CHARACTERISTICS OF MAGNETICALLY ENHANCED CAPACITIVELY COUPLED DISCHARGES*

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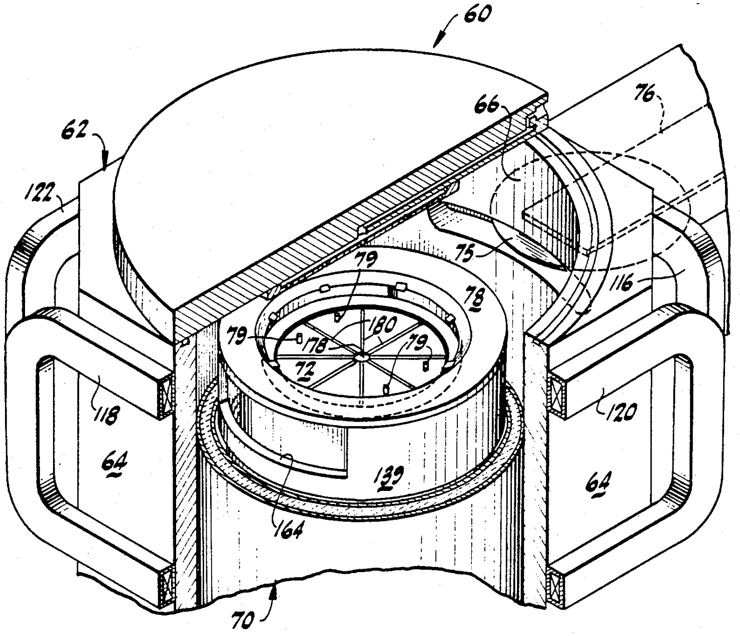
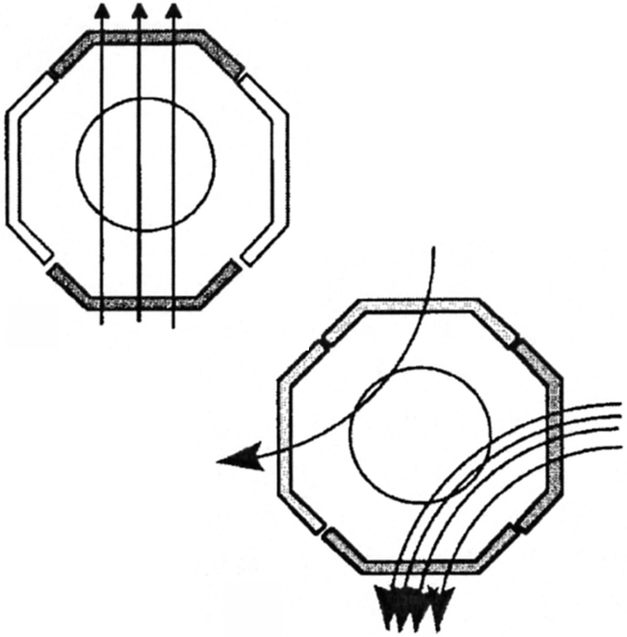
AGENDA

- Introduction to Magnetically Enhanced Reactive Ion Etching (MERIE) Plasma Sources.
- Description of Model
- Scaling of MERIE Properties
- Concluding Remarks

MERIE PLASMA SOURCES

- Magnetically Enhanced Reactive Ion Etching plasma sources use transverse static magnetic fields in capacitively coupled discharges for confinement to increase plasma density.





- D. Cheng et al, US Patent 4,842,683
- M. Buie et al, JVST A 16, 1464 (1998)

