MODELING OF MICRODISCHARGE DEVICES: PLASMA AND GAS DYNAMICS*

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AGENDA

- Scaling of Microdischarge Devices
- Description of model
- The annular sandwich MD
- The pyramidal MD
- Concluding Remarks.

- Acknowledgements: Ramesh Arakoni, Ananth Bhoj, Brian Lay

MICRODISCHARGE PLASMA SOURCES

- Microdischarges have demonstrated great promise for photon, radical and ionization sources, and laboratories for plasma and optical physics.
- Microdischarges leverage pd scaling to operate as dc atmospheric glows 10s –100s μm in size.
- MEMS enable innovative structures for displays and detectors.
- Although similar to PDP cells, MDs are 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.

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

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

WHAT CAN BE LEARNED FROM MODELING MICRODISCHARGES?

- Progress in other fields of low temperature plasmas has greatly benefited and been facilitated by modeling.
    - Plasma materials processing
    - Lasers
    - Pollution abatement
- Development of microdischarge technologies has been extremely successful without a strong legacy of modeling.
- What can be learned from modeling microdischarges (that we didn't already know)?
- What capabilities in modeling are required?

GOAL FOR THIS TALK: MODELING AS A BASIS OF FUNDAMENTAL UNDERSTANDING AND SCALING

- Discussion of modeling MDs with goals of
  - Fundamental parameters and operating characteristics
  - Scaling
  - Use of MDs as sources of radicals and thrust

- Modeling Platform: *Nonpdpsim* 2-dimensional plasma hydrodynamics model

DESCRIPTION OF nonPDPSIM

- To investigate scaling processes in microdischarge sources, nonPDPSIM has been developed, a 2-dimensional model.
  - Rectilinear or cylindrical unstructured mesh
  - Implicit drift-diffusion-advection for charged species
  - Navier-Stokes for neutral species
  - Poisson's equation (volume, surface charge, material conduction.
  - Circuit model
  - Electron energy equation coupled with Boltzmann solution
  - Monte Carlo beam electrons
  - Optically thick radiation transport with photoionization
  - Secondary electrons by impact, thermionics, photo-emission
  - Surface chemistry.

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:**

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

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

DESCRIPTION OF MODEL:
ELECTRON ENERGY, TRANSPORT COEFFICIENTS

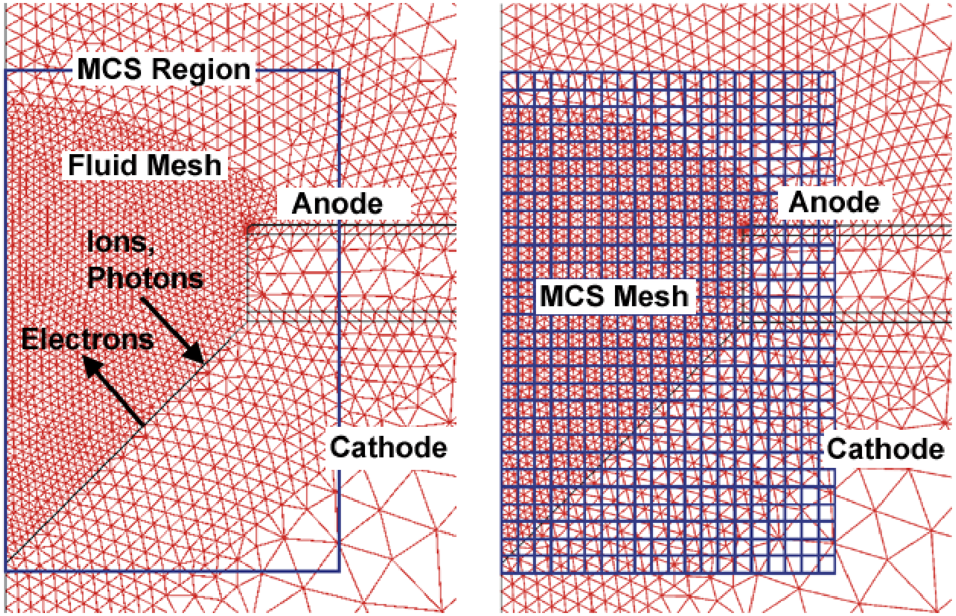
- **Electron energy equation implicitly integrated using Successive-Over-Relaxation:**

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

- **Electron transport coefficients obtained from 2-term spherical harmonic expansion of Boltzmann’s Equation.**
- **Ion transport coefficients obtained from tabulated values from the literature or using conventional approximation techniques.**

DESCRIPTION OF MODEL: MCS AND MESHING

- Transport of energetic secondary electrons is addressed with a Monte Carlo Simulation.



- Superimpose Cartesian MCS mesh on unstructured fluid mesh. Construct Greens functions for interpolation between meshes.
- Electrons and their progeny are followed until slowing into bulk plasma or leaving MCS volume.
- Electron energy distribution is computed on MCS mesh.
- EED produces source functions for electron impact processes which are interpolated to fluid mesh.

DESCRIPTION OF MODEL: NEUTRAL PARTICLE TRANSPORT

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

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

$$\frac{\partial (\rho \vec{v})}{\partial t} = \nabla (NkT) - \nabla \cdot (\rho \vec{v} \vec{v}) - \nabla \cdot \overline{\mu} + \sum_i q_i N_i \vec{E}_i$$

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

- **Alternately, if only heat conduction is considered.**

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

DESCRIPTION OF MODEL: NEUTRAL PARTICLE UPDATE

- **Transport equations are implicitly solved using Successive-Over-Relaxation:**

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

- **Surface chemistry is addressed using “flux-in/flux-out” boundary conditions with reactive sticking coefficients**

$$S_{Si}=\sum_j\left(\nabla\cdot\vec{\phi}_j\right)\gamma_{ij}$$

METHOD OF SOLUTION

- **Finite volume techniques are used for flux conservation at all nodes.**

$$\frac{dN_i}{dt} = -\nabla \cdot \vec{\phi}_i = \frac{1}{V_i}\sum_j A_{ij}\phi_{ij}, \quad \phi_{ij} = \tfrac{1}{2}\left(\vec{\phi}_i + \vec{\phi}_i\right)\cdot \hat{a}_{ij}$$

- **Jacobian elements are numerically derived to produce a matrix of differential updates for timestep Δt.**

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

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

- **Iterative Newton's method is used to solved coupled charged particle transport and Poisson's equation.**

METHOD OF SOLUTION

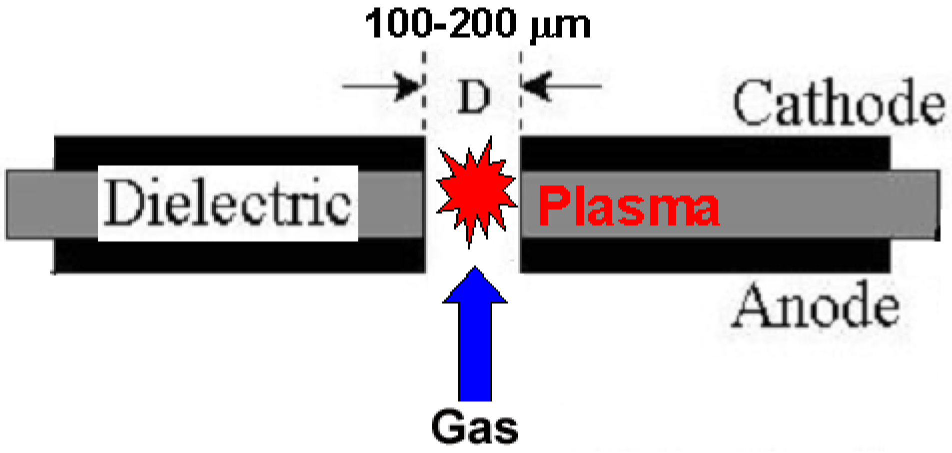
- **Time splicing acceleration techniques are used in which modules are sequentially executed.**

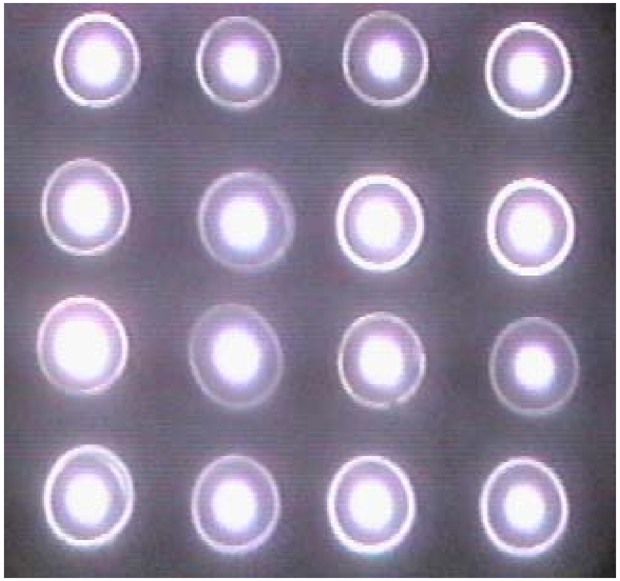
$$\begin{bmatrix} \textit{Charged Particles and Potential} \\ \to \textit{Electron Temperature} \\ \to \textit{Neutral Densities} \\ \to \textit{Surface Chemistry} \end{bmatrix}_{\Delta t_1} \to \begin{matrix} \begin{bmatrix} \textit{Electron} \\ \textit{Monte} \\ \textit{Carlo} \end{bmatrix}_{\Delta t_2} \\ \begin{bmatrix} \textit{Electron} \\ \textit{Transport} \\ \textit{Coefficients} \end{bmatrix}_{\Delta t_3} \\ \left[\textit{Electromagnetics} \right]_{\Delta t_4} \end{matrix} \to \begin{matrix} \begin{bmatrix} \textit{Navier} \\ \textit{Stokes} \end{bmatrix}_{\Delta t_5} \\ \begin{bmatrix} \textit{Neutral} \\ \textit{Densities} \end{bmatrix}_{\Delta t_5} \end{matrix}$$

- **If only the steady state is desired, the time steps taken in each module are usually different.**

ANNULAR SANDWICH MICRODISCHARGE

- MDs with 10s - 100s μm spacing with circular/annular electrode cavity.
- Operation of up to 1 atm in rare and molecular gases.
- 150-300 V, a few mA

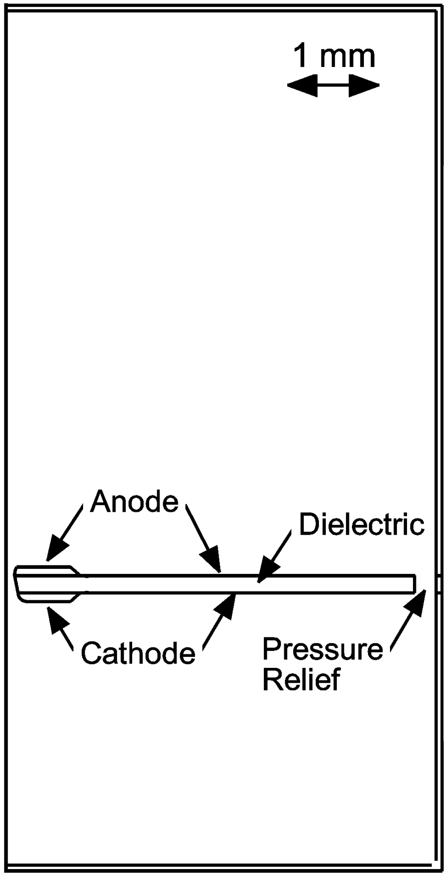


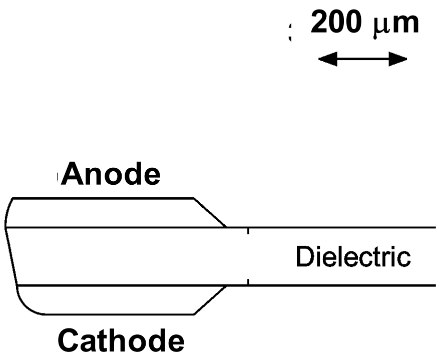


- Ref: Kurt Becker, GEC 2003

BASE CASE MICRODISCHARGE PARAMETERS

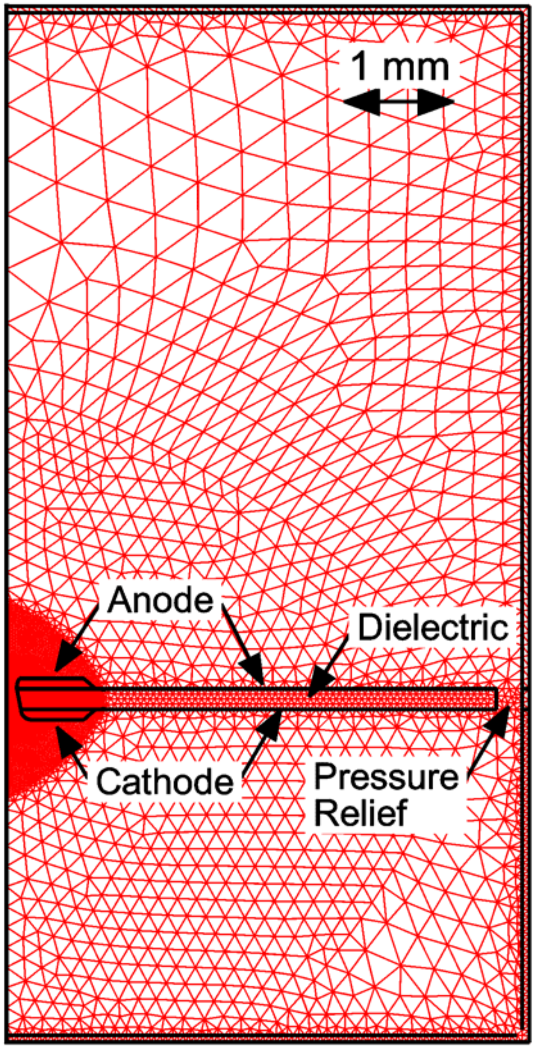
- A “sandwich” microdischarge device is the base case:

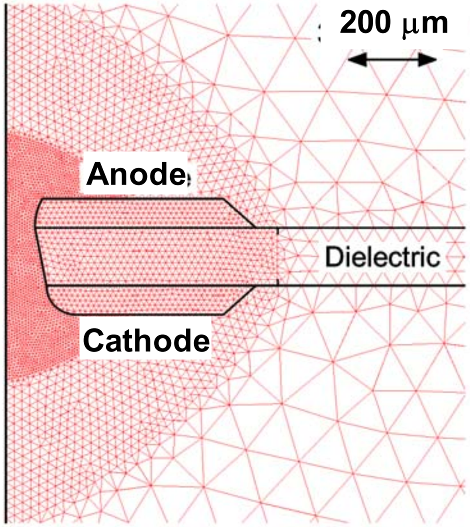




- Sloped dielectric (flow issues)
- Hole: 200 μm diameter at anode to 300 μm at cathode.
- Dielectric: 200 μm thick
- Anode/Cathode 100 μm thick
- Cylindrically symmetric
- Argon, 250 Torr, 2 mA (set by adjusting ballast resistor)

MESHING IS CRITICAL…

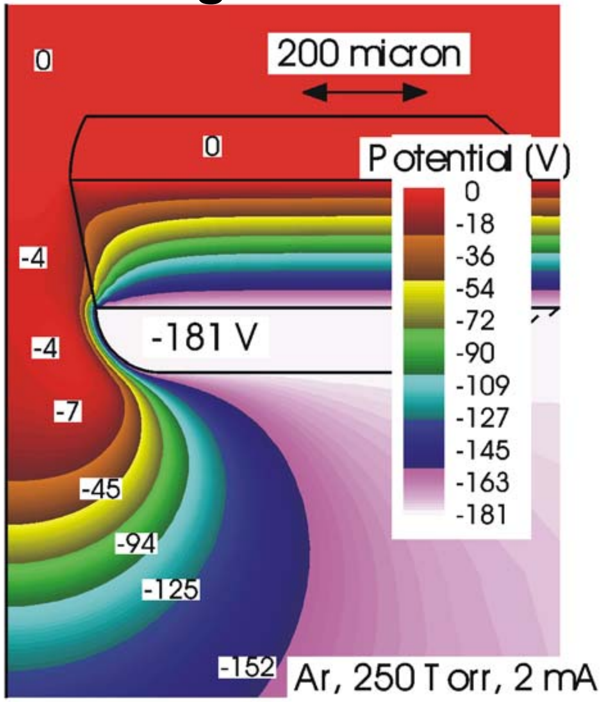




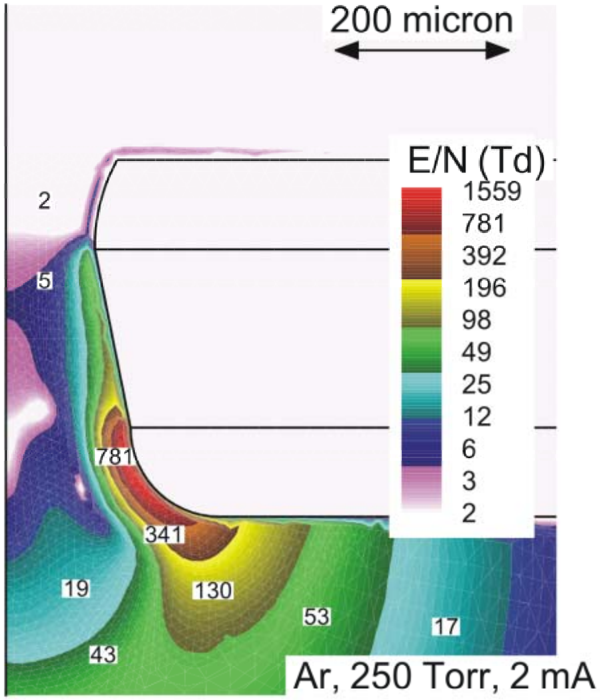
- **The choice of meshing is critical in resolving plasma transport in the discharge zone.**
- **Must resolve cathode fall as well as electrical and flow boundary conditions at large distances.**
- **Dynamic range 100-1000**
- **Total nodes: 5424**
  Plasma nodes: 3693

