INVESTIGATION OF AXIALLY FLOWING He/O_2 PLASMAS FOR OXYGEN-IODINE LASERS*

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AGENDA

- Introduction
    - Conventional vs. discharge COILs
    - Previous modeling

- Description of model
    - Axial flowing plasma kinetics model
    - Reaction mechanism

- Results
    - Yield scaling with energy deposition
    - Axial propagation of plasma zone
    - Pulse modulated rf discharges

- Conclusion

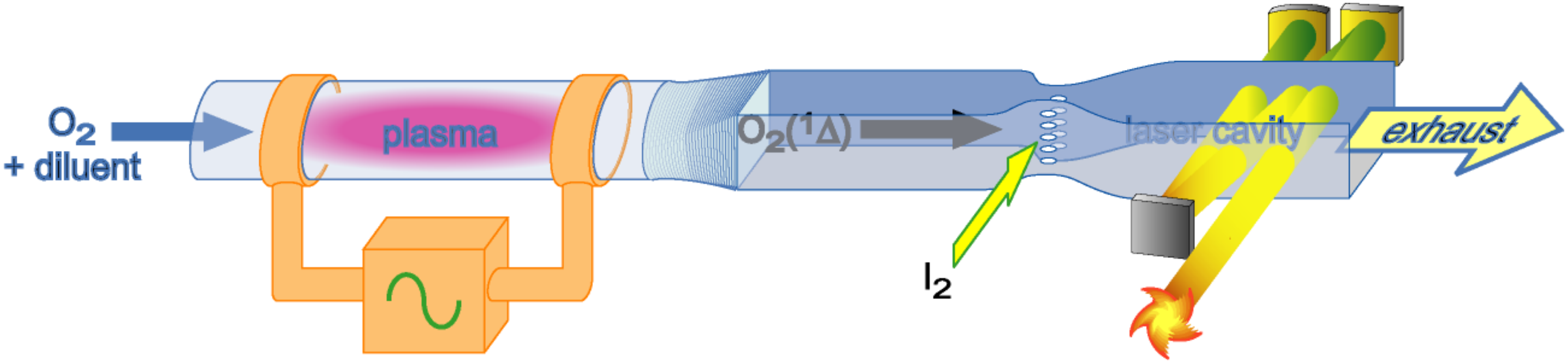
OXYGEN-IODINE LASERS

- $O_2(^1\Delta)$ dissociates I_2 and pumps I which lases on the $^2P_{1/2} \rightarrow {}^2P_{3/2}$ electronic transition.

$$O_2(^1\Delta) + I(^2P_{3/2}) \leftrightarrow O_2(^3\Sigma) + I(^2P_{1/2})$$

$$I(^2P_{1/2}) \rightarrow I(^2P_{3/2}) + h\nu \qquad (1.315\ \mu m)$$

- Conventional COILs obtain $O_2(^1\Delta)$ from a liquid phase reaction.
- Electrical COILs obtain $O_2(^1\Delta)$ by exciting O_2 in discharge.



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ELECTRIC DISCHARGE COIL MODELING

- **Zero-dimensional plug flow modeling results**
  - **$O_2(^1\Delta)$ yield scales with specific energy deposition into O_2 species, peaking near 5–8 eV/molecule.**
  - **Threshold yields of ~15%* have been demonstrated with adequate specific energy deposition.**

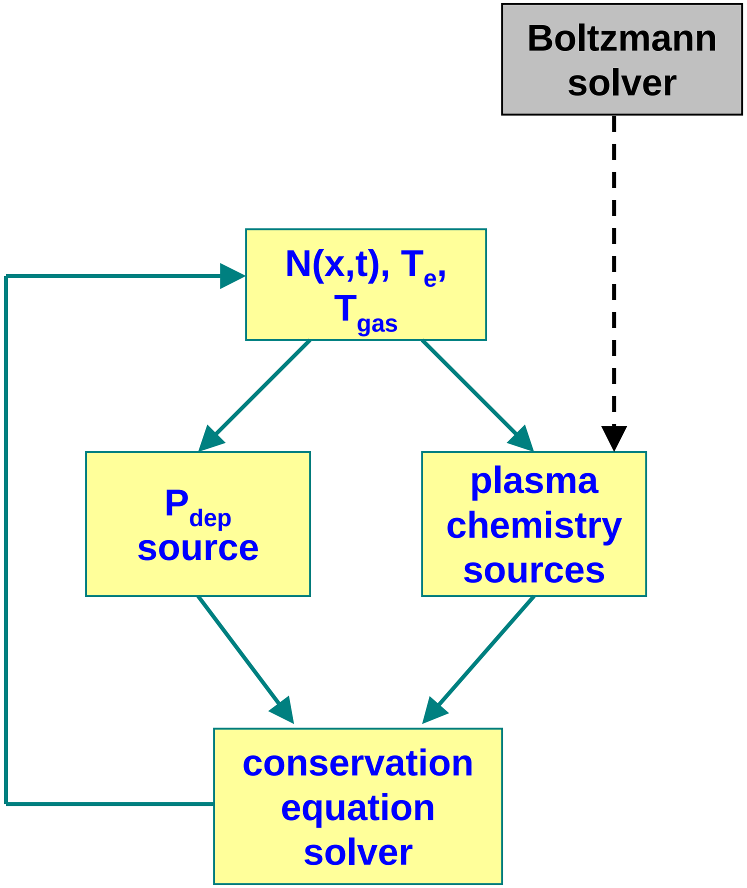
- **Further modeling needs**
  - **Axial-transport of species and effect on discharge kinetics.**
  - **Upstream and downstream propagation of the plasma expanding the power deposition zone.**
  - **Differences between CCP and ICP power deposition are difficult to address with 0-D model.**

- **A one-dimensional axial model was developed to address these needs.**

***D. Carroll, *et. al*, Appl. Phys. L. 85(8), 2004.**

COMPUTATIONAL SCHEME

- Conservation equations for species densities, gas energy, and electron energy are advanced for 1-D axial flow.
- Source terms are computed by plasma kinetics module.
- Power depositions are computed by CCP and ICP modules.
- Boltzmann solver periodically updates e-impact rate and transport coefficients as a function of position.



