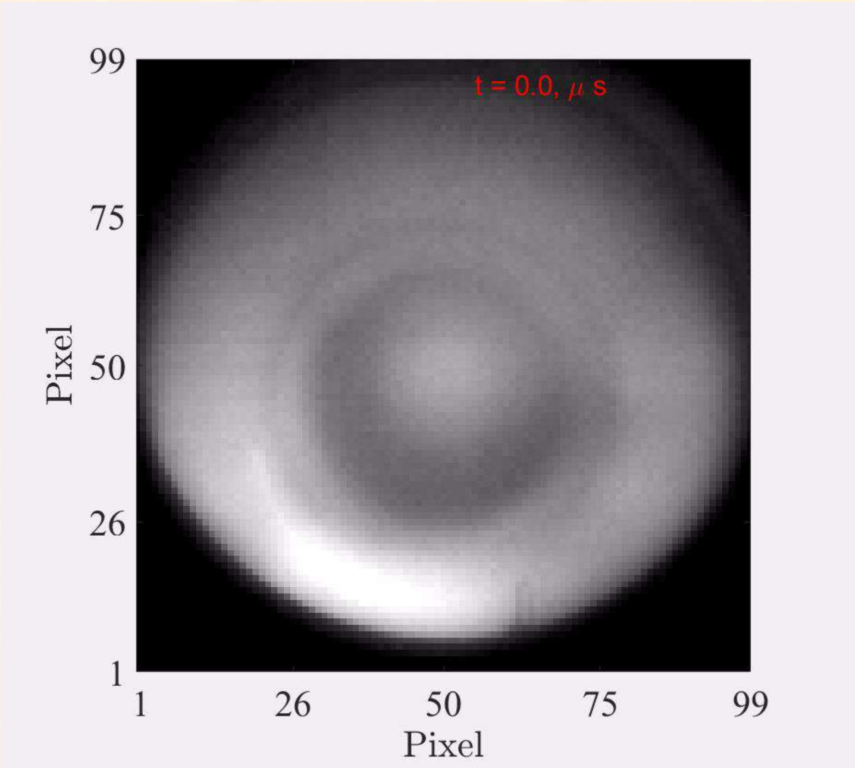


Spoke and breathing mode structures in CHT

Azimuthal and axial ionization modes in Hall thruster

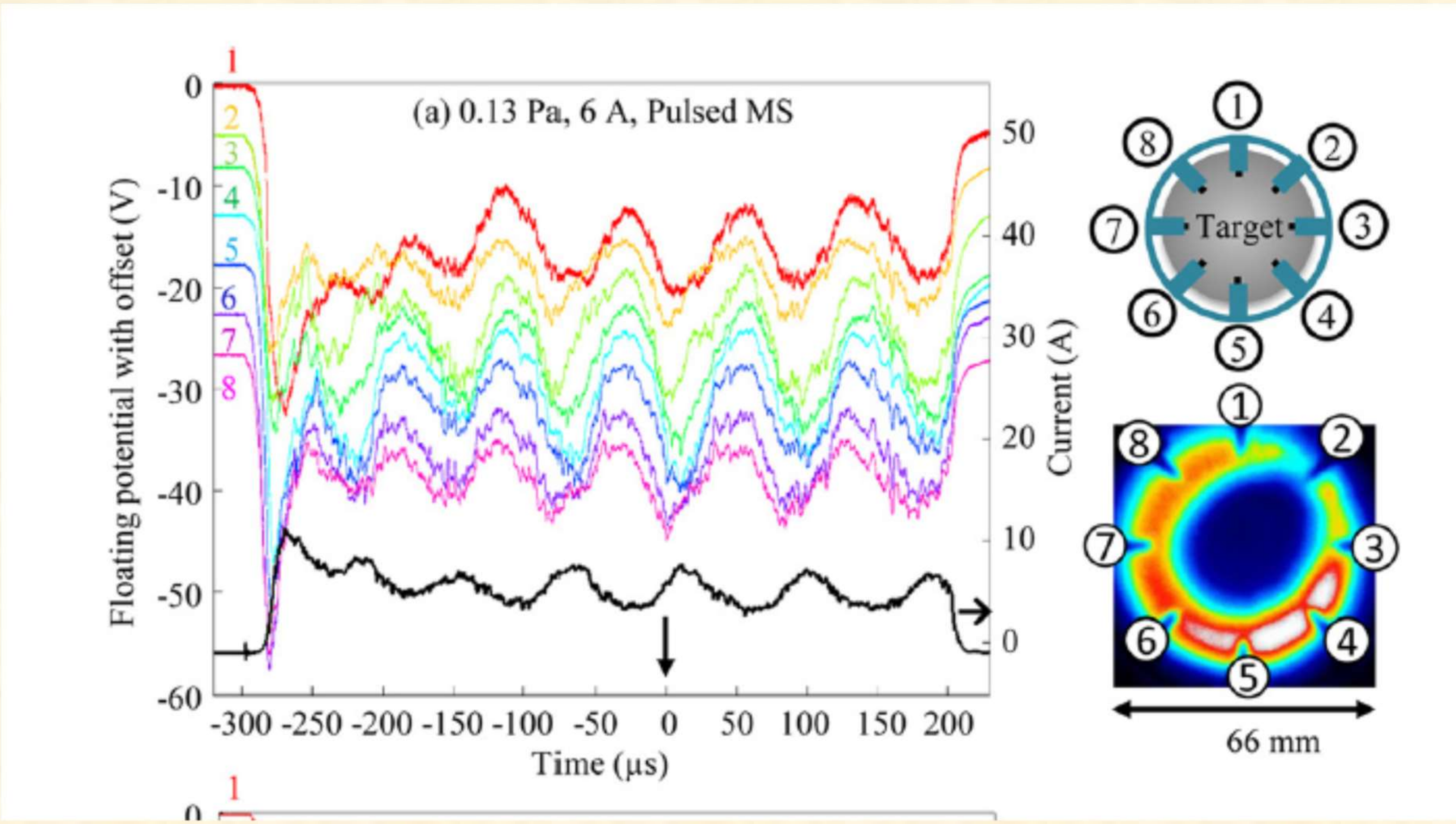


Azimuthal (spoke)



