

Development of the electric discharge oxygen-iodine laser

David L. Carroll^a, Joseph T. Verdeyen^a, Darren M. King^a, Andrew D. Palla^a, Julia K. Laystrom^a, Gabriel F. Benavides^a, Joseph W. Zimmerman^b, Brian S. Woodard^b, and Wayne C. Solomon^b

^aCU Aerospace, 2100 S. Oak St. – Suite 206, Champaign, IL 61820;

^bDept. Aero. Eng., Univ. of Ill. at Urbana-Champaign, 104 S. Wright St., Urbana, IL 61801

ABSTRACT

In the hybrid electric discharge Oxygen-Iodine laser (ElectricOIL), the desired $O_2(a^1\Delta)$ is produced using a low-to-medium pressure electric discharge. The discharge production of atomic oxygen, ozone, and other excited species adds higher levels of complexity to the post-discharge kinetics which are not encountered in a classic purely chemical $O_2(a^1\Delta)$ generation system. Experimental studies over the past six years using electric discharges have demonstrated $O_2(a)$ yields greater than 20%, gain, and cw laser power. Several modeling studies have also been performed for ElectricOIL and similar systems. As the development of this type of iodine laser continues, the roles of oxygen atoms and NO/NO₂ are found to be very significant in both the discharge region and downstream of the discharge region. A series of $O_2(^1\Delta)$ emission, I* emission, O-atom titrations, gain, and $O_2(^1\Delta)$ yield, NO₂* emission, and laser power measurements have been taken to explore the complex phenomena that are being observed. As the overall system is better understood improvements are being made in laser power and efficiency.

Keywords: hybrid electric discharge oxygen-iodine laser, ElectricOIL, EOIL, DOIL, HOIL, singlet oxygen

1. INTRODUCTION

Oxygen-iodine laser systems¹ operate on the $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ [hereafter denoted I* and I, respectively] electronic transition of the iodine atom at 1315 nm. The population inversion is produced by the near resonant energy transfer between the metastable excited singlet oxygen molecule, $O_2(a^1\Delta)$ [also denoted $O_2(a)$ hereafter], and the atomic iodine ground state. There are many system issues having to do with weight, safety and operational logistics in the production of the $O_2(a)$ by chemical means which have motivated investigations into methods to produce significant amounts of $O_2(a)$ using flowing electric discharges. Several investigations have been conducted into the possibility of a continuous flow hybrid Electrically driven Oxygen-Iodine Laser (ElectricOIL or EOIL) with electric discharges to produce the $O_2(a)$.²⁻¹⁹ These studies showed that flowing oxygen containing mixtures, typically diluted with a rare gas, through electric discharges can produce useful quantities of $O_2(a)$. Experimental studies over the past six years using electric discharges have demonstrated $O_2(a)$ yields greater than 15% using electric discharges.^{4,5,7-10,13-19} The first demonstrations of gain in an ElectricOIL system were made in a fast supersonic flow cavity,^{15,16} and were followed by demonstrations of gain in subsonic flow.¹⁷ The successful gain experiments were then followed by ElectricOIL cw power demonstrations in both supersonic^{18,19} and subsonic flow²⁰ cavities. Several modeling studies^{2,5,6-9,13,14,21-25} have also been performed for these discharge driven oxygen-iodine laser systems to better understand the complex kinetic processes being encountered. Results of those studies along with more recent experimental results show that electric excitation and the additional kinetics downstream of the discharge are complicated processes that must be investigated with advanced diagnostics along with modeling to better understand this highly complex system. As the development of this type of iodine laser continues, the roles of oxygen atoms and NO/NO₂ have been found to be very significant in both the discharge region and downstream of the discharge region. In this paper, recent experiments and modeling by the CU Aerospace / Univ. of Illinois team in the development of the ElectricOIL system are presented.

2. EXPERIMENTAL DEVELOPMENTS

During the course of the ElectricOIL research over the past six years, it was determined that electric discharge stability, temperature control, and understanding of critical kinetics (especially those related to oxygen atoms) were critical parameters to obtaining gain and lasing.¹⁵⁻²⁰ Electric discharges sustained in moderate pressures

(many to 10s of torr) of oxygen are prone to instabilities. The discharge production of O atoms, O₃ and other excited species adds higher levels of complexity to the downstream kinetics when the iodine donor species are added to the flow.

