PLASMA SOURCES FOR MICRO-THRUSTERS*

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AGENDA

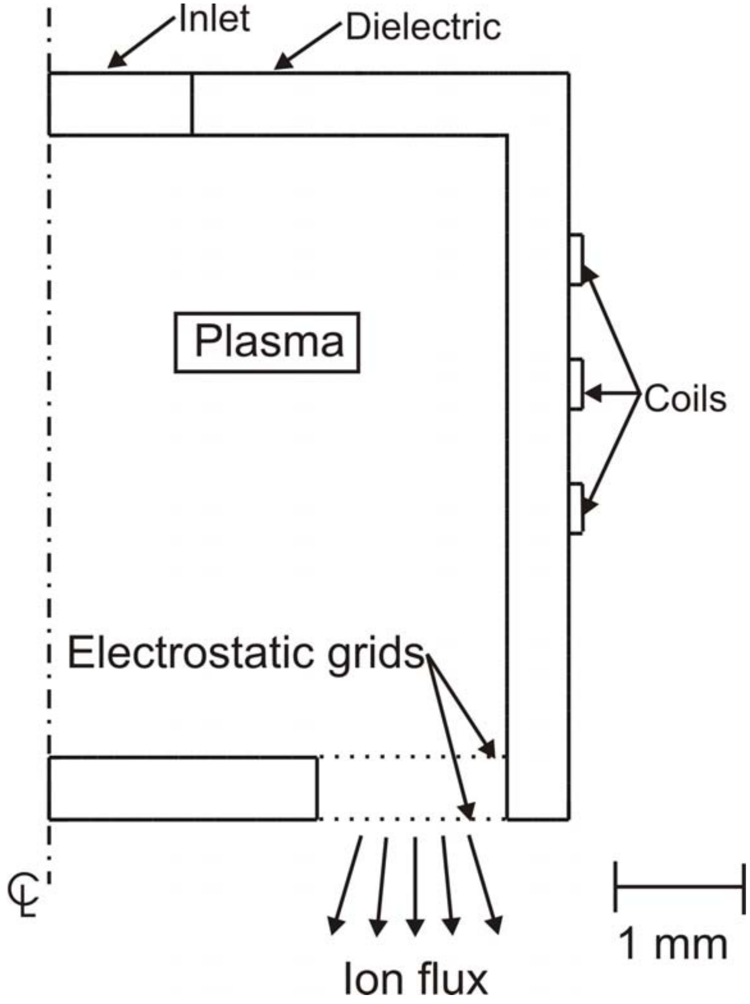
- Micro-Inductively Coupled Plasma (mICP) discharges: Applications to thrusters
- Description of model
- Results
  - Validation
  - Effect of flow
  - Ionization fraction
  - Effect of geometry
  - Sources of energetic neutrals
- Conclusions

MICRO THRUSTERS

- Micro-thrusters typically have diameters of a few cm and generate thrusts ranging from sub-μN 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 ~ 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 $O_2(^1\Delta)$.



Representative geometry of the reactor

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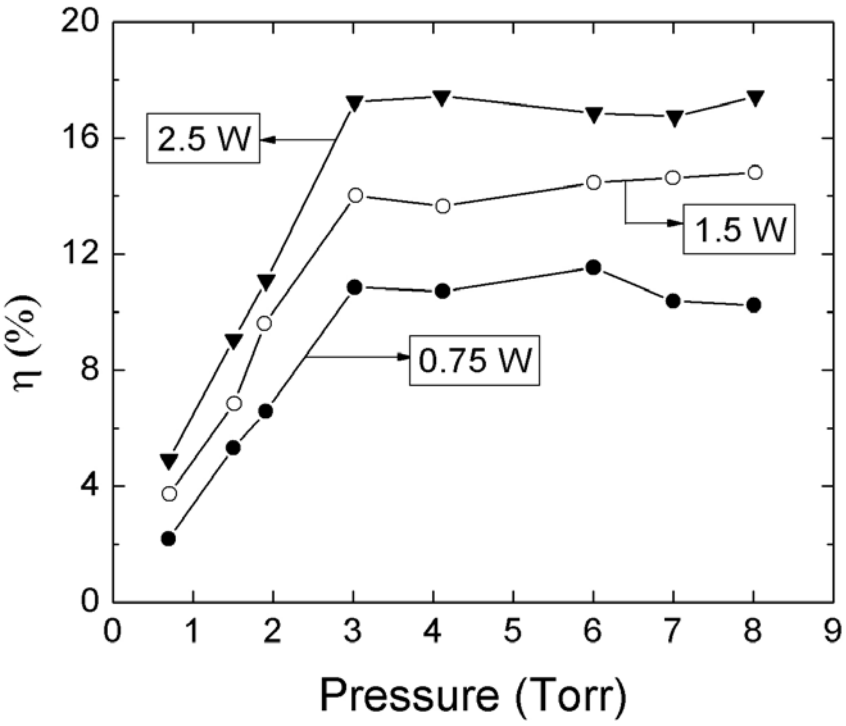
DETAILS OF THIS STUDY