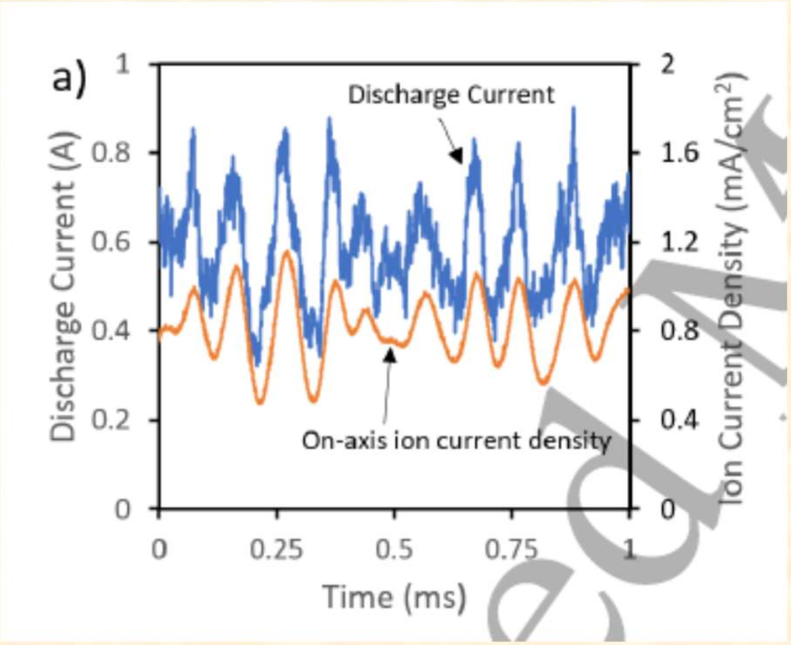
Azimuthal (spoke) and axial (breathing) modes

Azimuthally symmetric (m=0) mode in HPIMS

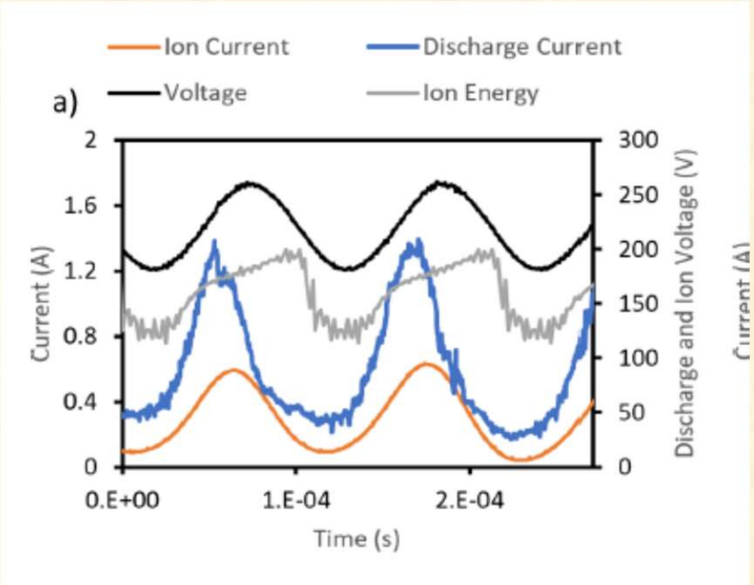


Y Yuchen, X Zhou, J Liu, and A Anders. "Evidence for Breathing Modes in Direct Current, Pulsed, and High Power Impulse Magnetron Sputtering Plasmas." *App Phys Lett* 108, 2016

- **Axial low frequency oscillations (breathing mode) is among the most pronounced modes in Hall thrusters.**
- **Its physics and conditions for the instability are not understood**



unmodulated



modulated

Experimental studies and modeling (**full model**) of a modulated Hall thruster,
J Simmonds, Y Raitses, A Smolyakov, O Chapurin.
2021 *Plasma Sources Sci. Technol.* **30** 055011

Breathing mode can be controlled externally (modulated) to improve the performance and/or facilitate diagnostics

Breathing mode models

- **There exist a number of full theoretical models claiming to describe/predict the behavior and characteristics of breathing modes**
- **Many models claim that with some adjustable parameters (and certain level of enthusiasm), the model(s) reasonably agree with experimental data.**
- **Many full models are complex: The physics and the conditions for the instability are not well understood**

Reduced (simplified) models are valuable as they may point to the critical parameters for the mode excitation

Physics ingredients in full breathing mode models:

- **Predator-prey competition: ion-neutral coupling via the ionization**
- **Self-consistent quasi-neutral model:**
  - **Electron resistivity and diffusion**
  - **Ion acceleration and inertia**
- **Temperature effects on ionization**
- **Electron energy equation and electron heat fluxes**

Full self-consistent model with electron mobility, energy evolution, heat flux and losses

$$\frac{\partial n}{\partial t}+\frac{\partial}{\partial x}(nv_i)=\beta nN-\nu_w n \qquad \frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(Nv_a)=-\beta nN+\nu_w n$$

$$m_i n\left(\frac{\partial v_i}{\partial t}+v_i\frac{\partial v_i}{\partial x}\right)=enE-\beta N m_i(v_i-v_a)$$

$$J_d=nv_i-n\mu_e E-\frac{\mu_e}{e}\frac{\partial(T_e n)}{\partial x}=const$$

$$\frac{3}{2}\frac{\partial(nT_e)}{\partial t}+\frac{5}{2}\frac{\partial}{\partial x}(nT_e v_{ex})+\frac{\partial}{\partial x}q_x=-env_{ex}E-nN_aK-nW$$

Anomalous transport, collisional (ionization) and anomalous (sheath) energy losses are all included

