PLASMA EXCITED CHEMICAL-OXYGEN-IODINE LASERS: OPTIMIZING INJECTION AND MIXING FOR POSITIVE GAIN*

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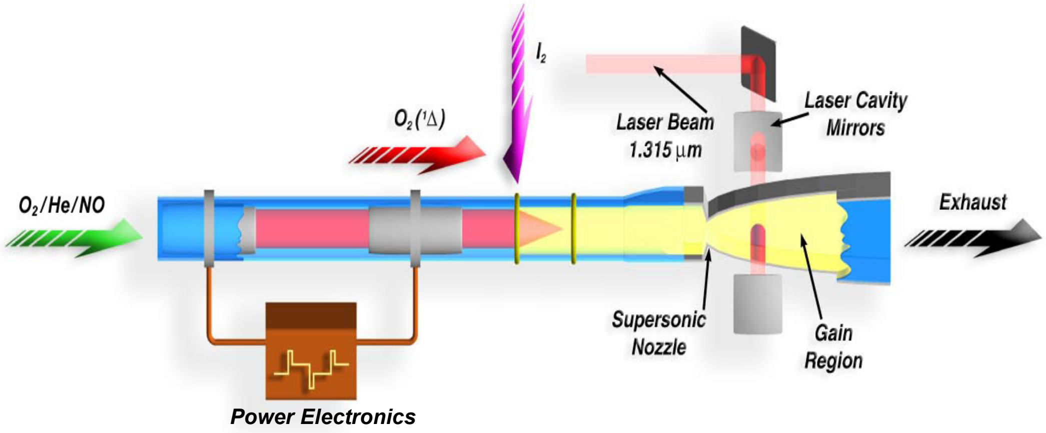
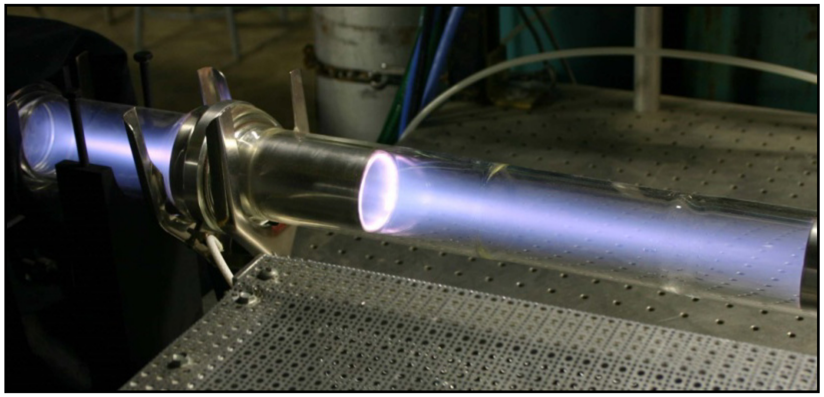
AGENDA

- Introduction to eCOIL
- Oxygen-iodine kinetics mechanism
- Description of model
- Gain and flow properties for I_2 injection strategies.
- Concluding Remarks

ELECTRICALLY EXCITED OXYGEN-IODINE LASERS

- In chemical oxygen-iodine lasers (COILs), oscillation at 1.315 µm $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ occurs by excitation transfer of $O_2(^1\Delta)$ to I_2 and I.
- Plasma production of $O_2(^1\Delta)$ in electrical COILs (eCOILs) eliminates liquid phase generators.

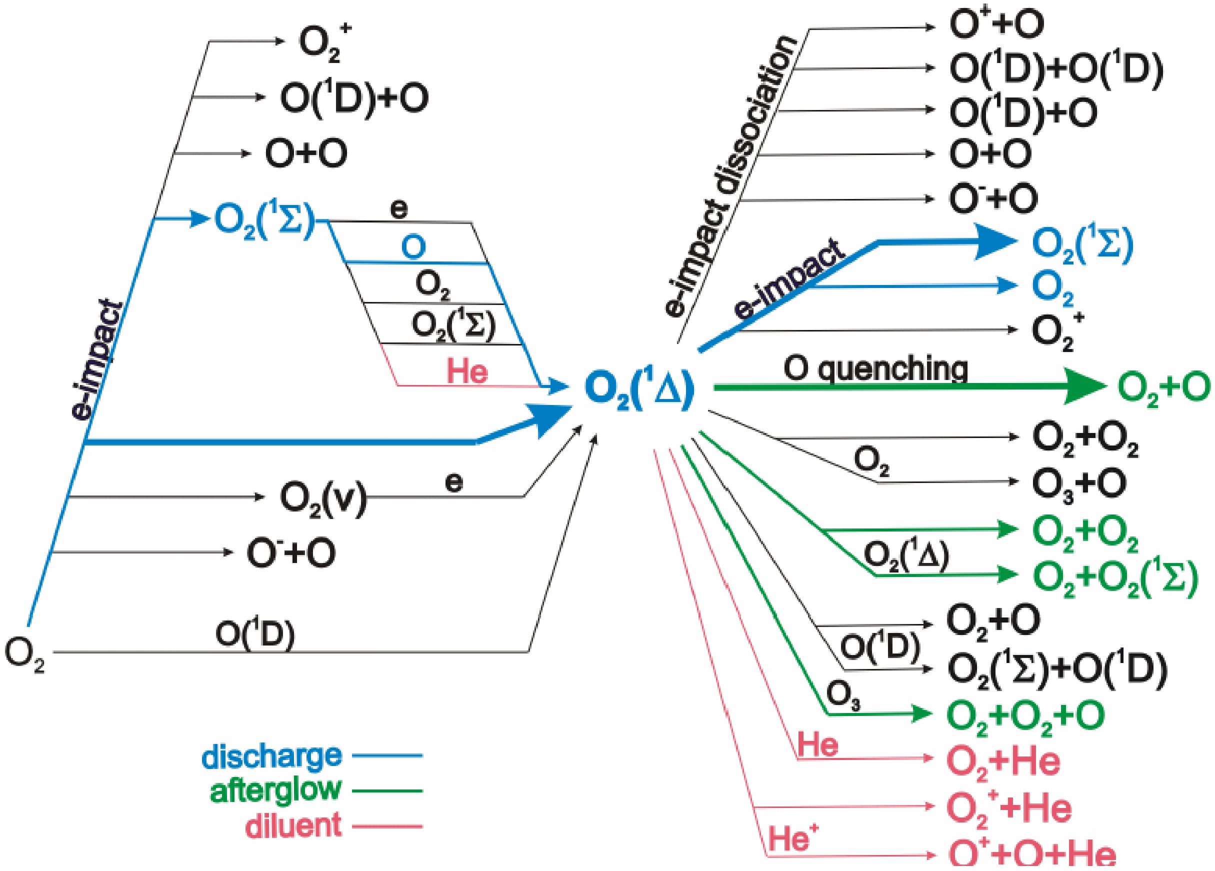




- I_2 injection and supersonic expansion (to lower T_{gas} for inversion) occurs downstream of the plasma zone.