ELECTRIC POTENTIAL AND FIELDS

- **Anode potential penetrates into lower plenum, producing hollow-cathode-like structure.**
- **Geometrical enhancement and space charge produce fields approaching 100 kV/cm.**



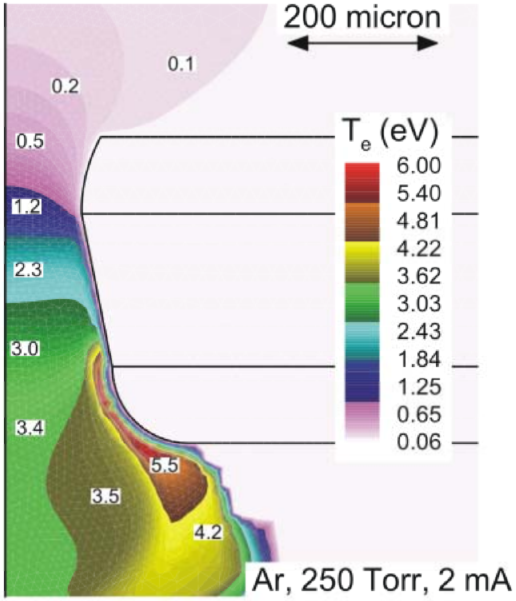
- **Electric Potential**



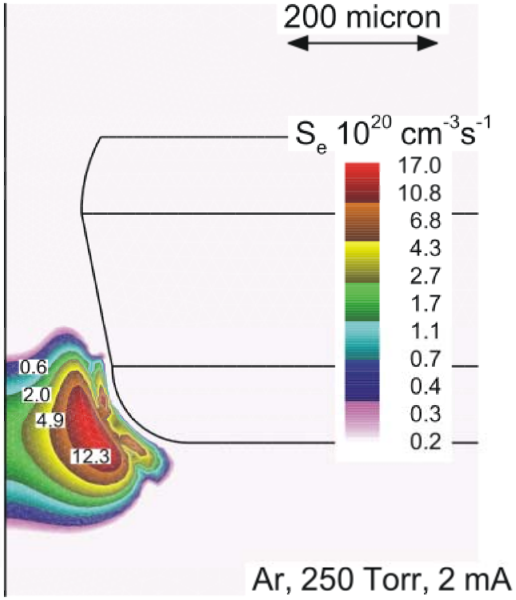
- **E/N (Electric Field/Gas Density) Max = 80 kV/cm**

ELECTRON TEMPERATURE AND IONIZATION SOURCES

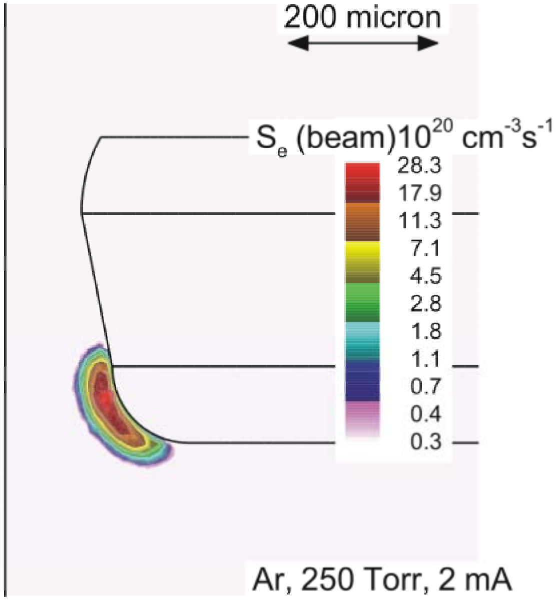
- In the bulk plasma, T_e of 3.5 eV suggests positive column conditions.
- Large contributions to ionization occur from both bulk and beam electrons



- Electron Temperature



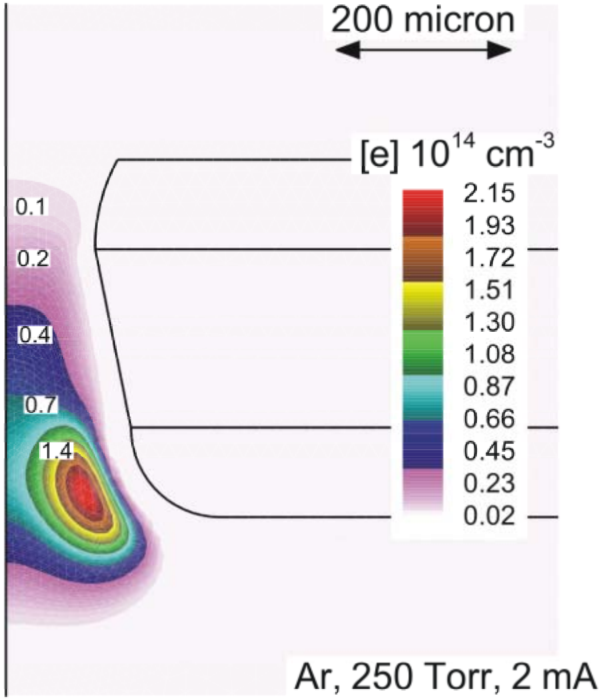
- Bulk Ionization



- Beam ionization

ELECTRON DENSITY

- **Peak electron densities of >10^{14} cm^{-3} are produced in the steady state.**
- **These high cw densities enable large rates of excitation of high lying electronic states.**



- **Electron density**

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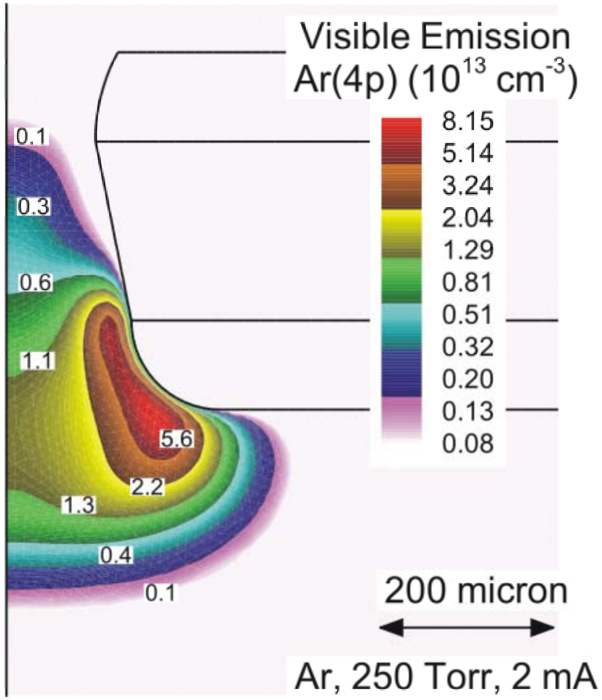
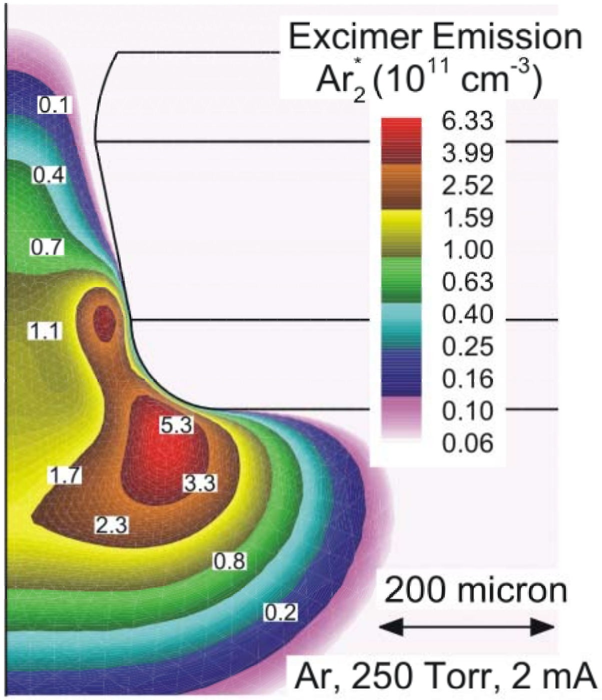
VISIBLE AND UV EMISSION

- **Visible emission is constrained to an annulus due to short lifetimes of states. UV emission from excimer is more distributed due to the large range of Ar(4s) metastable precursor.**

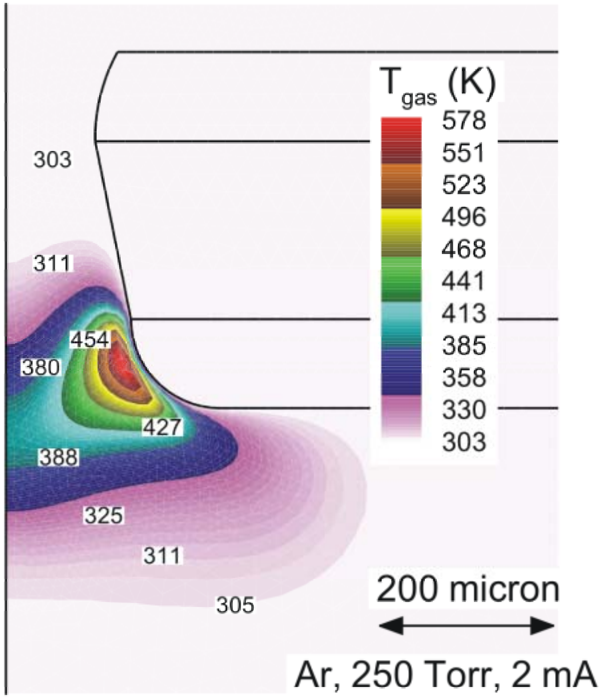




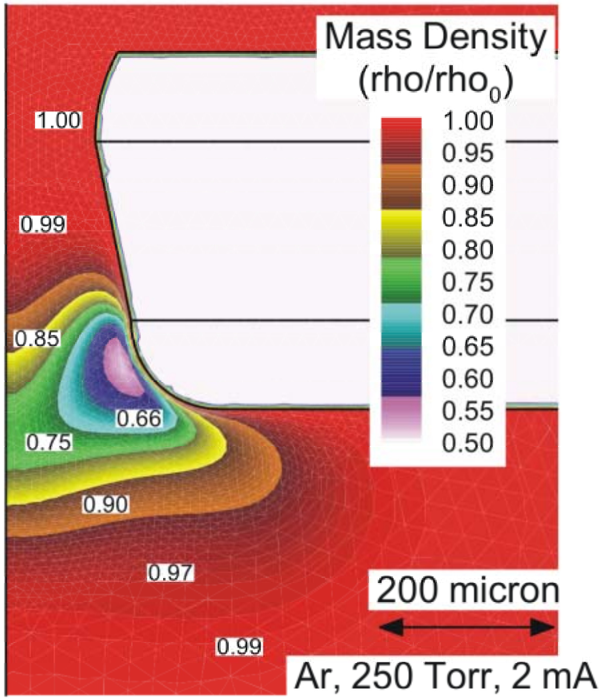
- **Ar(4p) Density (Visible Emission)**
- **Ar_2* Density (UV Emission)**

THERMODYNAMIC PROPERTIES

- Current densities of 5-10 A/cm^2 and power of 10’s-100 kW/cm^3 produce significant gas heating and rarefaction.
- Rarefaction increases range of secondary electrons.



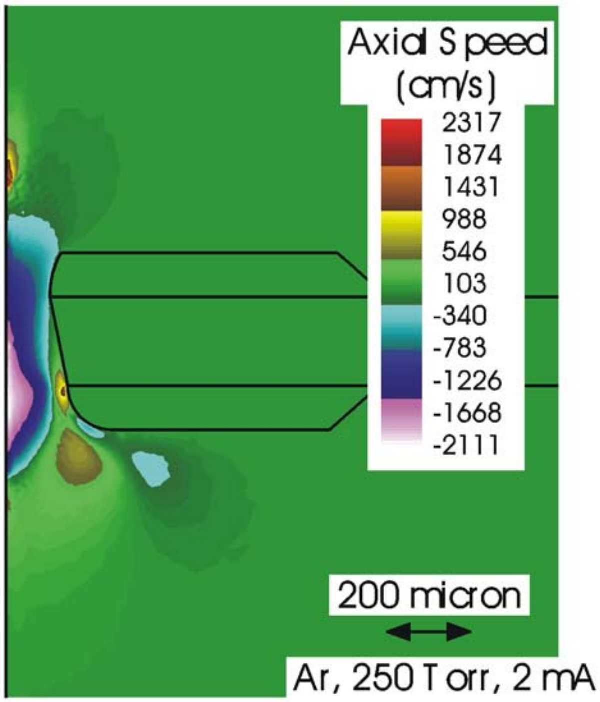
- Gas Temperature



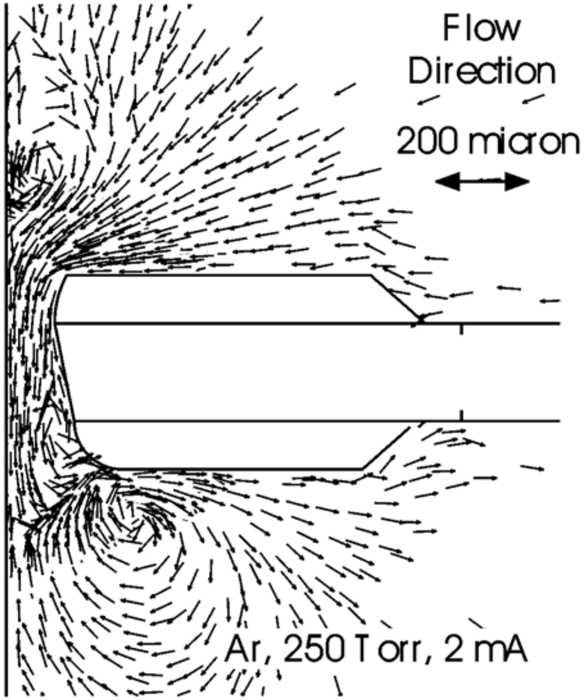
- Relative Mass Density

ADVECTIVE FLOWFIELD

- **Cataphoresis entrains gas, producing pumping action from above the plenum, through the hole to below the plenum.**
- **The jet experiences resistance in the stagnation zone below the plenum and recirculation results.**



