Axial equilibrium model of the Hall discharge and its far plume with electron inertia and other effects

E. Bello-Benítez & E. Ahedo

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Contents

Introduction

Motivation

- 1D axial models of Hall effect thrusters (HET) can capture the fundamental physics of the discharge.
- Very light computational workload.
- Fast parametric studies.
- Great flexibility to introduce and analyze modeling decisions (e.g., boundary conditions).

Novelties

- Azimuthal inertia terms.
- Finite thickness cathode.
- Coupled chamber and far-field regions.
- Thus, solutions including chamber and far-plume evolution.

Model formulation

Three-fluid model equations

- Neutrals: cold, wall source, ionization and CEX collisions.
- Ions: cold, unmagnetized, wall sink, ionization and CEX collisions
- Electrons: finite T_e, magnetized, wall effects; ionization, e-n elastic and turbulent collisions

$$\frac{1}{A}\frac{d}{dz}(An_eu_{ze}) = n_e(\nu_p - \nu_w) + \boldsymbol{S_c}$$

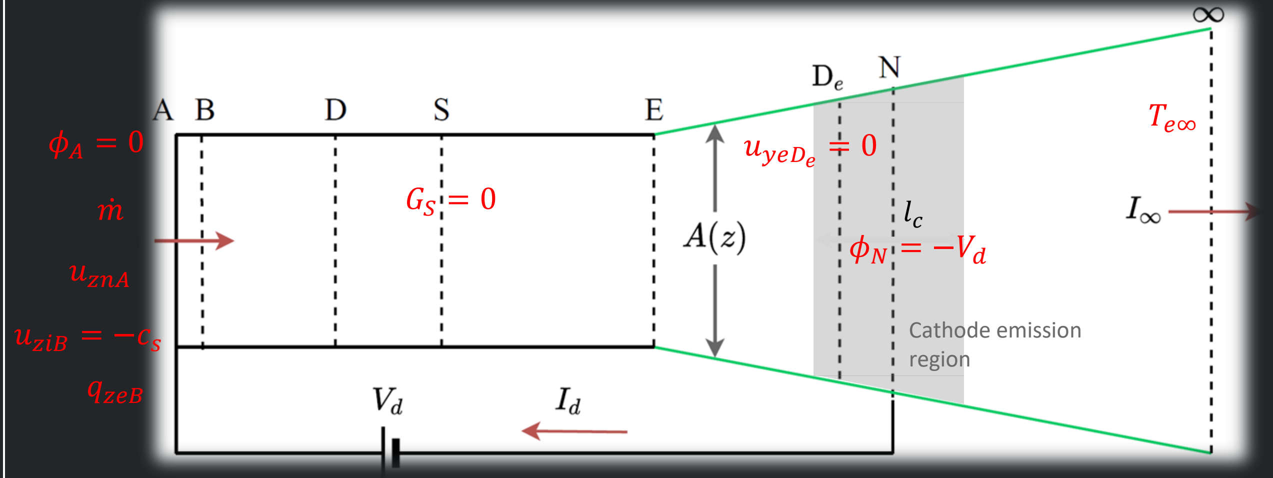
$$0 = -\frac{dp_e}{dz} + en_e\frac{d\phi}{dz} + eBn_eu_{ye} - m_en_e\nu_eu_{ze}$$

$$\boldsymbol{m_en_eu_{ze}\frac{du_{ye}}{dz}} = -eBn_eu_{ze} - m_en_e\nu_eu_{ye}$$

$$\frac{1}{A}\frac{d}{dz}\left[A\left(\frac{5}{2}n_eT_eu_{ze} + q_{ze}\right)\right] = u_{ze}\frac{dp_e}{dz} - n_e\nu_pE_{\text{inel}} - n_e\nu_{we}T_e + m_en_e\nu_eu_e^2 + \boldsymbol{S_cE_c}$$

$$q_{ze} = -\frac{5p_e}{2m_e\nu_e}\frac{1}{(1+\chi^2)}\frac{dT_e}{dz}$$

Boundary conditions



A ≡ Anode wall
B ≡ Anode sheath-Edge
D ≡ Ion stagnation point
S ≡ Ion Sonic point