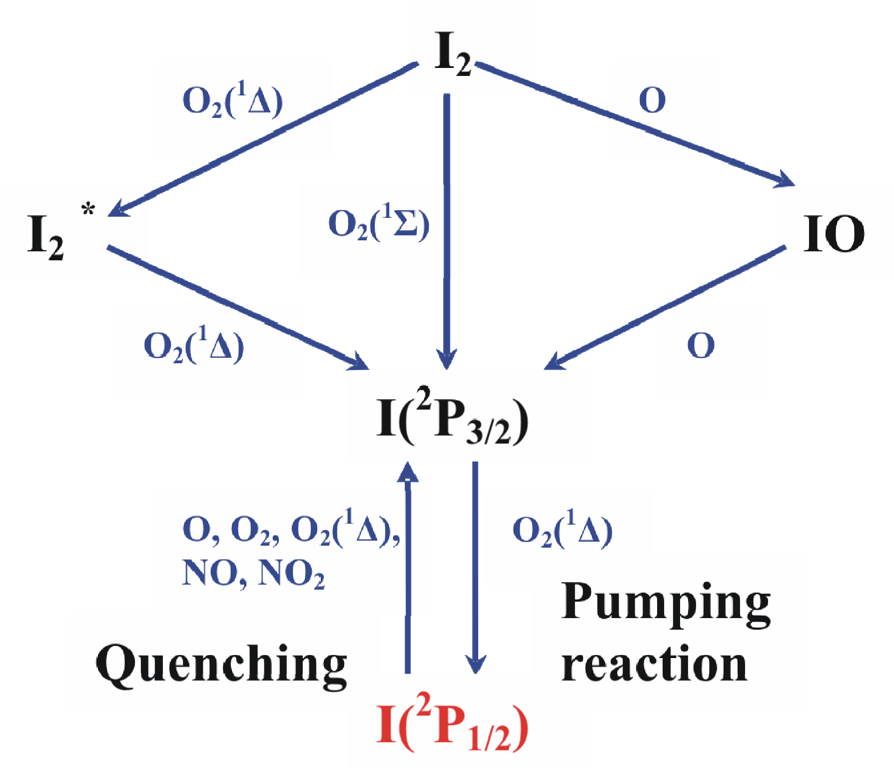
- Ref: CU Aerospace

$O_2(^1\Delta)$ KINETICS IN He/O_2 DISCHARGES



- Direct electron impact of excitation of O_2 to $O_2(^1\Delta)$ and $O_2(^1\Sigma)$ are main channels of $O_2(^1\Delta)$ production.
- Dissociation of O_2 limits $O_2(^1\Delta)$ production while O and O_3 are the main quenchers of $O_2(^1\Delta)$.

O_2-I_2 KINETICS



I_2

$O_2(^1\Delta)$

O

$I_2{}^*$

$O_2(^1\Sigma)$

IO

$O_2(^1\Delta)$

O

$I(^2P_{3/2})$

O, O_2, $O_2(^1\Delta)$, NO, NO_2

Quenching

$O_2(^1\Delta)$

Pumping reaction

$I(^2P_{1/2})$

- In conventional COILs, dissociation of I_2 is by excitation transfer from $O_2(^1\Delta, {}^1\Sigma)$.

$$I_2 + O_2\left(^1\Delta\right) \rightarrow I_2^* + O_2$$

$$I_2^* + O_2\left(^1\Delta\right) \rightarrow I\left(^2P_{3/2}\right) + I + O_2$$

$$I_2 + O_2\left(^1\Sigma\right) \rightarrow I\left(^2P_{3/2}\right) + I + O_2$$

- Excitation transfer from $O_2(^1\Delta)$ pumps the upper laser level.

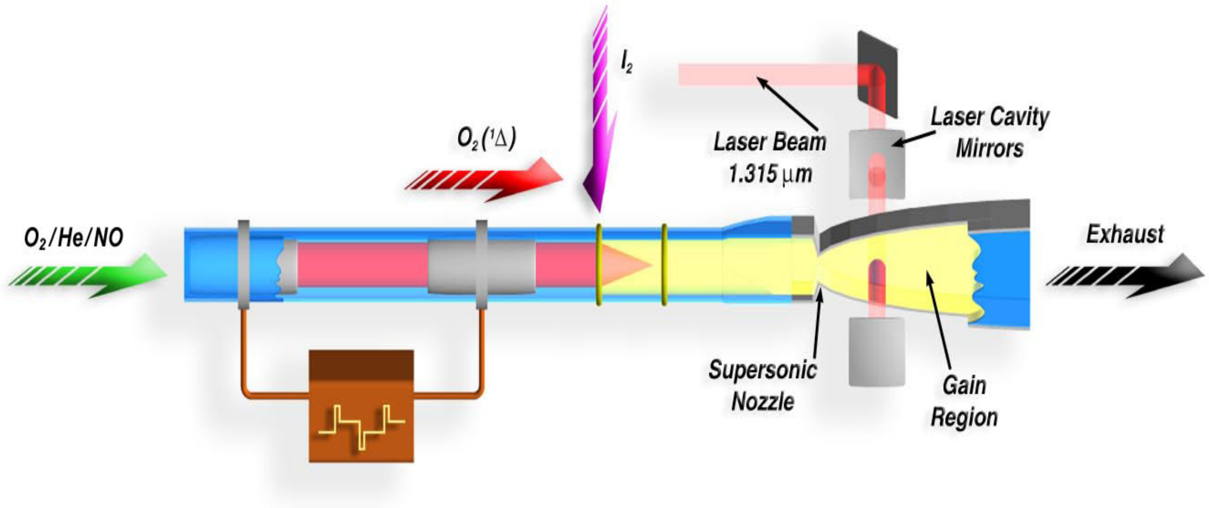
$$I\left(^2P_{3/2}\right) + O_2\left(^1\Delta\right) \rightarrow I\left(^2P_{1/2}\right) + O_2$$

- In eCOIL, O atoms additionally dissociate I_2 and quench $I(^2P_{1/2})$.

$$I_2 + O \rightarrow IO + I\left(^2P_{3/2}\right) \qquad I\left(^2P_{1/2}\right) + O \rightarrow O + I\left(^2P_{3/2}\right)$$

METHOD OF I_2 INJECTION

- In eCOILs, the strategy for I_2 injection is important to maximizing gain.



- Unlike conventional COIL, $O_2(^1\Delta)$, $O_2(^1\Sigma)$ and O are in the flow where I_2 is injected, thereby complicating the kinetics.
- In this talk, results from a computational investigation of I_2 injection in eCOILs will be discussed with the goal of maximizing gain.

- Ref: CU Aerospace

DESCRIPTION OF 2d-nonPDPSIM: CHARGED PARTICLES, SOURCES

- **Poisson's equation, continuity equations and surface charge are simultaneously solved using a Newton iteration technique.**

$$-\nabla\cdot\varepsilon\nabla\,\Phi=\sum_j N_j q_j+\rho_s$$

$$\frac{\partial N_j}{\partial t}=-\nabla\cdot\vec{\phi}_j+S_j$$

$$\frac{\partial\rho_s}{\partial t}=\sum_j -q_j(\nabla\cdot\vec{\phi}_j+S_j)-\nabla\cdot(\sigma(-\nabla\Phi))$$