AXIAL PLASMA MODEL

- **Conservation equations for species densities are solved for a constant mass flux:**

$$\rho\vec{v} = const. \qquad \frac{\partial N_i}{\partial t} = -\nabla \cdot \left[N_i\left(\vec{v} + \vec{v}_{diff,i} + \vec{v}_{drift,i}\right)\right] + S_i + W_i$$

- **Drift velocities are obtained by calculating the axial ambipolar electric field:**

$$\vec{E}_a = -\frac{\sum_i q_i N_i \vec{v}_{diff,i}}{\sum_i q_i^2 \mu_i N_i}$$

- **Gas and electron energy equations are integrated:**

$$\rho c_P \frac{\partial T}{\partial t} = -\rho\vec{v} c_P \cdot \nabla T - \nabla \cdot \vec{q} - \tau_{zz} \nabla \cdot \vec{v} + \frac{Dp}{Dt} + \frac{\kappa}{\Lambda^2}\left(T_{wall} - T_{gas}\right) + \Delta h_{rxn} + h_e$$

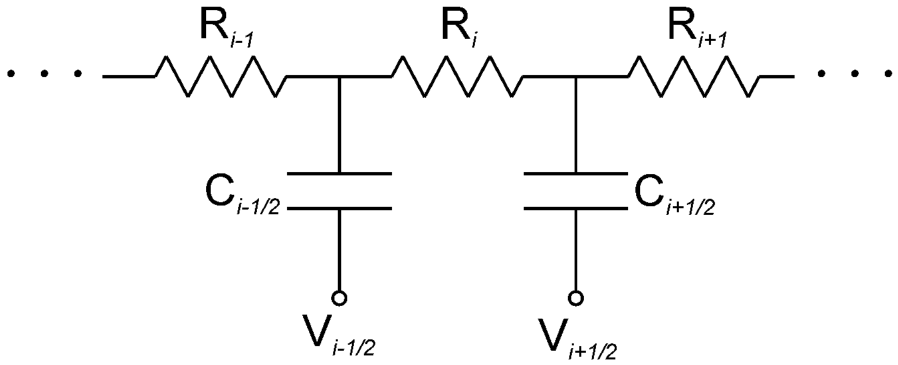
$$\frac{\partial\left(\frac{3}{2} n_e k_B T_e\right)}{\partial t} = -\nabla \cdot \vec{q}_e + P_d - h_e + \sum_l n_e k_l N_l \Delta\varepsilon_l$$

POWER DEPOSITION MODELS

- **ICP module estimates axial magnetic field from coils wound on discharge tube and includes skin depth effect:**

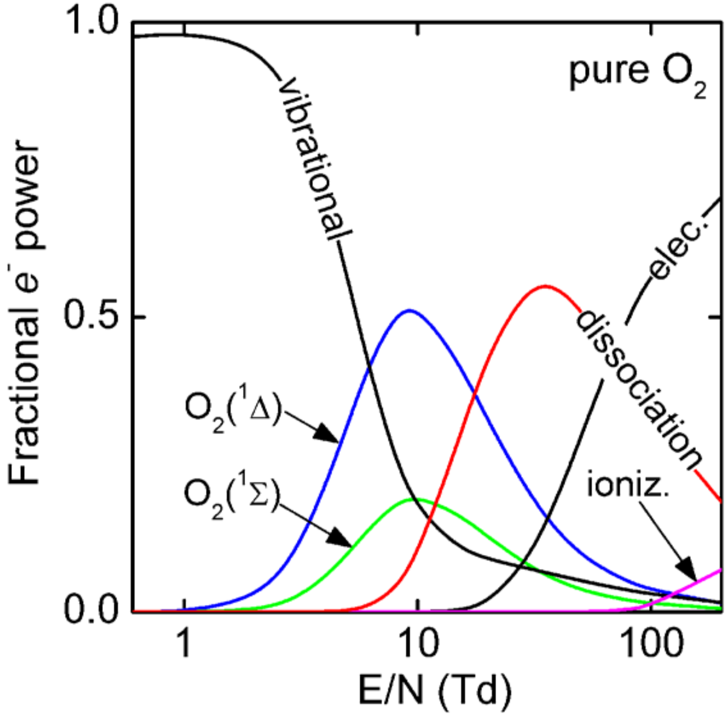
$$B_i = \sum_{j}^{N} \frac{2\mu_0 R^2 I}{4r_{ij}^3} \exp\left(\frac{-r_{ij}}{\delta_{ij}}\right)$$

- **CCP module models the discharge as a transmission line, where each grid point represents a node:**