- 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/O_2 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.**



- **O. B. Minayeva and J. Hopwood, J. Appl. Phys. 94, 2003**

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MODEL: POTENTIALS AND SOURCES

- **Poisson's equation with volume and surface charges for all charged species.**

$$-\nabla \cdot \varepsilon \nabla \Phi = \rho_V + \rho_S$$

$$\frac{\partial \rho_V}{\partial t} = \sum_i -\nabla \cdot \left(q_i \vec{\phi}_i \right)$$

$$\frac{\partial \rho_S}{\partial t} = \sum_i -\nabla \cdot \left(q_i \vec{\phi}_i (1 + \gamma_i) \right) - \nabla \cdot \left(\sigma (-\nabla \Phi) + \vec{j}_E \right)$$

- **Source densities due to e-impact, heavy particle reactions, and secondary emissions are included.**
- **Fluxes discretized using Scharfetter-Gummel technique.**

$$\frac{\partial N_i}{\partial t} = -\vec{\nabla} \cdot \vec{\phi}_i + S_i \qquad \vec{\phi}_{i+1/2} = \alpha \overline{D} \left(\frac{n_{i+1} - n_i \exp(\alpha \Delta x)}{1 - \exp(\alpha \Delta x)} \right)$$

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

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MODEL: TRANSPORT PROPERTIES

- **Maxwell's equations were solved for electromagnetic fields and power deposition.**

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

- **Navier-Stokes equations for gas velocities, temperature.**

Continuity $$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = 0$$

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

Energy $$\frac{\partial \rho c_p T}{\partial t} = -\nabla \cdot \left(\rho c_p \vec{v} T\right) - \nabla \cdot \left(\kappa \nabla T\right) + S_{plasma}$$

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

- **Table look-ups of cross-sections for calculating rate coefficients.**

MODEL: SOLUTION

- **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.**

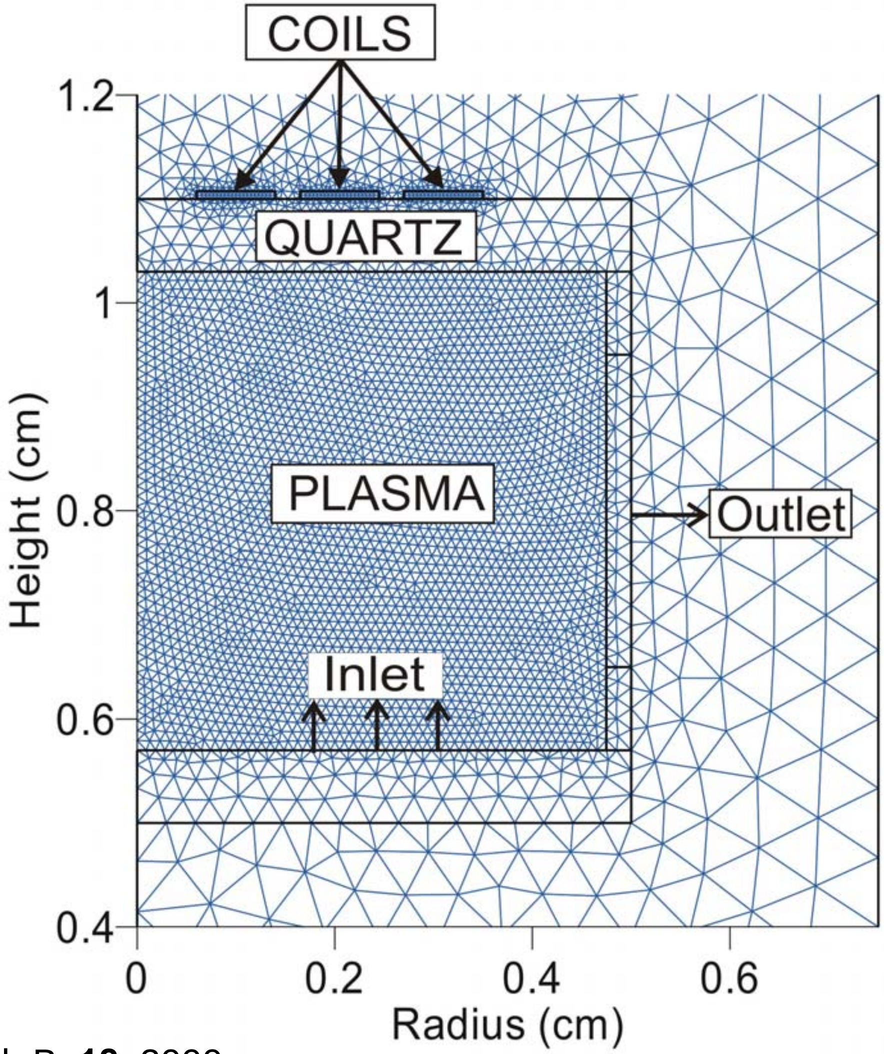
$$N_i(t + \Delta t) = N_i(t) + \Delta N_i \Delta t$$