$$W=\nu_\varepsilon\varepsilon\exp(-U/\varepsilon)$$

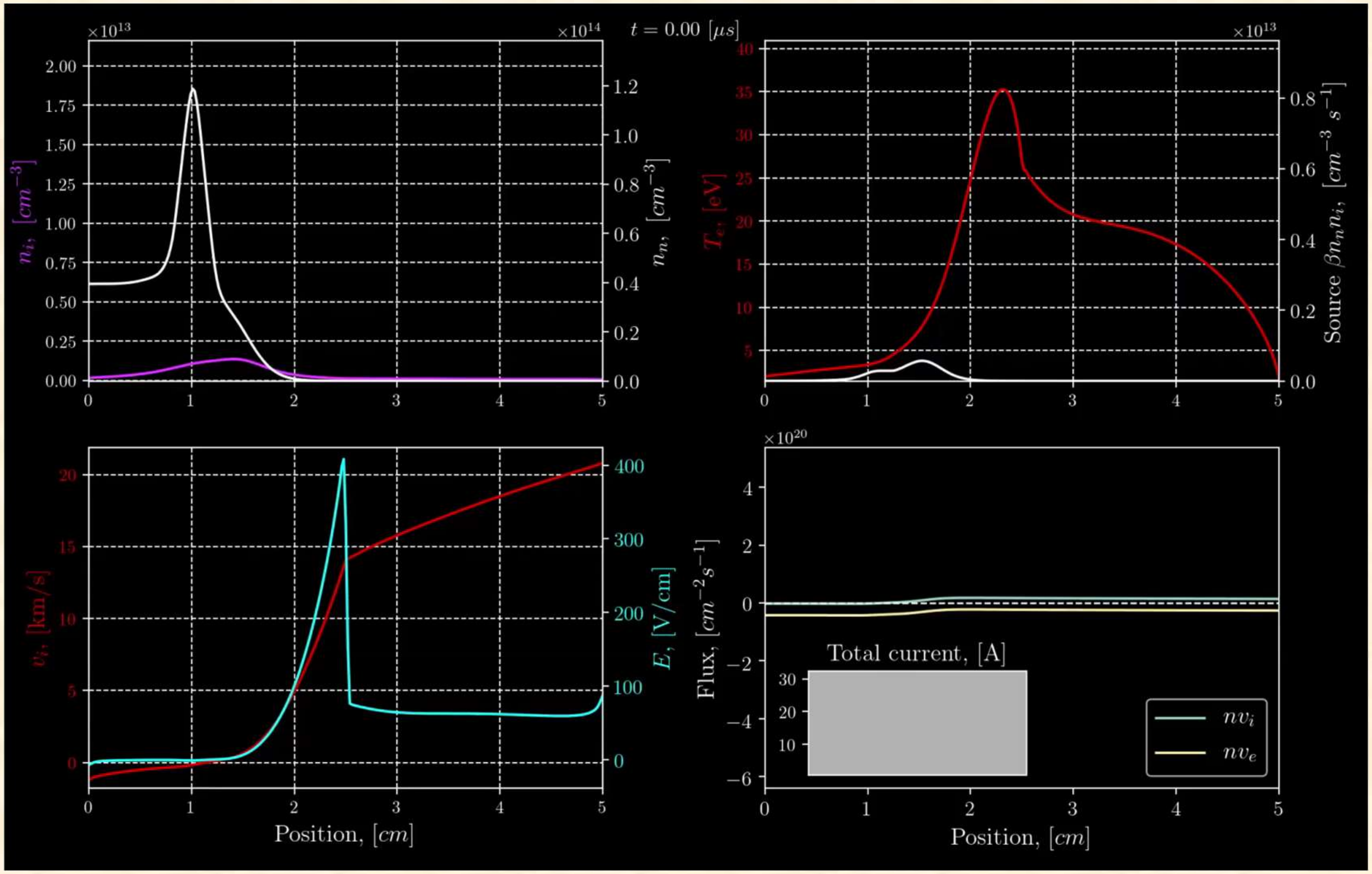
Chapurin et al, 2021

Breathing mode models

Morozov and V. Savelyev, “Fundamentals of stationary plasma thruster theory,” ..2000
S. Barral and E. Ahedo, “Low-frequency model of breathing oscillations in Hall discharges,” PRE 79, 046401 (2009).
J. Boeuf and L. Garrigues, “Low frequency oscillations in a stationary plasma thruster,” JAP (1998).
J .M. Fife, Hybrid-PIC modeling and electrostatic probe survey of Hall thrusters, Ph.D. thesis (1998).
S. Chable and F. Rogier, “Numerical investigation and modeling of stationary plasma thruster low frequency oscillations,” PoP (2005).
K. Hara, et al, “One-dimensional hybrid-direct kinetic simulation of the discharge plasma in a Hall thruster,” PoP (2012).
J. Fife, et al. Discharge oscillations in Hall thrusters,” in 33rd Joint Propulsion Conference and Exhibit (2012) p. 3052.
S. Barral and E. Ahedo, “On the origin of low frequency oscillations in Hall thrusters,” AIP Conf Proc 993, 439–442 (2008).
K. Hara, M. J. Sekerak, I. Boyd, and A. Gallimore, “Perturbation analysis of ionization oscillations in Hall effect thrusters,” PoP 2014.
C. Wang, et al, Basic Predator-Prey Type Model for Low Frequency Discharge Oscillations in Hall Thrusters,” CPP (2011).
E. Dale and B. Jorns, “Frequency scaling of the hall thruster breathing mode,” in AIAA Propulsion and Energy 2019 Forum (2019).
E. Dale and B. Jorns, “Two-zone Hall thruster breathing mode mechanism, Part I: Theory,” in 36th IEPC 2019.
E. Dale and B. Jorns, “Two-zone Hall thruster breathing mode mechanism, Part II: Experiment,” in 36th IEPC 2019.
N. Yamamoto, et al “Discharge plasma fluctuations in Hall thrusters,” Vacuum 65, 375–381 (2002).
N. Yamamoto, et al “Discharge current oscillation in Hall thrusters,” Journal of Propulsion and Power 21, 870–876 (2005).
J. Kurzyna, “Where is the breathing mode? AIP Conf Proceedings (2008).
…. …
For full publications details see, e.g. On the mechanism of ionization oscillations in Hall thrusters.
O. Chapurin, A. I. Smolyakov, G. Hagelaar, and Y. Raitses, Journal of Applied Physics 129, 233307 2021

Example of the breathing mode cycles

full mode



Reduced models analysis is desirable to single out the main physics mechanism(s) and conditions for the instability

E Dale , B Jorns, Frequency Scaling of the Hall Thruster Breathing Mode AIAA Propulsion and Energy 2019,

(a) Standard 0-D predator-prey model: Fife, 1998, Barral Ahedo, 2008, ..
(b) Resistive instability: Chable, Rogier, 2005; Koshkarov et al, 2017
(c) Neutral gas oscillations (sound waves)

"In total, of the three breathing mode models examined, none were found to agree with experimental data"

Reduced 1D continuum fluid model: ion-neutral coupling with the ion backflow region near the anode,
O. Chapurin, A. Smolyakov, G Hagelaar, Y Raitses, J Appl Phys 2021

What is special about the ionization (Breathing) modes in
Hall thrusters and related system?