2.1 Experimental Setup

A block diagram of the flow tube setup is shown in Fig. 1. A radio frequency (rf) discharge between two internal hollow cathode electrodes (each 13 cm long) operating at 13.56 MHz was used as the excitation source. The plasma zone is approximately 4.9 cm in diameter and 25 cm long. The subsonic diagnostic duct has four windows through which simultaneous measurements can be made of the optical emission from O₂(a) at 1268 nm, O₂(b¹Σ) [denoted O₂(b) hereafter] at 762 nm, I* at 1315 nm, and the gain/absorption proportional to $\{[I^*] - 0.5 \cdot [I]\}$. A Roper Scientific Optical Multi-channel Analyzer (OMA-V) was used for the spectral measurements at 1268 nm and 1315 nm. An Apogee E47 CCD camera coupled to a Roper Scientific/Acton Research monochromator was implemented to measure the emission of O₂(b) at 762 nm and the gas temperature through the rotational structure of the O₂(b) spectra. Measurements of gain (or absorption) were made with the Iodine-Scan diagnostic (ISD), developed by PSI.²⁷ The translational

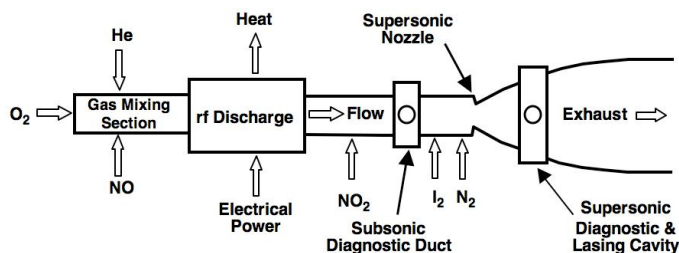


Figure 1: Schematic of the supersonic experimental apparatus.

temperature in the supersonic flow is determined from the Doppler component of the Voigt profile. The supersonic diagnostic and laser cavity is a Mach 2 nozzle with view port windows.

2.2 Importance of Atomic Oxygen

We had previously been unsuccessful in attaining positive gain (as had other groups) despite having achieved yields of O₂(a) with an electric discharge that were, in principle, high enough to do so. As such we began a rigorous investigation of the effects of iodine in the subsonic flow region without the added complication of the supersonic cavity. To perform these experiments we moved the iodine injection point upstream (approximately 20 cm) of a diagnostic section in the subsonic flow tube, Fig. 1. We made simultaneous measurements of the optical emission from O₂(a) at 1268 nm, O₂(b) at 762 nm, I* at 1315 nm, and the absorption through the optical windows in the subsonic diagnostic section.¹⁶ Two important things were immediately apparent from these data. First, for the zero iodine case there was a decrease in the 1268 signal at the highest powers, Fig. 2. This drop in signal is believed to be a consequence of instabilities and thermal constriction that visibly develop in our existing discharge under these flow conditions. We are presently investigating the discharge stability issues in an effort to improve the performance and yield of the discharge;

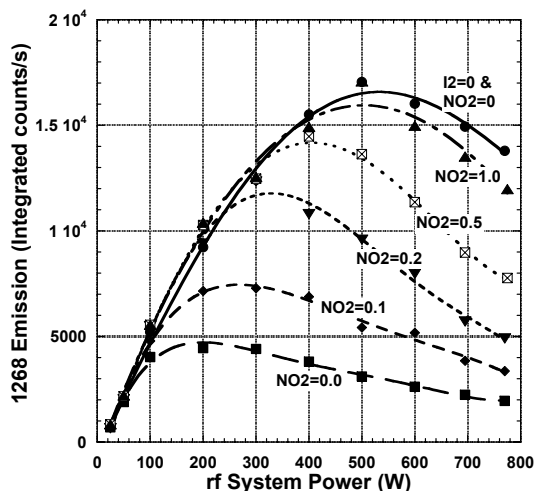


Figure 2: O₂(a) emission at 1268 nm with and without iodine at the subsonic diagnostic port as a function of system power and the NO₂ flow rate.

