PLASMA SOURCES FOR MICRO-THRUSTERS*

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June 2004

* Work supported by NSF, AFOSR
AGENDA

• Micro-Inductively Coupled Plasma (mICP) discharges: Applications to thrusters
• Description of model
• Results
  • Validation
  • Effect of flow
  • Ionization fraction
  • Effect of geometry
  • Sources of energetic neutrals
• Conclusions
MICRO THRUSTERS

- Micro-thrusters typically have diameters of a few cm and generate thrusts ranging from sub-$\mu$N to mN.

- Micro-plasma thrusters have high specific impulse, use inert non-contaminating propellants, and potentially have higher thrust-to-power ratios.

- Need to maximize the ionization fraction at low input power and sustain the plasma at high surface-to-volume ratios.

- Ionization fractions $\sim 0.1\%$ and higher can be obtained for spherical hollow cathode devices, but similar values have not been reported in mICPs.
ICP SOURCES: APPLICATIONS TO MICRO-THRUSTERS

- ICPs have potentially longer service lives due to the absence of electrodes.
- Need to operate at high frequencies to keep skin depth reasonably small.
- Scaling to smaller sizes may be limited by sheath width.
- These reactors can also be used as generators of energetic species such as $O_2(^1\Delta)$.
DETAILS OF THIS STUDY

• Computational investigation of 2-d cylindrically symmetric reactors.

• Reactor geometry:
  • Radius of 0.3 – 0.5 cm and height of 0.5 – 0.6 cm.

• Operating conditions:
  • 500 mTorr to 8 Torr gas pressures.
  • Pure Argon gas and He/O₂ gas mixtures.
  • 0.5 – 3.0 Watts input power, at 450 MHz for validation.
  • 0.15 – 1.0 Watts absorbed power, at 493 MHz.

• Goals:
  • Validate model with experimental data.
  • Compute ionization fraction at these conditions.
  • Study the effect of geometry on plasma characteristics.
POWER ABSORPTION EFFICIENCY

- Efficiency defined as power absorbed by the plasma to the input power.
- Efficiency is very low at low pressures because plasma is not collisional enough.
- At higher pressures, efficiency is bounded by losses in the electrical circuit.

MODEL: POTENTIALS AND SOURCES

- Poisson’s equation with volume and surface charges for all charged species.
  \[- \nabla \cdot \varepsilon \nabla \Phi = \rho_v + \rho_s\]

  \[\frac{\partial \rho_v}{\partial t} = \sum_i - \nabla \cdot (q_i \phi_i)\]

  \[\frac{\partial \rho_s}{\partial t} = \sum_i - \nabla \cdot (q_i \phi_i (1 + \gamma_i)) - \nabla \cdot (\sigma (-\nabla \Phi) + \vec{j}_E)\]

- Source densities due to e-impact, heavy particle reactions, and secondary emissions are included.

- Fluxes discretized using Scharfetter-Gummel technique.

  \[\frac{\partial N_i}{\partial t} = - \vec{\nabla} \cdot \vec{\phi}_i + S_i\]

  \[\vec{\phi}_{i+1/2} = \alpha D \left( \frac{n_{i+1} - n_i \exp(\alpha \Delta x)}{1 - \exp(\alpha \Delta x)} \right)\]

  \[\alpha = \left( \frac{q}{|q|} \right) \mu \left( \frac{\Phi_{i+1} - \Phi_i}{\Delta x} \right) - \vec{v}_{BULK}\]

  \[\frac{\partial \Phi_i}{\partial t} = \frac{V_i}{\Delta x^2} \left( \frac{\Phi_{i+1} - \Phi_i}{\Delta x} \right) - \frac{\partial}{\partial x} \left( \frac{\Phi_i}{\Delta x} \right) + \frac{q_i}{\Delta x} \left( \mu \Phi_i + \vec{v}_i \right)\]

  \[\Phi_i = \sum_j q_j \phi_j\]
MODEL: TRANSPORT PROPERTIES

• Maxwell’s equations were solved for electromagnetic fields and power deposition.

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\
\nabla \times \left( \frac{\vec{B}}{\mu_0} \right) = \frac{\partial}{\partial t} (\varepsilon \vec{E}) + \mathbf{J} \\
\[P = \frac{1}{2} \left( \sigma \vec{E} \right) \cdot \vec{E}
\n\]

• Navier-Stokes equations for gas velocities, temperature.