- **Electron energy equation:**

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

DESCRIPTION OF 2d-nonPDPSIM: NEUTRAL PARTICLE TRANSPORT

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

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

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

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

- **Individual fluid species diffuse in the bulk fluid.**

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

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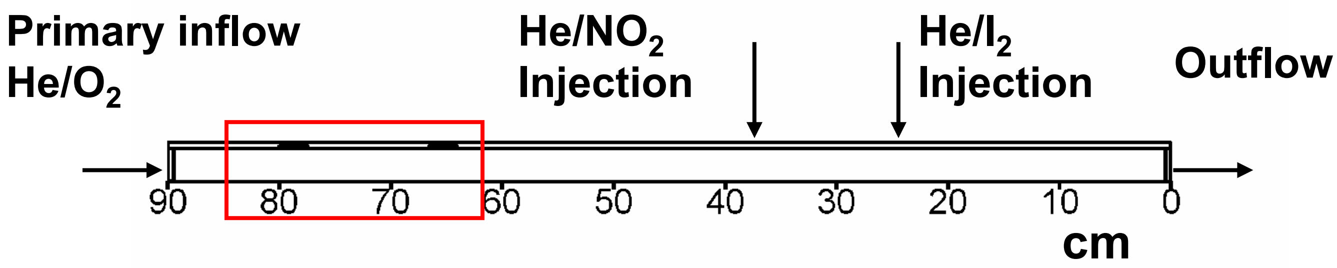
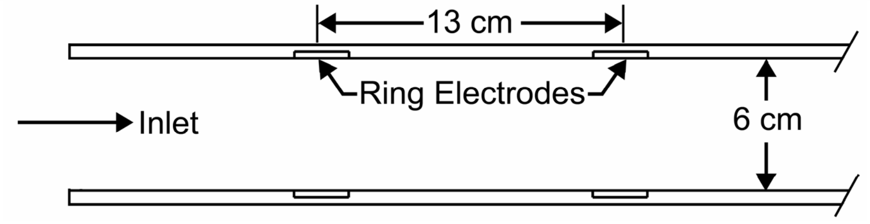
GEOMETRY AND CONDITIONS

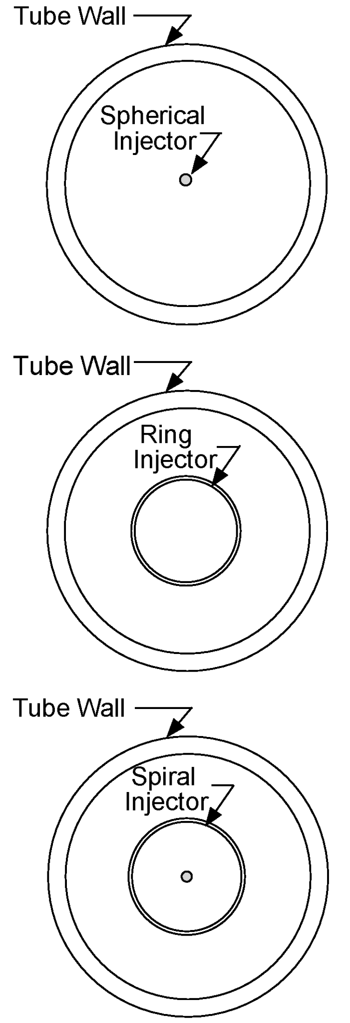




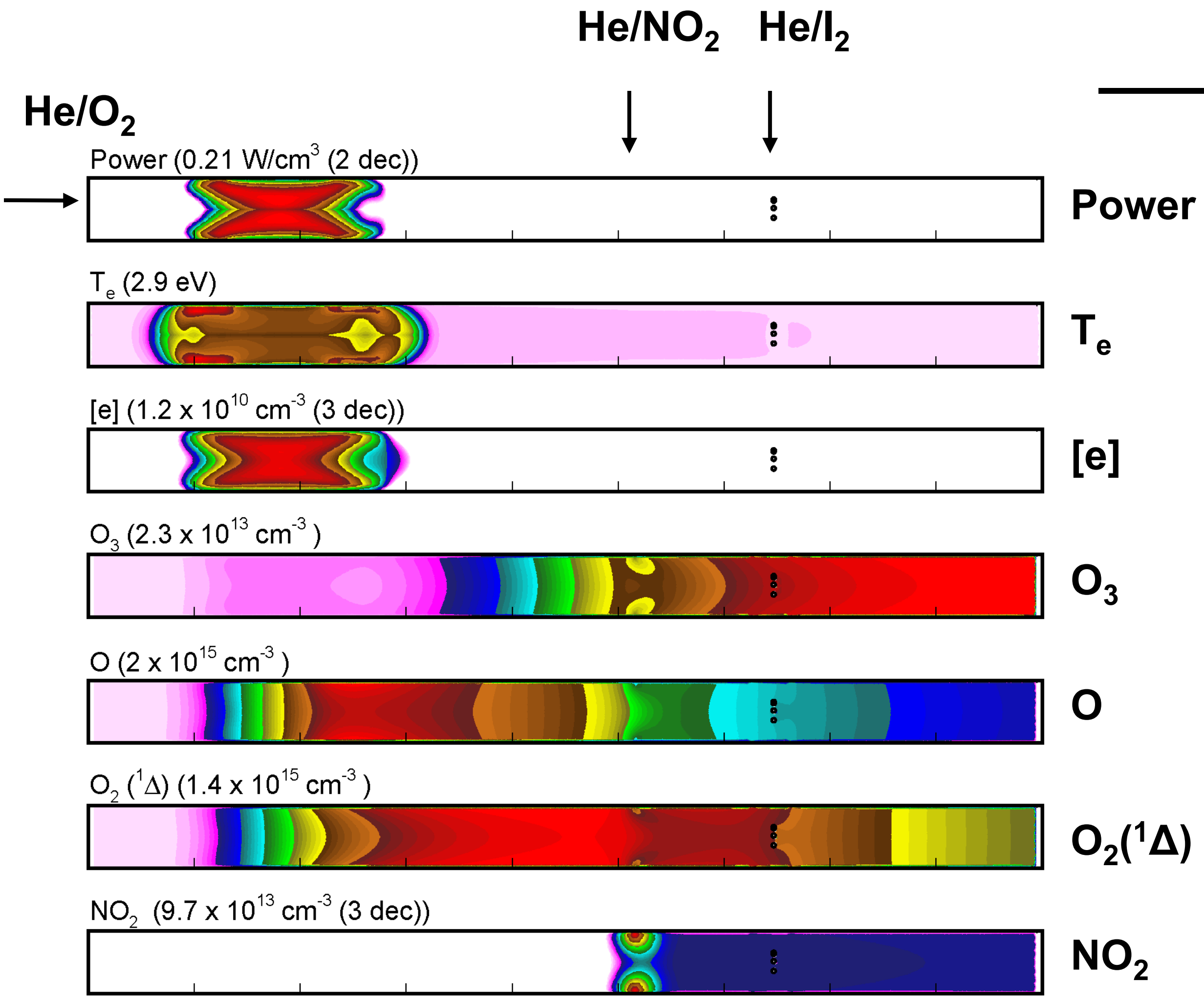
- Cylindrical flow tube 6 cm diameter
- Capacitive excitation (25 MHz) using ring electrodes.
- He/O_2=70/30, 3 Torr, 40 W, 6 lpm (980 cm/s, 60 ms residence time)
- NO_2 injection to control O atom inventory.
- "Cold" equivalent reaction rates for forward and backward reactions:

