HALL THRUSTER

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INTRODUCTION

- Electric propulsion in early 20th century (Goddard [2] & Tsiolkovskiy [3]).
- First ion thruster launched into orbit in 60s and Russia developed the first Hall Thruster for station-keeping on communication satellites (1971) [4].
- The actual use of Hall Thruster began with SMART-1 in 2003 with a lunar mission by ESA. In 2010 the aerojet BPT-4000 reached the highest power until that date, 4.5 kW and not only performed station-keeping tasks but also provided orbit-raising capabilities.
- Actually, SpaceX uses Hall Thrusters in the StarLink constellation with argon as a propellant.

INTRODUCTION

- In 2023 was launched Psyche, the first spacecraft powered by Hall Thrusters beyond Earth's SOI.
- In parallel, the laboratory PEPL in the University of Michigan has developed a Hall Thruster (X3) with a power throttling range from 2 kW to 200 kW offering unprecedented flexibility in adapting to mission requirements.
- Another important state of the art is the NASA Hall Thruster HERMeS [6] for the ARTEMIS program. It operates at 13 kW, offering 3000 s of Isp with maximum thrust of 600 mN and efficiency of 68.2%. High Isp and thrust with small power source.

HALL THRUSTER DESCRIPTION

Two Types:

1- Hall Thruster with dielectric walls.

2- Hall Thruster with Anode Layer (TAL).

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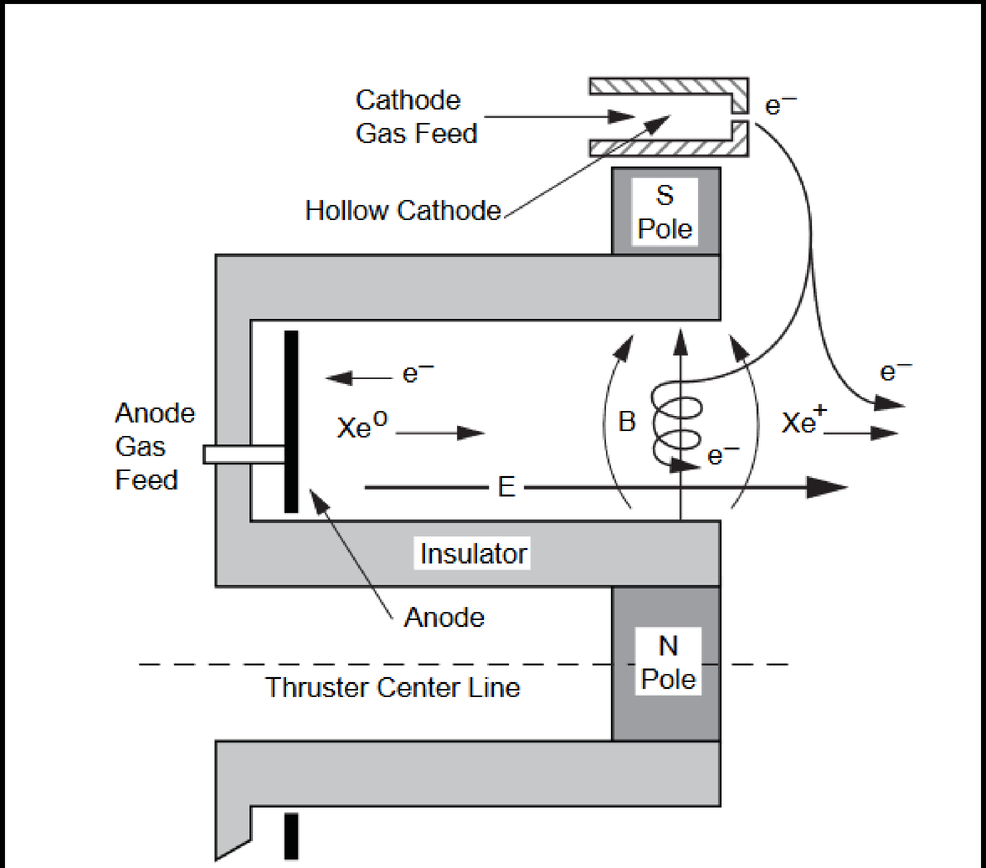

Cross-section schematic of a Hall Thruster with dielectric walls. The thruster is composed by an anode, a cathode and a magnetic and electric field. The path of the ions and electrons are also shown [1].

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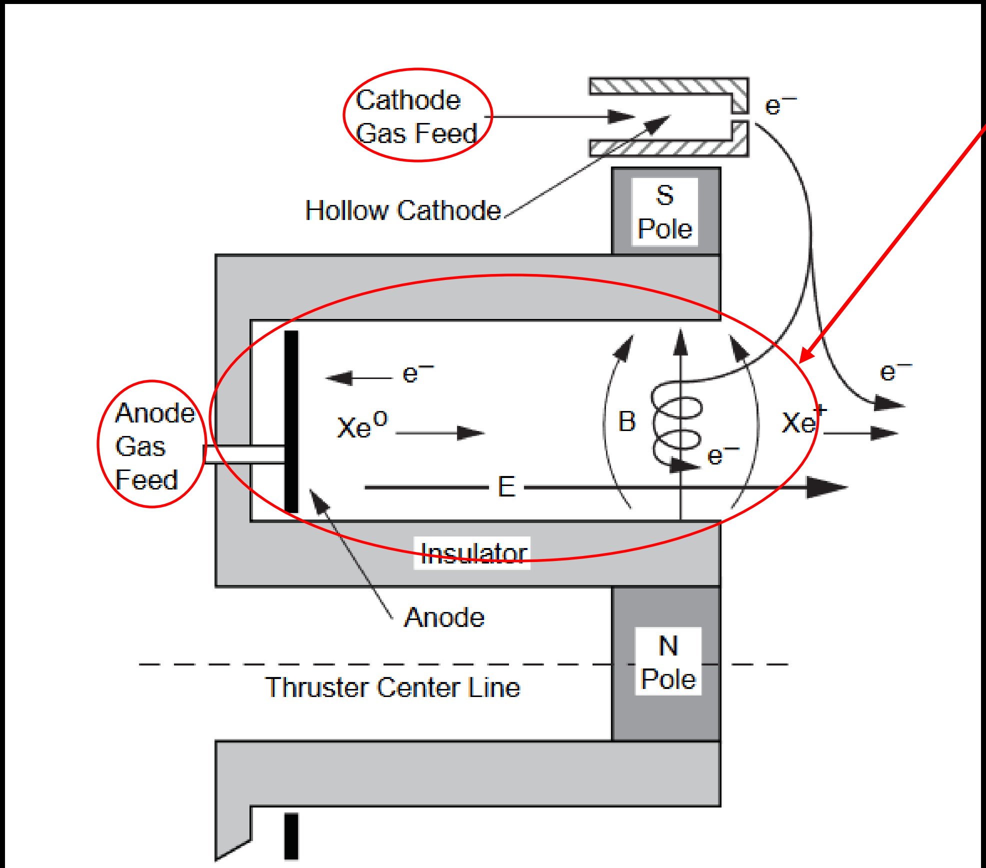
Discharge Channel