-- Free-fall (ballistic) ion motion in the electric field

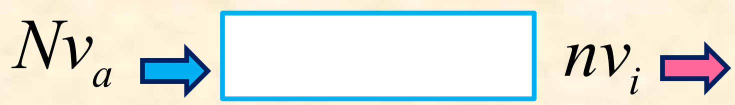
-- Beam of injected neutrals

Predator-prey model (J .M. Fife, 1988)

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(nv_i) = \beta n N$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}(Nv_a) = -\beta n N$$

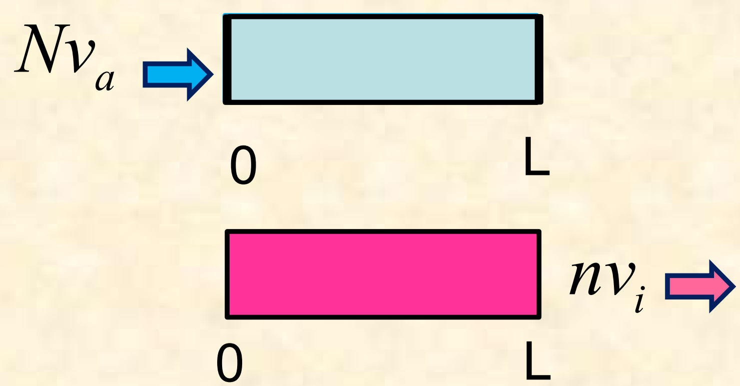
$$n_i v_i\big|_0 = 0 \qquad n_i v_i\big|_L = nv_i$$



$$N_a\big|_0 = N \qquad N_a\big|_L = 0$$

$$\frac{\partial n_i}{\partial t} + \frac{1}{L} nv_i = \beta n N$$
$$\frac{\partial N}{\partial t} - \frac{1}{L} nv_a = -\beta n N$$

Lotka-Volterra equations



Neutrals is a prey
Plasma (ions) is a predator

Ordinary (ODE) in time,
no spatial dependence, 0-D

$$\omega^2 = v_i v_a / L^2$$

$v_i = \text{const}$

$v_a = \text{const}$

Predator-prey model (J .M. Fife, 1988) is simple and attractive, but …

- No instability…
- Oscillating N_a at anode is inconsistent with fixed injection rate, *Barral 2009*
- Continuous 1D predator-prey does not oscillate at all (only damped mode)

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(N v_a\right)=-\beta n N$$

No oscillations

$$\frac{\partial n_i}{\partial t}+\frac{\partial}{\partial x}\left(n v_i\right)=\beta n N$$

Modified model: $N_a\big|_0 = N_0 = const$

$N_a\big|_L = N(t)$ Neutral density oscillates at the exit

Damped oscillations only,
Additional physics -- temperature fluctuations
need to be included, Hara 2014– alternative mechanism

Reduced mode: One-dimensional (continuum) predator-prey type model with a non-uniform ion velocity

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}\left(n v_i\right) = \beta n N$$

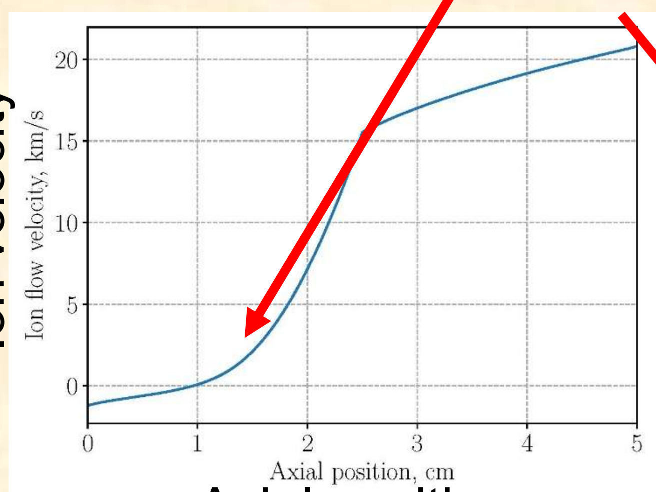
$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(N v_a\right) = -\beta n N$$

$$v_i = v_i\left(x\right) \qquad v_i\big|_{anode} < 0$$

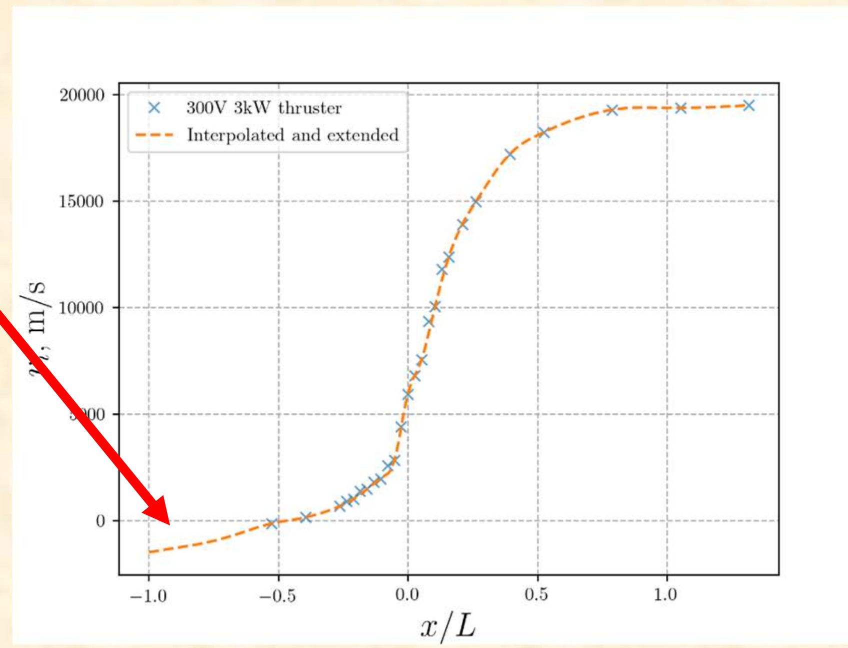
Ion backflow near anode

backflow

Ion velocity



Axial position



From theoretical full model
Chapurin et al. .. 2021

Experimental profile, E Dale

Physics of the ion backflow region and the instability

anode "presheath"

