SCALING OF PLASMA SOURCES FOR $O_2(^1\Delta)$ GENERATION FOR CHEMICAL OXYGEN-IODINE LASERS

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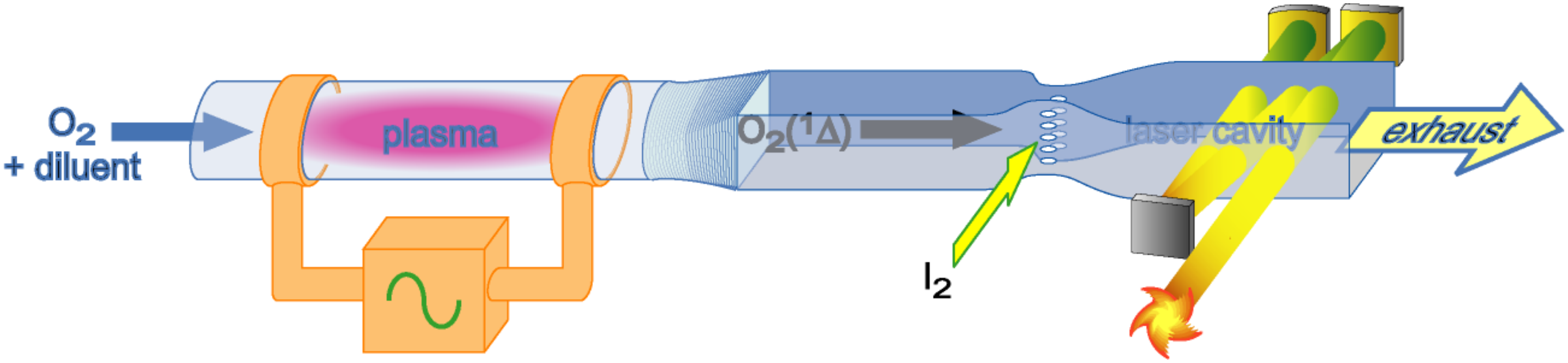
OXYGEN-IODINE LASERS

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

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

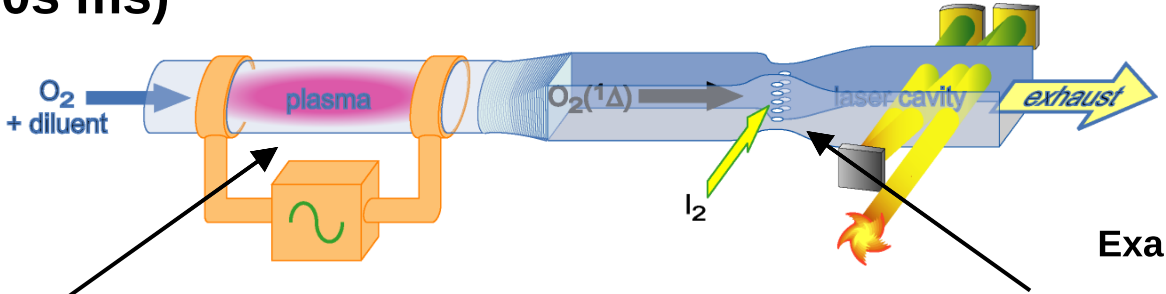
$$I(^2P_{1/2}) \rightarrow I(^2P_{3/2}) + h\nu \qquad (1.315\mu m)$$

- 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.