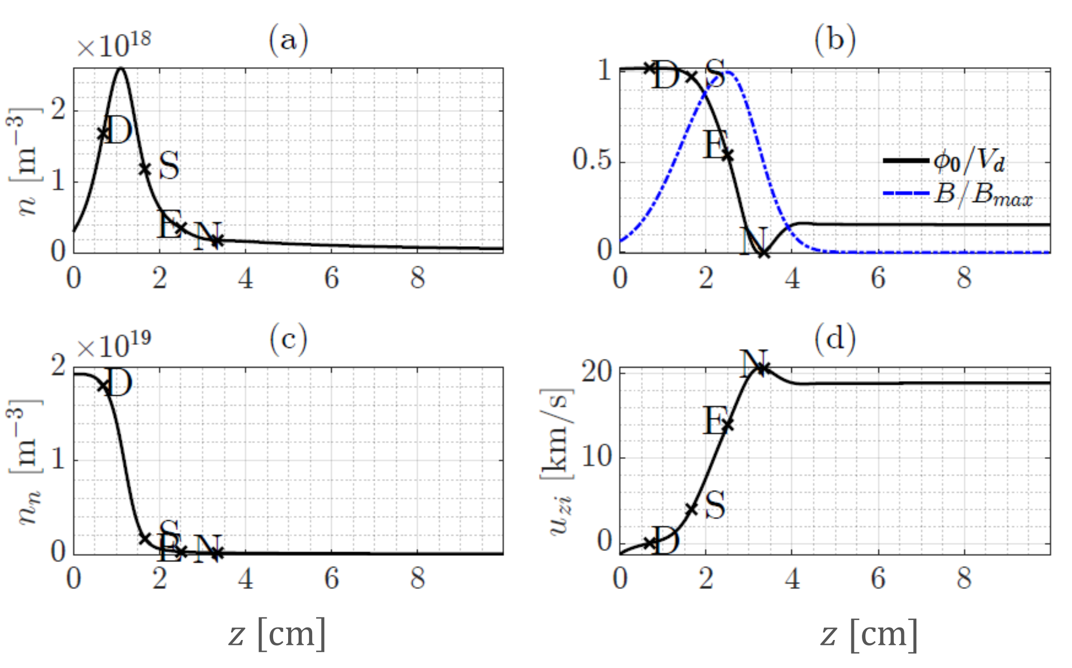
E ≡ Thruster exit
De ≡ Electron stagnation point
N ≡ Cathode center
∞ ≡ Far-field boundary

Nominal solution

$\dot{m}$	4.75 mg s^{-1}	V_d	300 V
B_m	247 G	z_m	2.5 cm
A_{in}	40 cm^2	R	4.25 cm
u_{znB}	300 m s^{-1}	$T_{e\infty}$	1 eV
I_∞	0	l_c	1 cm
E_c	7.5 eV	$L_{N\infty}$	40 cm
L_E	2.5 cm	L_N	3.35 cm
$L_{m,\text{in}}$	1.5 cm	$L_{m,\text{out}}$	1.0 cm