$$\Delta N_i = N_i(t + \Delta t) - N_i(t) = \frac{\partial N_i}{\partial t}(t + \Delta t) \cdot \Delta t + \sum_j \left(\frac{\partial N_i}{\partial N_j} \right) \Delta N_j$$

- **Time integration was carried out until steady state was achieved.**

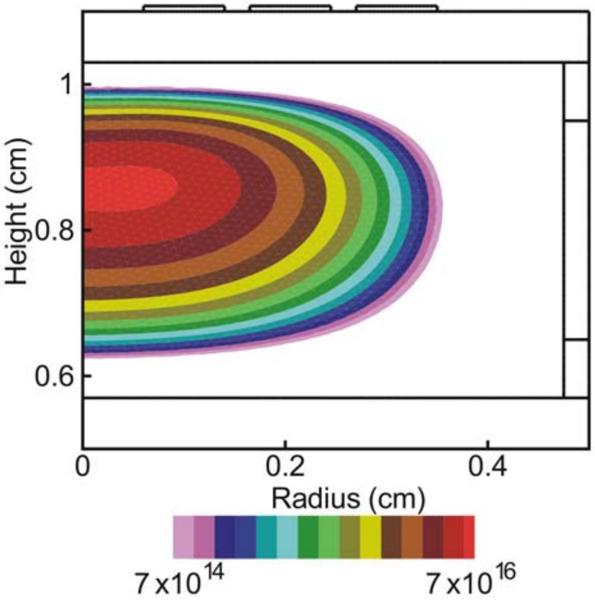
VALIDATION: GEOMETRY AND CONDITIONS

- 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.