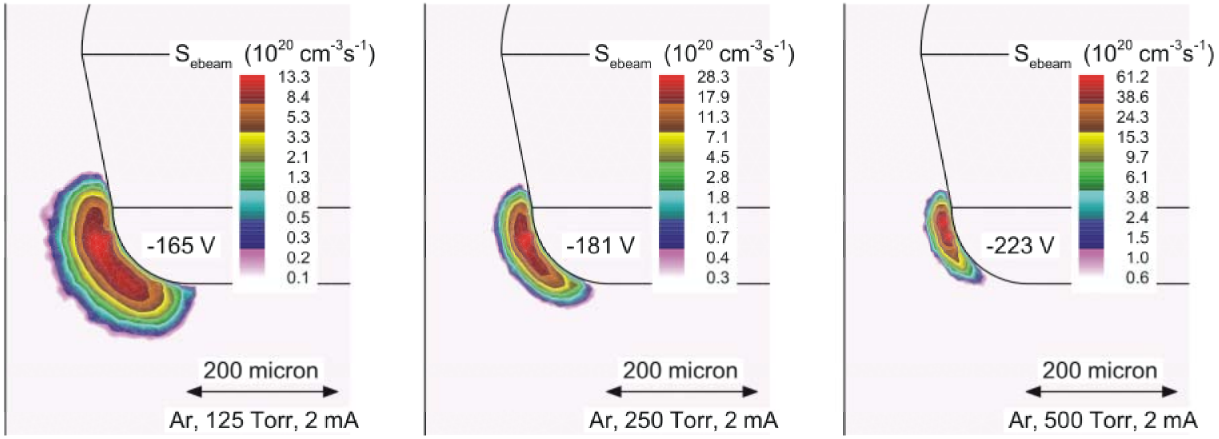
- **Axial Gas Speed**



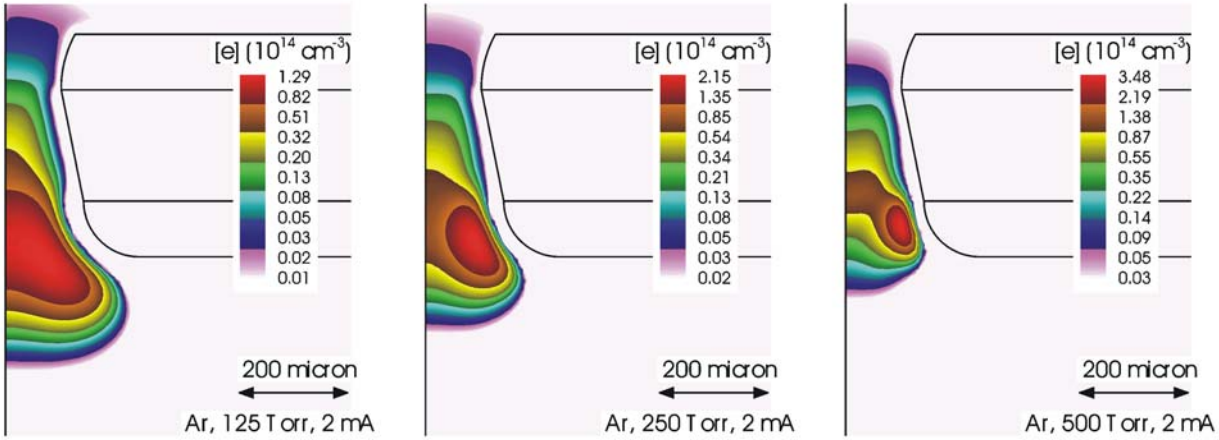
- **Flow Direction**

MD PROPERTIES vs PRESSURE

- **Beam Ionization**



- **Electron Density**

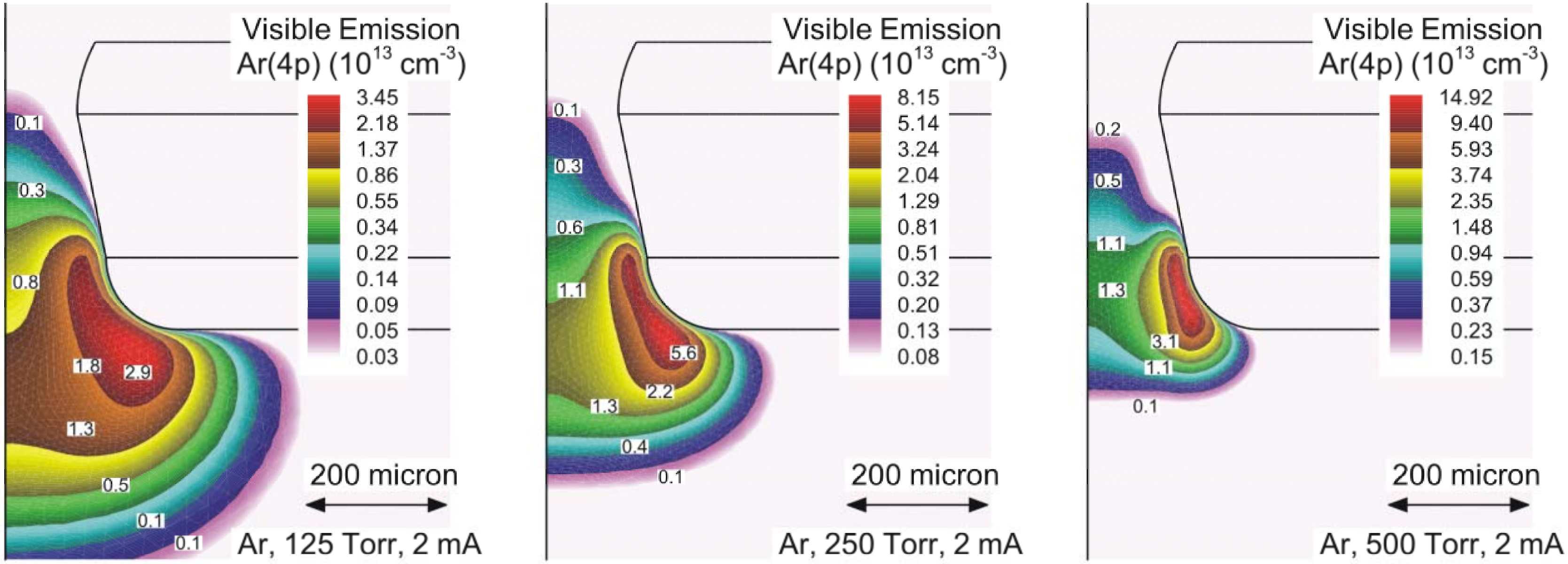


- **125 Torr**
  1.3×10^{14}
- **250 Torr**
  2.1×10^{14}
- **500 Torr**
  3.5×10^{14}

- **Decreasing pressure enables deeper penetration of beam electrons in spite of the lower cathode voltage.**
- **The result is more confinement at higher pressure and higher peak electron density.**
- **Ar, 2 mA**

MD PROPERTIES vs PRESSURE: VISIBLE EMISSION

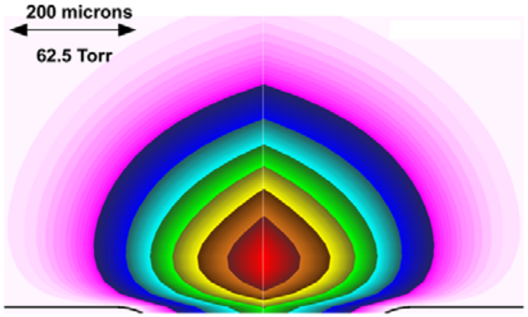
- **Visible emission is significantly more extended at low pressure, penetrating far out the hole. Peak emission is greater at higher pressure due to confinement of beam component.**



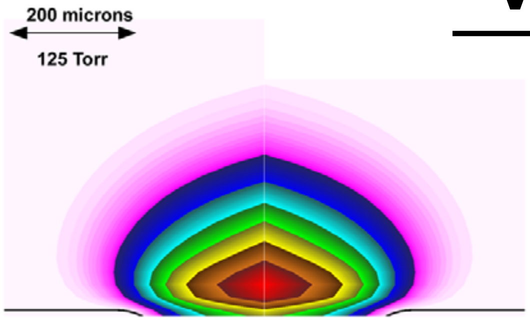
- **125 Torr**
- **250 Torr**
- **500 Torr**

MD PROPERTIES vs PRESSURE: VISIBLE EMISSION

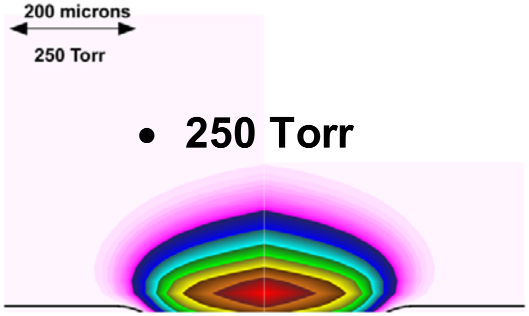
- 62.5 Torr



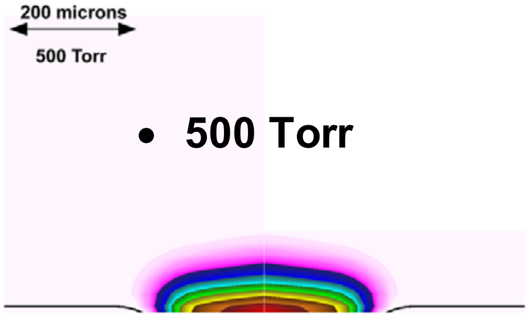
- 125 Torr



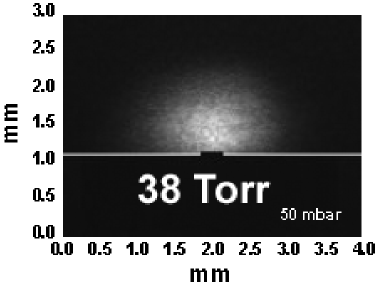
- 250 Torr

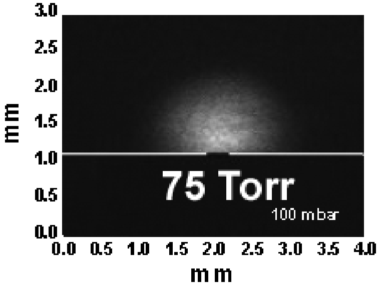


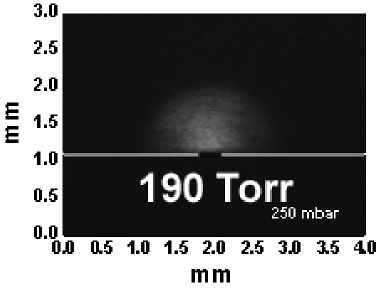
- 500 Torr



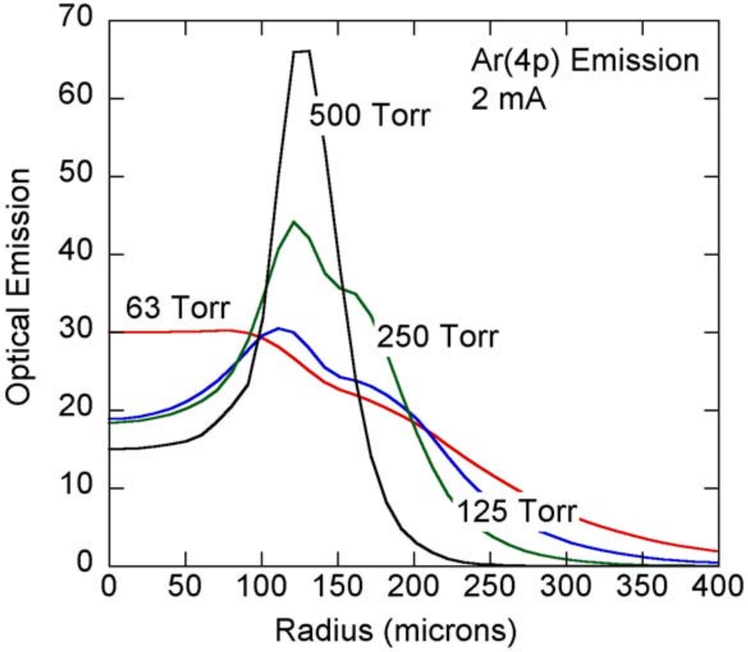
- Experimental trends are reproduced for contraction of optical emission at high pressure.
- Ref: Maria Cristina Penache, Thesis, 2002
- Ar, 2 mA, synthesized side views





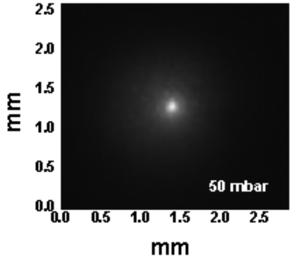


MD PROPERTIES vs PRESSURE: VISIBLE EMISSION

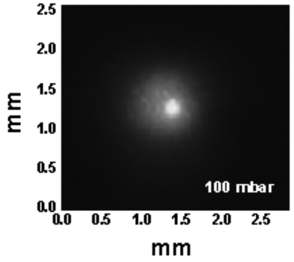


- **Experimental trends are reproduced for contraction of optical emission with increasing pressure.**
- **Ref: Maria Cristina Penache, Thesis, 2002**

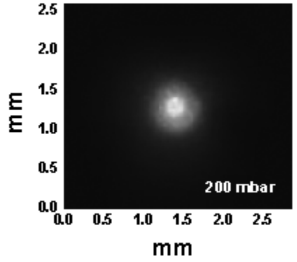
38 Torr



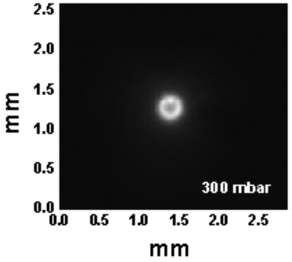
75 Torr

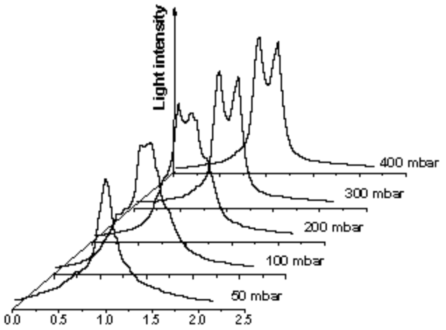


150 Torr

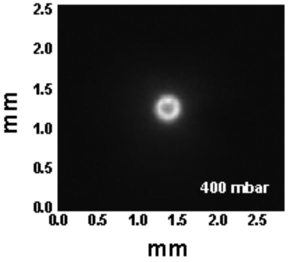


225 Torr



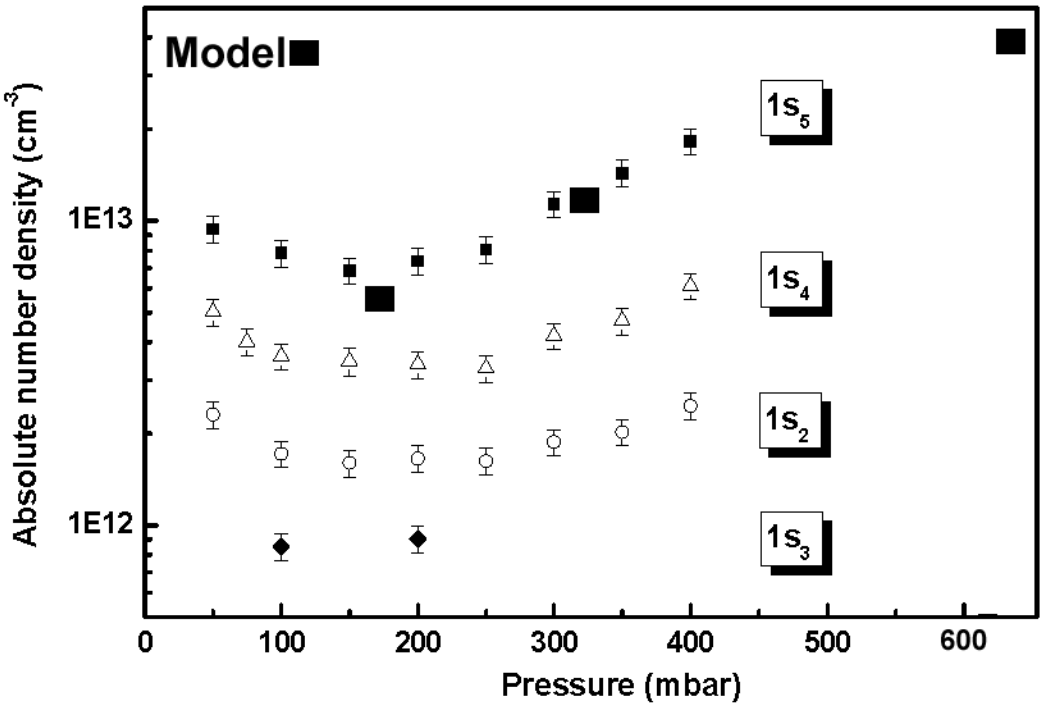


300 Torr



MD PROPERTIES vs PRESSURE: Ar(4s) DENSITY

- **Large metastable densities produce efficient excimer emission at higher pressures.**

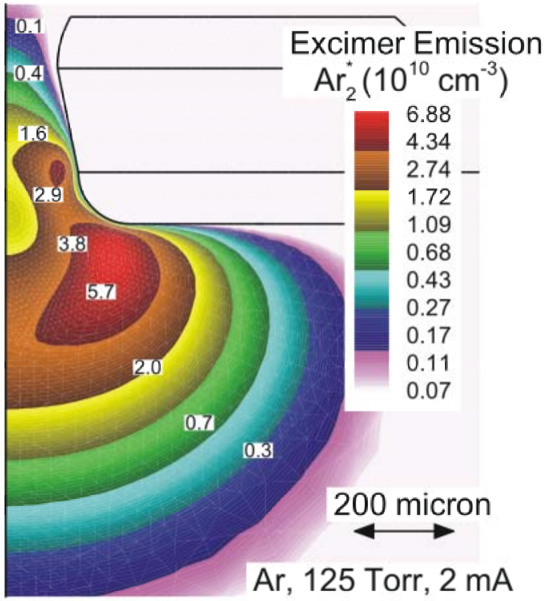


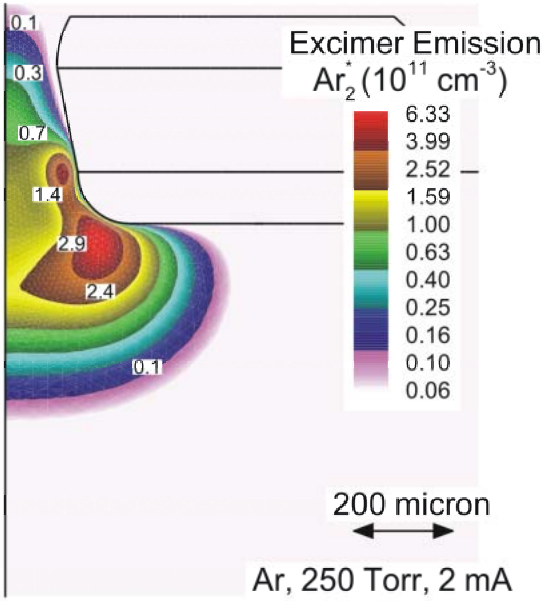
- **Ref: Maria Cristina Penache, Thesis, 2002**

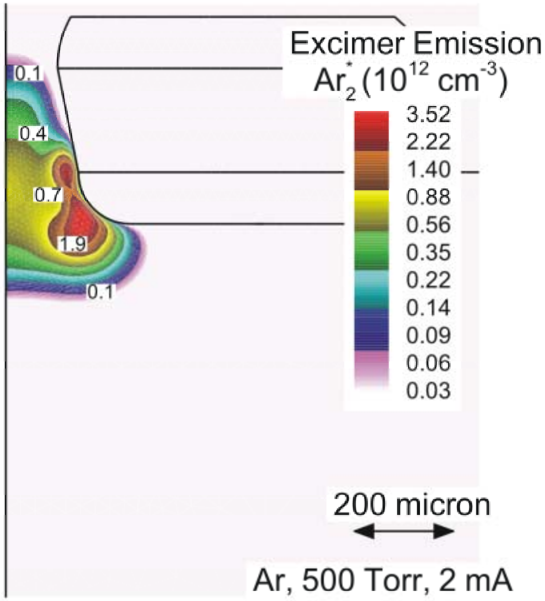
- **Ar, 2 mA**

MD PROPERTIES vs PRESSURE: UV-EXCIMER EMISSION

- The disparity between uniformity of and peak emission is greater for the UV-excimer due to greater diffusivity of Ar(4s) at low pressure and higher rate of dimer formation at high pressure.







