2D Hybrid Fluid-Analytical Model of Inductive/Capacitive Plasma Discharges

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Overview

A ***fast*** 2D TCP Reactor Model was developed:

- EM Model with ***inductive and capacitive coupling*** of source coils to plasma, and capacitive bias option for wafer electrode.
- Quasi-neutral Bulk Plasma Fluid Model which solves ion continuity and electron energy balance coupled to an Analytical Sheath Model with ***electron and ion sheath heating***.
- Gas Flow Fluid Model with reactive gas chemistries.

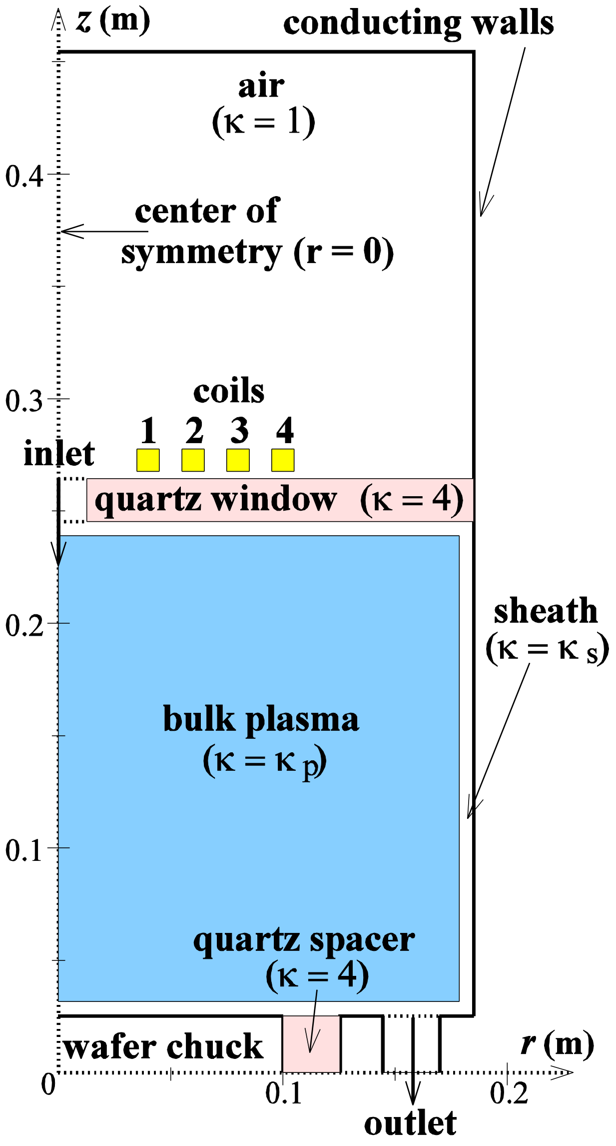
  (Hsu et al, *J. Phys. D.* **39**, 3272, 2006)
- A portable, user-friendly Comsol-Matlab platform.
- Good agreement with experimental Cl_2 TCP reactor study.

TCP Reactor Geometry

- Axisymmetric cylindrical geometry.
- Outer surface is a perfect conductor
- Wafer chuck insulated from walls by quartz dielectric spacer ($\kappa = 4$).
- 4-turn stove-top coil set on top of quartz dielectric window ($\kappa = 4$).
- Thin vacuum sheath around plasma.
- Relative dielectric constant of plasma:

$$\kappa_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu_m)}$$

- Coil 1 is attached to an rf current source while Coil 4 is grounded.



EM Model

- Coils produce inductive TE fields (E_ϕ, H_r, H_z) and capacitive TM fields (H_ϕ, E_r, E_z).
- Solve for one field in each trio, get other two via Maxwell's equations.
- Assume all fields $\mathbf{F} \propto \exp(j\omega t)$ and solve Helmholtz

  $$(\nabla^2 + (\omega\kappa/c)^2)\mathbf{F} + f = 0$$

  in each region.
- Plasma is a lossy dielectric since κ_p has an imaginary (dissipative) part.

Inductive TE Simulations (E_ϕ ,H_r ,H_z)

- Dependent variable is $V=2\pi rE_\phi$, the loop voltage at radius r.

- Solve Helmholtz Eq. for V with boundary conditions:

  $V = 0$ on all outer surfaces and center of symmetry

  $V = V_n$ on the perimeter of the nth coil

- V_n are determined for a given input current I_{in} to the coil set.

Capacitive TM Simulations (H_ϕ ,E_r ,E_z)

- Dependent variable is $I=2\pi r H_\phi$, the *z*-directed current intercepting the cross-sectional area of radius *r*.
- Solve Helmholtz Eq. for *I* with boundary conditions:

  $\mathbf{n}\cdot\nabla I = 0$ on all outer surfaces

  $I = 0$ on center of symmetry since $I \propto r$
- Each coil is supplied by an axial feed current i_n.
- i_n are determined for a given input current I_{in} to the coil set.