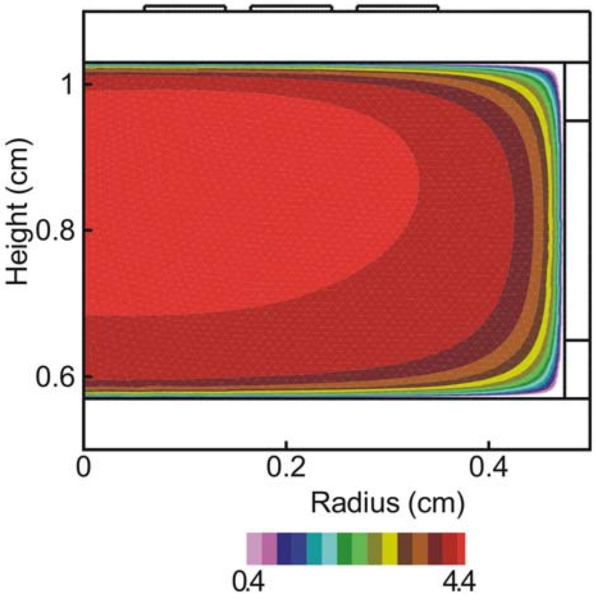


[1] J. Hopwood, O.B. Minayeva, Y. Yin, J. Vac. Sci. Tech B, **18**, 2000

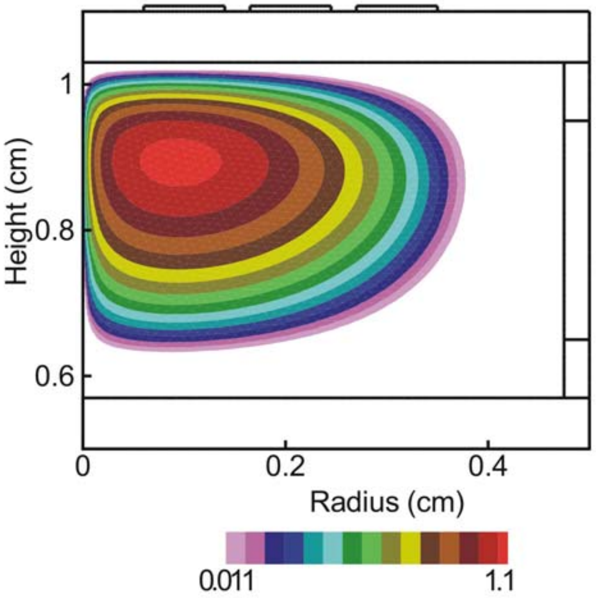
VALIDATION: BASE CASE RESULTS



- [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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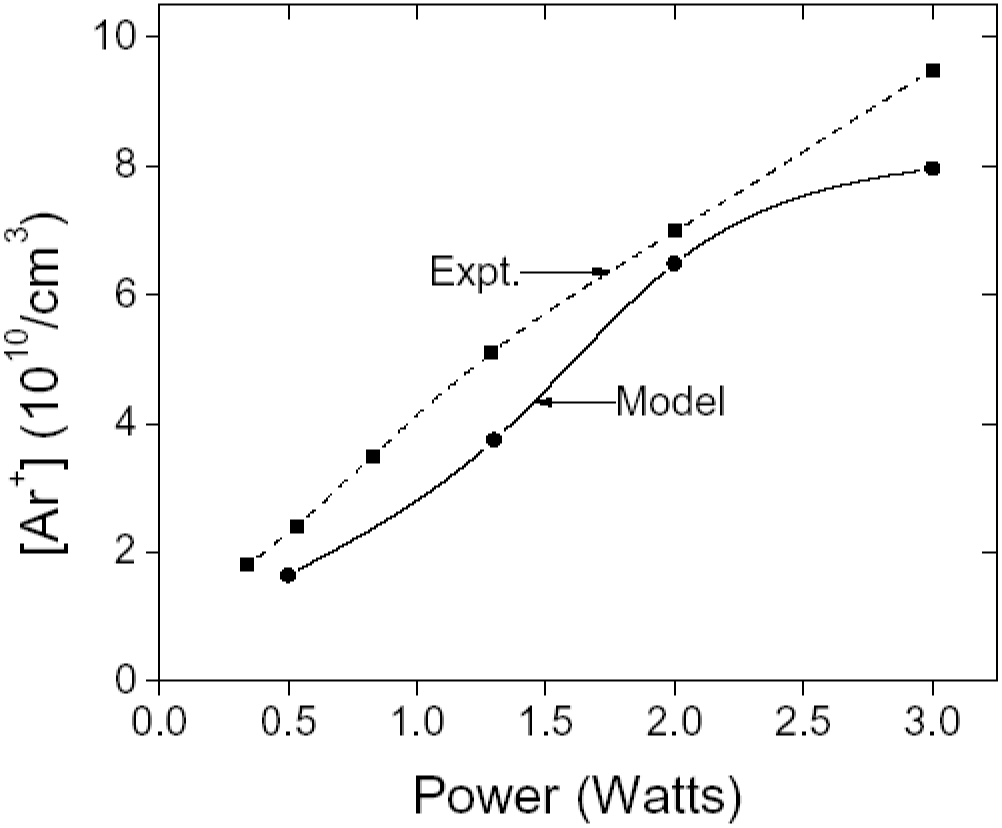
VALIDATION: ION DENSITY

