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

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AGENDA

- Overview of $O_2(^1\Delta)$ kinetics in non-equilibrium discharges
- Energy scaling of $O_2(^1\Delta)$ yield
- T_e (E/N) engineering to maximize yield
- System studies
- Concluding remarks

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OXYGEN-IODINE LASERS

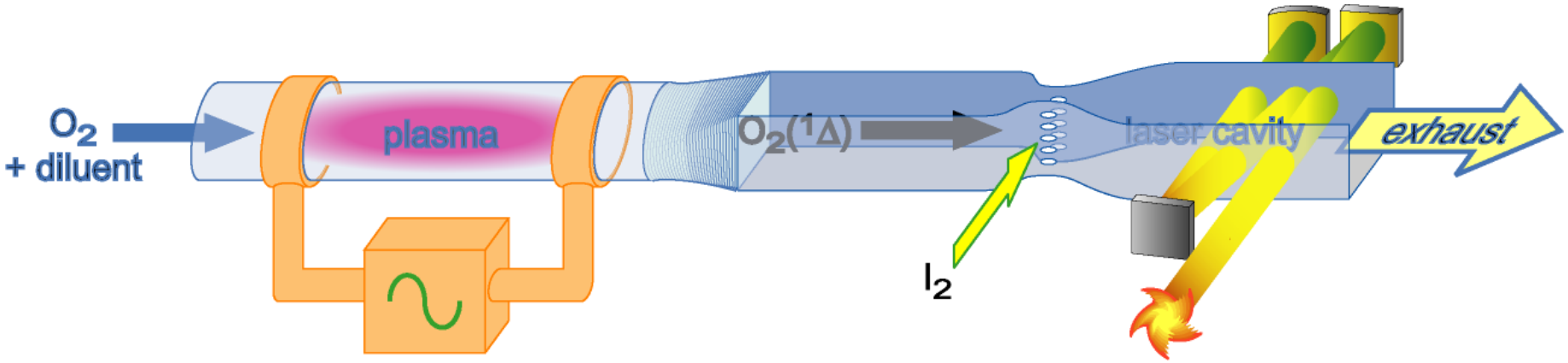
- $O_2(^1\Delta)$ dissociates I_2 and pumps I which lases on the $^2P_{1/2} \rightarrow {}^2P_{3/2}$ electronic transition.

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

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

- 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.



ELECTRIC DISCHARGE COILS

- **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**

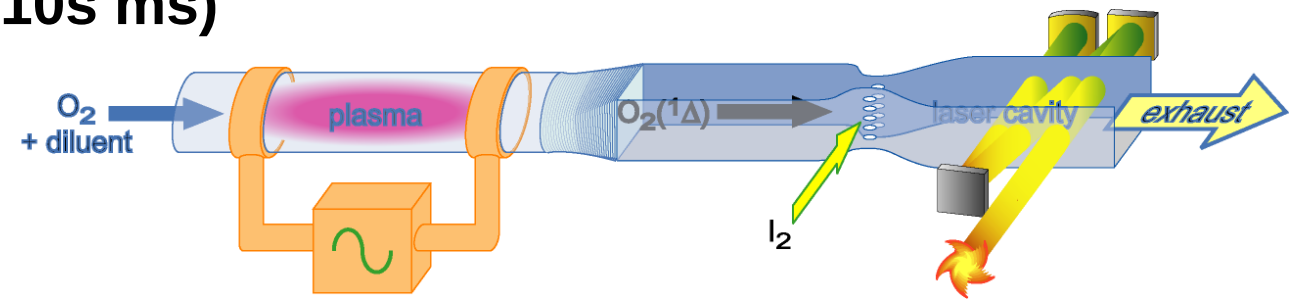
.... and (historical) Disadvantages

  - **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

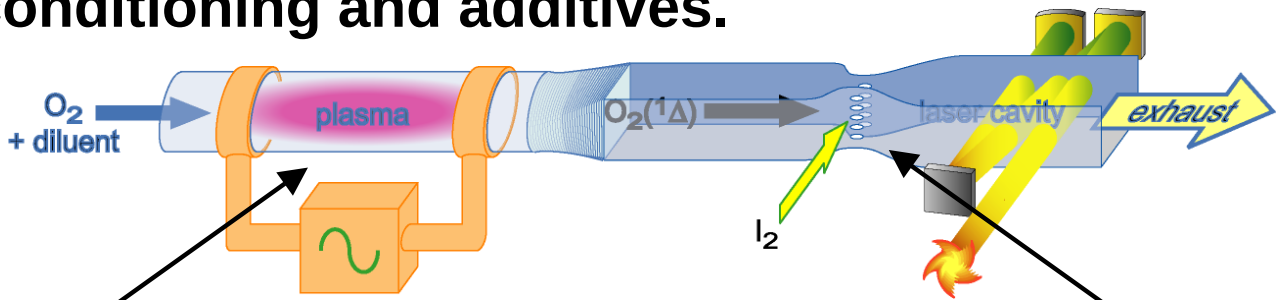
- **Pressures: a few to 10s Torr**
  - **Higher is better to provide back pressure for expansion**
- **Mixtures: He/O_2 , $f(O_2)$ = 10's – 50%**
  - **Need He for discharge stability, tailoring E/N, high thermal conductivity.**
- **Size: Flow tube 3-10 cm diameter (pump limited?)**
- **Flow speeds: 10s m/s (plasma residence time many ms, flow times 10s ms)**

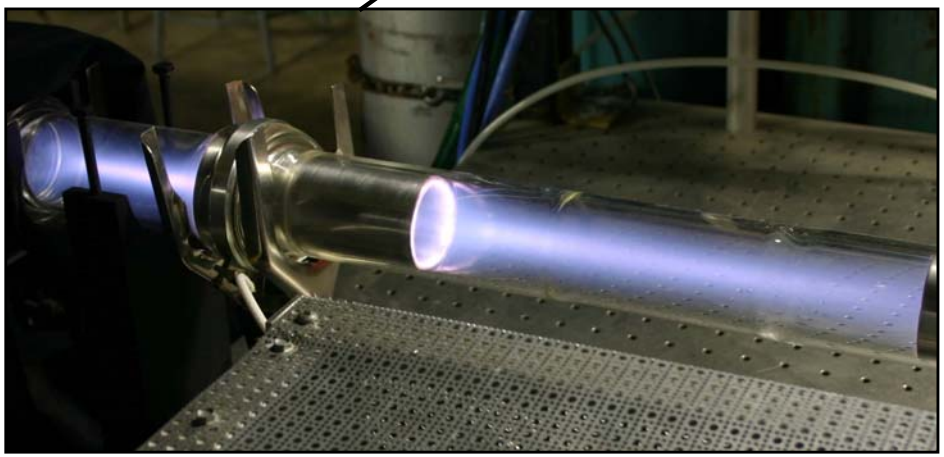


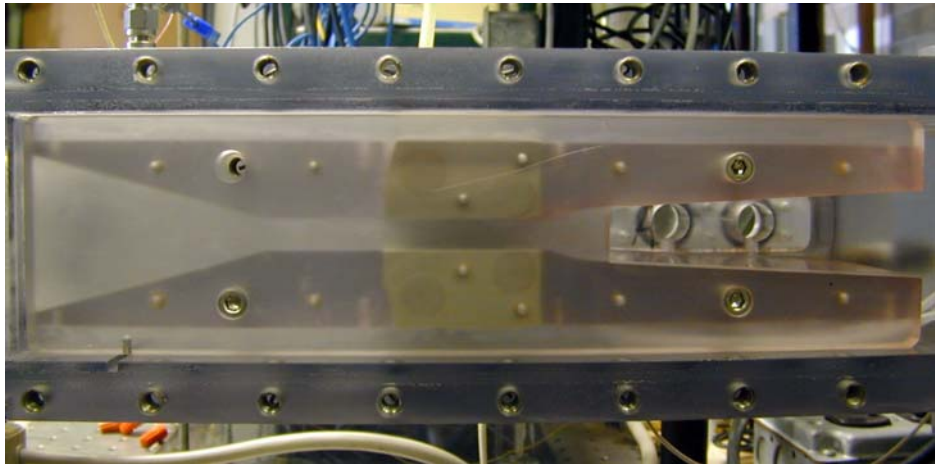
CURRENT IMPLEMENTATION: CU AEROSPACE

- **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.**







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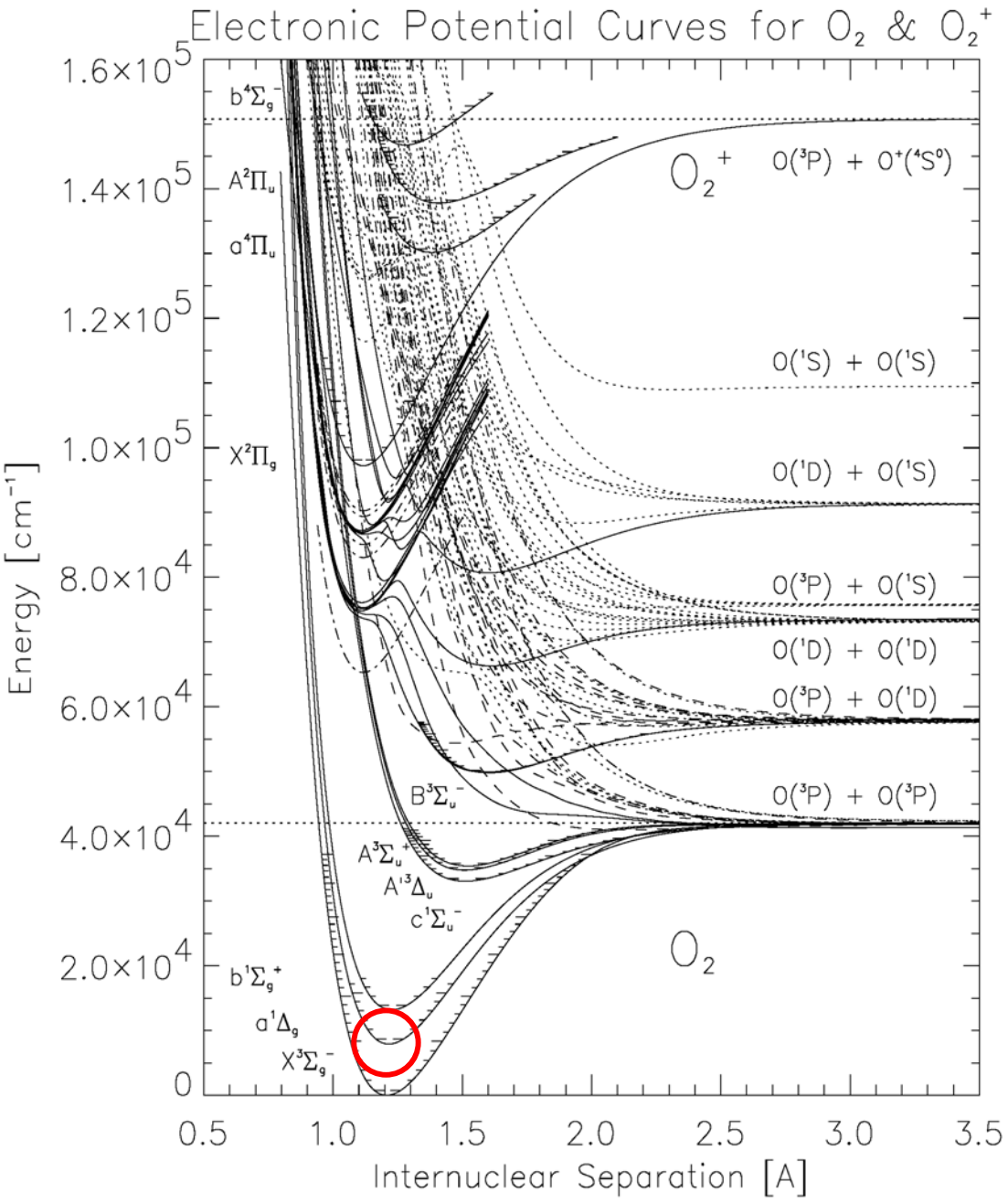
GROUND RULES

- **This talk will focus on $O_2(^1\Delta)$ generation in low pressure quasi-cw plasmas for COIL.**
  - **The COIL community will know what to do with a large enough yield…. I_2-$O_2(^1\Delta)$ 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

- **$O_2(^1\Delta)$ is a remarkably robust molecule. Once produced, its reactivity and quenching are low**
  - **Low efficiency systems can produce large yields of $O_2(^1\Delta)$ 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.

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

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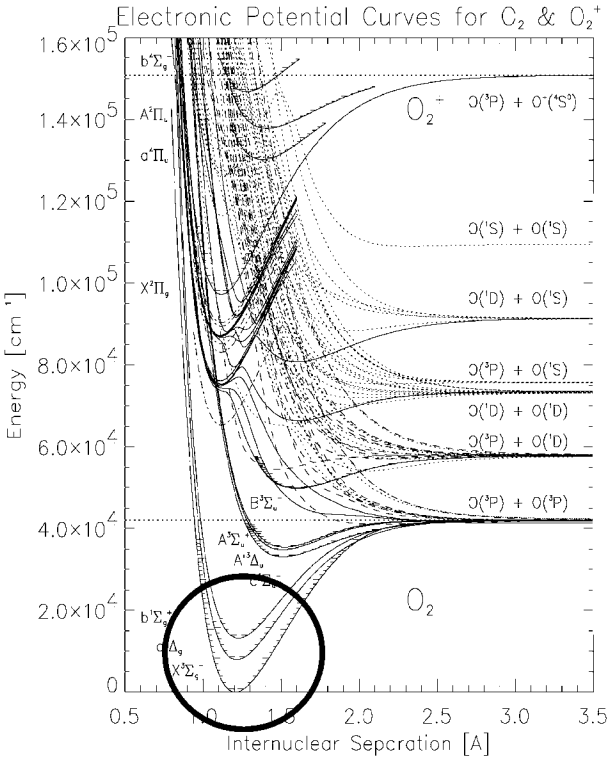
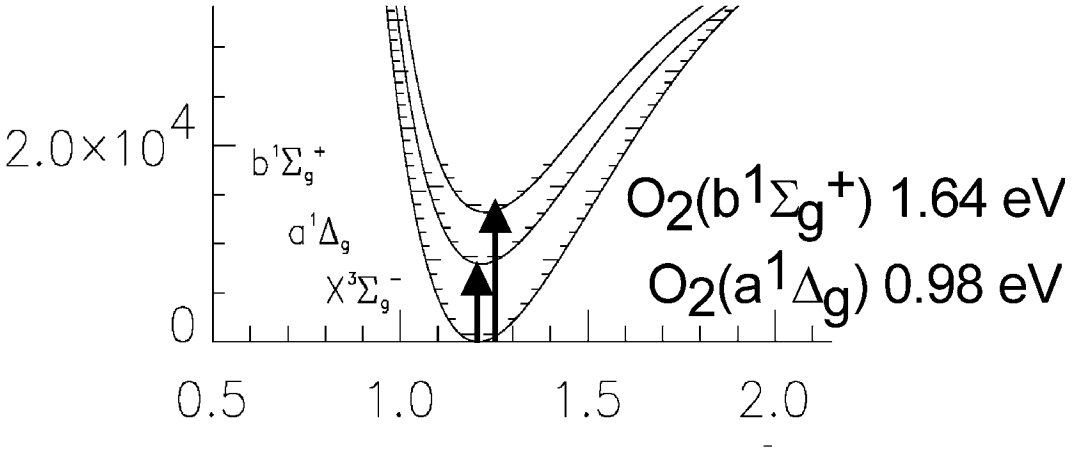
O_2 ELECTRONIC EXCITATION: THE GOOD….