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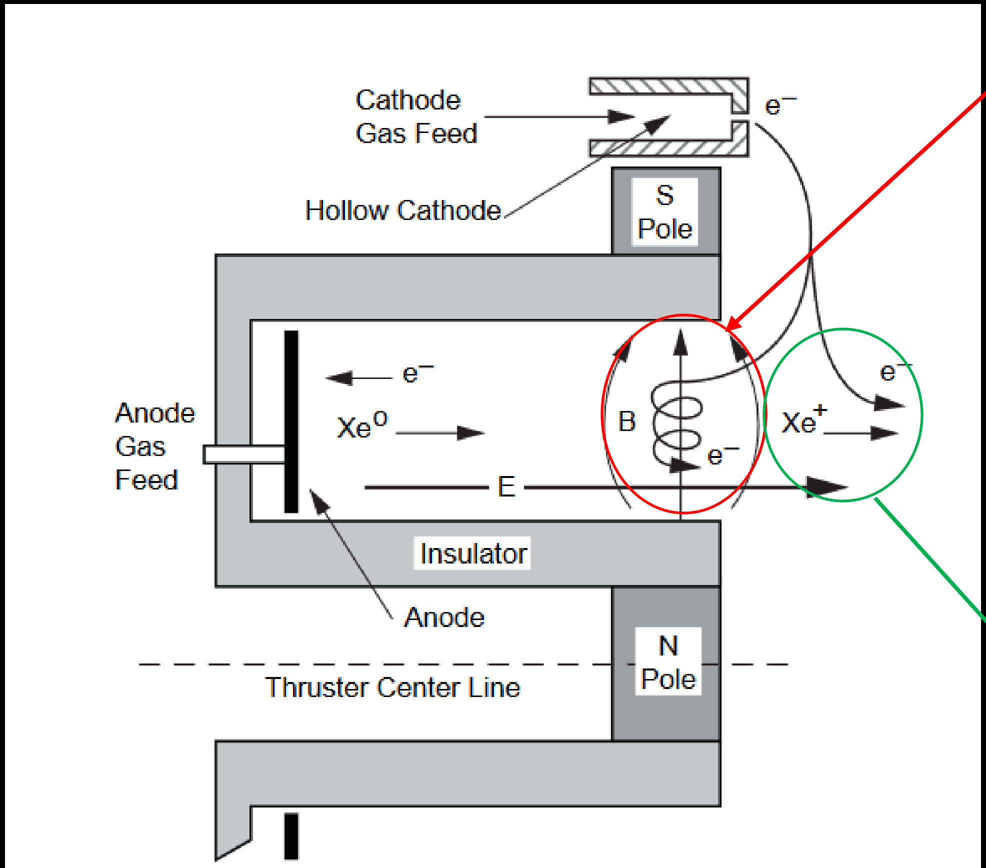


Cross-section schematic of a Hall Thruster with dielectric walls. The thruster is composed by an anode, a cathode and a magnetic and electric field. The path of the ions and electrons are also shown [1].

-Electrons orbit magnetic field lines.

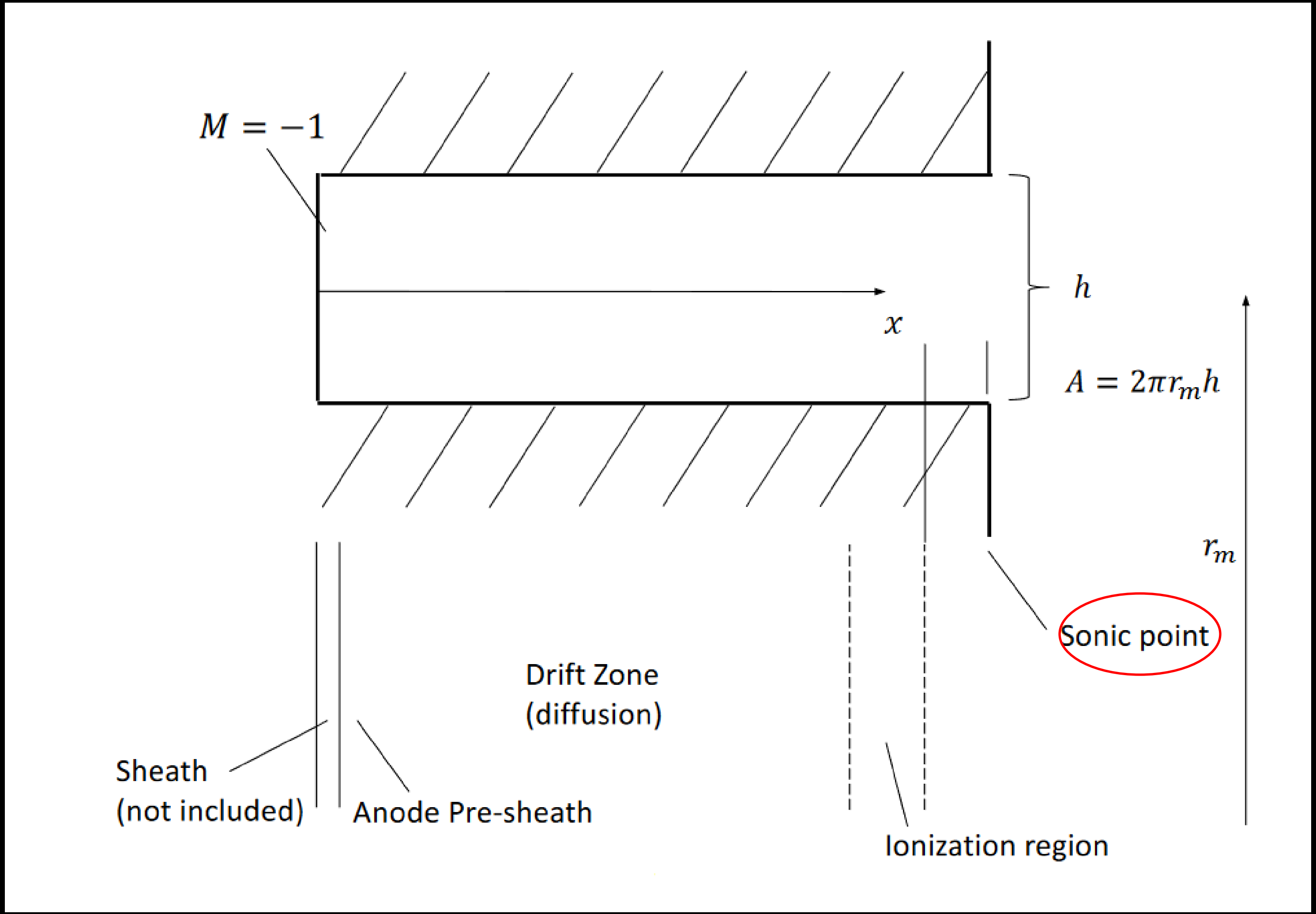
-**Hall Current** is formed around the cylinder.

-**Ionization** and **acceleration** of the ions with the electric field.

-Accelerate plasma and thrust is generated.

-Device electrically neutral.

NUMERICAL ANALYSIS: 1D HALL MODEL



One dimension Hall Thruster model. Figure has been taken from [2].

NUMERICAL ANALYSIS: 1D HALL MODEL

NON-DIMENSIONAL PARAMETERS

Ion Velocity

$$\left[\frac{5}{3}\hat{T}_e - \hat{v_i}^2\right]\frac{d\hat{v}_i}{d\hat{x}} = \frac{5}{3}\left(\hat{v}_i - \frac{\hat{\Gamma}_d}{\hat{n}_e}\right)\hat{\nu_e}\hat{v}_i + \hat{\nu_{ion}}\left\{\frac{5}{3}\hat{T}_e + \hat{v}_i(\hat{v}_i - \hat{v}_n) - \frac{\hat{v}_i}{\hat{v_{ex}}}\left(\frac{2}{3}\hat{E}_i' + \frac{5}{3}\hat{T}_e\right)\right\} \quad (3)$$

Electron Density

$$\left[\frac{5}{3}\hat{T}_e - \hat{v_i}^2\right]\frac{d\hat{n}_e}{d\hat{x}} = -\frac{5}{3}\frac{m_e}{m_i}\hat{n}_e\hat{v_{ex}}\hat{\nu_e} - \hat{n}_e\hat{\nu_{ion}}\left\{(2\hat{v}_i - \hat{v}_n) - \left[\frac{2}{3}\hat{E}_i' + \frac{5}{3}\hat{T}_e\right]\frac{1}{\hat{v_{ex}}}\right\} \quad (4)$$

Electron Temperature

$$\left[\frac{5}{3}\hat{T}_e - \hat{v_i}^2\right]\frac{d\hat{T}_e}{d\hat{x}} = -\frac{2}{3}\hat{v}_i^2\frac{m_e}{m_i}\hat{v_{ex}}\hat{\nu_e} - \hat{\nu_{ion}}\left\{\frac{2}{3}\hat{T}_e(2\hat{v}_i - \hat{v}_n) - \left(\frac{\hat{v_i}^2 - \hat{T}_e}{\hat{v_{ex}}}\right)\left(\frac{2}{3}\hat{E}_i' + \frac{5}{3}\hat{T}_e\right)\right\} \quad (5)$$