- **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.**

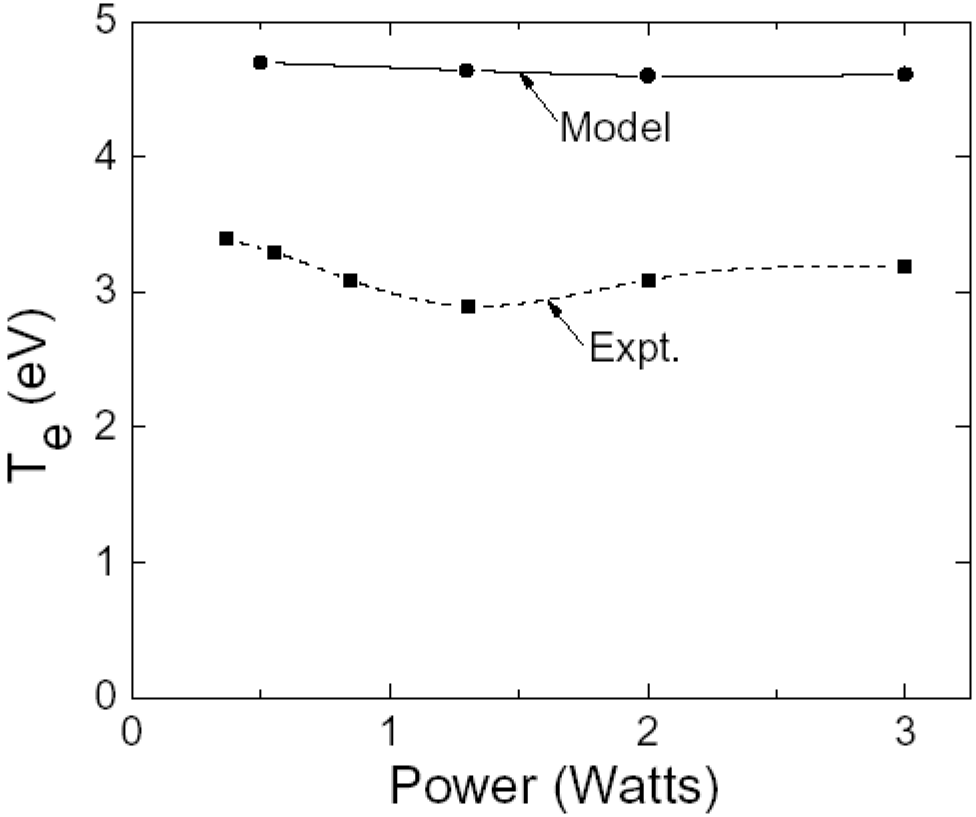


- **500 mTorr, 1 sccm Ar, 450 MHz**

[2] O. B. Minayeva and J. Hopwood, J. Appl. Phys. **94**, 2003

VALIDATION: ELECTRON TEMPERATURE

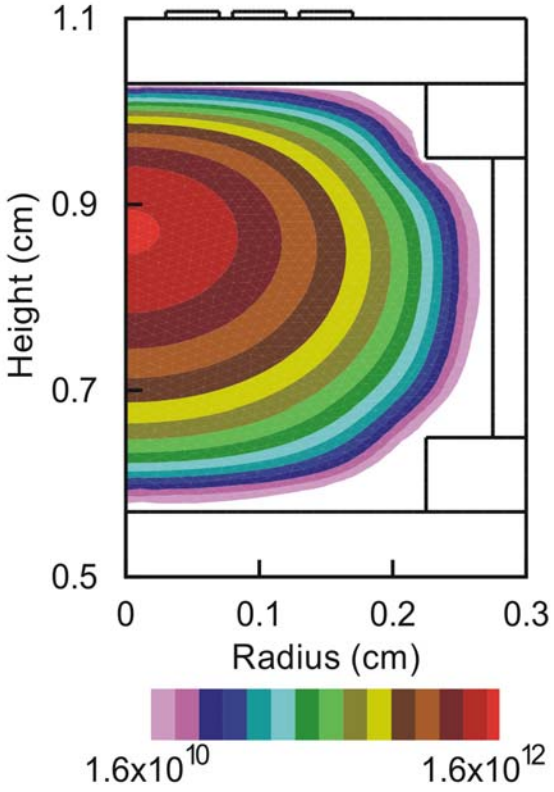
- **Model overpredicts electron temperature.**
- **Model may underpredict multi-step ionization.**