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

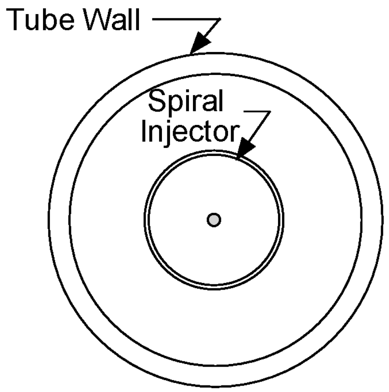
- I_2 Injectors



TYPICAL PLASMA PARAMETERS



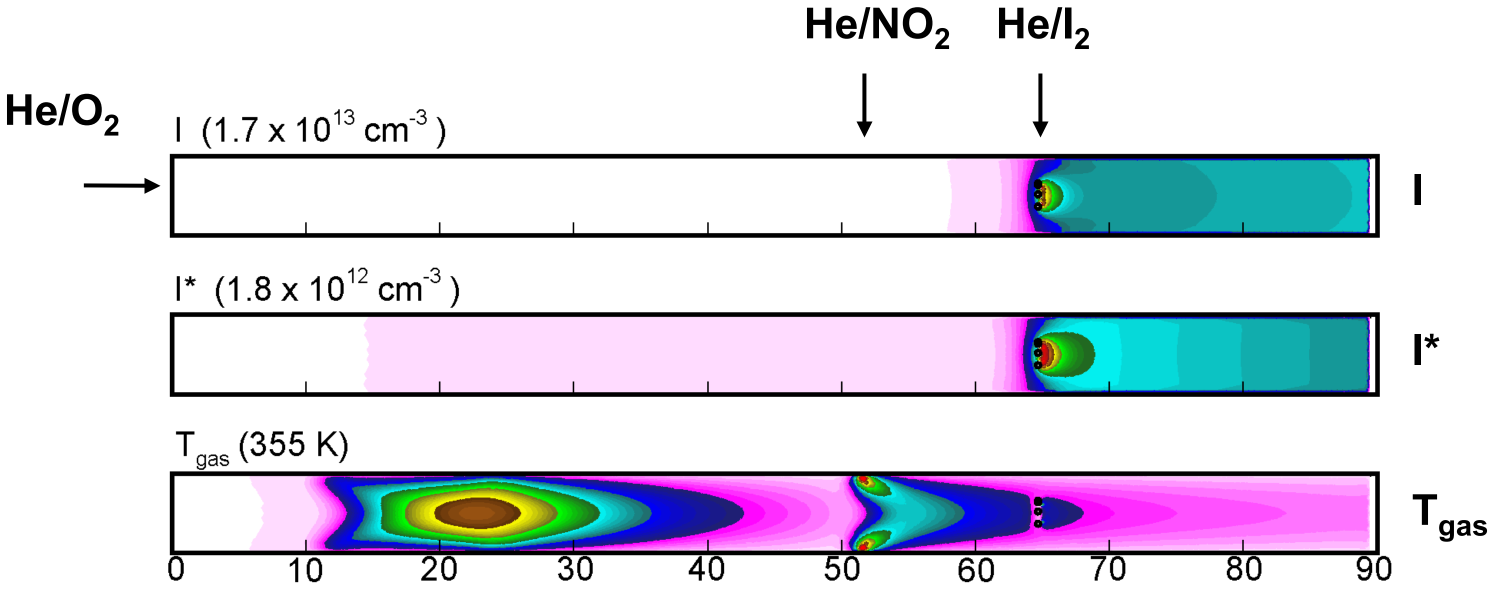
- [e] = 1.2 x 10^{10} cm^{-3}, T$_e$ = 2.9 eV
- O and O$_2$($^1\Delta$) reach 1-2 x 10^{15} cm^{-3} by electron impact.
- NO$_2$ injection throttles O density.



- Spiral I$_2$ Injector

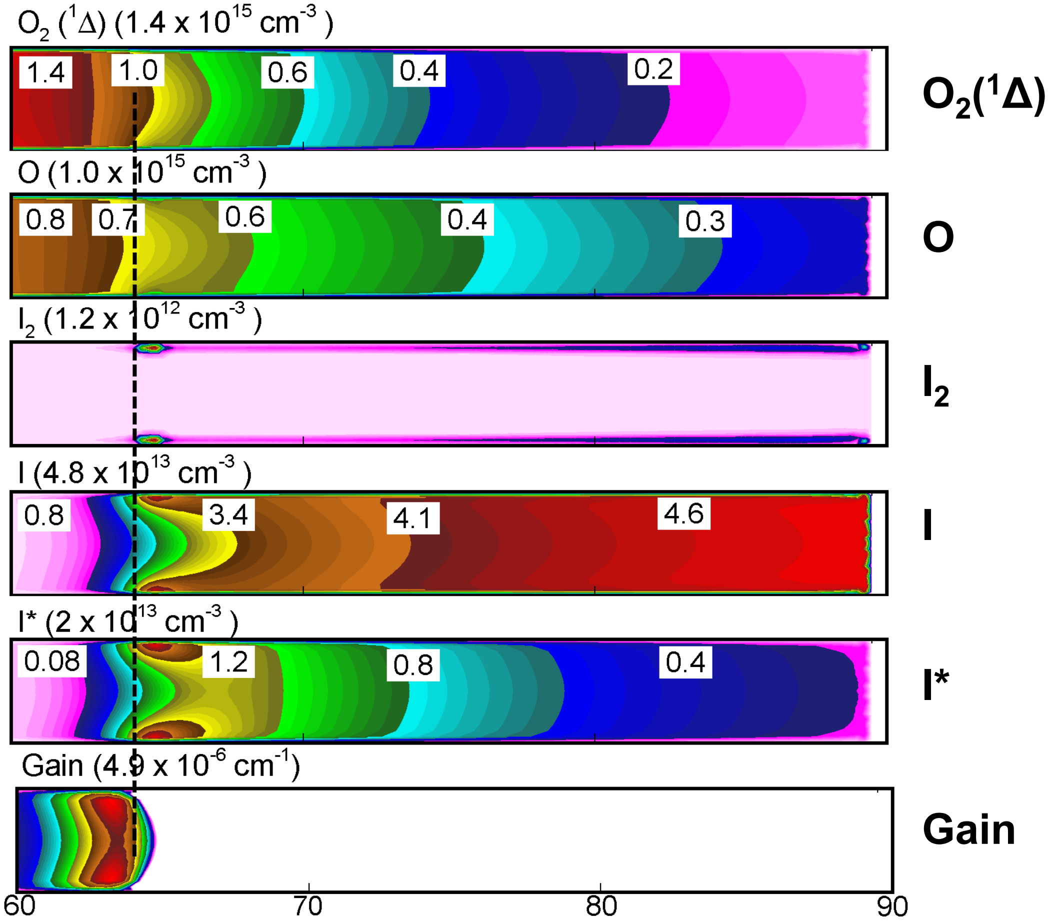
- He/O$_2$=70/30, 3 Torr, 40 W, 6 lpm: Injection: He/I$_2$=99.5/0.5, 36 sccm

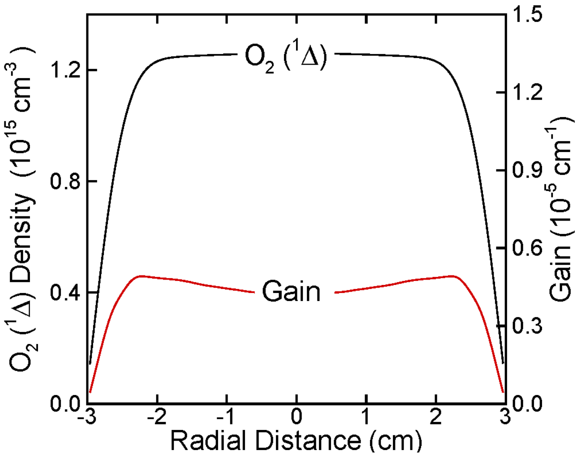
TYPICAL PLASMA PARAMETERS (cont.)