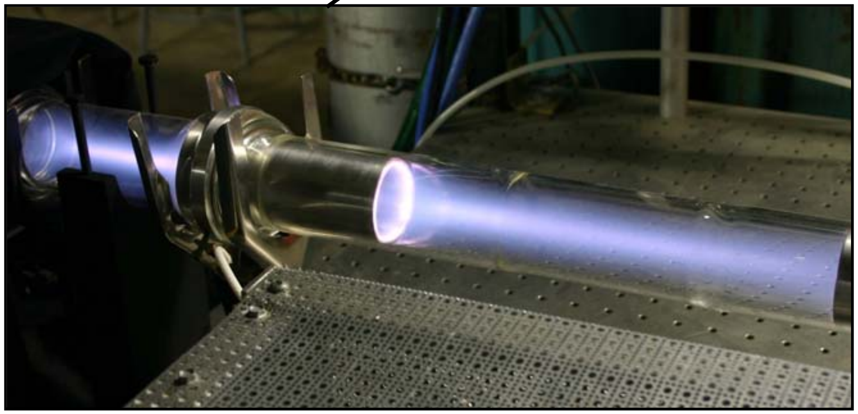


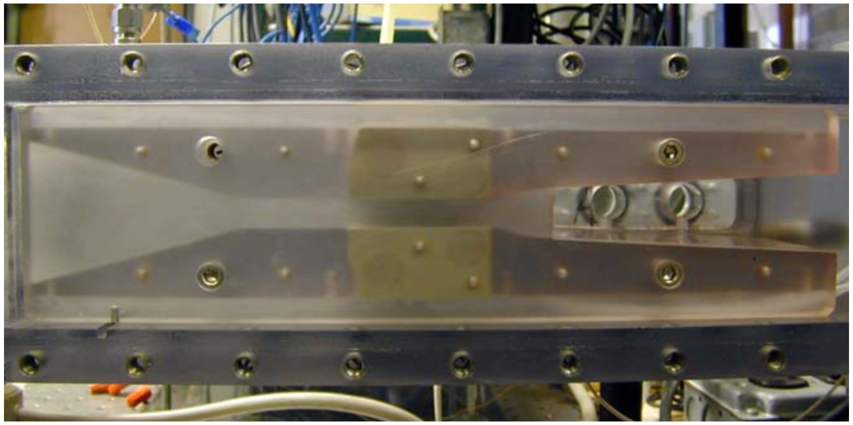
TYPICAL CONDITIONS

- **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)**

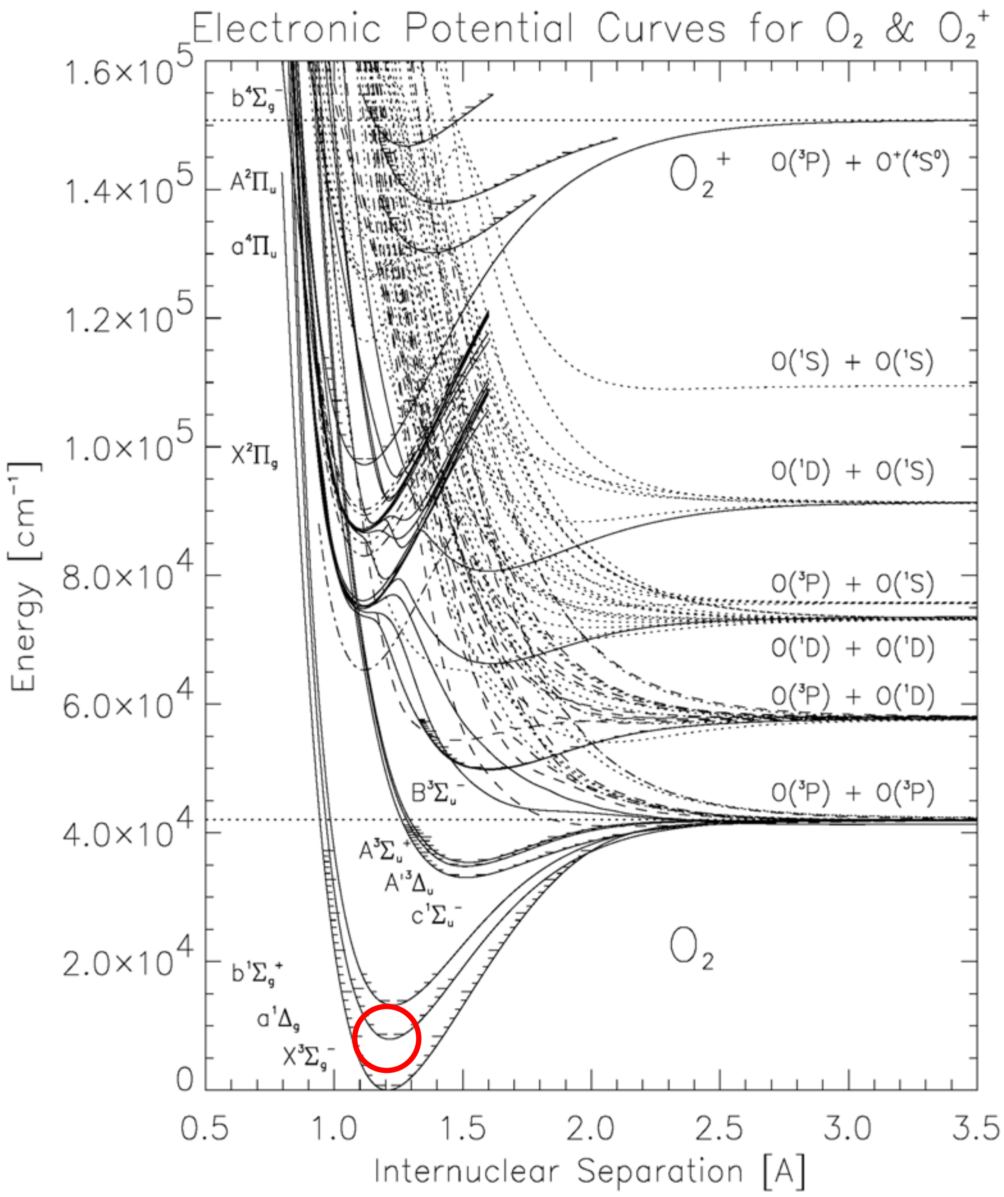


Example: CU Aerospace





O_2 ENERGY POTENTIAL ENERGY DIAGRAM

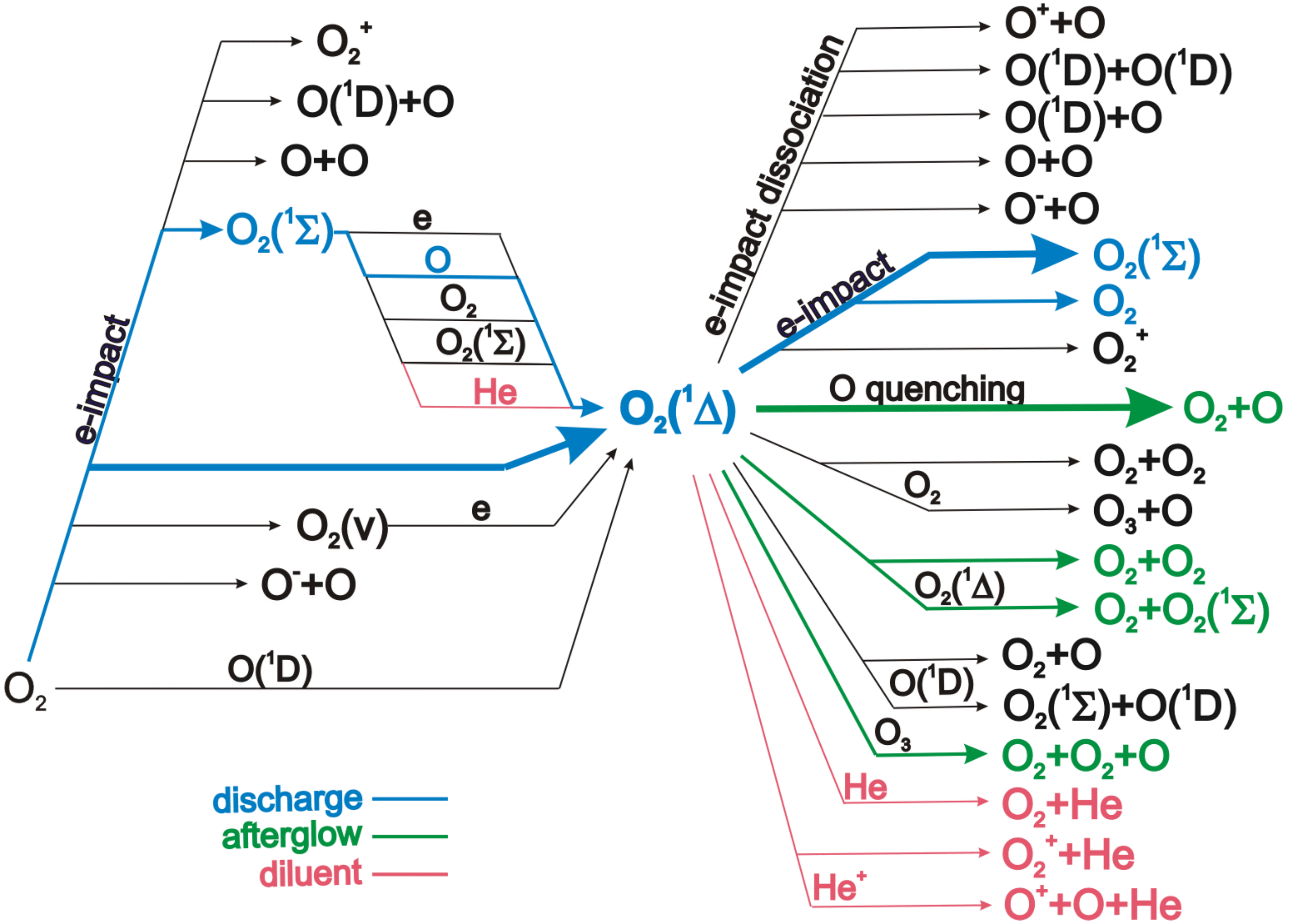


- O_2 is unique among common diatomic molecules as having low lying electronic states.

- $O_2(^1\Delta)$ [0.98 eV] and $O_2(^1\Sigma)$ [1.6 eV] are readily accessible in the Frank-Condon corridor.

