Fluid simulation of low frequency ionization oscillations in Hall thrusters

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Introduction

The main objective is to develop 1D fluid numerical model that describes how Hall thrusters work with focus on low frequency ionization oscillations.

Ionization Oscillations

In the Hall thrusters, ionization oscillations in the 10 kHz to 20 kHz frequency range take place because of the following. The atom flow in the large magnetic field region is strongly ionized. This makes the atom front move upstream into a lower magnetic field region where the electron mobility is larger and so the ionization is less efficient. As a result the current is decreased until the neutral atom front moves back where intense ionization takes place again. Since this problem is non-linear we attempt to model it.

Model

The model we attempt to develop is based on models in [1, 2]. In this 1D fluid model we assume quasineutrality and plasma's azimuthal and radial uniformity. The model consists of following equations:

Continuity equation for neutral atoms

$$\frac{\partial n_g}{\partial t} + \frac{\partial (n_g v_g)}{\partial z} = -n_g n K_{iz} + \nu_{iw} n, \tag{1}$$

continuity equation for ions

$$\frac{\partial n}{\partial t} + \frac{\partial (n v_{iz})}{\partial z} = +n_g n K_{iz} - \nu_{iw} n, \tag{2}$$

ion momentum equation

$$\frac{\partial n v_{iz}}{\partial t} + \frac{\partial (n v_{iz}^2)}{\partial z} = \frac{|q| n E}{M} + n_g n K_{iz} v_g, \tag{3}$$

electron equation of motion

$$0 = -|q| n (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \nabla(|q| n T_e) - m n \boldsymbol{v}_e \nu_m, \tag{4}$$

and electron energy equation

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\frac{1}{2} m n v_e^2 + \frac{3}{2} n |q| T_e\right) + \nabla \cdot \left(\frac{1}{2} m n v_e^2 \boldsymbol{v}_e + \frac{5}{2} n |q| T_e \boldsymbol{v}_e\right) = \\ &= -|q| n \boldsymbol{E} \cdot \boldsymbol{v}_e - n_g n K_{iz} |q| \epsilon_{ion} \gamma_i - \nu_{ew} n |q| \epsilon_w - \frac{m v_e^2}{2} K_{iz} n_g n + \frac{m v_e^2}{2} n \nu_{ew}. \end{aligned} \tag{5}$$

Parameters

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U	210 V
B_{max}	22 mT
$\dot{m}$	$5\,\mathrm{mg \cdot s^{-1}}$
v_g	$200\,\mathrm{m \cdot s^{-1}}$
l_b	1.25 cm
l_c	2.5 cm
ϵ_{ion}	12.1 eV
ϵ_s	50 eV
K_{el}	$2.5 \times 10^{-13}\,\mathrm{m^2 s^{-1}}$
K_0	$1.8 \times 10^{-13}\,\mathrm{m^2 s^{-1}}$
ϵ_{ave}	$\frac{3}{2} T_e$
c_s	$\sqrt{\frac{q T_e}{M}}$
γ_i	3

$$B(z) = B_{max} \exp\left[-\frac{(z - l_c)^2}{l_b^2}\right] \tag{6}$$

$$\nu_{iw} = \frac{4}{3} \frac{c_s}{R_2 - R_1} \tag{7}$$

$$\nu_{ew} = \frac{\nu_{iw}}{1 - \sigma} \tag{8}$$

$$\nu_m = n_g K_{el} + \frac{\omega_c}{160} + \nu_{ew} \tag{9}$$

$$K_{iz} = K_0 \left(\frac{\epsilon_{ave}}{\epsilon_{ion}}\right)^{\frac{1}{4}} \exp\left(-2\frac{\epsilon_{ion}}{\epsilon_{ave}}\right) \tag{10}$$

$$\epsilon_w = 2T_e + E_{kin} + (1 - \sigma) T_e \ln\left[\sqrt{\frac{M}{2\pi m}}(1 - \sigma)\right] \tag{11}$$