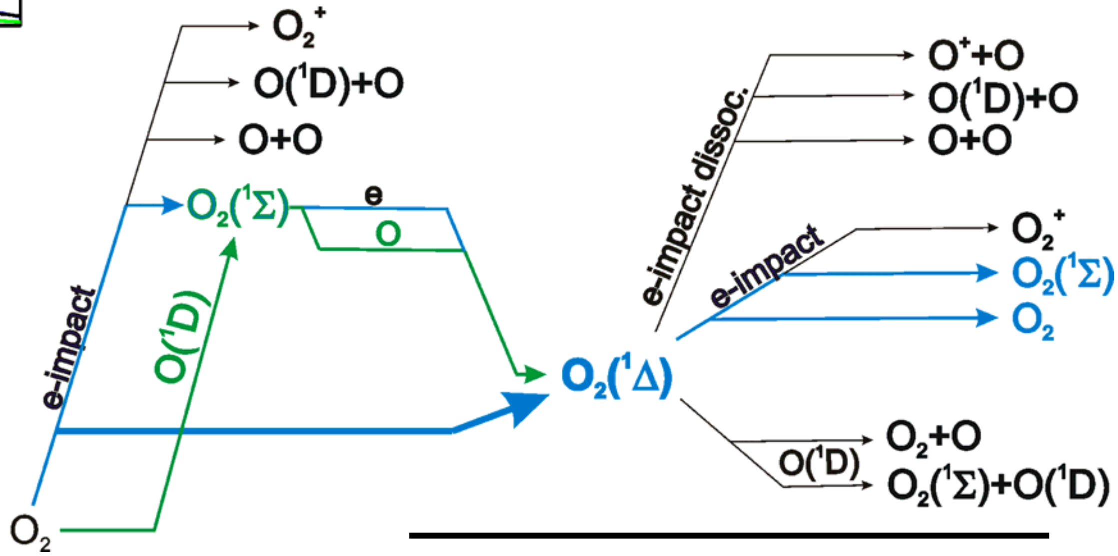
$$P_{d,i} = \Re\left(\frac{V_{R,i} V_{R,i}^*}{R_i}\right)$$

REACTION MECHANISM

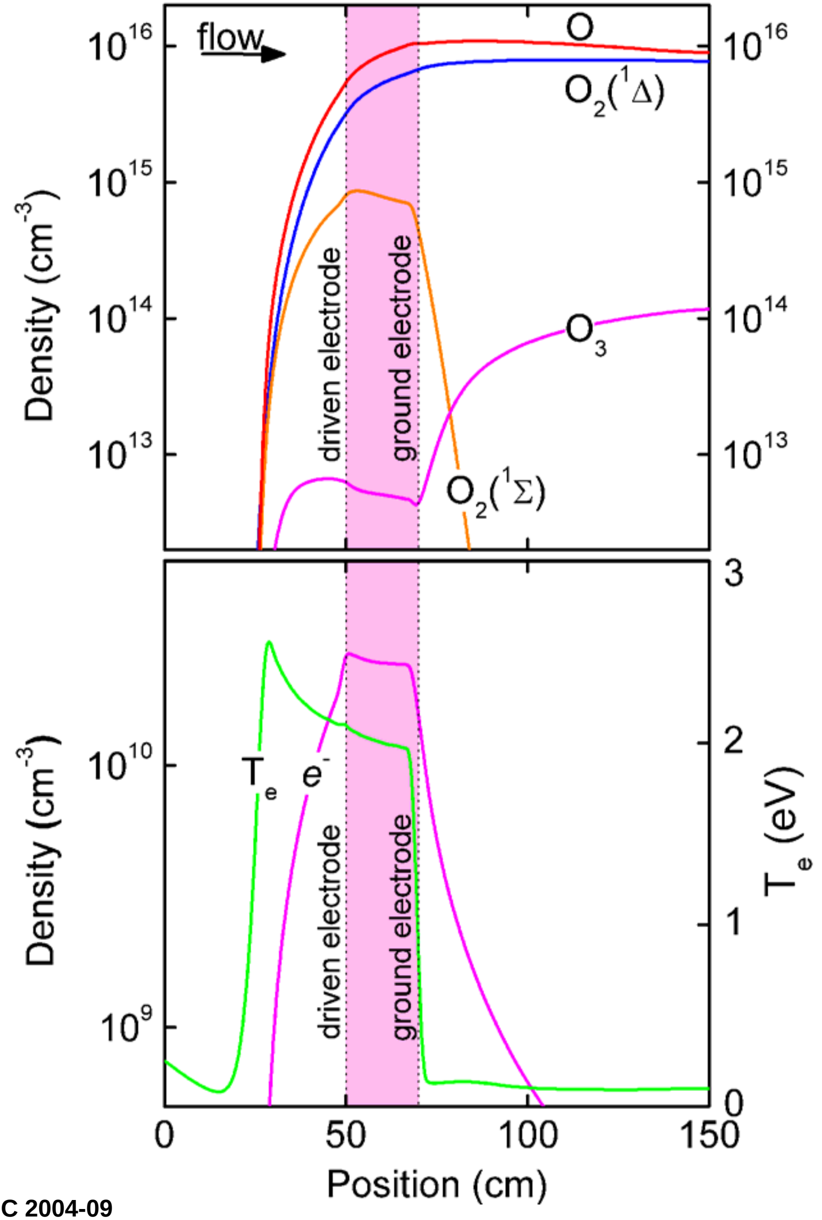


- **Discharge kinetics are dominated by e-impact excitation of $O_2(^3\Sigma)$ to $O_2(^1\Delta)$, and by excitation and dissociation of $O_2(^1\Delta)$.**