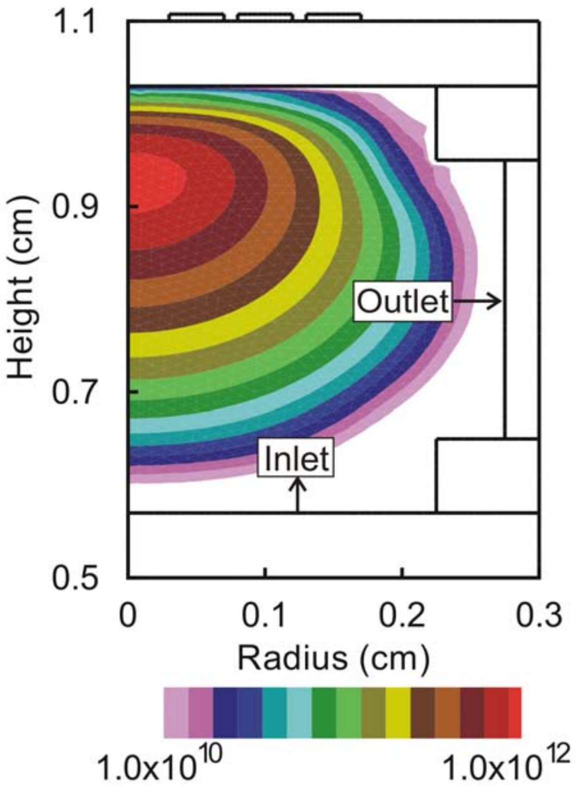
- **500 mTorr, 1 sccm Ar, 450 MHz**
- **Expt: Hopwood, Minayeva, J. Vac. Sci. Tech. B., 18, 2000**

