INVESTIGATION OF AXIALLY FLOWING He/O₂ 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

- $\text{O}_2(^1\Delta)$ dissociates $\text{I}_2$ and pumps it which lases on the $^2P_{1/2} \rightarrow ^2P_{3/2}$ electronic transition.

  $$\text{O}_2(^1\Delta) + \text{I}(^2P_{3/2}) \leftrightarrow \text{O}_2(^3\Sigma) + \text{I}(^2P_{1/2})$$

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

- Conventional COILs obtain $\text{O}_2(^1\Delta)$ from a liquid phase reaction.

- Electrical COILs obtain $\text{O}_2(^1\Delta)$ by exciting $\text{O}_2$ 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 $\sim 15\%$* 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.

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

- Drift velocities are obtained by calculating the axial ambipolar electric field:
  \[ \bar{E}_a = - \sum_i \frac{q_i N_i \bar{v}_{\text{diff},i}}{\sum_i q_i^2 \mu_i N_i} \]

- Gas and electron energy equations are integrated:
  \[ \rho c_p \frac{\partial T}{\partial t} = - \rho \bar{v} c_p \cdot \nabla T - \nabla \cdot \bar{q} - \tau_{zz} \nabla \cdot \bar{v} + \frac{Dp}{Dt} + \frac{\kappa}{\Lambda^2} \left( T_{\text{wall}} - T_{\text{gas}} \right) + \Delta h_{\text{rxn}} + h_e \]
  \[ \frac{\partial}{\partial t} \left( \frac{3}{2} n_e k_B T_e \right) = -\nabla \cdot \bar{q}_e + P_d - h_e + \sum_l n_e k_l N_l \Delta \varepsilon_l \]
POWER DEPOSITION MODELS

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

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

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

\[ P_{d,i} = \Re\left(\frac{V_{R,i}V_{R,i}^*}{R_i}\right) \]
• 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/O₂=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.

$$\beta = f\left(\frac{eV}{O_2,\text{inlet}}\right)$$
• 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:

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

20 mmol/s, He/O$_2$=8/2 at 10.6 Torr. Power = 340 W (0.88 eV/molecule).

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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$_2$(^1Δ) production.

• Overall efficiency of pre-ionization depends on the extent of pre-ionization and the delay between pulses.
PULSED CCP: PULSE DELAY & AMPLITUDE

- Average $T_e$ of pulsed discharge is reduced $\approx 1$ 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 $O_2(\text{^1}\Delta)$ 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.
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, $\approx 50\%$ higher than CCP, by reducing the $T_e$ below the self-sustaining value.

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