Potential

$$\left[\frac{5}{3}\hat{T}_e - \hat{v_i}^2\right]\frac{d\hat{\phi}}{d\hat{x}} = -\frac{5}{3}\frac{m_e}{m_i}\hat{v_{ex}}\hat{\nu_e}\hat{v_i}^2 - \hat{\nu_{ion}}\left\{\frac{5}{3}\hat{T}_e(2\hat{v}_i - \hat{v}_n) - \frac{\hat{v_i}^2}{\hat{v_{ex}}}\left[\frac{2}{3}\hat{E}_i' + \frac{5}{3}\hat{T}_e\right]\right\} \quad (6)$$

NUMERICAL ANALYSIS: 1D HALL MODEL

NON-DIMENSIONAL PARAMETERS TO PARAMETERS

$$\hat{v_{ex}} = \left(\hat{v_i} - \frac{\hat{\Gamma_d}}{\hat{n_e}}\right) \quad ; \quad n_n = n_* \left(\frac{\hat{\Gamma_m}}{\hat{c_n}} - \hat{n_e}\frac{\hat{v_i}}{\hat{c_n}}\right)$$

$$\hat{\nu_{en}} = \left(\frac{\hat{\Gamma_m}}{\hat{c_n}} - \hat{n_e}\frac{\hat{v_i}}{\hat{c_n}}\right)\frac{\sigma_{en}}{\sigma_0}\sqrt{\frac{8}{\pi}\hat{T_e}}$$

$$\hat{\omega_c} = \frac{qB}{m_e \nu_*} \quad ; \quad \hat{\nu_e} = \frac{\hat{\omega_c}^2}{\hat{\nu_{en}} + \alpha_B \hat{\omega_c}}$$

$$\hat{\nu_{ion}} = \frac{n_n}{n_*}\sqrt{\frac{8}{\pi}\hat{T_e}}(1 + 2\hat{T_e}) \exp\left(-\frac{1}{\hat{T_e}}\right)$$

$$\hat{T_e} = \frac{kT_e}{T_*} \quad ; \quad \hat{v_i} = \frac{v_i}{v_*} \quad ; \quad \hat{n_e} = \frac{n_e}{n_*} \quad ; \quad \hat{\phi} = \frac{e\phi}{T_*}$$

$$n_e = \hat{n_e} n_* \quad ; \quad \Gamma_i = \hat{v_i}\hat{n_e}\Gamma_* \quad ; \quad kT_e = \frac{\hat{T_e}T_*}{e} \ (\text{eV}) \quad ; \quad \phi = \hat{\phi}\frac{T_*}{e}$$

$$M = \frac{\hat{v_i}}{\sqrt{\frac{5}{3}\hat{T_e}}} \quad ; \quad x = \hat{x} l_*$$

Electron Density

Ion Flux Density

Electron Energy

Potential

Mach Number

Channel Position

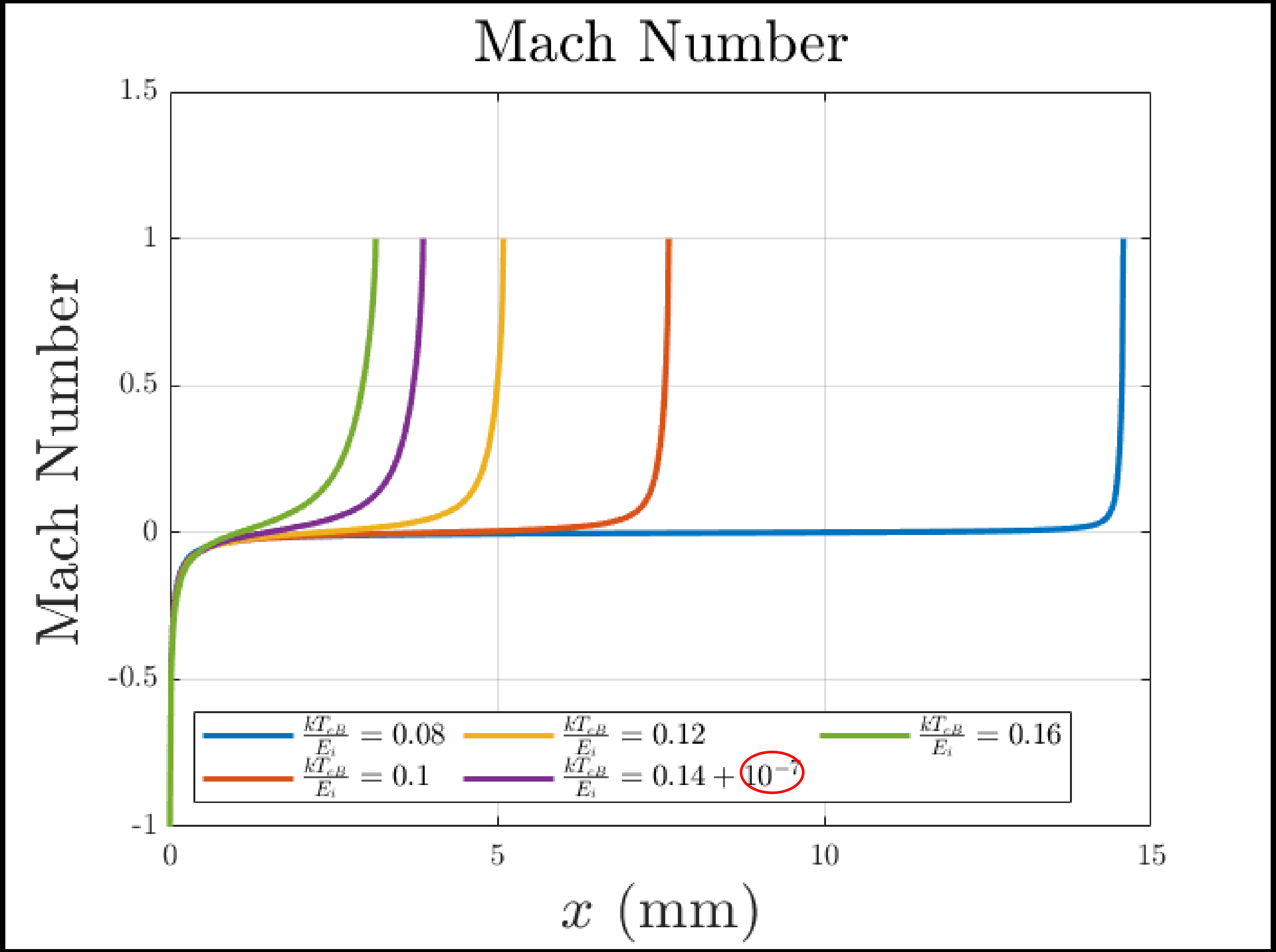
NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS

$$\hat{v}_i(0) = -\sqrt{\frac{5}{3}\frac{kT_{eB}}{E_i}} \quad ; \quad \hat{n}_e(0) = \frac{\Gamma_{iB}}{\Gamma_* \hat{v}_i(0)}$$

