SCALING OF ELECTRICALLY EXCITED CHEMICAL OXYGEN-IODINE LASERS (COIL)*

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May 2004

* Work supported by Air Force Office of Scientific Research and Air Force Research Laboratories
AGENDA

• Overview of $\text{O}_2(^1\Delta)$ kinetics in non-equilibrium discharges

• Energy scaling of $\text{O}_2(^1\Delta)$ yield

• $T_e$ (E/N) engineering to maximize yield

• System studies

• Concluding remarks
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.

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

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

- 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.
Advantages of Electrical $O_2(^1\Delta)$ Generation

- Low system mass – no liquid storage
- Safe chemistry – no hazardous chemicals
- Simple design – no recycling/disposal systems

.... and (historical) Disadvantages

- Yield is low – reported yields are 10 – 30%.
- Discharge heating – laser gain kinetics favor low temperatures
- Discharge is non-selective – dissociation, ionization

\[ Yield = \frac{[O_2(^1\Delta)]}{[O_2] + [O_2(^1\Delta)] + [O_2(^1\Sigma)] + 0.5[O] + 1.5[O_3]} \]
TYPICAL CONDITIONS

• Pressures: a few to 10s Torr
  • Higher is better to provide back pressure for expansion

• Mixtures: He/O_2, f(O_2) = 10’s – 50%
  • Need He for discharge stability, tailoring E/N, high thermal conductivity.

• Size: Flow tube 3-10 cm diameter (pump limited?)

• Flow speeds: 10s m/s (plasma residence time many ms, flow times 10s ms)
CURRENT IMPLEMENTATION: CU AEROSPACE

- Many efforts worldwide are addressing these challenges with the goal of demonstrating gain and laser oscillation.

- Example: CU Aerospace: CW rf excitation, supersonic expansion, flow conditioning and additives.
GROUND RULES

• This talk will focus on $\text{O}_2(^1\Delta)$ generation in low pressure quasi-cw plasmas for COIL.

  • The COIL community will know what to do with a large enough yield…. $\text{I}_2-\text{O}_2(^1\Delta)$ kinetics will not be addressed.

  • We are addressing strategies and techniques, not design of a particular system, though the parameter space will be relevant (a few to 10’s Torr, He/O$_2$ mixtures).

• Yield is paramount, efficiency is important.

• 50,000 ft view of the landscape…Let’s not worry about too fine a level of detail (and no, I’m not comparing to experiments).

• What is the physics you need to address to optimize yield?
PRELIMINARY REMARKS

- $\text{O}_2(1^\Delta)$ is a remarkably robust molecule. Once produced, its reactivity and quenching are low.

- Low efficiency systems can produce large yields of $\text{O}_2(1^\Delta)$ by simply integrating excitation over long periods of time.

- As such, yield is energy driven (not power driven). Producing a given yield requires a given eV/molecule.

- The value of the eV/molecule for a given yield depends on efficiency.

- The ability to deposit a large enough eV/molecule to achieve high yields will ultimately depend on discharge stability.
**O$_2$ ENERGY POTENTIAL ENERGY DIAGRAM**

- O$_2$ is unique among common diatomic molecules as having low lying electronic states.

- O$_2$(^1$\Delta$) [0.98 eV] and O$_2$(^1$\Sigma$) [1.6 eV] are readily accessible in the Frank-Condon corridor.


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Production of $\text{O}_2(^1\Delta)$ is by direct electron impact [0.98 eV] or through excitation of $\text{O}_2(^1\Sigma)$ [1.6 eV] with subsequent rapid (and efficient) quenching to $\text{O}_2(^1\Delta)$.
**O₂ ELECTRONIC EXCITATION: THE BAD....**

- Excitation to O₂(A³Σ) and O₂(B³Σ) are dissociative which depletes the ground state; reformation of O₂ is slow.
- The O atoms rapidly quench O₂(¹Σ) → O₂(¹Δ).
- O(¹D) produces O₂(¹Δ) through collisions with O₂.
O₂ IONIZATION: THE UGLY....

