MODELING OF MICRODISCHARGES FOR USE AS MICROTHRUSTERS

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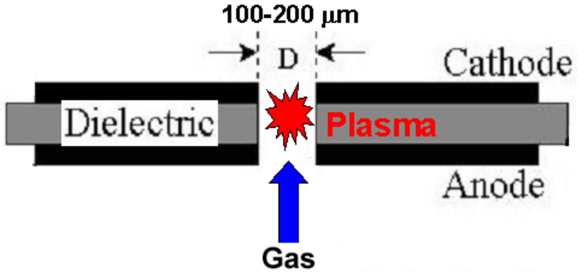
AGENDA

- Introduction to microdischarge (MD) devices
- Description of model
- Reactor geometry and parameters
- Plasma characteristics
- Effect of geometry, and power
- Incremental thrust, and effect of power
- Concluding Remarks

MICRODISCHARGE PLASMA SOURCES

- Microdischarges are plasma devices which leverage pd scaling to operate dc atmospheric glows 10s –100s μm in size.
- Few 100s V, a few mA
- Although similar to PDP cells, MDs are usually dc devices which largely rely on nonequilibrium beam components of the EED.
- Electrostatic nonequilibrium results from their small size. Debye lengths and cathode falls are commensurate with size of devices.



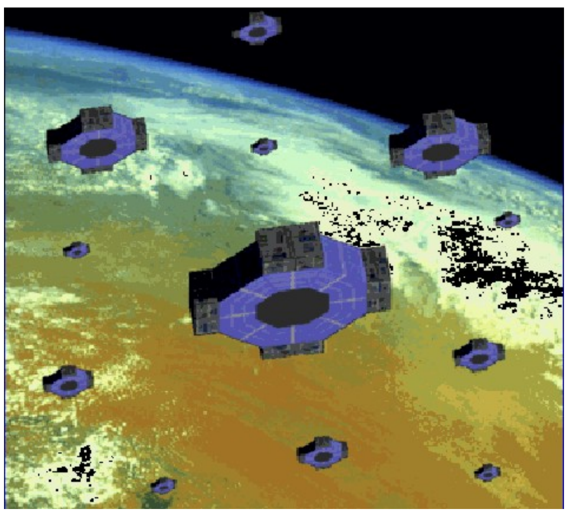
$$L_{cathodeFall} = \left(2V_c\varepsilon_0 / \left(qn_I\right)\right)^{1/2} \approx 10 - 20\,\mu m$$

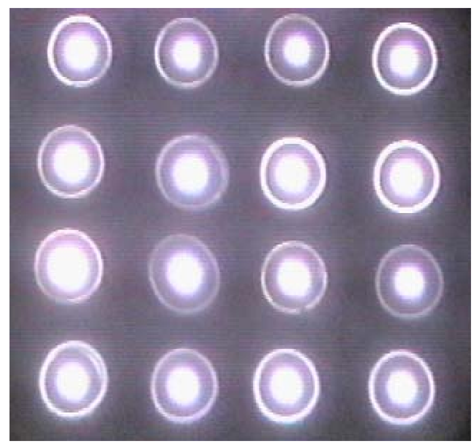
$$\lambda_D \approx 750\left(\frac{T_{eV}}{n_e(cm^{-3})}\right)^{1/2} cm \approx 10\,\mu m,$$

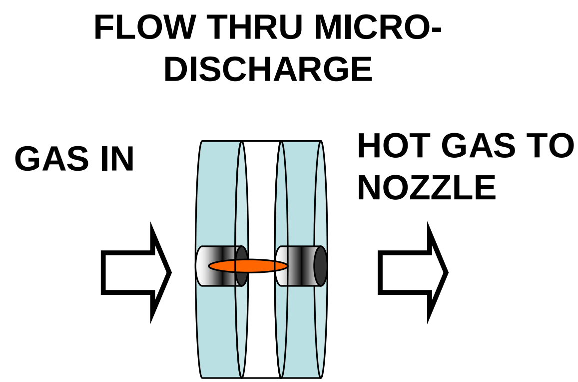
- Ref: Kurt Becker, GEC 2003

APPLICATIONS OF MICRODISCHARGES

- **MEMS fabrication techniques enable innovative structures for displays and detectors.**
- **MDs can be used as microthrusters in small spacecraft for precise control which are requisites for array of satellites.**







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Ref: http://www.design.caltech.edu/micropropulsion

DESCRIPTION OF MODEL

- **To investigate microdischarge sources, nonPDPSIM, a 2-dimensional plasma code was developed with added capabilities for pulsed operation.**
  - **Finite volume method in rectilinear or cylindrical unstructured meshes.**
  - **Implicit drift-diffusion-advection for charged species**
  - **Navier-Stokes for neutral species**
  - **Poisson's equation (volume, surface charge, material conduction)**
  - **Secondary electrons by impact, thermionics, photo-emission**
  - **Electron energy equation coupled with Boltzmann solution**
  - **Monte Carlo simulation for beam electrons.**
  - **Circuit, radiation transport and photoionization, surface chemistry models.**

DESCRIPTION OF MODEL: CHARGED PARTICLE, SOURCES

- **Continuity (sources from electron and heavy particle collisions, surface chemistry, photo-ionization, secondary emission), fluxes by modified Sharfetter-Gummel with advective flow field.**

$$\frac{\partial N_i}{\partial t} = -\vec{\nabla} \cdot \vec{\phi} + S_i$$

- **Poisson's Equation for Electric Potential:** $-\nabla \cdot \varepsilon \nabla \Phi = \rho_V + \rho_S$

- **Photoionization, electric field and secondary emission:**

$$S_{Pi}(\vec{r}) = \int \frac{N_i(\vec{r})\sigma_{ij} N_j(\vec{r}')\exp\left(\frac{-\left|\vec{r}' - \vec{r}\right|}{\lambda}\right) d^3\vec{r}'}{4\pi\left|\vec{r}' - \vec{r}\right|^2}$$

$$S_{Si} = -\nabla \cdot j, \quad j_E = AT^2 \exp\left(\frac{-\left(\Phi_W - \left(q^3 \mathrm{E}/\varepsilon_0\right)^{1/2}\right)}{kT_S}\right), \quad j_S = \sum_j \gamma_{ij}\phi_j$$

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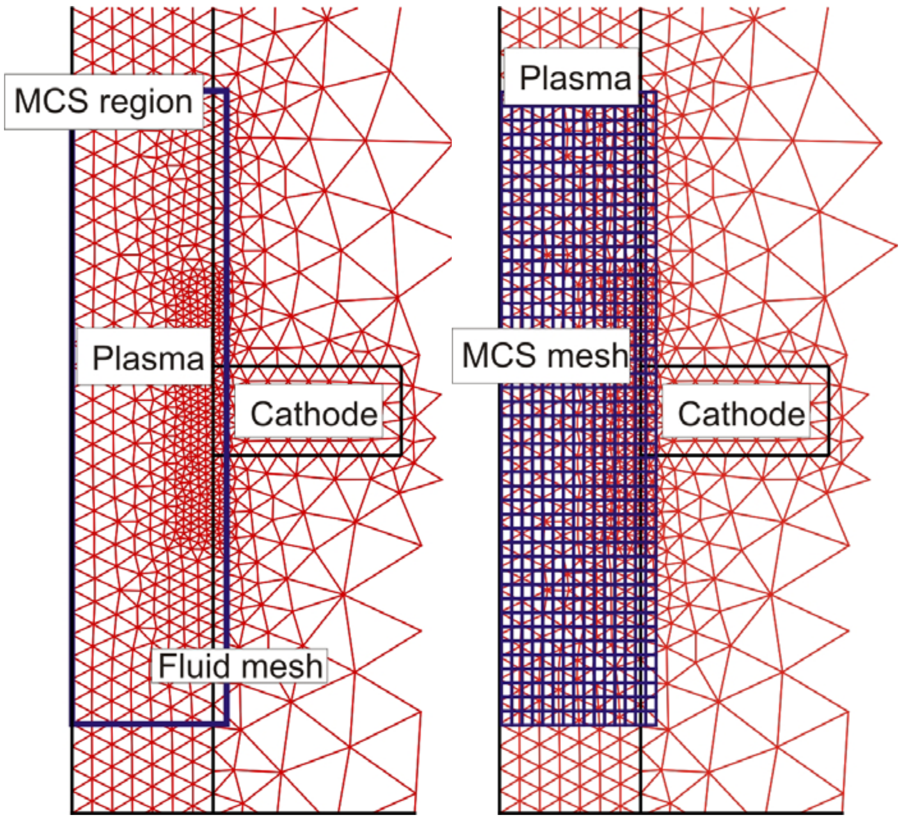
ELECTRON ENERGY, TRANSPORT COEFFICIENTS