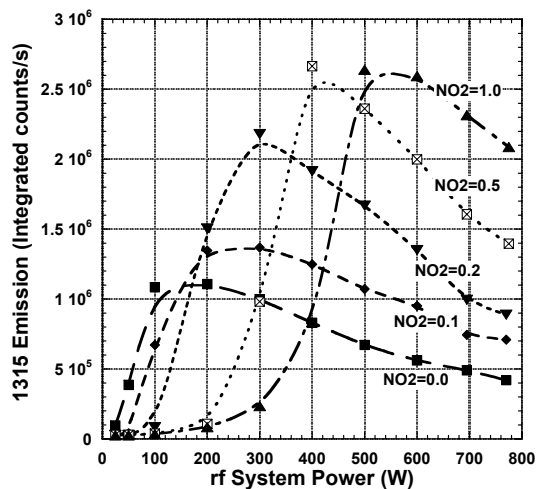


Figure 3: I* emission at 1315 nm at the subsonic diagnostic port as a function of system power and the NO₂ flow rate.

two factors that have improved stability are the type of discharge implemented (discussed below) and the use of a flow conditioner²⁸ upstream of the discharge to improve thermal transport in the discharge itself (and thus reduce the effects of thermal constriction). The second and more troubling observation was that when very small amounts of molecular iodine were added to the flow, the level of O₂(a) emission at 1268 nm dropped dramatically, by a factor of more than 5 at 500 W, Fig. 2. The concentration of atomic iodine, approximately 2% of the O₂(a), was far too low to explain a significant drop in O₂(a) from the pumping reaction. These data led us to the determination that oxygen atoms played not only a positive role in dissociating the I₂, but also a major detrimental role in the kinetics downstream of the discharge region via a quenching reaction $I^* + O \rightarrow I + O$ first postulated by Heaven.²⁹ Rawlins *et al.*⁹ and Azyazov *et al.*³⁰ have recently measured this rate to be approximately 1.2×10^{-11} cm³/molecule-s. This reaction rate is fast enough to significantly deplete the I*, and consequently the O₂(a), unless the O atoms are controlled, e.g., through the use of NO or NO₂, Figs. 2 and 3.

2.3 Supersonic Flow Gain and Lasing Demonstrations

Once the importance of the I*+O quenching reaction was realized, the O atoms were controlled by the use of NO and/or NO₂ and the first demonstrations of gain^{15,16} and lasing^{18,19} were achieved in supersonic flow. Over the past two years of research and development, continual improvements in gain and lasing power have been obtained. The gain has risen from the initial demonstration of 0.002% cm⁻¹ by more than an order of magnitude to 0.027% cm⁻¹, Fig. 4, and similarly the outcoupled laser power has risen from 0.16 W to 1.47 W. One of the significant characteristics of the ElectricOIL system is the ability to cycle the power on-and-off (literally with the flick of a single switch) and obtain reliable repeatability, Fig. 5.

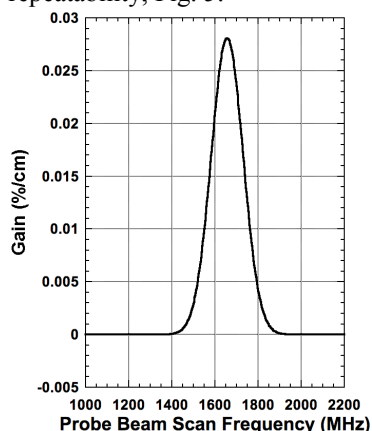


Figure 4: Digitally filtered gain signal in the supersonic cavity as a function of probe beam scan frequency with $P_{total} = 20$ Torr discharge.

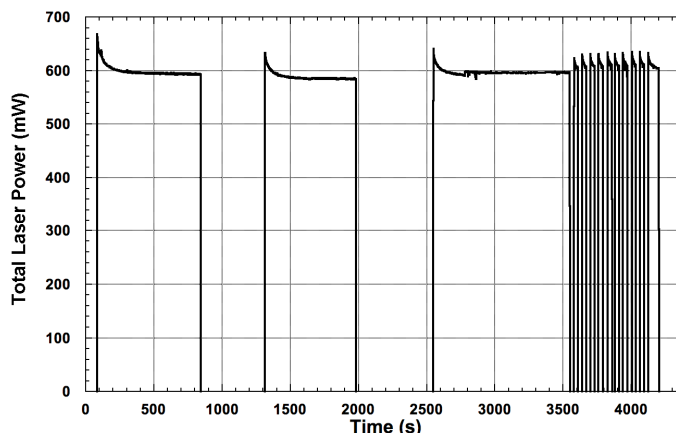


Figure 5: Continuous and cycled ElectricOIL laser power as a function of time with $P_{total} = 16$ Torr discharge.