Continuity \[\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0\]

Momentum \[\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \left[ \mu \left( \nabla \vec{v} + (\nabla \vec{v})^T - \frac{2}{3} (\nabla \cdot \vec{v}) \mathbf{l} \right) \right] + \mathbf{S}_{\text{plasma}}\]

Energy \[\frac{\partial \rho c_p T}{\partial t} = -\nabla \cdot (\rho c_p \vec{v} T) - \nabla \cdot (\kappa \nabla T) + \mathbf{S}_{\text{plasma}}\]

• Electron energy equation coupled with Boltzmann solution for electron transport coefficients.

• Table look-ups of cross-sections for calculating rate coefficients.
Finite volume techniques were used for 2-d unstructured triangulated meshes.

Equations solved using implicit time-stepping using an iterative Newton’s method with numerically derived Jacobian elements.

\[
N_i(t + Δt) = N_i(t) + ΔN_i Δt
\]

\[
ΔN_i = N_i(t + Δt) - N_i(t) = \frac{∂N_i}{∂t} (t + Δt) · Δt + \sum_j \left( \frac{∂N_i}{∂N_j} \right) ΔN_j
\]

Time integration was carried out until steady state was achieved.
Investigations of a 2-d cylindrically symmetric micro-ICP reactor were conducted.

Geometry and conditions were based on Hopwood et. al [1].
- 500 mTorr, 1 sccm Ar
- 450 MHz ICP
- 0.5 – 3.0 Watts(Input)

Ion densities, and $T_e$ at the center of the reactor (0.0, 0.8 cm) are reported.

VALIDATION: BASE CASE RESULTS

- [e-Source] (cm\(^{-3}\) s\(^{-1}\))
- \(T_e\) (eV)
- Power (W/cm\(^3\))

- Skin depth of a couple of mm.
- Debye length of 0.1 mm near the center of the reactor.

Operating conditions:
- 500 mTorr, 1 sccm Ar
- 1.3 Watts, 450 MHz

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Ion densities were maximum close to the center of the reactor.

Power deposited in the plasma was 2.5% of the generator power[2].

Ion densities of $10^{10}$-$10^{11}$ obtained with power density of 0.1 – 1.0 W/cm$^3$.

Lower densities could be attributed to effect of flow.

- 500 mTorr, 1 sccm Ar, 450 MHz

- Model overpredicts electron temperature.
- Model may underpredict multi-step ionization.

**500 mTorr, 1 sccm Ar, 450 MHz**

**Expt: Hopwood, Minayeva, J. Vac. Sci. Tech. B., 18, 2000**
EFFECT OF FLOW: ION DENSITY

- Conditions:
  - 2 Torr, 1.5 Watt
  - 493 MHz ICP
- Coupling between the ions and the neutrals can affect the ion flux and the flow.
- Can be important at higher pressures (>1 Torr) and when there are large gradients in ion densities.

- $[\text{Ar}^+]$ without flow
- $[\text{Ar}^+]$ with 2 sccm flow
• Ar$^+$ is the predominant ion as the pressure is too low for Ar$_2^+$ to efficiently form.

• Ionization fraction increases with pressure.

• Higher ionization than those reported are required for effective use as a thruster.
EFFECT OF GEOMETRY

Solenoidal

“Stove-top”

- Power (W/cm³)
- Conditions:
  - 2 Torr, 1.5 Watt
  - 493 MHz ICP
  - 2 sccm Ar
- Power deposition governed by penetration of electric field into the plasma.
- Steeper gradients of species densities caused by nonuniform power deposition affects the flowfield.

- [Ar⁺] at outlet

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SOURCES OF ENERGETIC NEUTRALS

- \([O_2(^1\Delta)] \text{ (cm}^{-3}\text{)}\)

- **Conditions:**
  - 2 Torr, 1.5 Watt
  - 493 MHz ICP
  - He/O\(_2\) (70:30)
  - 10 sccm

- \([O_2^+] \text{ (cm}^{-3}\text{)}\)

- Energetic species such as \(O_2(^1\Delta)\) can be used in chemical LASERs.

- \([O_2(^1\Delta)] / [O_2] \sim 0.3\%\) is achieved with the current conditions although higher values are required.

- Power (W/cm\(^3\))

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CONCLUSIONS

- Ion densities of $10^{10}$-10$^{12}$ cm$^{-3}$ (Ionization fractions of 10$^{-5}$ to 10$^{-4}$) were generated at modest power levels at pressures ranging from 0.5 - 8 Torr.

- At higher pressures, the momentum transfer between ions and neutrals is important.

- The effect of the geometry of the coils on power deposition and plasma characteristics were studied.

- \([O_2(1\Delta)]\) production was simulated using the micro-ICP reactor and \([O_2(1\Delta)] / [O_2] \approx 0.3\%\) was achieved using the base case conditions.