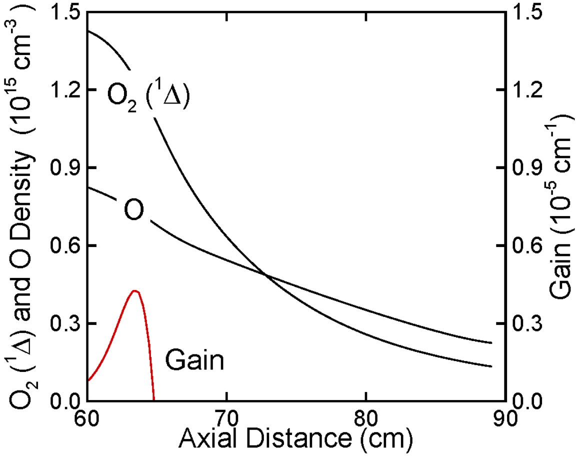


- I$_2$, injected through spiral coil on axis, is completely dissociated by reactions with O and O$_2$($^1\Delta$).
- I and I* peak near inlets.
- Two high temperature zones: Joule and Frank-Condon heating in discharge zone; and exothermic reactions from NO$_2$ injection.
  - He/O$_2$=70/30, 3 Torr, 40 W, 6 lpm: Injection: He/I$_2$=99.5/0.5, 36 sccm

I_2 WALL INJECTION

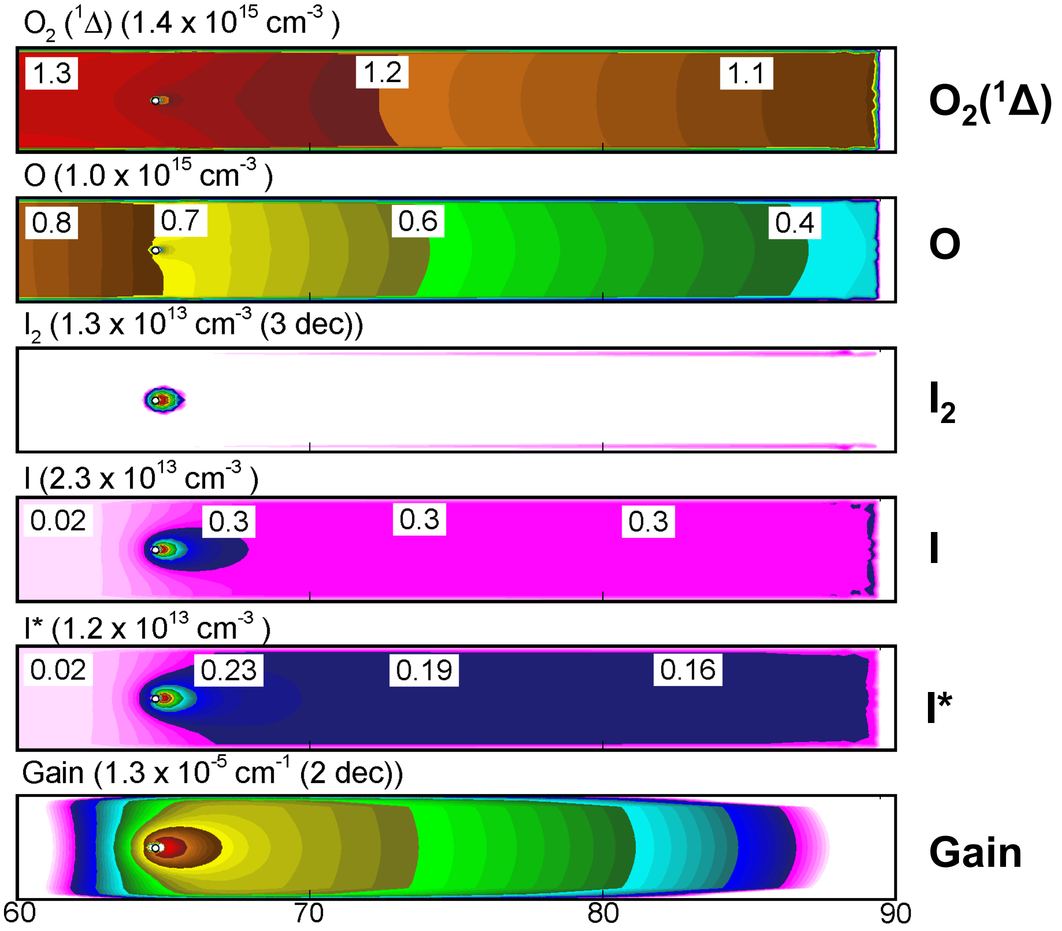






- **$O_2(^1\Delta)$ is depleted in pumping reaction. O totally dissociates I_2.**
- **I* maximum at injector due to O quenching and $O_2(^1\Delta)$ depletion.**
- **Small gain in a narrow layer upstream. Low utilization of $O_2(^1\Delta)$**

I_2 INJECTOR ON AXIS


O_2 ($^1\Delta$) (1.4 x 10^{15} cm^{-3})

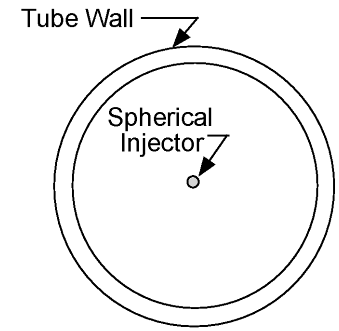
O (1.0 x 10^{15} cm^{-3})

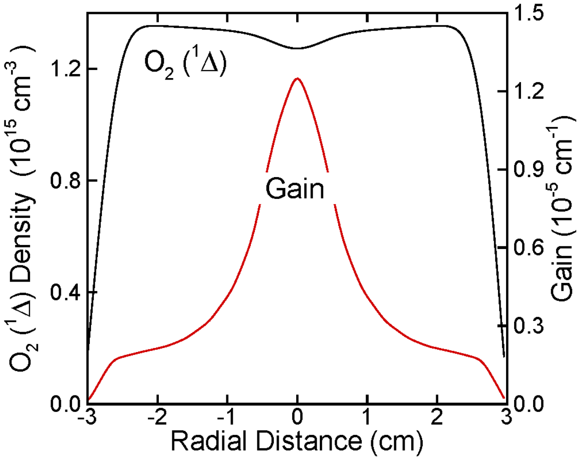
I_2 (1.3 x 10^{13} cm^{-3} (3 dec))

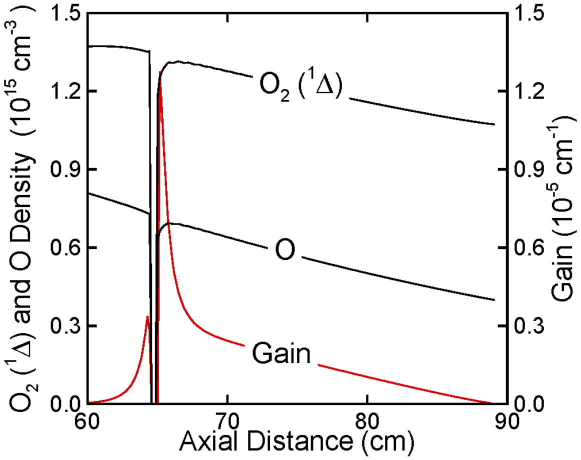
I (2.3 x 10^{13} cm^{-3})

I* (1.2 x 10^{13} cm^{-3})

Gain (1.3 x 10^{-5} cm^{-1} (2 dec))