Details of the system improvements have been documented in Refs. 19 and 28, but are principally a result of continual improvements in the understanding of this complex electro-kinetic system and the trade offs between different processes. The most important improvements have occurred as a result of discharge improvements that have enabled the discharge to operate in a stable fashion at higher pressures and flow rates. Other critical factors have been the use of NO as a discharge additive (discussed further in Section 2.5 below), the use of high reflectivity mirrors for our relatively small gain length of 5 cm, proper flow rates of iodine relative to the O atom and O₂(a) flows, and cooling of the discharge gas to lower the flow temperature.

2.4 Subsonic Flow Gain and Lasing Demonstrations

Following the first measurement of gain in supersonic flow and a better understanding of the I*+O quenching, Rawlins *et al.*¹⁷ made the first measurement of gain in a ≈ 350 K subsonic flow reactor system, but the magnitude of the gain, 8×10^{-5} % cm⁻¹, was too small to obtain lasing with existing mirrors. In our ElectricOIL system, the measured yields of O₂(¹ Δ) of > 0.16 at reasonable pressures of > 10 Torr, and the ability to minimize the deleterious deactivation of I* by atomic oxygen through the use of NO and or NO₂,¹⁶ suggested that the simple injection of cold N₂ would lower the temperature sufficiently to lead to positive gain and lasing in subsonic flow. Post-discharge modeling²⁴ supported that it might be possible to obtain high enough gain for lasing in a flowing subsonic arrangement after cold N₂ injection. Two of the advantages to slower flowing subsonic systems are (i) the number densities of I(²P_{1/2}) and O₂(¹ Δ) are higher than

with supersonic expansion, and (ii) stimulated emission can extract more of the excited state energy by virtue of the longer residence time which the excited species spend within the optical resonator.³¹

A block diagram of the experimental setup for the subsonic lasing demonstration is shown in Fig. 6. An rf electric discharge at 13.56 MHz operating between two internal hollow cathode electrodes was again used as the excitation source (see above). The subsonic cavity has a 2.54 cm x 5.08 cm cross-section flow channel. The discharge

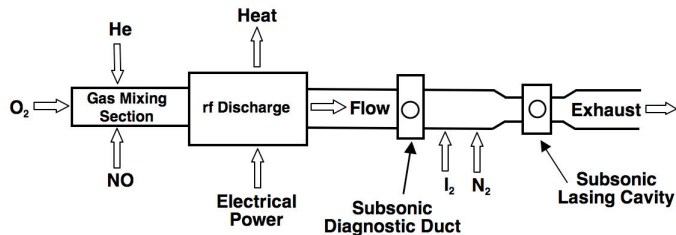


Figure 6: Schematic of the subsonic experimental apparatus.

flow conditions used in these experiments were 3.0 mmol/s of O₂ mixed with 16.0 mmol/s of He and 0.15 mmol/s of NO flowing through the rf discharge at 12.5 Torr (similar to those used for the supersonic laser demonstration discussed above). A secondary stream of ≈0.014 mmol/s of I₂ with 2.0 mmol/s of secondary He diluent was injected 64.8 cm downstream from the exit of the discharge. A tertiary flow of ≈185 mmol/s of cold N₂ gas (≈88 K) was injected further downstream to

lower the temperature and to raise the pressure. The pressures in the discharge flow tube and in the subsonic laser cavity were 12.5 Torr and 8.4 Torr, respectively. The pressure ratio indicates that the flow was approximately Mach 0.80 in the subsonic laser cavity. Gain for the above flow conditions at 500 W of rf discharge power is shown in Fig. 7 and peaks at 0.009% cm⁻¹ at line center. The lineshape indicates a temperature of ≈180 K. The laser resonator was subsequently installed around the subsonic cavity. Laser power and O₂(¹Δ) yield measurements were made as a function of rf discharge power as shown in Fig. 8. For the above flow conditions and 500 W rf power, a laser output power of 540 mW was obtained.²⁰ For approximately the same discharge and iodine flow conditions, rf power, and laser mirrors, 260 mW were obtained with a supersonic laser cavity¹⁹; therefore, the subsonic cavity demonstrated significant energy extraction advantages over a supersonic cavity due to higher number densities and longer residence time in the resonator.

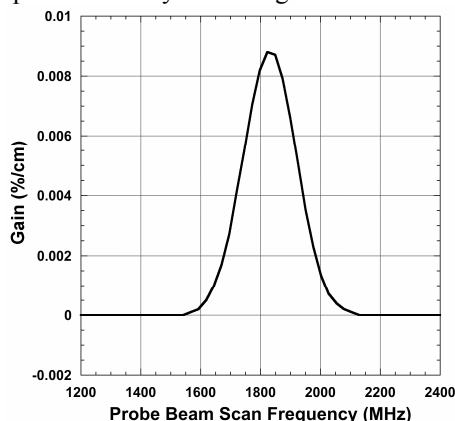


Figure 7: Digitally filtered gain signal in the subsonic cavity as a function of probe beam scan frequency measured prior to lasing experiments.