- **Bulk electrons: Electron energy equation with coefficients obtained from Boltzmann's equation solution for EED.**

$$\frac{\partial(n_e\varepsilon)}{\partial t} = \vec{j}\cdot\vec{E} + \sigma E_{EM}^2 - n_e\sum_i N_i\kappa_i - \nabla\cdot\left(\frac{5}{2}\varepsilon\varphi - \lambda\nabla T_e\right), \quad \vec{j} = q\vec{\phi}_e$$



- **Beam Electrons: Monte Carlo Simulation**
- **Cartesian MCS mesh superimposed on unstructured fluid mesh. Construct Greens functions for interpolation between meshes.**

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DESCRIPTION OF MODEL: NEUTRAL PARTICLE TRANSPORT

- **Fluid averaged values of mass density, mass momentum and thermal energy density obtained using unsteady, compressible algorithms.**

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + (inlets, pumps)$$

$$\frac{\partial(\rho \vec{v})}{\partial t} = \nabla\left(\sum_i N_i k T_i\right) - \nabla \cdot (\rho \vec{v}\vec{v}) - \vec{\nabla} \cdot \vec{\vec{\tau}} + \sum_i \left(q_i N_i \vec{E}_i - S_i m_i \mu_i q_i \vec{E}\right)$$

$$\frac{\partial(\rho c_p T)}{\partial t} = -\nabla\left(-\kappa \nabla T + \rho \vec{v} c_p T\right) + P_i \nabla \cdot v_f - \sum_i R_i \Delta H_i + \sum_i \vec{j}_i \cdot \vec{E}$$

- **Individual species are addressed with superimposed diffusive transport.**

$$N_i(t+\Delta t) = N_i(t) - \nabla \cdot \left(\vec{v}_f - D_i N_T \nabla\left(\frac{N_i(t+\Delta t)}{N_T}\right)\right) + S_V + S_S$$

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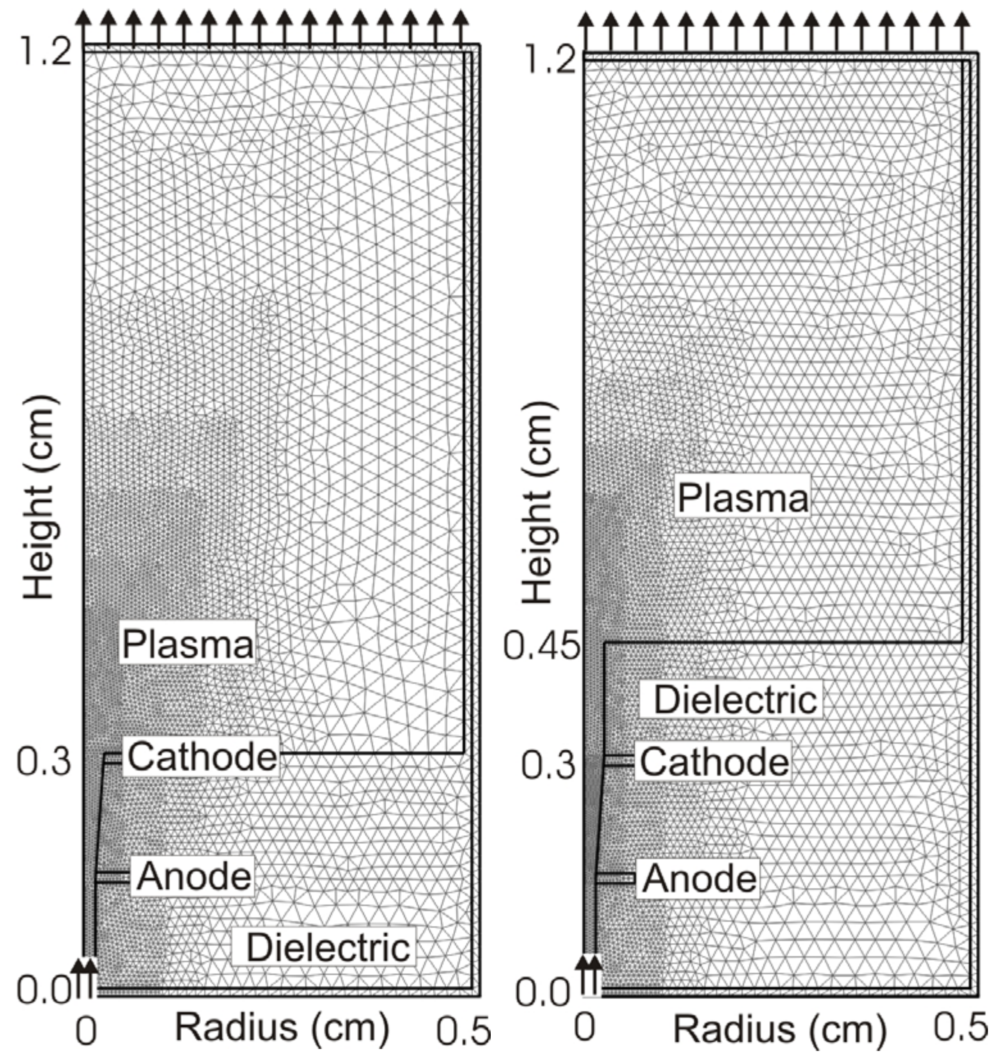
GEOMETRY AND MESH

- Plasma dia: 150 μm at inlet, 250 μm at cathode.
- Electrodes 130 μm thick.
- Dielectric gap 1.5 mm.
- Geometry B: 1.5 mm dielectric above the cathode.
- Fine meshing near electrodes, less refined near exit.
- Anode grounded; cathode bias varied based on power deposition (0.25 - 1.0 W).
- 10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.