- Ionization of O₂ sustains the discharge but...
- O₂⁺ dissociatively recombines (a loss) or neutralizes with O₂⁻ and O⁻, possible dissociatively (a loss).
- Any subsequent formation of O₂(1Δ) is at high energy cost.
IMPORTANT CHEMISTRY

- $\text{O}_2(^1\Delta)$ is a remarkably robust molecule whose density can accumulate. Its reactivity and quenching rates are low.

  \[ O_2(^1\Delta) + O_2 \rightarrow O_2 + O_2 \quad k = 3 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}, \quad \tau = 2 \text{ s} \]

  \[ O_2(^1\Delta) + O \rightarrow O + O_2 \quad k = 2 \times 10^{-16} \text{ cm}^3 \text{s}^{-1}, \quad \tau = 30 \text{ ms} \]

- $\text{O}_2(^1\Sigma)$ is rapidly quenched to $\text{O}_2(^1\Delta) \rightarrow \text{O}_2(^1\Sigma)$. As such its production is equivalent $\text{O}_2(^1\Delta)$

  \[ O + O_2(^1\Sigma) \rightarrow O + O_2(^1\Sigma) \quad k = 7.2 \times 10^{-14} \text{ cm}^3 \text{s}^{-1}, \quad \tau = 0.2 \text{ ms} \]

- $\text{O}(^1\text{D})$ production is bad due to dissociation having occurred. However, if any $\text{O}_2$ remains, $\text{O}_2(^1\Delta, ^1\Sigma)$ is recouped.

  \[ O(^1\text{D}) + O_2 \rightarrow O + O_2(^1\Delta, ^1\Sigma) \quad k = 3.4 \times 10^{-11} \text{ cm}^3 \text{s}^{-1}, \quad \tau = 10 \text{ s} \mu\text{s} \]
IMPORTANT CHEMISTRY

- O$_2$(^1Δ) energy pooling recycles into O$_2$(^1Σ) or quenches to O$_2$. In either case, the rates are slow

\[
O_2(^1Δ) + O_2(^1Δ) \rightarrow O_2 + O_2 \quad k = 1.4 \times 10^{-17} \text{ cm}^3 \text{s}^{-1}, \quad \tau = 1 \text{ s}
\]

- O$_3$ is a rapid quencher of most states and could be an issue at slower flow rates.

\[
O + O_2 + M \rightarrow O_3 + M \quad k = 3 - 6 \times 10^{-34} \text{ cm}^6 \text{s}^{-1}, \quad \tau = 10 \text{ ms}
\]

- Except at the most dilute of mixtures, excitation transfer from He*, He$^+$ is not important due to the low rate of production of these species.
DESCRIPTION OF GLOBAL_KIN

- Global model with a user defined gas and surface reaction mechanism.
- Boltzmann’s equation solved for electron distribution (linked to cross section database).
- Ion transport linked to database.
- Electric field obtained from circuit model or electro-magnetics-power balance.
- Plug flow model includes enthalpy induced change in flow speeds.
nonPDPSIM: 2-DIMENSIONAL PLASMA DYNAMICS

- nonPDPSIM was developed to investigate plasma hydrodynamics at moderate to high pressures in complex geometries.
  - 2-d rectilinear or cylindrical unstructured mesh
  - Implicit drift-diffusion for charged
  - Poisson’s equation with volume and surface charge, and material conduction.
  - Circuit model
  - Electron energy equation coupled with Boltzmann solution for electron transport coefficients
  - Optically thick radiation transport with photoionization
  - Secondary electron emission by impact, thermally enhanced electric field emission, photoemission
  - Surface chemistry.
  - Monte Carlo Simulation for secondary electrons
  - Navier-Stokes for neutrals with individual diffusion speeds
DESCRIPTION OF MODEL: CHARGED PARTICLE, SOURCES

- Continuity (sources from electron and heavy particle collisions, surface chemistry, photo-ionization, secondary emission), fluxes by modified Sharfetter-Gummel with advective flow field.

