Plasma Adiabaticity in a Diverging Magnetic Nozzle

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Abstract

A mechanism for ambipolar ion acceleration in a magnetic nozzle is proposed. The plasma is adiabatic (i.e. transfers no heat to or from its surroundings) in the diverging section of a magnetic nozzle so any energy lost by the electrons must be transferred to the ions via the electric field. Fluid theory indicates that the change in average electron energy equals the change in plasma potential. These predictions were validated by measurements in VASIMR which has experimental conditions conducive to ambipolar ion acceleration. Applications to the development of the CubeSat Ambipolar Thruster (CAT) are outlined.
Helicons and magnetic nozzles

• **Helicons**
  – Radio frequency
  – High ionizing efficiency
  – Electron heating

• **Magnetic nozzle**
  – Functions like physical nozzle
  – Accelerates ions
  – Converts thermal energy into directed kinetic energy
Double layers in helicons

- Narrow layer (10s of $\lambda_d$) of large potential jump (several $T_e/e$)
- Isothermal
- Occurs downstream of nozzle
- Current free, expanding
- Accelerates ions
- May be thrust mechanism in helicon thrusters

Ion acceleration in VASIMR®

- VASIMR: < 200 kW helicon + ICH thruster
- Went looking for double layers, but found none!
- $V_p$, $n_e$, and $T_e$ derivatives coincide
- Long length scales: 1000s of $\lambda_d$
- Corroborated with RPA

Plasma in nozzle is adiabatic

• Electron pressure in Maxwellian plasma:
  \[ p_e = n_e T_e \]

• Adiabatic pressure:
  \[ p_e = C n^\gamma \]
  \[ \gamma = \frac{N + 2}{N} \]

• Momentum balance equation:
  \[ \frac{\partial p_e}{\partial s} = n_e \frac{\partial (e\varphi)}{\partial s} \]

• Average electron energy:
  \[ \frac{\partial \langle E \rangle}{\partial s} = \frac{\partial (e\varphi)}{\partial s} \]
Helicon experiment using VASIMR hardware
Plasma parameters were measured with a planar Langmuir probe

- $P = 15 - 30 \text{ kW}$
- $\dot{m} = 50 - 140 \text{ mg/s}$
- $V_p < 20 \text{ V}$
- $T_e < 15 \text{ eV}$
- $n_e = 10^{10} - 10^{12} \text{ cm}^{-3}$

- Planar tungsten probe
- No RF compensation needed
- Guard ring reduces sheath expansion effects
- Parameters extracted from $I$-$V$ traces
  - $V_p$: knee
  - $T_e$: semilog
  - $n_e$: saturation current
Parametric study of operating parameters

• Measured at fixed position
  – 50 mm from throat
  – Highest density where probe could survive

• Lower mass flow rate
  – Higher $T_e$, $V_p$
  – Lower $n_e$

• Power flow density $\propto$ input energy per ion
  – Optimize energy deposition for given flow rate
\( V_p, T_e, \) and \( n_e \) decay downstream

- Axial measurements
- Lowest and highest mass flow rates are shown
- Temperature decay: plasma is not isothermal
- Length scale: 1000s of \( \lambda_d \)
- No double layer
Radial parameters were measured

- 50 mm from throat
- Density profile consistent with plume
- Small radial acceleration
- Significant temperature fluctuations
Data are consistent with adiabatic theory

- Plasma potential decays proportionally to electron temperature
- Some electron energy may be lost to other sinks

\[
\frac{\partial (e\varphi)}{\partial s} = 1.17 \frac{\partial T_e}{\partial s}
\]

\[
\frac{\partial (e\varphi)}{\partial s} = 0.78 \frac{\partial \langle E \rangle}{\partial s}
\]
Electrodeless thruster design and open questions

• Ambipolar ion acceleration
  – Ion energy limited by electron temperature
  – Not by density drop
  – Boltzmann relation does not hold
• Electrons energy transfer to ions
• Re-thermalization
• Thruster generation
CAT design uses a helicon plasma and a magnetic nozzle

- Quartz plasma liner with showerhead
- Converging nozzle matches magnetic field
- Radially oriented magnets produce magnetic nozzle
- Copper helical half-twist helicon antenna for plasma generation/heating
- Faraday cage to isolate RF
- Diameter < 10 cm to fit CubeSat form factor
Permanent magnet nozzle

- NdFeB permanent magnets
- Rings divided into radially oriented arc magnets for ease of manufacturing
- Magnetic field at throat: 1100 G
- Decays to earth’s magnetic field within 40 cm
- Assume plasma detaches at 0.5 G at the furthest
- Nozzle efficiency: 83%
Experiment parameters

- ~10 Watts
- 27.13 MHz
- Propellant
  - Argon: initial testing
  - Water
  - Liquid metal
- 0.1 – 1 sccm
- ~1100 G maximum B field
- Magnetic nozzle field will decrease to strength of earth’s before reaching vacuum chamber wall
Conclusion

- Adiabatic plasma expansion
  - Non-isothermal
  - Long length scales
  - Ion acceleration limited by electron temperature

- CubeSat Ambipolar Thruster
  - Helicon thruster designed specifically for small satellites
  - Large ΔV maneuvers
  - Solid or liquid storable propellants
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