Capacitive Bias Option for Wafer Electrode

- Solve capacitive Helmholtz Eq. for $I=2\pi r H_\phi$ with

  $\mathbf{n}\cdot\nabla I = 0$ on all conducting walls

  $I = 0$ on center of symmetry

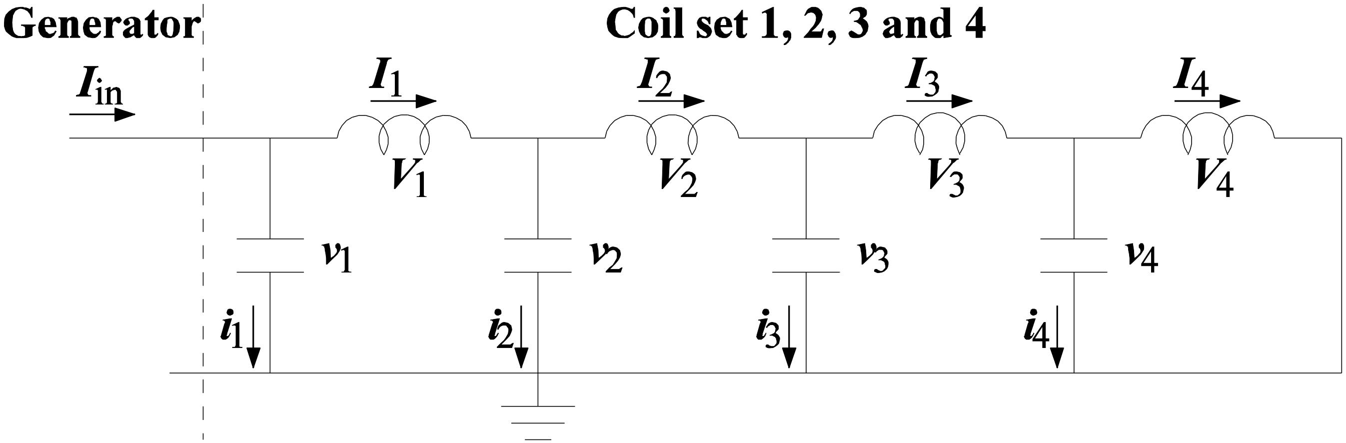
  $I = \text{const} = \mathrm{I}_{rf}$ on bottom surface of dielectric spacer

- TCP coils are floating (coil currents $i_n = 0$).

- rf voltage supplied by the bias is: $\mathrm{V}_{rf} = \int_{\substack{\text{spacer}\\ \text{bottom}}} E_r \, \mathrm{d}r$

- rf power is $P_{rf} = 0.5\mathrm{Re}(I_{rf} V_{rf}^{*})$

TCP Coil Circuit



- Inductance matrix L relates $\mathbf{V}_L=(V_1,V_2,V_3,V_4)$ with $\mathbf{I}_L=(I_1,I_2,I_3,I_4)$: $\mathbf{V}_L = j\omega\,\mathbf{L}\,\mathbf{I}_L$
- Capacitance matrix C relates $\mathbf{i}_c=(i_1, i_2, i_3, i_4)$ to $\mathbf{v}_c=(v_1, v_2, v_3, v_4)$: $\mathbf{i}_c = j\omega\,\mathbf{C}\,\mathbf{v}_c$
- Find **L** by conducting 4 orthonormal TE simulations in which $V_k=1$ for the *n*th coil while $V_k=0$ for other 3 coils. Take line integral of **H** around *m*th coil to get currents $I_{mn} \Rightarrow L_{mn}$.
- Find **C** by conducting 4 orthonormal TM simulations in which $i_k=1$ for the *n*th coil while $i_k=0$ for other 3 coils. Take line integral of **E** from *m*th coil to ground to get voltages $v_{mn} \Rightarrow C_{mn}$.
- $\Rightarrow$ For a given I_{in}, can solve circuit to get all i_k, v_k, I_k, V_k.

Bulk Plasma Power Deposition

- Inductive TE and capacitive TM equations are solved simultaneously to obtain all the fields.

- The total plasma current density is given by

$$\mathbf{J}_T = (\sigma_p + j\omega\varepsilon_0)\mathbf{E}$$

where $\sigma_p = j\omega\varepsilon_0(\kappa_p - 1)$ is the plasma conductivity.

- Time averaged power density profile in the plasma is:

$$p_{\mathrm{dep}} = 0.5\,\mathrm{Re}(J_T \cdot E^*) = 0.5\,\mathrm{Re}(\sigma_p)\left(\underbrace{|E_\varphi|^2}_{\text{inductive}} + \underbrace{|E_r|^2 + |E_z|^2}_{\text{capacitive}}\right)$$

- p_{dep} is used as input in the electron energy balance equation of the Bulk Plasma Fluid Model.