- 125 Torr
- 250 Torr
- 500 Torr

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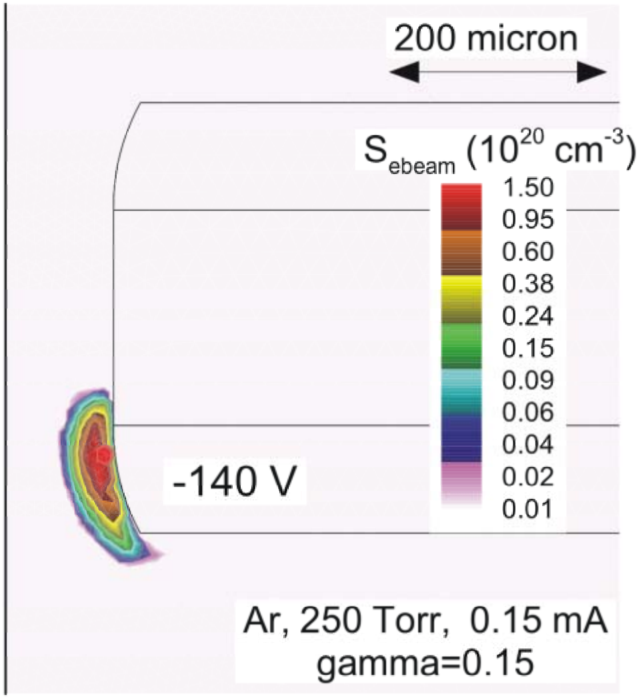
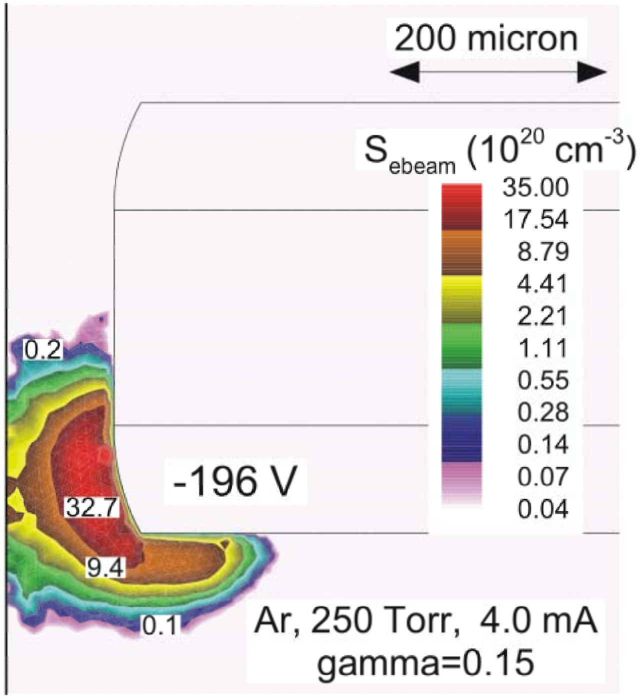
MD PROPERTIES vs CURRENT: BEAM IONIZATION

- Thermodynamics cannot be ignored in operation of MDs. Contrasting, low (0.15 mA) and high (4.0 mA) operation, the physical extent of beam ionization is greater at the higher current.



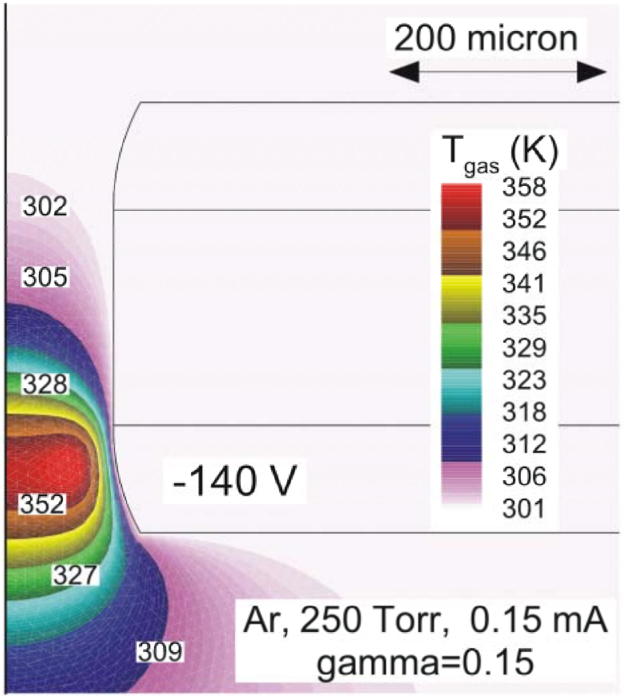
- 0.15 mA



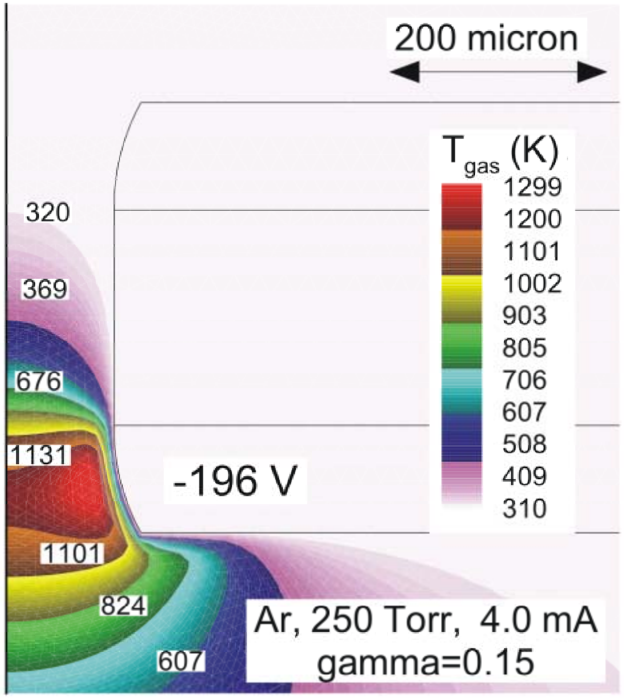
- 4.0 mA

MD PROPERTIES vs CURRENT: GAS TEMPERATURE

- ….which results in part from larger cathode voltage and in part from rarefaction produced by gas heating.



- 0.15 mA



- 4.0 mA

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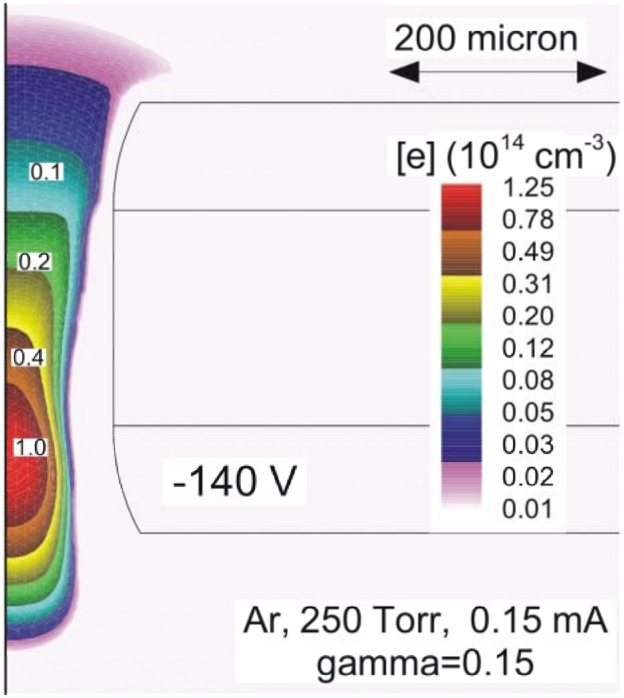
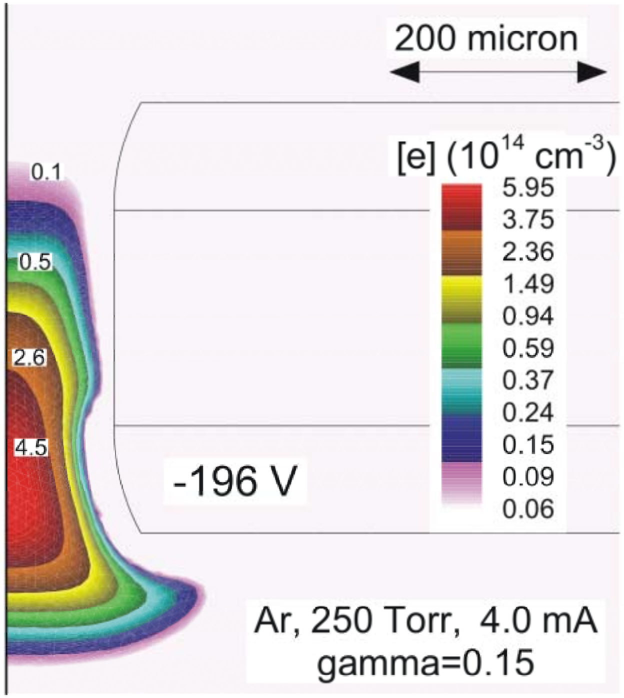
MD PROPERTIES vs CURRENT: ELECTRON DENSITY

- **The end result is a more tightly confined plasma at the lower pressure.**



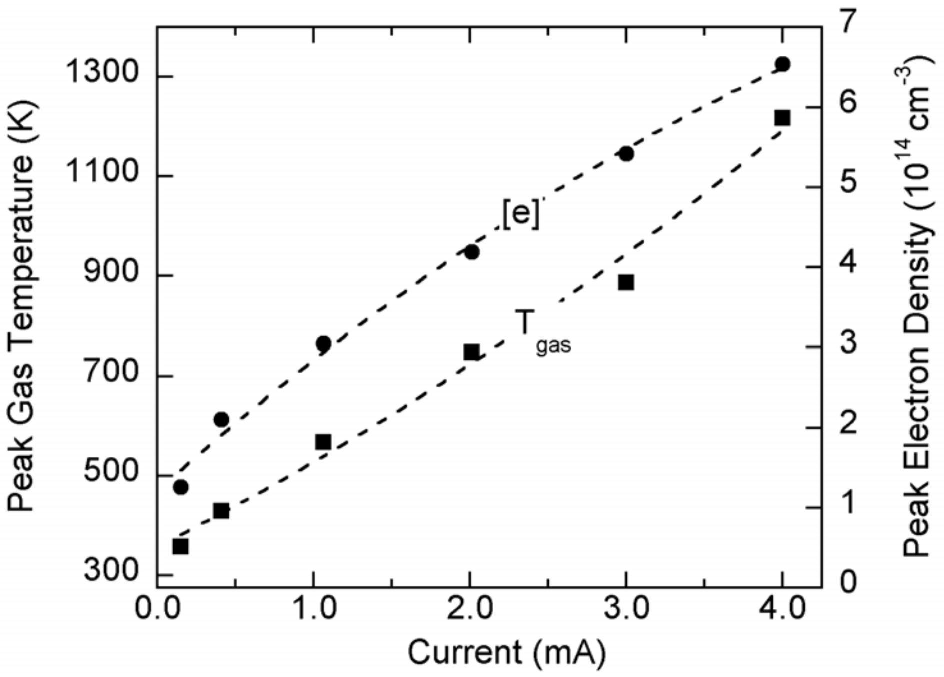
- **0.15 mA**



- **4.0 mA**

MD PROPERTIES vs CURRENT: T(gas), [e]

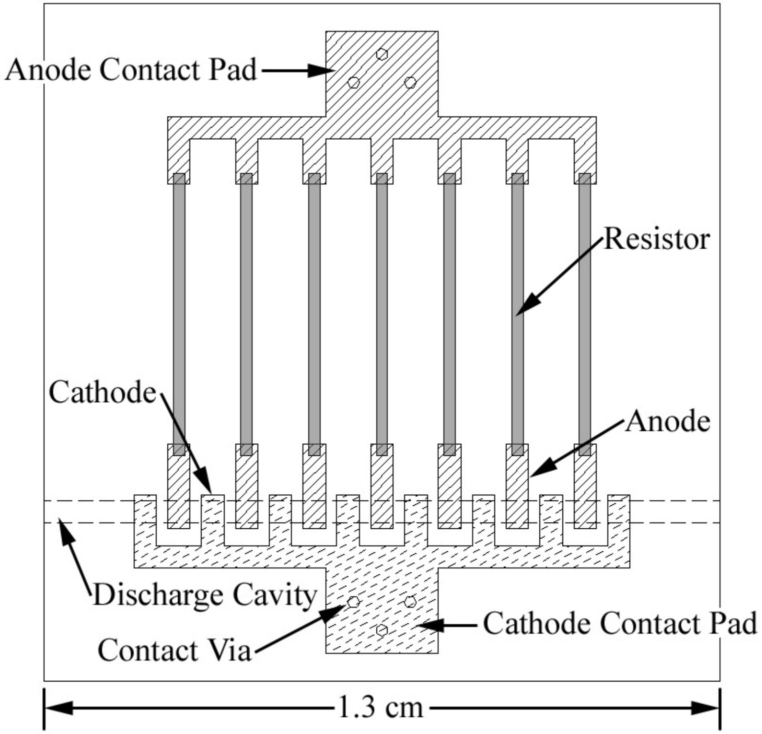
- **Peak electron density and gas temperature scales nearly linearly with current density.**



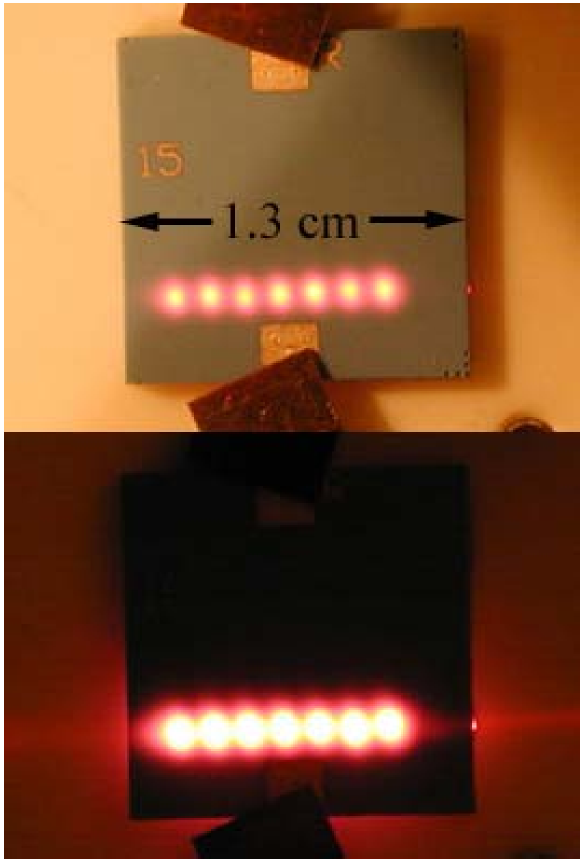
- **Ar, 250 Torr, γ = 0.15**

MULTISTAGE DEVICES

- Multistage MDs are desirable for long gain lengths for lasers.
- The design of such devices requires attention to thermodynamics issues.



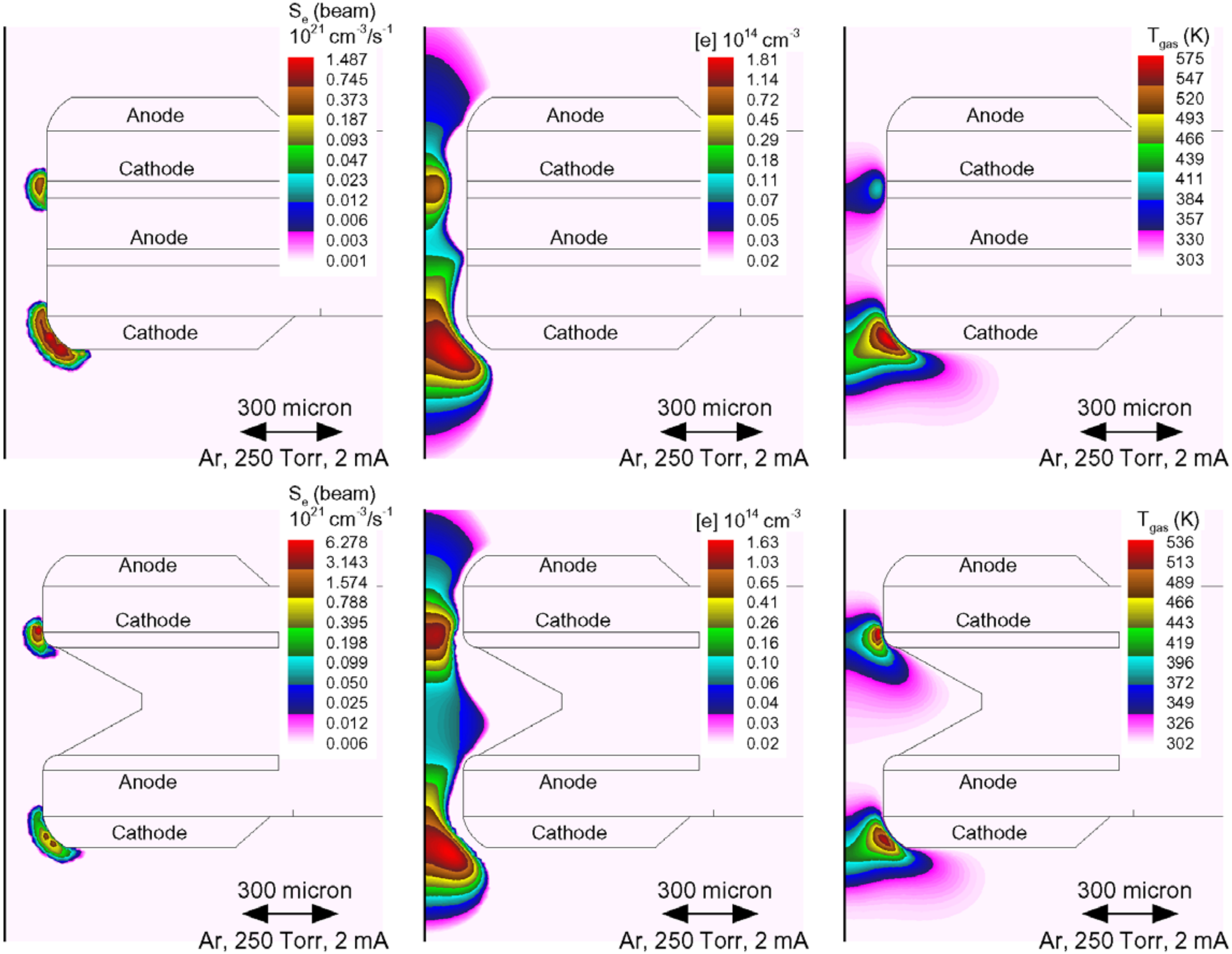
- Ref: J. G. Eden



- 600 Torr Ne.