- Geometry A
- Geometry B



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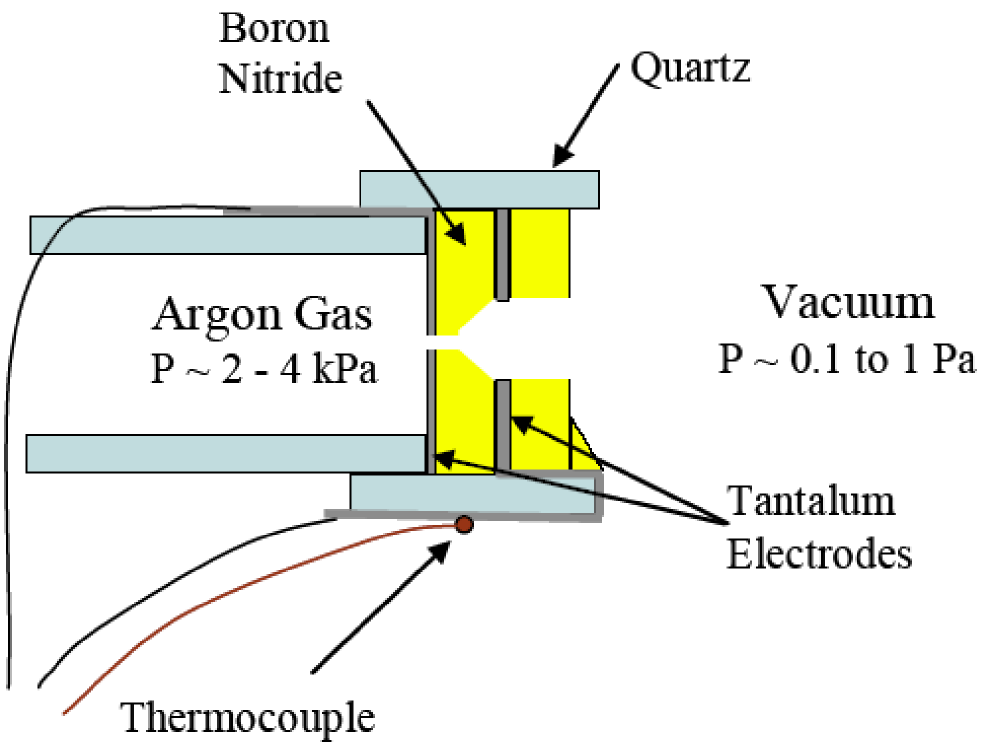
EXPERIMENT: GEOMETRY



- **Modeled geometry similar to experimental setup.**
- **Plume characterized by densities of excited states.**

- **Ref: John Slough, J.J. Ewing, AIAA 2005-4074**

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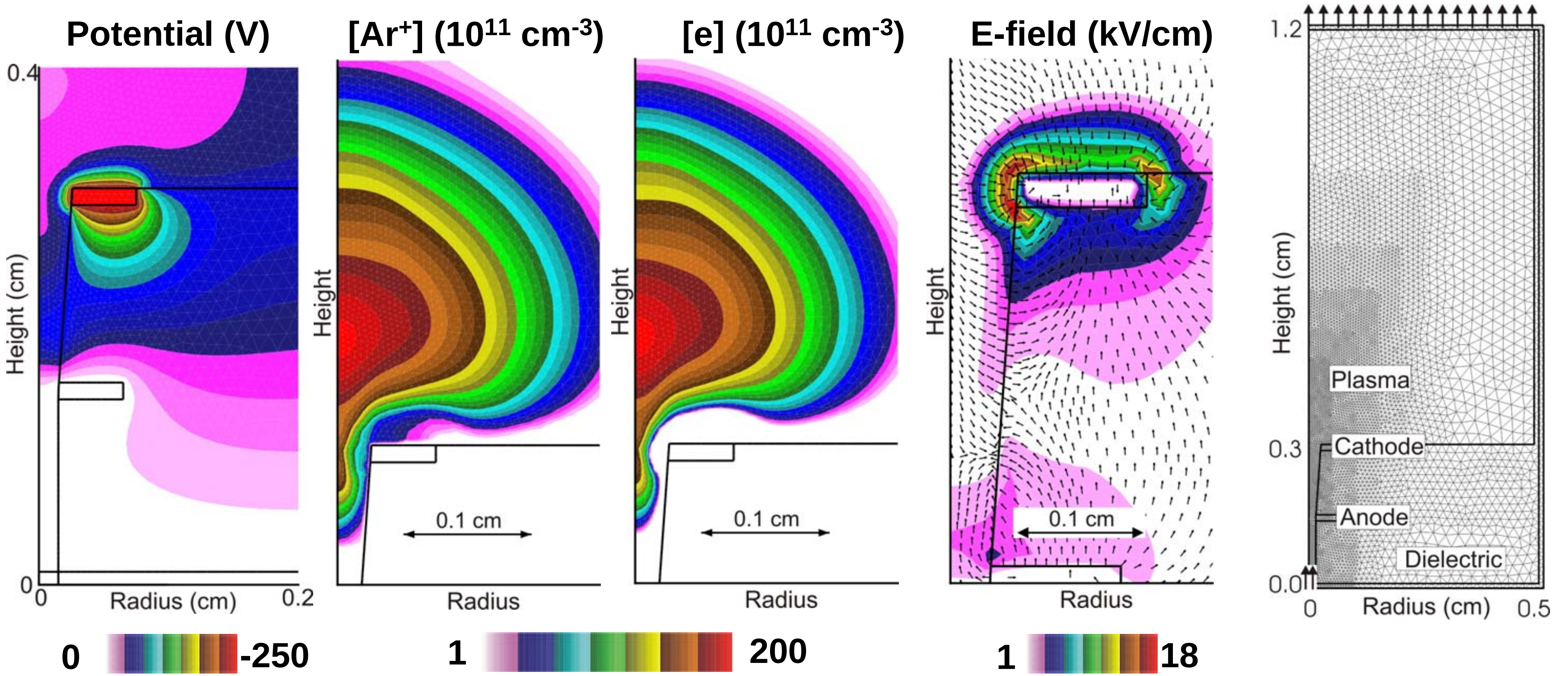
CHARGED SPECIES: GEOMETRY A

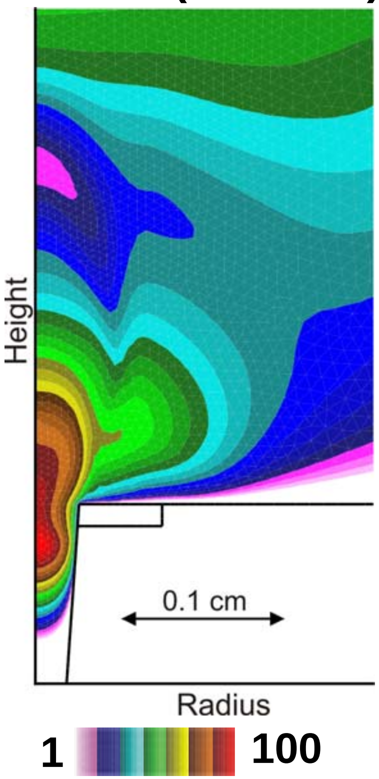


- Power deposition occurs in the cathode fall by collisions with hot electrons.
- Very high electric fields near cathode.

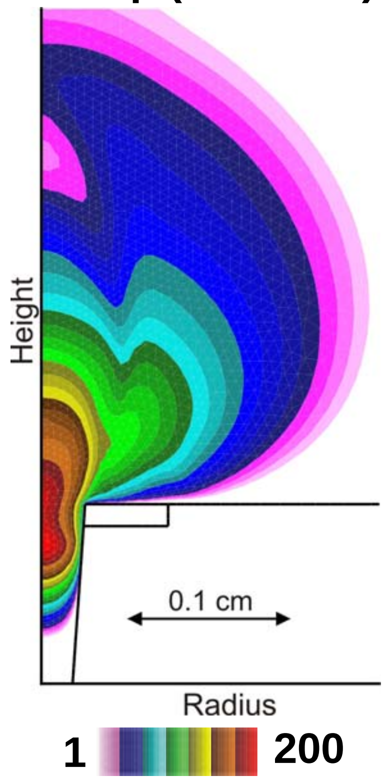
- 10 sccm Ar, 0.5 W

NEUTRAL FLUID PROPERTIES: GEOMETRY A

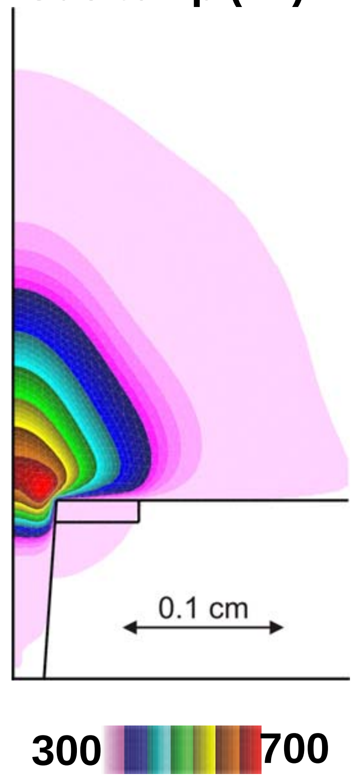
Ar 4s (10^{11} cm^{-3})