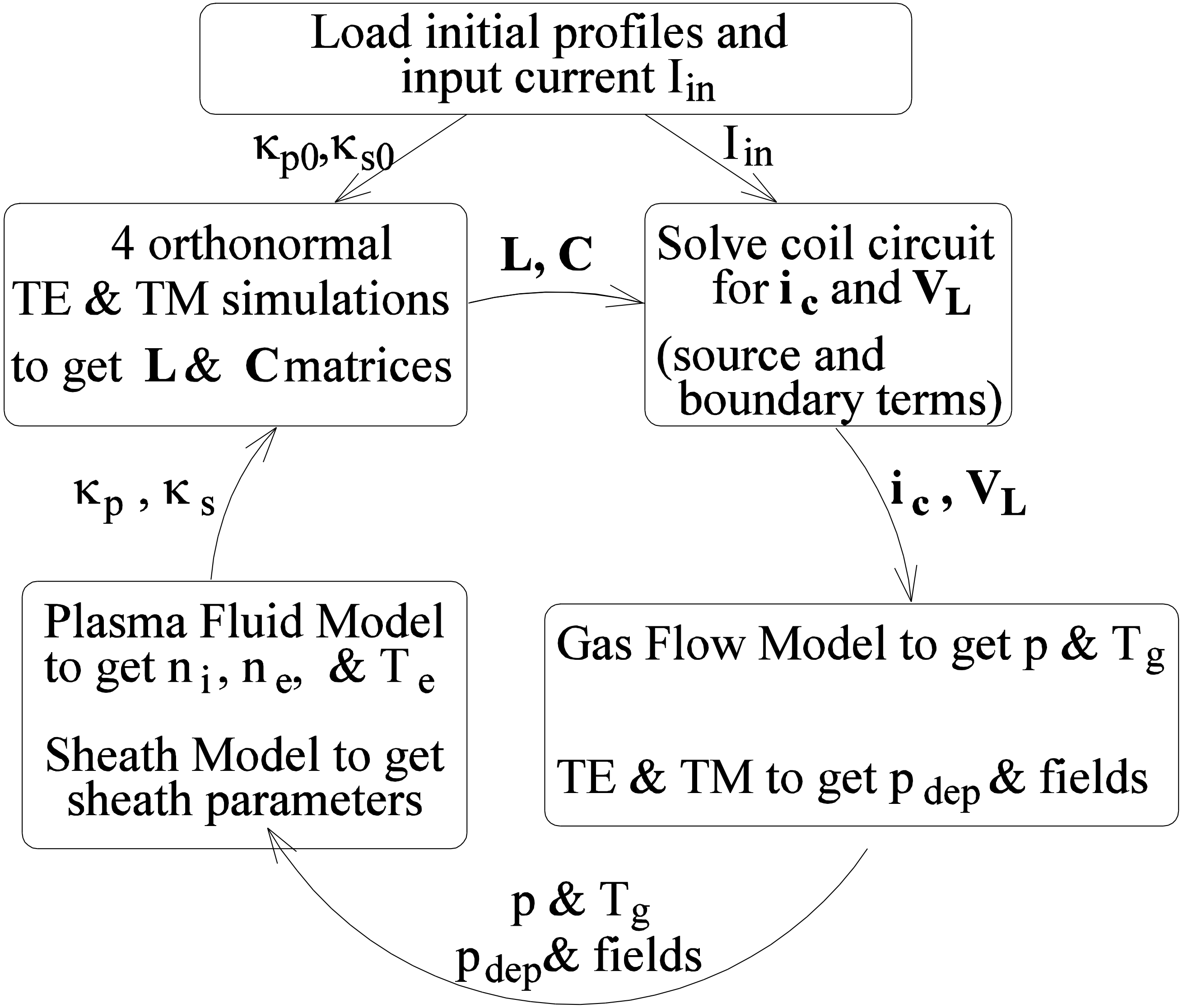
Fixed Width Sheath Model

- Sheath width s depends on local $\mathbf{E}$, n_e and T_e.
- Computationally inconvenient to adjust position of plasma-sheath boundary.
- Sheath with constant width s_0 and varying dielectric constant $\kappa_s = s_0/s$ used to mimic a vacuum sheath ($\kappa = 1$) with varying width s.
  (Lee et al, *PSST* **17**, 015018, 2008)
- The sheath voltage V_{sh} same for both cases:

$$V_{sh} = |(\mathbf{E_{vac}} / \kappa_s)\cdot\mathbf{n}| s_0 = |\mathbf{E_{vac}} \cdot\mathbf{n}| s$$

- Modified Lee et al by (i) treating electron sheath heating as an incoming energy flux to the electron energy balance equation, and by (ii) adding a dissipative (imaginary) term to κ_s to account for the electron and ion sheath heating.

Outline of TCP Model



Load initial profiles and input current I_{in}

κ_{p0}, κ_{s0}

I_{in}

4 orthonormal TE & TM simulations to get **L** & **C** matrices

L, C

Solve coil circuit for $\mathbf{i_c}$ and $\mathbf{V_L}$ (source and boundary terms)