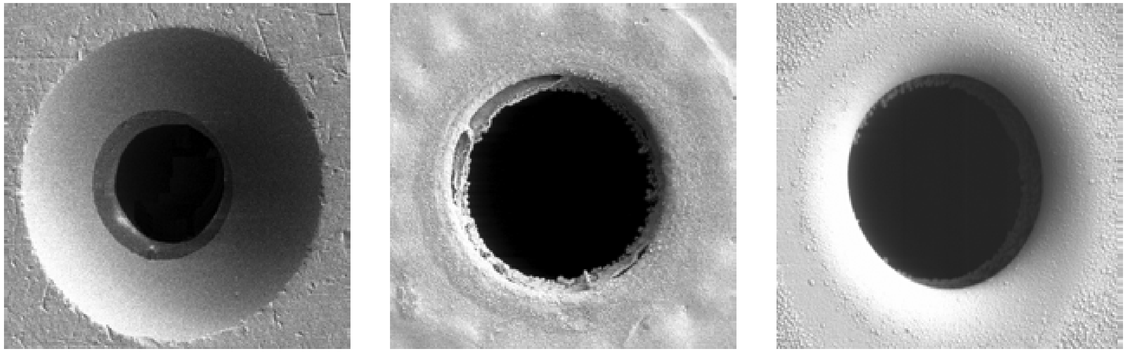
EXAMPLES OF 2-STAGE MDs

- **Design affects gas heating, rarefaction; range and influence of secondary electrons and division of current.**



DESIGNING MDs AS VISIBLE SOURCES: AGING

- **As MDs age with use, critical dimensions and material properties (such as secondary emission coefficients) often change.**
- **Modeling is valuable in the design process to determine the sensitivity of optical properties to aging related changes in device parameters.**



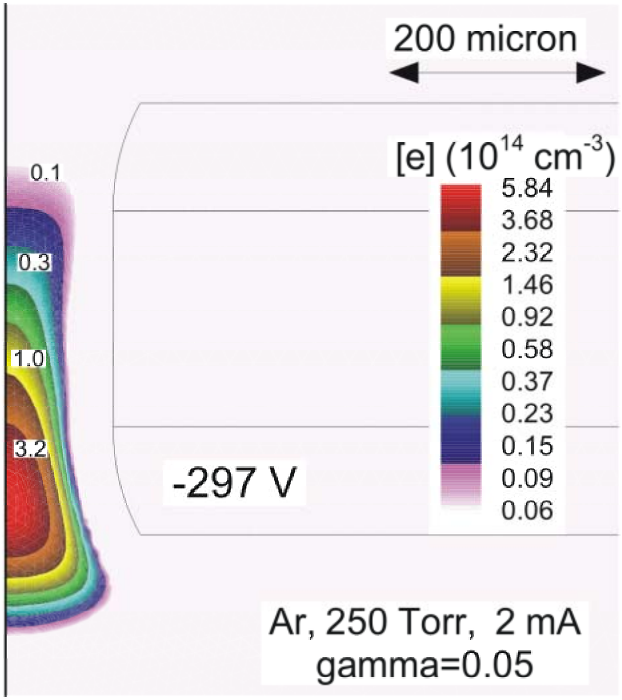
New Anode (aged) Cathode (aged)

Ar, 380 Torr, 5 mA, 10 hours

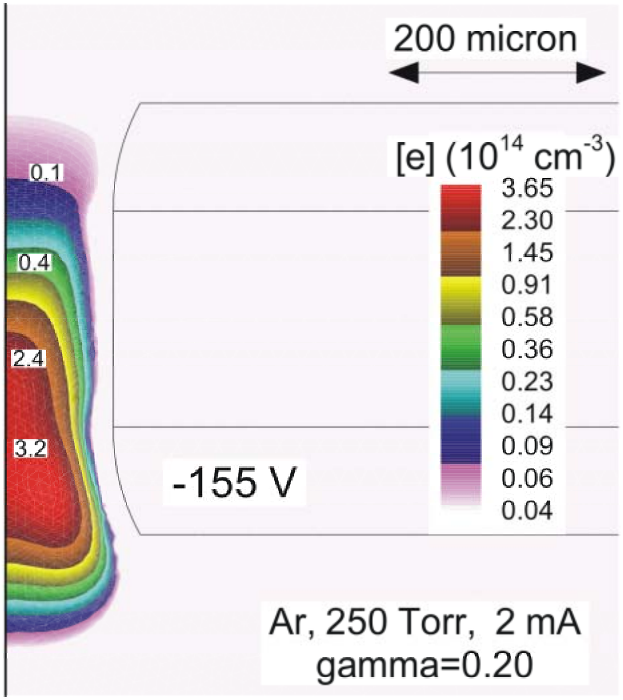
- **Ref: Maria Cristina Penache, Thesis, 2002**

SENSITIVITY TO γ (SECONDARY EMISSION): [e]

- **The electron density increases with decreasing γ, a counter-intuitive result likely produced by more efficient ionization by the more energetic secondary electrons.**



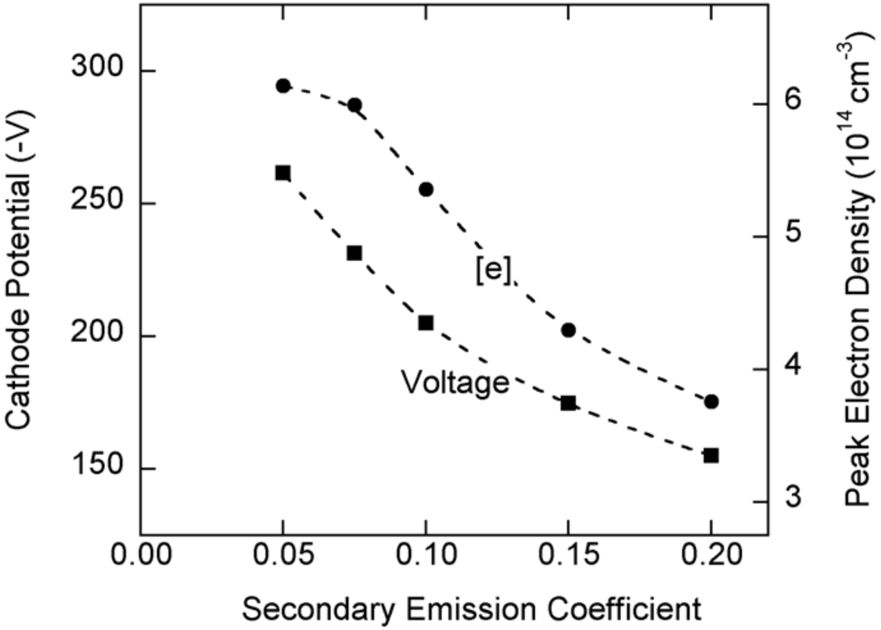
- **$\gamma = 0.05$**



- **$\gamma = 0.20$**

SENSITIVITY TO γ (SECONDARY EMISSION): VOLTAGE, [e]

- **Voltage and peak electron density increases with decreasing γ to counter smaller flux of beam electrons which ionize efficiently.**
- **Power increases when holding current constant.**



- **Ar, 250 Torr, 2 mA**

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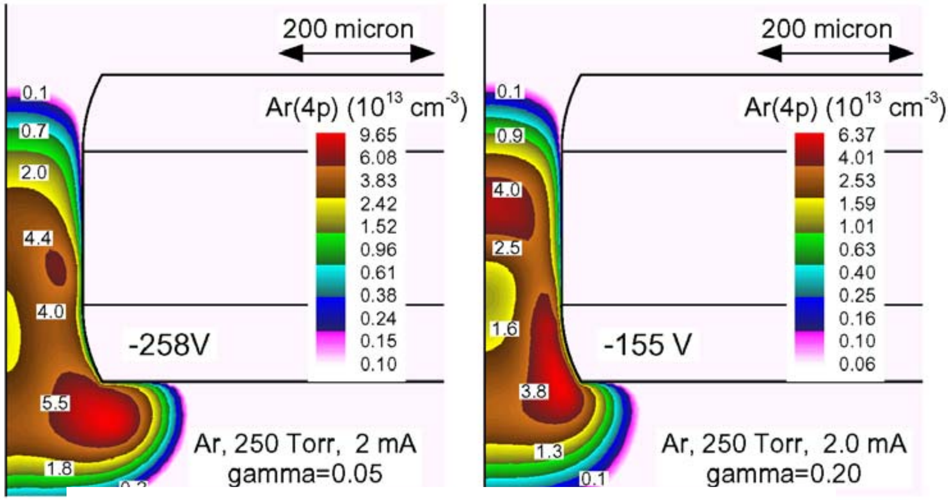
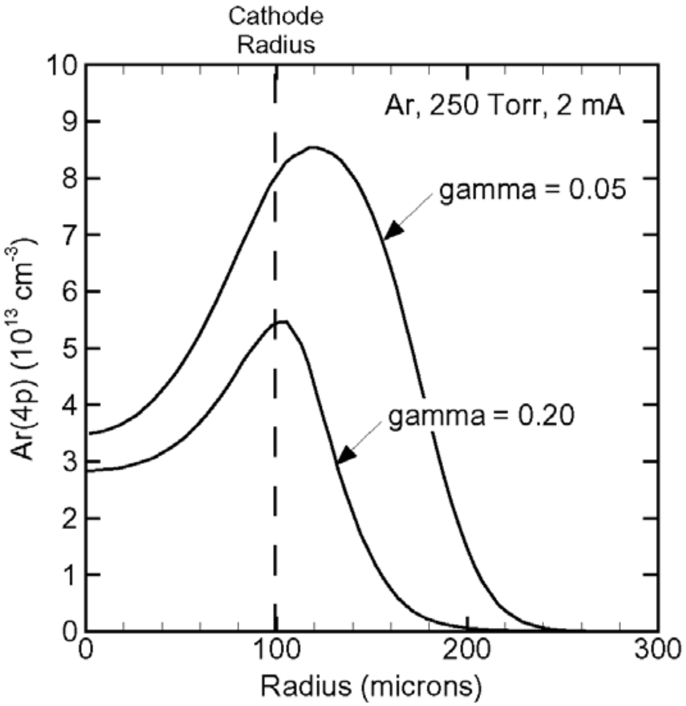
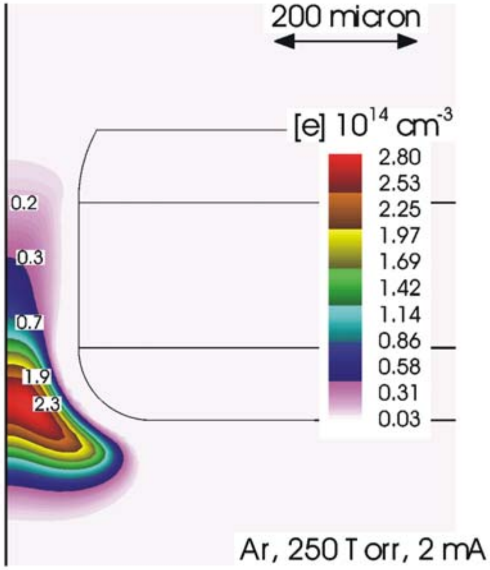
SENSITIVITY TO γ : VISIBLE EMISSION

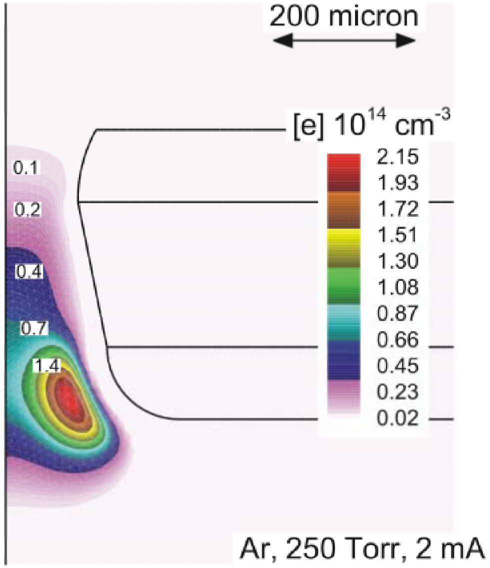




- Visible emission increases as γ decreases, in part reflecting increase in power.
- Distribution of emission also shifts to being more dominated by beam electrons.
  - Ar, 250 Torr, 2 mA



- **Straight**



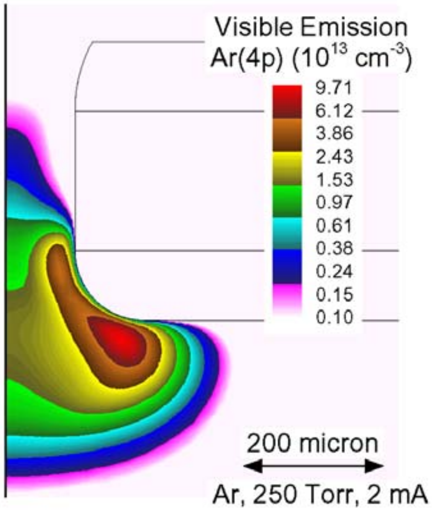
- **Tapered**

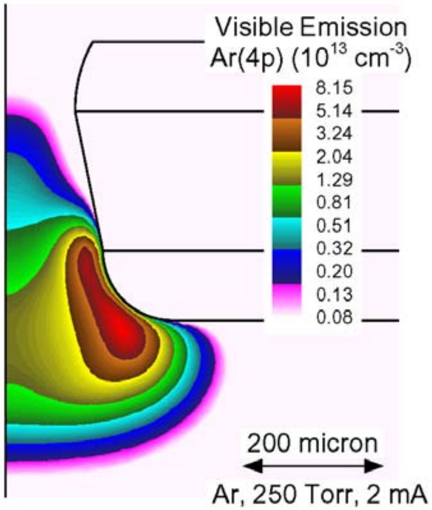
SENSITIVITY TO CRITICAL DIMENSIONS: [e]

- **Device-to-device variation in fabrication or erosion/wear during operation my change critical dimensions. How sensitive are operating characteristics?**
- **Contrast straight and tapered dielectrics.**
- **Peak electron density is higher and more distributed in straight MD.**

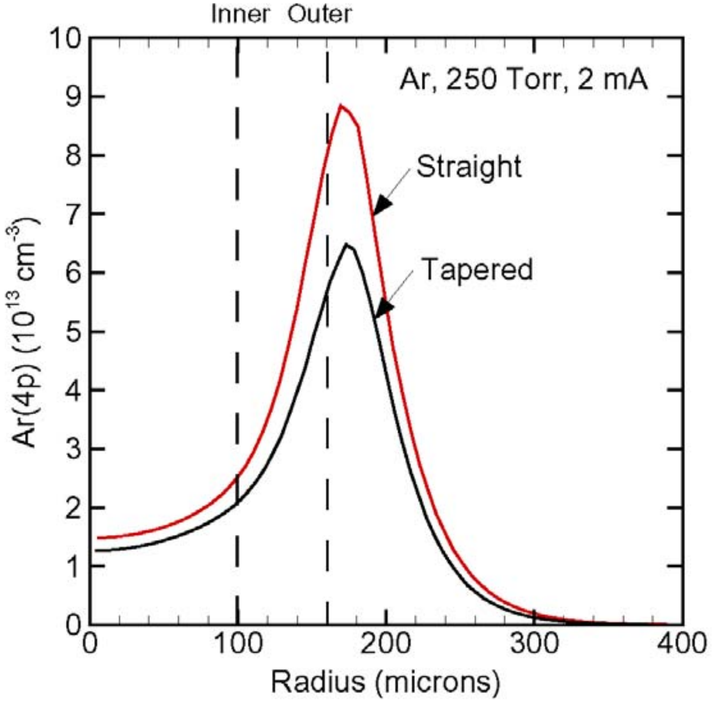
- **Ar, 250 Torr, 2 mA**

SENSITIVITY TO CRITICAL DIMENSIONS: VISIBLE EMISSION





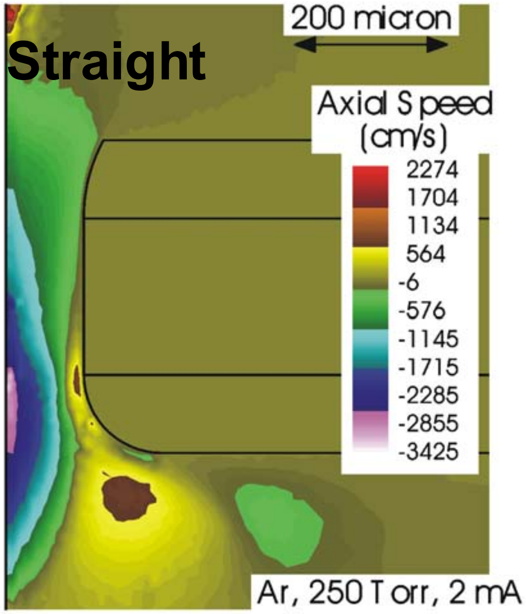
- **Straight**
- **Tapered**



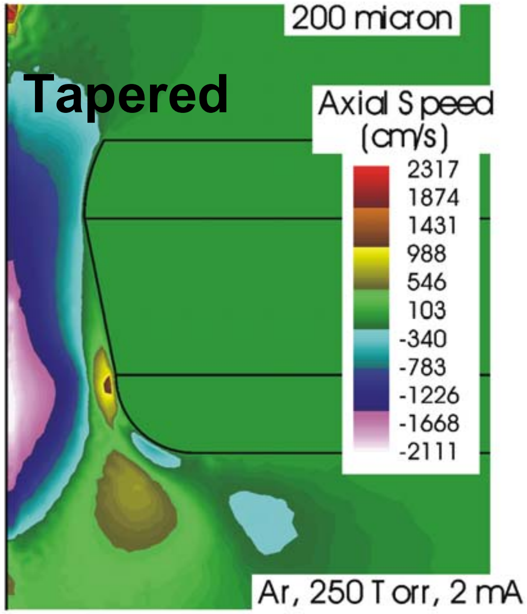
- **Magnitude of visible emission is sensitive to loss in critical dimension.**
- **Distribution is less sensitive.**
- **Robust designs are possible which are tolerant to erosion and loss of critical dimension.**
- **Ar, 250 Torr, 2 mA**