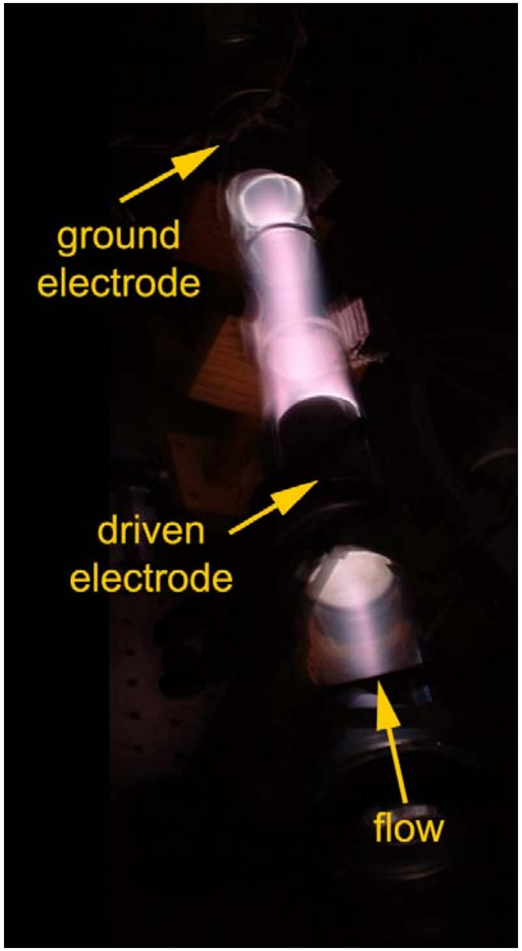
- **Recent efforts have focused on reducing the operating E/N to improve efficiency of $O_2(^1\Delta)$ production.**



BASE CASE: ElectriCOIL EXPERIMENT



20 mmol/s of He/O_2=8/2 at 10.6 Torr.
Power = 340 W CCP at 13.56 MHz.