$\mathbf{i_c}$, $\mathbf{V_L}$

Gas Flow Model to get p & T_g

TE & TM to get p_{dep} & fields

p & T_g
p_{dep} & fields

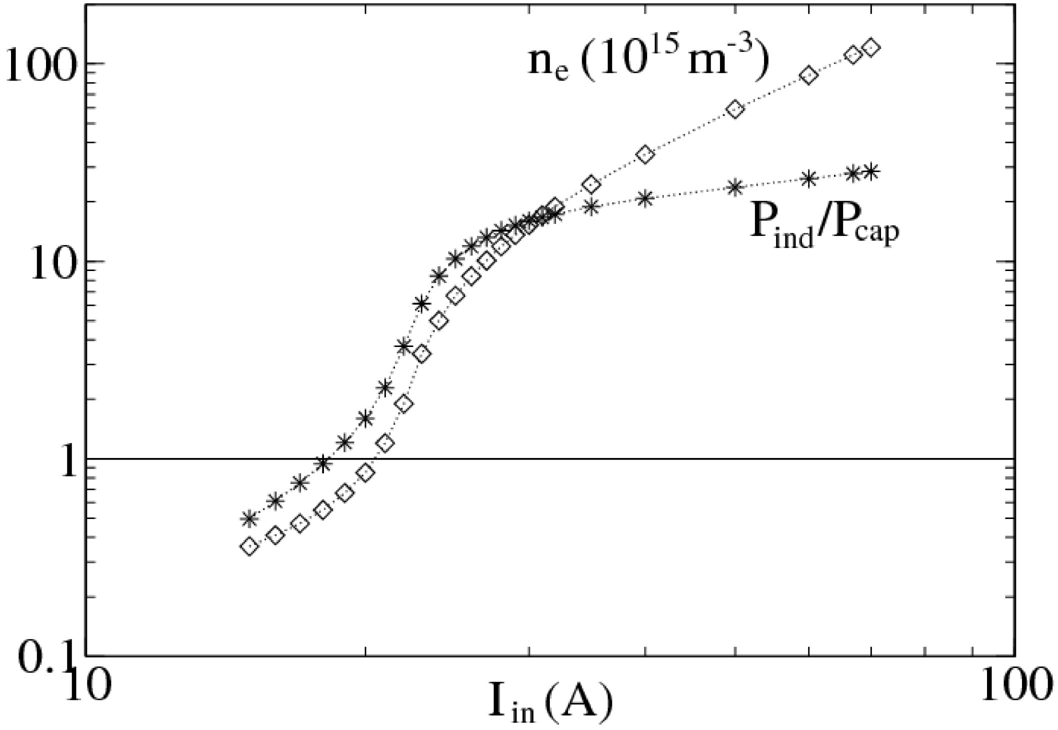
Plasma Fluid Model to get n_i, n_e, & T_e

Sheath Model to get sheath parameters

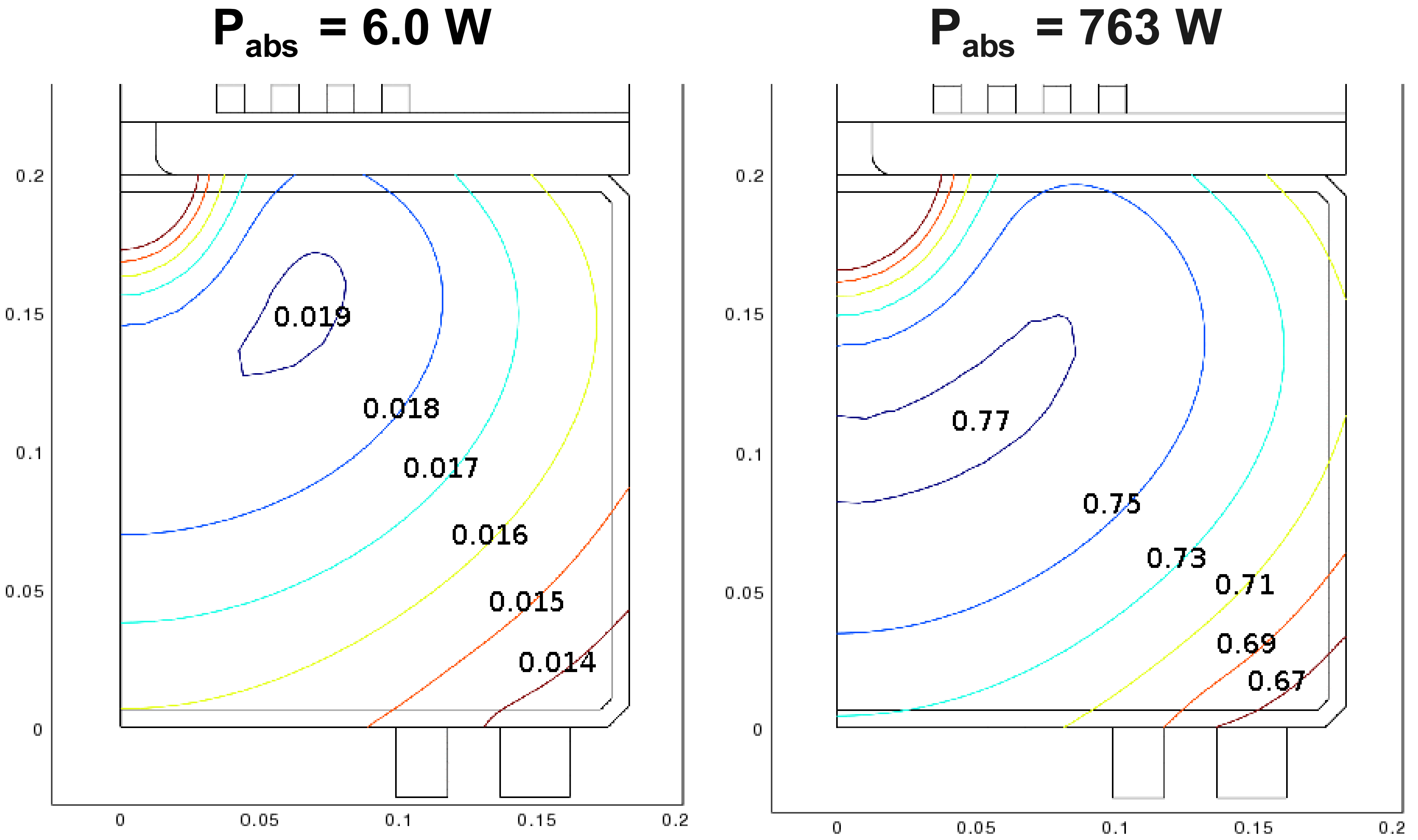
κ_p , κ_s

TCP Reactor Simulations

- 10 mTorr, 13.56 MHz, 100 sccm Cl_2 plasma with I_{in}=15–70A (P_{abs} = 5.3 to 813 W). Cl_2 reaction set from Thorsteinsson & Gudmundsson, *PSST* **19**, 015015 (2010).
- Each simulation on a moderate 2GHz CPU, 4GB RAM PC ~ 70 min.
- As I_{in} ↑, low density capacitive → high density inductive mode.