SENSITIVITY TO CRITICAL DIMENSIONS : AXIAL FLOW

- Straight



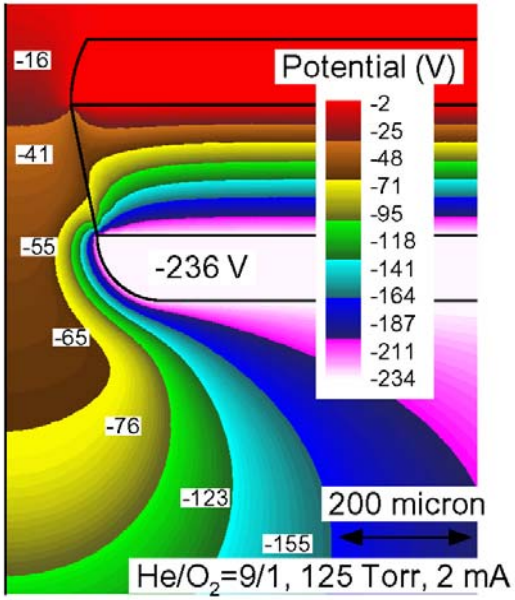
- Tapered

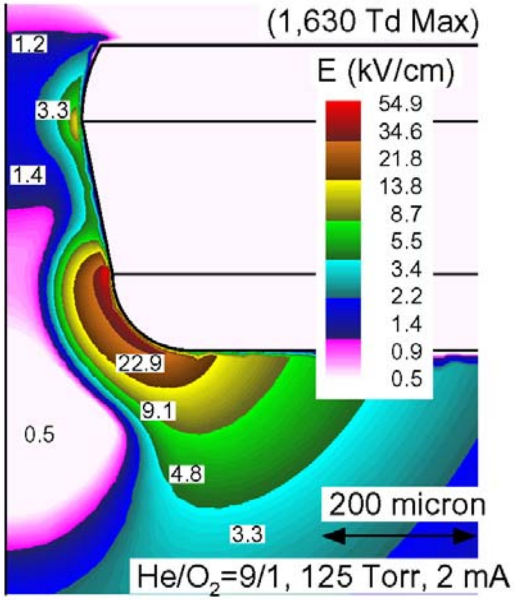


- Speed of (downward) axial flow produced by cataphoresis is > 50% higher in the less tapered MD.
- Higher current density, larger E/N, larger on-axis plasma density all contribute.
- Ar, 250 Torr, 2 mA

MD AS A RADICAL SOURCE: He/O_2

- Large current densities and intrinsically high gas flow makes MDs ideal for reactant generators. Demonstrate with electronegative He/O_2 mixture.

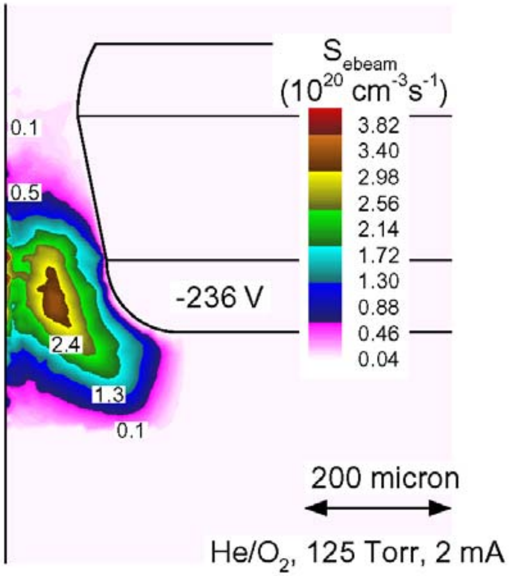




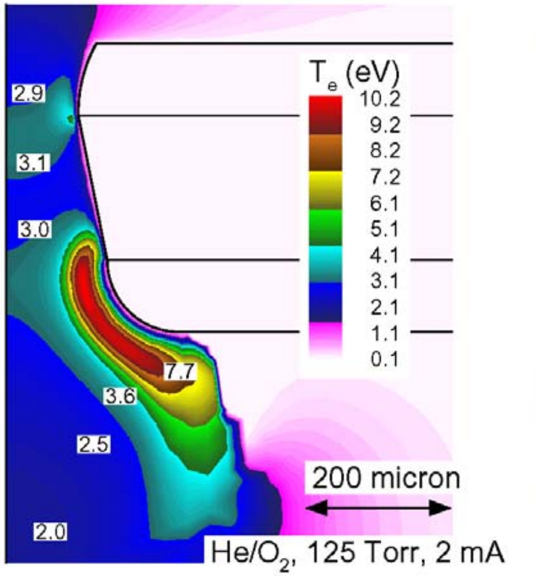
- Higher collisionality produces larger operating voltages, larger electric fields.

- He/O_2=90/10, 125 Torr, 2 mA

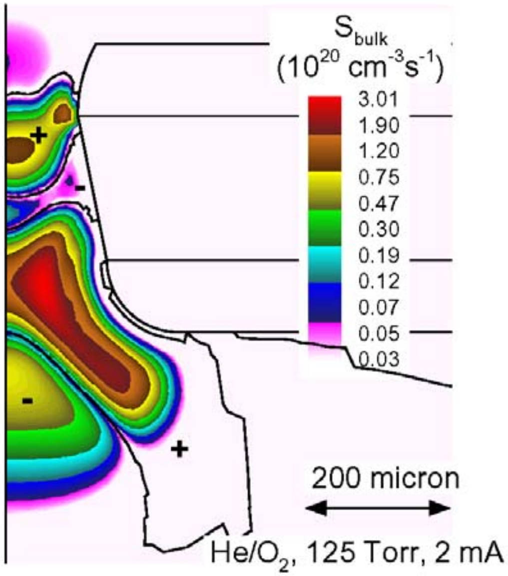
MD SUSTAINED IN He/O_2: ELECTRON SOURCES



- **S(beam)**



- **T_e**

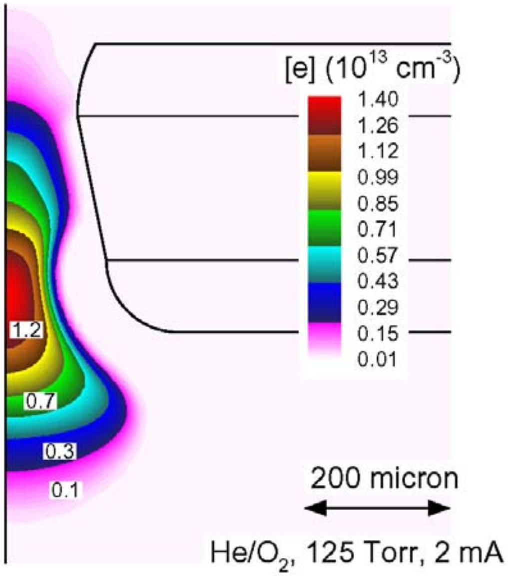


- **S(bulk)**

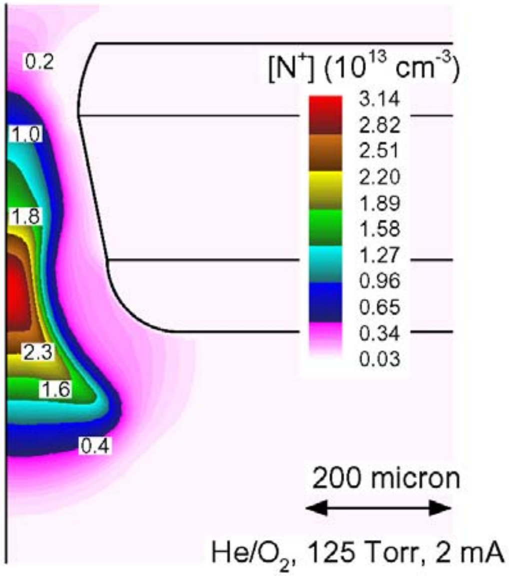
- **Larger voltage enables efficiency beam ionization deep into plasma. Volumetric attachment produces distinct regions of positive and negative bulk sources**

  - **He/O_2=90/10, 125 Torr, 2 mA**

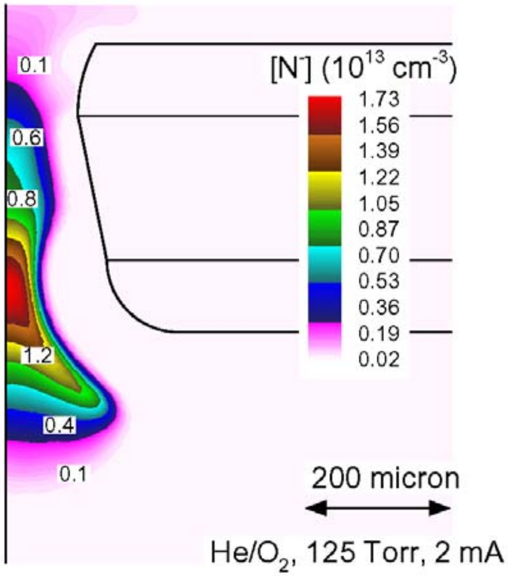
MD SUSTAINED IN He/O_2: ELECTRON, ION DENSITIES



- [e]



- [N^+]

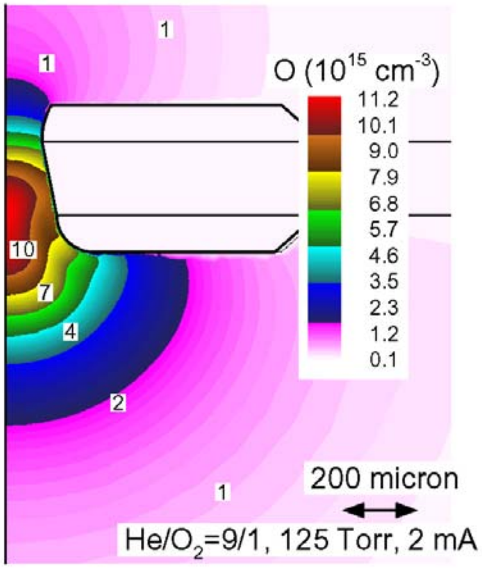


- [N^-]

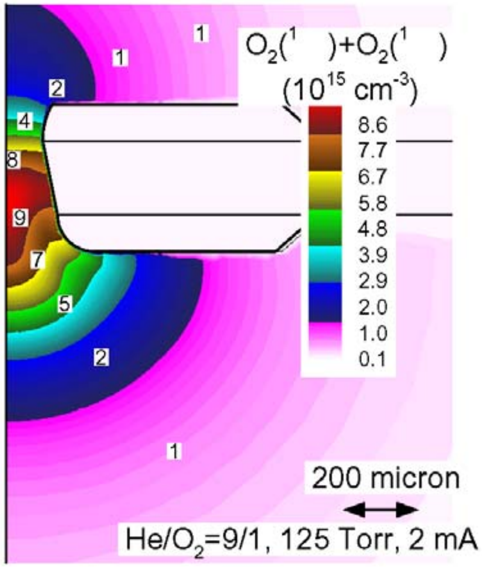
- Negative ions are dominated by O_2- at pressures of 100s Torr.

- He/O_2=90/10, 125 Torr, 2 mA

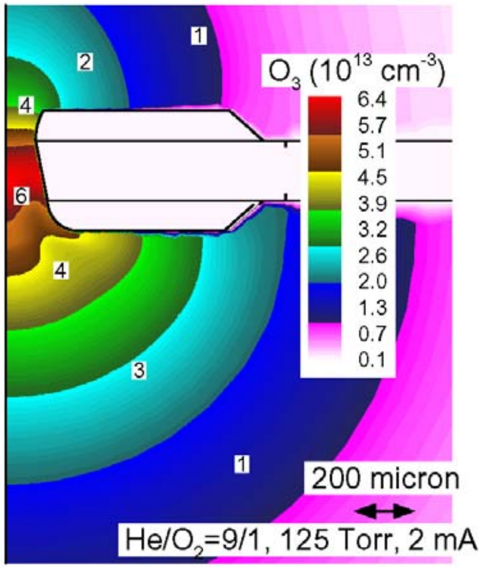
MD SUSTAINED IN He/O_2: RADICAL, EXCITED STATE DENSITIES



- [O]



- [$O_2(^1\Delta)$]

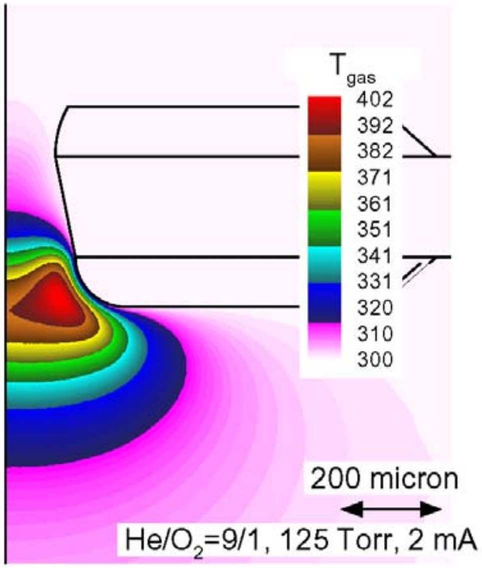


- [O_3]

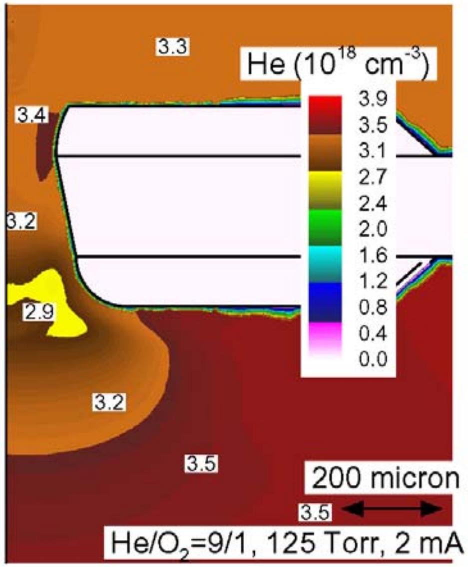
- The range of O atoms is limited by recombination and ozone formation. $O_2(^1\Delta)$ and O_3 are final products, having longer ranges.
- Cataphoresis induced flow preferentially ejects reactants downward.

  - He/O_2=90/10, 125 Torr, 2 mA

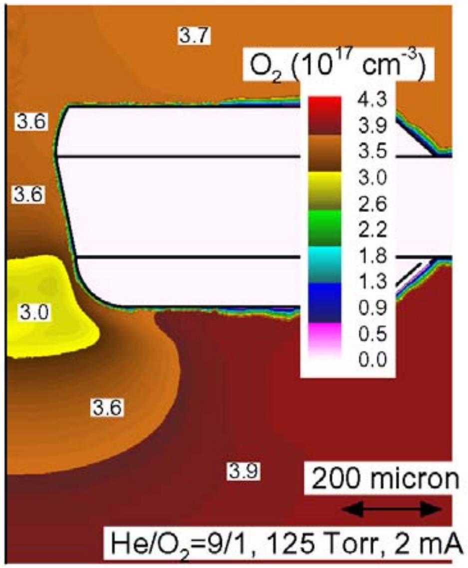
MD SUSTAINED IN He/O$_2$: FLOW PROPERTIES



- T(gas)



- [He]

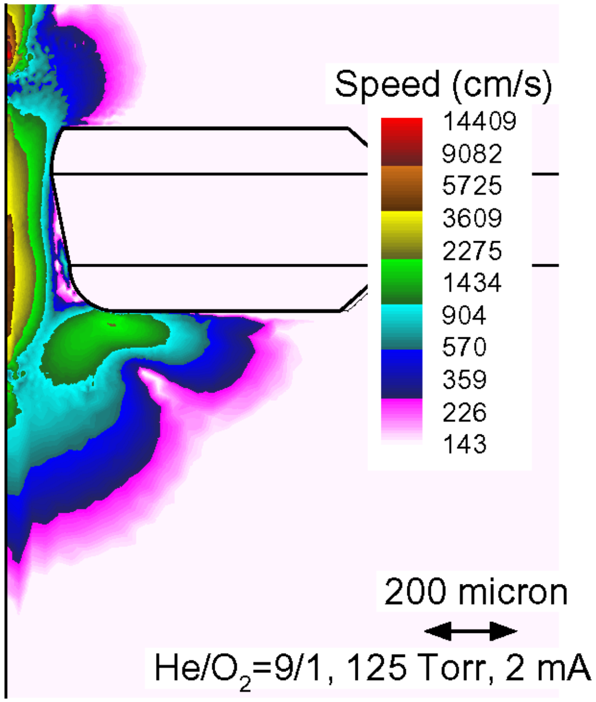


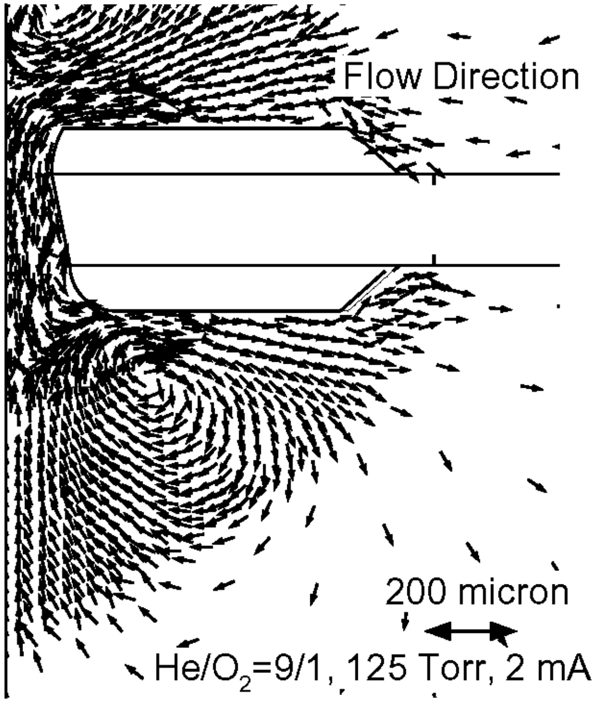
- [O$_2$]

- In spite of Frank-Condon heating, gas temperatures are lower (for a give current) than in argon due to higher thermal conductivity of He.