- **Production of $O_2(^1\Delta)$ is by direct electron impact [0.98 eV] or through excitation of $O_2(^1\Sigma)$ [1.6 eV] with subsequent rapid (and efficient) quenching to $O_2(^1\Delta)$.**





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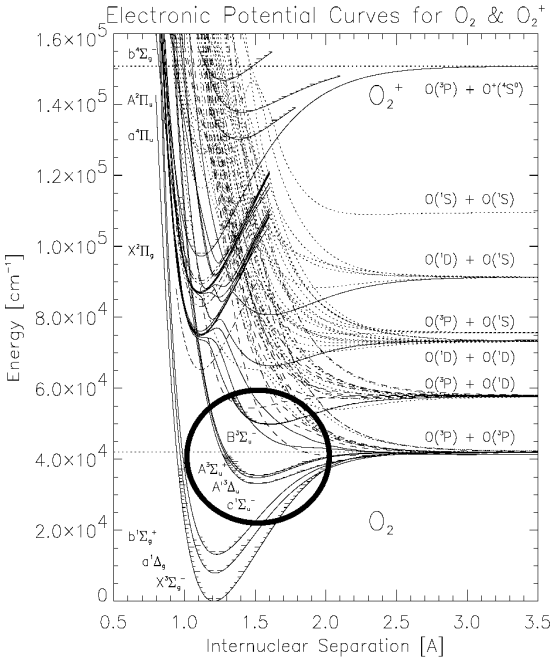
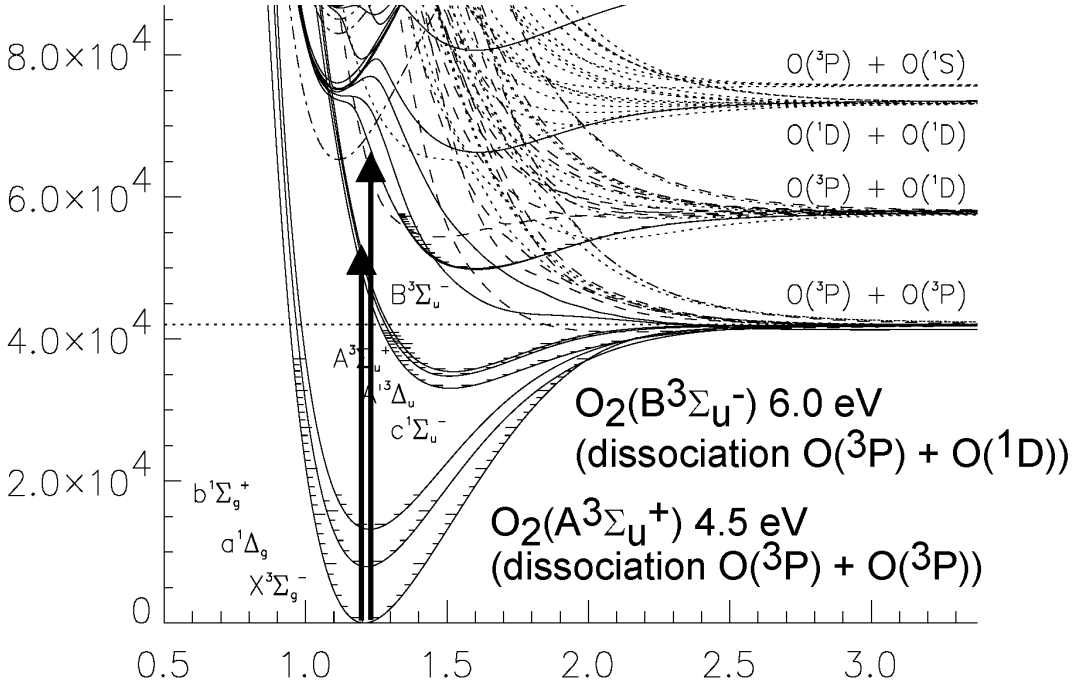
O_2 ELECTRONIC EXCITATION: THE BAD….

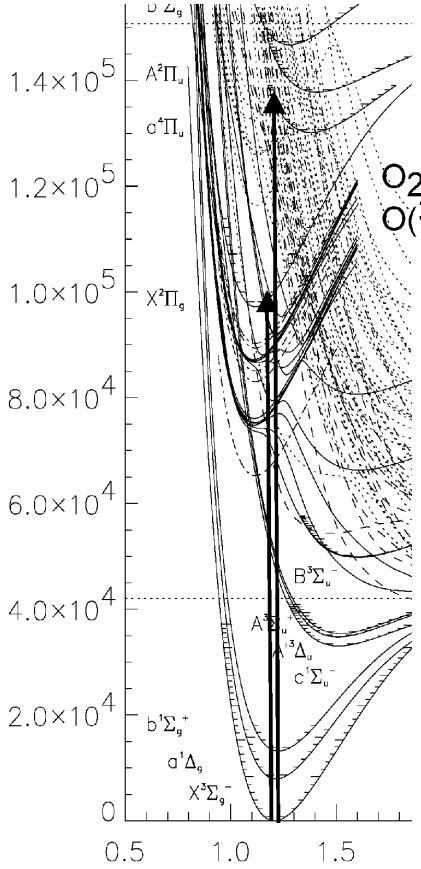
- **Excitation to $O_2(A^3\Sigma)$ and $O_2(B^3\Sigma)$ are dissociative which depletes the ground state; reformation of O_2 is slow.**
- **The O atoms rapidly quench $O_2(^1\Sigma) \rightarrow O_2(^1\Delta)$.**
- **$O(^1D)$ produces $O_2(^1\Delta)$ through collisions with O_2.**





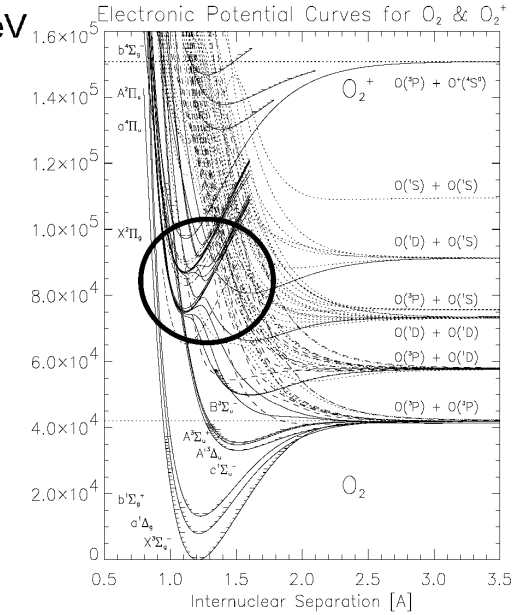
O_2 IONIZATION: THE UGLY….

- **Ionization of O_2 sustains the discharge but…**
- **O_2^+ dissociatively recombines (a loss) or neutralizes with O_2^- and O^-, possible dissociatively (a loss).**
- **Any subsequent formation of $O_2(^1\Delta)$ is at high energy cost.**

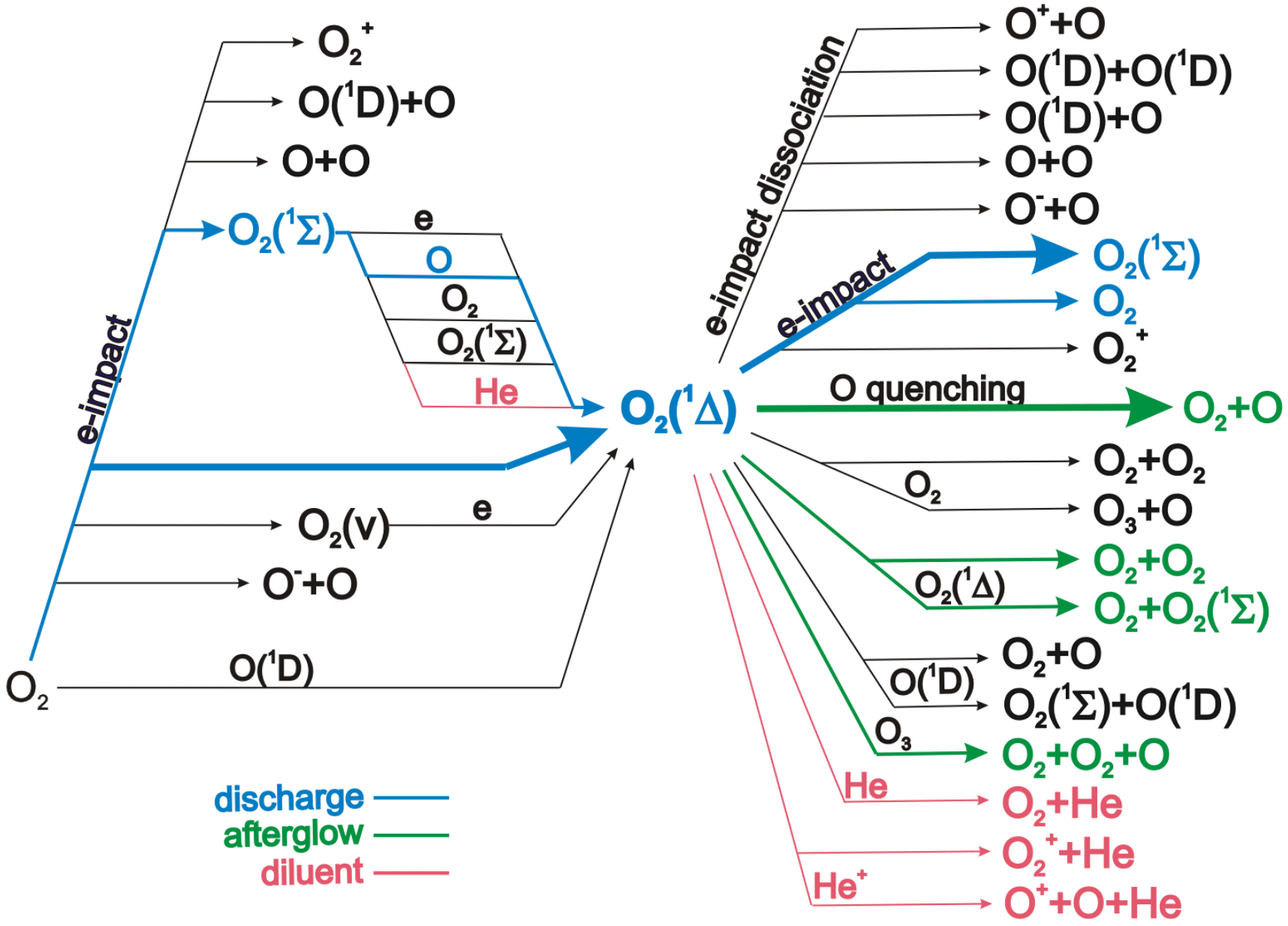


$O_2^+(A^2\Pi_u, a^4\Pi_u)$ 14.7 eV
$O(^3P) + O(^4S_0)^+$

$O_2^+(^2\Pi g)$ 12.1 eV



REACTION MECHANISM



IMPORTANT CHEMISTRY

- **$O_2(^1\Delta)$ is a remarkably robust molecule whose density can accumulate. Its reactivity and quenching rates are low.**

$$O_2\left(^1\Delta\right)+O_2 \rightarrow O_2+O_2 \quad k=3\times10^{-18}\,cm^3s^{-1}, \quad \tau=2\ s$$
$$O_2\left(^1\Delta\right)+O \rightarrow O+O_2 \quad k=2\times10^{-16}\,cm^3s^{-1}, \quad \tau=30\ ms$$

- **$O_2(^1\Sigma)$ is rapidly quenched to $O_2(^1\Delta) \rightarrow O_2(^1\Sigma)$. As such its production is equivalent $O_2(^1\Delta)$**

$$O+O_2\left(^1\Sigma\right)\rightarrow O+O_2\left(^1\Sigma\right) \quad k=7.2\times10^{-14}\,cm^3s^{-1}, \quad \tau=0.2\ ms$$

- **$O(^1D)$ production is bad due to dissociation having occurred. However, if any O_2 remains, $O_2(^1\Delta, ^1\Sigma)$ is recouped.**

$$O\left(^1D\right)+O_2 \rightarrow O+O_2\left(^1\Delta,^1\Sigma\right) \quad k=3.4\times10^{-11}\,cm^3s^{-1}, \quad \tau=10s\ \mu s$$

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IMPORTANT CHEMISTRY

- **$O_2(^1\Delta)$ energy pooling recycles into $O_2(^1\Sigma)$ or quenches to O_2. In either case, the rates are slow**

$$O_2\left(^1\Delta\right)+O_2\left(^1\Delta\right)\rightarrow O_2+O_2 \quad k=1.4\times10^{-17}\,cm^3s^{-1}, \quad \tau=1\,s$$

- **O_3 is a rapid quencher of most states and could be an issue at slower flow rates.**

$$O+O_2+M\rightarrow O_3+M \qquad k=3-6\times10^{-34}\,cm^6s^{-1}, \quad \tau=10\,ms$$

- **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.**

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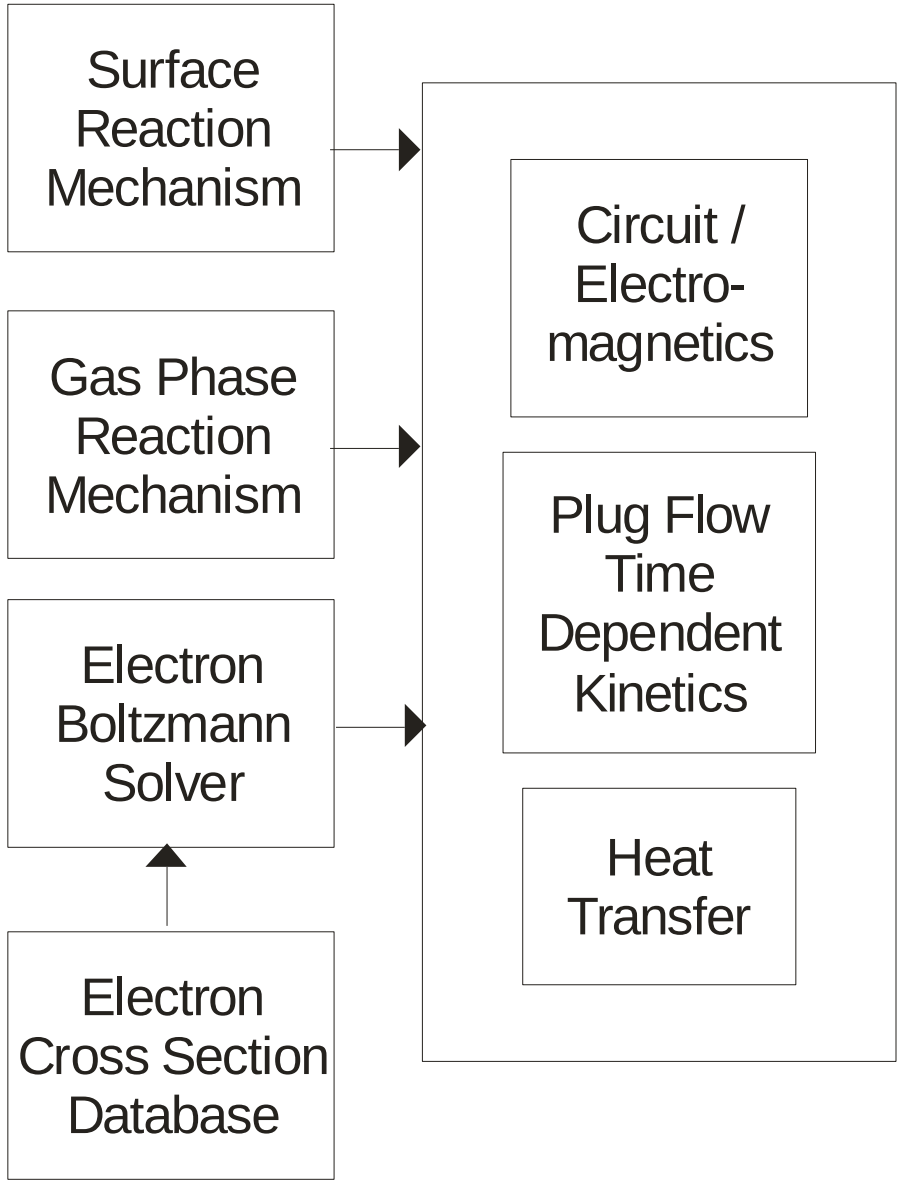
DESCRIPTION OF GLOBAL_KIN

- **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.**

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

- **Poisson's Equation for Electric Potential:** $-\nabla\cdot\varepsilon\nabla\Phi = \rho_V + \rho_S$
- **Photoionization, electric field and secondary emission:**

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

$$S_{Si} = -\nabla\cdot j, \quad j_E = AT^2\exp\left(\frac{-\left(\Phi_W - \left(q^3\mathrm{E}/\varepsilon_0\right)^{1/2}\right)}{kT_S}\right), \quad j_S = \sum_j \gamma_{ij}\phi_j$$

DESCRIPTION OF MODEL: CHARGED PARTICLE, SOURCES

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

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

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

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

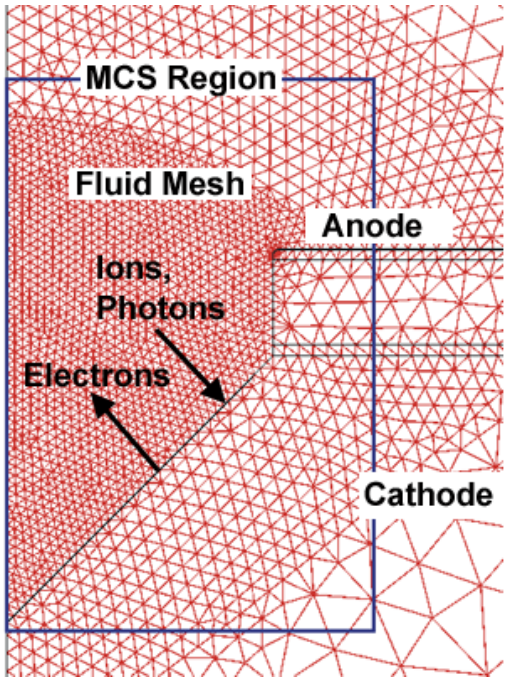
- **Individual fluid species diffuse in the bulk fluid.**