\[ \frac{\partial N_i}{\partial t} = -\nabla \cdot \vec{\phi} + S_i \]

- Poisson’s Equation for Electric Potential:

\[ -\nabla \cdot \varepsilon \nabla \Phi = \rho_V + \rho_S \]

- Photoionization, electric field and secondary emission:

\[ S_{Si}(\vec{r}) = \int \frac{N_i(\vec{r})\sigma_{ij}N_j(\vec{r}')\exp\left(-\frac{|\vec{r}' - \vec{r}|}{\lambda}\right)}{4\pi|\vec{r}' - \vec{r}|^2} \, d^3\vec{r}' \]

\[ S_{Si} = -\nabla \cdot j, \quad j_E = AT^2 \exp\left(-\frac{\left(\Phi_W - \left(q^3E/\varepsilon_0\right)^{1/2}\right)}{kT_S}\right), \quad j_S = \sum_j \gamma_{ij} \phi_j \]
DESCRIPTION OF MODEL: CHARGED PARTICLE, SOURCES

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

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

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

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

- 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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ELECTRON TRANSPORT: BULK AND BEAM

• Bulk electron energy equation with Boltzmann’s equation derived transport coefficients.

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

• Transport of energetic secondary electrons is addressed with a Monte Carlo Simulation.

• Electrons and their progeny are followed until slowing into bulk plasma or leaving MCS volume.
FRACTIONAL POWER DEPOSITION

- Significant power can be channeled into excitation of $O_2(1^\Delta)$ and $O_2(1^\Sigma)$.

- Optimum conditions are $T_e = 1-1.2$ eV, $E/N = 8-10$ Td.

- The challenge is operating at those values.

- Self sustaining (based on attachment) for $He/O_2 = 50/50 = 3$ eV, 80 Td. Higher with diffusion losses.
ELECTRON ENERGY DISTRIBUTIONS IN He/O₂ MIXTURES

- The electron energy distribution for a given E/N can be adjusted by use of gas mixtures.
- Dilution with He generally increases excitation rates at constant E/N by raising the tail of the EED.
POWER PARTITIONING: $T_e$ vs He/O$_2$

- The fractional power into O$_2$(^1\Delta, ^1\Sigma)$ maximizes with $T_e=1-1.5$ eV independent of gas mixtures as it is “cross section driven.”
- He dilution only reduces the power into O$_2$(^1\Delta, ^1\Sigma)$ at a given $T_e$ but may enable operation at a lower $T_e$.
  - Reduces attachment losses but increases diffusion losses.
DISCHARGE PARAMETERS: SELF-SUSTAIN vs OPTIMUM

- Self sustaining based on balance between ionization and attachment for ground state feedstock gases.
- Optimum conditions based on maximum power dissipated in $O_2(^1\Delta, ^1\Sigma)$ excitation.
• Use of He does reduce the self-sustaining $E/N$ closer to the optimum (which is a weaker function of $E/N$).

• This is traded against there being less fractional power into $O_2(^1\Delta, ^1\Sigma)$.
TYPICAL PLASMA PROPERTIES: He/O₂ = 50/50, 5 Torr

- Plug flow model with inductively coupled plasma (nearly always a self-sustaining.)

- Initial high Tₑ to avalanche plasma favors dissociative attachment and formation of O⁻.

- Steady state Tₑ = 2.1 eV exceeds optimum to excite O₂(¹Δ, ¹Σ ).

- He/O₂ = 50/50, 5 Torr, v₀ = 10 m/s, 1 W/cm³
TYPICAL PLASMA PROPERTIES: He/O₂ = 50/50, 5 Torr

- O₂(¹Σ) is quickly collisionally converted to O₂(¹∆) after the plasma zone. O₂(¹∆) is robust and resists quenching when energy pooling is not important.

- O atom production nearly equals O₂(¹∆).