$$\sigma = \min\left(\frac{2T_e}{\epsilon_s}, 0.986\right) \tag{12}$$

Results

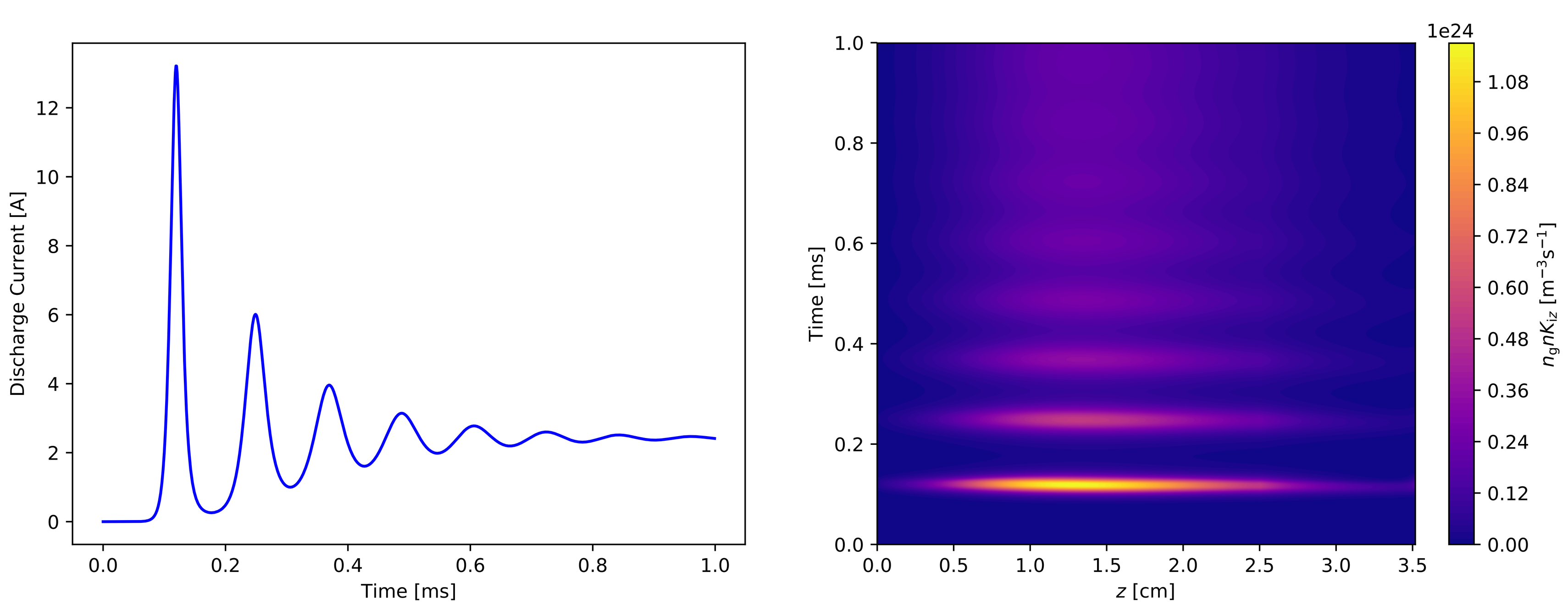

Figure 1 and 2: Discharge current as a function of time and the ionization source term as a function of space and time.