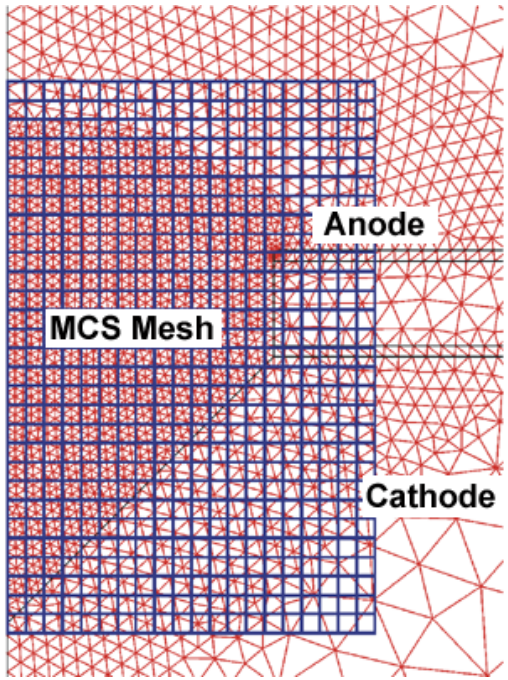
$$N_i(t + \Delta t) = N_i(t) - \nabla \cdot \left(\vec{v}_f - D_i N_T \nabla \left(\frac{N_i(t + \Delta t)}{N_T} \right) \right) + S_V + S_S$$

ELECTRON TRANSPORT: BULK AND BEAM

- **Bulk electron energy equation with Boltzmann's equation derived transport coefficients.**

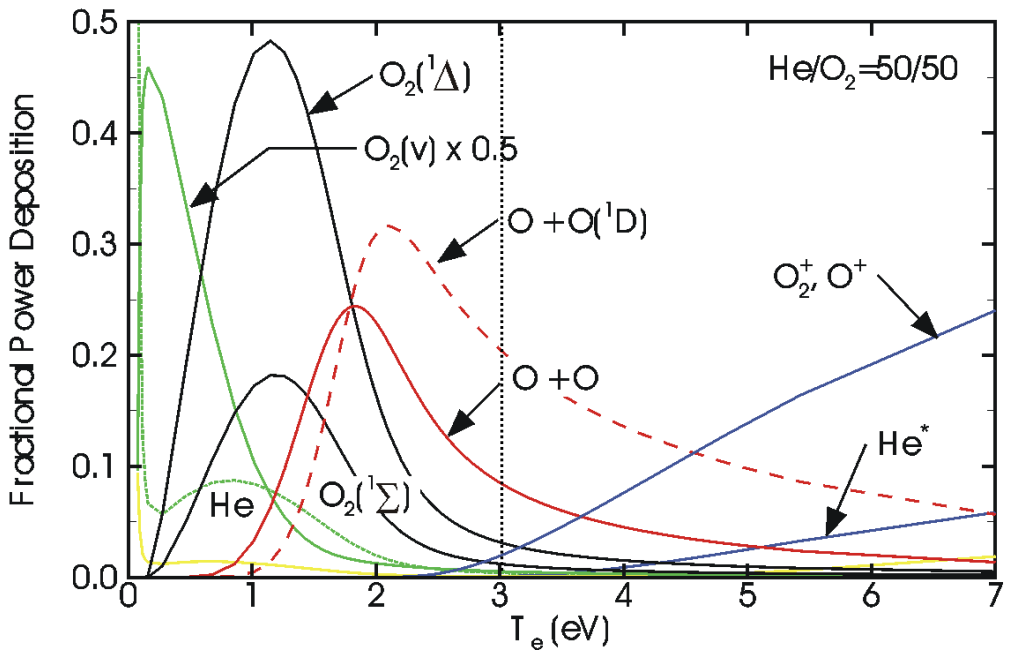
$$\frac{\partial(n_e\varepsilon)}{\partial t} = \vec{j}\cdot\vec{E} - n_e\sum_i N_i\kappa_i - \nabla\cdot\left(\frac{5}{2}\varepsilon\varphi - \lambda\nabla T_e\right), \quad \vec{j} = q\vec{\phi}_e$$

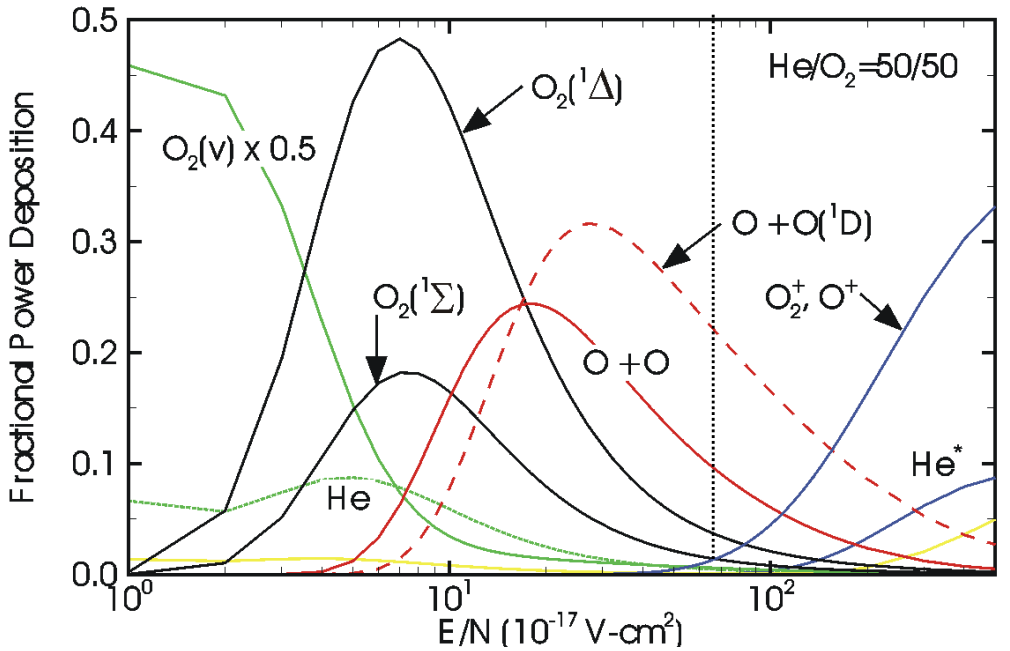




- **Transport of energetic secondary electrons is addressed with a Monte Carlo Simulation.**
- **Electrons and their progeny are followed until slowing into bulk plasma or leaving MCS volume.**

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.**

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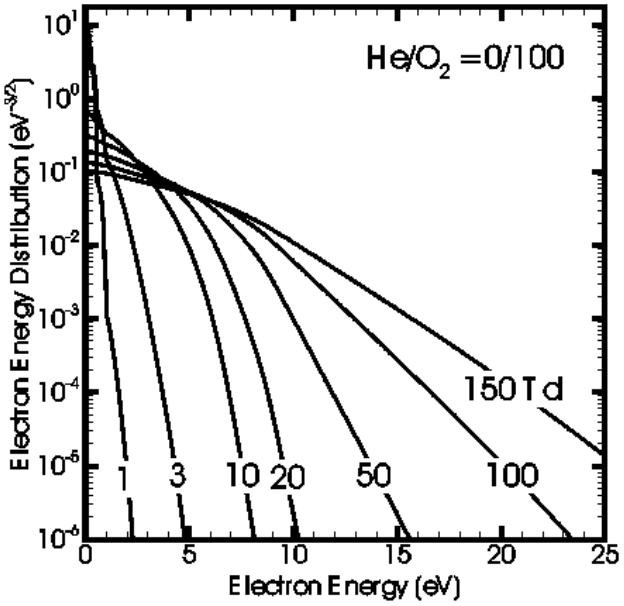
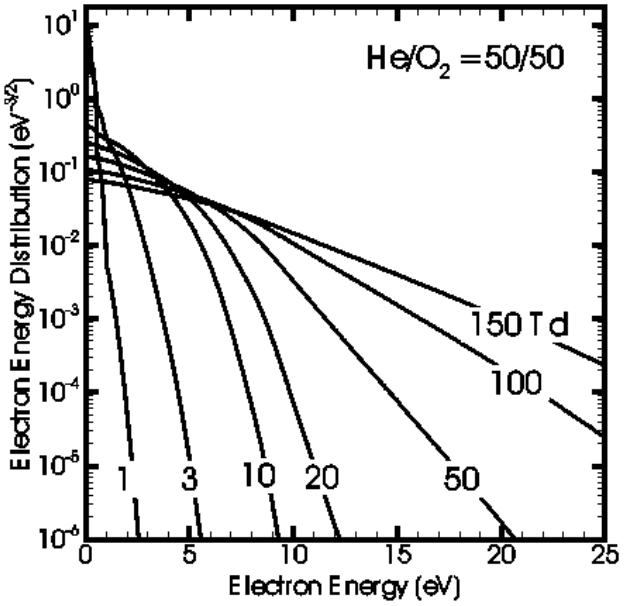
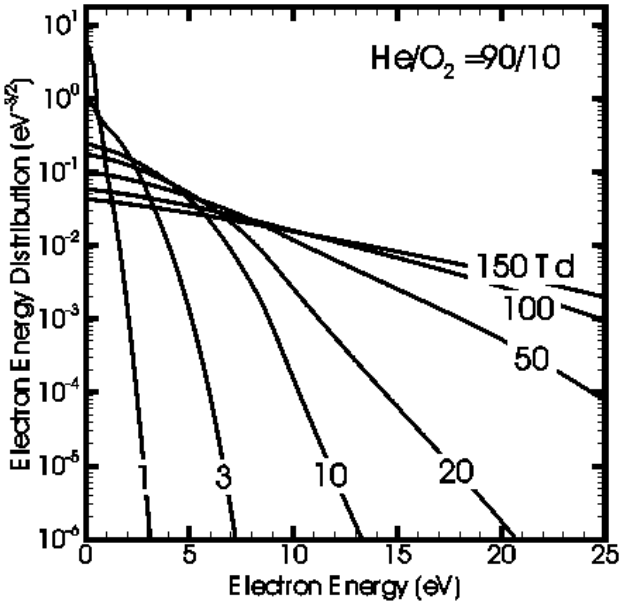
ELECTRON ENERGY DISTRIBUTIONS IN He/O_2 MIXTURES

- **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.**







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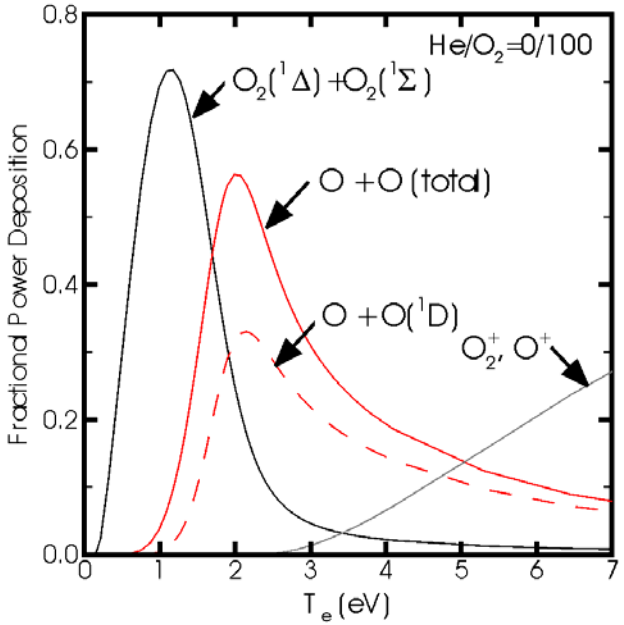
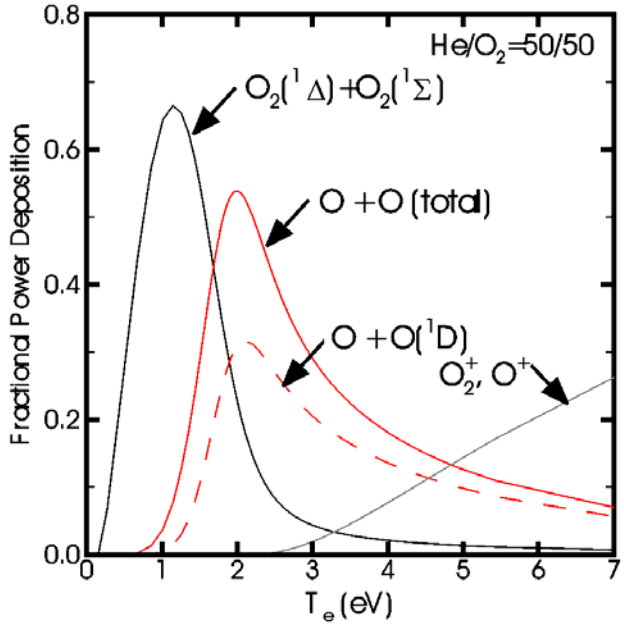
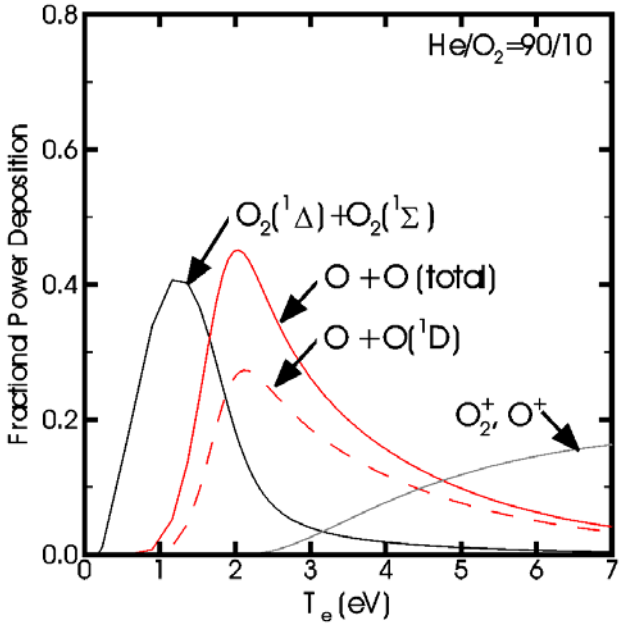
POWER PARTITIONING: T_e vs He/O_2

- 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.