$$\hat{T}_e(0) = \frac{kT_{eB}}{E_i} \quad ; \quad \hat{\phi}(0) = 0$$

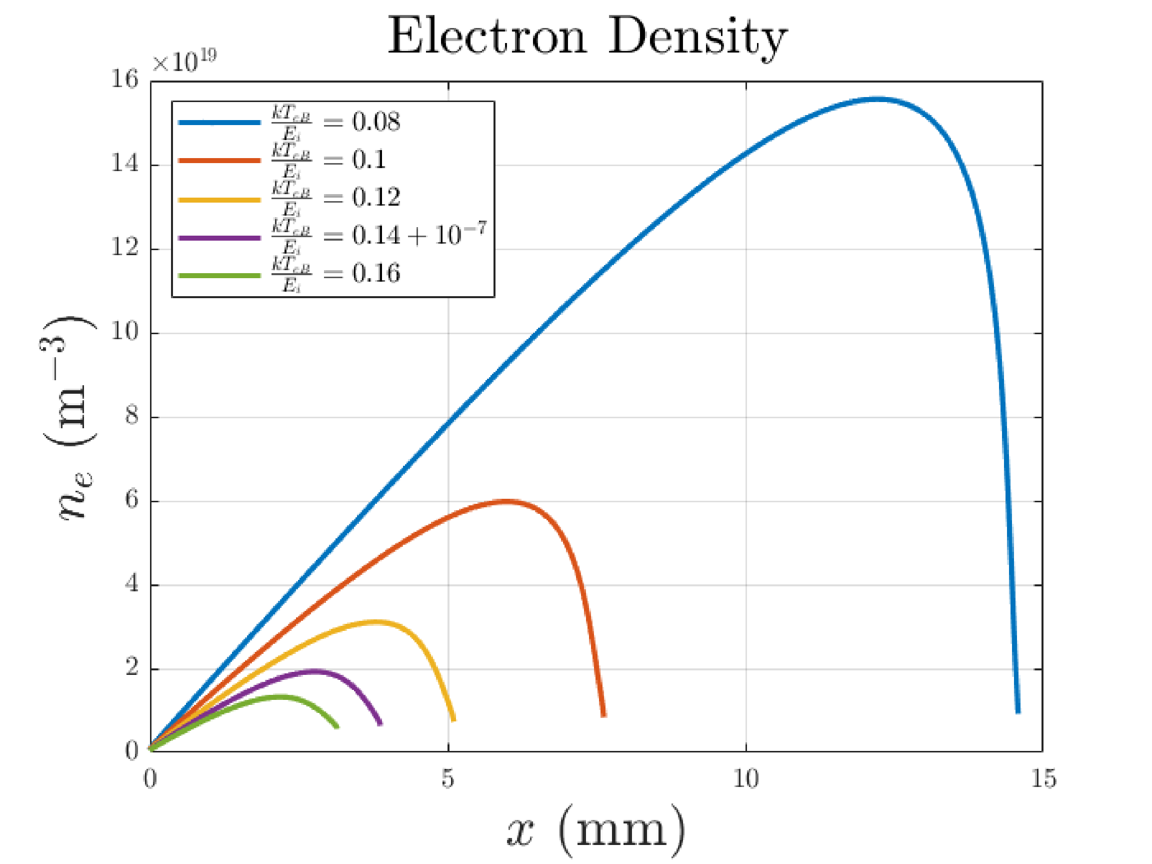
Initial Values



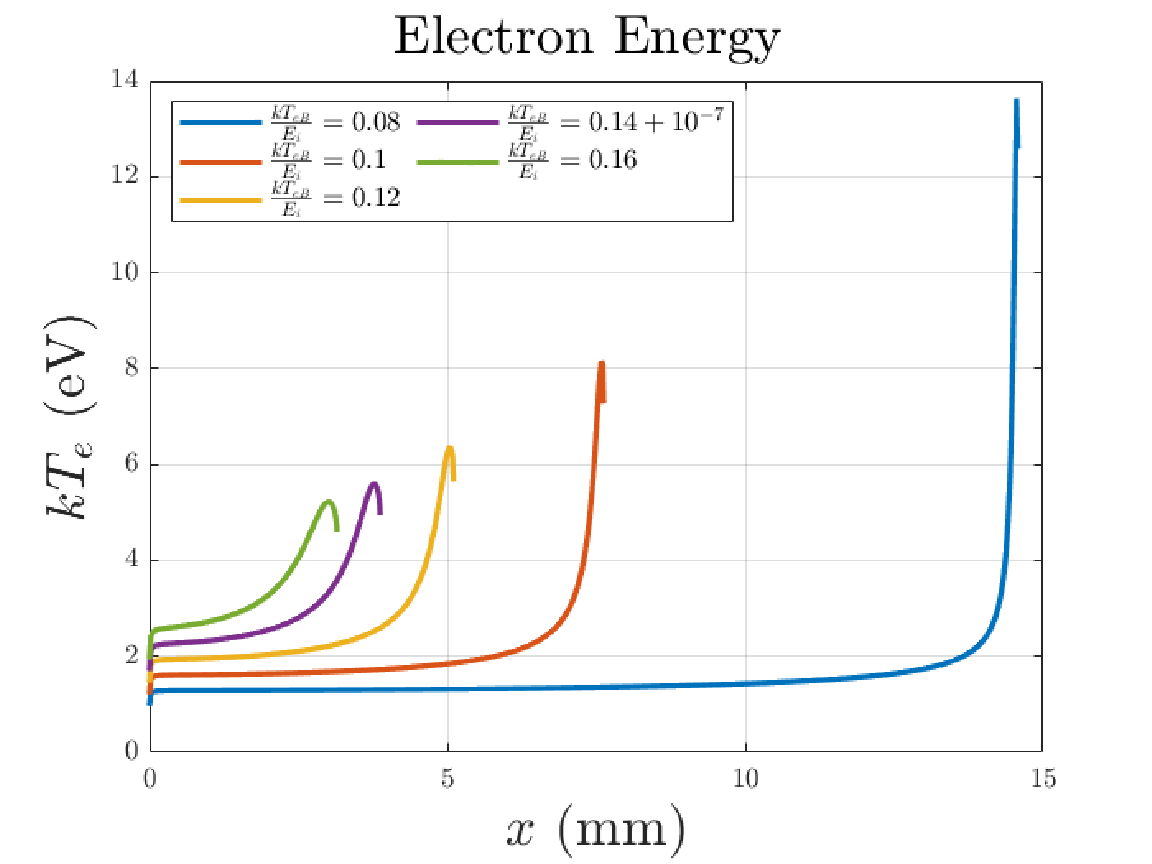
Mach number vs channel length in mm for the five requested initial values.

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS



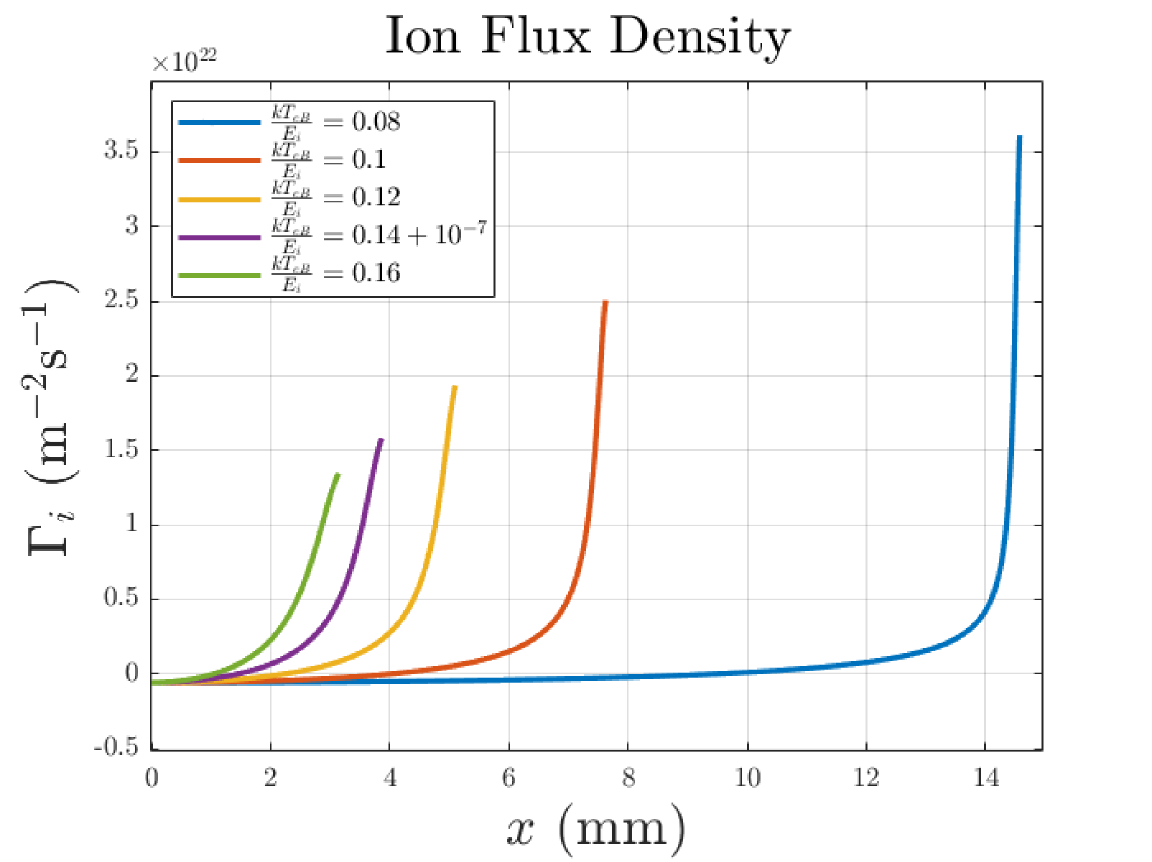
Electron density in m−3 vs channel length in mm for the five requested initial values.