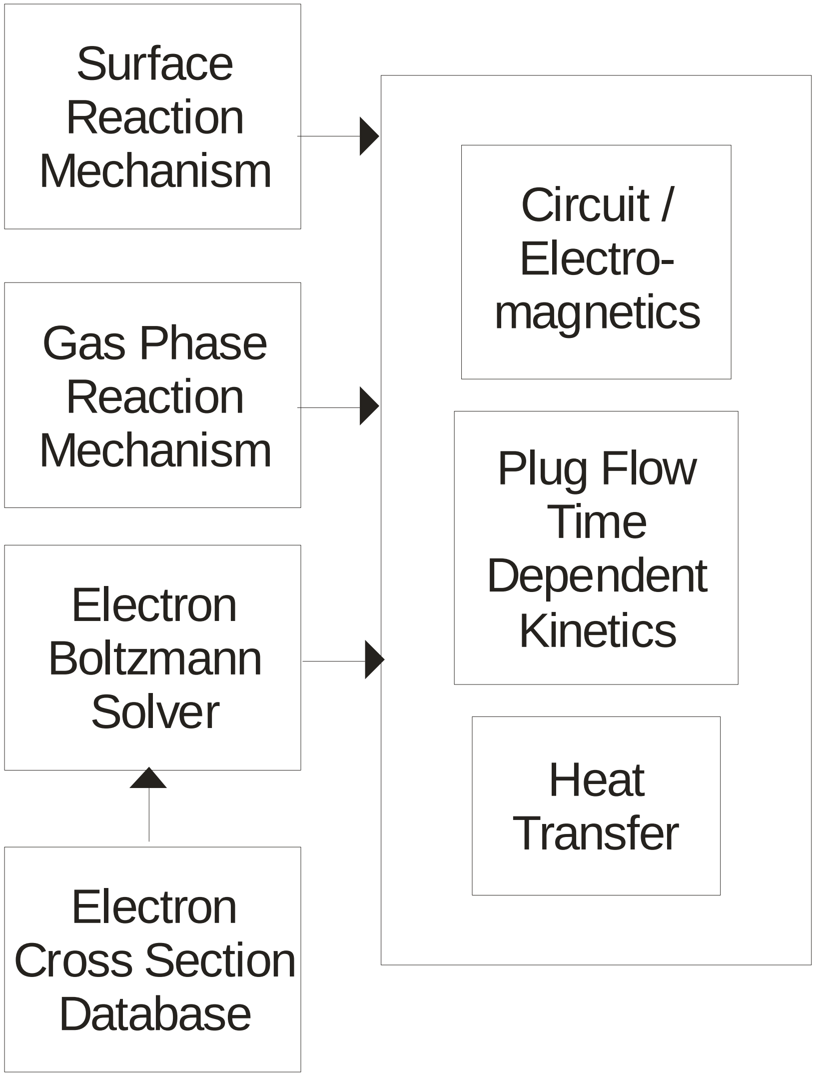
- J. S. Morrill, et al, www.nist.gov

REACTION MECHANISM



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.**



Surface Reaction Mechanism

Gas Phase Reaction Mechanism

Electron Boltzmann Solver

Electron Cross Section Database

Circuit / Electro-magnetics

Plug Flow Time Dependent Kinetics

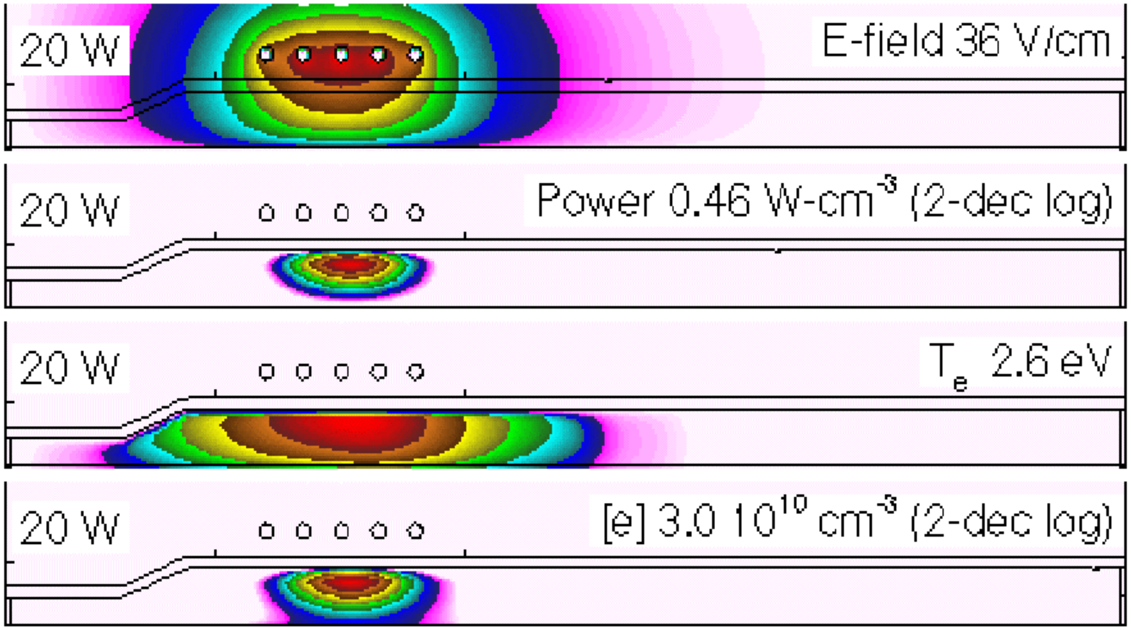
Heat Transfer

nonPDPSIM: 2-DIMENSIONAL PLASMA DYNAMICS

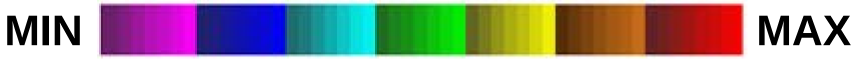
- nonPDPSIM was developed to investigate plasma hydrodynamics at moderate to high pressures in complex geometries.
  - 2-d rectilinear or cylindrical unstructured mesh
  - Implicit drift-diffusion for charged
  - Poisson's equation with volume and surface charge, and material conduction.
  - Circuit 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

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.**

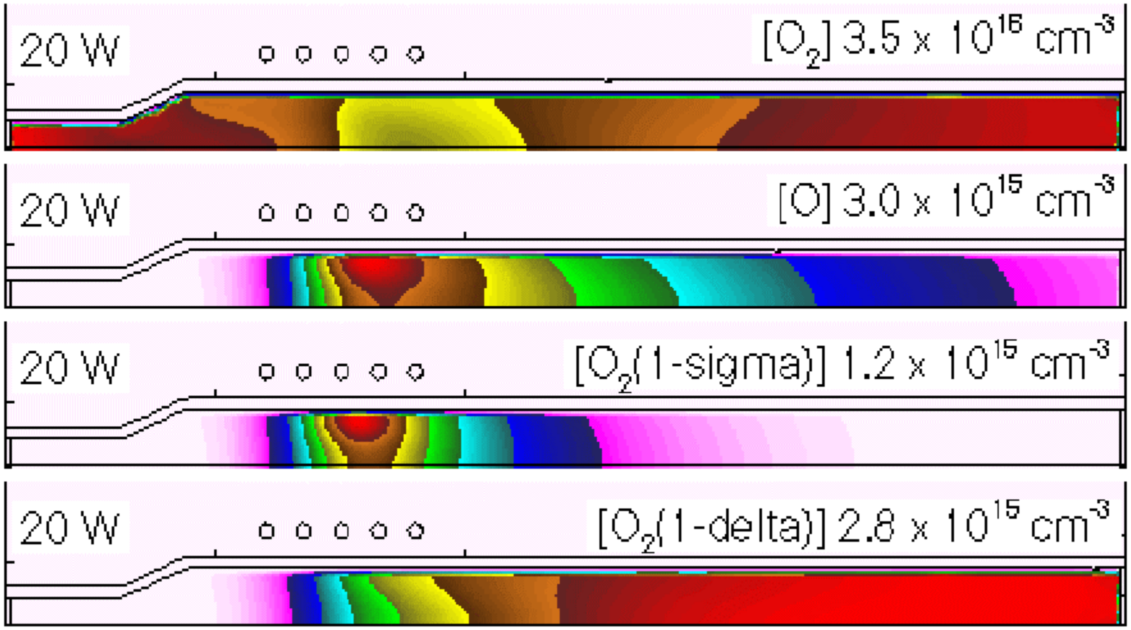


- **3 Torr, He/O_2=0.7/0.3, 6000 sccm, 20 W**



OXYGEN ATOMIC AND MOLECULAR DENSITIES

- $O_2(^1\Sigma)$ and O densities are maximum near peak power deposition.
- $O_2(^1\Delta)$ increases downstream as $O_2(^1\Sigma)$ is quenched and transfer occurs from $O(^1D)$. Yield here is 8%.
- O_2 is depleted by dissociation and gas heating.