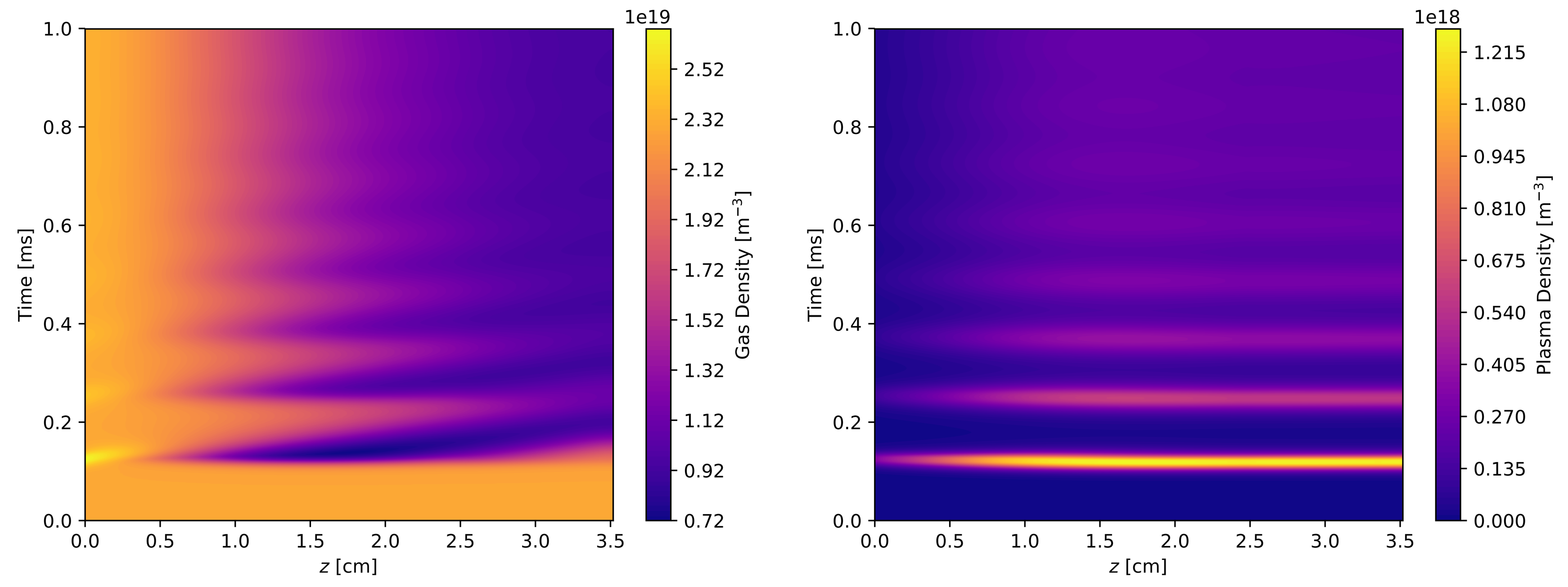

Figure 3 and 4: Gas and plasma density as a function of space and time.

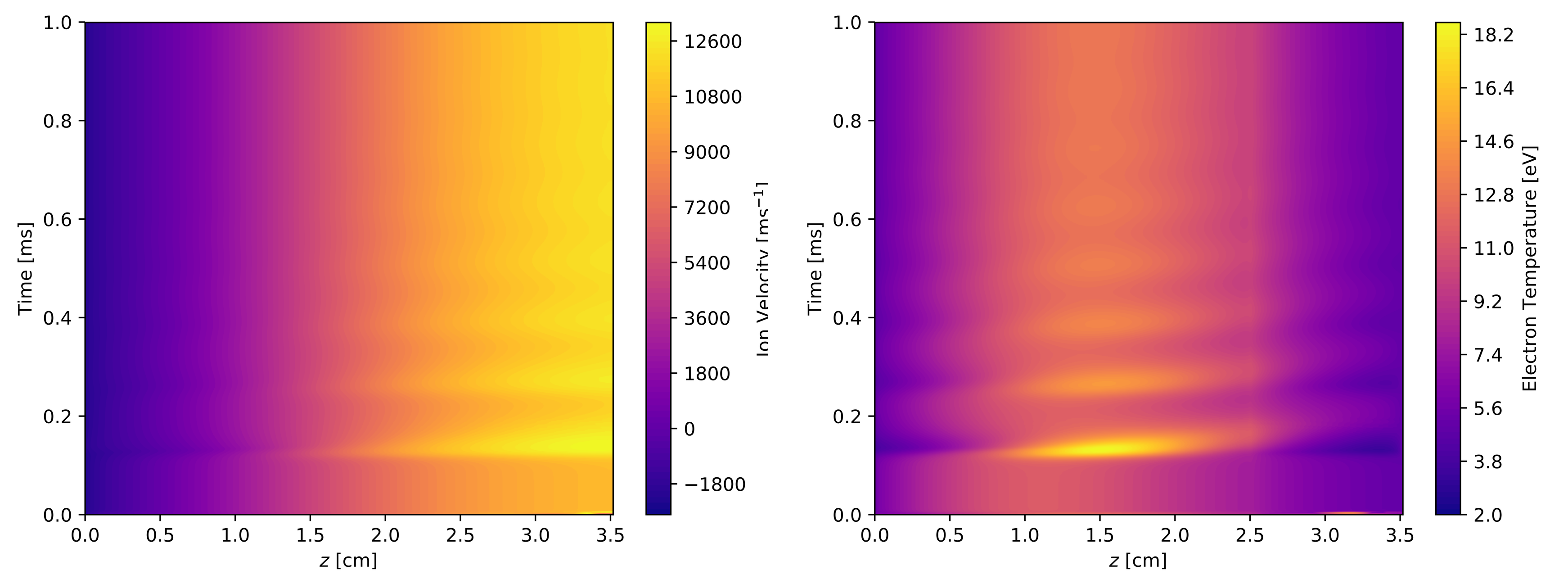

Figure 5 and 6: Ion velocity and electron temperature as a function of space and time.