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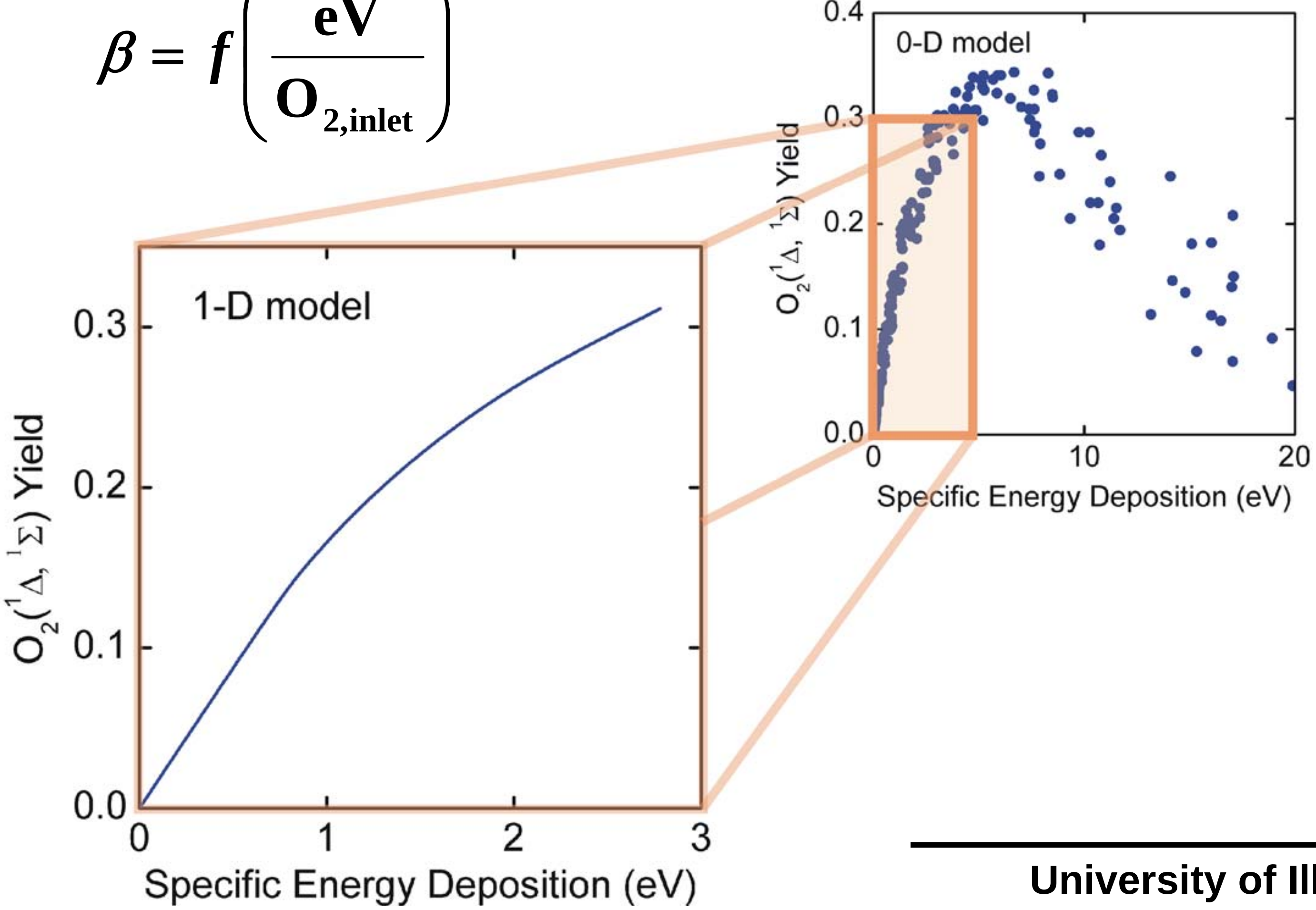
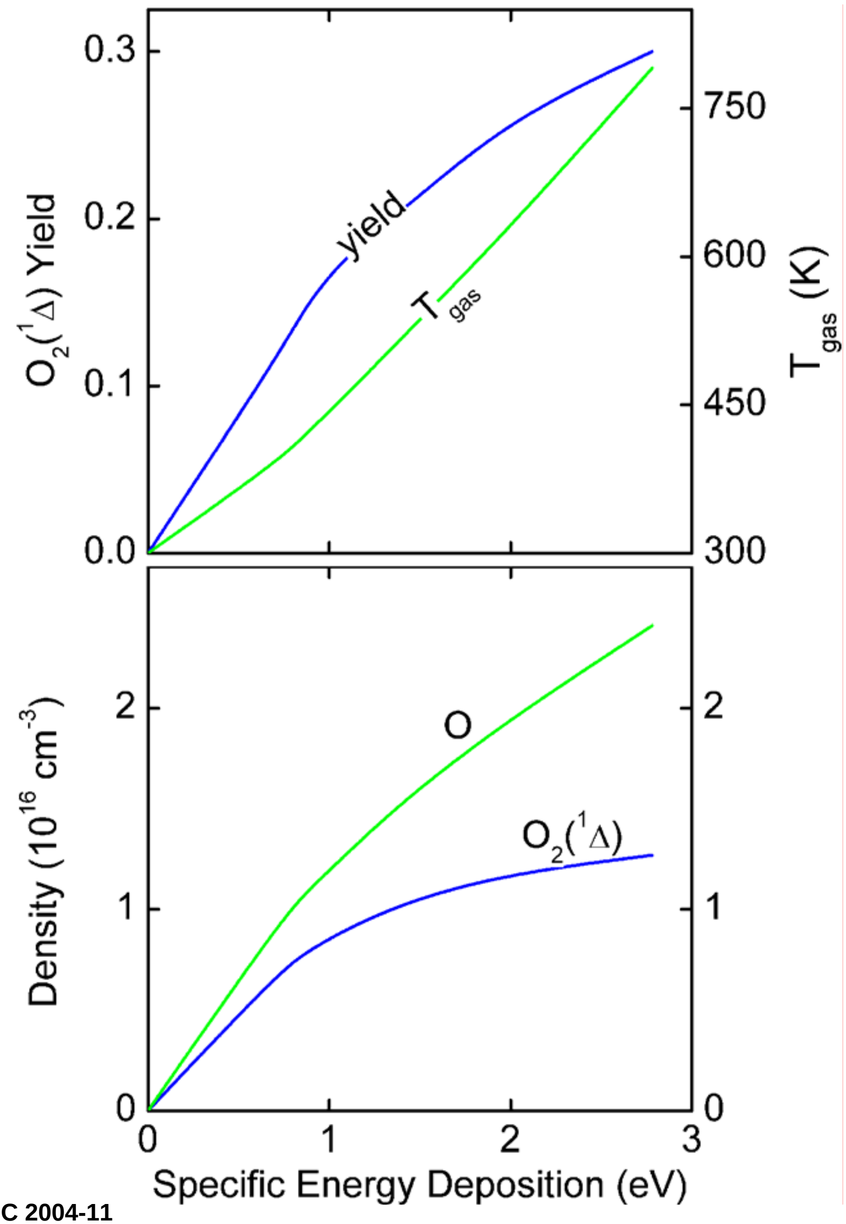
SPECIFIC ENERGY DEPOSITION SCALING

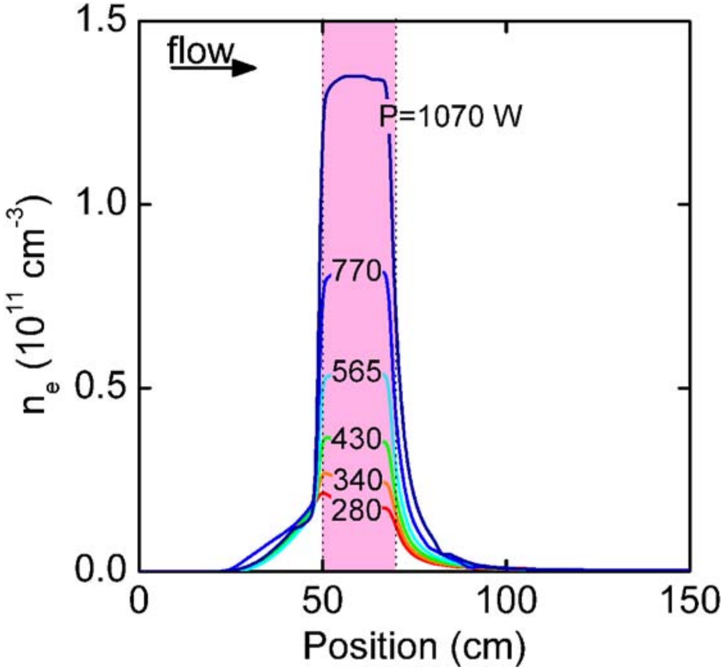
- $O_2(^1\Delta)$ yield scales with specific energy input to O_2 species as predicted by 0-D model.