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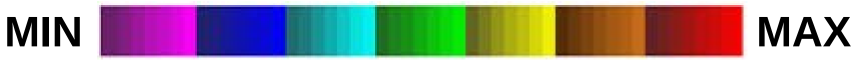
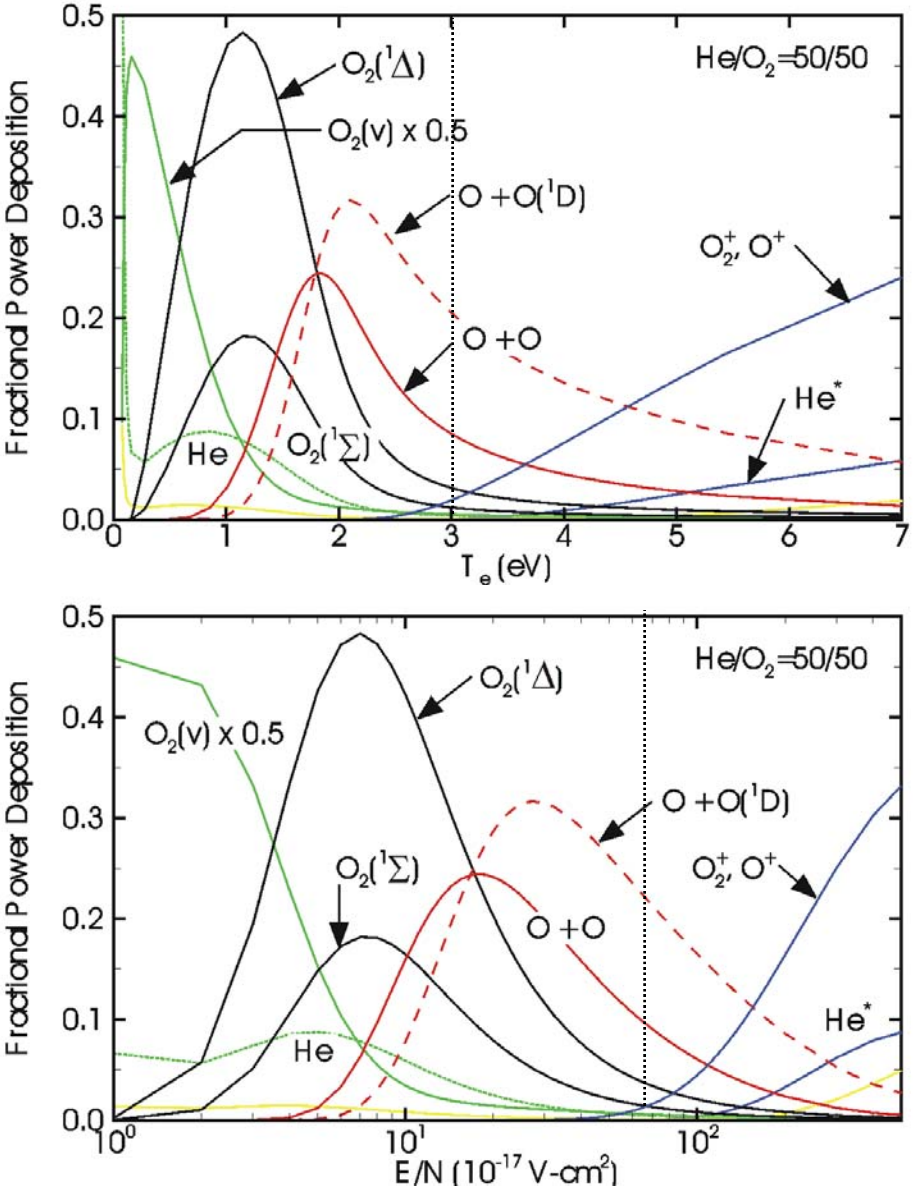


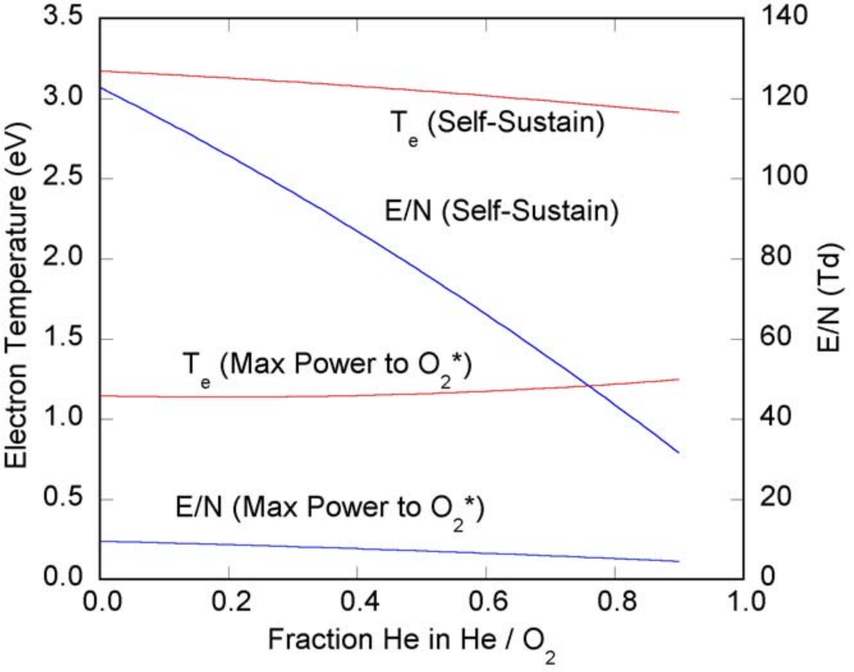
FRACTIONAL POWER DEPOSITION

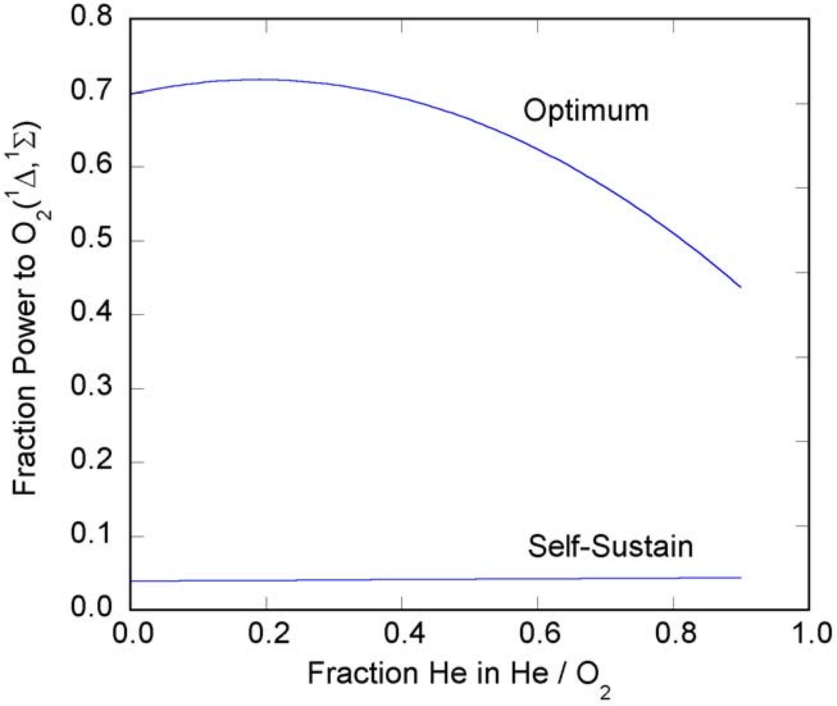


- **Significant power can be channeled into excitation of $O_2(^1\Delta)$ and $O_2(^1\Sigma)$.**
- **Optimum conditions are T_e = 1-1.2 eV, E/N = 8-10 Td.**
- **The challenge is operating at those values.**
- **Self sustaining (based on attachment) for He/O_2 = 50/50 = 3 eV, 80 Td. Higher with diffusion losses.**