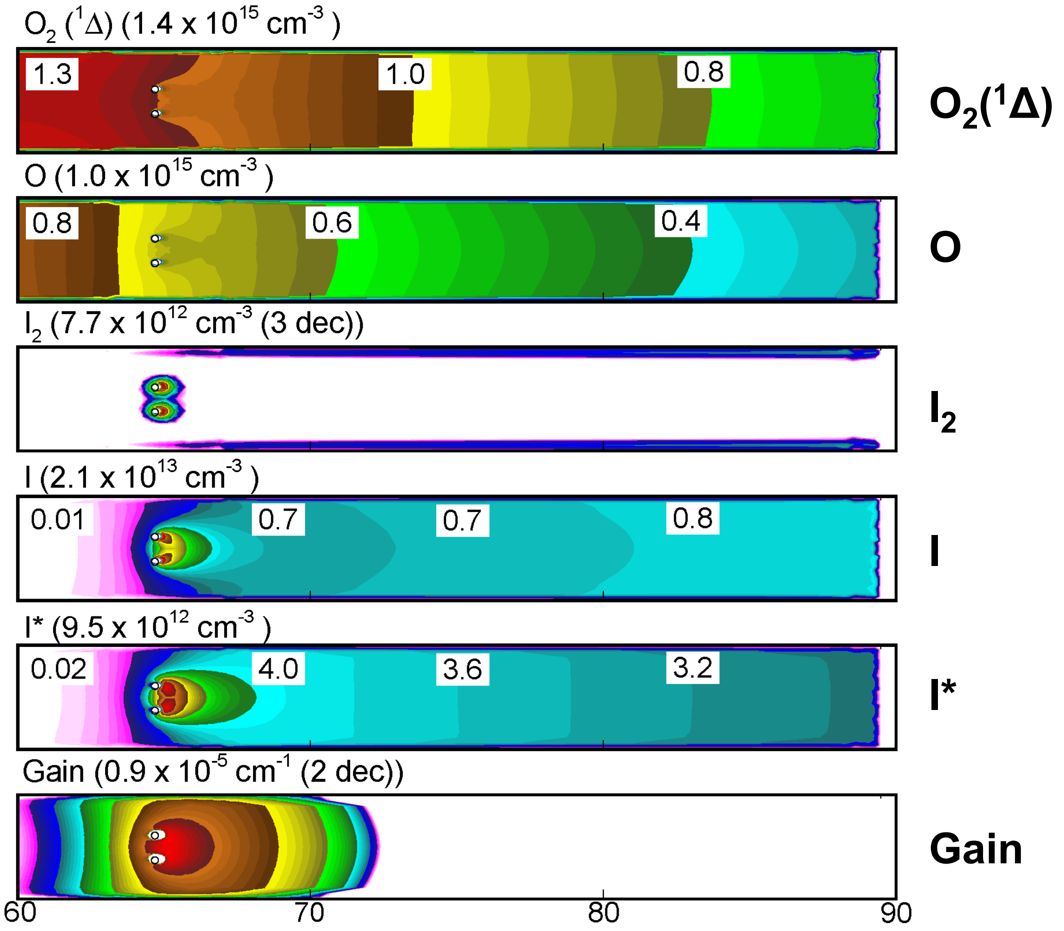


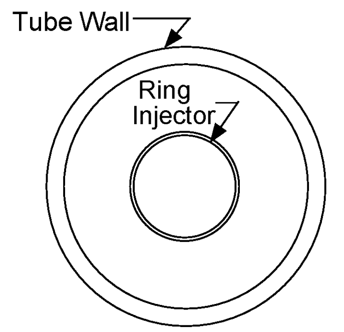


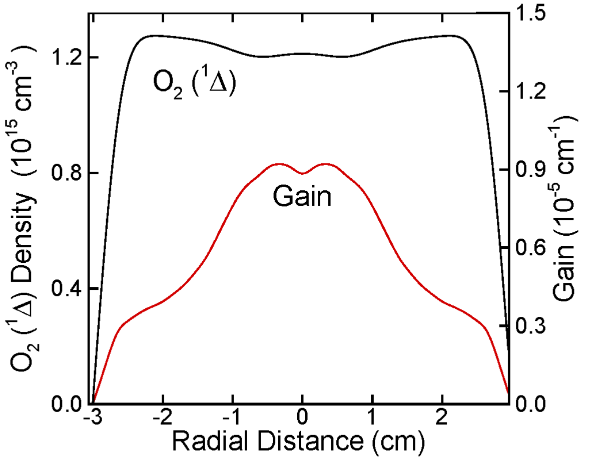
- **Same rate of I_2 injection into center of $O_2(^1\Delta)$ flow increases local gain but reduces overall utilization of $O_2(^1\Delta)$. Note gain upstream.**