$v_i = v_i(x) \qquad v_i\big|_{anode} < 0$

Quasineutrality and ambipolarity

$$n_e = n_i$$

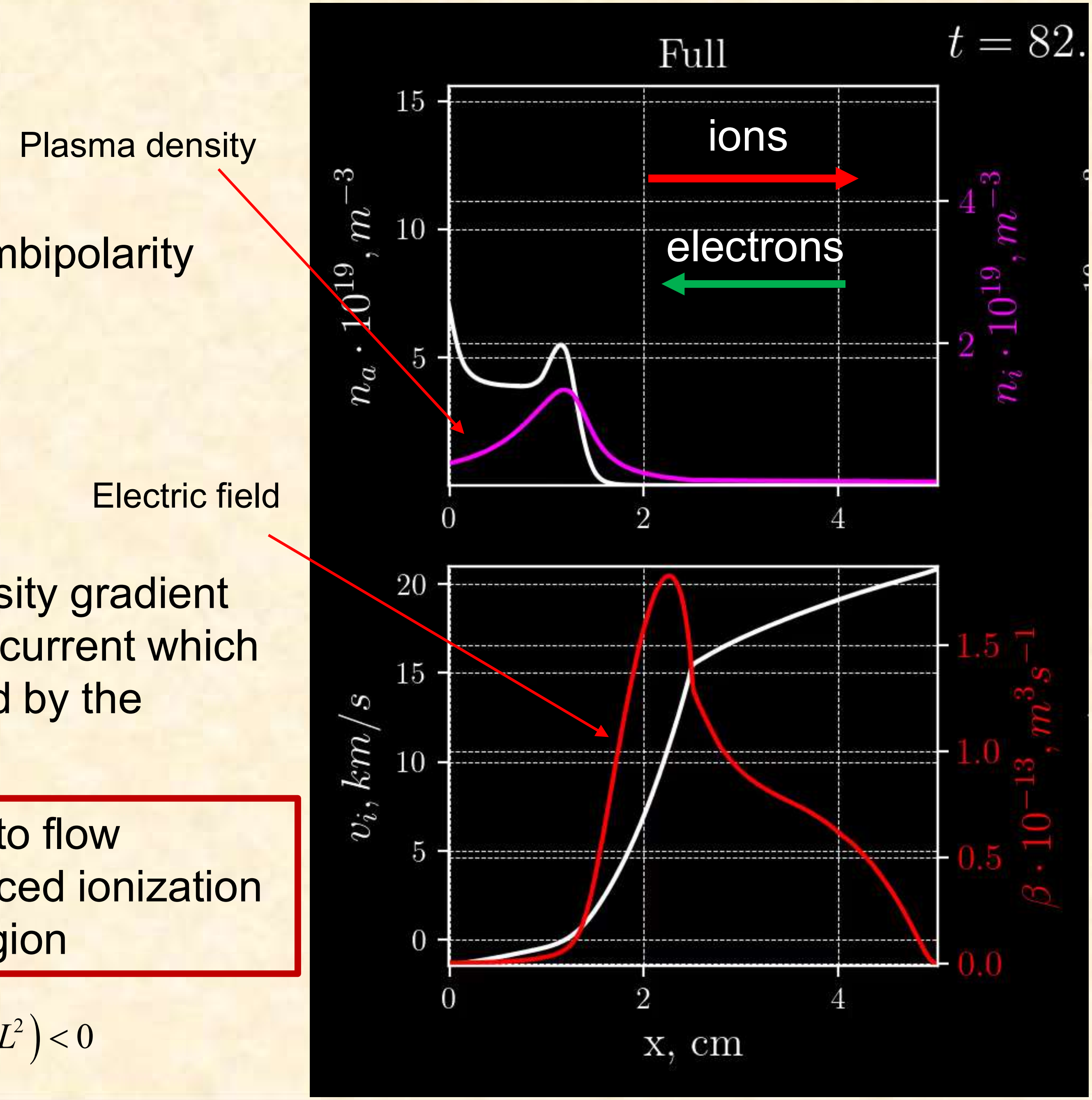
$$J_i + J_e = const$$

$$V_e = -\mu_e E - D\frac{\partial n}{\partial z}$$

Enhanced plasma density gradient Increases the electron current which has to be compensated by the reversed ion flow

Instability occurs due to flow stagnation and enhanced ionization in the ion backflow region