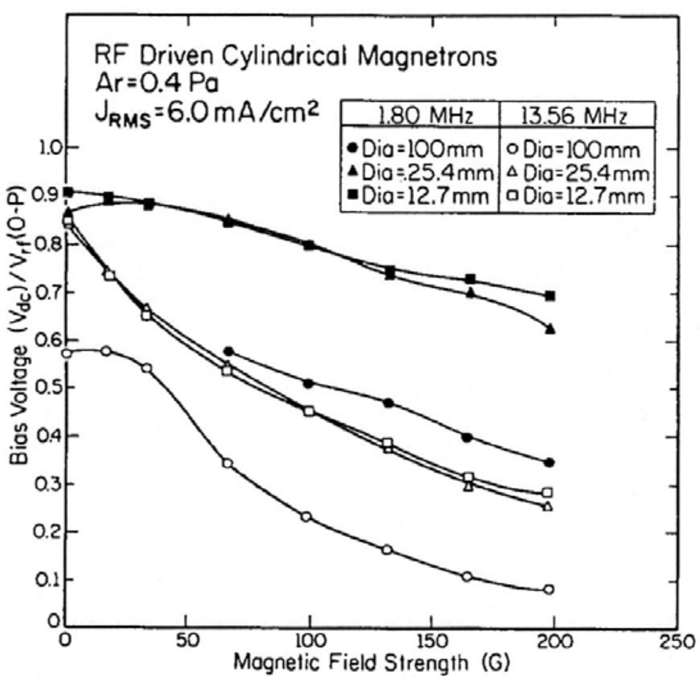
INVESTIGATIONS OF MERIE SYSTEMS

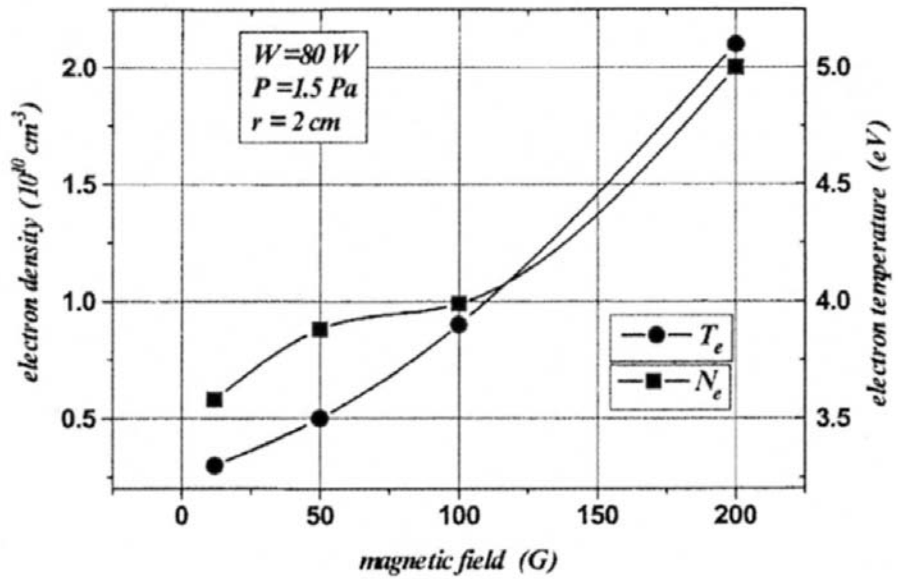
- **Although MERIEs have been used in industry for many years there are a surprisingly small number of published works on the fundamentals of these systems.**

- **G. Y. Yeom, et al, JAP 65, 3825 (1989) [Bias, potential measurements]**
- **A. P. Paranjpe, et al, JVSTA 10, 1140 (1991) [Model]**
- **K. E. Davies, et al, JVSTA 11, 2752 (1993) [Etch rate optimization]**
- **D. Hutchinson, et al, TPS 23, 636 (1995) [PIC Simulation]**
- **S. V. Avtaeva, et al, JPD 30, 3000 (1997) [Probe, OES]**
- **M. J. Buie, et al, JVSTA 16, 1464 (1998) [Etch uniformity optimization]**
- **S. Rauf, et al, ICOPS (2002) [2-D Modeling]**

SCALING OF MERIE SYSTEMS

- **General scalings: More confinement due to B-field has geometric and kinetics effects.**





- **More positive bias with B-field**
- **G. Y. Yeom, et al JAP 65, 3825 (1989)**

- **Larger [e], T_e with B-field**
- **S. V. Avtaeva, et al JPD 30, 3000 (1997)**

MODELING OF MERIE

- <u>Hybrid Plasma Equipment Model</u>

- Electron energy equation for bulk electrons
- Monte Carlo Simulation for high energy secondary electrons from biased surfaces
- Continuity, Momentum and Energy (temperature) equations for all neutral and ion species.
- Poisson equation for electrostatic potential
- Circuit model for bias
- Monte Carlo Simulation for ion transport to obtain IEADs

ELECTRON ENERGY TRANSPORT

$$\partial\left(\frac{3}{2}n_e kT_e\right)/\partial t = S(T_e) - L(T_e) - \nabla\cdot\left(\frac{5}{2}\overline{\Phi}kT_e - \overline{\overline{\kappa}}(T_e)\cdot\nabla T_e\right) + S_{EB}$$

$$\overline{\Phi} = qn_e\overline{\overline{\mu}}_e\cdot\overline{E} - \overline{\overline{D}}\cdot\nabla n_e$$

$S(T_e)$ = Power deposition from electric fields
$L(T_e)$ = Electron power loss due to collisions
Φ = Electron flux
$\kappa(T_e)$ = Electron thermal conductivity tensor
S_{EB} = Power source source from beam electrons

- **All transport coefficients are tensors:**

$$\overline{\overline{A}} = A_o\frac{m\nu_m}{q\alpha}\frac{1}{\left(\alpha^2+\left|\vec{B}\right|^2\right)}\begin{pmatrix} \alpha^2+B_r^2 & \alpha B_z + B_r B_\theta & -\alpha B_\theta + B_r B_z \\ -\alpha B_z + B_r B_\theta & \alpha^2 + B_\theta^2 & \alpha B_r + B_\theta B_z \\ -\alpha B_\theta + B_r B_z & -\alpha B_r + B_\theta B_z & \alpha^2 + B_z^2 \end{pmatrix}$$

$$\alpha = \frac{(i\omega+\nu_m)}{q/m}, \quad A_o = isotropic$$

PLASMA CHEMISTRY, TRANSPORT AND ELECTROSTATICS

- **Continuity, momentum and energy equations are solved for each species (with jump conditions at boundaries)**

$$\frac{\partial N_i}{\partial t} = -\nabla\cdot(N_i\vec{\mathrm{v}}_i) + S_i$$

$$\frac{\partial\left(N_i\vec{v}_i\right)}{\partial t} = \frac{1}{m_i}\nabla\left(kN_iT_i\right) - \nabla\cdot\left(N_i\vec{v}_i\vec{v}_i\right) + \frac{q_iN_i}{m_i}\left(\vec{E}+\vec{v}_i\times\vec{B}\right) - \nabla\cdot\overline{\mu}_i - \sum_j \frac{m_j}{m_i+m_j} N_iN_j\left(\vec{v}_i-\vec{v}_j\right)\nu_{ij}$$