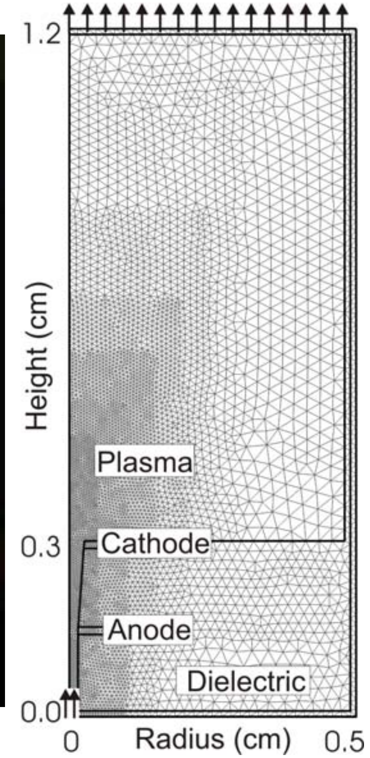


Ar 4p (10^{11} cm^{-3})



Gas temp (°K)





- **Plume extends downstream, can be used for diagnosis.**
- **Gas heating and consequent expansion is a source of thrust.**

- **10 sccm Ar, 30 – 10 Torr**
- **0.5 W.**

- **Ref: John Slough, J.J. Ewing, AIAA 2005-4074**

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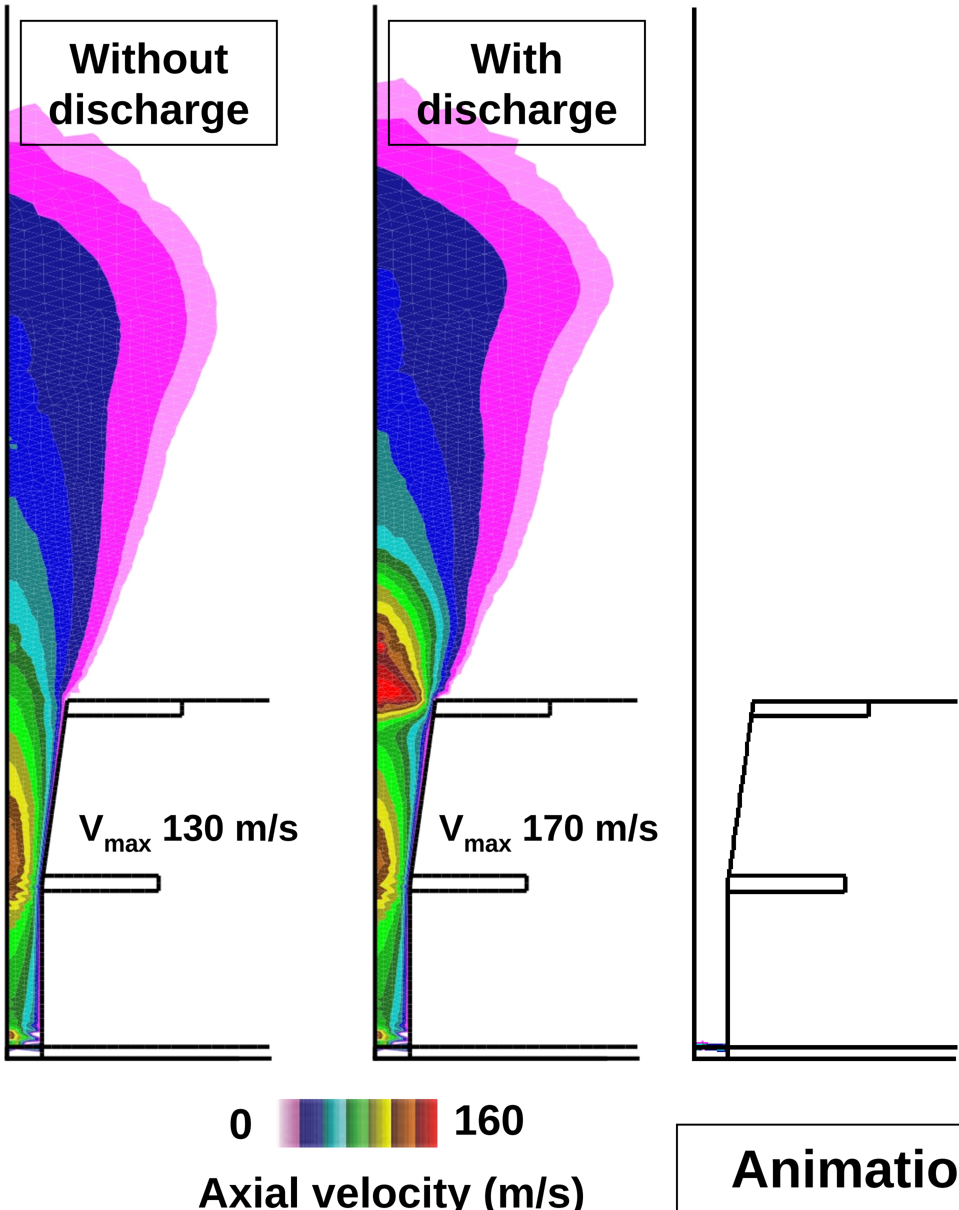
VELOCITY INCREASE WITH DISCHARGE



- Gas heating and subsequent expansion causes increase in velocity.
- Steady state after one or two bursts of flow.
- At high plasma density, momentum transfer between charged species and neutrals is also important.

- 10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.
- 0.5 Watts.
- Power turned on at 0.5 ms.