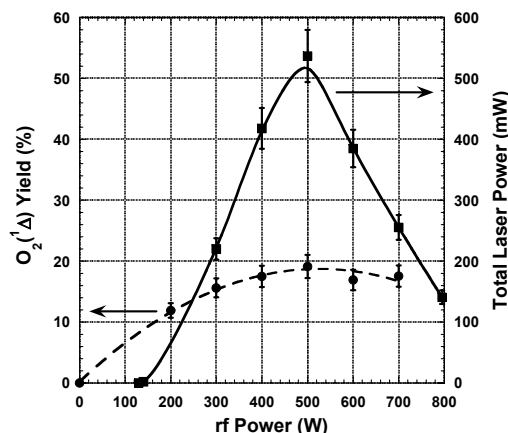
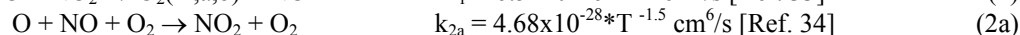
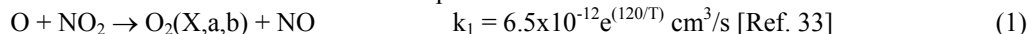
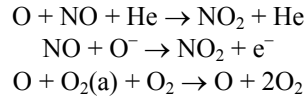


Figure 8: O₂(¹Δ) yield in the flow tube diagnostic section and total laser power in the subsonic cavity as a function of rf discharge power.

2.5 Important Kinetic Effects with NO and NO₂

As discussed above, NO and NO₂ have played an important role in attaining gain and lasing in ElectricOIL,¹⁵⁻¹⁹ however, more recent data are indicating other very interesting phenomena.³² Figure 9 shows the effect of NO and NO₂ added in three conditions for a discharge flow of He:O₂=16:3 mmol/s. The three conditions are (i) NO₂ downstream of the discharge, (ii) NO downstream of the discharge, and (iii) NO through the discharge. First let us examine the cases of NO and NO₂ injection downstream of the discharge. The injection of either NO or NO₂ downstream leads to approximately the same significant benefit for the O₂(a) yield (~9% to 13.5%, approximately a 50% increase in magnitude); the increase leveled off after ~0.03 mmol/s NO or NO₂. The beneficial effect is likely due to a combination of neutral and ion kinetics with a complexity too great to discuss here. At most, we can merely list some of the possible reactions and note that various combinations lead to endless speculation at this time.





$$k_{2b} = 2.08 \times 10^{-28} * T^{-1.41} \text{ cm}^6/\text{s} \text{ [Ref. 34]} \quad (2b)$$

$$k_3 = \text{unknown} \quad (3)$$

$$k_4 = 1 \times 10^{-32} \text{ cm}^6/\text{s} \text{ [Ref. 7]} \quad (4)$$

The harpoon reaction (1) is highly exothermic (1.995 eV) and fast, thereby rapidly reducing the free atomic oxygen density. Note that one of the products of reactions (2a), (2b), and (3) is NO₂, which is then utilized in (1) to replenish the NO needed for these reactions and thereby reducing the deleterious deactivation of O₂(a) by reaction (4). While the experimental evidence is clear and unambiguous that a small amount of NO added to (or downstream of) the discharge results in a significant boost in O₂(a) yield, the theory is far from complete at this time.

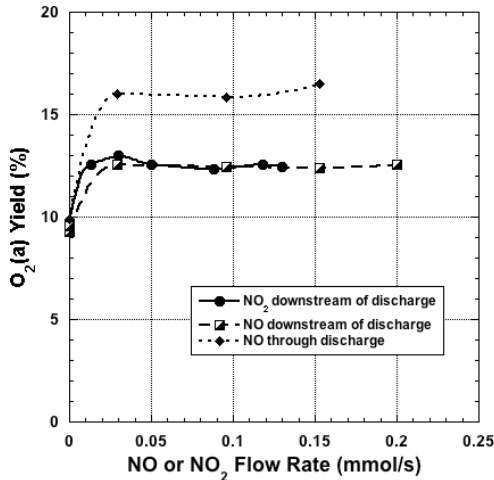


Figure 9. The effect of NO and NO₂ injection on the behavior of O₂(a) in 16:3 mmol/s He:O₂, at 500 W RF, 12.5 Torr. The downstream injector is 15.2 cm downstream of the downstream hollow cathode, and measurements are made 65.4 cm from the injector.