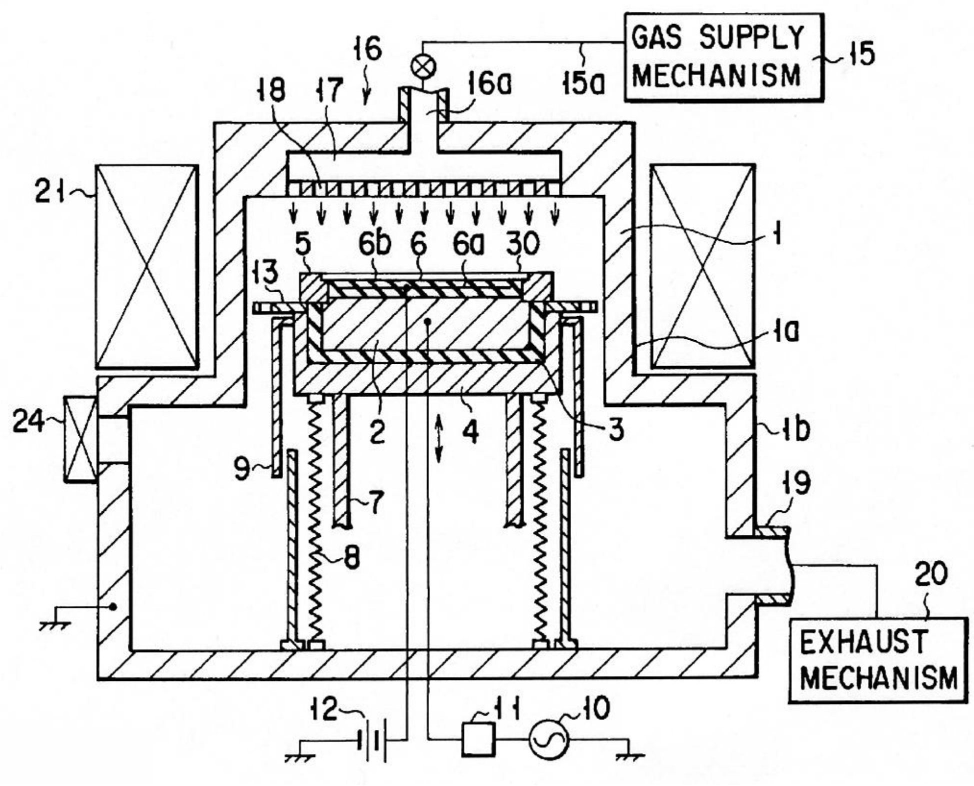
$$\frac{\partial\left(N_i\varepsilon_i\right)}{\partial t} + \nabla\cdot\mathrm{Q}_i + P_i\nabla\cdot\mathrm{U}_i + \nabla\cdot(N_i\mathrm{U}_i\varepsilon_i) = \frac{N_iq_i^2\nu_i}{m_i(\nu_i^2+\omega^2)}E^2 + \frac{N_iq_i^2}{m_i\nu_i}E_s^2 + \sum_j 3\frac{m_{ij}}{m_i+m_j}N_iN_jR_{ij}k_B(T_j-T_i) \pm \sum_j 3N_iN_jR_{ij}k_BT_j$$

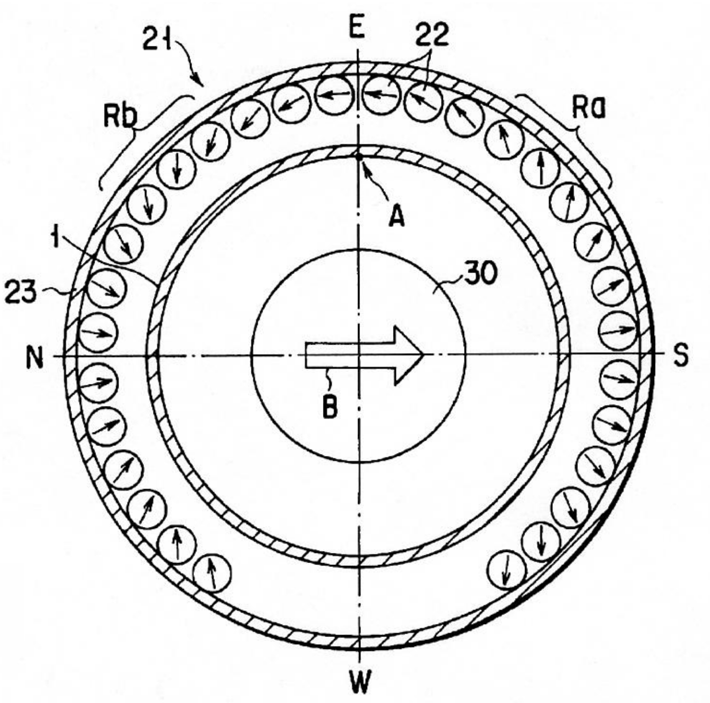
- **Implicit solution of Poisson's equation**

$$\nabla\cdot\varepsilon\nabla\Phi\left(t+\Delta t\right) = -\left(\rho_s + \sum_i q_iN_i - \Delta\mathrm{t}\cdot\sum_{\mathrm{i}}\left(\mathrm{q_i}\nabla\cdot\vec{\phi}_i\right)\right)$$