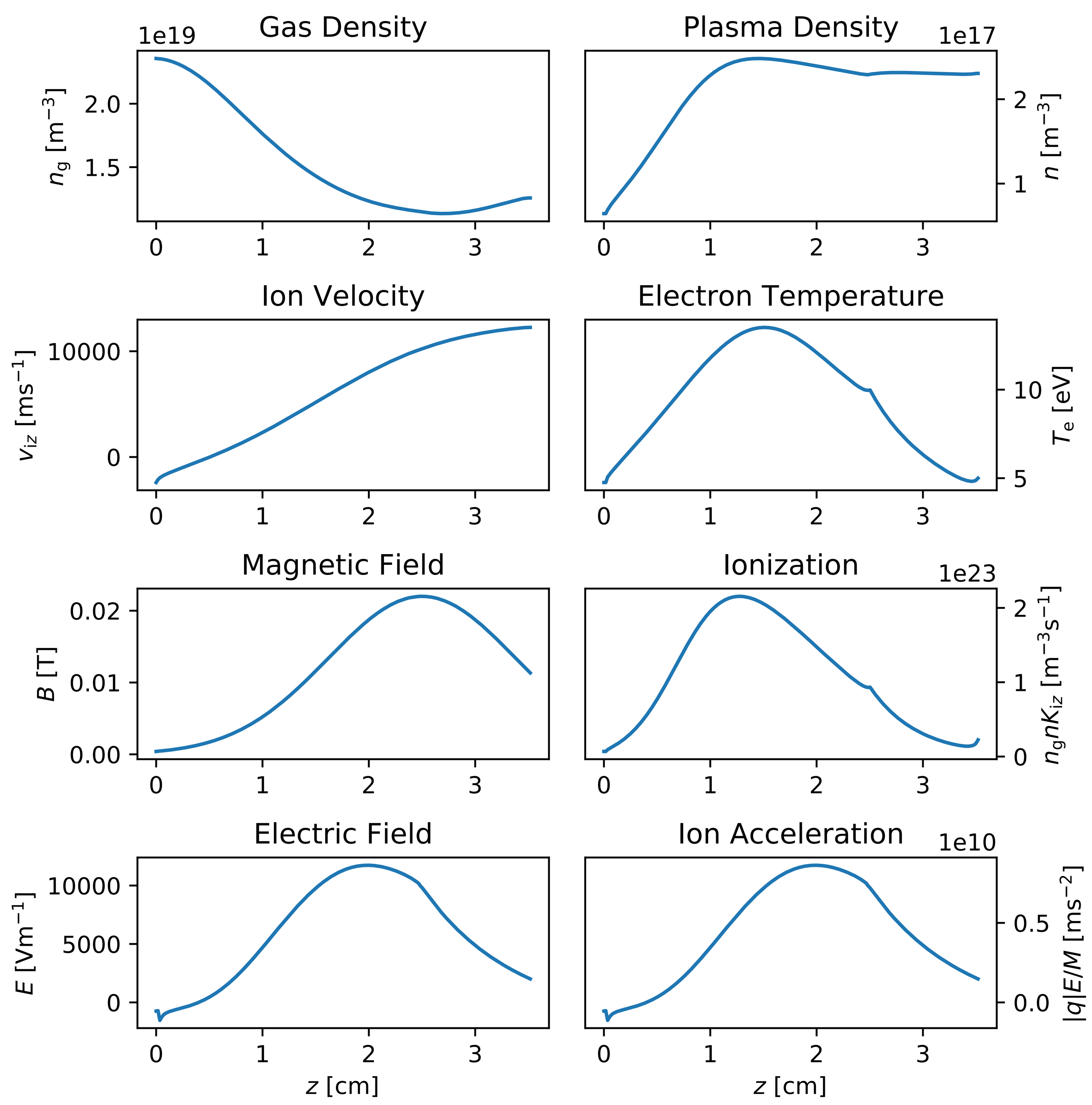

Figure 7: Axial distributions averaged over the third period of the ionization oscillations. This enabled us to calculate steady-state parameters such as the power spent on acceleration (440 W) and ionization (80 W), the thrust (40 mN) and the utilization factor (65 %).

Conclusion

- The ionization oscillations were successfully depicted by the model.
- The model enabled us to calculate the plasma properties and parameters such as the thrust, the discharge current and the utilization factor.
- The apparent damping in the results was unexpected. We are commited to finding the cause of the damping and further improving the model.

References

[1] S. Barral, E. Ahedo, *Low-frequency model of breathing oscillations in Hall discharges*, Physical Review **79**, 046401 (2009).

[2] R. Martorelli, T. Lafleur, A. Bourdon, P. Chabert, *Comparison between ad-hoc and instability-induced electron anomalous transport in a 1D fluid simulation of Hall-effect thruster*, Phys. Plasmas **26**, 083502 (2019).