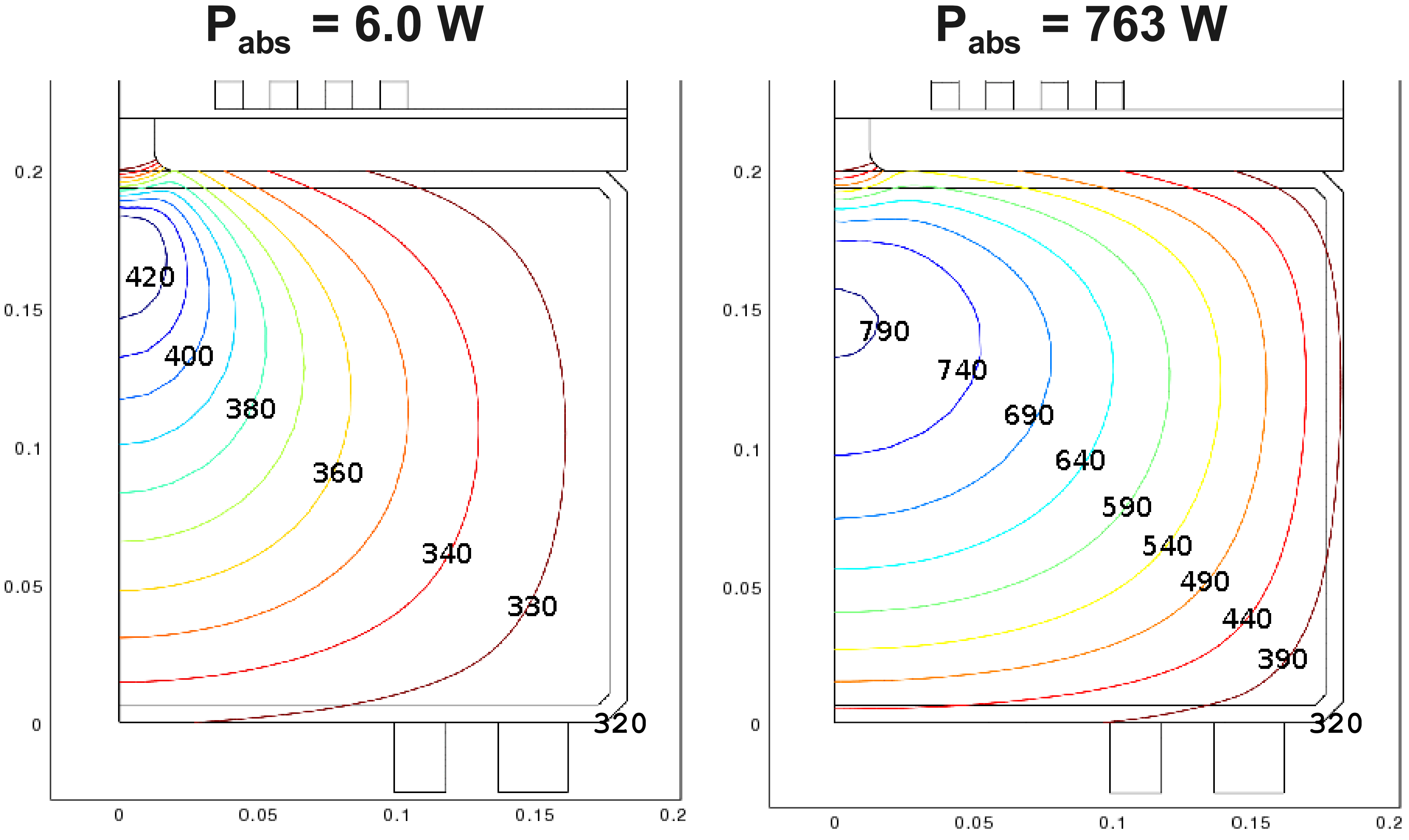
Molar Fraction of Cl (10 mT, 100 sccm Cl_2)