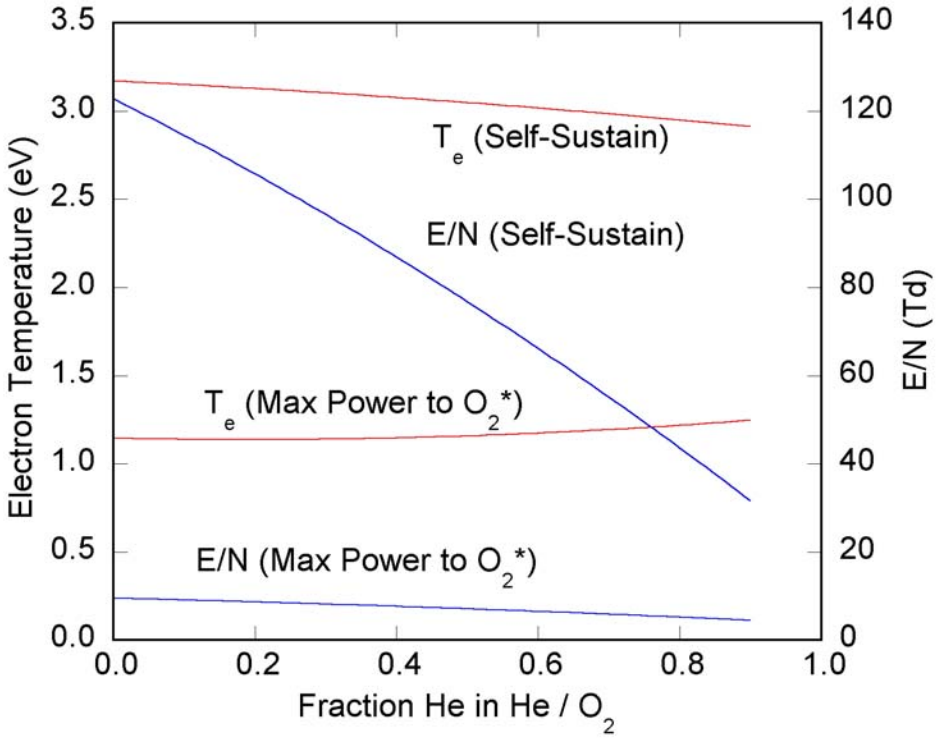


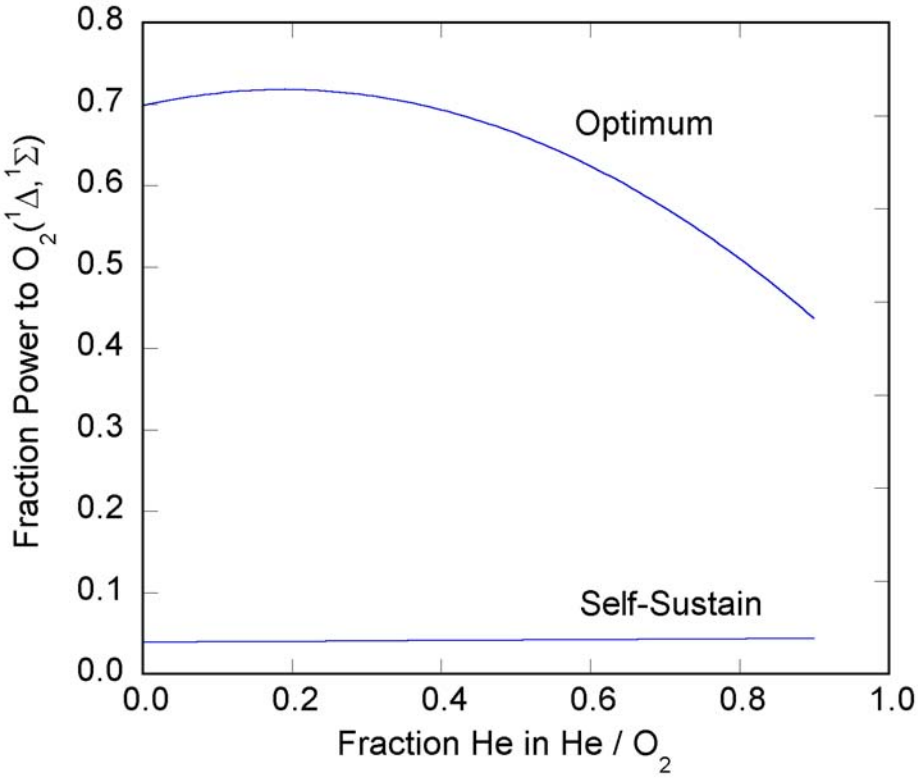




DISCHARGE PARAMETERS: SELF-SUSTAIN vs OPTIMUM

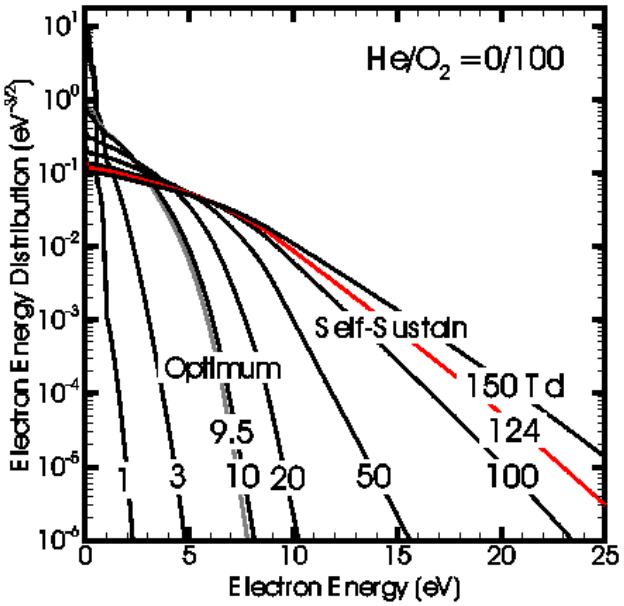
- **Self sustaining based on balance between ionization and attachment for ground state feedstock gases.**
- **Optimum conditions based on maximum power dissipated in $O_2(^1\Delta, ^1\Sigma)$ excitation.**

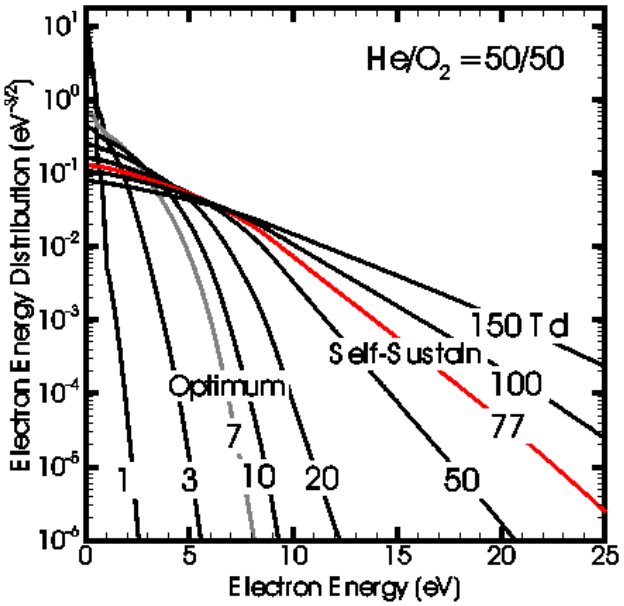


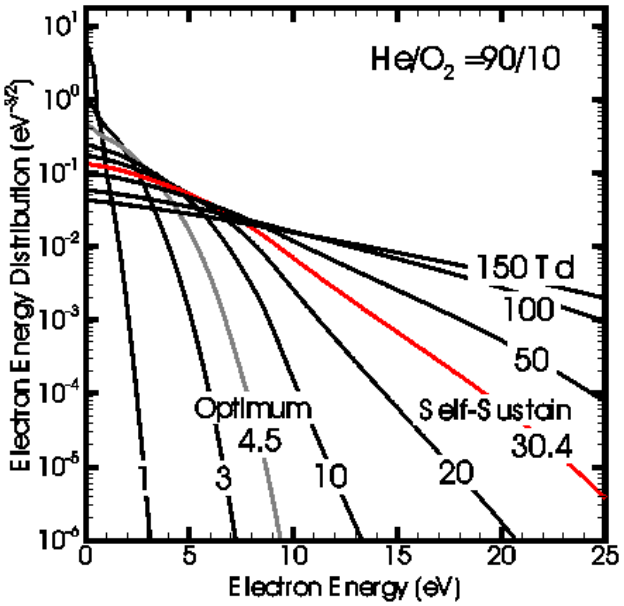


EEDs IN He/O_2 MIXTURES: SELF SUSTAIN vs OPTIMUM

- **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 $O_2(^1\Delta, ^1\Sigma)$.**







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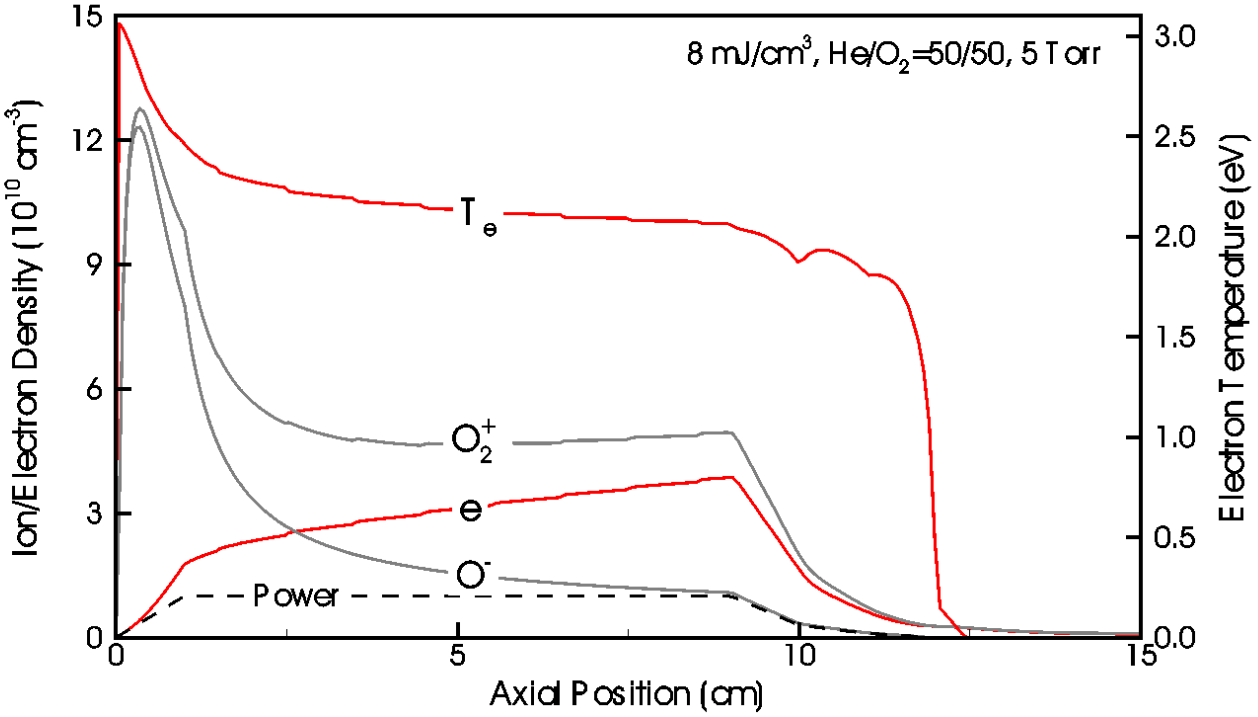
TYPICAL PLASMA PROPERTIES: He/O_2 = 50/50, 5 Torr

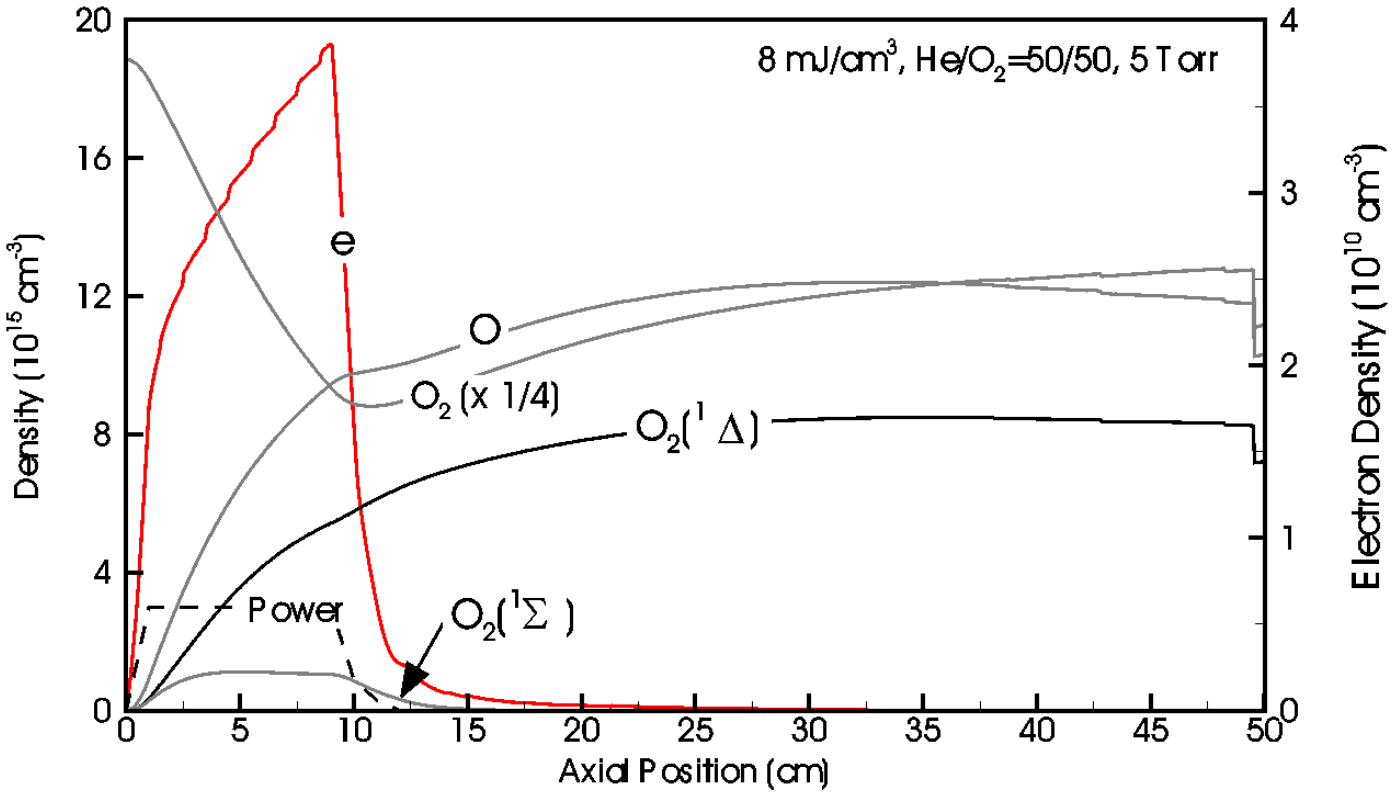
- **Plug flow model with inductively coupled plasma (nearly always a self-sustaining.)**
- **Initial high T_e to avalanche plasma favors dissociative attachment and formation of O-.**
- **Steady state T_e= 2.1 eV exceeds optimum to excite $O_2(^1\Delta, ^1\Sigma)$.**



- **He/O_2 = 50/50, 5 Torr, v_0 = 10 m/s, 1 W/cm³**

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

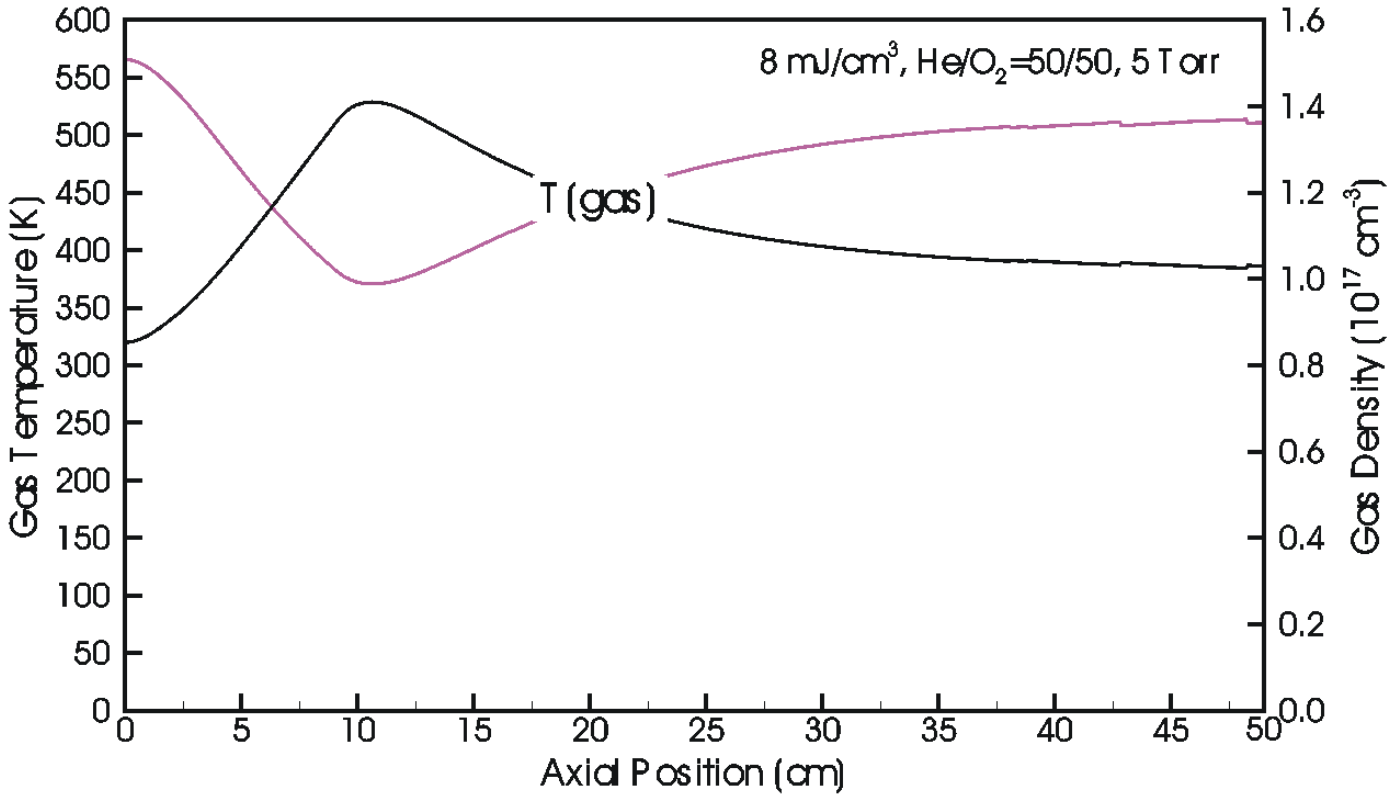
- $O_2(^1\Sigma)$ is quickly collisionally converted to $O_2(^1\Delta)$ after the plasma zone. $O_2(^1\Delta)$ is robust and resists quenching when energy pooling is not important.
- O atom production nearly equals $O_2(^1\Delta)$.