Simplistically $\omega^2 = \left(v_a v_i / L^2\right) < 0$

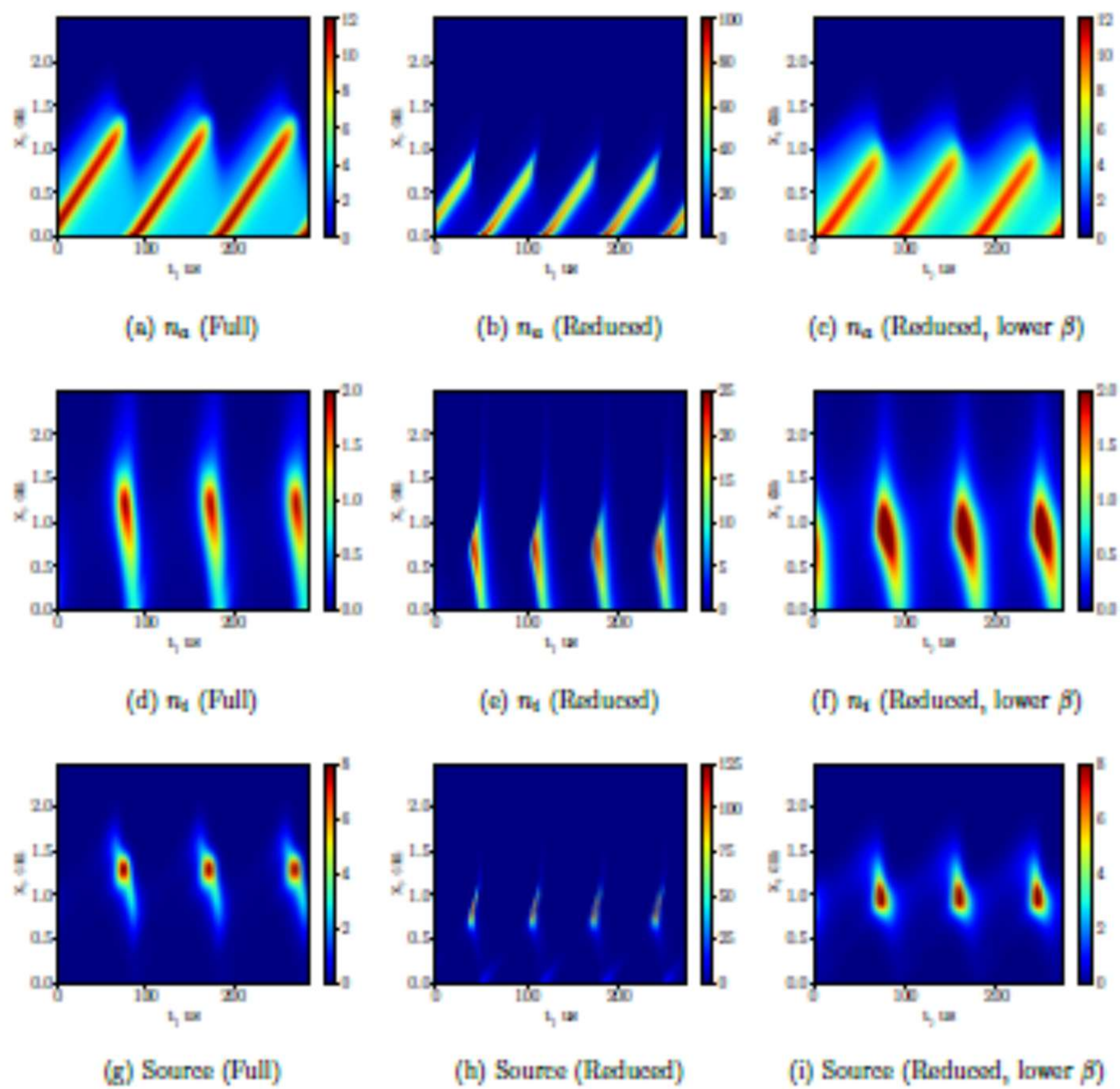


Properties of the reduced model: I

Neutral density

Ion density

Ionization source



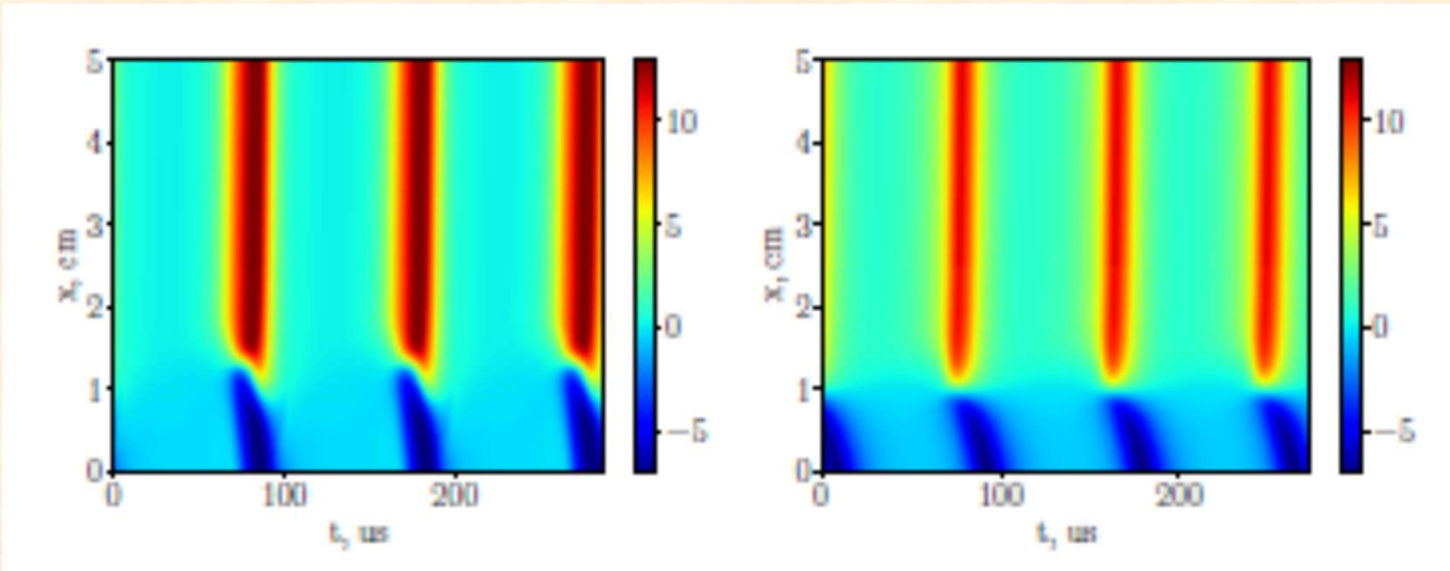
Full

Reduced m

Reduced model with lower ionization

Properties of the reduced model: II

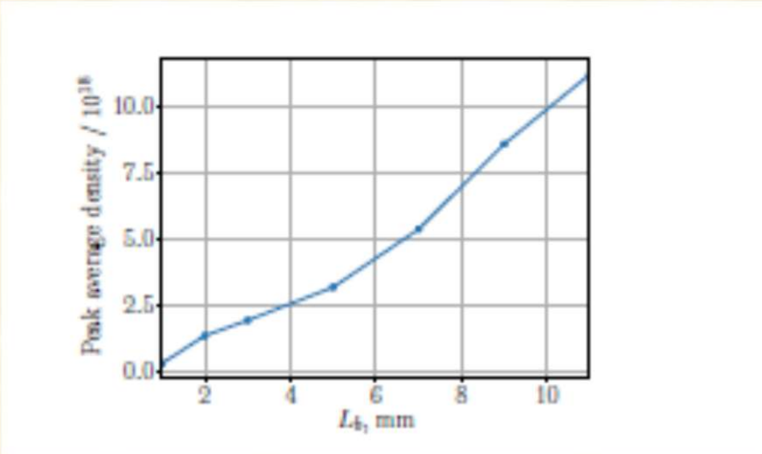
Ion current



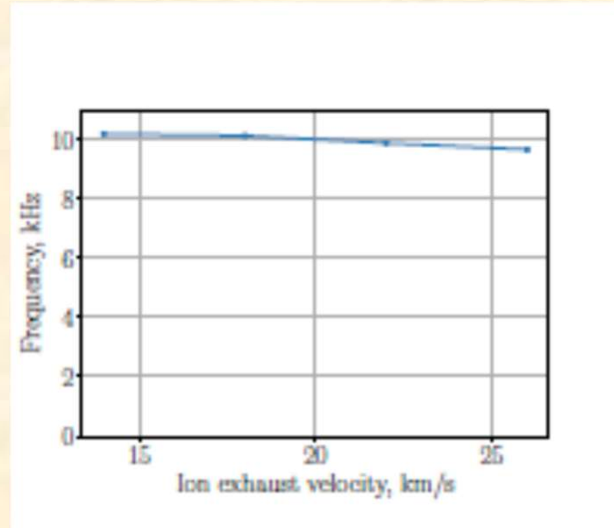
Full

Reduced model with lower ionization