DISCHARGE PARAMETERS: SELF-SUSTAIN vs OPTIMUM

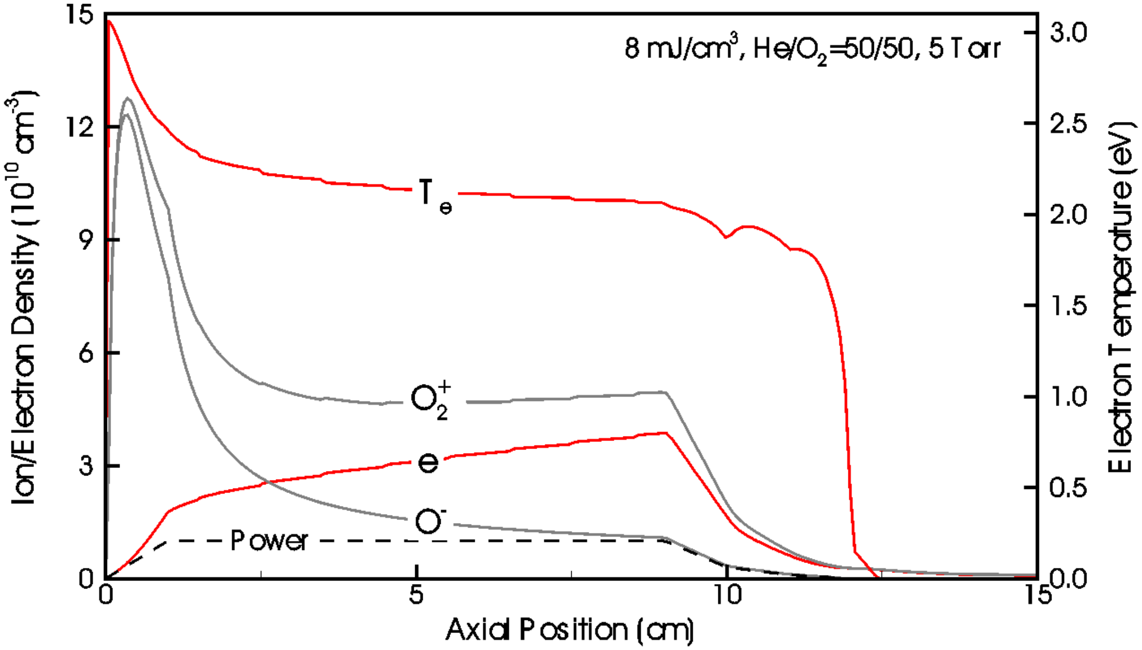
- **Self sustaining based on balance between ionization and attachment for ground state feedstock gases.**
- **Optimum conditions based on maximum power dissipated in $O_2(^1\Delta, ^1\Sigma)$ excitation.**
- **Dilution does not achieve significant improvements.**





TYPICAL PLASMA PROPERTIES: He/O_2 = 50/50, 5 Torr

- **Plug flow model with inductively coupled plasma (nearly always a self-sustaining.)**
- **Initial high T_e to avalanche plasma favors dissociative attachment and formation of O-.**
- **Steady state T_e= 2.1 eV exceeds optimum to excite $O_2(^1\Delta, ^1\Sigma)$.**



- **He/O_2 = 50/50, 5 Torr, v_0 = 10 m/s, 1 W/cm^3**

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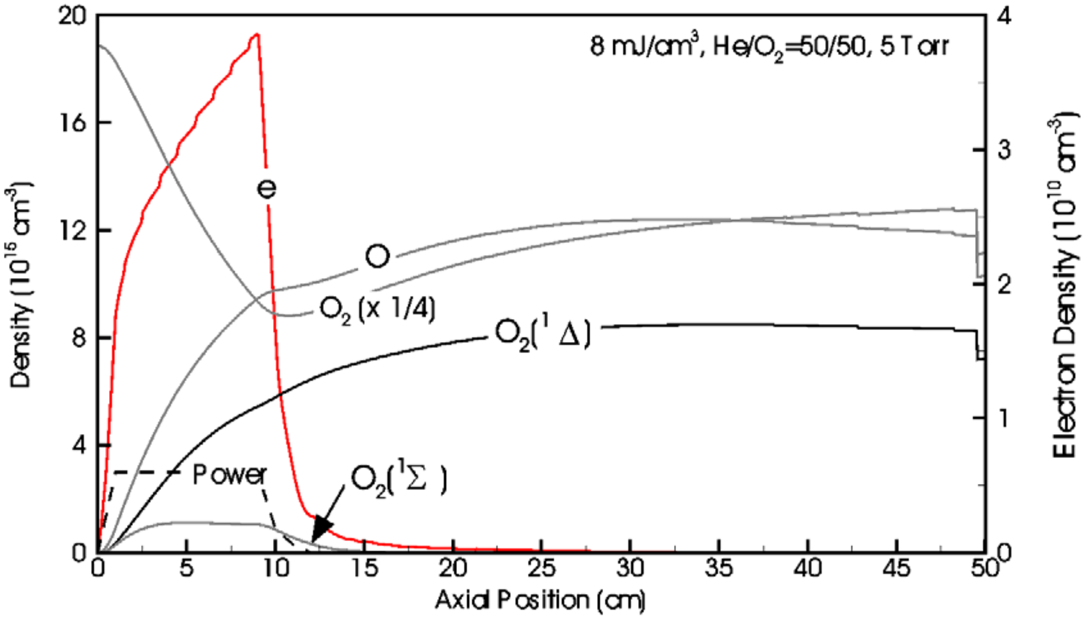
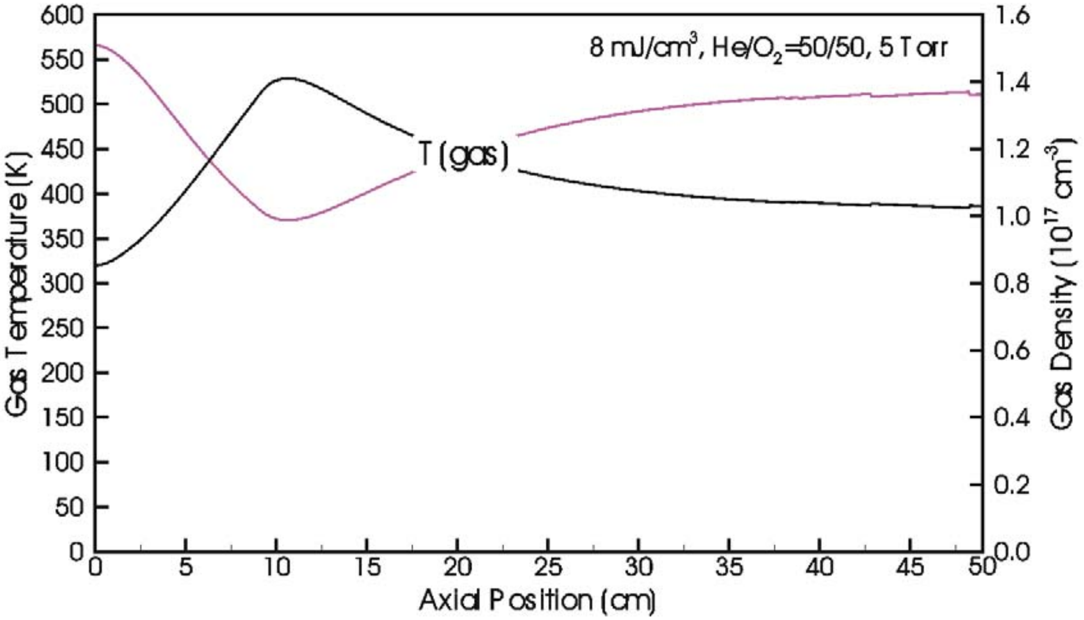
Optical and Discharge Physics