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

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

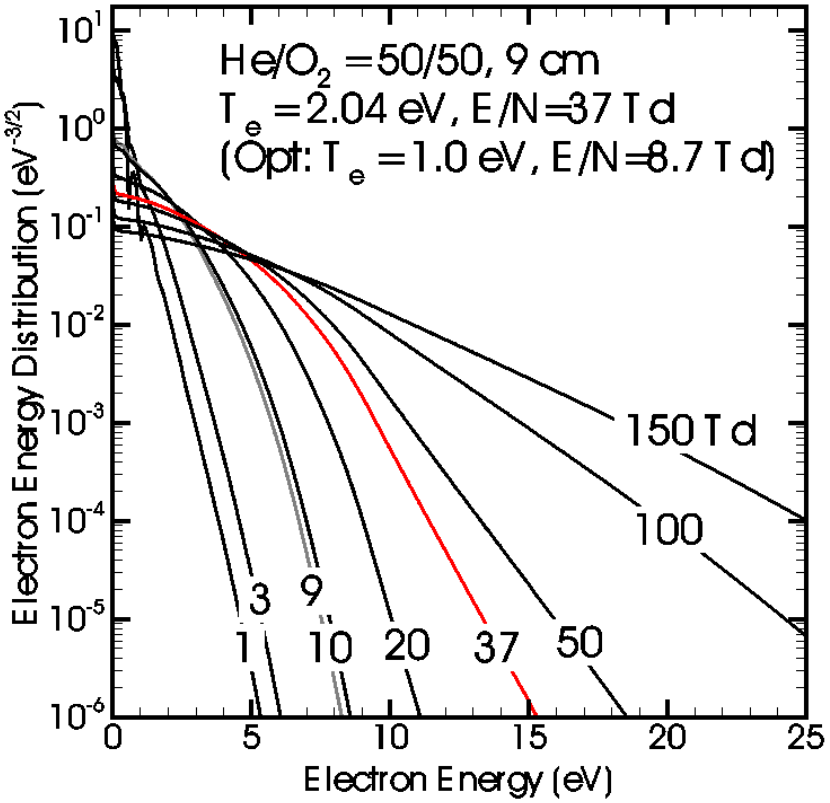
- **Gas heating is significant, due largely to V-T relaxation, Frank-Condon heating.**
- **Downstream chemical kinetics depends on active vs passive cooling.**



- **He/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):

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

- 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

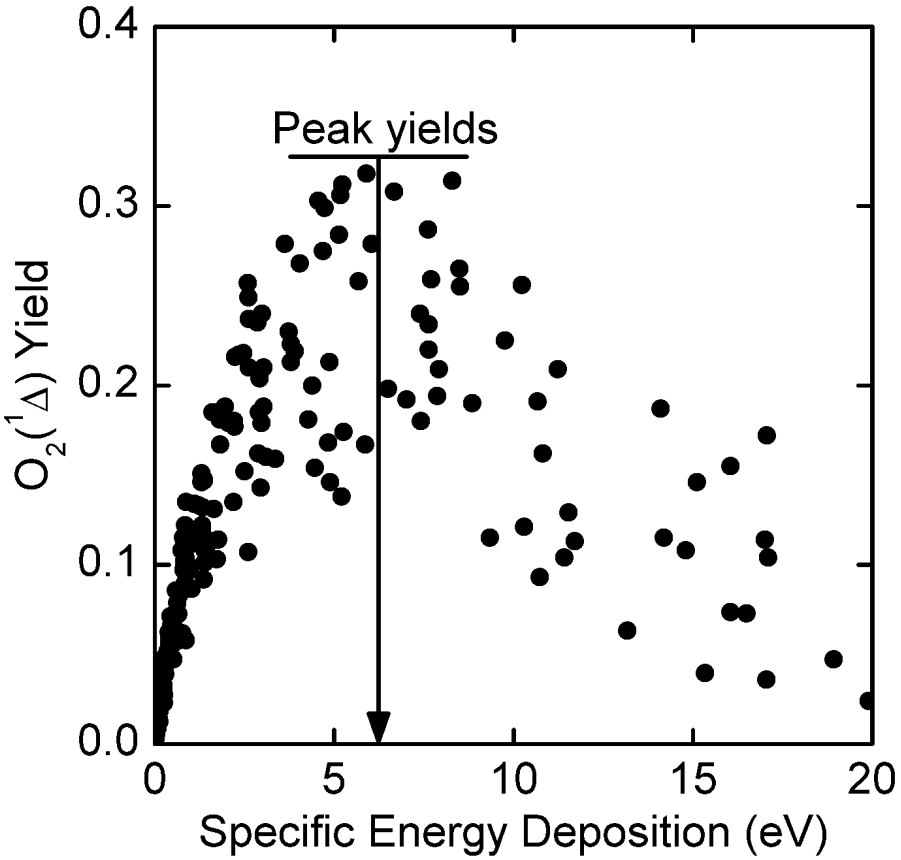
} These ranges give specific energies of 0 – 250 eV

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

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

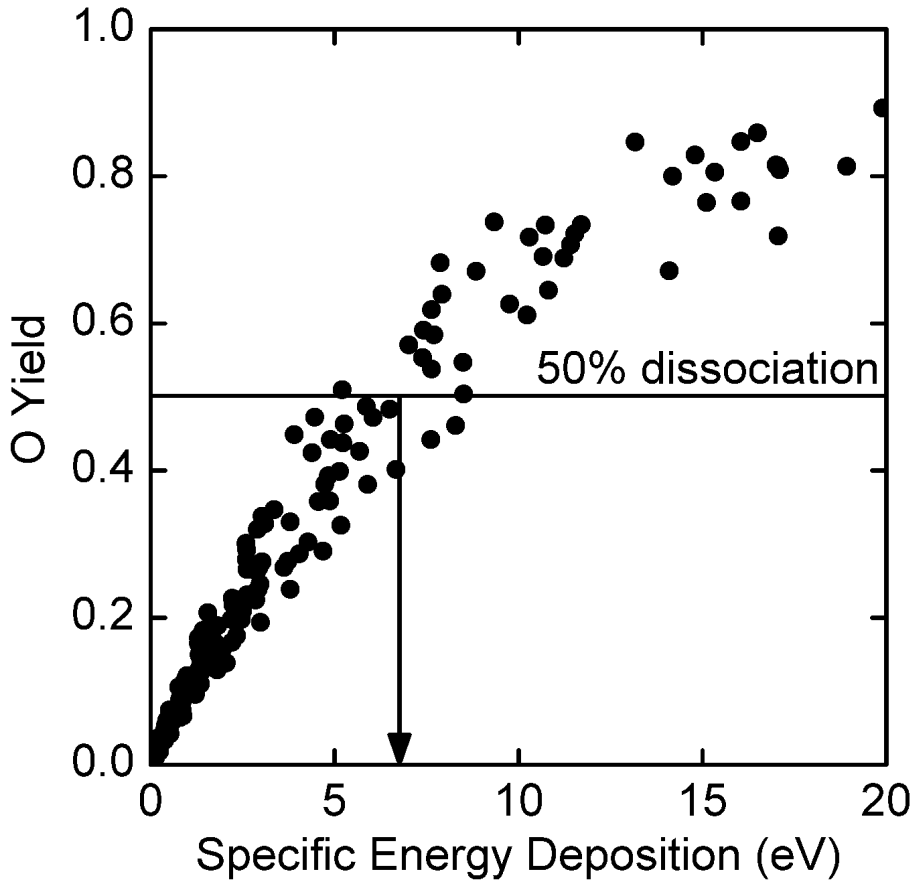
$$\beta = f\left(\frac{eV}{O_{2,inlet}}\right)$$

- **$O_2(^1\Delta)$ 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).**



O YIELD VS. SPECIFIC ENERGY DEPOSITION

- **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.**



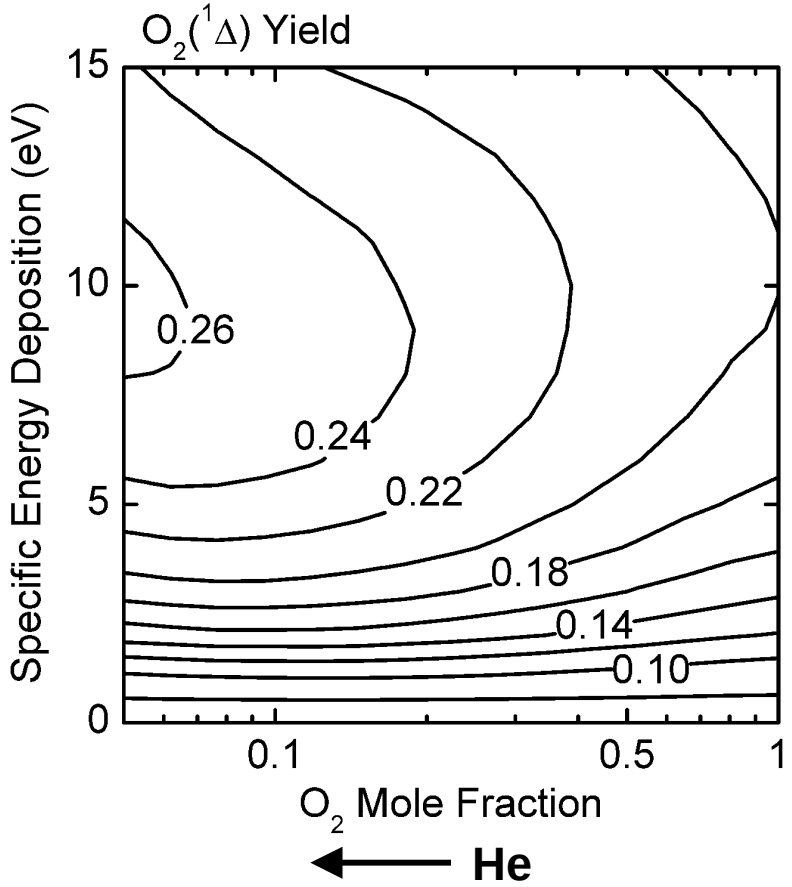
$$\beta = \frac{0.5[O]}{[O_2] + [O_2(^1\Delta)] + 0.5[O] + 1.5[O_3]}$$

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:**

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



Conditions:

- **V_{inlet} = 2500 cm/s**
- **Power = 21 W/cc**
- **P_{O2} = 4.2 Torr**
- **L_{disch} determined by energy dep.**

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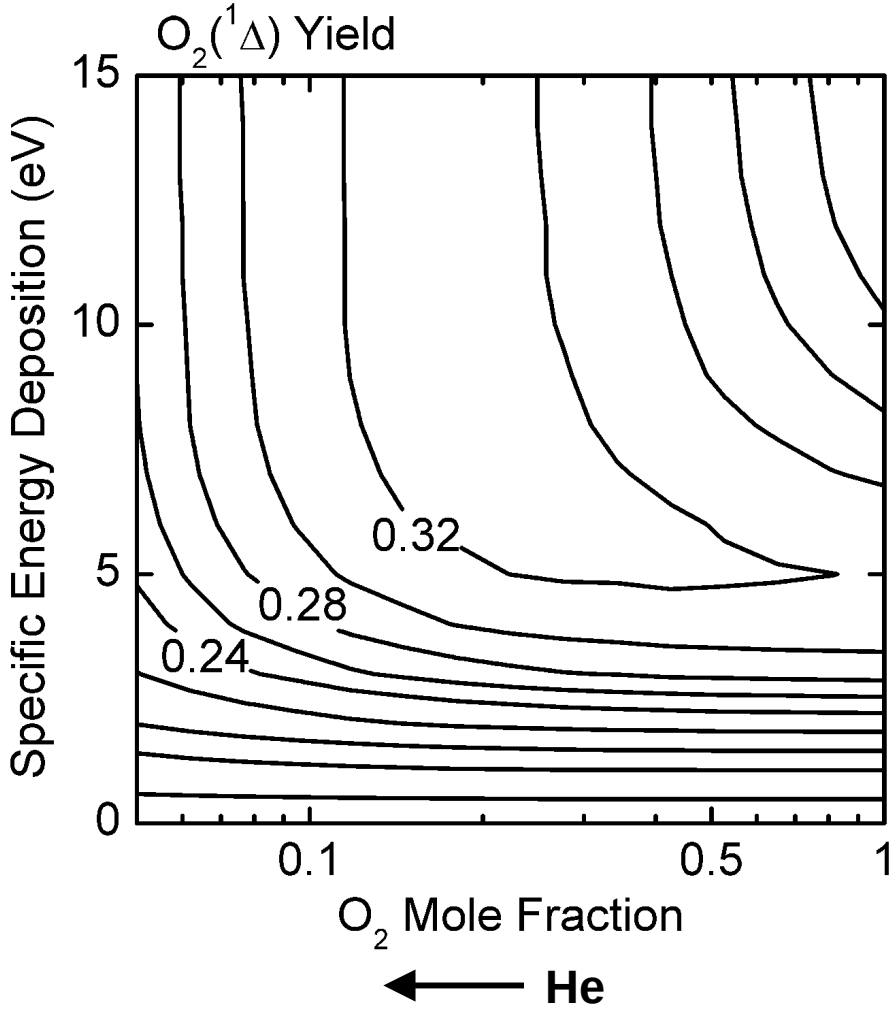
SECONDARY EFFECTS: DILUENT (NO HEATING)

- 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_{inlet} = 2500 cm/s
- Power = 21 W/cc
- P_{O2} = 4.2 Torr
- L_{disch} determined by energy dep.

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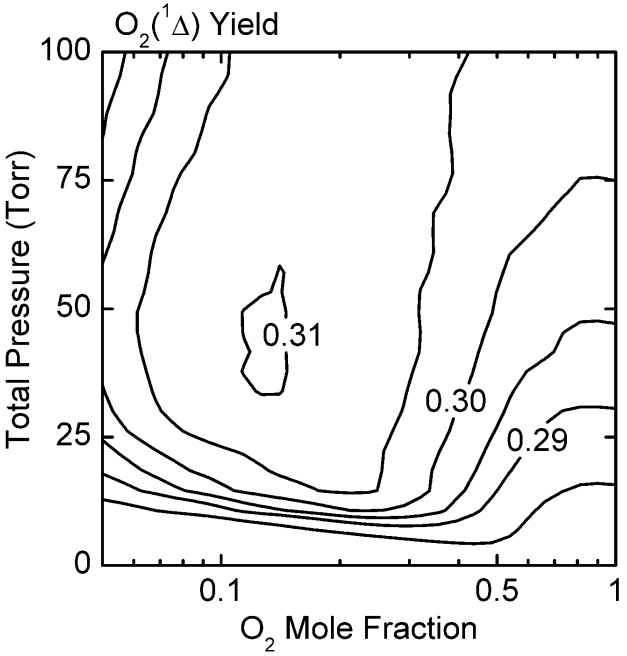
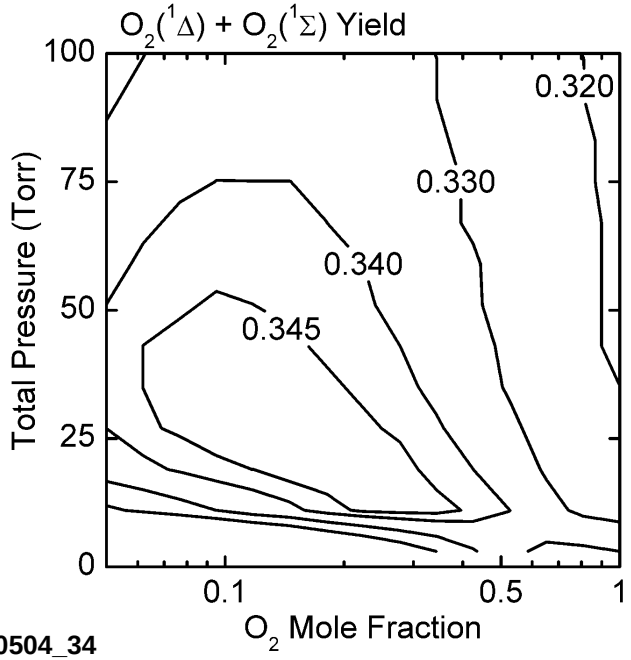
SECONDARY EFFECTS: PRESSURE





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

Conditions:

- **V_{inlet} = 500 cm/s**
- **Power = 3 W/cc/Torr O_2**
- **L_{disch} determined by energy dep.**

