Modeling the effect of neutral dynamics on magnetic nozzle performances

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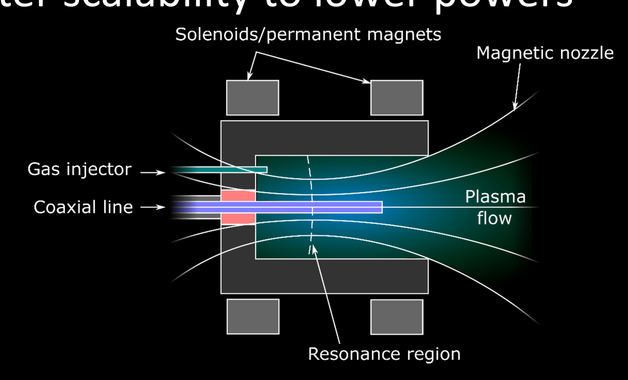
Magnetic Nozzles (MNs) are a key feature of Electrodeless Plasma Thrusters (EPTs). Here we use a three fluid code to study the influence of ionization and charge-exchange collisions on the performance of an axisymmetric MN. Results show an increase of the total thrust produced by the MN even with decreased final ion velocity due to the late acceleration of slow ions.

Electric Propulsion

- Advantages over chemical propulsión:
  - Higher specific impulse
  - Higher efficiencies
  - Lower propellant mass.
- Electric Propulsion Devices:
  - Mature Technologies:
    - Gridded Ion Thruster
    - Hall Effect Thruster
  - Development:
    - Electrodeless plasma thrusters (EPTs)

Electrodeless Plasma Thrusters

- Operational principle
  - Energizing electrons via electromagnetic waves.
  - Accelerations of partially magnetized plasma in the magnetic nozzle.
- Expansion of plasma in the magnetic nozzle:
  - Convergent-Divergent magnetic field.
    - Confinement and magnetic thrust thanks to Lorentz force
    - Conversion of electron thermal energy into ion kinetic energy via ambipolar electric field.
- Advantages over HET and GIT:
  - No plasma-wetted electrodes:
    - Longer thruster lifetimes
    - Use of alternative propellants
    - Simple electronics.
  - Better scalability to lower powers



Objectives of the work

Background pressure has been shown to play a big role on magnetic nozzle performance.

- Some authors have shown enhanced thrust production due to ion-neutral collisions [1][2].
- Other authors observe thrust reduction, argued to stem from electron-neutral collisions.[3]
- Preliminary model to partially account for ion-neutral collisions in the nozzle.

Model Overview

- Three-fluid model:
  - Electrons:
    - Inertialess
    - Polytropic $T_e = T_{e0}\frac{n^{\gamma_e}}{n_0^{\gamma_e}}$
    - Fully magnetized
  - Ions:
    - Cold
    - Singly charged
    - Partially magnetised
  - Neutrals:
    - Polytropic $T_n = T_{n0}\frac{n_n^{\gamma_n}}{n_{n0}^{\gamma_e}}$
- $\beta = 0$

Model Equations

$$\partial_t n + \nabla\cdot n\,\boldsymbol{u_e} = S$$

$$0 = -\nabla n T_e + n\,\nabla\phi - n\boldsymbol{u_e}\times\boldsymbol{B}$$

$$\partial_t n + \nabla\cdot n\,\boldsymbol{u_i} = S$$

$$\partial_t n\boldsymbol{u_i} + \nabla\cdot(n\boldsymbol{u_i}\otimes\boldsymbol{u_i}) = -n\,\nabla\phi + n\,\boldsymbol{u_i}\times\boldsymbol{B} + S_i\,\boldsymbol{u_n} + S_{cex}\,(\boldsymbol{u_n}-\boldsymbol{u_i})$$

$$\partial_t n_n + \nabla\cdot n_n\,\boldsymbol{u_n} = -S$$

$$\partial_t n_n\boldsymbol{u_n} + \nabla\cdot(n_n\boldsymbol{u_n}\otimes\boldsymbol{u_n}) = -\nabla n_n T_n - S_i\,\boldsymbol{u_n} + S_{cex}\,(\boldsymbol{u_i}-\boldsymbol{u_n})$$