Nominal solution

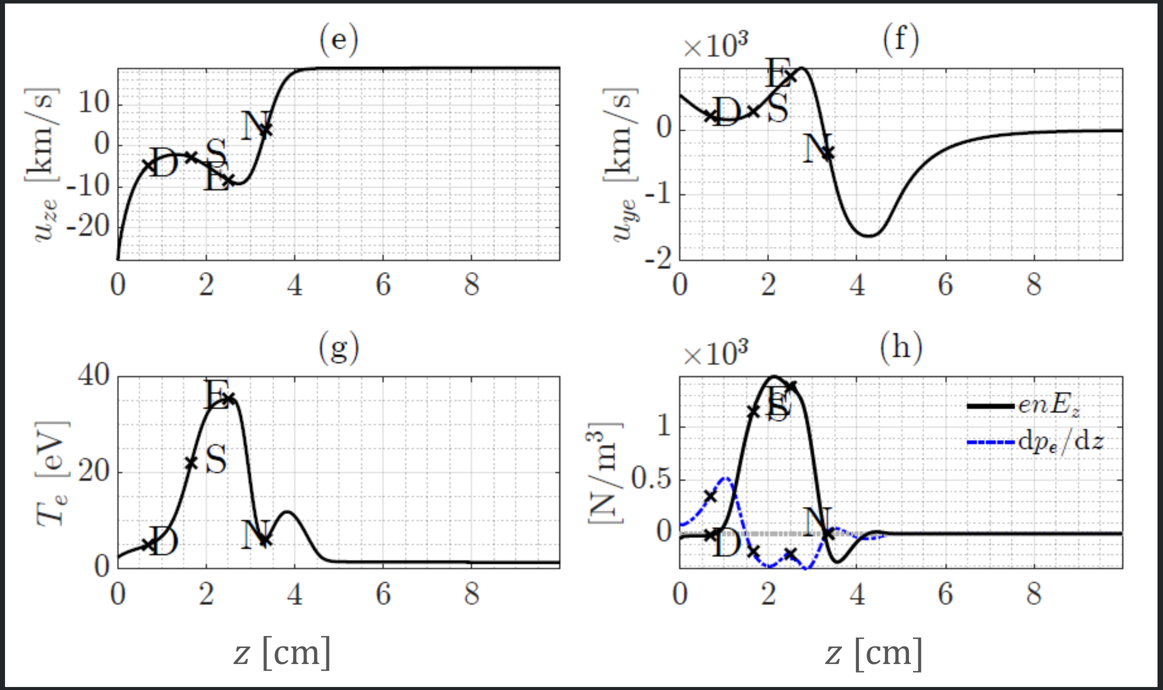
Heavy-species behavior



From left to right:

- Ion-backstreaming region
- Ionization region
- Acceleration region
- Deceleration and mild acceleration

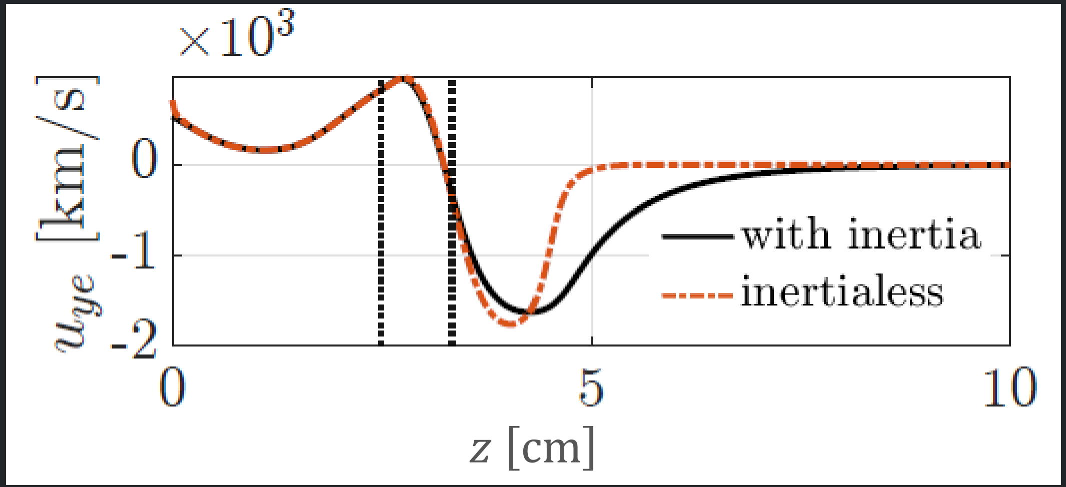
Electron behavior



- u_{ze} reversed by the cathode effect.
- u_{ye} close to anode is mostly a diamagnetic drift.
- u_{ye} in rest of chamber and near plume is mostly an ExB drift.
- Slow decay of u_{ye} in the far plume due to Coulomb collisions.
- T_e increases close to cathode because of Joule heating.
- T_e decreases in the chamber due to ionization and wall losses.
- $T_e(z)$ is almost flat in the far plume due to the large thermal conductivity.