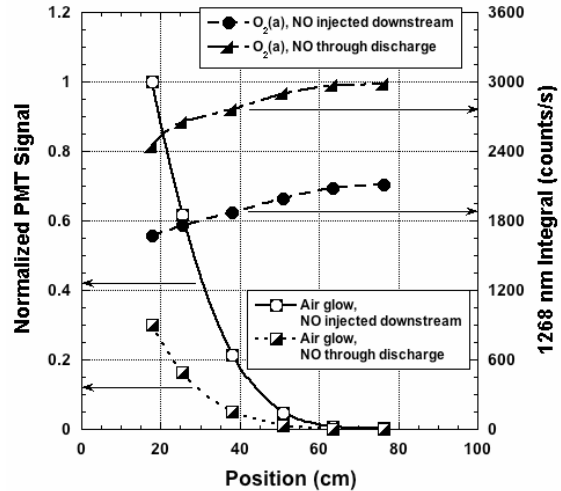


Figure 10. Spatial behavior of PMT signal and O₂(a) density. The NO flow is 0.2 mmol/s. Position is referenced to the downstream injector, which is 42 cm downstream of driven electrode. The atom flow rate in the downstream injection case was 0.32 mmol/s.

Figure 10 shows a similar NO injection case in which we plot the filtered air-glow intensity (at 590 nm) measured with a Photo-Multiplier Tube (PMT) and the 1268 nm O₂(a) emission as a function of distance for 16:3 mmol/s He:O₂ at 19.9 Torr at 500 W of rf power. In both cases (upstream and downstream injection), the air afterglow, which is proportional to oxygen atom density, decays to zero while O₂(a) density increases. When NO is flown through the discharge, the air afterglow is reduced to about a third of that when NO is injected downstream. Assuming that the local NO density is the same in either case, this suggests a proportional decrease in oxygen atom flow rate, i.e., that the O atom flow rate has dropped by approximately a factor of 3. The increase in O₂(a) density over the flow distance is similar for both injection points, with the NO through the discharge resulting in significantly higher yields.

2.6 Dipolar Excitation (Transverse) Discharge Experiments

We have typically utilized either a longitudinal or an inductive rf discharge in our ElectricOIL experiments, but as discussed above, this type of discharge has typically resulted in discharge instabilities that would occur at around 500 W in our small system. In an effort to improve the discharge stability we implemented a “dipolar excitation” (transverse) discharge concept. This concept places contoured capacitive electrodes along the length of the discharge section, similar to experiments being performed at Moscow State University.^{7,8,13,14} One significant advantage of this technique is that it provides capacitive ballasting which inhibits current constriction and arcing. Another major advantage of the transverse discharge is that it provides better stability at higher discharge pressures.¹¹ Experiments performed in our laboratory with this setup resulted in significant yields at pressures of 20 and 30 torr, Fig. 11; these yields were significantly higher (greater than a factor of 1.5 improvement) than we had previously been able to obtain with a longitudinal discharge. Also very importantly we were able to attain significant fractions of the power deposited into the flow going into the desired O₂(a) state at higher pressures, Fig. 12; >30% at a pressure of 20 torr and >25% at 30 torr. With the dipolar excitor discharge a gain of 0.027%/cm was obtained at 20 torr, Fig. 4 (above).

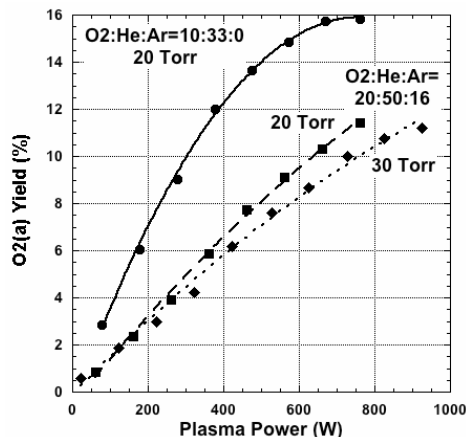


Figure 11: Yield of O₂(a) vs. rf power absorbed by the plasma as a function of flow rate and pressure using an rf transverse discharge.