Electron Momentum

- Under given assumptions electron equations are algebraic [4]:
  - Electron momentum is solved a priori leading to thermalized potential H_e

$$H_e = \frac{\gamma}{\gamma-1}(n^{\gamma-1}-1)-\phi$$

$$u_{ye}(\psi_B) = \frac{-1}{B}\frac{\partial H_e}{\partial \mathbf{1}_\perp} = -\frac{\partial H_e}{\partial \psi_B}$$

- Ion equations are similar to Euler eqs.
  - Forcement given by:
    - Thermalized potential
      - Encapsulates ambipolar electric field.
    - Ion magnetization
    - Collisional source terms

Collision model

- Ionization:

$$S_i = n\,\nu_i = n\,n_n c_e \sigma_i$$

$$\sigma_i = \sigma_{i0}\left(1+\frac{T_e E_i}{(T_e+E_i)^2}\right)e^{-E_i/T_e}$$

$$\sigma_{i0} = 5\times10^{-20}\,m^{-2}\quad E_i = 12.1\,eV$$

- Charge Exchange:

$$S_{cex} = n\,\nu_{cex} = n\,n_n c_{in}\sigma_{cex}$$

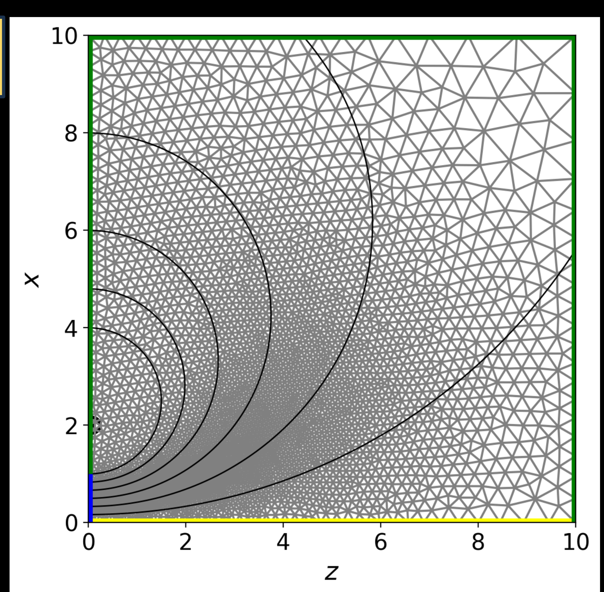
$$\sigma_{cex} = \sigma_{cex\,0}\left(1-0.2\,\log\left(\frac{c_{in}}{1\,km/s}\right)\right)$$

$$\sigma_{cex\,0} = 81\times10^{-20}\,m^{-2}$$

$$c_{in} = |u_{zi} - u_{zn}|$$

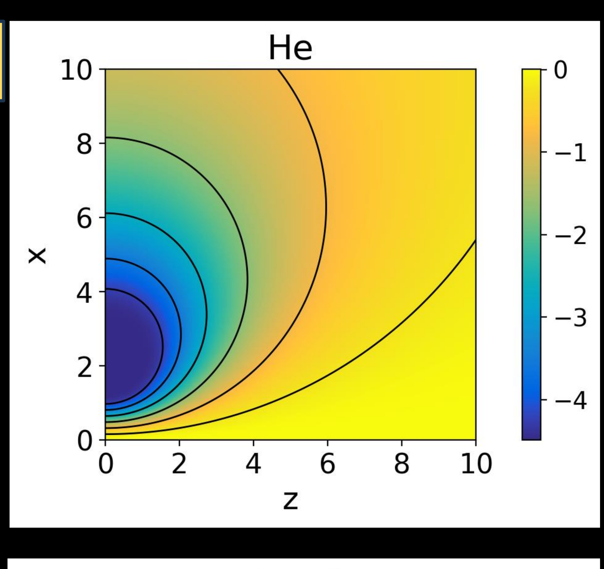
Solver

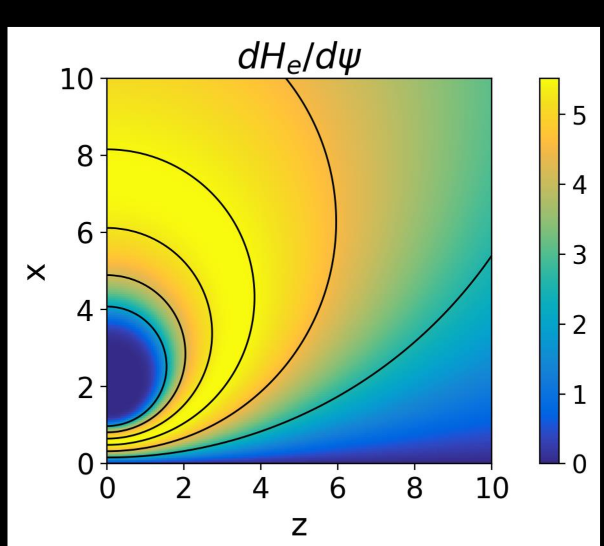
- Discontinuous Galerkin Spatial discretization (FEniCS)
  - Runge Kutta timestepping.
- Unstructured mesh (Gmsh):
  - Cell diam such that the throat is resolved in 40 cells.
  - Order 1 elements.