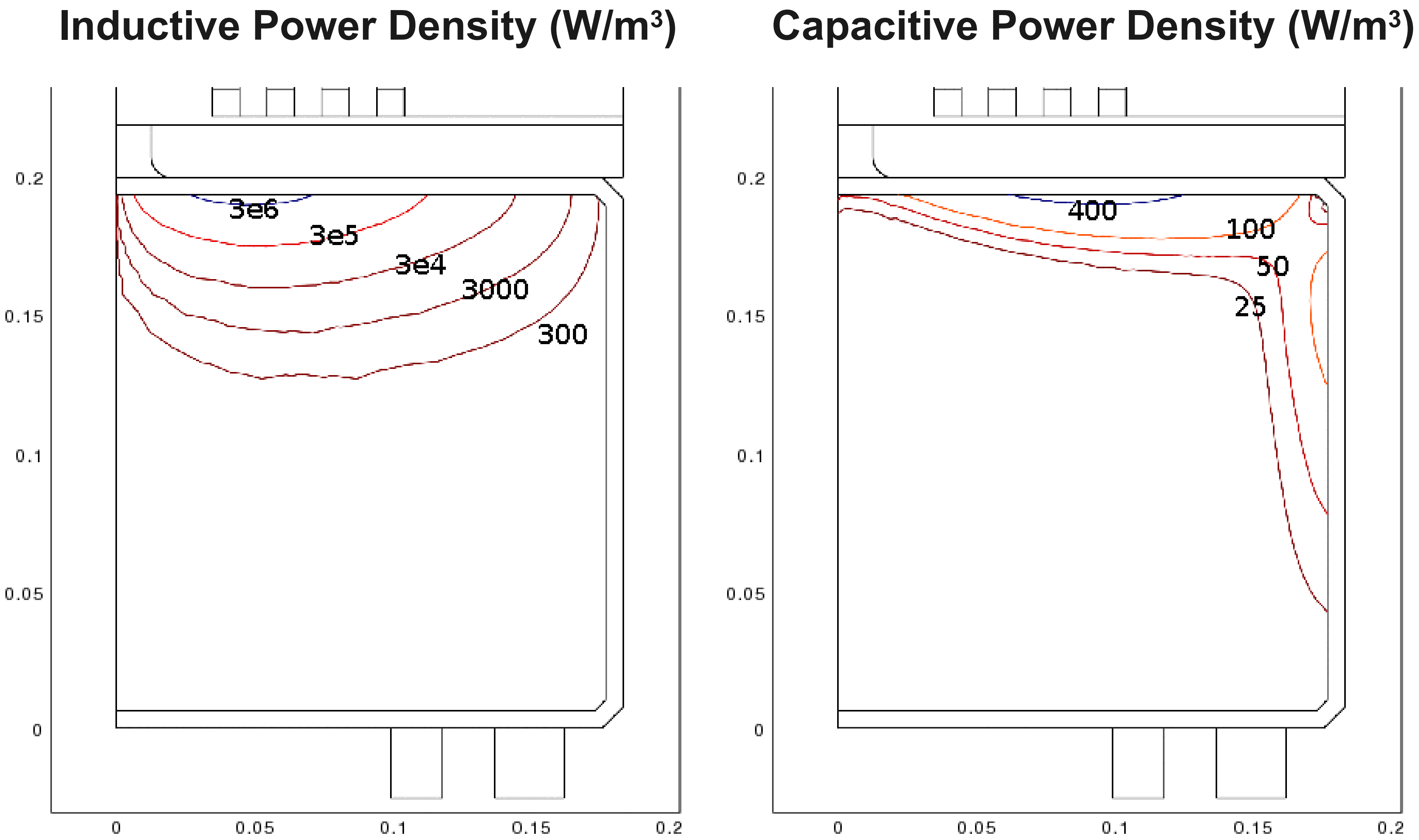
P_{abs} = 6.0 W

P_{abs} = 763 W

Gas Temperature (K) (10 mT, 100 sccm Cl_2)



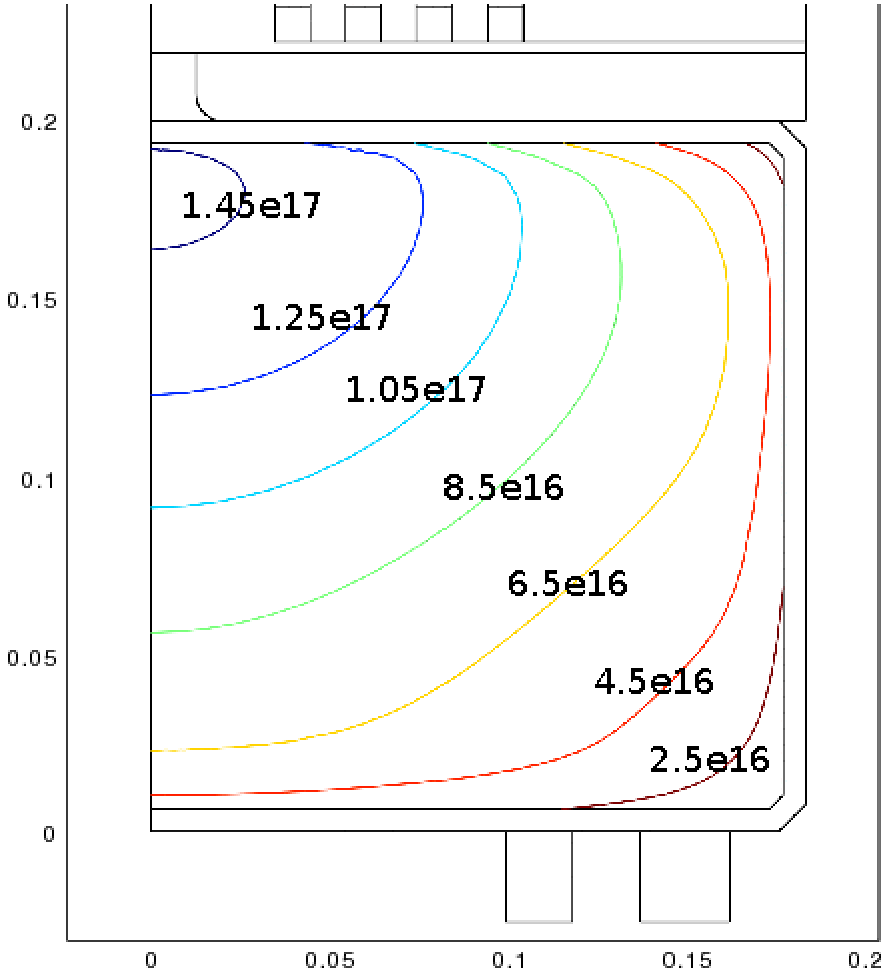
Inductive vs. Capacitive (763 W, 10 mT, 100 sccm Cl_2)