Sensitivity analysis

Electron inertia



In the far plume, where $B \approx 0$:

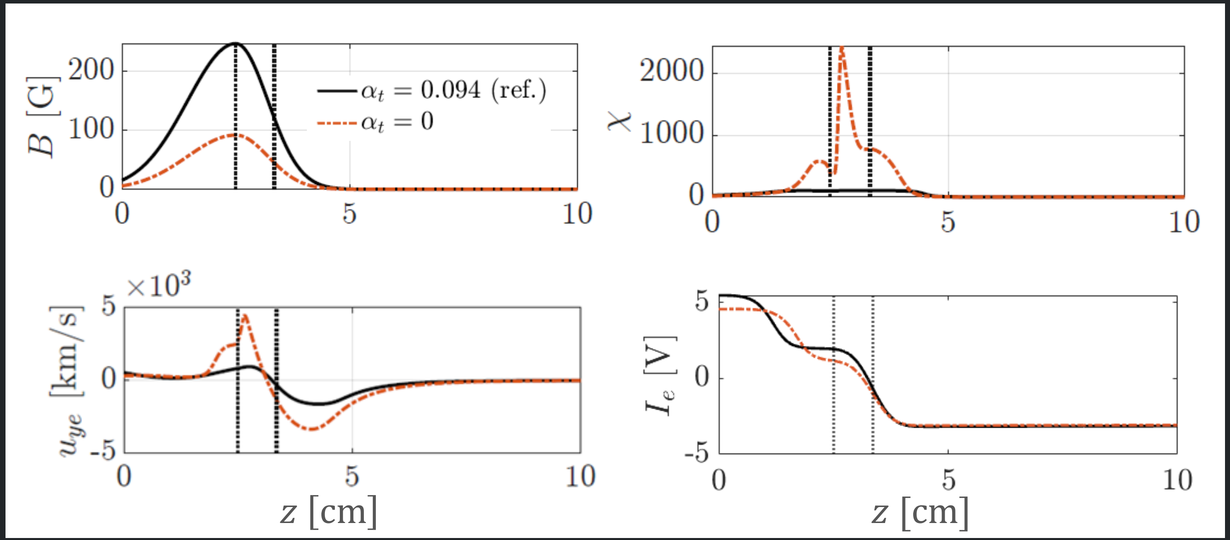
- Without azimuthal inertia, the vanishing of the magnetic force implies the vanishing of azimuthal collisions.