$$\beta = f\left(\frac{\mathrm{eV}}{\mathrm{O}_{2,\mathrm{inlet}}}\right)$$



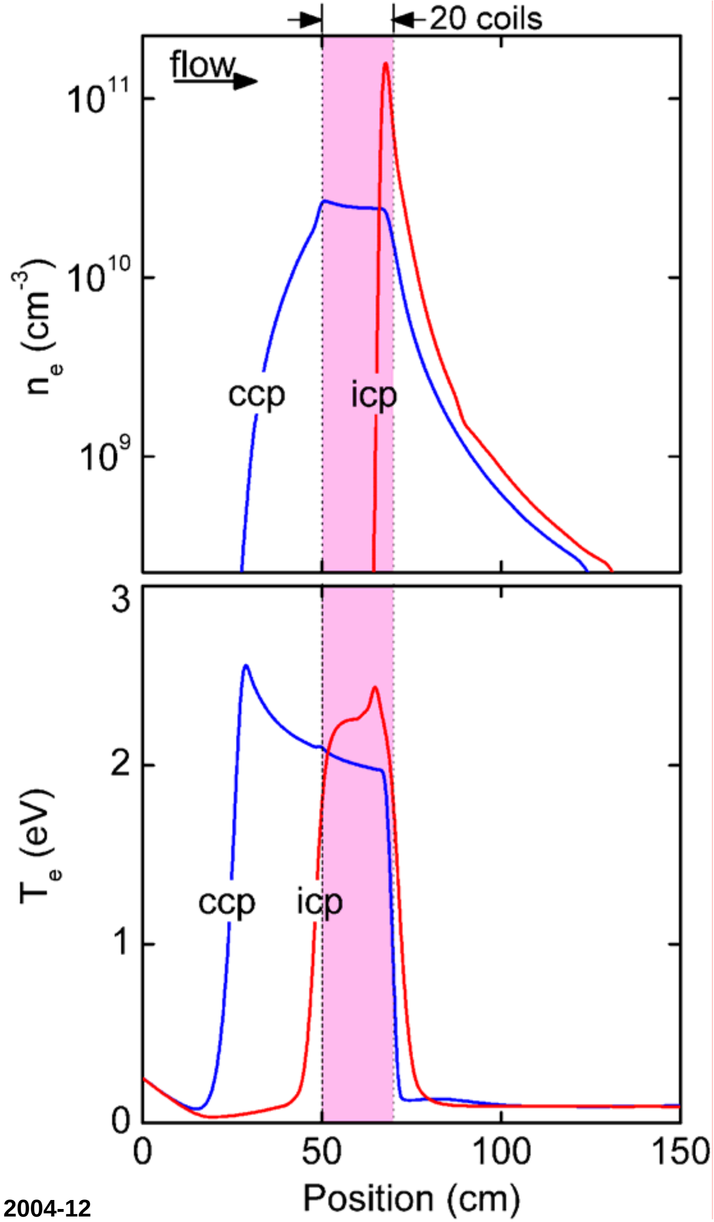
EFFECT OF CCP POWER

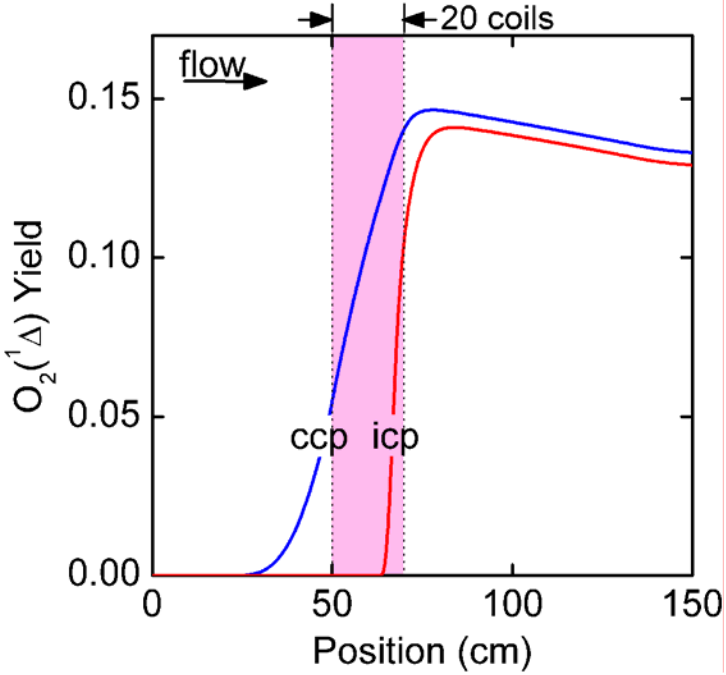




- **Dissociation increases at large specific energy, reducing the efficiency of $O_2(^1\Delta)$ production.**
- **Increased conductivity causes plasma zone to spread at higher powers.**