MERIE REACTOR

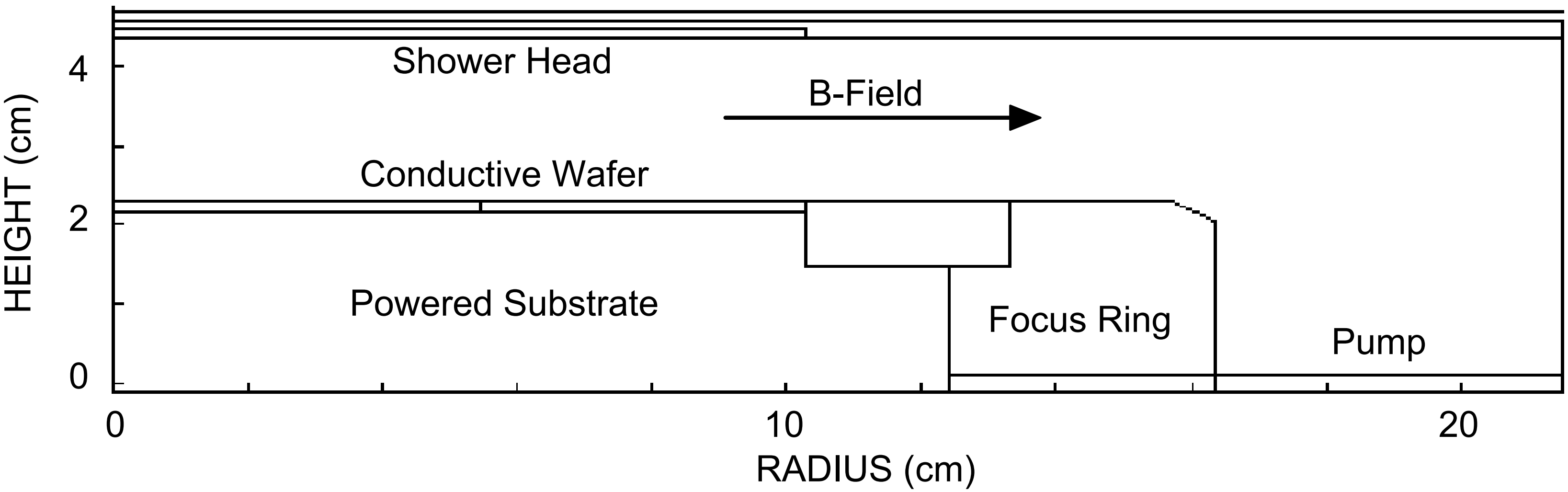
- **The model reactor is based on a TEL Design having a transverse magnetic field.**





- **K. Kubota et al, US Patent 6,190,495 (2001)**

MERIE REACTOR: MODEL REPRESENTATION



- **2-D, Cylindrically Symmetric**
- **Magnetic field is purely radial, an approximation validated by 2-D Cartesian comparisons.**

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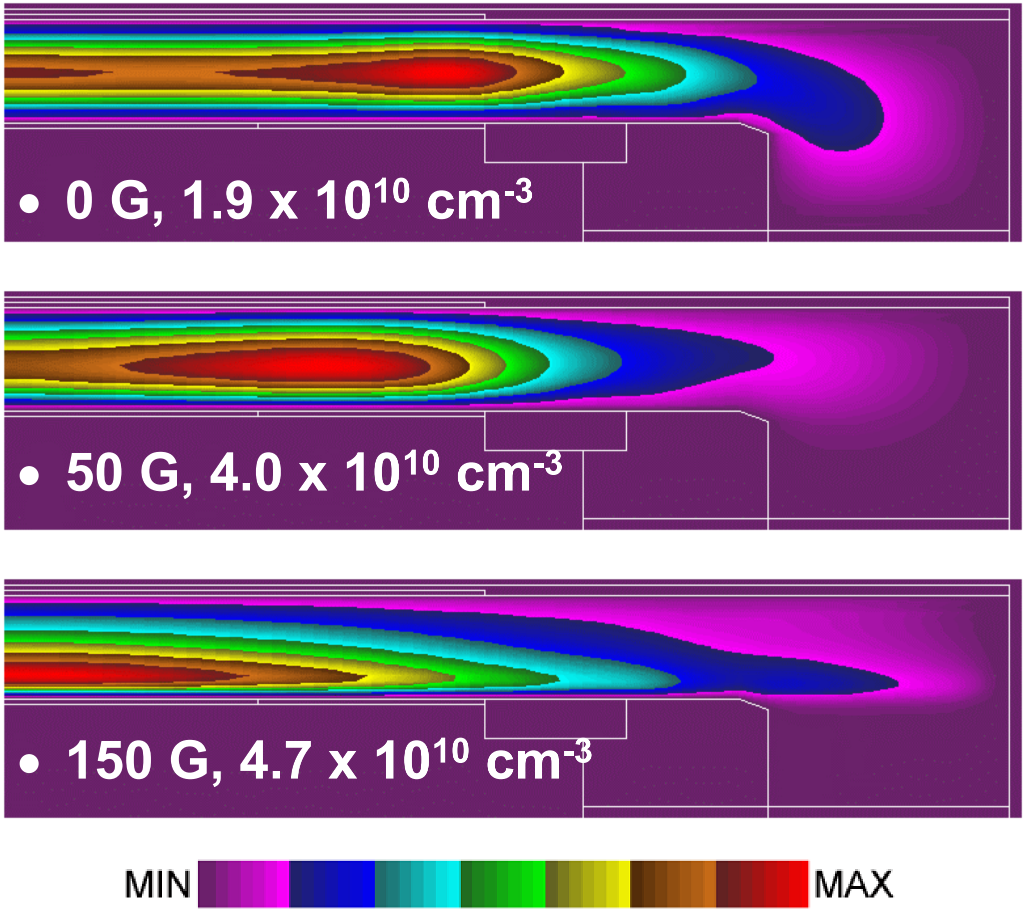
Optical and Discharge Physics

Ar^+ DENSITY vs MAGNETIC FIELD



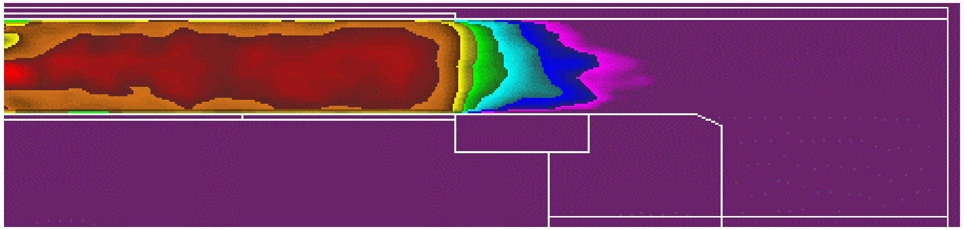
- 0 G, 1.9×10^{10} cm^{-3}
- 50 G, 4.0×10^{10} cm^{-3}
- 150 G, 4.7×10^{10} cm^{-3}