- He/O₂ = 50/50, 5 Torr, v₀ = 10 m/s, 1 W/cm³
TYPICAL PLASMA PROPERTIES: He/O₂ = 50/50, 5 Torr

- Gas heating is significant, due largely to V-T relaxation, Frank-Condon heating.

- Downstream chemical kinetics depends on active vs passive cooling.

- He/O₂ = 50/50, 5 Torr, v₀ = 10 m/s, 1 W/cm³
**LIFE IS BETTER THAN ADVERTISED: WHAT SAVES YOU?**

- Performance of self sustained discharges is better than advertised with more optimum production of $\text{O}_2(^1\Delta)$.

- Dissociation and excitation of $\text{O}_2$ results in:
  - Less attachment
  - More efficient ionization
  - Lower self-sustaining $T_e$
  - Higher fractional power into $\text{O}_2(^1\Delta, ^1\Sigma)$ provided dissociation is not large.

- For $\text{He}/\text{O}_2 = 50/50$, opt $T_e = 1.0$ eV. Self sustaining is
  - 3.1 eV ($x = 0$ cm)
  - 2.0 eV ($x = 9$ cm)
A full factorial parameterization of velocity, pressure, power, and mixture was performed to determine scaling laws for $O_2(^1\Delta)$ yield.

A scaling law is proposed giving yield ($\beta$) as a function of specific energy deposition (in eV per inlet $O_2$ molecule):

$$\beta = \frac{[O_2(^1\Delta) + 0.5[O] + 1.5[O_3]]}{[O_2] + [O_2(^1\Delta)]} \implies \beta = f\left(\frac{\text{eV}}{O_{2,\text{inlet}}} \right)$$

Parameter ranges for ideal plug-flow system:

- Velocity: 500 – 5000 cm/s
- Pressure: 1 – 20 Torr
- Power: 0.1 – 1.5 W/cc
- Mixture: 3 – 100% $O_2$ in He
- Length: 20 cm

These ranges give specific energies of 0 – 250 eV

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O₂(1Δ) YIELD VS. SPECIFIC ENERGY DEPOSITION

- O₂(1Δ) yield obeys energy deposition scaling law to 1st order:

  \[ \beta = f \left( \frac{\text{eV}}{O_2,\text{inlet}} \right) \]

- O₂(1Δ) yield increases with energy as inventory integrates.

- O₂(1Δ) yield decreases > 5 – 8 eV as dissociation depletes ground state and O₂(1Δ).

- Scatter is due to secondary effects (mixture, pressure, power).
Atomic O yield increases monotonically with specific energy until near complete dissociation is achieved.

50% dissociation occurs by 5 – 8 eV, when $O_2(^1\Delta)$ yield begins to decrease.

$$\beta = \frac{0.5[O]}{[O_2] + [O_2(^1\Delta)] + 0.5[O] + 1.5[O_3]}$$
SECONDARY EFFECTS: DILUENT

- Addition of He increases yield at high specific energy deposition by reducing E/N and increasing thermal conductivity.

- Scaling laws apply to mixtures with diluents:

\[ \beta = f\left( \frac{eV}{O_{2,\text{inlet}}} \right) \]

Conditions:
- \( V_{\text{inlet}} = 2500 \text{ cm/s} \)
- Power = 21 W/cc
- \( P_{O_2} = 4.2 \text{ Torr} \)
- \( L_{\text{disch}} \) determined by energy dep.
SECONDARY EFFECTS: DILUENT (NO HEATING)

- When fixing gas temperature (no heating, no expansion) the benefits of He dilution are less clear.

- Yields are system specific due to thermodynamics of flow which feed back to self sustaining conditions.

Conditions:
- \( V_{\text{inlet}} = 2500 \text{ cm/s} \)
- Power = 21 W/cc
- \( P_{O_2} = 4.2 \text{ Torr} \)
- \( L_{\text{disch}} \) determined by energy dep.

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SECONDARY EFFECTS: PRESSURE

- Optimum 8 eV/molecule
- Increasing total pressure increases potential yield, particularly below 40 Torr.
- Operation at more optimum E/N.