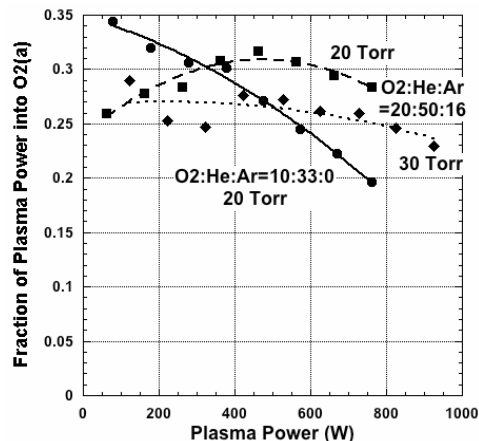


Figure 12: Fraction of plasma power deposited into O₂(a) vs. rf power absorbed by the plasma as a function of flow rate and pressure using an rf transverse discharge.

2.7 Pulsar-Sustainer Discharge Experiments

It has long been understood that control of the E/N parameter is critical to producing high yields of O₂(a), where E is the electric field in units of V-cm⁻¹ and N is the gas number density in units of cm⁻³. Theoretical calculations in Refs. 6 and 22 illustrate the functional dependence of how much electrical power can be deposited into the important O₂(a) and O₂(b) states as a function of E/N (or equivalently electron temperature). With the longitudinal, capacitive, and inductive RF discharges, we typically operate with an average E/N in the range of 15 to 25 Townsend (Td), dependent upon flow conditions. [Note: 1 Td = 10⁻¹⁷ V-cm²]. From Refs. 6 and 22 it is clear that optimal power deposition occurs in the region of 5-10 Td.

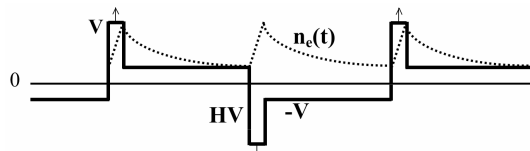


Figure 13: Illustration of Pulsar-Sustainer concept waveform; a bipolar shape is illustrated and used.

can be controlled by the sustainer field, Figure 13. The optimum repetition rate of the pulser is determined by the decay of excess ionization. Early experiments²⁸ are very encouraging and have demonstrated three primary advantages with this concept, (i) some control of the critical E/N parameter, (ii) a more stable discharge at higher average power, and (iii) a more stable discharge at higher pressure, all of which are critical issues for enhancing the ElectricOIL system.

3. POST-DISCHARGE MODELING STUDIES

Since ElectricOIL development is impacted by an imperfect understanding of post-discharge physics, the Blaze-II chemical laser model³⁵ was improved²⁴ to allow broader studies of ElectricOIL post-discharge kinetics and laser performance. The accuracy of Blaze-II calculations is critically dependent on the accuracy of the input chemical kinetic reaction set. As such, the chemical kinetic reaction set was expanded to include 28 species and 105 reactions.²⁴ Further, a number of temperature dependent reactions have been included because the temperature range in the post-discharge laser system can be as large as 600 K at the exit of the discharge to near 100 K in the supersonic laser cavity. A two stream mixing model was found to give reasonable qualitative and quantitative agreement with data,²⁴ such as that shown in Figs. 2 and 3, and considerably better agreement than did premixed simulations.

Initial simulations were performed to study the effect of NO and NO₂ on atomic oxygen levels in the post-discharge kinetics. The importance of the internal production of NO₂ by the three-body recombination reactions, O + NO + M → NO₂ + M, reaction (2), followed by the fast reaction of NO₂ with O, reaction (1), is illustrated in Fig. 14. As shown, the presence of reaction (2b) makes a dramatic difference in the predicted atomic oxygen concentration downstream of the discharge.

For the $O_2:He:NO = 3:16:0.15$ mmol/s flow conditions discussed above with an rf power of 450 W, the predicted $O_2(a)$ yield as a function of distance from the discharge exit is shown in Fig. 15 for three different I_2 flow rates. Two of the interesting features that are observed in Fig. 15 are:

1. the pre- I_2 injection drop in $O_2(a)$ yield is due to (in order of significance): (i) the 3-body quenching $O_2(a)+O_2+O \rightarrow O_2+O_2+O$, reaction (3); (ii) the pooling reaction $O_2(a)+O_2(a) \rightarrow O_2(b)+O_2$; and (iii) quenching by O, O_3 , and $O_2(a)$;
2. higher I_2 flow rates result in lower $O_2(a)$ yields downstream in the laser cavity, which is principally due to the effects of the $I^* + O$ quenching reaction; the I^*+O quenching is clearly an extremely critical mechanism.