Animation
0 – 0.55 ms

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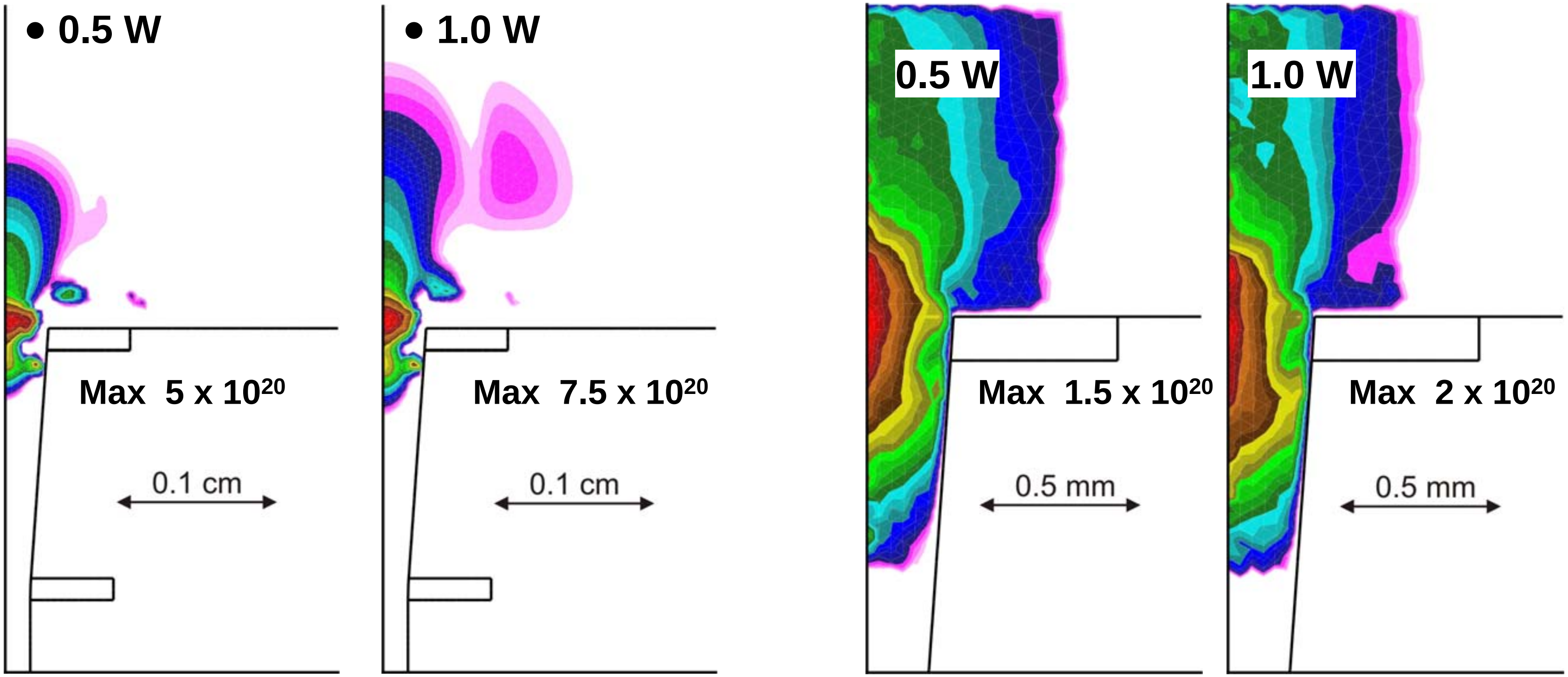
POWER DEPOSITION: IONIZATION SOURCES



Bulk ionization (cm^{-3} sec^{-1}) 1 — 100 Beam ionization (cm^{-3} sec^{-1})

- **Ionization rates increase with power.**
- **Beam electrons are equally as important as bulk electrons.**

- **10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.**

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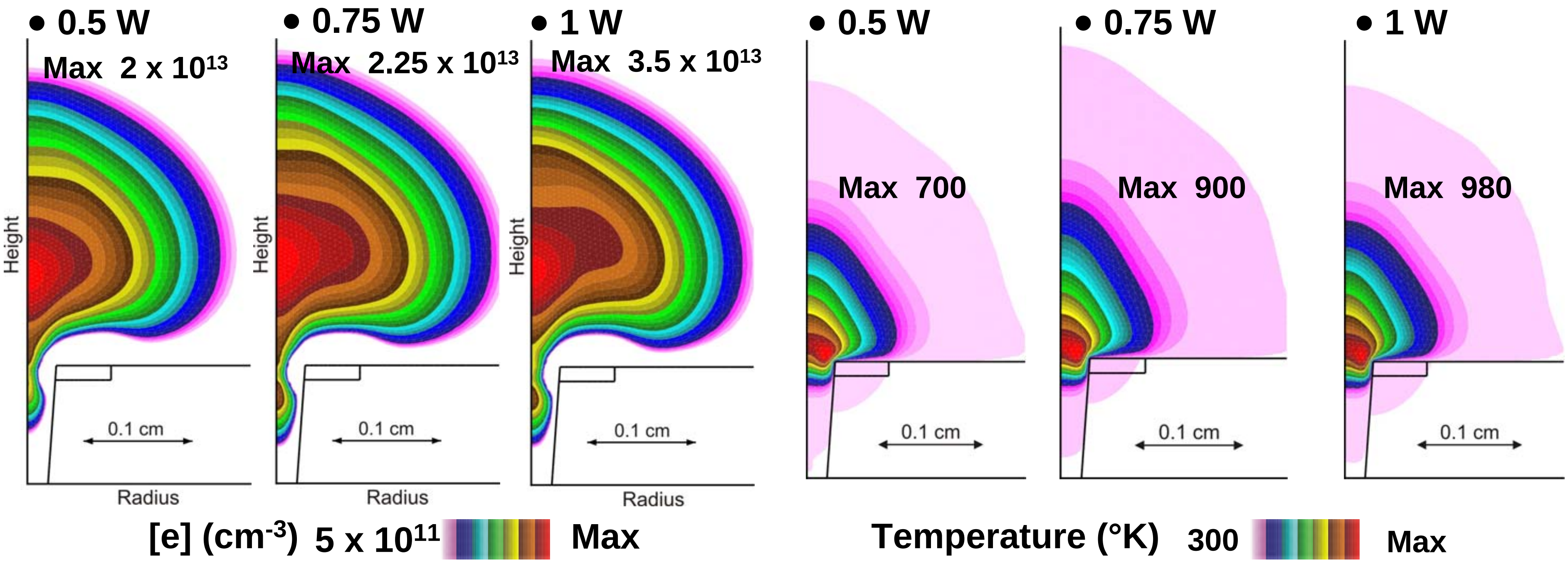
POWER DEPOSITION: PLASMA PROPERTIES



- **Hotter gases lead to higher ΔV and higher thrust production.**
- **Increase in mean free path due to rarefaction may affect power deposited to neutrals.**
- **With increasing [e], increase in production of electronically excited states.**