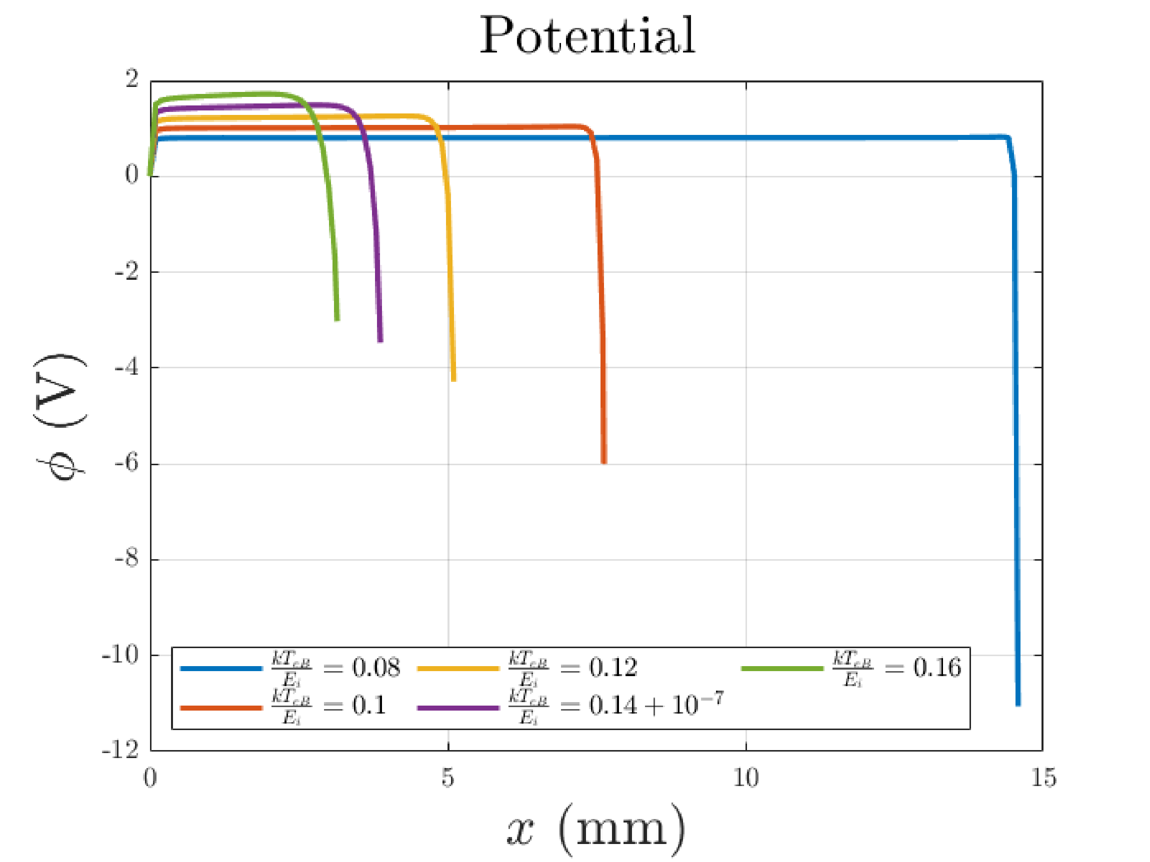
Electron energy in eV vs channel length in mm for the five requested initial values.

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS



Ion flux density in m−2s−1 vs channel length in mm for the five requested initial values.



Potential in V vs channel length in mm for the five requested initial values.

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS

Utilization factor

$$\eta_u = \frac{\dot{m}_i}{\dot{m}}$$

$$\eta_u = \frac{(n_e/n_n)(c_i/c_n)}{1 + (n_e/n_n)(c_i/c_n)}$$

Back-Streaming efficiency

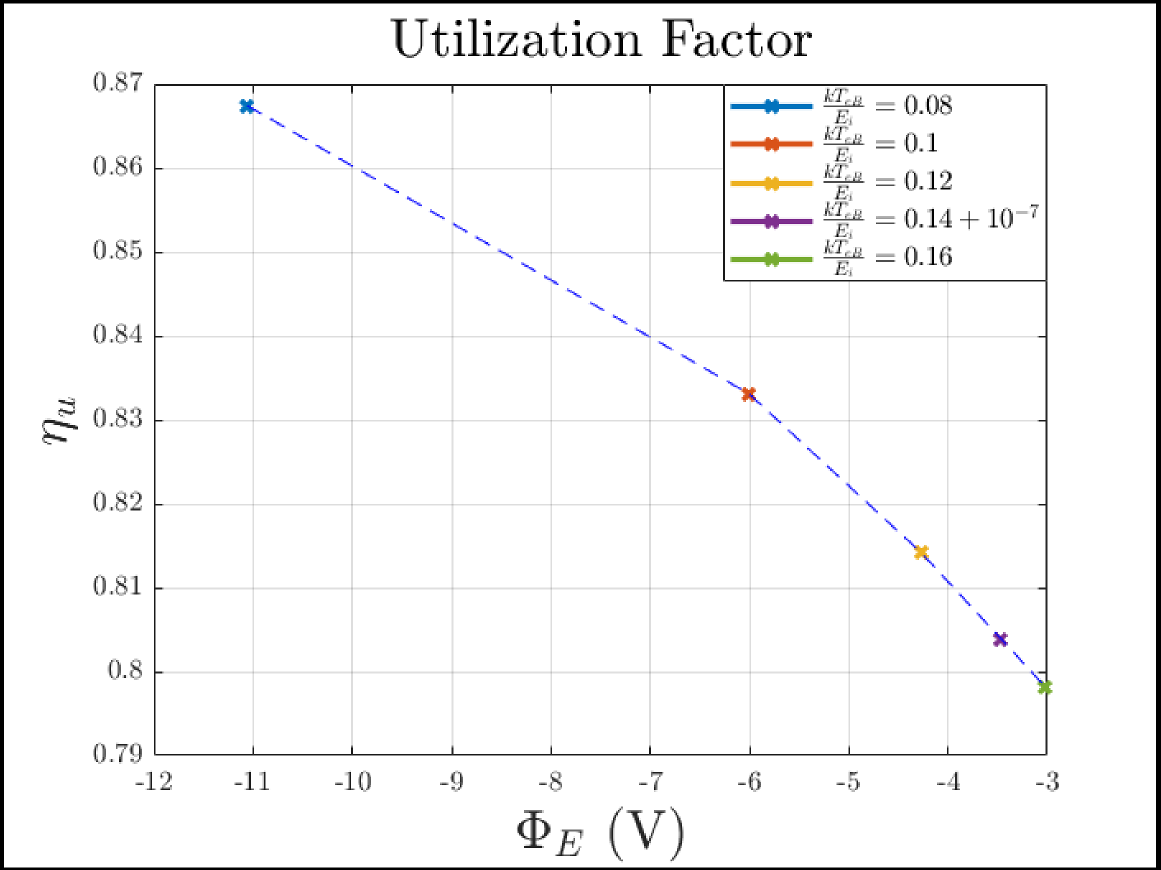
$$\Gamma_d = \frac{n_e e(v_i - v_e)A}{Ae} = \frac{I_a}{Ae}$$