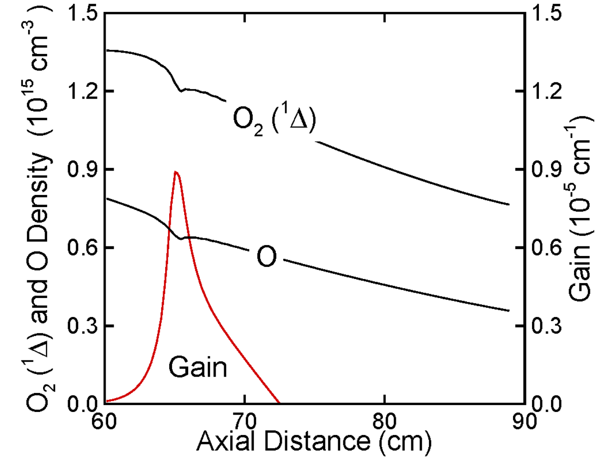
MIN  **MAX**

I_2 RING INJECTOR



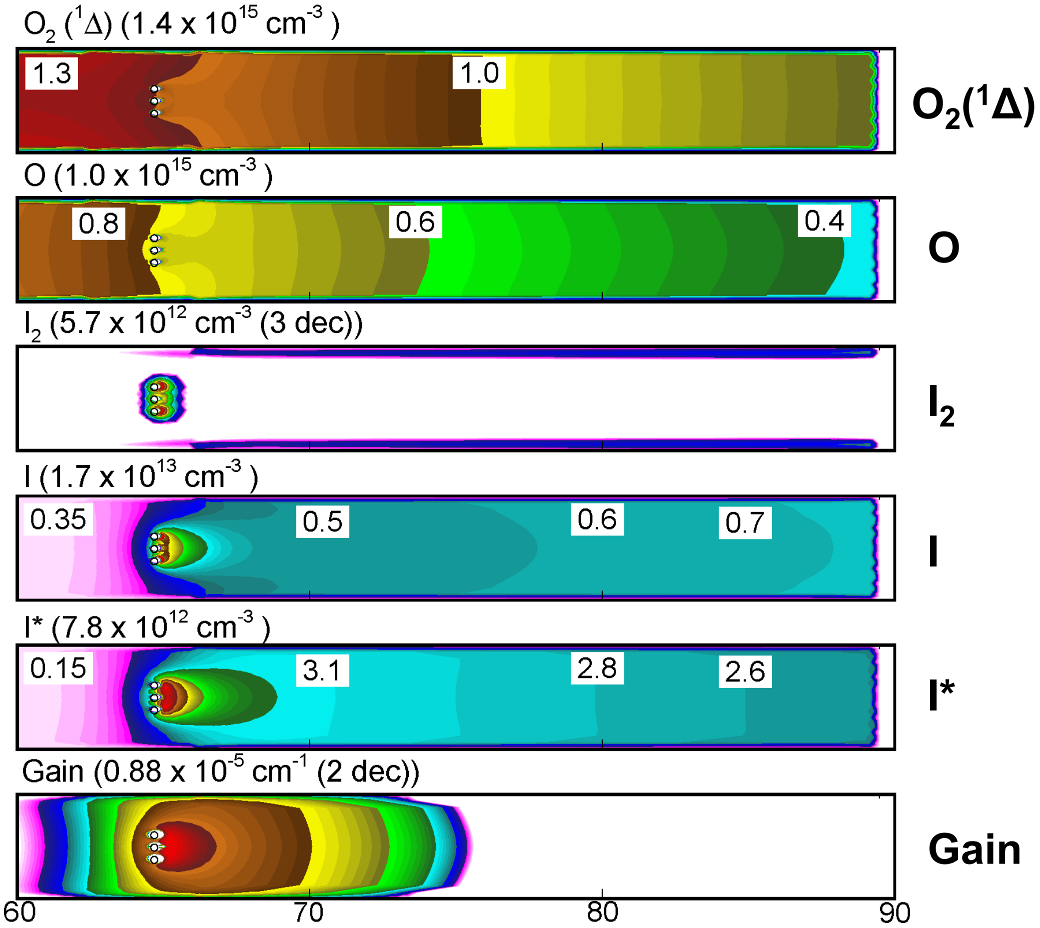


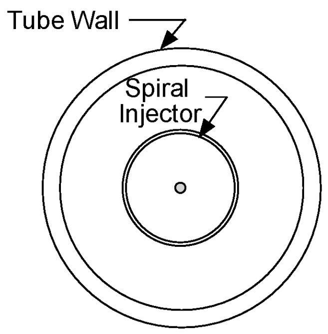


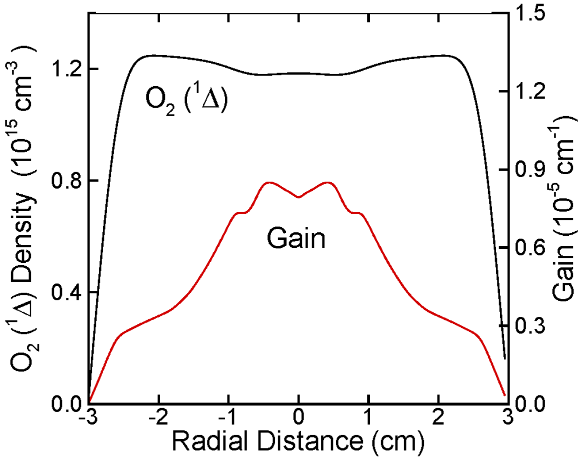


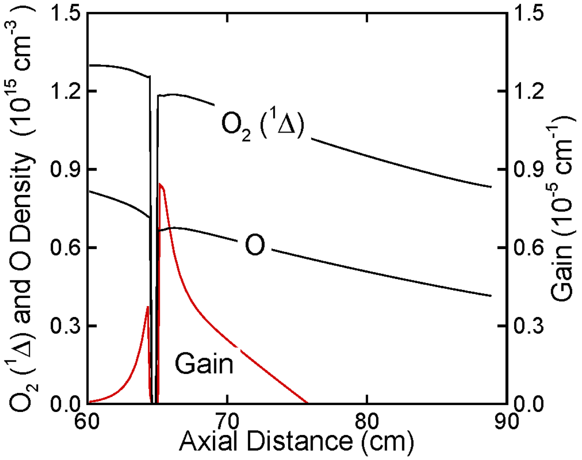
- **More distributed injection of I_2 better utilizes $O_2(^1\Delta)$ producing broader region of gain. Note I_2 recombination on walls.**

I_2 SPIRAL INJECTOR









- **Spiral injector provides better match between flow of I_2 and incoming flux of $O_2(^1\Delta)$; and better radial uniformity of gain.**

MIN ▨ **MAX**

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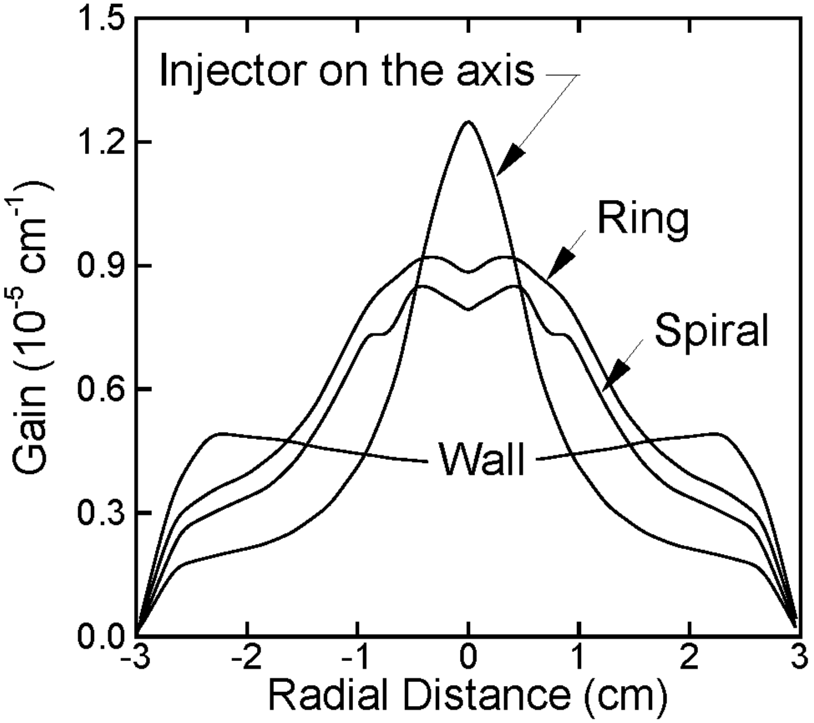
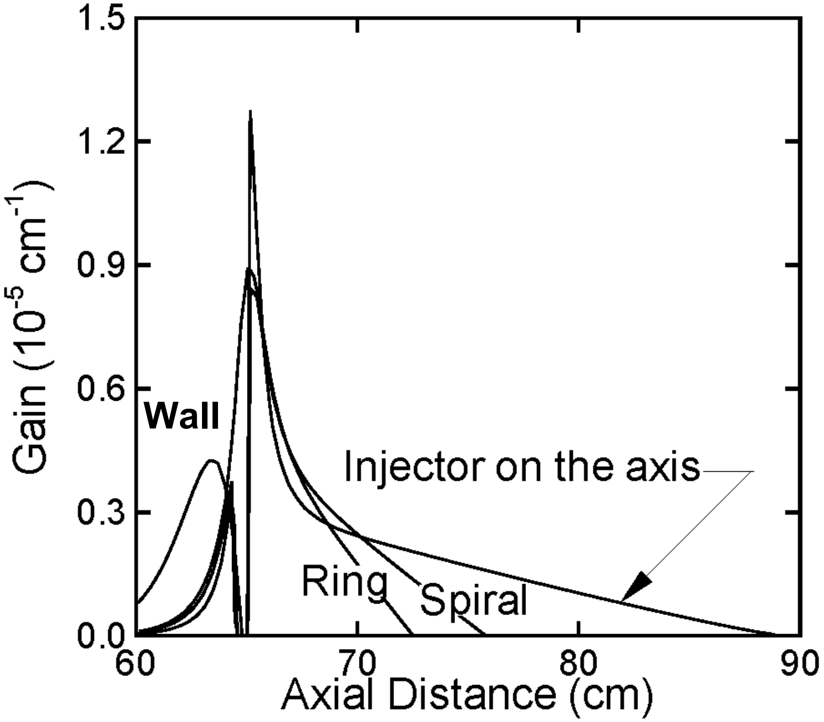
COMPARISON OF INJECTION METHODS