Properties of the reduced model: III

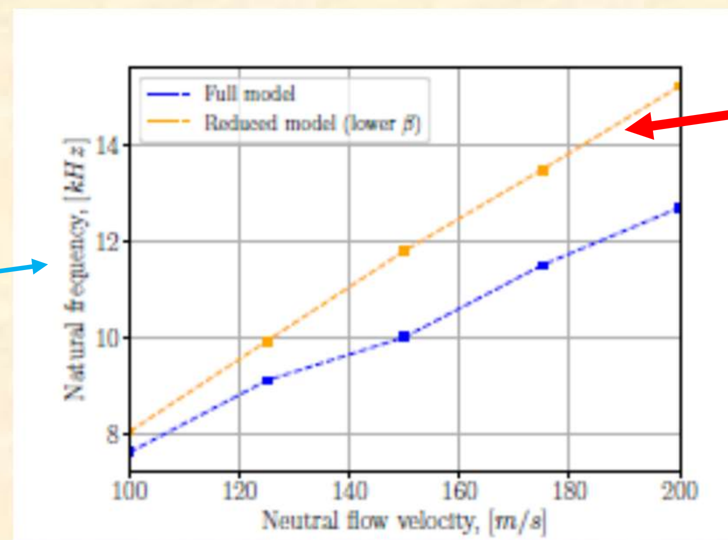


The amplitude of the peak density with the backflow width



Very little frequency dependence on the ion velocity

Almost linear scaling of the frequency on the neutral flow velocity. Not too far from the prediction of the full model

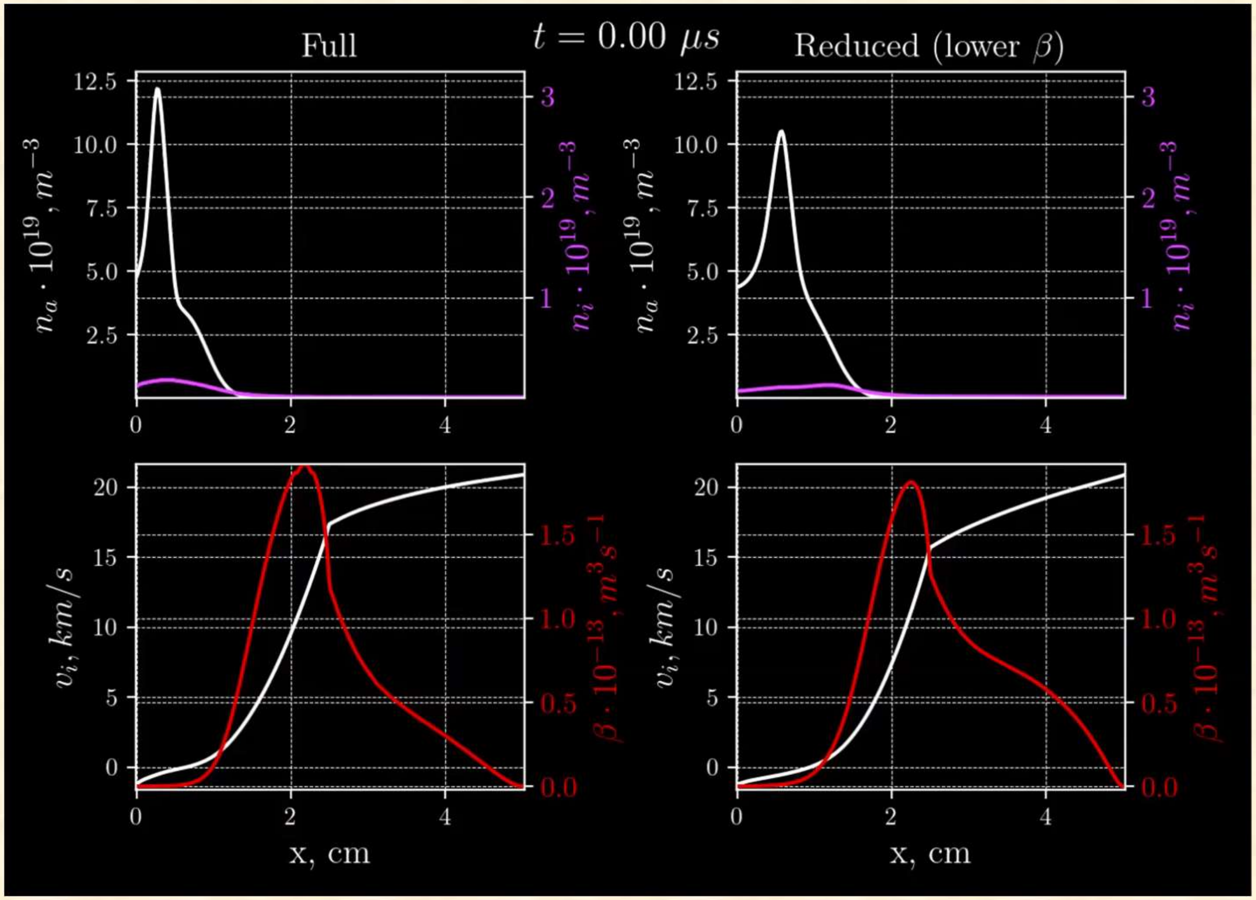


Reduced model

Full model

The breathing mode frequency is f =4*v_a/L.