ICP vs CCP





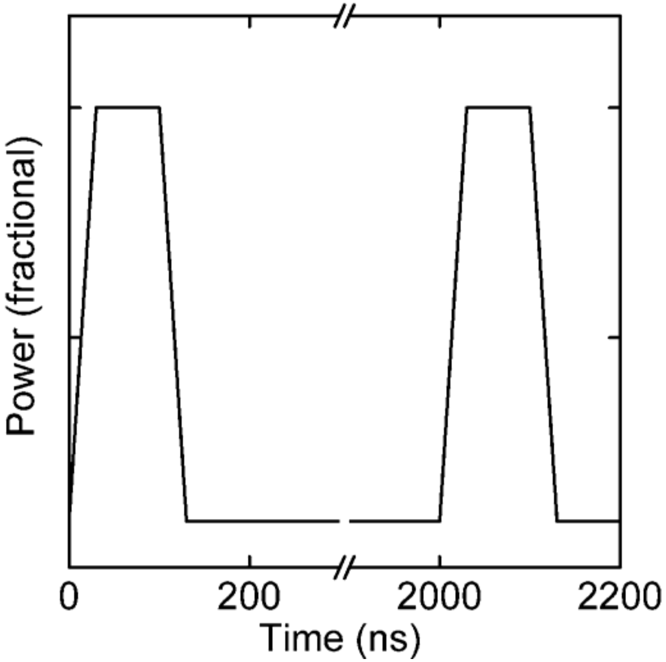
- **CCP T_e, n_e maximize production rate of $O_2(^1\Delta)$ relative to ICP:**

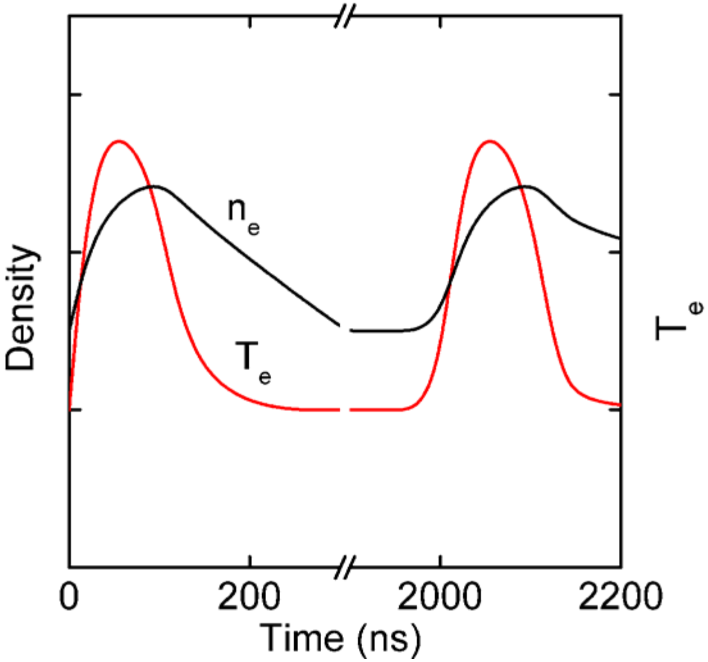
$$\text{rate} \propto \int_{\text{distance}} n_e(x) k_{rate}(T_e(x))\, dx$$

20 mmol/s, He/O_2=8/2 at 10.6 Torr.
Power = 340 W (0.88 eV/molecule).

PULSED CCP

- **Pre-ionizing the plasma with a high power pulse allows discharge to operate below the self-sustained E/N, nearer to the optimal E/N for $O_2(^1\Delta)$ production.**
- **Overall efficiency of pre-ionization depends on the extent of pre-ionization and the delay between pulses.**





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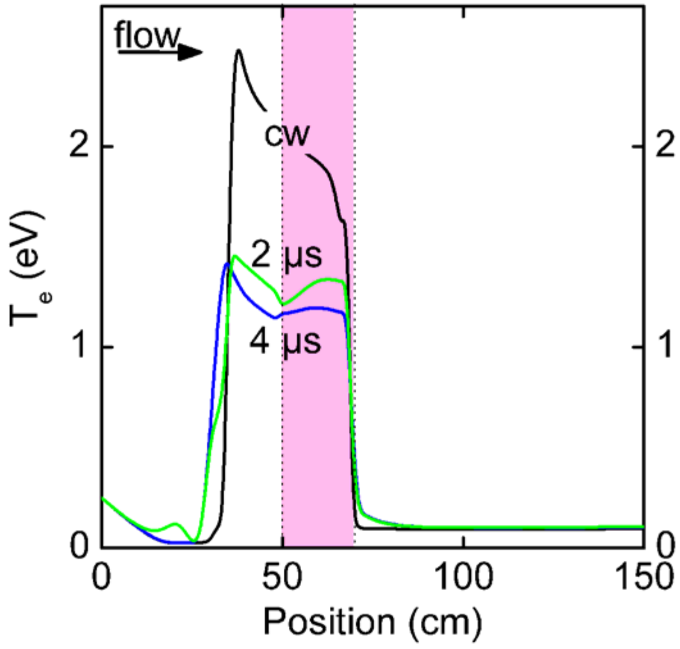
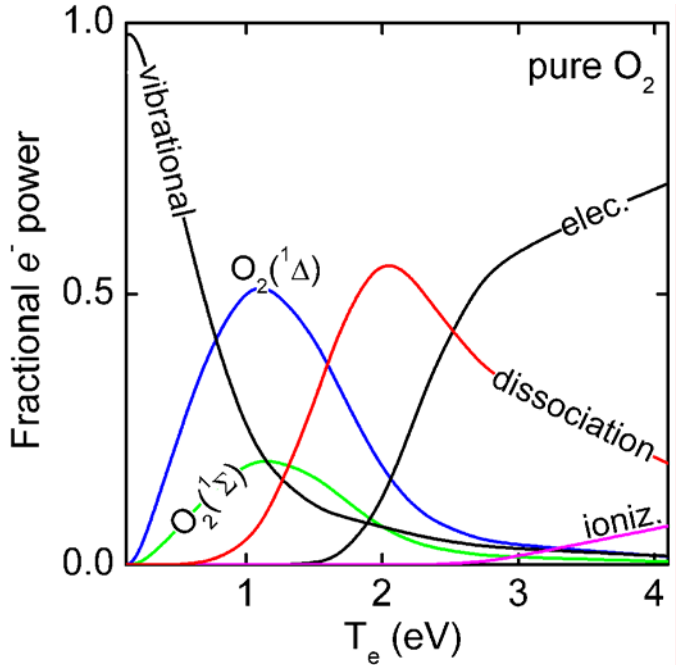
PULSED CCP: PULSE DELAY & AMPLITUDE