$$0 \approx -m_e n_e \nu_e u_{ye}$$

- With azimuthal inertia, there is a slower collisional decay of u_{ye}

$$m_e n_e u_{ze} \frac{du_{ye}}{dz} \approx -m_e n_e \nu_e u_{ye}$$

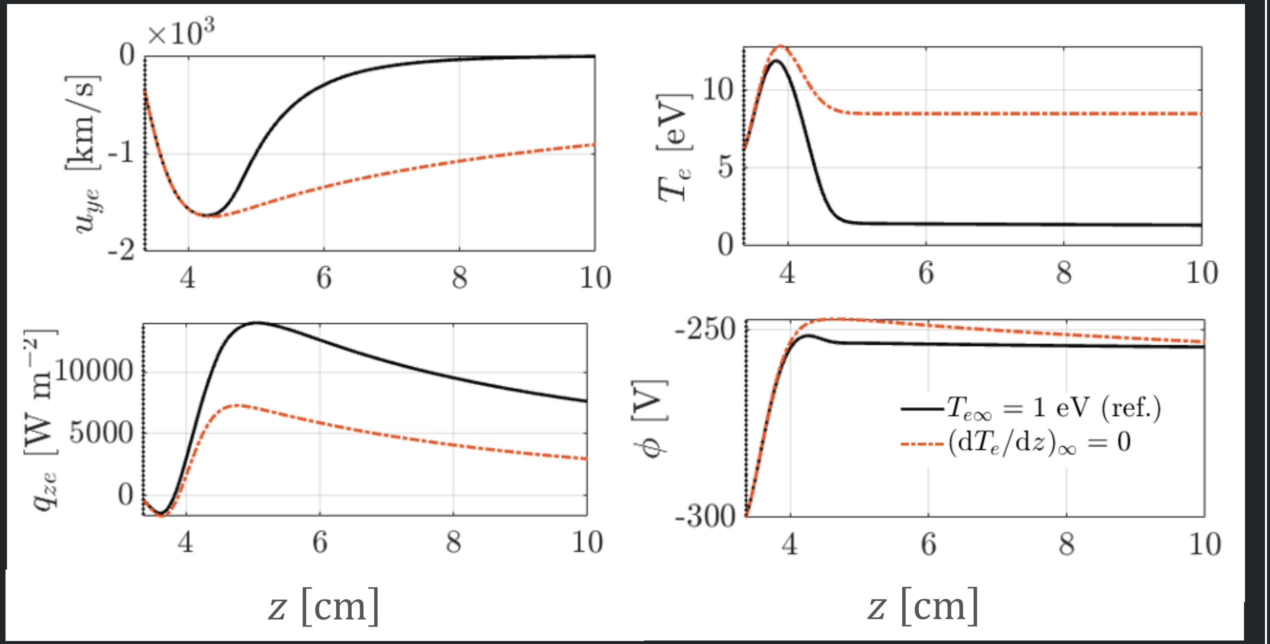
Turbulent parameter α_t



- We had to decrease B_m from 247 G to 92 G to find a stationary solution with $\alpha_t = 0$.
- Even so, maximum Hall parameter χ increases from 105 to 2440 indicating a much stronger electron confinement.
- Close to anode the solutions are much similar since other collisions (e-n, e-i) are equaly important as ν_t.
- Close to exit, a much larger u_{ye} is needed to balance the axial electric force.
- The value of I_e reaching the anode is 1 A smaller, with I_i similar in both cases. Thus, having a more effcient operation.