$$I_{leak} = e n_e \frac{E}{B}\frac{\nu_e}{\omega_c}$$

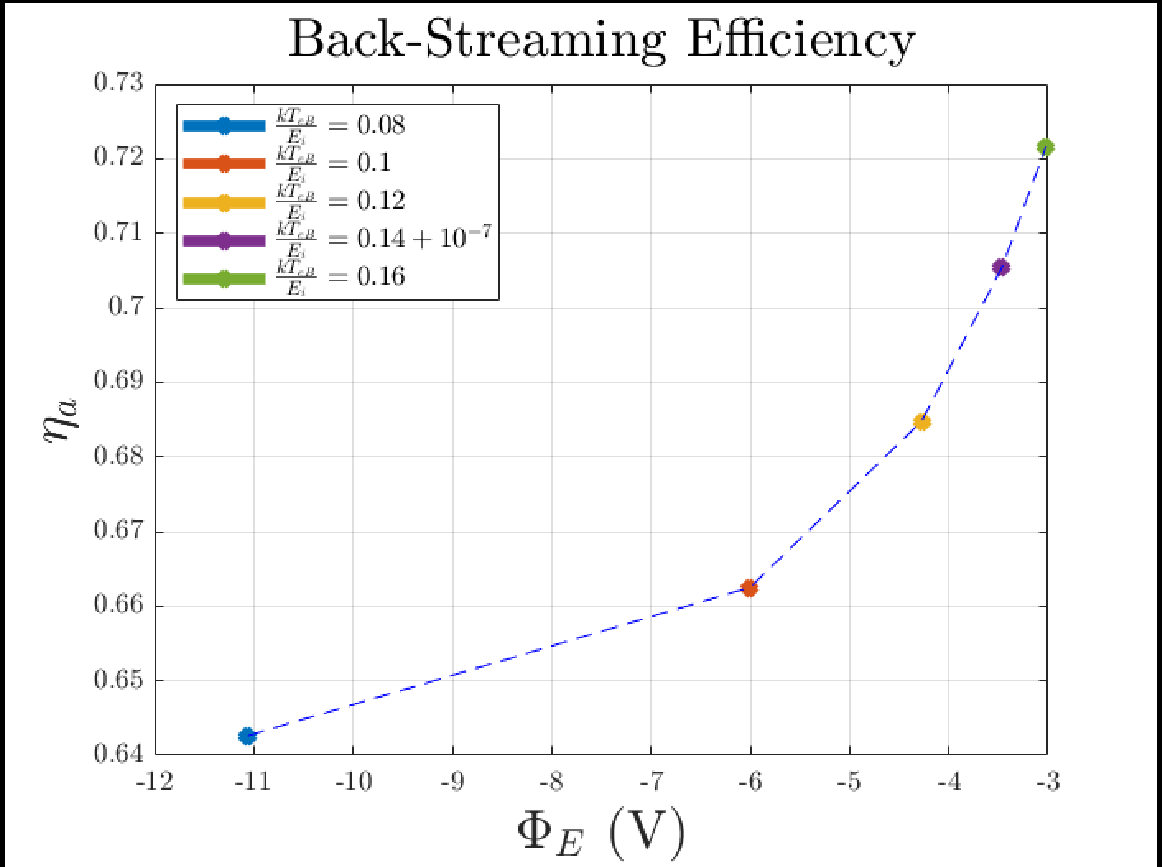
$$\eta_a = 1 - \frac{I_{leak}}{I_a}$$

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS



Utilization factor vs difference of potential in V



Back-Streaming efficiency vs difference of potential in V

NUMERICAL ANALYSIS: 1D HALL MODEL

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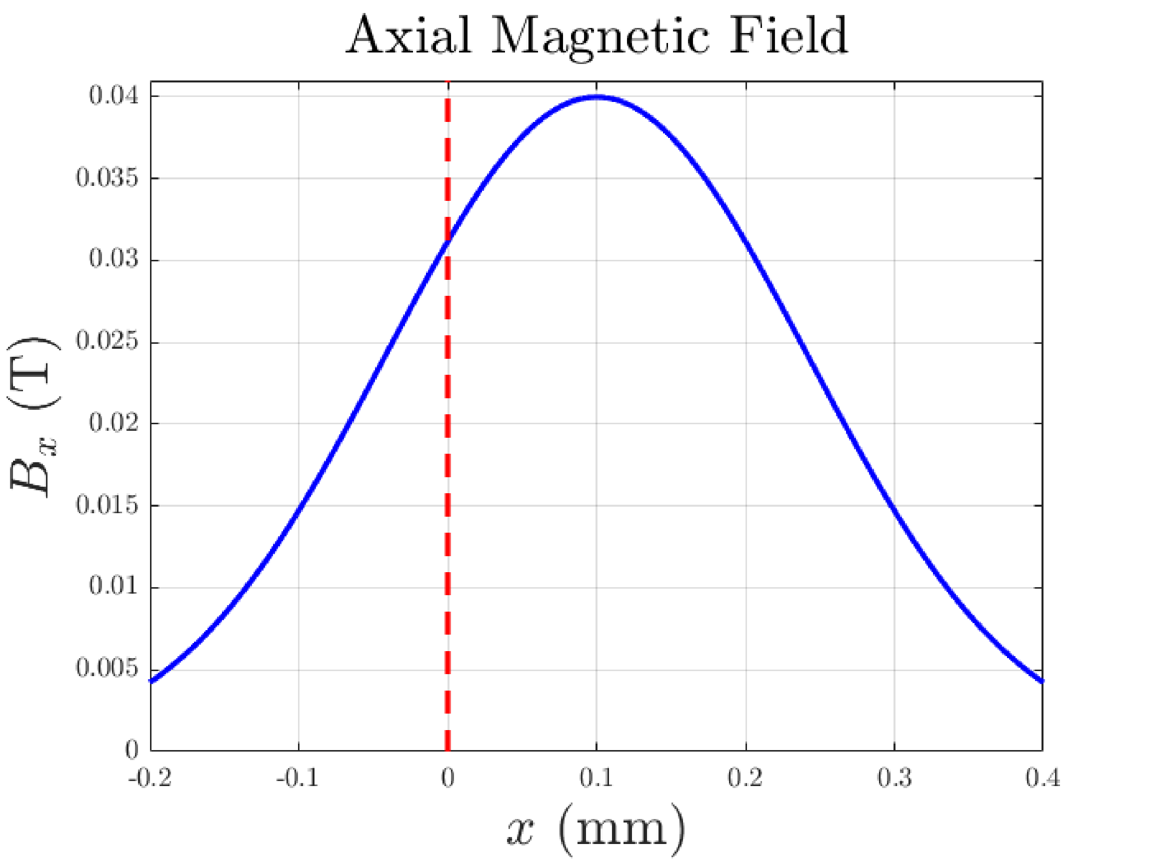
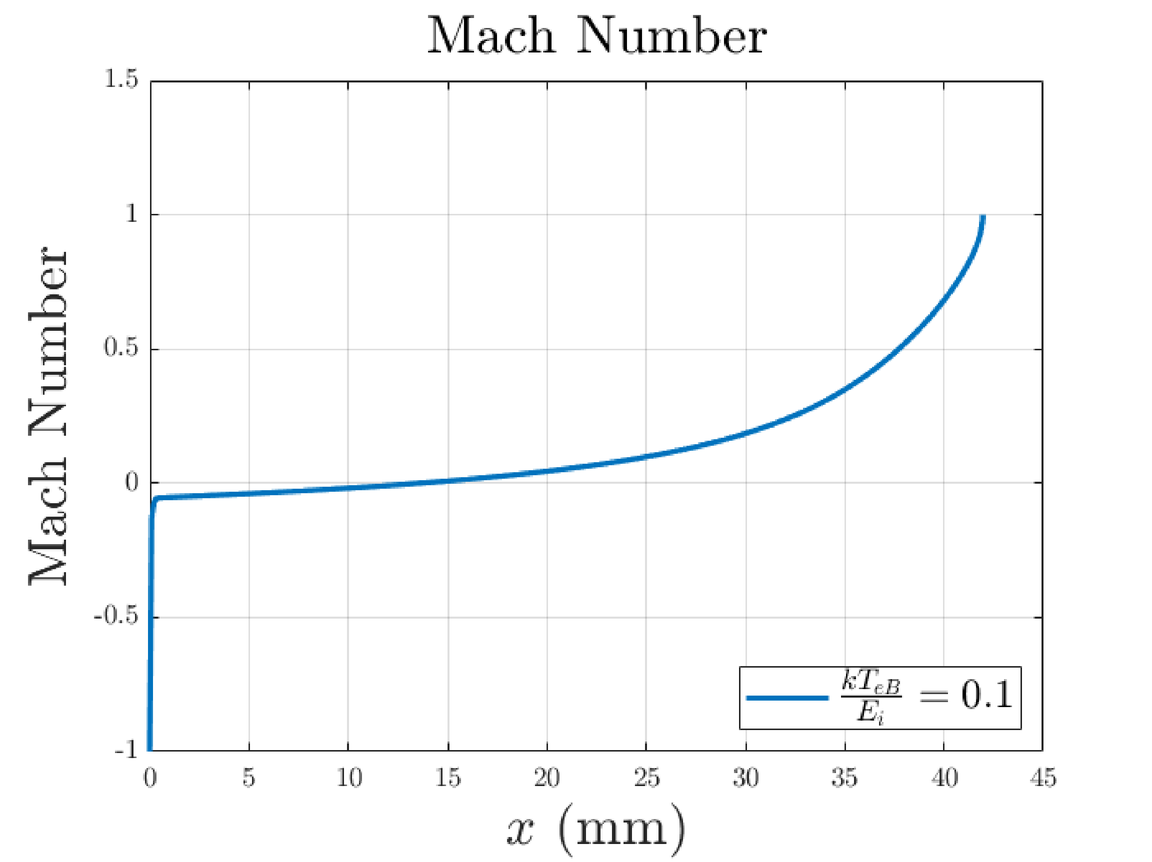