Inductive Power Density (W/m³)

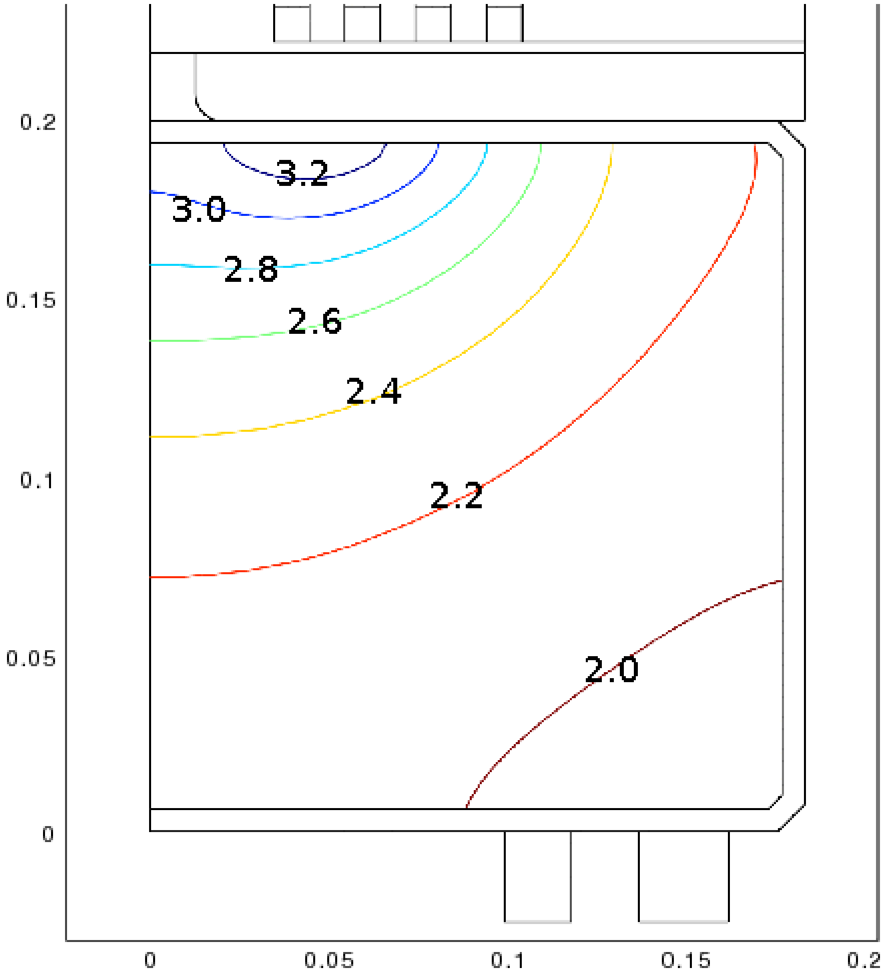
Capacitive Power Density (W/m³)

n_e and T_e (763 W, 10 mT, 100 sccm Cl_2)

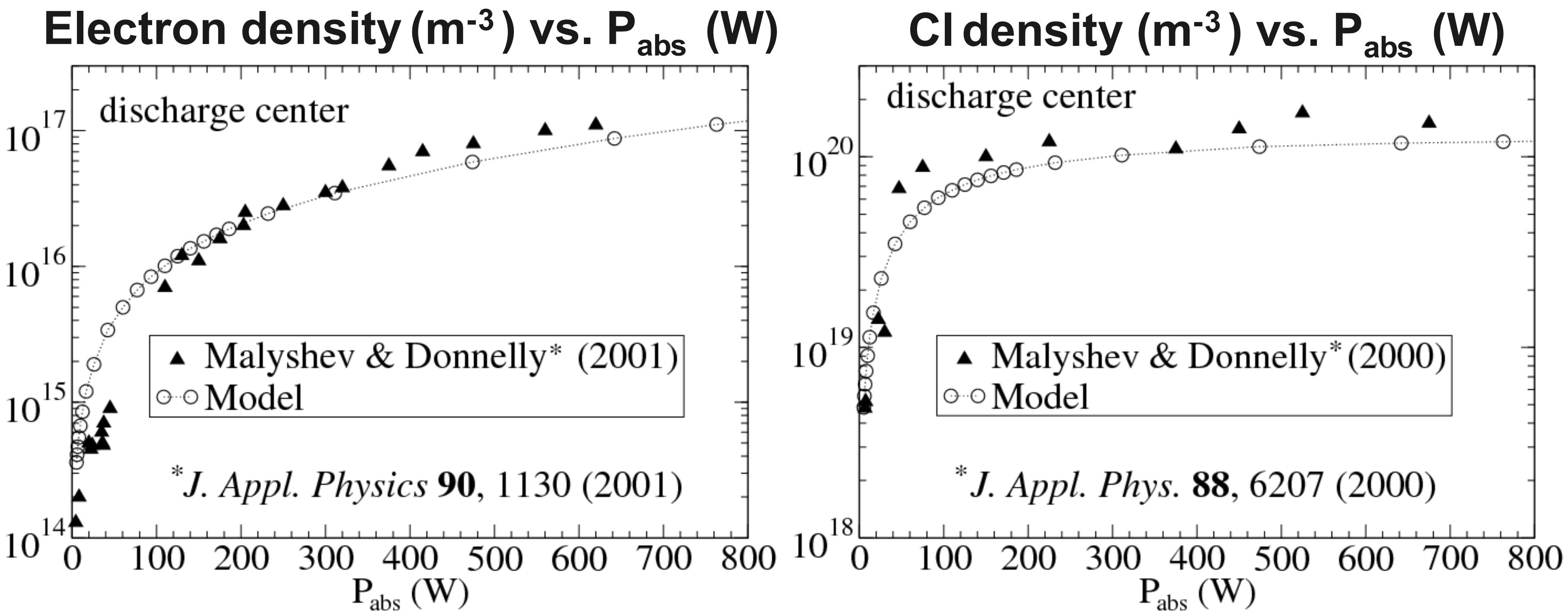
Electron Density (m^{-3})