- He/O$_2$=90/10, 125 Torr, 2 mA

MD SUSTAINED IN He/O_2: FLOW PROPERTIES



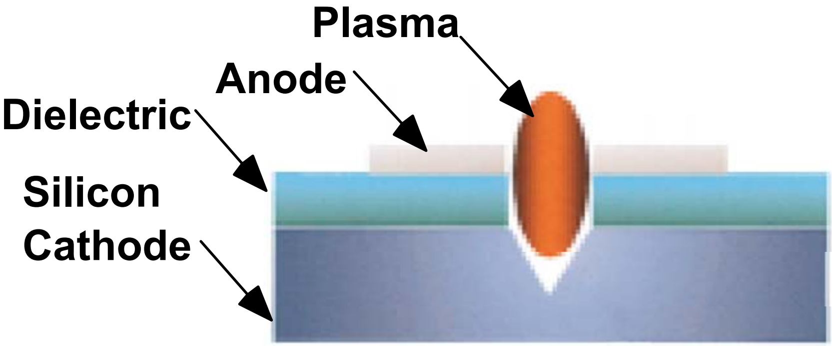


- **Optimization of MDs as radical sources will require careful attention to flow properties to maximize delivery of reactants.**

  - **He/O_2=90/10, 125 Torr, 2 mA**

PYRAMIDAL MICRODISCHARGE DEVICES

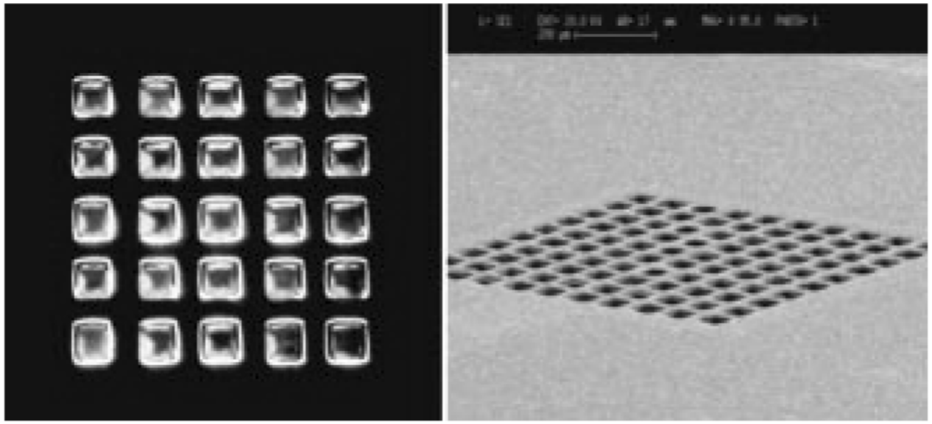
- Si MDs with 10s μm pyramidal cavities display nonequilibrium behavior: Townsend to negative glow transitions.
- Small size also implies electrostatic nonequilibrium.

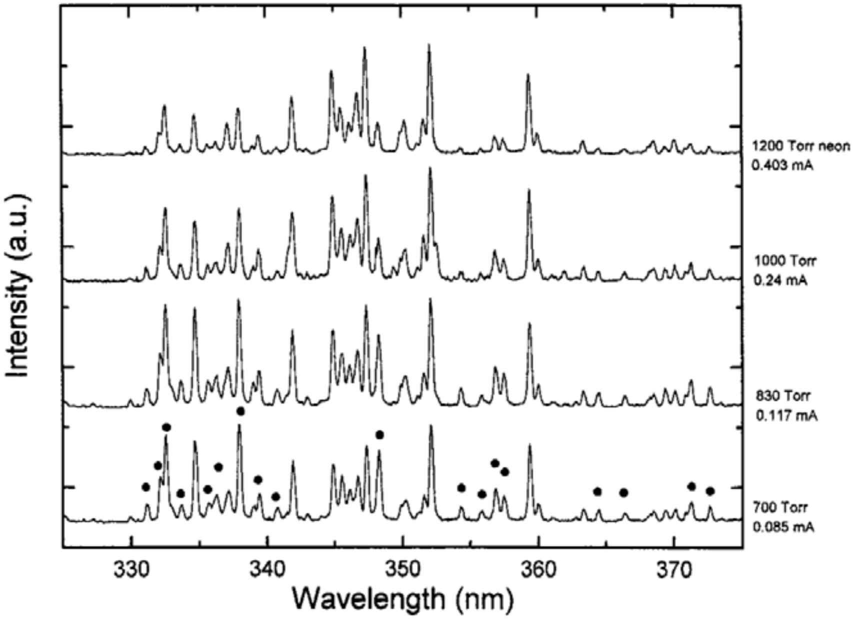

Plasma

Anode

Dielectric

Silicon Cathode

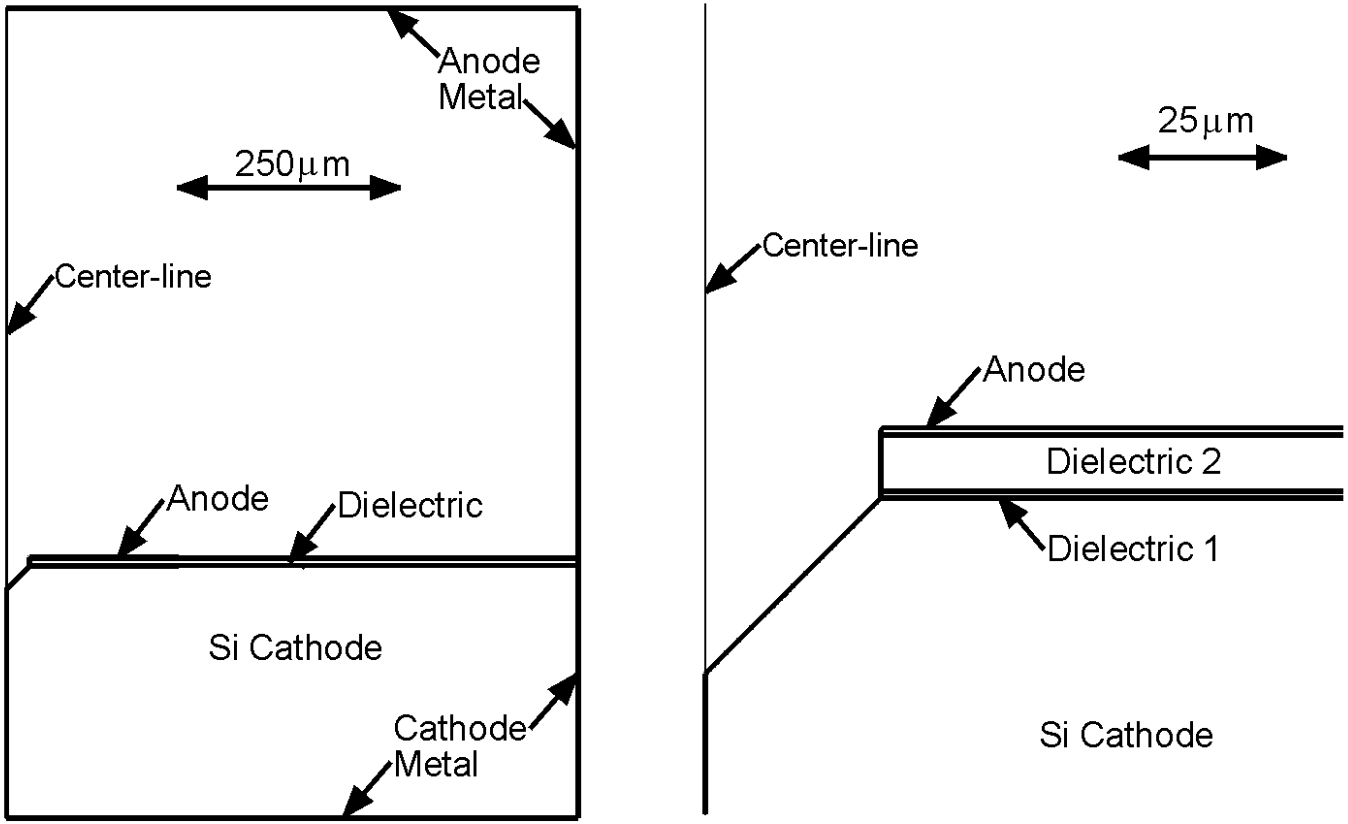




- S.-J. Park, et al., J. Sel. Topics Quant. Electron 8, 387 (2002); Appl. Phys. Lett. 78, 419 (2001).

MODEL GEOMETRY: Si PYRAMID MICRODISCHARGE

- **Investigations of a cylindrically symmetric Si pyramid microdischarge were performed.**



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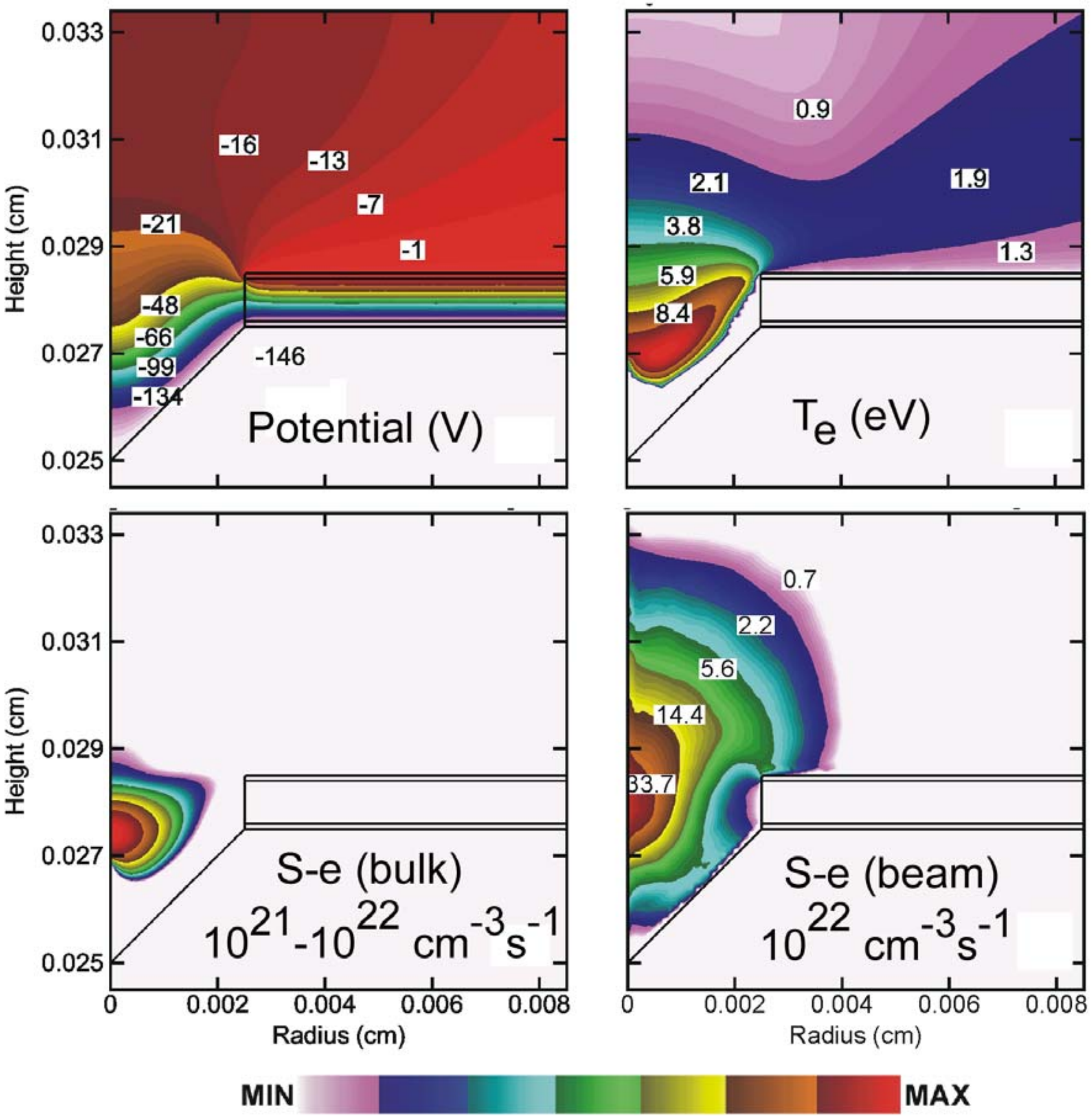
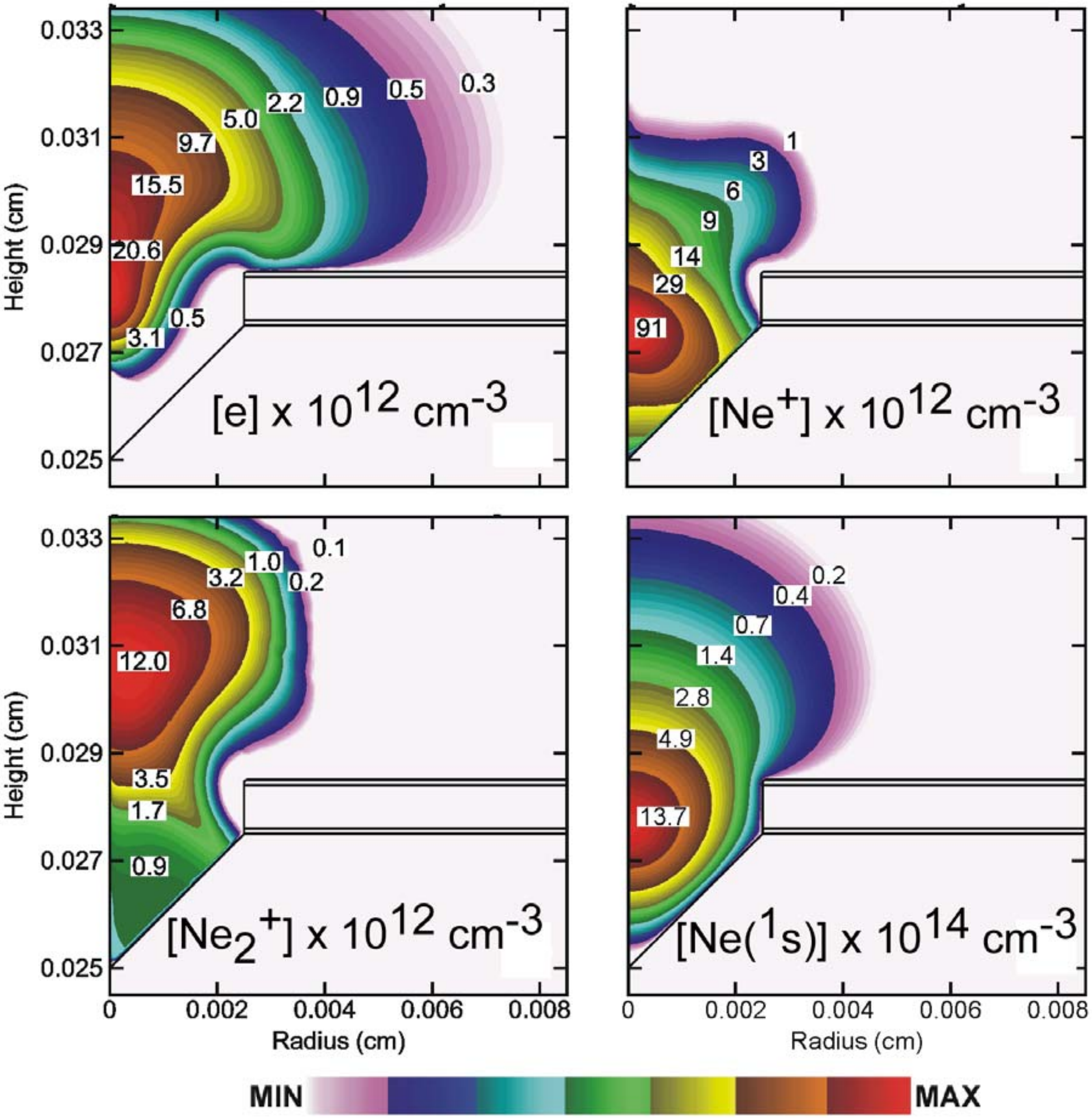
BASE CASE: Ne, 600 Torr, 50 μm DIAMETER



- **Optimum operation produces large enough charge density to warp electric potential into cathode well.**
- **In spite of large T_e, ionization is dominated by beam electrons**
  - **Ne, 600 Torr, 50 μm, 200 V, 1 MΩ**

BASE CASE: Ne, 600 Torr 50 μm DIAMETER



- There is essentially no region of quasi-neutrality or which is positive column-like.
- Monomer and dimer ions are segregated.
- Excited state densities > 10^{15} cm^{-3} rival macroscopic devices
  - Ne, 600 Torr, 50 μm, 200 V, 1 MΩ