Conditions:
- $V_{inlet} = 500 \text{ cm/s}$
- Power = 3 W/cc/Torr O$_2$
- $L_{disch}$ determined by energy dep.

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SECONDARY EFFECTS: POWER DEPOSITION

- Optimum 8 eV/molecule

- Low power produces the highest yields as thermodynamically closer to “steady state.”

- Cooler, more O re-association....

- However, low power requires longer residence times, which may not be practical.

Conditions:
- $V_{\text{inlet}} = 2500 \text{ cm/s}$
- $P_{O_2} = 3 \text{ Torr}$
- $L_{\text{disch}}$ determined by energy deposition.
NON-SELF SUSTAINED DISCHARGES

- Self sustained systems are limited by need to balance attachment and diffusion losses by ionization.

- This pushes system to larger $T_e$ or $E/N$.

- Externally sustained system provides means to reduce $T_e$ or $E/N$ to more optimum regime.

- Example: E-beam sustained plug flow system.

- Low-energy deposition yield (molecules/eV) vs Fraction of energy from E-beam (5 Torr).
PLUG-FLOW WITH E-BEAM POWER DEPOSITION: $T_e$

- E-beam power distributed using $W$-values obtained from Boltzmann slowing down code.

- Increasing fraction of e-beam power lower $T_e$, saturating at 5-6%

- $\text{He/O}_2 = 50/50$, 5 Torr, $v_0 = 10$ m/s

- 1 W/cm$^3$,
PLUG-FLOW WITH E-BEAM POWER DEPOSITION: e, O$_2$(^1$\Delta$)

- 1 W/cm$^3$,

- Reduction in T$_e$ shifts operating point closer to optimum value, increasing yield from 15% to 26%.

- Increase in yield is enhanced by larger [e] and reduced dissociation of O$_2$.

- He/O$_2$ = 50/50, 5 Torr, v$_0$ = 10 m/s
IN SITU “EXTERNAL” IONIZATION: SPIKER SUSTAINER

- Spiker-sustainer circuit provides in situ “external ionization”

- Short high voltage (power) pulse is followed by plateau of lower voltage (power).

- Excess ionization in “afterglow” following spiker enables sustainer to operate below self sustaining $T_e (E/N)$.

- Optimum timing of spiker/sustainer is determined by ionization equilibration (how long to get back to self-sustain).

- Most beneficial effect of spiker (analogue to excimer avalanche discharge lasers) may be preionization which enables more uniform power deposition or larger volumes.
SPIKER-SUSTAINER

- High power spiker followed by plateau of lower power sustainer.

- Excess ionization decays within 0.5-1 \( \mu \)s.

- During period of excess ionization, \( T_e \) is below self sustaining values.

- \( \text{He/O}_2 = 50/50, \) 5 Torr

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SPIKER-SUSTAINER: $O_2(\,^1\Delta, \,^1\Sigma)$ PRODUCTION EFFICIENCY

- Lower $T_e$ during sustain pulse better matches cross sections for excitation of $O_2(\,^1\Delta, \,^1\Sigma)$. 
- End result is a higher energy efficiency for $O_2(\,^1\Delta, \,^1\Sigma)$ production.

- He/O$_2$ = 50/50, 5 Torr
• The optimum length of the sustainer pulse is limited by the recovery time for $T_e$.

• The recovery time is in turn determined by the equilibration time for excess electron density.

• He/O₂ = 50/50, 5 Torr
The improved efficiency of production of \( O_2(1\Delta, 1\Sigma) \) decreases as the self-sustain pulse lengthens.

- \( \text{He/O}_2 = 50/50, 5 \text{ Torr} \)
APPLICATION TO AN IDEALIZED SYSTEM

- Idealized system is based in CU Aerospace ECOIL experiment.
- Continuous rf source (capacitive in experiment, inductive here).
- 3 Torr, He/O₂=0.7/0.3, 6000 sccm
ELECTRICAL AND ELECTRON PARAMETERS

- Thermal conduction and diffusion produces warm electrons upstream. Electron density peaks near maximum in $T_e$ as attachment distance is short.