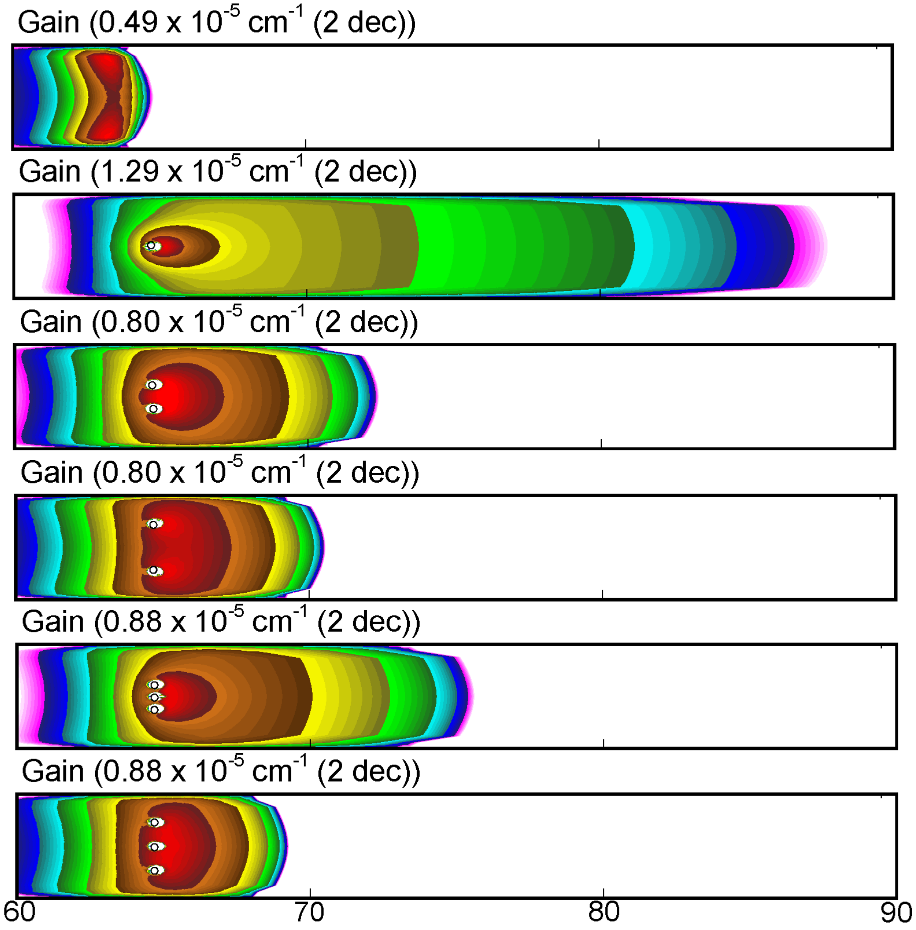


- **Wall injection results in small gain due to slow mixing and low utilization of $O_2(^1\Delta)$.**
- **Moderately high but narrow gain with one injector on axis.**
- **Optimum utilization with ring and spiral injectors.**

MIN **MAX**

GAIN AND T_{gas} vs INJECTOR SEPARATION

- **Gain**



Gain (0.49 x 10^{-5} cm^{-1} (2 dec))

Gain (1.29 x 10^{-5} cm^{-1} (2 dec))

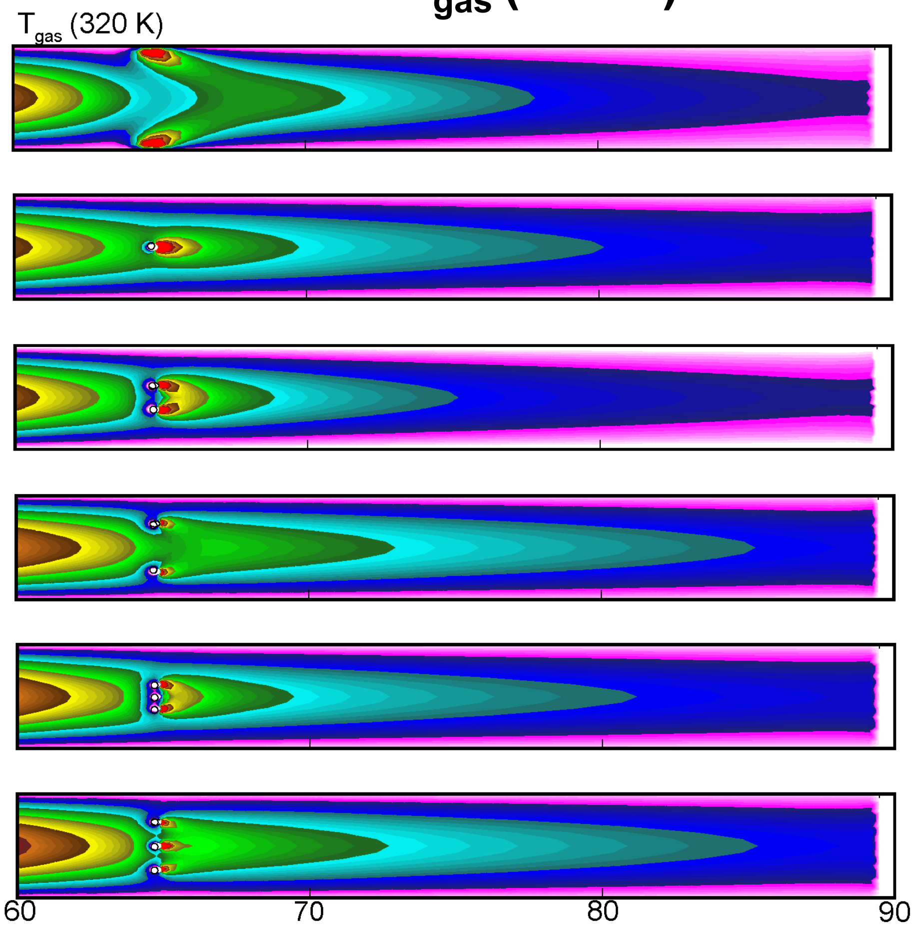
Gain (0.80 x 10^{-5} cm^{-1} (2 dec))

Gain (0.80 x 10^{-5} cm^{-1} (2 dec))

Gain (0.88 x 10^{-5} cm^{-1} (2 dec))

Gain (0.88 x 10^{-5} cm^{-1} (2 dec))

- **T_{gas} (320 K)**



T_{gas} (320 K)

- **Exothermicity of dissociation reactions heats gas.**
- **Spacing of nozzles determines utilization of of $O_2(^1\Delta)$.**

CONCLUDING REMARKS

- Oxygen-iodine kinetics in flowing afterglows for electrically excited chemical-oxygen-iodine lasers has been computationally investigated.
- Gain was optimized using different injection strategies:
    - Wall injection: small and uniform radial gain.
    - One spherical injector: high but narrow radial gain.
    - Ring and spiral injectors can optimize gain: high and uniform gain due to complete $O_2(^1\Delta)/I_2$ mixing.
    - Increasing radius of ring/spiral injectors results in more uniform gain along tube radius due to better $O_2(^1\Delta)$ utilization.