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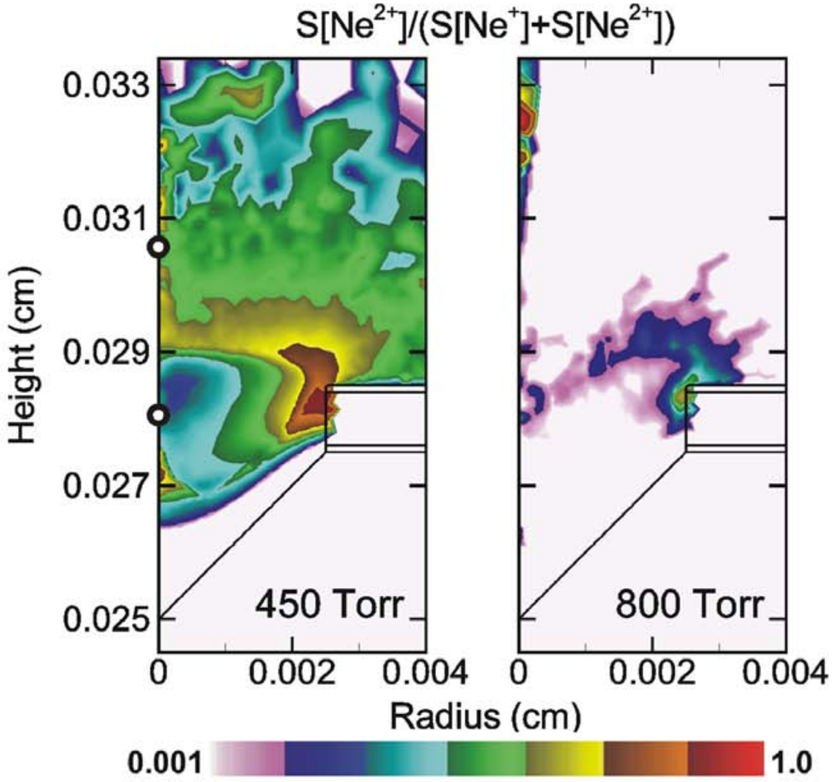
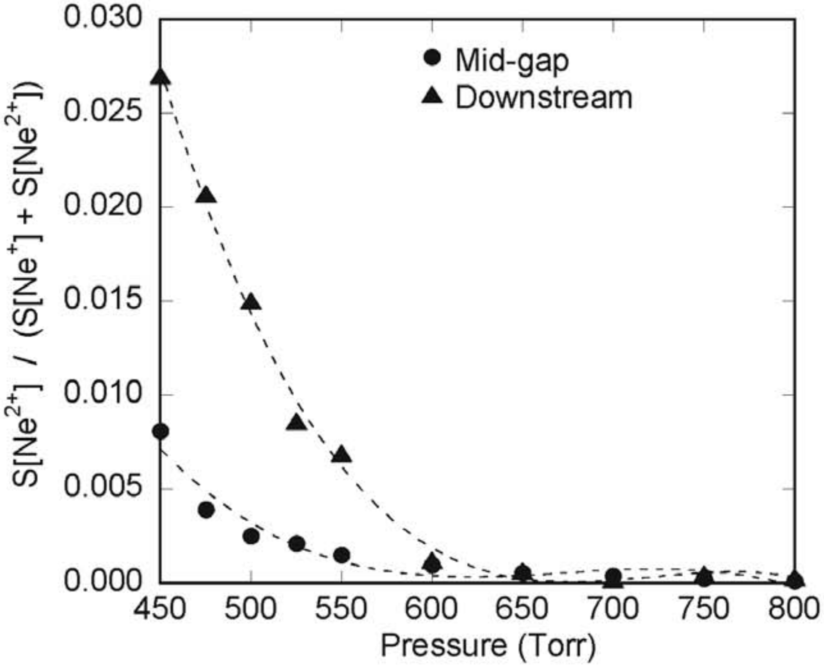
TRANSITION TO NEGATIVE-GLOW BEHAVIOR

- Although geometry precludes true hollow cathode behavior, negative glow behavior sets in a lower pressures.
- Characterize negative glow by $S[Ne^{2+}] / (S[Ne^{+}] + S[Ne^{2+}])$



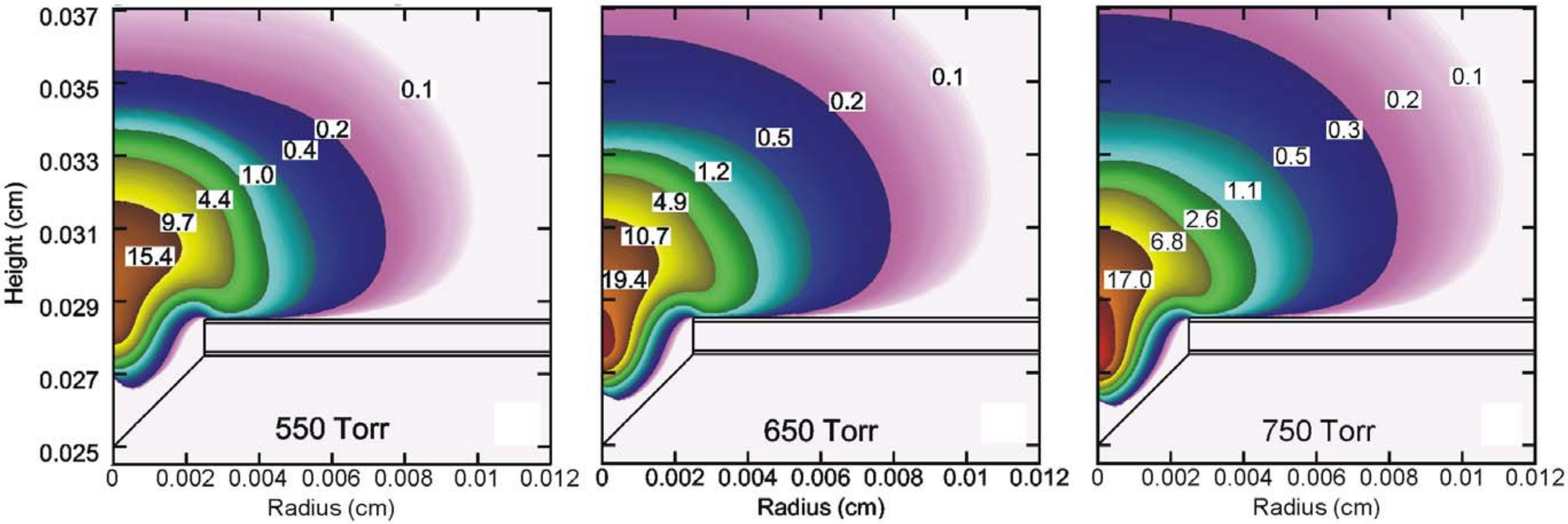


- Ne, 50 μm diameter, 200 V, 1 MΩ

SCALING WITH PRESSURE: PLASMA PROPERTIES

- **Over a range of pressures that V(applied) and R(ballast) can be constant, confinement at higher pressures produces higher peak plasma densities.**

- **[e] x 10^{12} cm^{-3}**



- **550 Torr**
[2.1 x 10^{13} cm^{-3}]

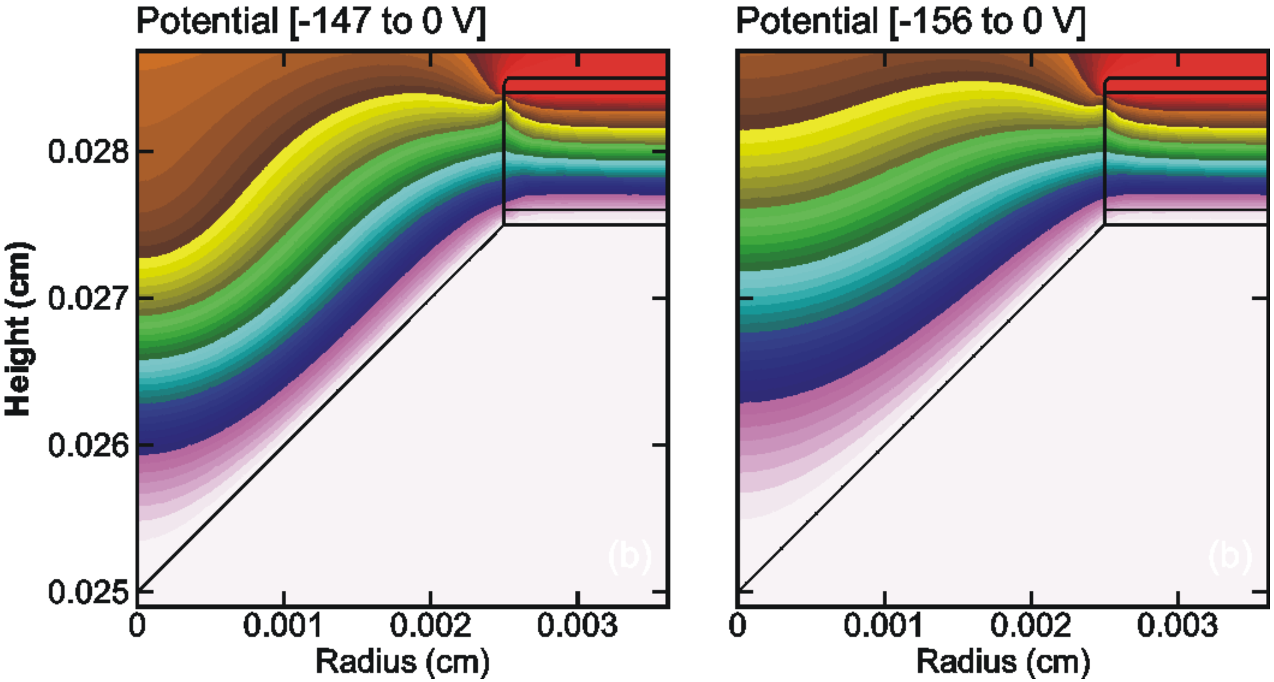
- **650 Torr**
[3.9 x 10^{13} cm^{-3}]

- **750 Torr**
[5.6 x 10^{13} cm^{-3}]

- **Ne, 50 μm diameter, 200V, 1 MΩ**

SCALING CONSIDERATIONS: CATHODE FALL THICKNESS

- In MDs, the cathode fall thickness may be commensurate with cavity size. Current density is therefore critical to scaling.



- Low j (and [e]) may result in cathode fall not being conformal to cathode.

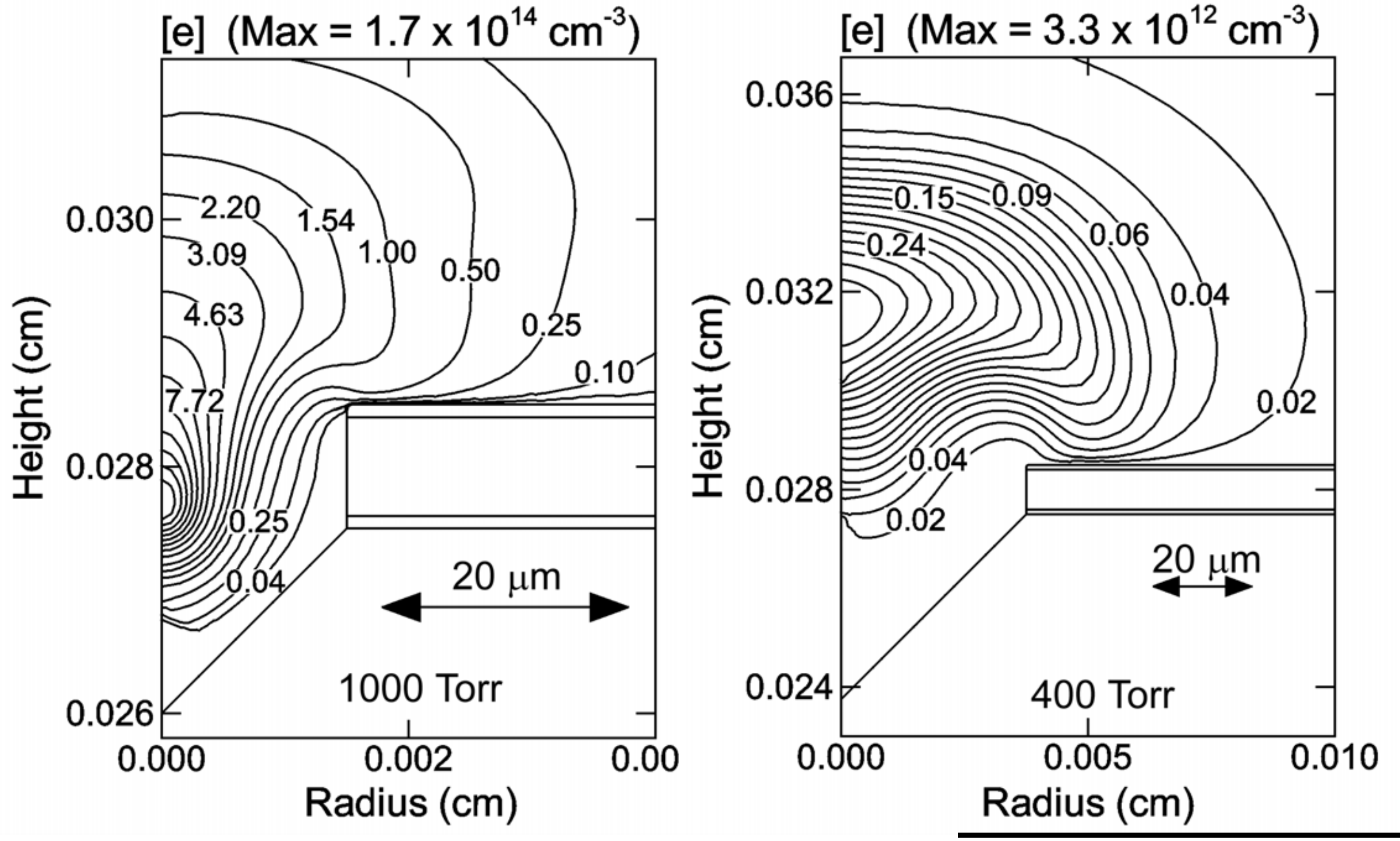
- -210 V, 1 MΩ
  [e]= 4.9 x 10^{13} cm^{-3}

- -200 V, 1.75 MΩ
  [e]= 5.3 x 10^{12} cm^{-3}

- Ne, 50 μm diameter, 600 Torr

SCALING WITH SIZE: pd, BALLAST = CONSTANT

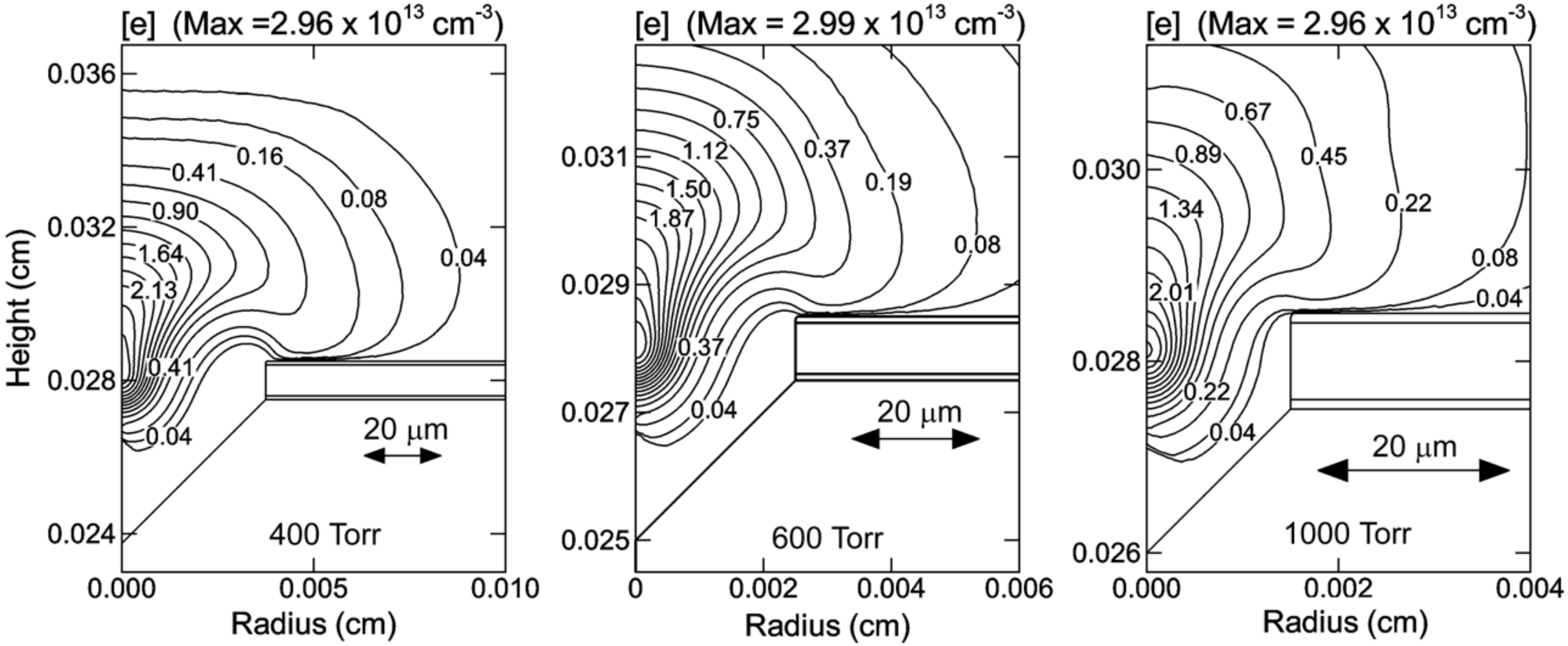
- **Scaling while maintaining pd, V(applied) and R(ballast) constant results in a reduced j and [e] in the larger device. The plasma is not conformal to the cathode.**



- **Ne, -200 V, 1 MΩ**

SCALING WITH SIZE: pd, j = CONSTANT

- **Scaling while maintaining pd and j constant produces similar plasma densities and conformality to the cathode.**



- **400 Torr**
- **600 Torr**
- **1000 Torr**

- **Ne, -200 V**

CONCLUDING REMARKS

- MDs (even in a dc mode) are dynamic entities with strong coupling between electron and ion transport, gas dynamics and chemical processes.
- Subtle changes in geometry, physical parameters (e.g., secondary emission coefficient) can have profound impact on operating characteristics.
- There are significant differences in pd scaling between devices with L > Debye lengths (or cathode fall) and $L < \lambda$, d.
- As MDs age with use, critical dimensions and material properties (such as secondary emission coefficients) often change.
- Modeling is valuable in the design process to determine the sensitivity of operating characteristics to aging related changes in device parameters.