TYPICAL PLASMA PROPERTIES: He/O_2 = 50/50, 5 Torr



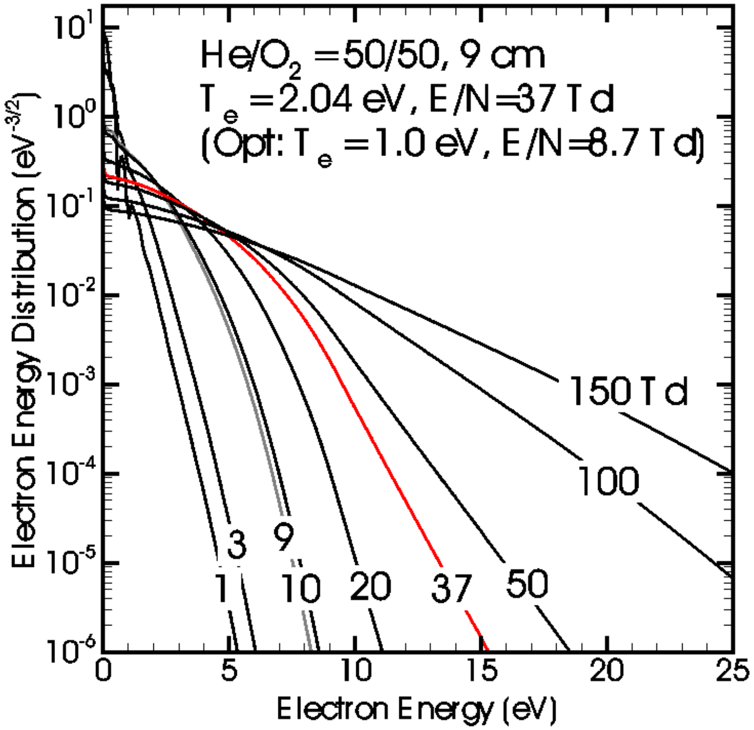


- $O_2(^1\Sigma)$ is collisionally quenched to $O_2(^1\Delta)$ after the plasma zone. $O_2(^1\Delta)$ resists quenching when energy pooling is not important.
- O atom production nearly equals $O_2(^1\Delta)$.
- Gas heating is significant, due to V-T relaxation, Frank-Condon heating.

- He/O_2 = 50/50, 5 Torr, v_0 = 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 $O_2(^1\Delta)$.**
- **Dissociation and excitation of O_2 results in:**
  - **Less attachment**
  - **More efficient ionization**
  - **Lower self-sustaining Te**
  - **Higher fractional power into $O_2(^1\Delta, ^1\Sigma)$ provided dissociation is not large.**
- **For He/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)**



PROPOSED SCALING LAW

- 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 (β) as a function of specific energy deposition (in eV per inlet O_2 molecule):

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

- Parameter ranges for ideal plug-flow system

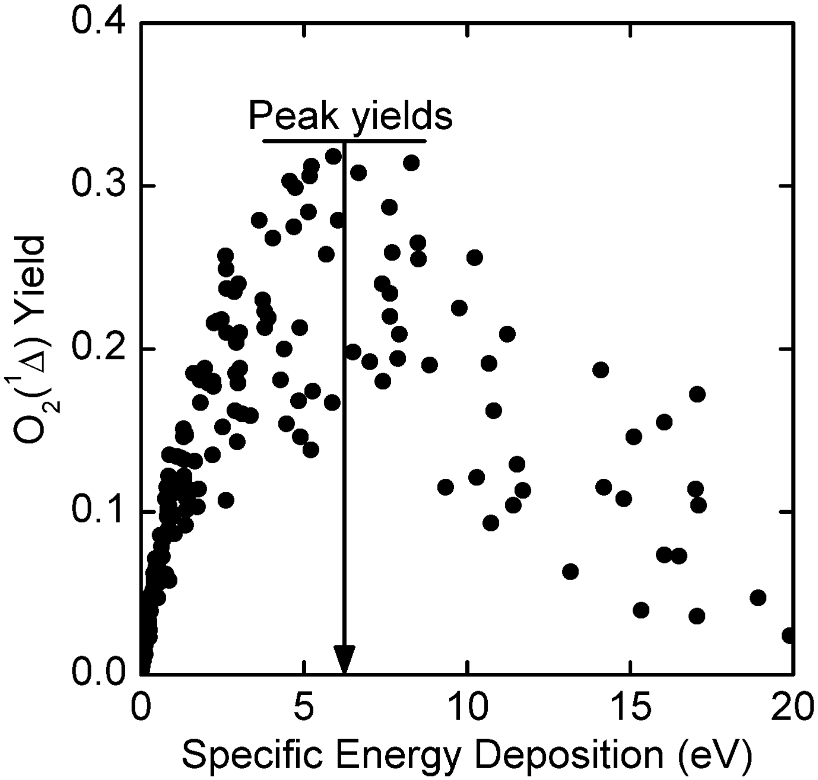
• Velocity:	500 – 5000 cm/s	These ranges give specific energies of 0 – 250 eV
• Pressure:	1 – 20 Torr	
• Power:	0.1 – 1.5 W/cc	
• Mixture:	3 – 100% O_2 in He	
• Length:	20 cm	

$O_2(^1\Delta)$ YIELD VS. SPECIFIC ENERGY DEPOSITION

- **$O_2(^1\Delta)$ yield obeys energy deposition scaling law to 1st order:**

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

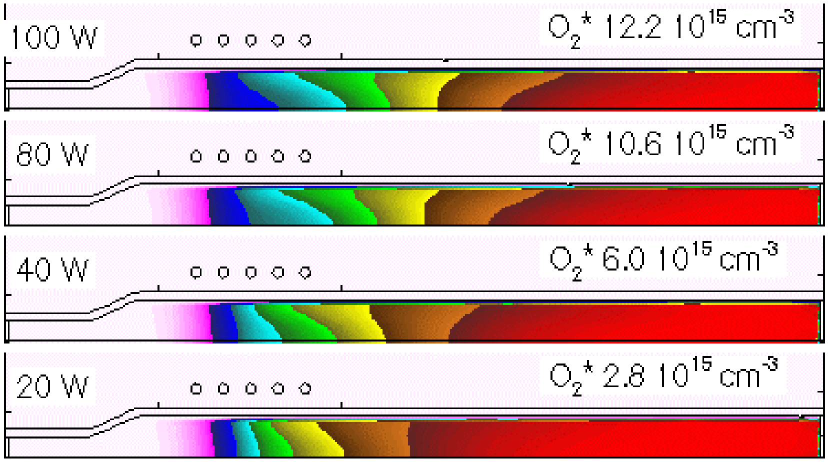
- **$O_2(^1\Delta)$ yield increases with energy as inventory integrates.**
- **$O_2(^1\Delta)$ yield decreases > 5 – 8 eV as dissociation depletes ground state and $O_2(^1\Delta)$.**
- **Scatter is due to secondary effects (mixture, pressure, power).**