- **10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.**

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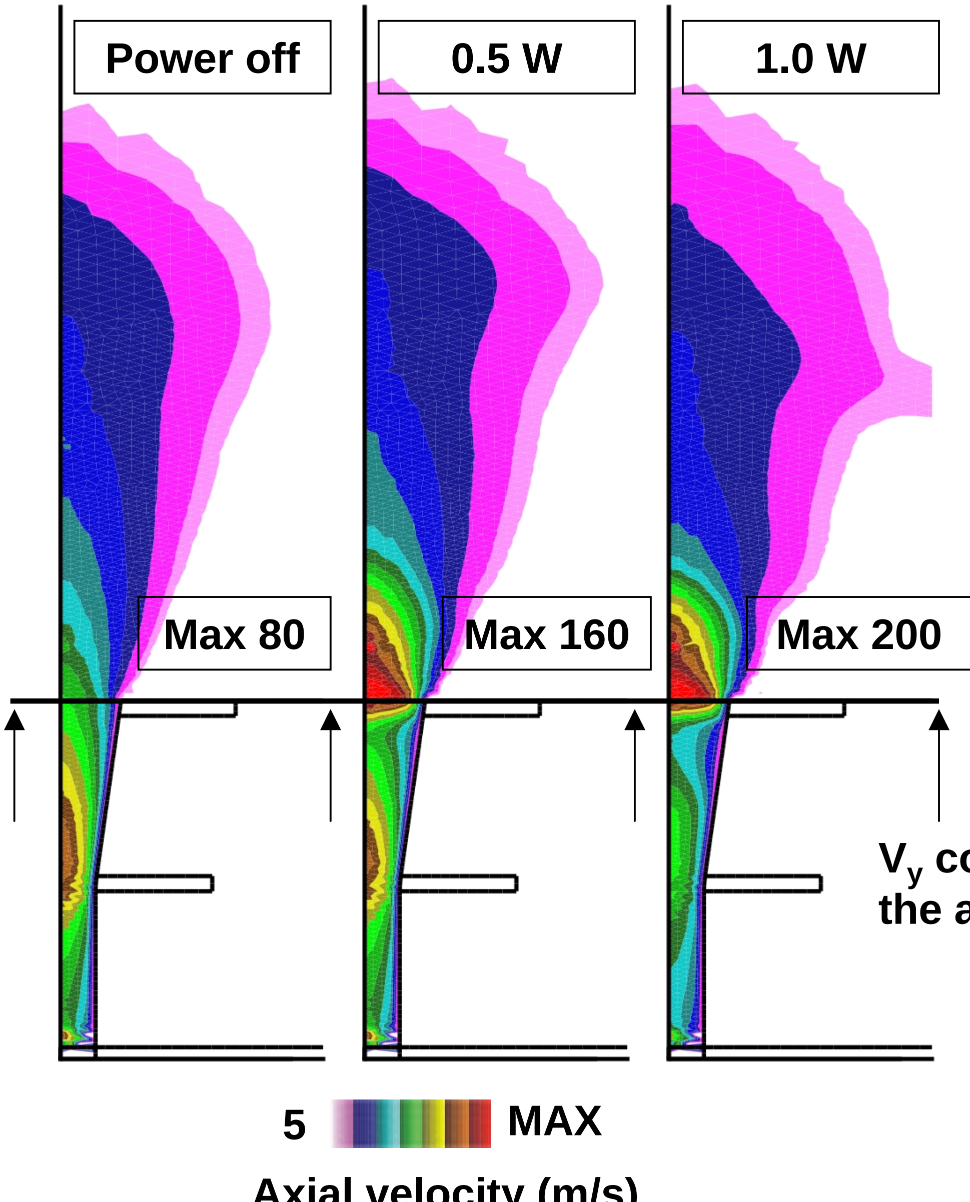
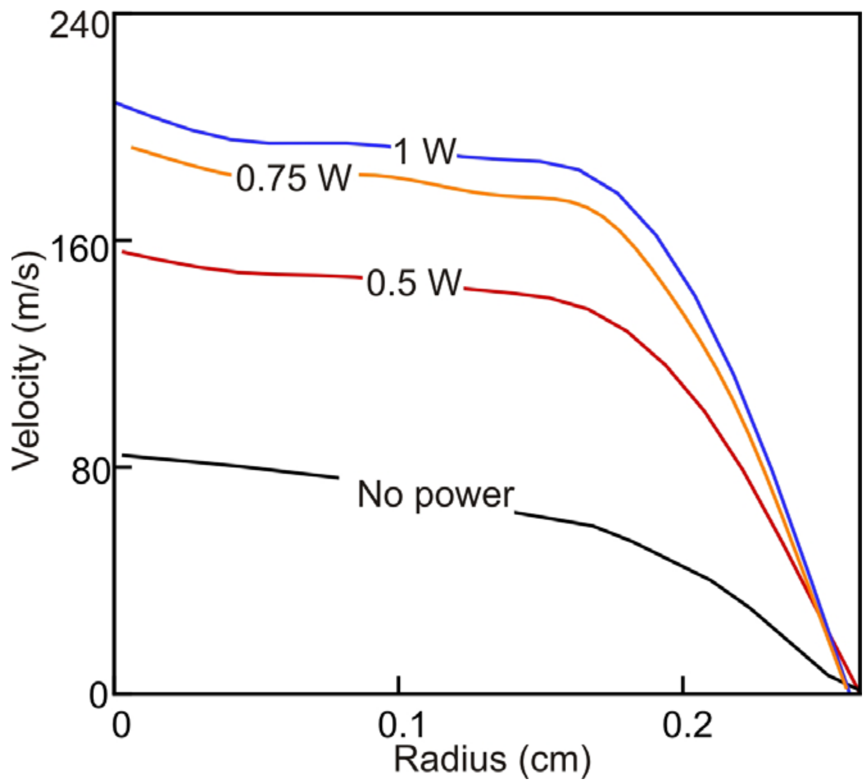
POWER DEPOSITION: FLOW VELOCITY





V_y compared in the above plane.

- 10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.
- Power turned on at 0.5 ms.

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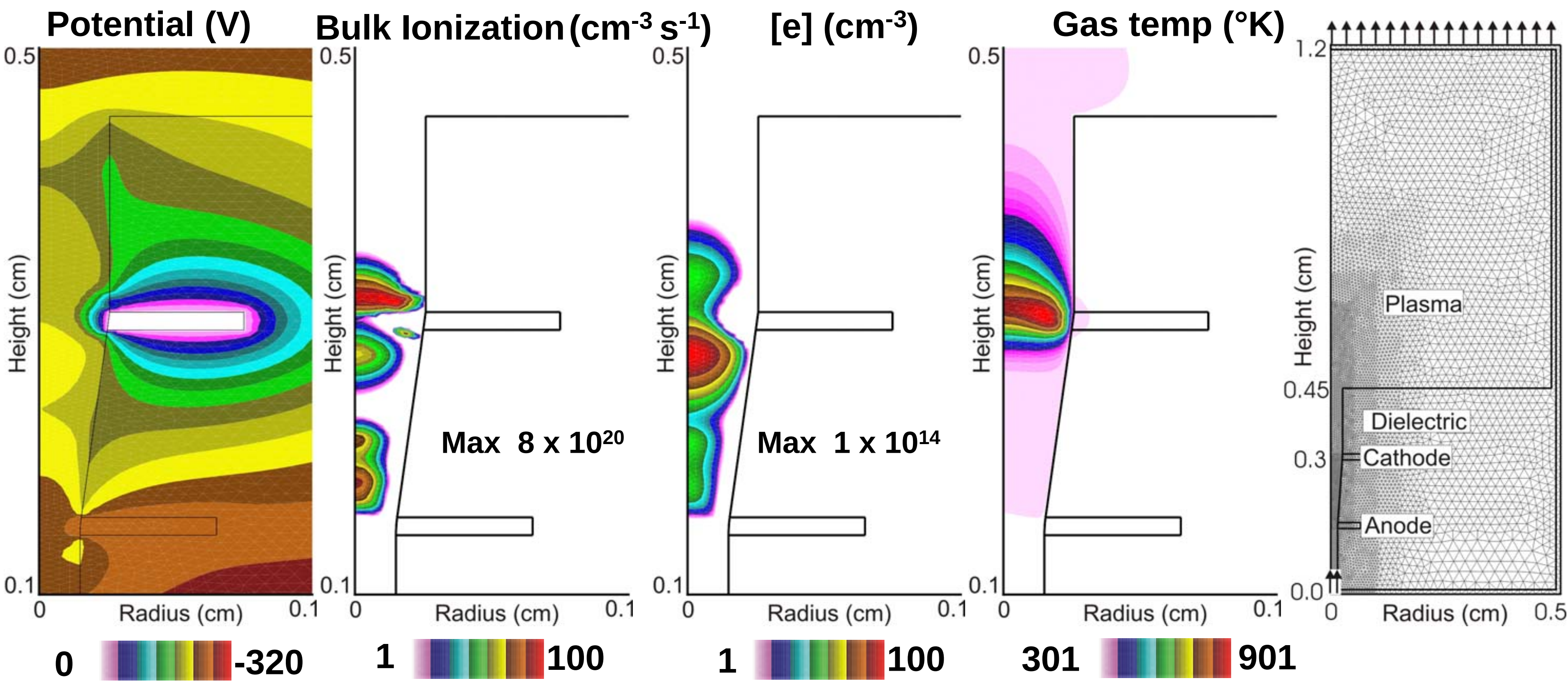
BASE CASE RESULTS: GEOMETRY B



- Electrons are confined, discharge operates in an unsteady regime.
- Ionization pulses travel towards anode.
- Power densities are greater than that of Geometry A.