Electron Temperature (V)



Model vs. Experiment (10 mT, 100 sccm Cl_2)



Electron density (m^{-3}) vs. P_{abs} (W)

Cl density (m^{-3}) vs. P_{abs} (W)

J. Appl. Physics* **90, 1130 (2001)

J. Appl. Phys.* **88, 6207 (2000)

- P_{abs} /P_{rf} = 0.75 for Malyshev & Donnelly reactor.

(Hopwood, *PSST* **3**, 460 1994)

- Cl recombination coefficient = 0.02 at walls.

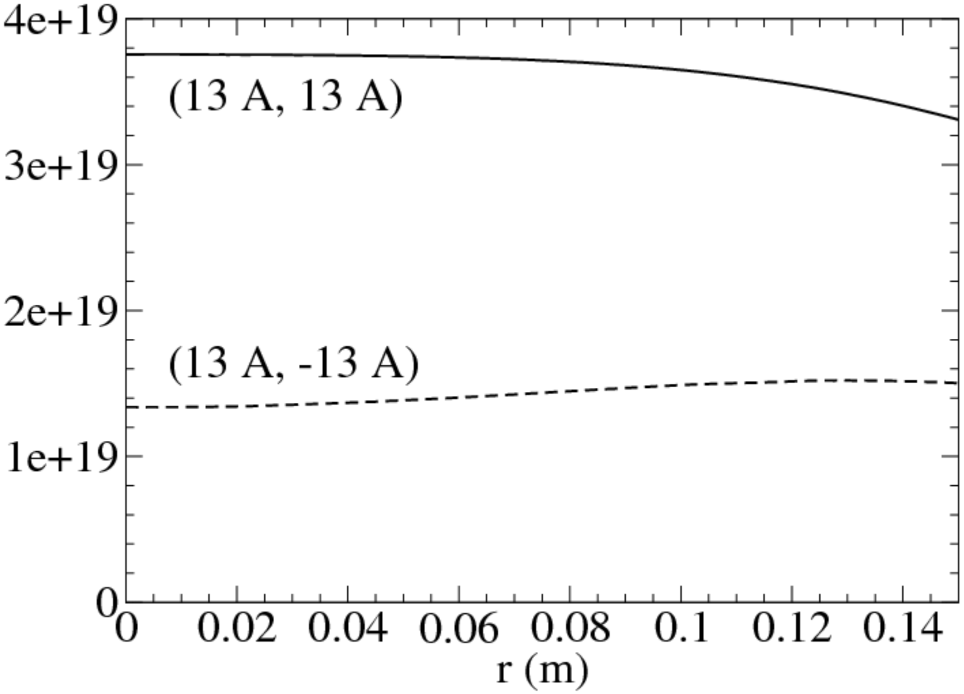
(Corr et al, *J. Phys. D*. **41**, 185202, 2008)

Uniformity in a Two Coil Set TCP Reactor

10 mTorr, 200 sccm ***two*** coil set Cl_2 TCP reactor with $I_{1in} = \pm I_{2in}$

- I_{1in} = 13 A = I_{2in}, P_{abs} = 923 W, P_{cap} = 116 W, P_{ind} = 807 W
- I_{1in} = 13 A = $-I_{2in}$, P_{abs} = 431 W, P_{cap} = 81 W, P_{ind} = 350 W

Cl_2 ion flux at wafer (m^{-2}/s)



Reverse currents control uniformity by suppressing inductive mode

Conclusions

- Hybrid fluid-analytical TCP Reactor Model allows fast computation of chemically active plasmas with flow and calculates both the inductive and capacitive fields.
- Capacitive fields → sheath width and voltage → electron and ion sheath heating → etch rate predictions.
- As P_{abs} rises, inductive coupling, plasma density, gas heating, and Cl_2 dissociation all rise.
- TCP Reactor Model shows good agreement with Malyshev and Donnelly's experimental data.
- Next steps include more chemistries (currently Ar, O_2, Cl_2), multi-frequency sheath and matching network models, and coupling with particle codes to get IEDs and IADs at the wafer.