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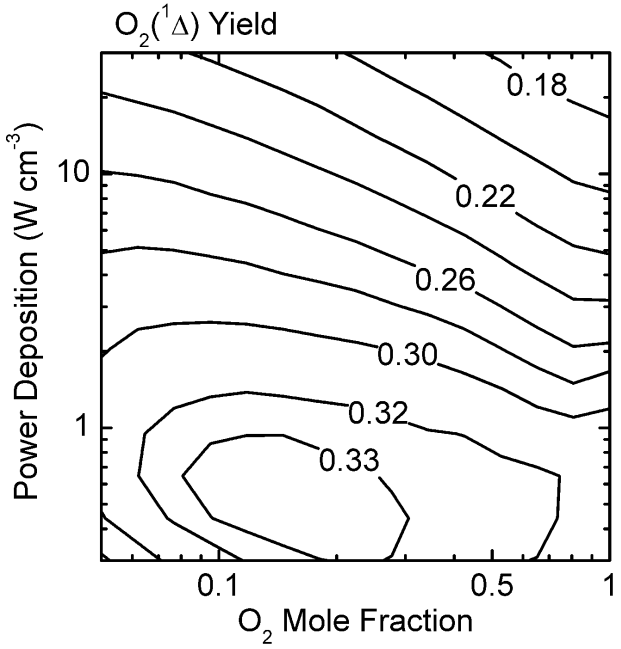
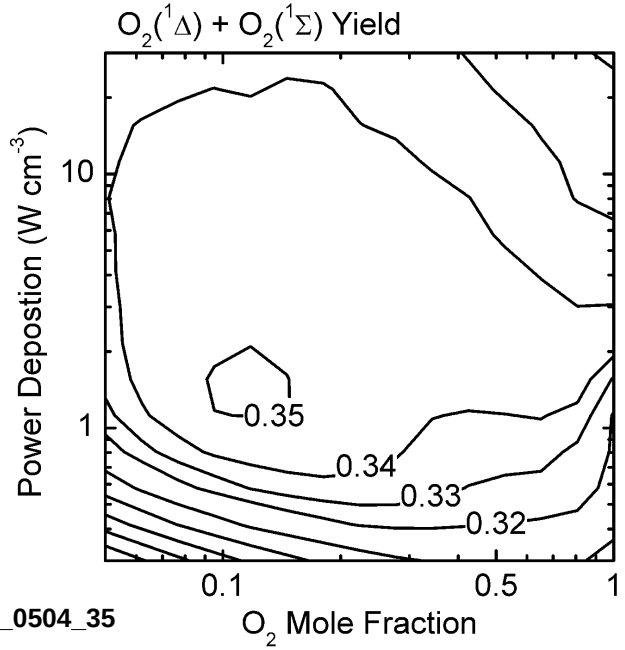
SECONDARY EFFECTS: POWER DEPOSITION





- **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_{inlet} = 2500 cm/s**
- **P_{O2} = 3 Torr**
- **L_{disch} determined by energy deposition.**

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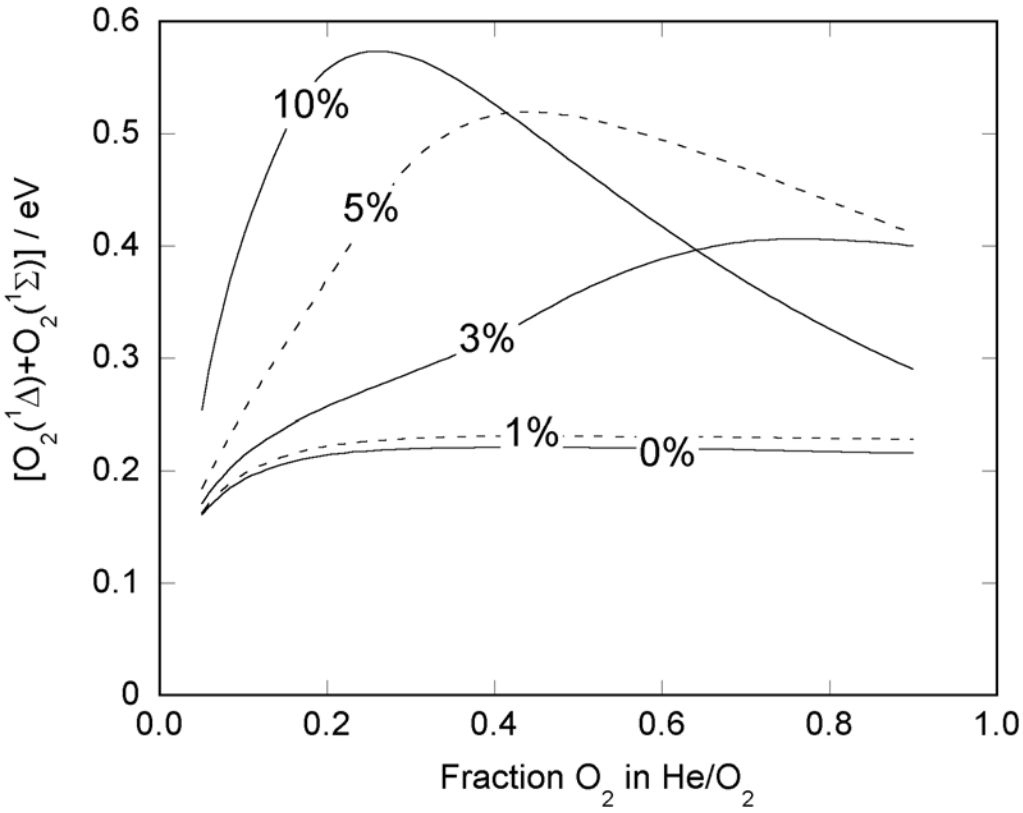
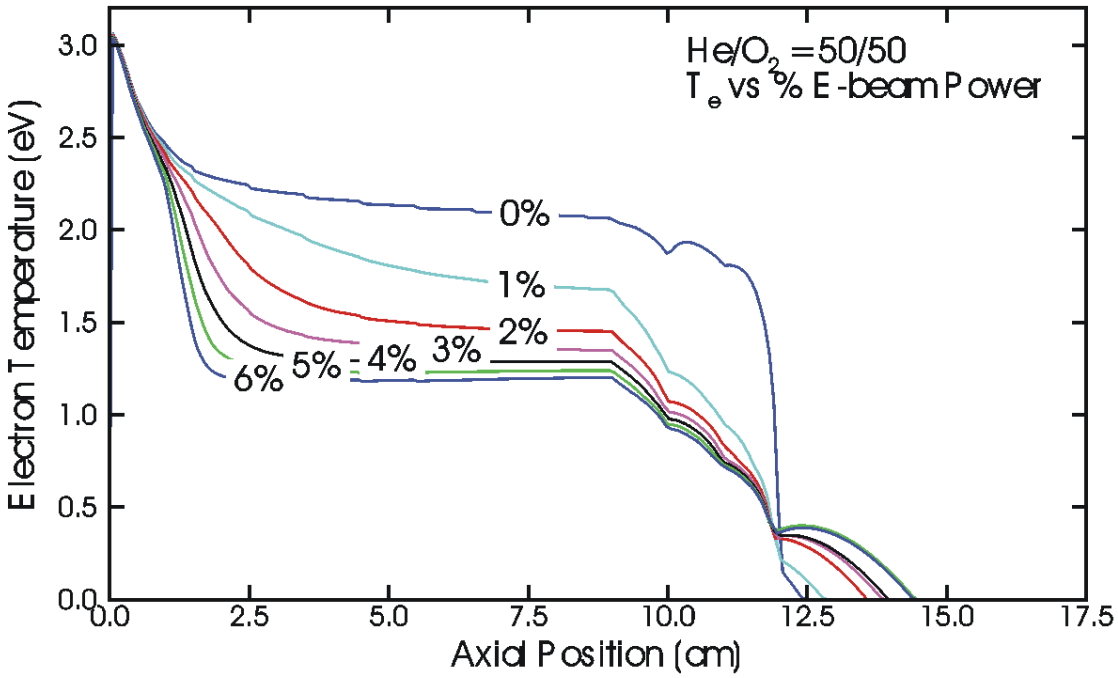
NON-SELF SUSTAINED DISCHARGES

- **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



- **1 W/cm^3,**

- **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%**

- **He/O_2 = 50/50, 5 Torr, v_0 = 10 m/s**

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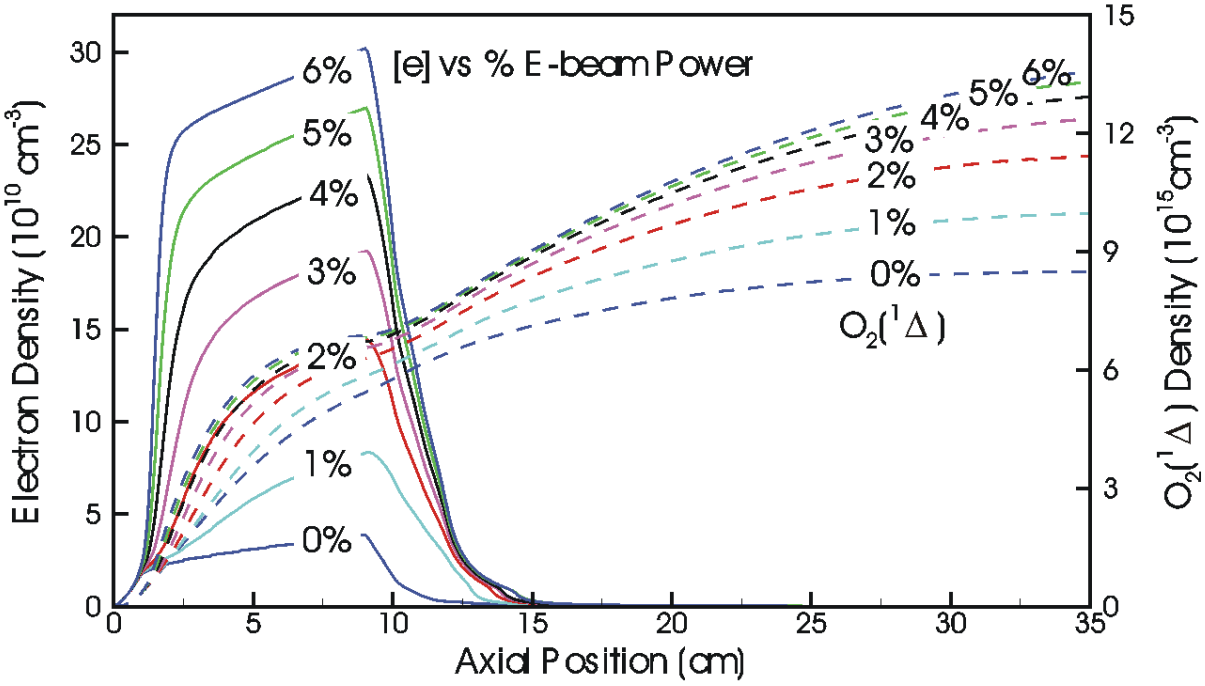
PLUG-FLOW WITH E-BEAM POWER DEPOSITION: e, $O_2(^1\Delta)$



- 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

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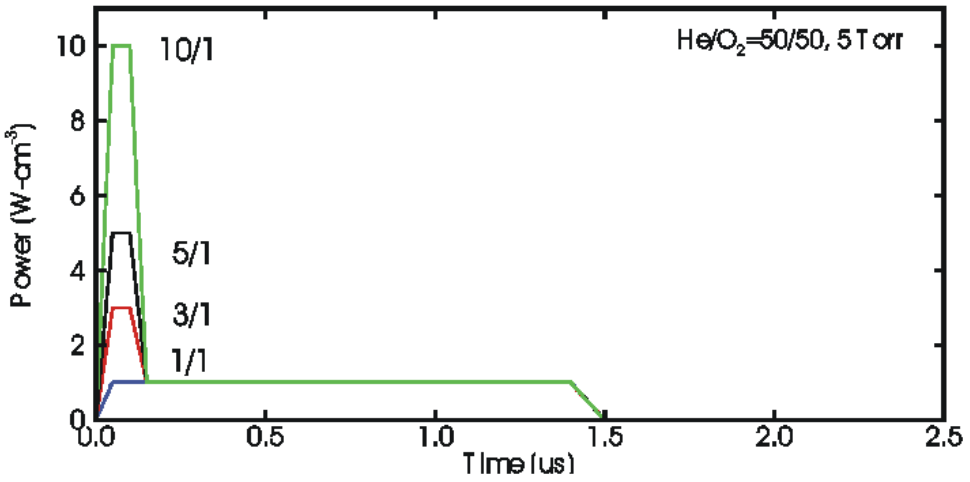
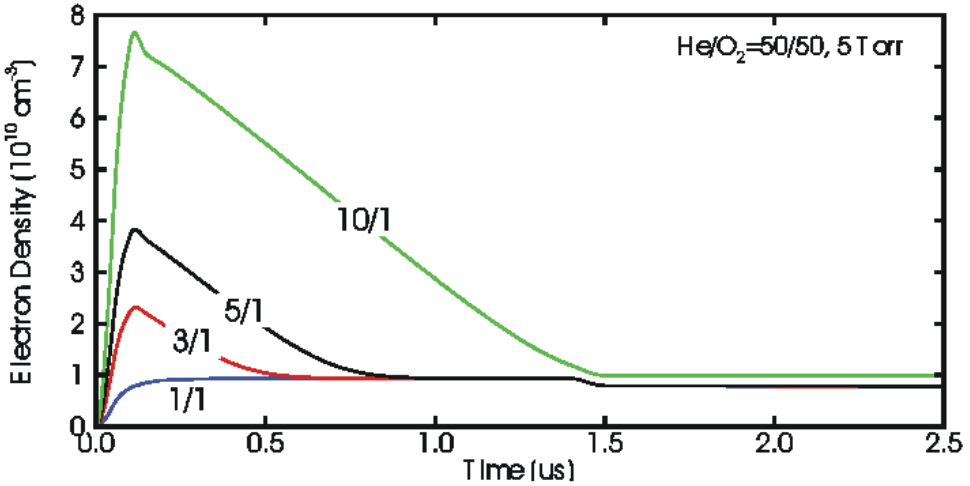
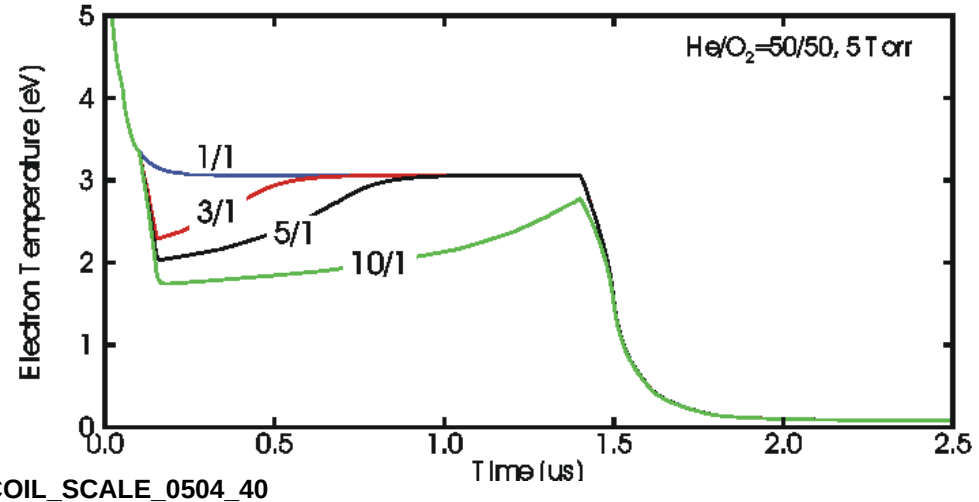
IN SITU "EXTERNAL" IONIZATION: SPIKER SUSTAINER

- **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 μs.**
- **During period of excess ionization, T_e is below self sustaining values.**

- **He/O_2 = 50/50, 5 Torr**

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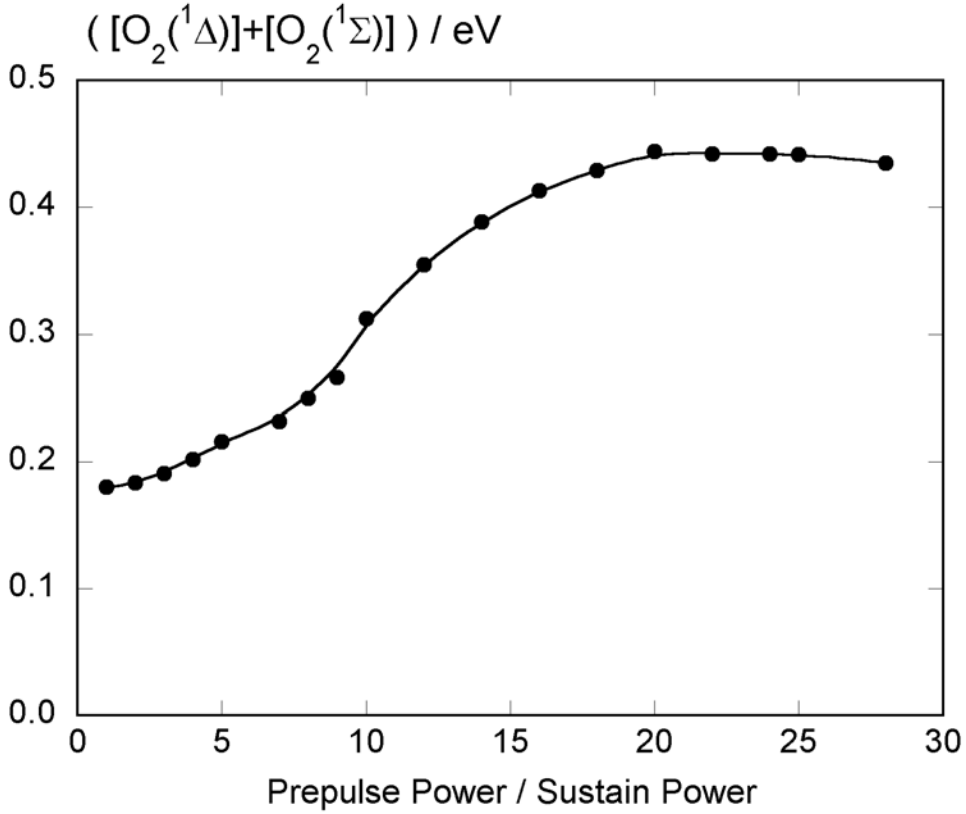
SPIKER-SUSTAINER: $O_2(^1\Delta, ^1\Sigma)$ PRODUCTION EFFEICIENCY