Axial magnetic field in Teslas vs channel lenght in millimetres. The red dashed line mars the x=0 position, remarking the initial point on the Hall Thruster.

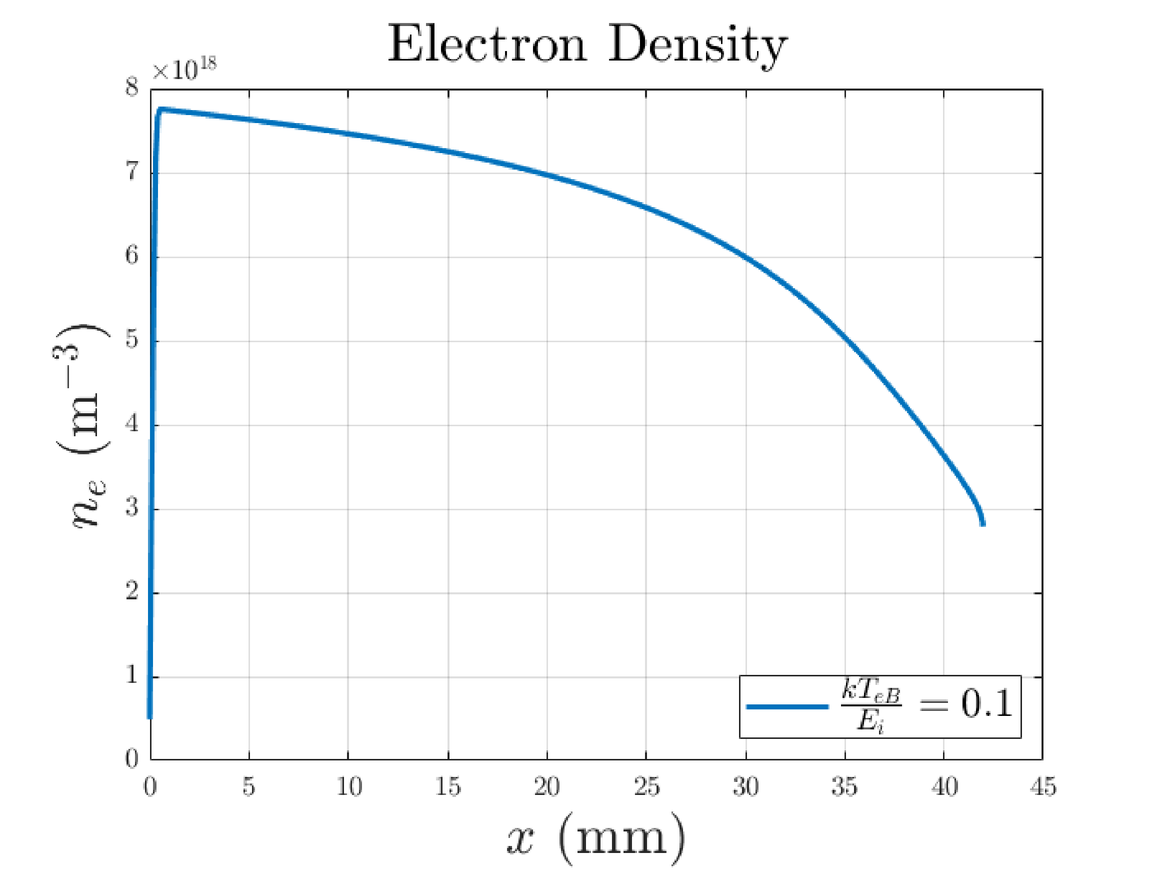


Mach number vs channel length in mm for the gaussian axial magnetic field.