Simulation setup

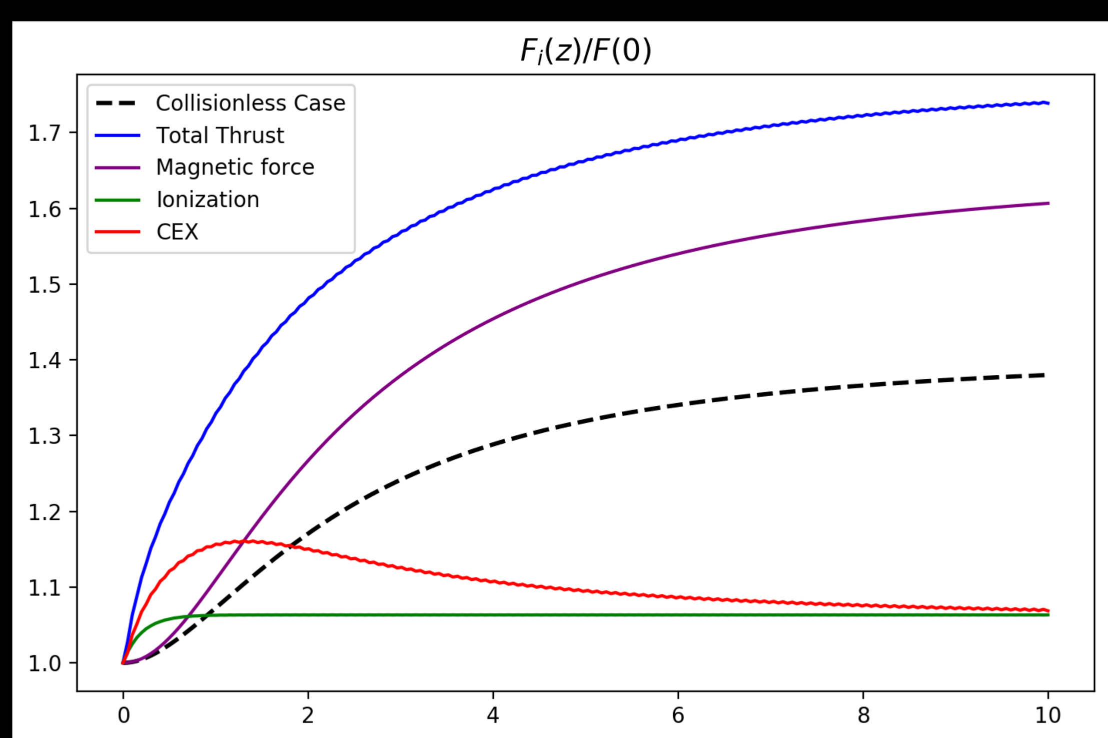
- Normalization:
  - Model is normalized with
    - Throat radius.
    - Electron charge.
    - Ion mass
    - Electron properties the center of the throat: n_0, T_{e0}, c_s
- Physical Parameters of nominal case:
  - Gaussian profile: $n(0) = n_0$ and $n(R_0) = 10^{-3}n_0$
  - $n_{n\,0} = 20\,n_0$
  - Coil radius: $R_L = 2\,R_0$
  - Sonic axial velocity for both ions and neutrals.
  - $\gamma_e = 1.2$ and $\gamma_n = 5/3$
  - $T_e = 20\,eV$ $T_n = 300\,K$