- **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**

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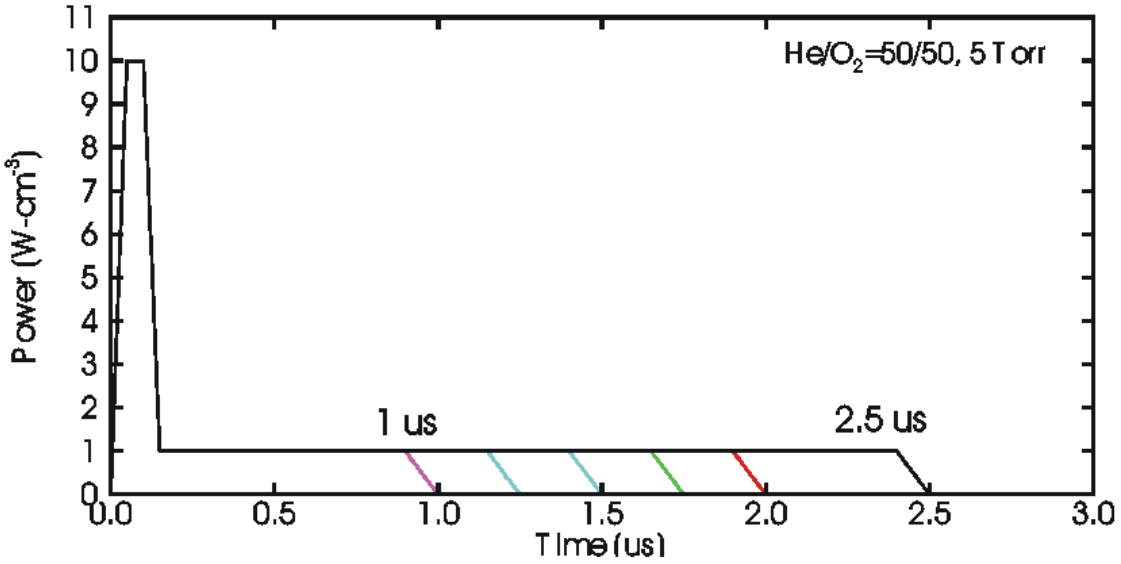
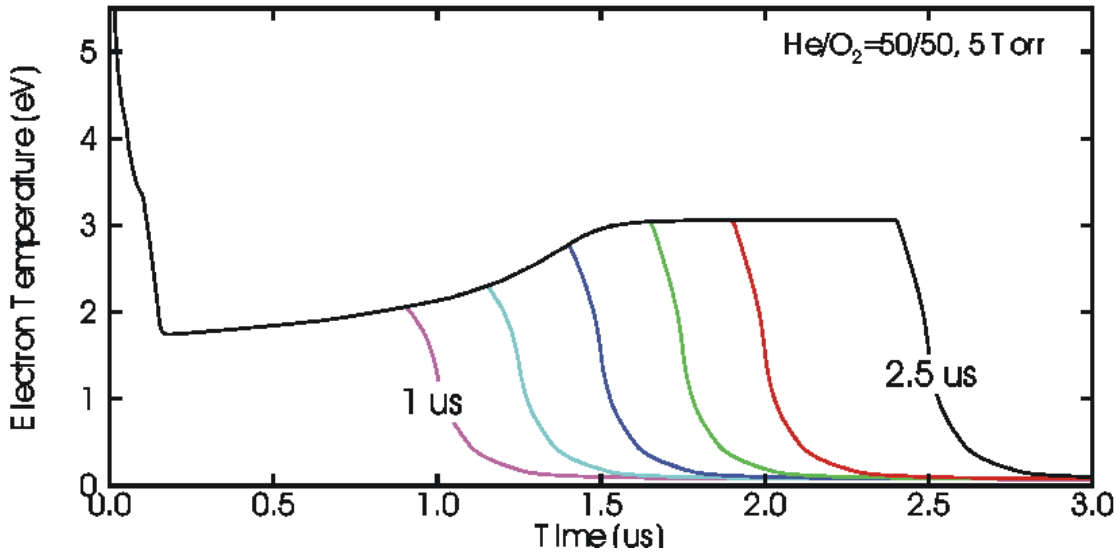
LENGTH OF SUSTAINER PULSE





- 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/O_2 = 50/50, 5 Torr

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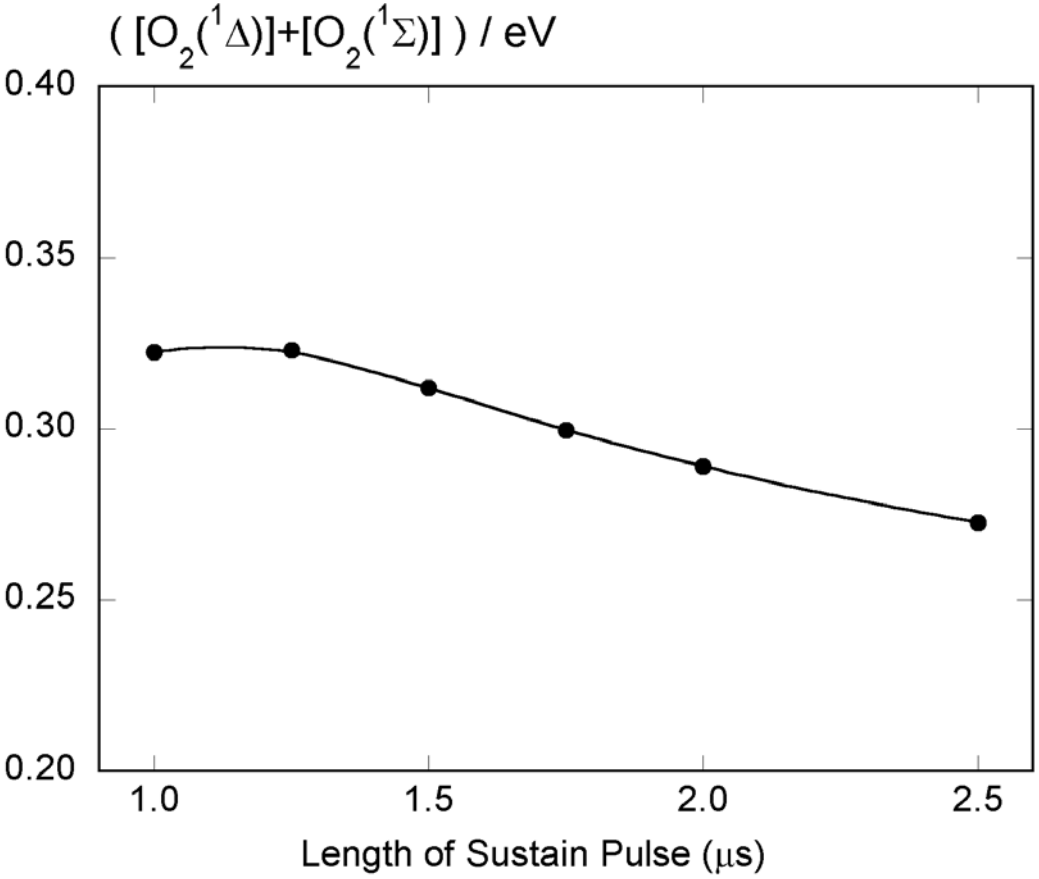
LENGTH OF SUSTAINER PULSE



- **The improved efficiency of production of $O_2(^1\Delta, ^1\Sigma)$ decreases as the self-sustain pulse lengthens.**

- **He/O_2 = 50/50, 5 Torr**

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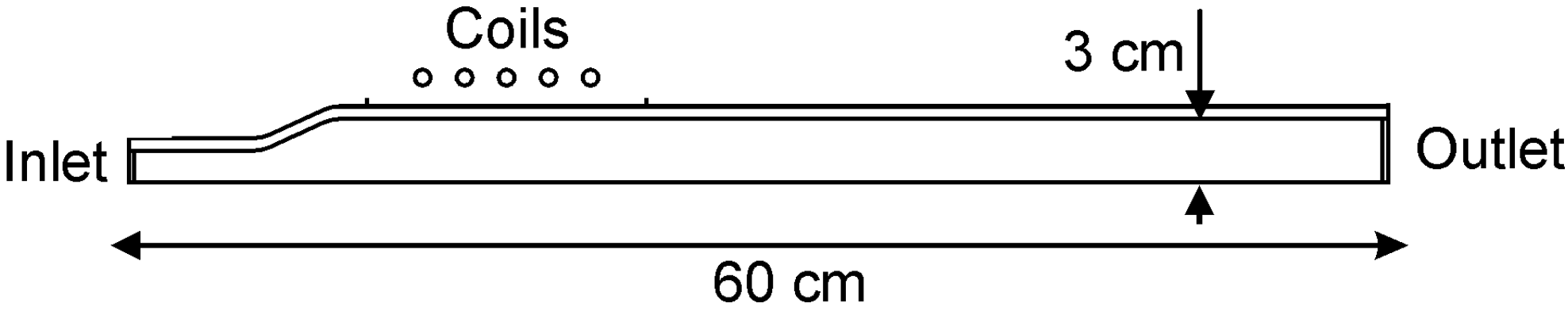
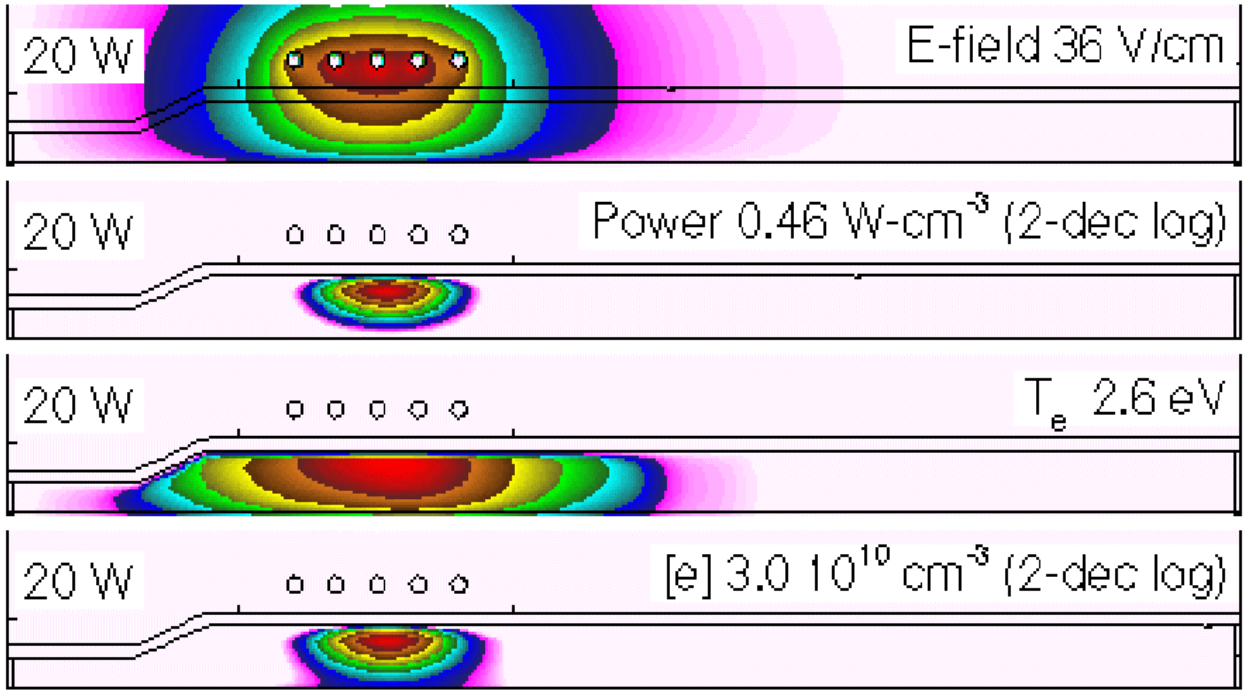
APPLICATION TO AN IDEALIZED SYSTEM

- **Idealized system is based in CU Aerospace ECOIL experiment.**
- **Continuous rf source (capacitive in experiment, inductive here).**
- **3 Torr, He/O_2=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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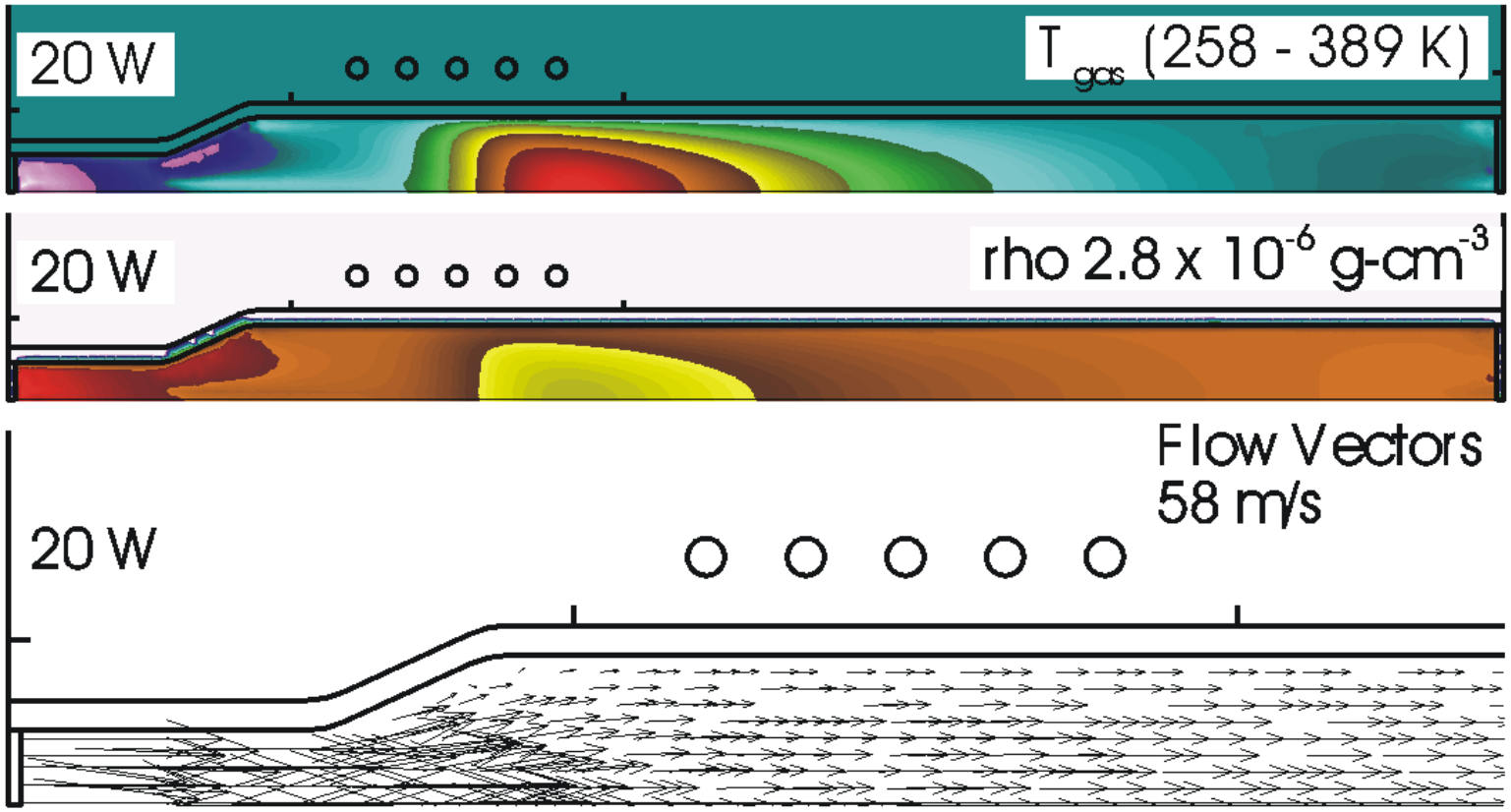
FLUID DYNAMICS