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.**



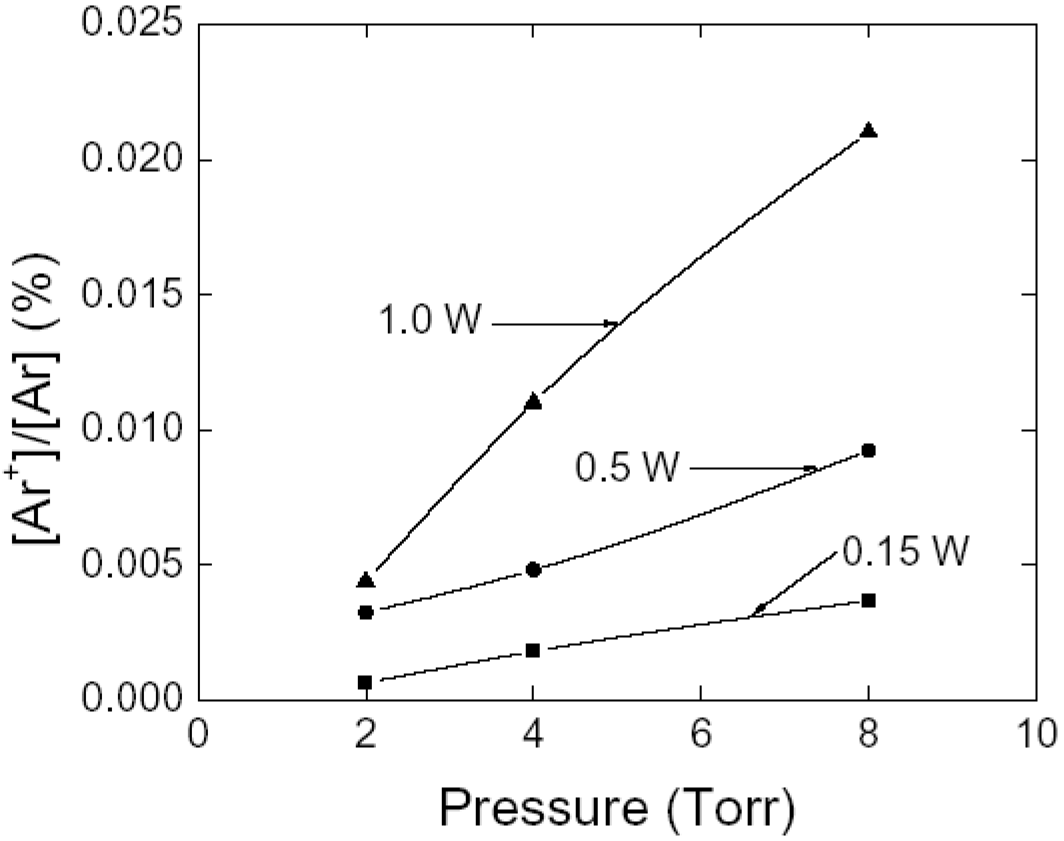
- **[Ar$^+$] without flow**



- **[Ar$^+$] with 2 sccm flow**

IONIZATION FRACTION

- **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.**



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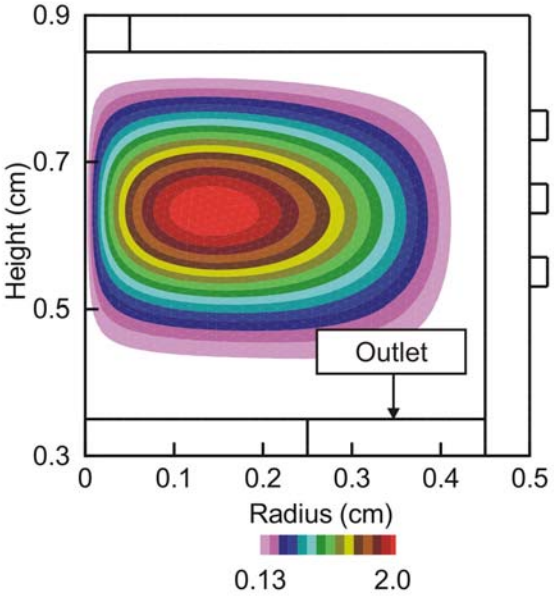
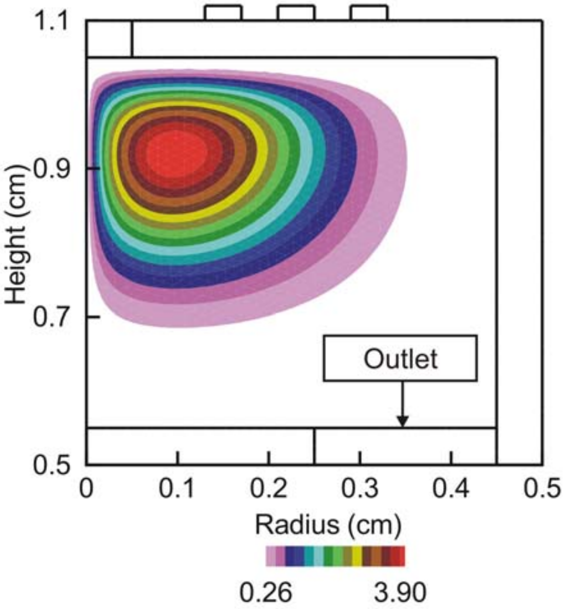
EFFECT OF GEOMETRY

Solenoidal

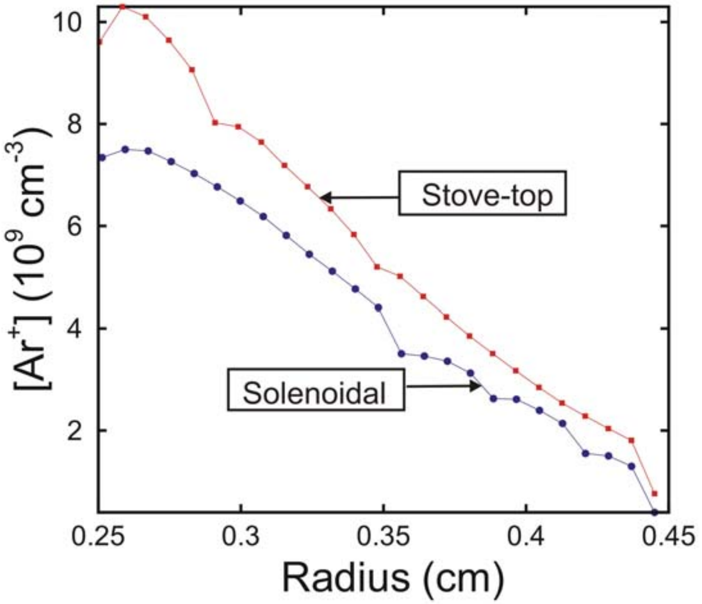


- Power (W/cm^3)