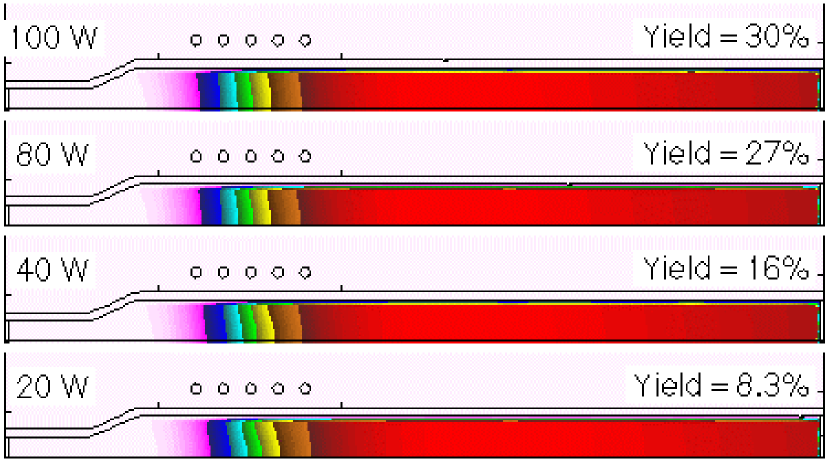


$$\text{Yield} = \frac{[O_2(^1\Delta)]}{[O_2]+[O_2(^1\Delta)]+[O_2(^1\Sigma)]+0.5[O]+1.5[O_3]}$$

$O_2(^1\Delta)$ AND YIELD vs POWER

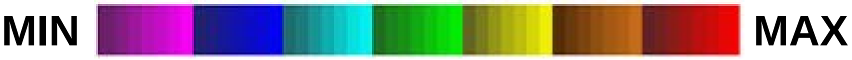
- **Yield scales sub-linearly with power in a parameter space where energy scaling should be valid.**
- **Increasingly less uniform power deposition and local depletion of O_2 is likely the cause.**





- **Energy scaling says yield=40%**

- **3 Torr, He/O_2=0.7/0.3, 6000 sccm**



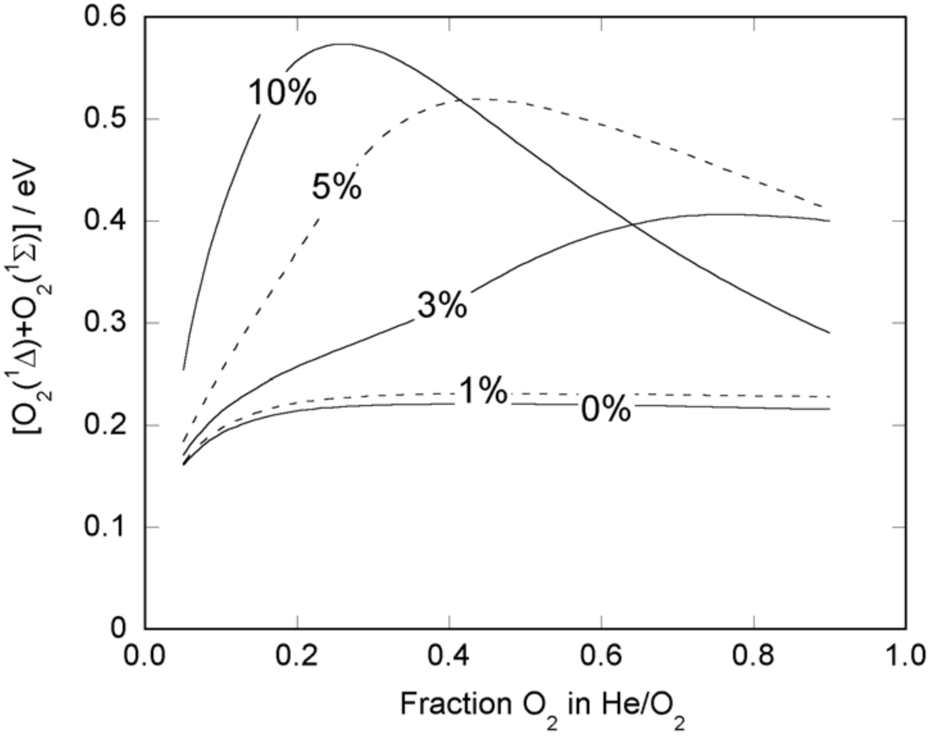
NON-SELF SUSTAINED DISCHARGES

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

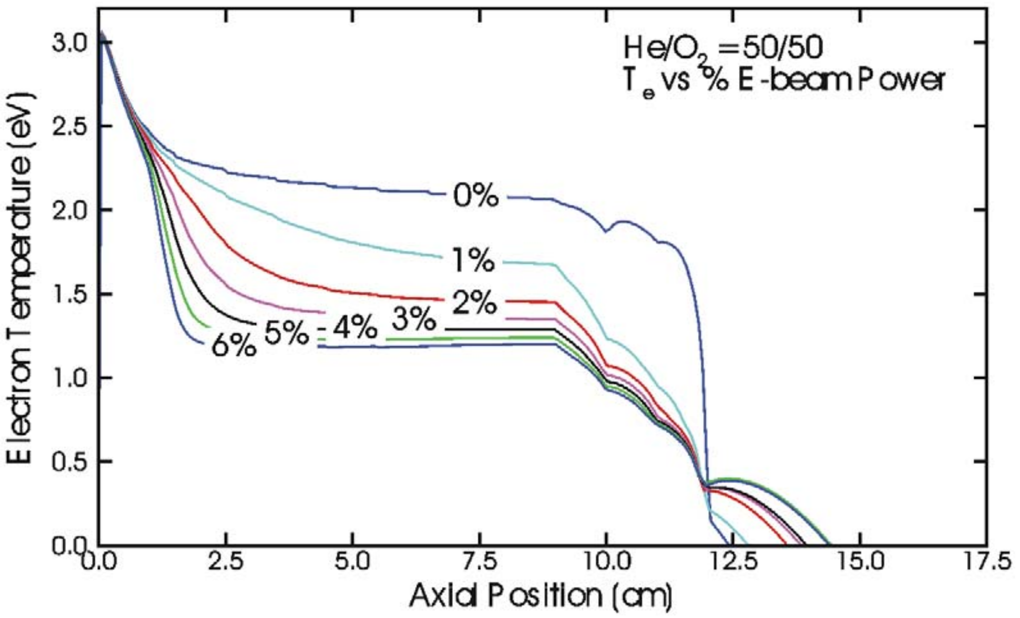
- This pushes system to larger T_e or E/N.

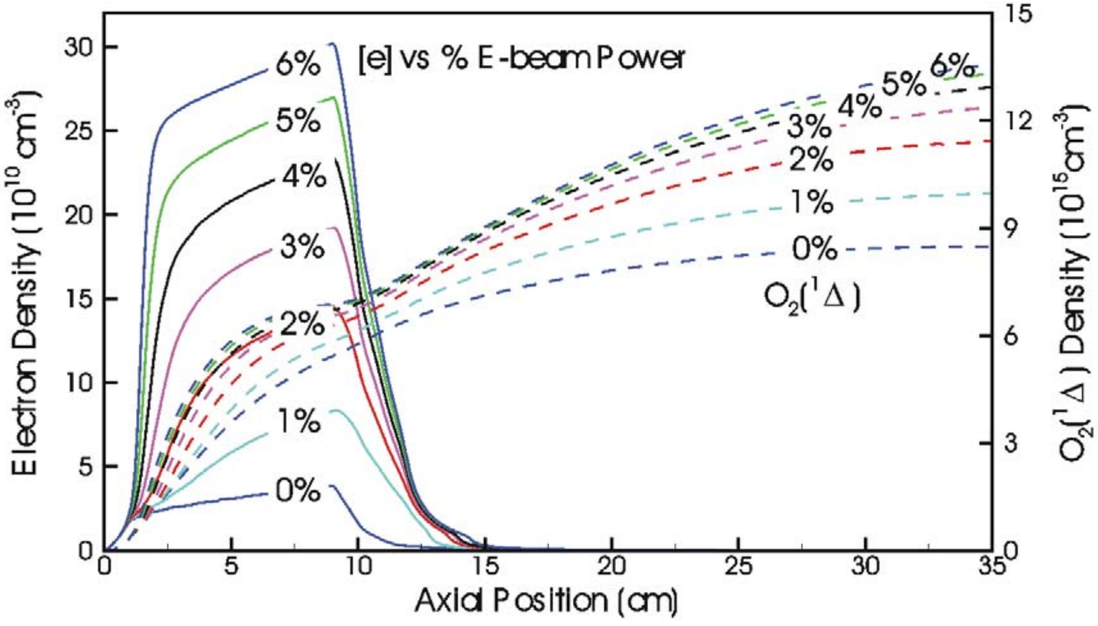
- Externally sustained system provides means to reduce T_e or E/N. to more optimum regime.