Properties of the reduced model: IV



Full

Reduced

Summary

- The investigation of the 1D continuum predator-prey type model shows good agreement with the results of the full model and promising agreement with experimental data; backflow characteristics and ionization rate profiles are required as input parameters
- Reduced (simplified) models are valuable because they not only reasonably predict important characteristics of the breathing mode but, even more importantly, may indicate the critical physics parameters for the mode excitation and characteristics

Caveat(s)

- Two different regimes of axial oscillations are identified: (a) “solo” low frequency (10-14 kHz); and (b) low frequency (10-14 kHz) coexisting with high frequency (~100 kHz) modes,

  The high frequency modes are identified as resistive axial flow instability
- The behavior of the solo low frequency mode can qualitatively be described by a predator-prey PDE model with the ion backflow region, while the regime with coexisting low and high frequency modes is more complicated
- Other types of breathing modes/mechanism may be relevant in some regimes

Smolyakov et al, AIAA 2019, Chapurin et al, JAP 2021

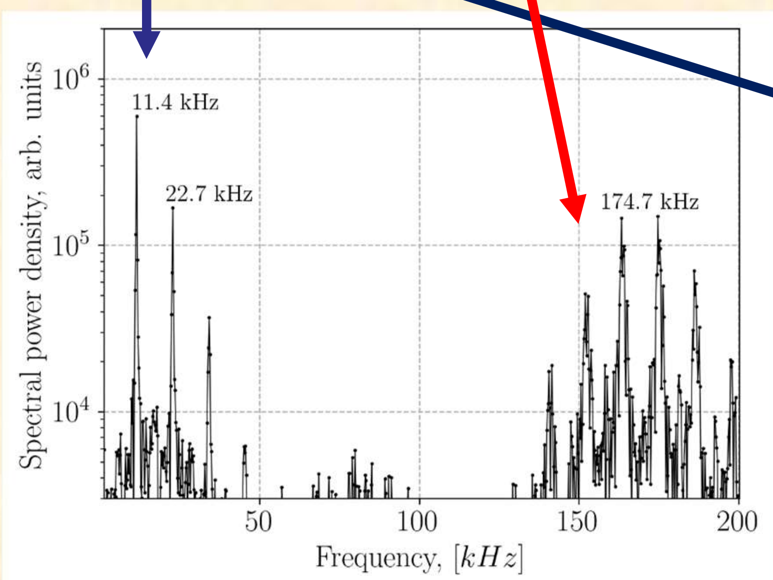
Two different type of modes are identified depending on the level of energy losses

- Anode (presheath) backflow region dominated:

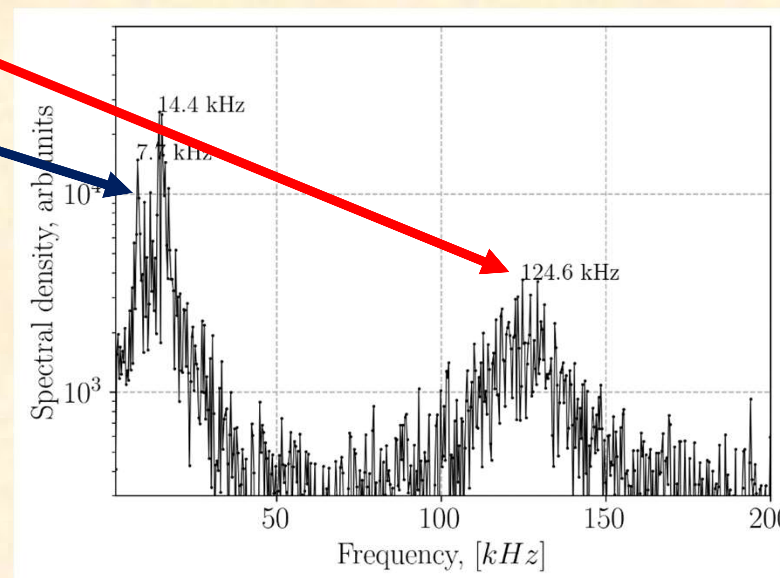
  Low frequency mode only

- Coexistence of low and high frequency oscillations

  Low and high frequency modes present



Fluid simulations spectra



Hybrid simulations spectra

Summary

- The continuum (2 PDE's) model for breathing mode is proposed with a key feature of the fixed non-uniform velocity profile with a backflow region near the anode
- The investigation of the 1D continuous predator-prey type model shows good agreement with the results of the full model and promising agreement with experimental data; backflow characteristics and ionization profiles are required as input parameters
- Reduced (simplified) models are valuable because they not only reasonably predict important characteristics of the breathing mode but, even more importantly, may indicate the critical physics parameters for the mode excitation and characteristics

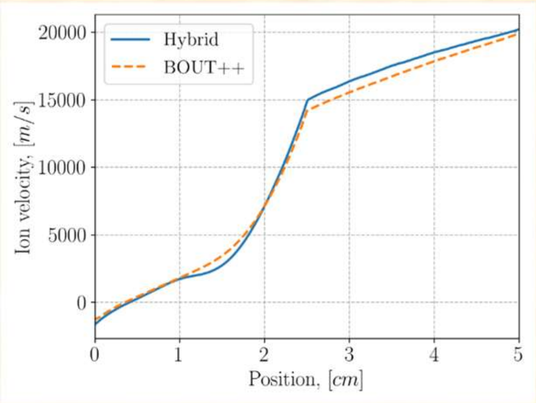
Thank you for your attention!

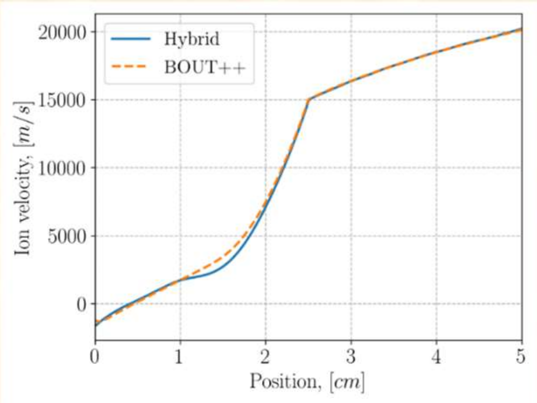
Fluid vs Hybrid codes benchmarking:

- Hybrid model has fluid electrons but ions and neutrals are kinetic
- Two models were compared: **Full Fluid**: UofS implementation, O. Chapurin, UofS and **Hybrid**: (fluid electrons + kinetic ions and neutrals) G. Hagelaar et al, LAPLACE,

  O.Chapurin et al., Physics of Plasmas, 2020; A. Smolyakov et al., AIAA Propulsion and Energy, 2019
- Agreement in averaged profiles is pretty good, oscillations amplitude can be up 50% different
- **Different physics for ions and neutrals in fluid and kinetic models.** Different boundary conditions on the ion velocity: Anode sheath effects?
- Ions and neutrals can have the finite energy. Agreement is improved when finite pressure is added to the fluid equations

Ion velocity





Chapurin et al, 2020