- 10 sccm Ar, 30 – 10 Torr
- 0.5 W, turned on at 0.5 ms

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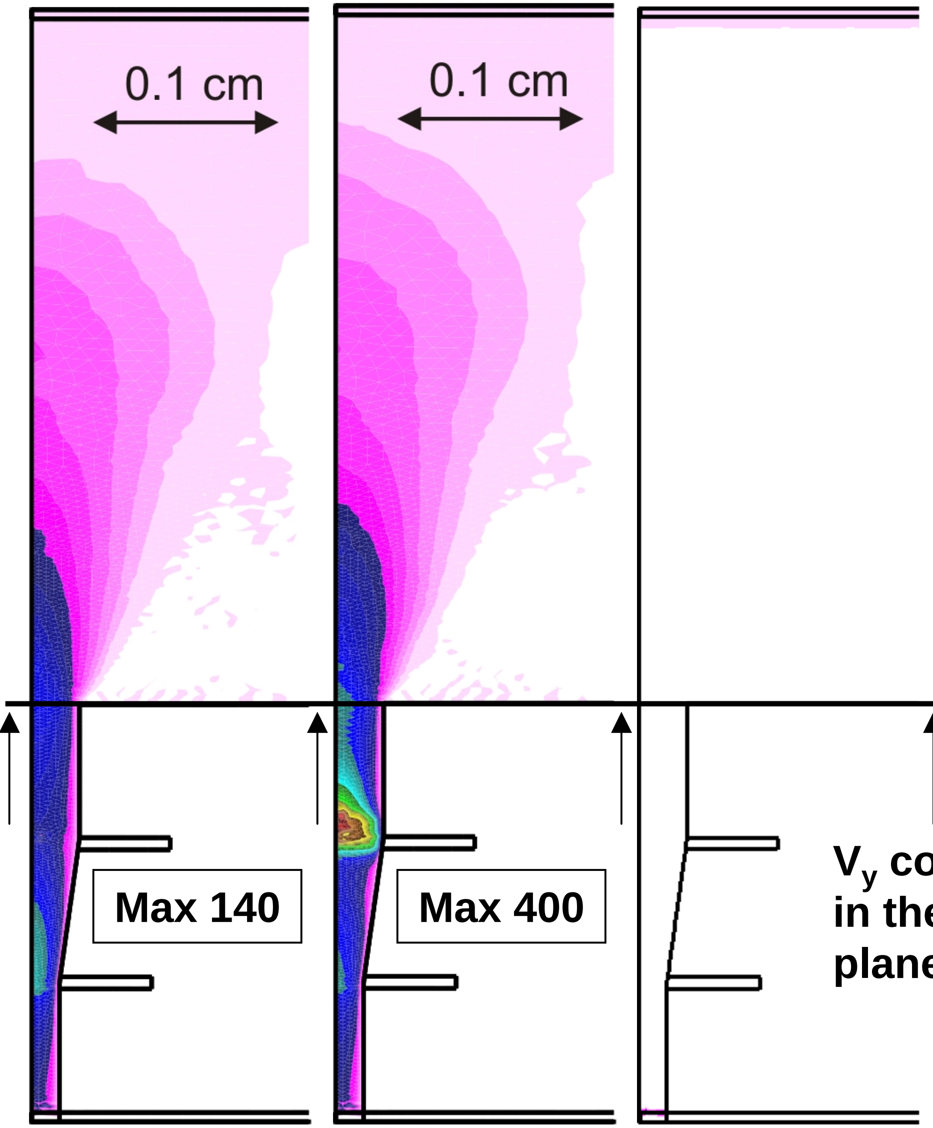
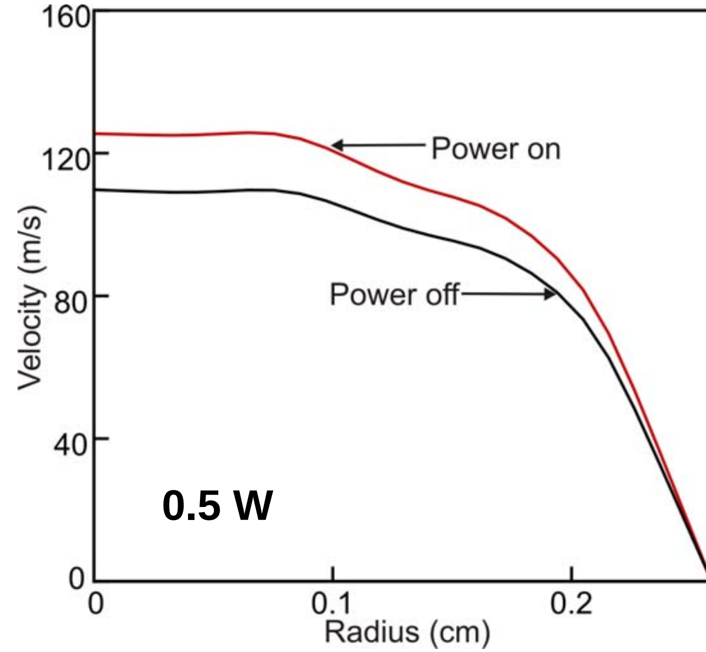
VELOCITY INCREASE: GEOMETRY B



V_y compared in the above plane.



- Increase in velocity is due to expansion of hot gas.
- Axial-velocity increase not substantial at exit.
  - 10 sccm Ar, 30 – 10 Torr
  - 0.5 W, turned on at 0.5 ms

5 MAX Axial velocity (m/s)

Animation
0 – 0.65 ms

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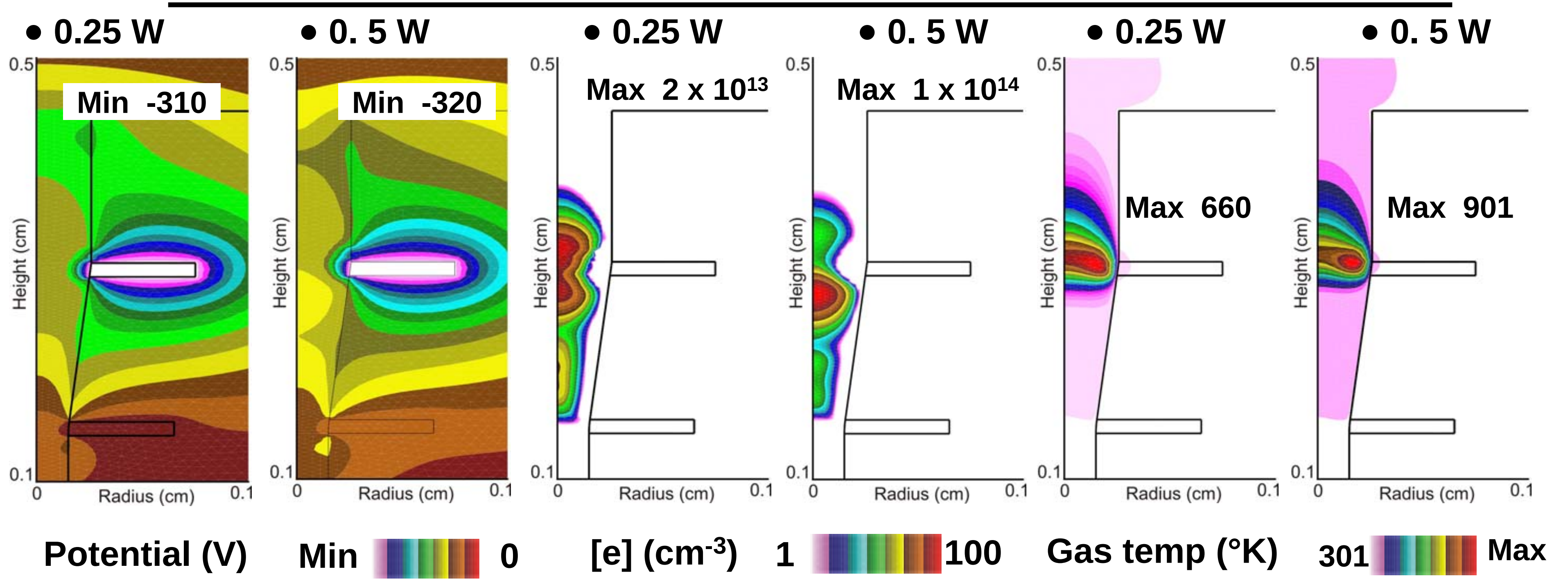
POWER DEPOSITION: GEOMETRY B



- Discharge operates in normal glow, current increases with power, whereas voltage marginally increases.
- [e] increases substantially with increase in power.
- With increasing [e], charge buildup on the dielectric can be high.