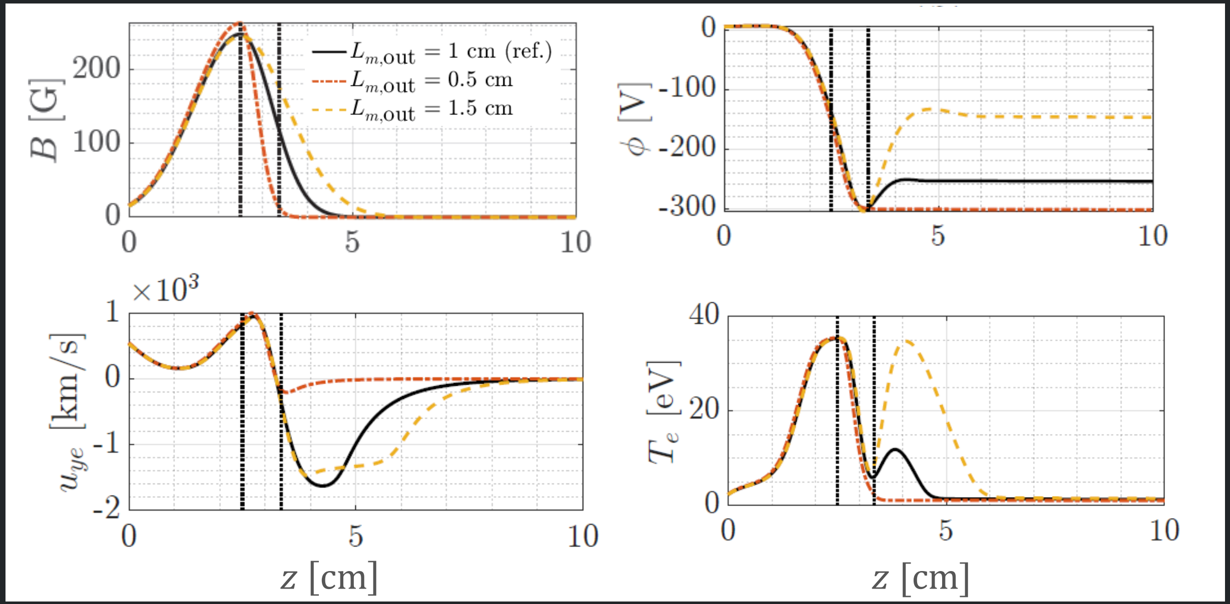
Sensitivity analysis

Far-field boundary condition



- The $(dT_e/dz)_\infty = 0$ case leads to a larger $T_{e\infty}$, that results in smaller ν_{ei} and, thus, is a slower decay of u_{ye}.
- In the far plume $\frac{1}{A}\frac{d}{dz}\left[A\left(\frac{5}{2}n_eT_eu_{ze} + q_{ze}\right)\right] \approx u_{ze}T_e\frac{dn_e}{dz} \approx -eu_{ze}n_eE_z$
- In both cases $\left[A\left(\frac{5}{2}n_eT_eu_{ze} + q_{ze}\right)\right]_E$ is very similar.
- In the $(dT_e/dz)_\infty = 0$ case the far-plume q_{ze} is limited, T_e is larger and, thus, an also larger E_z is developed.

Magnetic decay in the plume



- A slow decay of B leads to a large E_z in the near plume, under the current geometrical configuration.
- This E_z may produce a large heating of electrons.
- Also, deceleration of ions in the near plume.
- The plasma-thuster interaction in the plume past the cathode produces drag, and this is effect is enhanced in the slowest-decay cases.
- Thrust (faster to slowe decay): 91, 83 and 59 mN.

Conclusion and future work

Conclusion

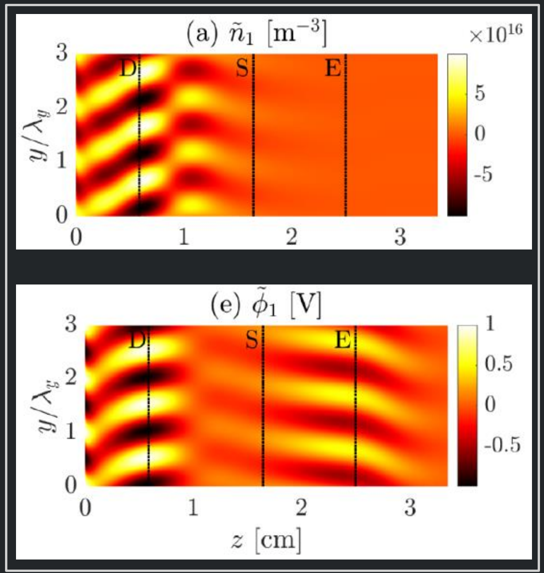
- We have presented a study of a 1D-axial stationary model of the Hall discharge with main novelties:
  - Electron azimuthal inertia in momentum balance.
  - Finite cathode model.
  - Analysis of the far-field plasma behavior.
  - Sensitivity analyses to different aspects.
- The finite cathode couples the interior and exterior regions of the discharge, although the behavior of the interior plasma is quite independent of far-field conditions.
- The electron azimuthal drift decays there, due to collisions. The decay rate is largely dependent on the plume temperature.

Future work

- Investigate the stability of these equilibrium solutions, extending the analysis to the plume past the cathode. In previous works (below) we focused on the region between anode and cathode.

E. Bello-Benítez and E. Ahedo, "Axial-azimuthal, high-frequency modes from global linear-stability model of a Hall thruster", *Plasma Sources Science and Technology*, Vol. 30, 2021, pp. 035003.

Near-anode instability (241 kHz)



Near-plume instability (2.87 MHz)