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

MIN MAX

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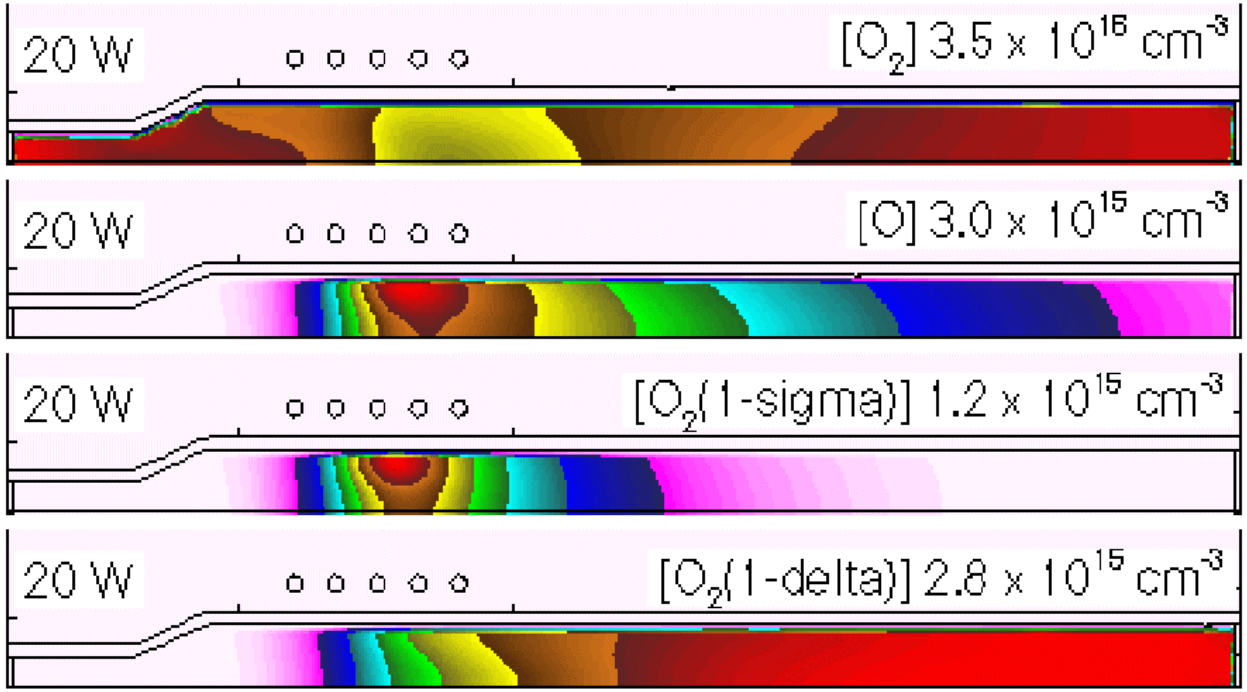
OXYGEN ATOMIC AND MOLECULAR DENSITIES

- $O_2(^1\Sigma)$ 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.



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

MIN MAX

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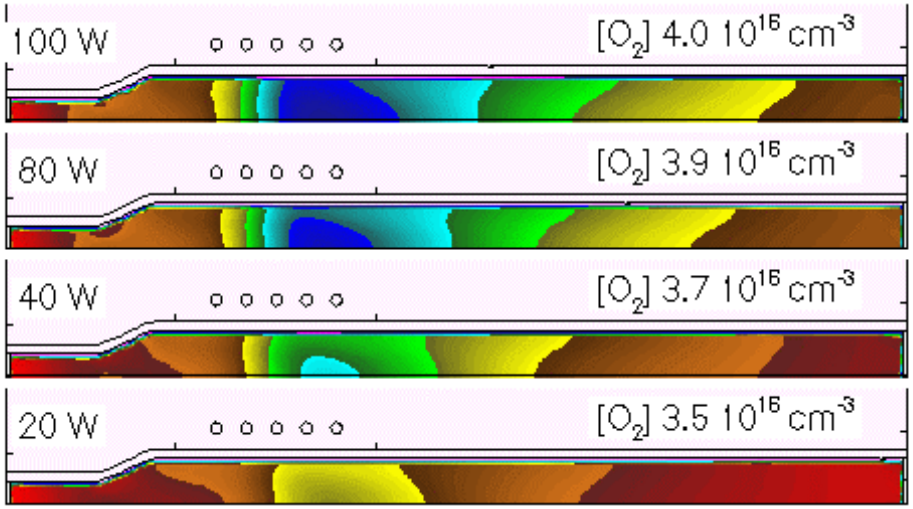
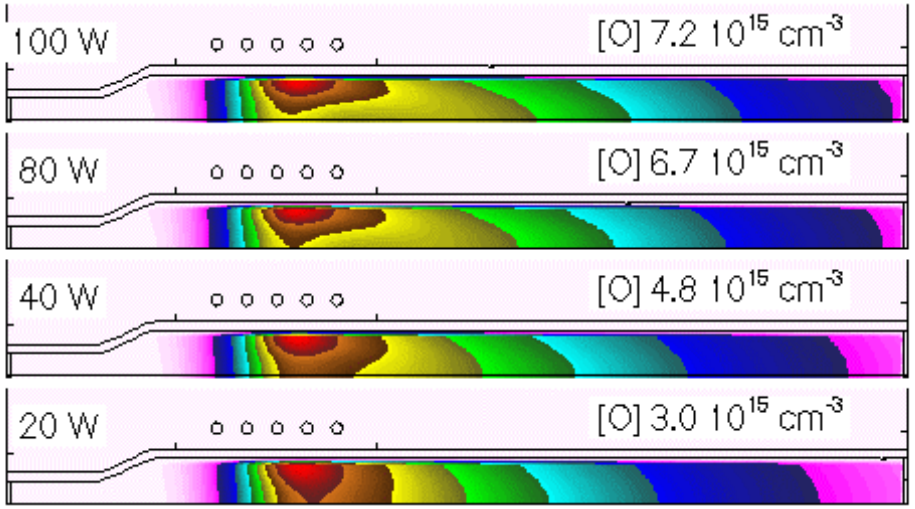
$O_2(^1\Delta)$ AND O vs POWER

- **Increasing power increases local specific power deposition nonlinearly, thereby producing less uniform excitation.**





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

MIN **MAX**

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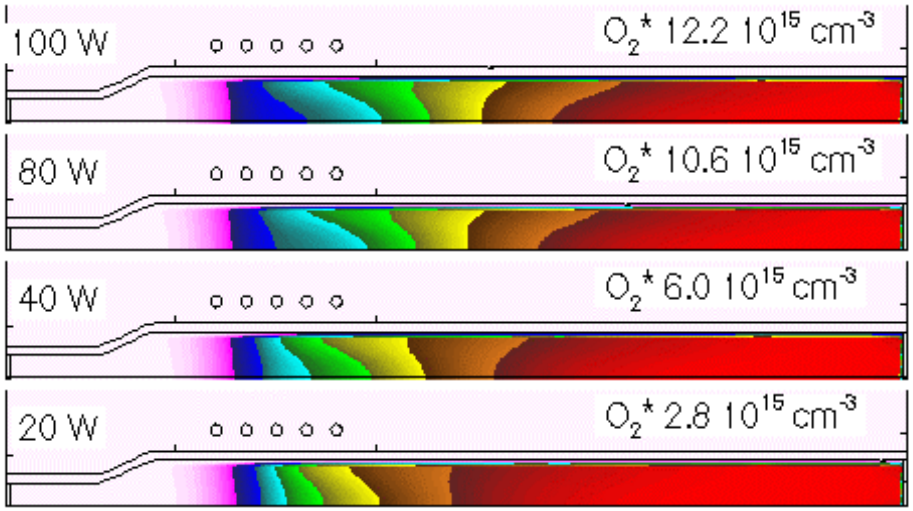
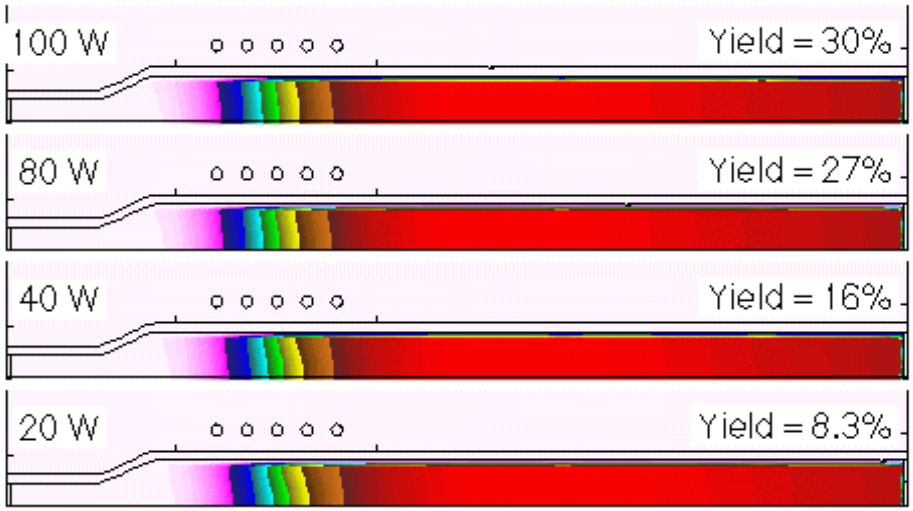
$O_2(^1\Delta)$ AND YIELD vs POWER

- **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**

MIN **MAX**

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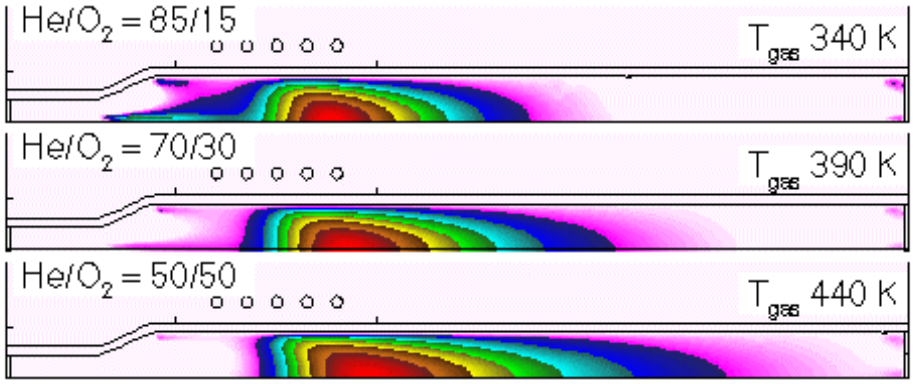
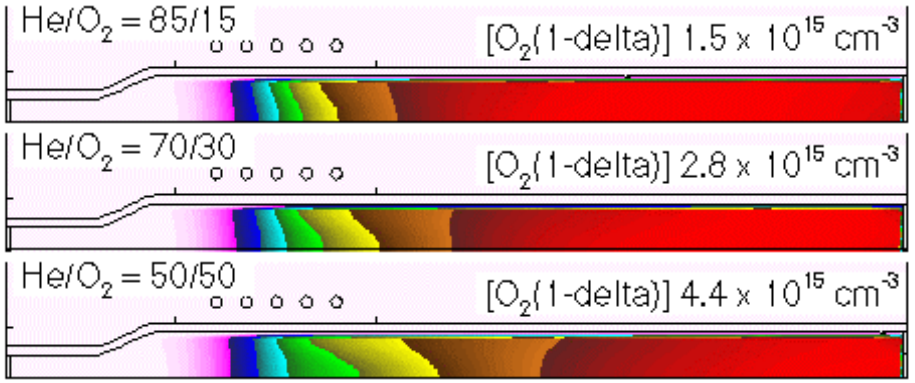
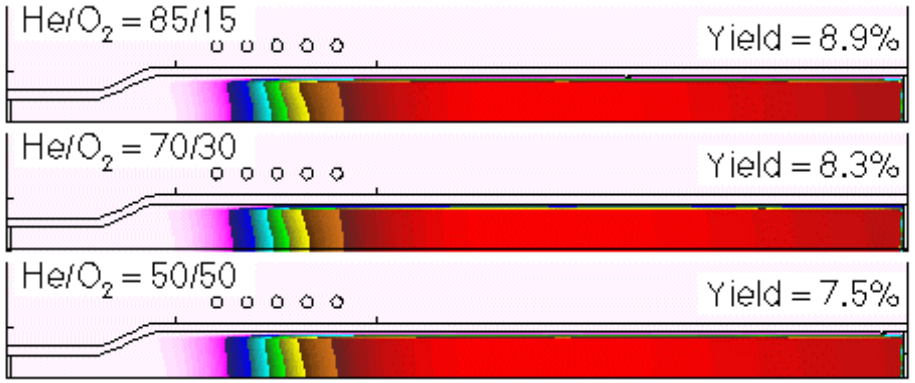
$O_2(^1\Delta)$ AND YIELD vs MIXTURE



- **Yield decreases with increasing O_2 (but not a lot)**
- **lower thermal conductivity**
- **More Frank Condon heating.**
- **Less uniform power**
- **Less optimum E/N**





- **3 Torr, 20 W, 6000 sccm**

MIN **MAX**

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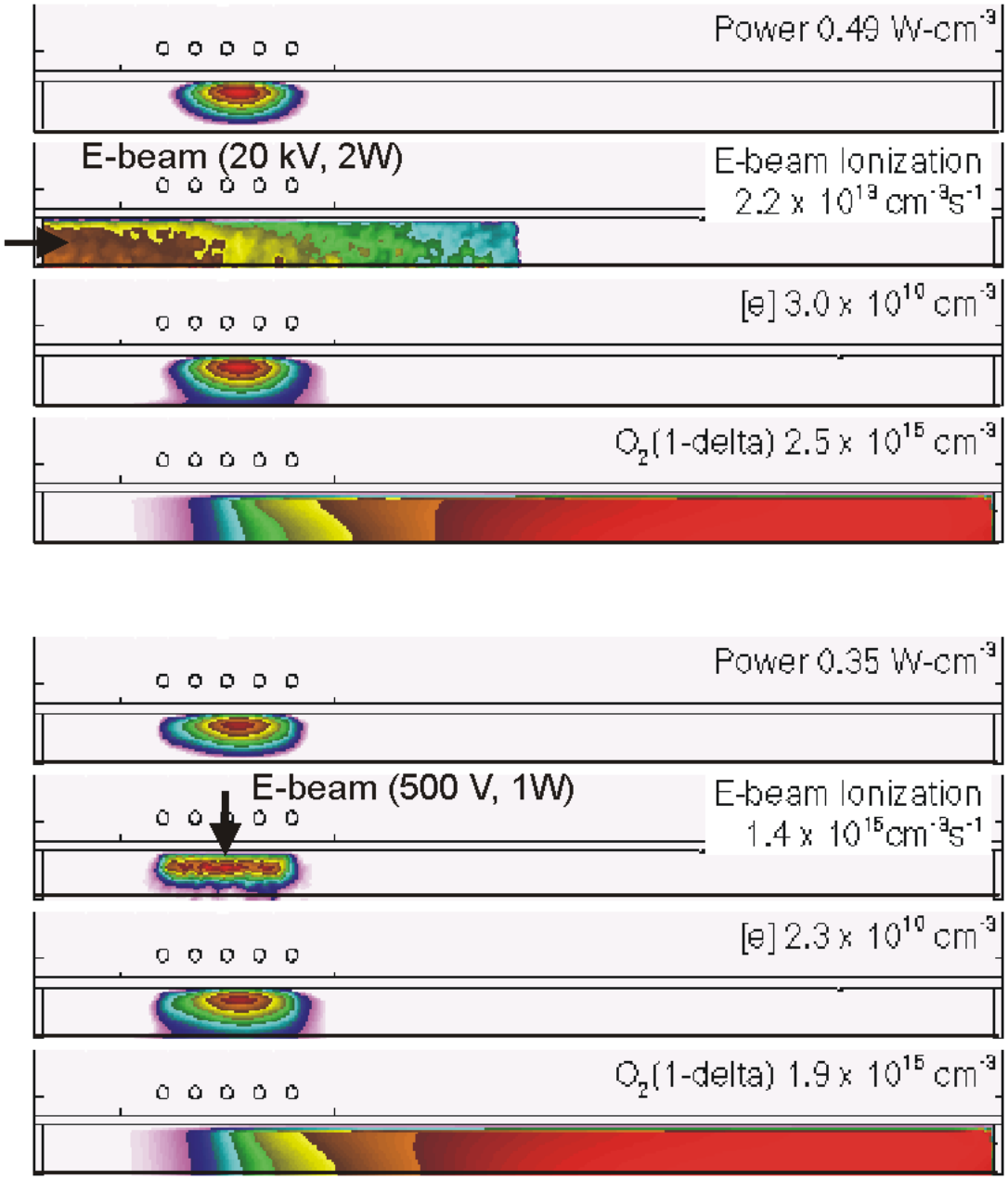
ECOIL_SCALE_0504_50

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**

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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.**