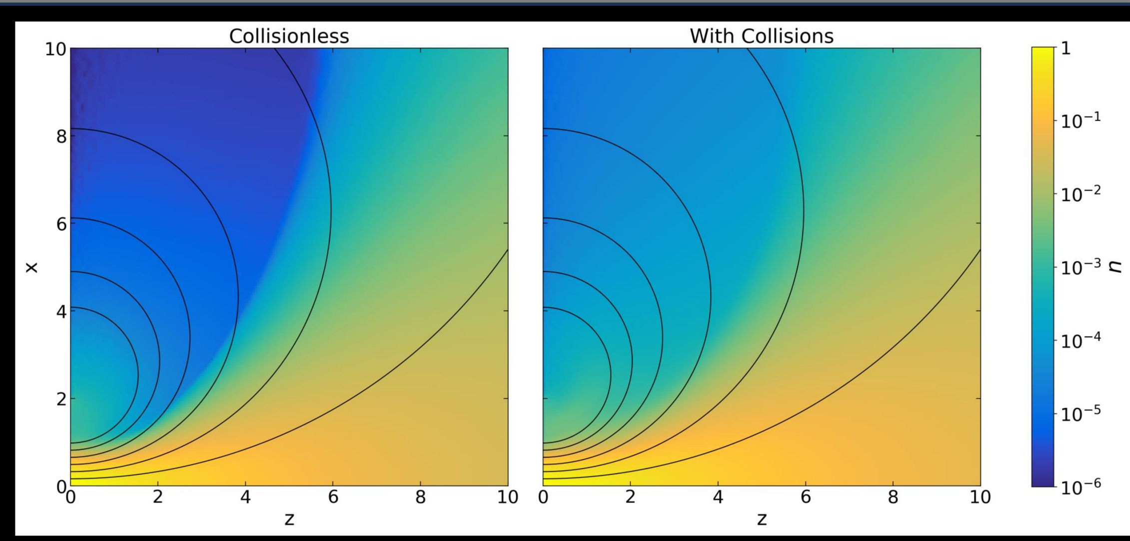


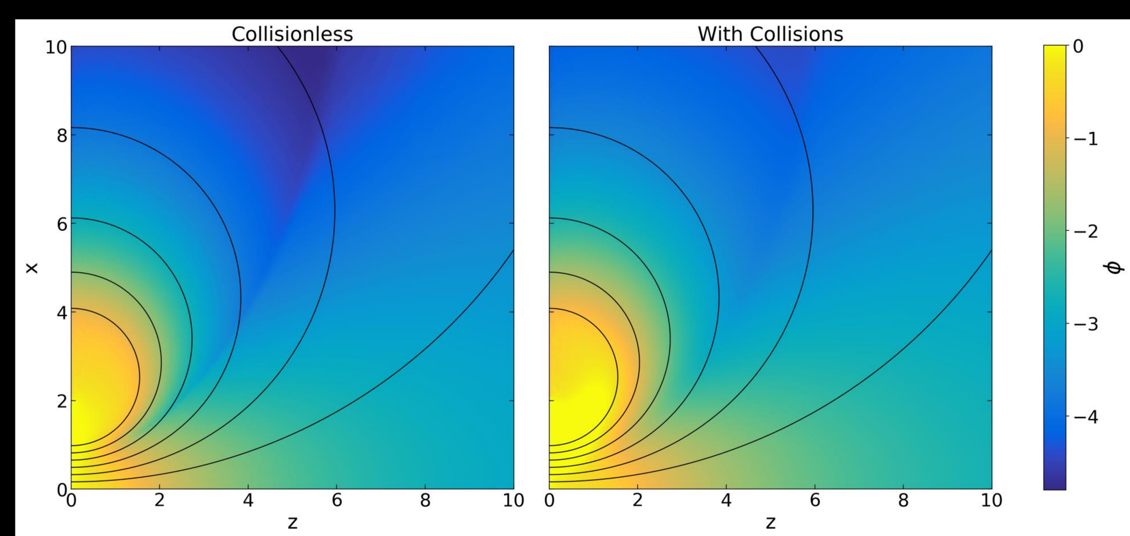


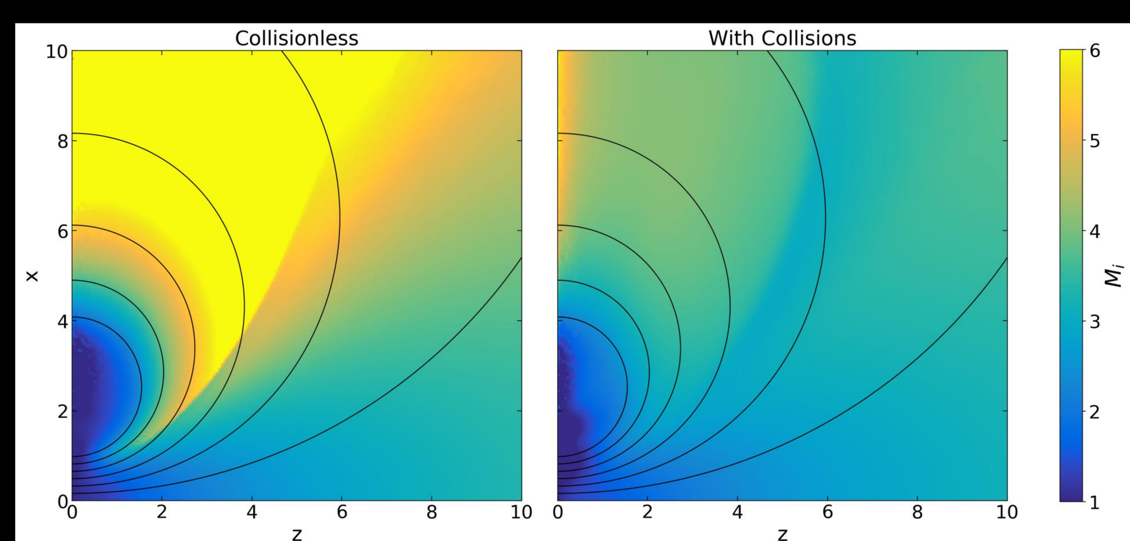
Discussion of Results

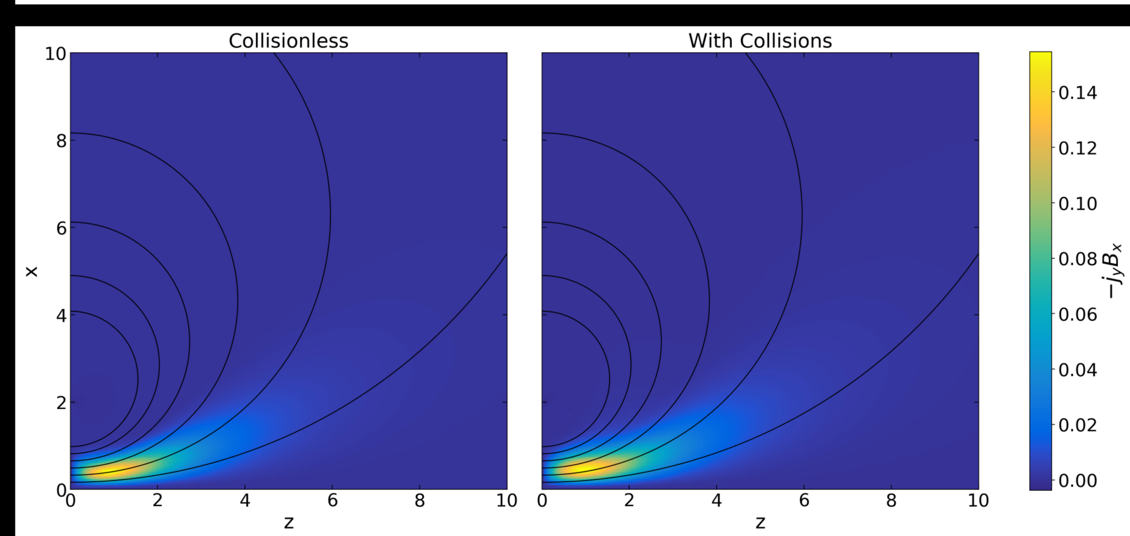
- Collisional processes reduce the potential drop and therefore the final ion velocity.
- Nonetheless total thrust increases:
  - New sources of ion momentum:
    - Momentum transfer from neutral population to ion population.
    - Increased magnetic force due to increased mass of plasma subject to acceleration.
      - This leads to a net increase in the thrust produced by the nozzle.
      - Total thrust gain $\sim 0{,}22F_i(0)$ (Difference between purple and black lines)











Conclusions

- First step to study the effect of neutral dynamics on nozzle performance.
  - Late ionization has a noticeable effect on ion dynamics:
    - Late ionization could be a major source of thrust in cases with poor ionization.
- Limitations:
  - As seen by some authors [3] electron-neutral collisions could yield lower potential fall and reduce thrust.
  - A full assessment on the effect of neutral dynamics on nozzle response should include these effects.
  - Future developments of the model will implement collisions in the electron momentum equation.

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