- Ar, 40 mTorr, 100 W, 10 MHz

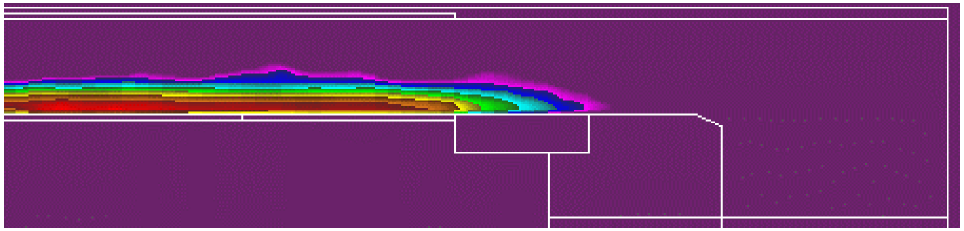
- Purely radial B-field parallel to electrodes
- Increasing B-field shifts plasma towards center and increases density.
- Plasma is localized closer to wafer.

IONIZATION BY SECONDARY ELECTRONS

- The localization of plasma density near the powered electrode at large magnetic fields is partly attributable to the confinement of secondary electrons.



- 12.5 G: 3.7 x 10^{13} $cm^{-3}s^{-1}$



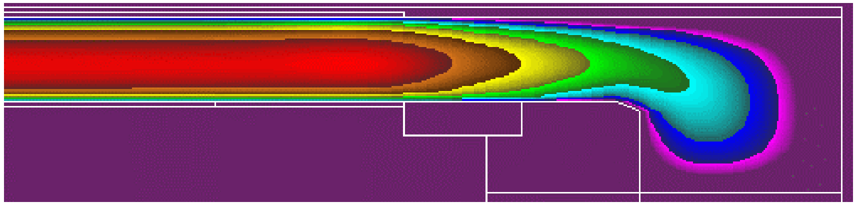
- 150 G: 1.3 x 10^{14} $cm^{-3}s^{-1}$

- Ionization by secondary electrons is uniform across the gap at low B-field; localized at high B-field.

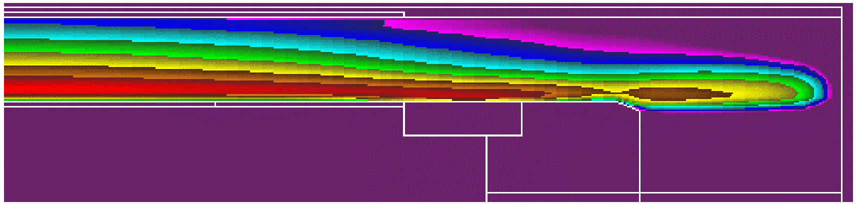
- Ar, 40 mTorr, 100 W, 10 MHz

IONIZATION BY BULK ELECTRONS

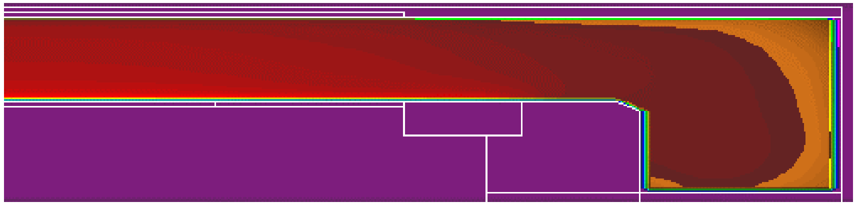
- Similar trends are seen for bulk electrons. The transverse thermal conductivity decreases with increasing B-field, producing more localized hot electrons.