"Stove-top"



- Power (W/cm^3)

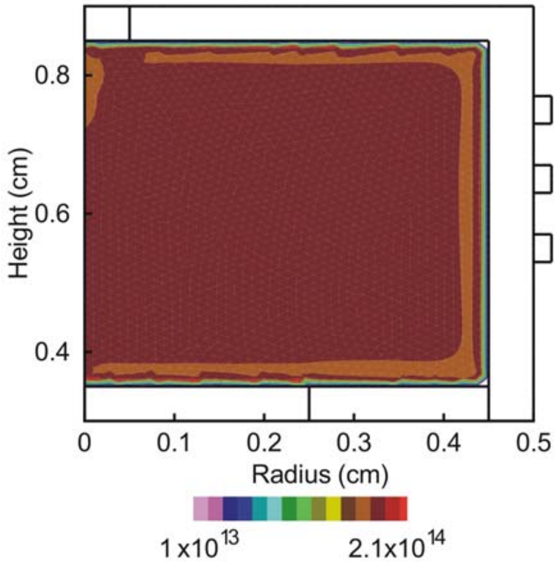


- [Ar$^+$] at outlet

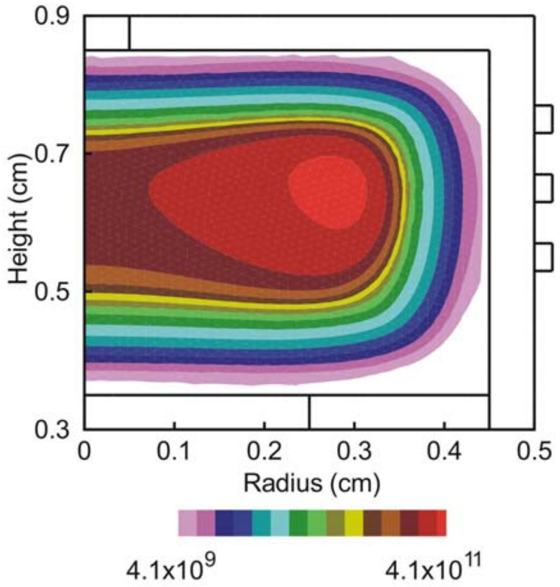
- Conditions:
  - 2 Torr, 1.5 Watt
  - 493 MHz ICP
  - 2 sccm Ar

- Power deposition governed by penetration of electric field into the plasma.
- Steeper gradients of species densities caused by nonuniform power deposition affects the flowfield.

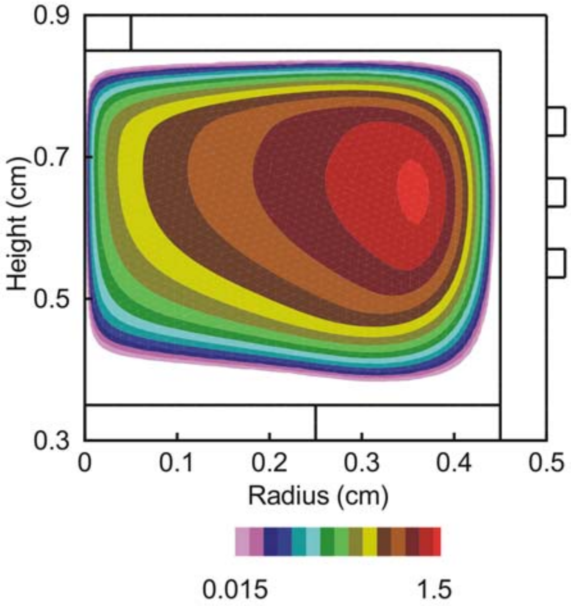
SOURCES OF ENERGETIC NEUTRALS



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



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



- Power (W/cm^3)

- Conditions:
  - 2 Torr, 1.5 Watt
  - 493 MHz ICP
  - He/O_2 (70:30)
  - 10 sccm

- 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.

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 $[O_2(^1\Delta)] / [O_2]$ ~ 0.3% was achieved using the base case conditions.