- **Average T_e of pulsed discharge is reduced ≈1 eV relative to cw discharge.**

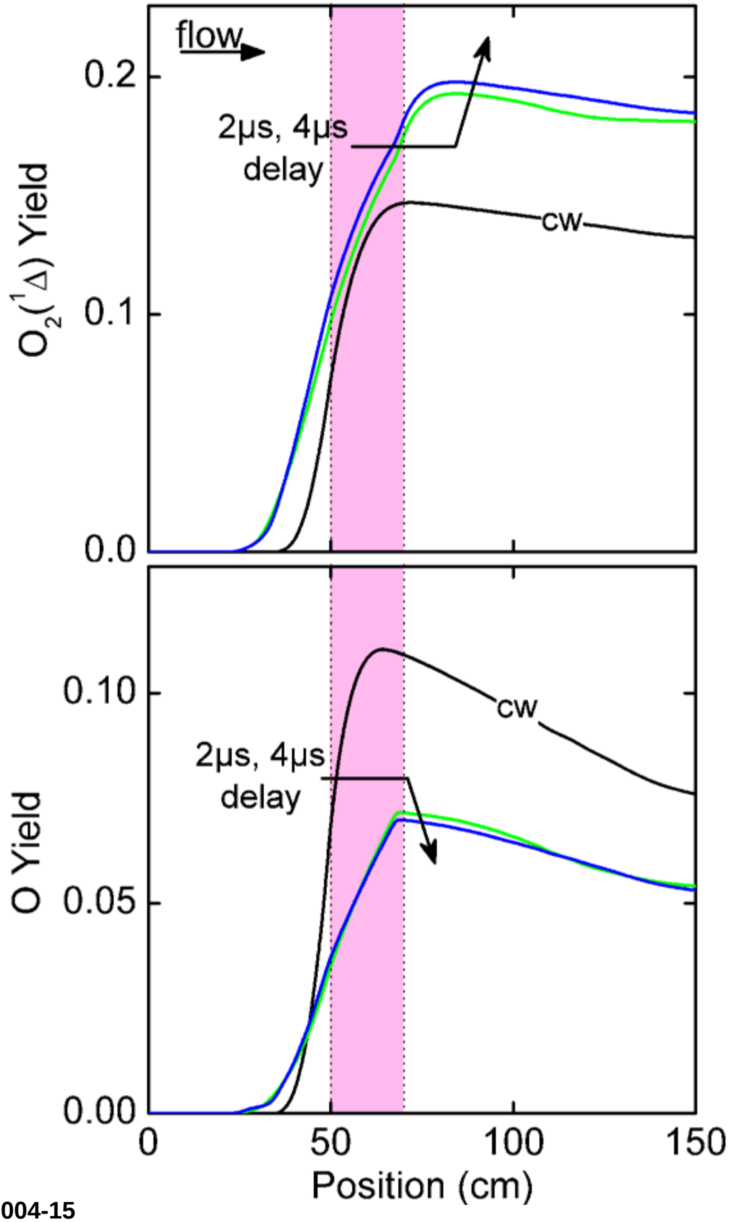
- **In cw discharge T_e is optimal for dissociation, but in pulsed discharge T_e is optimal for $O_2(^1\Delta)$ production.**





20 mmol/s, He/O_2=8/2 at 10.6 Torr.
Peak 2.5 kW, avg. 340 W CCP at 100 MHz.

PULSED CCP vs. CW



- **Modest pulsing schemes significantly outperform cw discharges at these conditions.**

- **Pulsing reduces the average T_e (and E/N), increasing $O_2(^1\Delta)$ production and reducing dissociation to O atoms.**

20 mmol/s, He/O_2=8/2 at 10.6 Torr.
Peak 2.5 kW, avg. 340 W CCP at 100 MHz.

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CONCLUSIONS

- **A 1-D axially flowing discharge model was developed to investigate the effects of axial transport on $O_2(^1\Delta)$ yields.**

- **Conservation equations for species densities, gas energy, and electron energy were solved.**

- **$O_2(^1\Delta)$ yield in rf ICP and CCP discharges was found to scale with specific energy deposition into O_2 species.**

- **CCP discharges produced somewhat higher $O_2(^1\Delta)$ yields than ICP discharges due to their broader power deposition zone.**

- **Pulsed discharges using a high power pre-ionizing pulse produced the highest yields, ≈50% higher than CCP, by reducing the T_e below the self-sustaining value.**

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