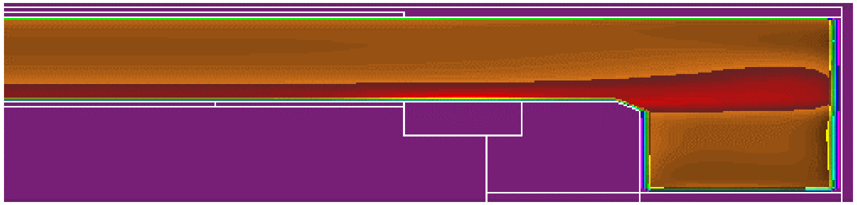
- 12.5 G: 4.6 x 10^{15} cm^{-3}s^{-1}



- 150 G: 9.9 x 10^{15} cm^{-3}s^{-1}
- Bulk Ionization Rate



- 12.5 G: 4.9 eV

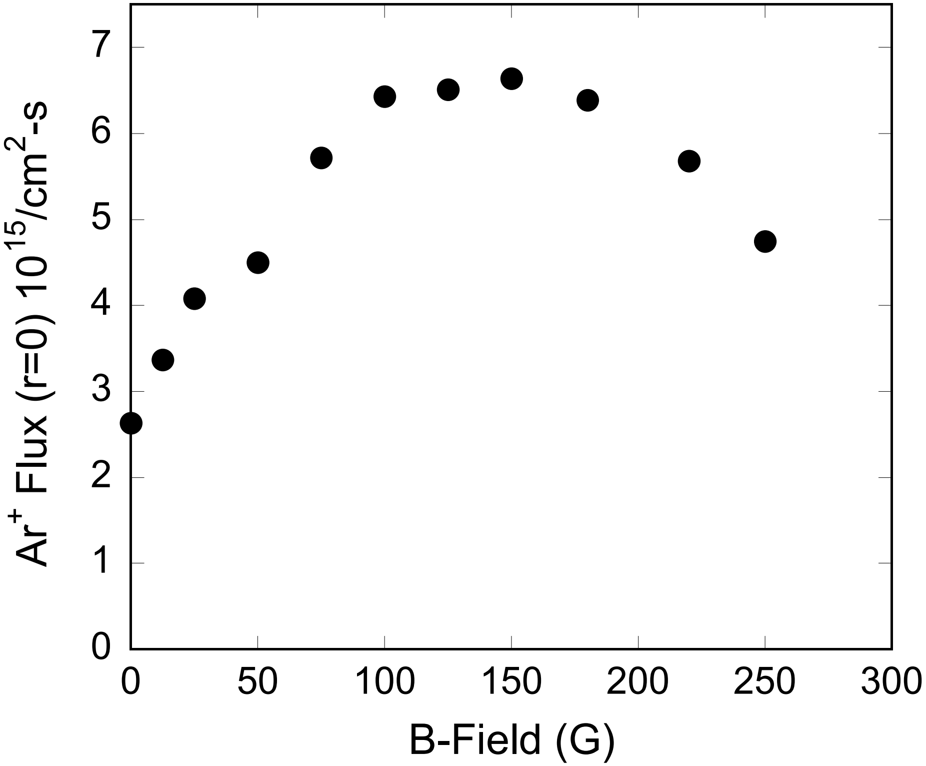


- 150 G: 5.2 eV
- Electron Temperature

- Ar, 40 mTorr, 100 W, 10 MHz

ION FLUX TO SUBSTRATE

- **The ion flux increases with increasing B-field due to lower transverse losses.**



- **Ar^+ Flux at r=0 (10^{15} cm^{-2}s^{-1})**

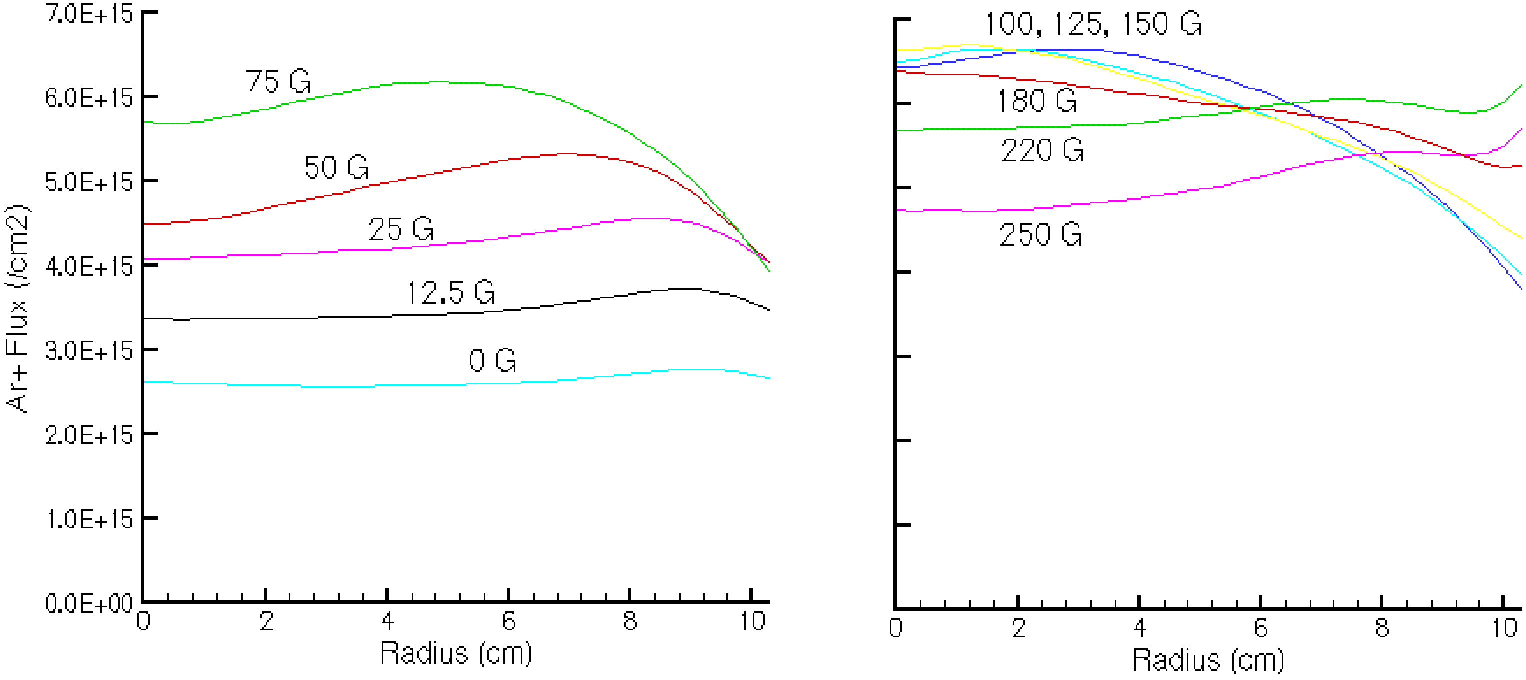
- **Ar* transport, unaffected by B-field, has more rapid losses as source approaches substrate.**

- **Reduction in efficiency of ionization by smaller multi-step rate lowers ion flux.**