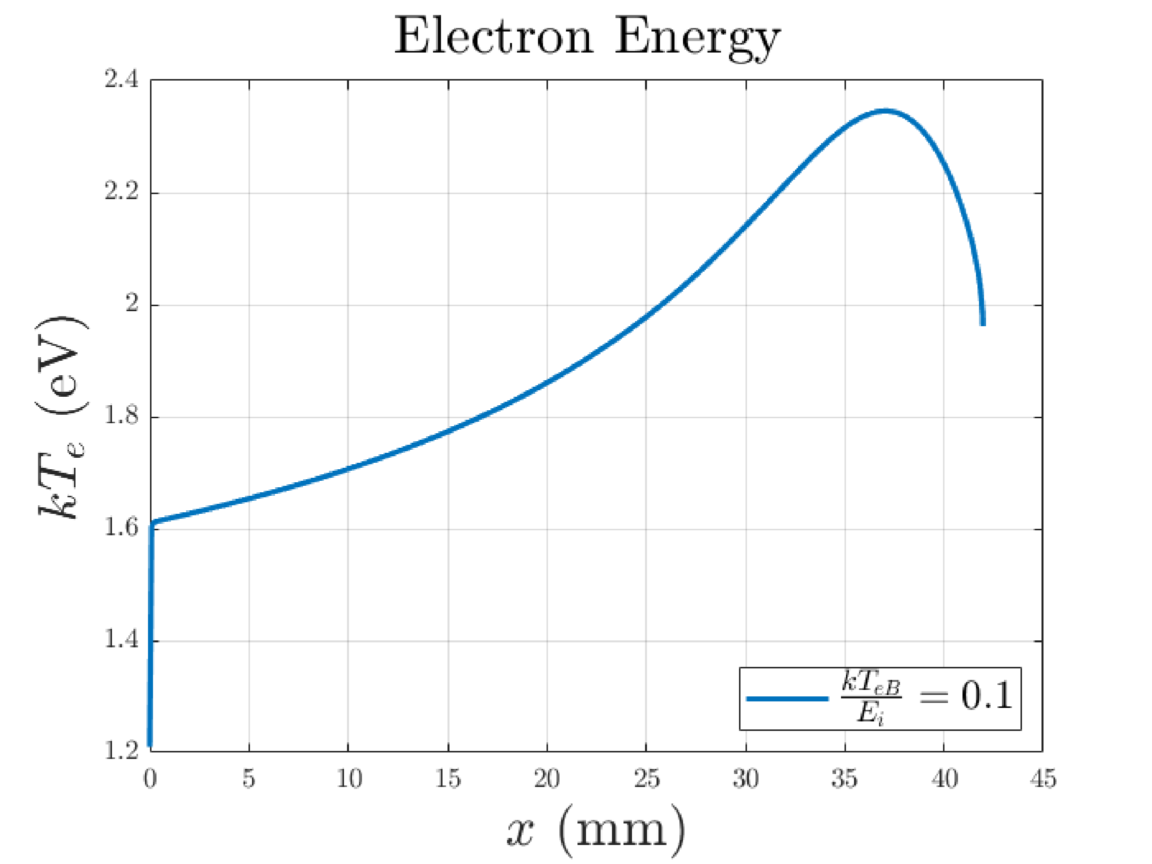
Change Axial Magnetic Field

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS



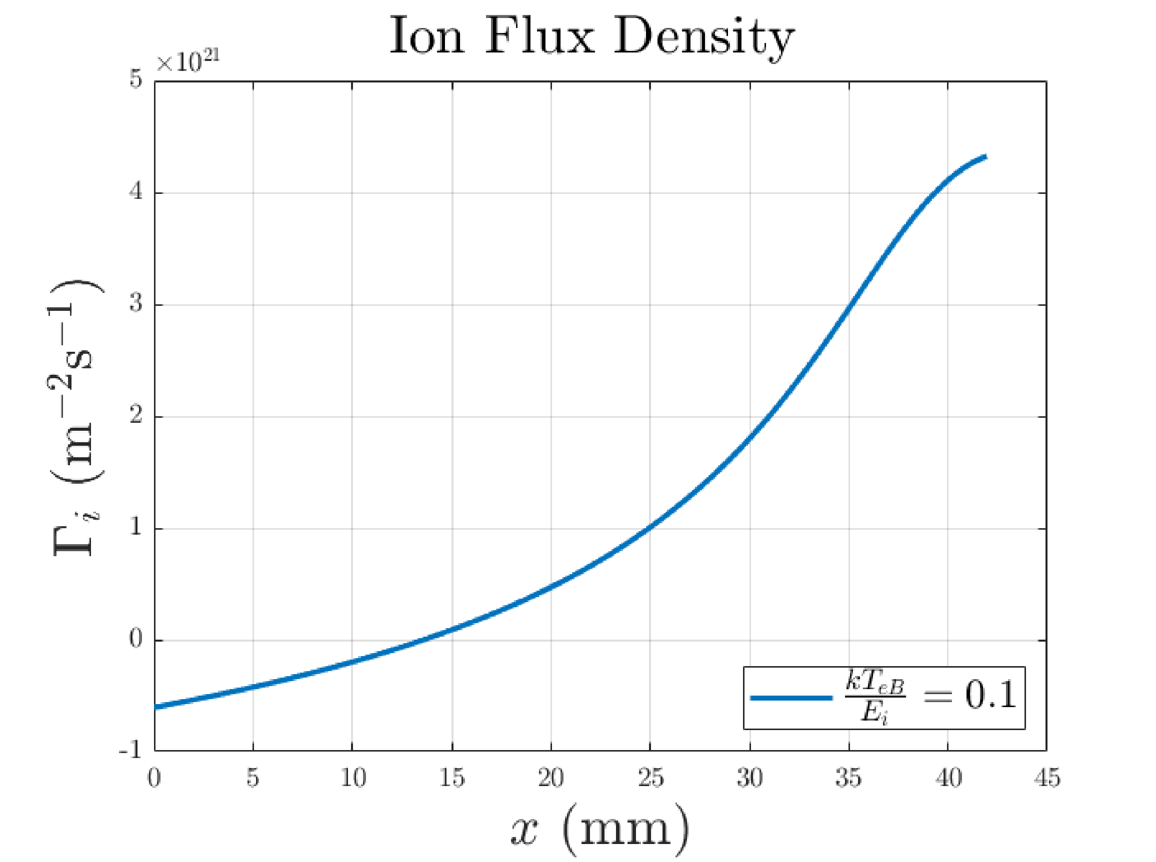
Electron density in m−3 vs channel length in mm for gaussian axial magnetic field.



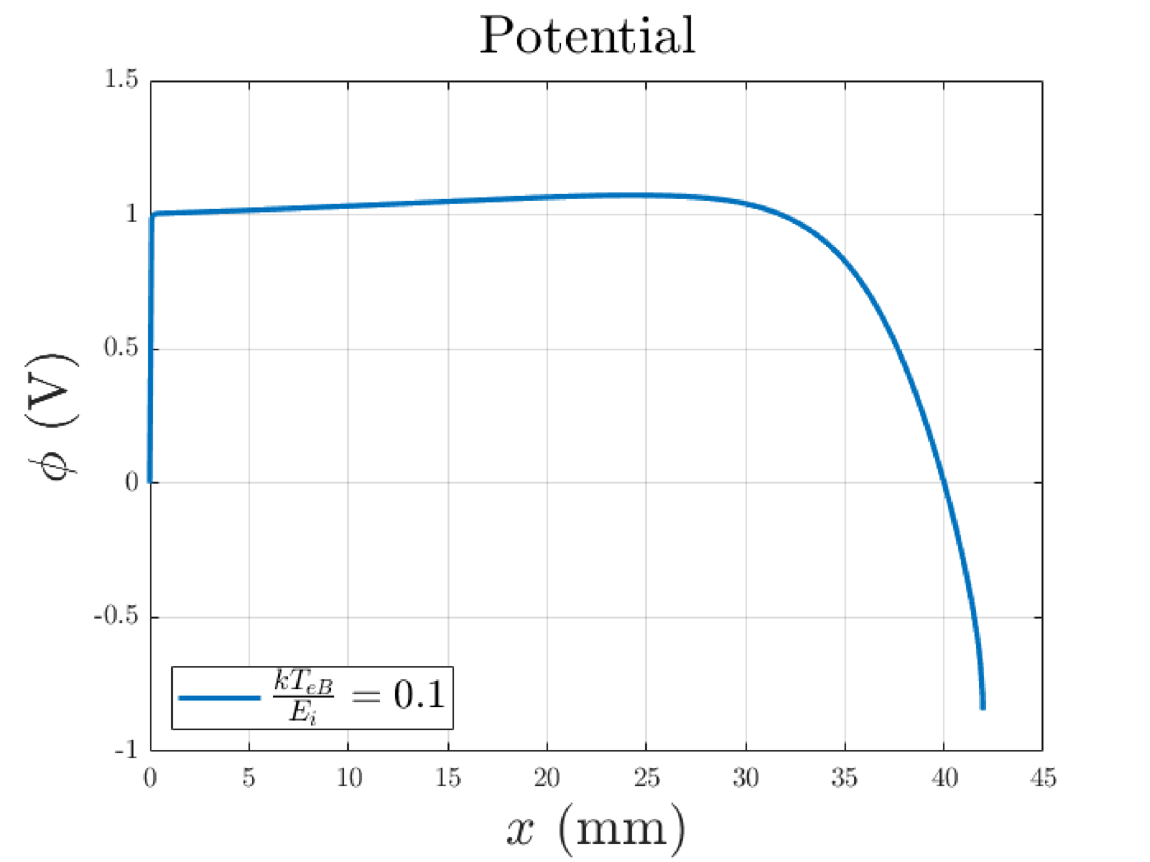
Electron energy in eV vs channel length in mm for gaussian axial magnetic field.

NUMERICAL ANALYSIS: 1D HALL MODEL

RESULTS



Ion flux density in m−2s−1 vs channel length in mm for the five requested initial values.



Potential in V vs channel length in mm for the five requested initial values.

CONCLUSIONS

- State of the art of the Hall Thruster.
- Description of a Hall Thruster.
- Parametric analysis using a 1-D model.
- Channel lenght was determined using the Mach number.
- Behaviour of the electrons and ions in the channel was obtained using a constant and gaussian form axial magnetic fields.

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[4]- A. Morozov, "The conceptual development of stationary plasma thrusters," Plasma Physics Reports, vol. 29, pp. 235–250, 2003.

[5]- P. Y. Peterson, H. Kamhawi, W. Huang, G. Williams, J. H. Gilland, J. Yim, R. R. Hofer, and D. A. Herman, "Nasa's hermes hall thruster electrical configuration characterization," in 52nd AIAA/SAE/ASEE Joint Propulsion Conference, p. 5027, 2016.