- Example: E-beam sustained plug flow system.



- Low-energy deposition yield (molecules/eV) vs Fraction of energy from E-beam (5 Torr).



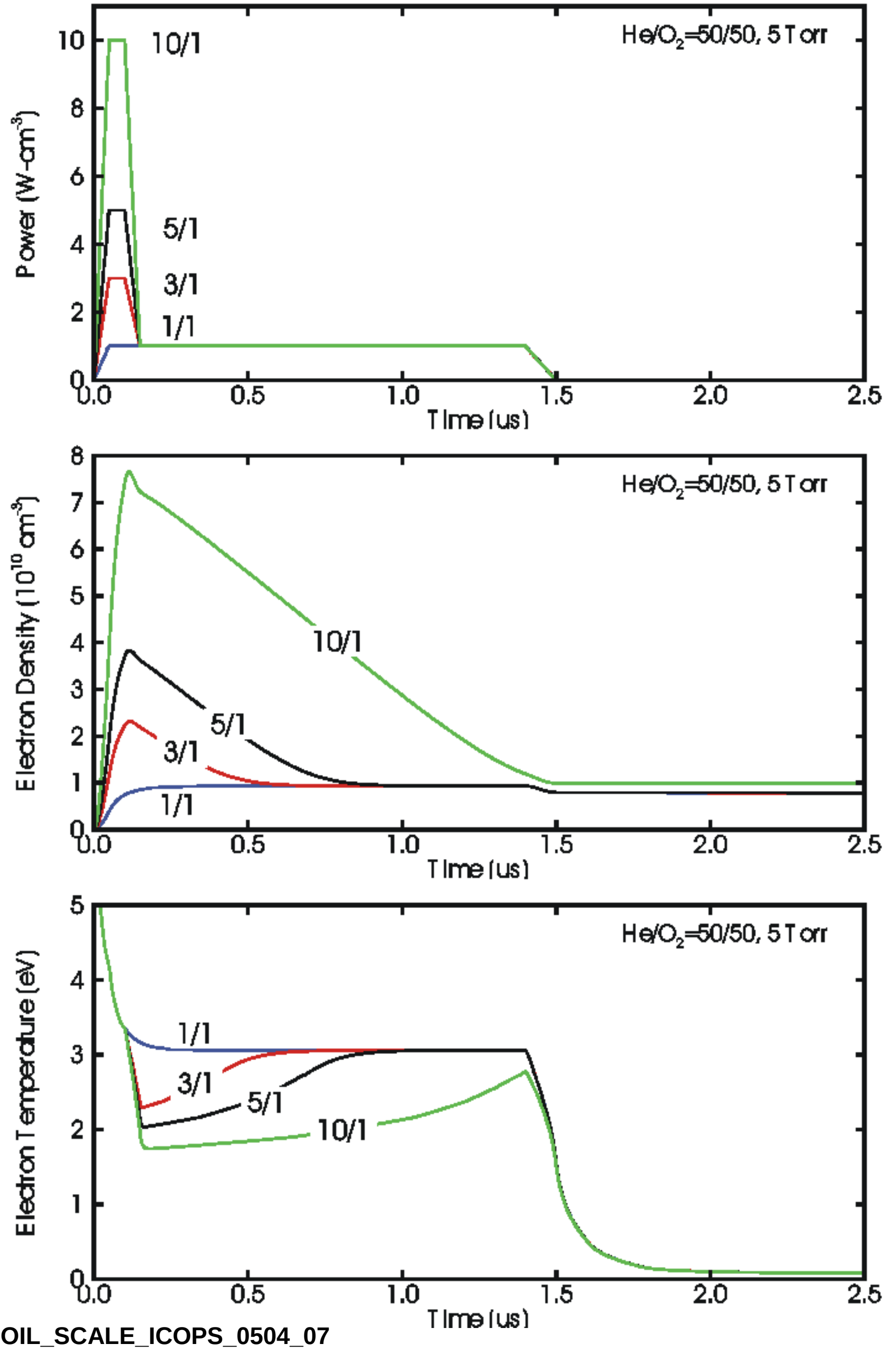


- **He/O$_2$ = 50/50, 5 Torr, v$_0$ = 10 m/s**

PLUG-FLOW WITH E-BEAM POWER DEPOSITION

- **Increasing fraction of e-beam power lowers T$_e$, saturating at 5-6%**
- **Reduction in T$_e$ shifts operating point closer to optimum value, increasing yield from 15% to 26%; and reducing dissociation.**
- **1 W/cm^3**

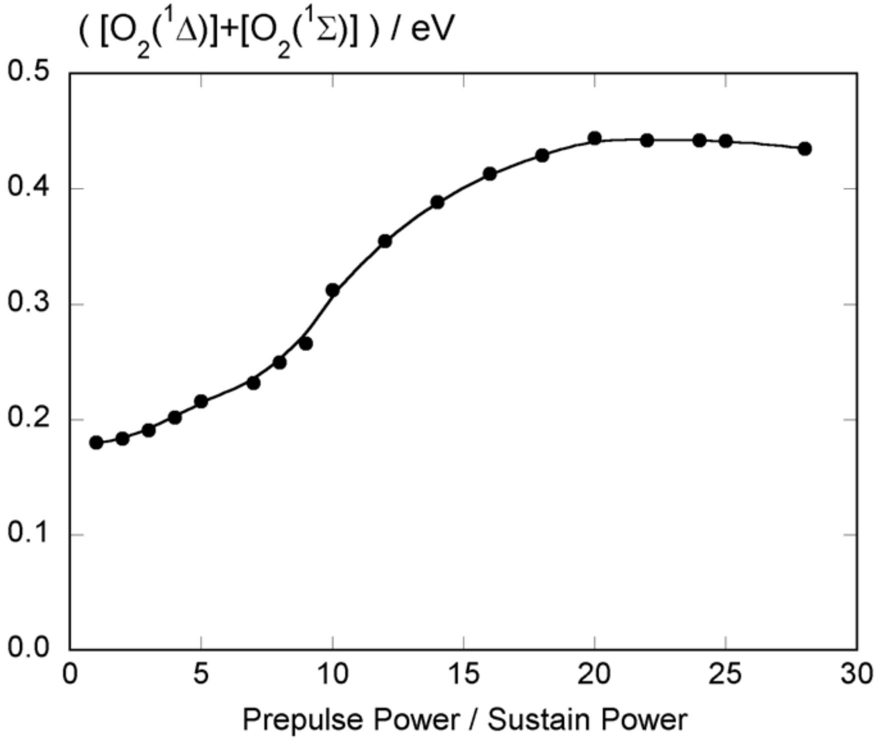
SPIKER-SUSTAINER



- **Spiker-sustainer circuit provides in situ “external ionization”**
- **Short high voltage (power) pulse is followed by plateau of lower voltage (power).**
- **Excess ionization in “after-glow” following spiker allows sustainer to operate below self sustaining T_e (E/N).**
- **Excess ionization decays within 0.5-1.5 μs, during which T_e is below self sustaining value.**

- **He/O$_2$ = 50/50, 5 Torr**

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



- **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**

CONCLUDING REMARKS

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