- **Ar, 40 mTorr, 100 W, 10 MHz**

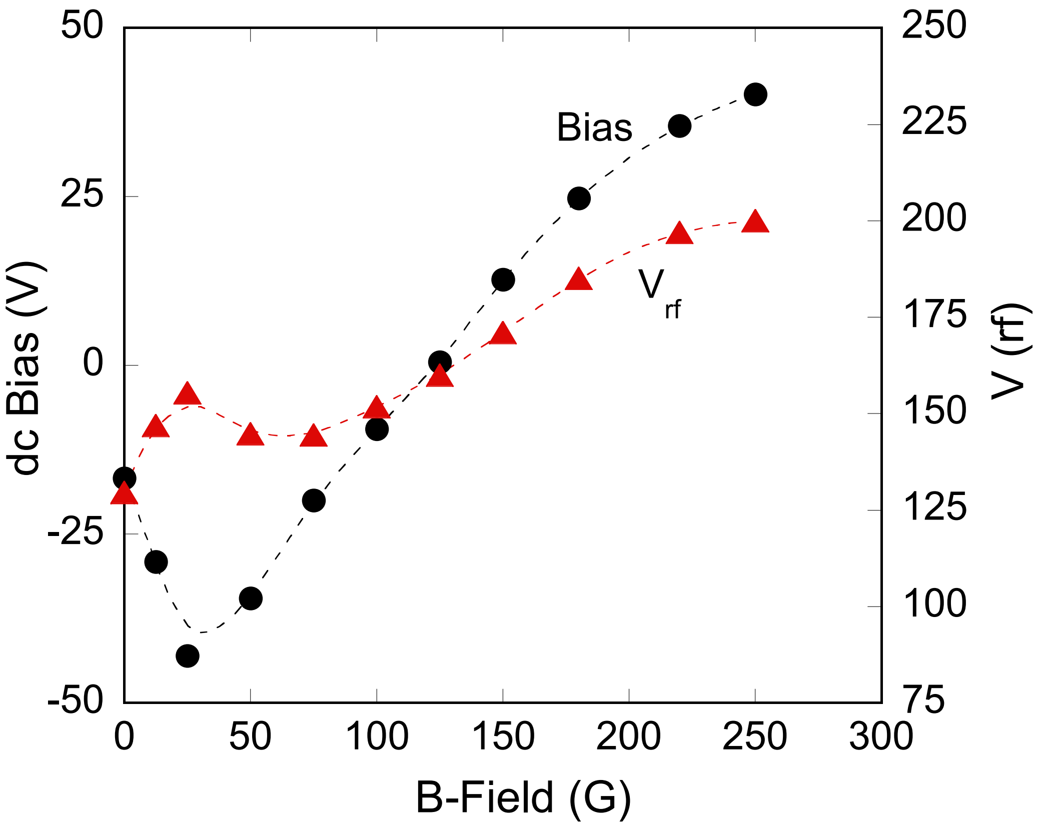
ION FLUX vs RADIUS

- **Ion flux becomes center peaked at intermediate B-field; regaining uniformity at large B-field with stronger confinement.**



- **Ar, 40 mTorr, 100 W, 10 MHz**

dc BIAS AND RF VOLTAGE



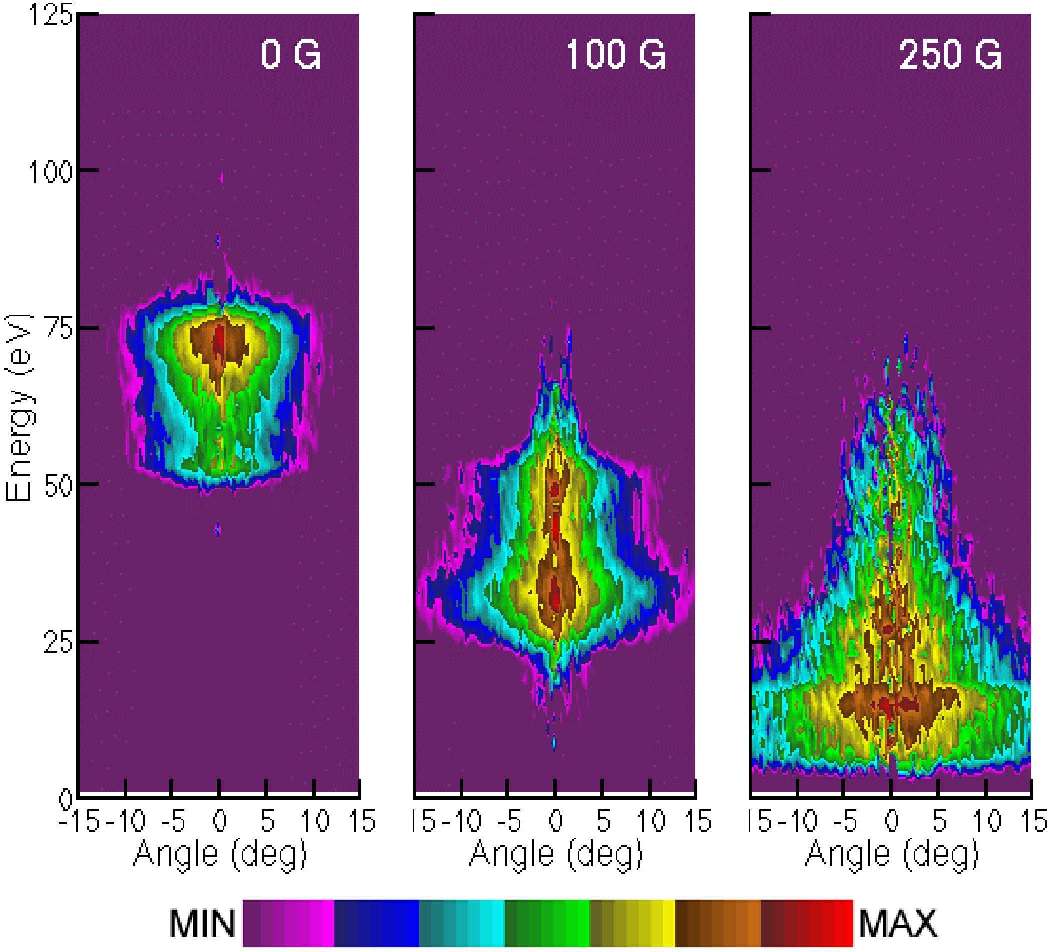
- **The dc bias generally becomes more positive with increasing B-field as the plasma is confined closer to the powered electrode.**