- 3 Torr, He/O$_2$=0.7/0.3, 6000 sccm, 20 W

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FLUID DYNAMICS

- Flow is laminar with gas heating dominated by Frank Condon heating and V-T relaxation. Downstream dynamics are dominated by conduction to the wall.

- 3 Torr, He/O₂=0.7/0.3, 6000 sccm, 20 W
**OXYGEN ATOMIC AND MOLECULAR DENSITIES**

- $\text{O}_2(^1\Sigma)$ and O densities are maximum near peak power deposition.

- $\text{O}_2(^1\Delta)$ increases downstream as $\text{O}_2(^1\Sigma)$ is quenched and transfer occurs from $\text{O}(^1\text{D})$. Yield here is 8%.

- $\text{O}_2$ is depleted by dissociation and gas heating.

- 3 Torr, $\text{He}/\text{O}_2=0.7/0.3$, 6000 sccm, 20 W

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**MIN**

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<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>MAX</th>
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![Diagram showing oxygen densities with color scale and values](image)
Increasing power increases local specific power deposition nonlinearly, thereby producing less uniform excitation.

- 3 Torr, He/O$_2$=0.7/0.3, 6000 sccm
O$_2$(^1Δ) AND YIELD vs POWER

- Yield scales sub-linearly with power in a parameter space where energy scaling should be valid.
- Increasingly less uniform power deposition and local depletion of O$_2$ is likely the cause.

* Energy scaling says yield=40%

* 3 Torr, He/O$_2$=0.7/0.3, 6000 sccm

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O₂(¹Δ) AND YIELD vs MIXTURE

- Yield decreases with increasing O₂ (but not a lot)
- lower thermal conductivity
- More Frank Condon heating.
- Less uniform power
- Less optimum E/N

He/O₂ = 85/15  T_gas 340 K
He/O₂ = 70/30  T_gas 390 K
He/O₂ = 50/50  T_gas 440 K

He/O₂ = 85/15  [O₂(1-delta)] 1.5 x 10¹⁵ cm⁻³  Yield = 8.9%
He/O₂ = 70/30  [O₂(1-delta)] 2.8 x 10¹⁵ cm⁻³  Yield = 8.3%
He/O₂ = 50/50  [O₂(1-delta)] 4.4 x 10¹⁵ cm⁻³  Yield = 7.5%

- 3 Torr, 20 W, 6000 sccm
LEARN FROM FAILURES:
$O_2(^1\Delta)$ YIELD ENHANCEMENT WITH E-BEAMS

- The implementation of external sources of ionization must be done very carefully.
- Due to the short distances for electron loss processes and low mobility of ions, the physical overlap between external ionization sources of discharge power must be well managed.
- Scenarios were investigated with low voltage (a few to 20 kV) e-beam injection into flow tubes.
- Instances where the overlap is not optimized actually lowered yield due to poor utilization of e-beam power.
WORK IN PROGRESS: $O_2(^1\Delta)$ YIELD ENHANCEMENT WITH E-BEAMS

- No successful enhancement so far...
- Spiker sustainers being investigated...

- 3 Torr, 20 W, 6000 sccm
CONCLUDING REMARKS

• $O_2(^1\Delta)$ production is largely an energy driven process. Yields scale as eV/molecule. Low efficiency systems can produce large yield.

• Yield will ultimately either be statistically limited (e.g., super-elastic relaxation) or limited by depletion of fuel (e.g., dissociation).

• Efficiency of yield is largely determined by lowering $T_e$ ($E/N$) to better match cross sections for $O_2(^1\Delta, ^1\Sigma)$. Negative-glow like devices might be ideal.

• Secondary effect of $T_e$ ($E/N$) engineering is reducing dissociation rates (less depletion of fuel).

• External sources and spiker-sustainers are both attractive, though utmost care must be taken in physical overlap of two regimes.