- 10 sccm Ar, 30 Torr at inlet, 10 Torr at exit.

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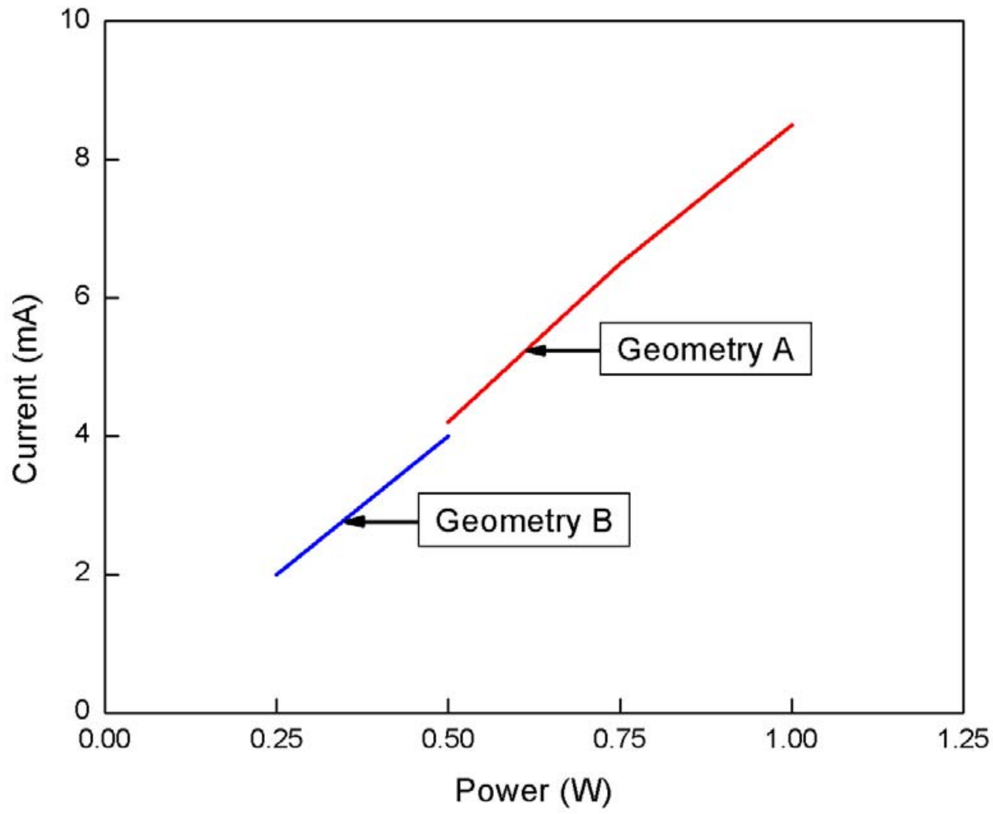
CURRENT VOLTAGE CHARACTERISTICS

- **Operating voltage for geometry A remains almost a constant (260 V), whereas slight changes observed for geometry B.**

- **Discharge resistance R_D of 43 kΩ.**



INCREMENTAL THRUST

- **Thrust calculated by:**

$$F = \frac{dm}{dt}V_e + A_e\left(P_e - P_a\right)$$

- **Increase in thrust is the rate of momentum transfer to the neutrals when the discharge is switched on.**

$$\overrightarrow{\delta F} = \left(\frac{dm}{dt}\vec{V}\right)_{pulse} - \left(\frac{dm}{dt}\vec{V}\right)_{nopulse}$$

- **Meaningful incremental thrust occurs when power deposited to plasma is greater than that contained in the flow.**

$$\vec{j}.\vec{E} \geq \frac{1}{2}\dot{\rho}v^2$$

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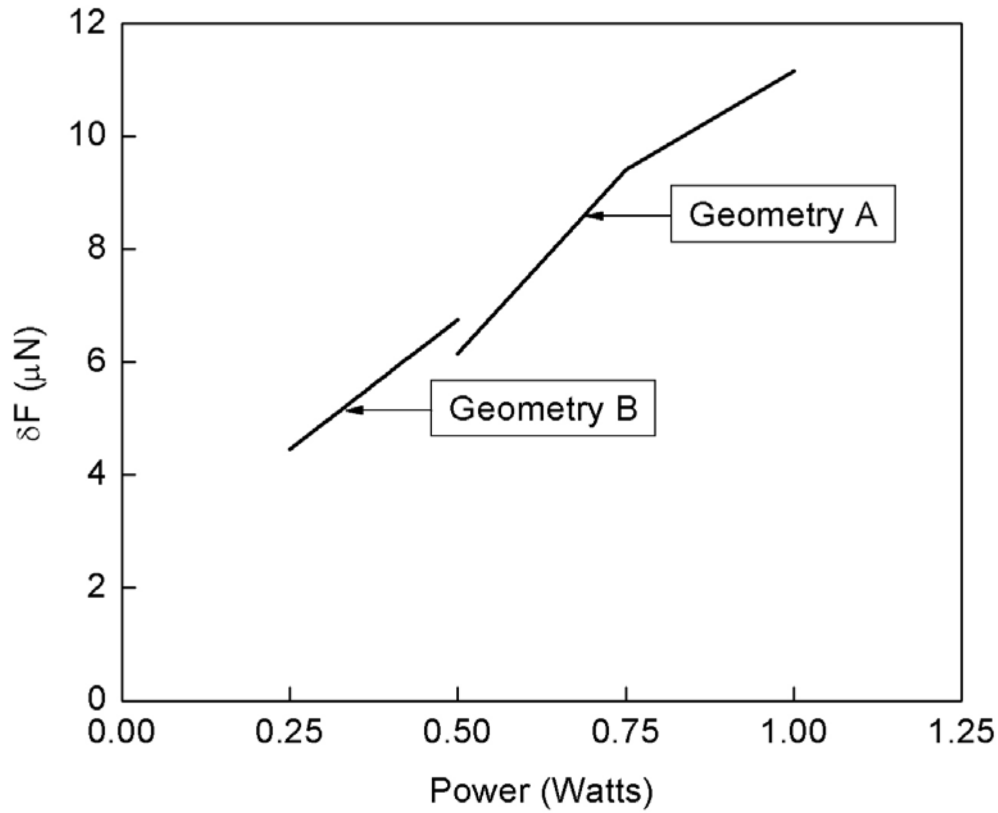
INCREMENTAL THRUST: EFFECT OF POWER

- Thrust increases with power deposited.
- Zero-power thrust:

  Geometry A: 8μN

  Geometry B: 12 μN
- Geometry has marginal effect on incremental thrust.



- 10 sccm Ar, 30 Torr upstream, 10 Torr downstream.
- Power turned on at 0.5 ms

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CONCLUDING REMARKS

- An axially symmetric microdischarge was computationally investigated with potential application to microthrusters.
- Studies were conducted to investigate the effect of parameters such as power deposition, and the geometry of the reactor.
- The geometry affected the plasma characteristics significantly, whereas there was no significant difference to incremental thrust.
- At higher power, higher gas temperatures lead to higher thrust.
- Rarefaction at high temperatures decreases mean free path and could limit thrust produced.