- **Constant power, decreasing ion flux, increasing bias voltage → More resistive plasma.**

- **Ar, 40 mTorr, 100 W, 10 MHz**

Ar^+ ENERGY AND ANGLE DISTRIBUTIONS

- **The more positive dc bias reduces the sheath potential.**



- **The resulting IEAD is lower in energy and broader.**

- **Ar, 40 mTorr, 100 W, 10 MHz**

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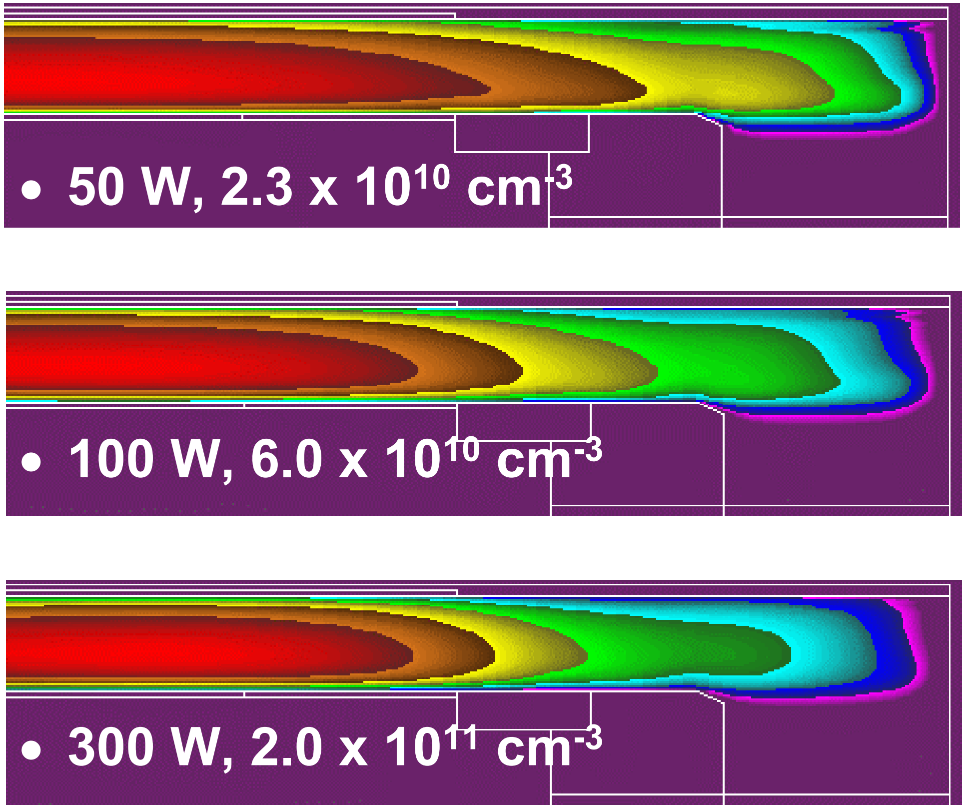
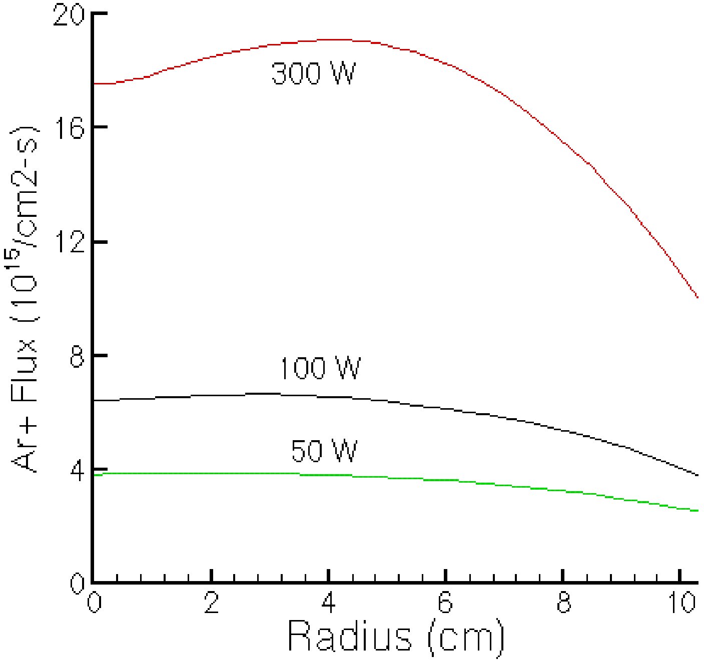
Ar$^+$ DENSITY/FLUX vs POWER



- 50 W, 2.3×10^{10} cm^{-3}
- 100 W, 6.0×10^{10} cm^{-3}
- 300 W, 2.0×10^{11} cm^{-3}



- Power produces more than linear increase in peak [Ar$^+$] and sub-linear increase in flux with decrease in uniformity

- Ar, 40 mTorr, 100 G, 10 MHz

CONCLUDING REMARKS

- Scaling laws for an industrial MERIE reactor have been computationally investigated; and map well onto experimental results.

- Increasing B-field localizes plasma near powered electrode, resulting in:
    - Increase in [e]
    - More localized ionization sources
    - Small but localized increase in T_e
    - More positive V_{dc}

- Lack of “response” of Ar* to B-field may decrease ion fluxes by lowering multistep processes as sources move towards surface.

- IEADs are sensitive to B-field due to scaling of V_{dc}.