Gain calculations were also run for these flow conditions.²⁴ Downstream of the throat the gain was predicted to increase significantly in the supersonic cavity (not shown for brevity). For I_2 flow rates of 0.008 and 0.036 mmol/s, the peak gain in the nozzle was predicted to be approximately 0.0085 and 0.0168 %/cm, respectively. As shown in Ref. 24, the prediction of gain for both the 0.008 and the 0.036 mmol/s of I_2 cases are in reasonably good agreement with the measured gains¹³ of 0.0067 and 0.0156 %/cm, respectively, for these conditions.

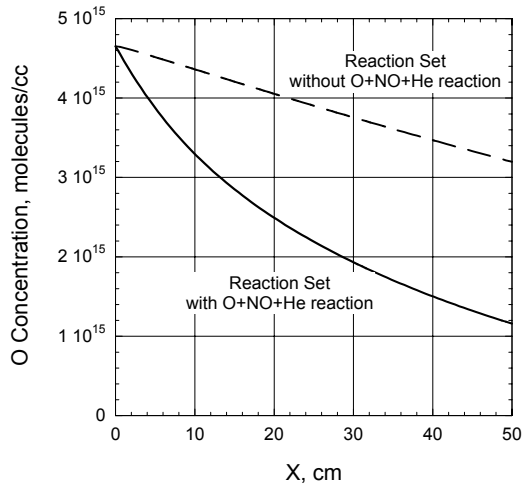


Figure 14: Baseline ElectricOIL mixing predictions of O concentration as a function of axial location with and without the O + NO + He reaction (2b).

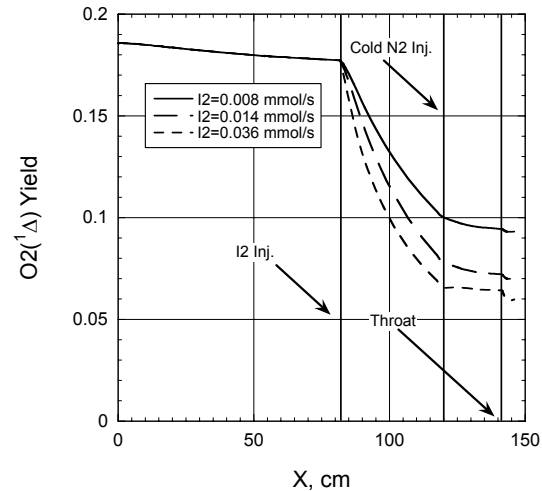


Figure 15: Mixing predictions of $O_2(1\Delta)$ yield as a function of axial position vs. I_2 flow rate, $O_2:He:NO:N_2 = 3:16:0.15:55$ mmol/s.

4. CONCLUDING REMARKS

Over the past two years of research and development, continual improvements in gain and lasing power have been obtained. $O_2(a)$ yields greater than 20% have been demonstrated along with positive gain and cw laser power in both supersonic and subsonic flow systems. The gain has risen from the initial demonstration of $0.002\% \text{ cm}^{-1}$ by more than an order of magnitude to $0.027\% \text{ cm}^{-1}$, and similarly the outcoupled laser power has risen from 0.16 W to 1.47 W. We are now obtaining >30% energy coupling (and for the higher rf power cases more than 200 W of the power) into the desired $O_2(a)$ state, but significant improvements still need to be made in regards to laser extraction of this energy. While O atoms permit rapid dissociation of the I_2 molecule, they appear to be major problem for energy extraction (as they also act as a quencher). The Pulsar-Sustainer discharge concept shows significant promise and may play a significant role in future developments and the evolution of the system.

The Blaze-II laser system model enhanced and updated with a 105 reaction, 28 specie set to model the ElectricOIL system to better understand the post-discharge physics and kinetics. Overall the Blaze-II model with the inclusion of mixing effects appears to be predicting many of the observed qualitative trends that have been measured, and several quantitative comparisons to data are reasonable. Improvements in the knowledge of the kinetics will likely also play a crucial role in better modeling of the system.

In summary, we believe that continuing studies will enable significant performance improvements as this complex electro-kinetic system is better understood and ways to overcome current challenges are solved.

ACKNOWLEDGEMENTS

This work was supported by the Missile Defense Agency (MDA) through the U.S. Army Space and Missile Defense Command (USA SMDC), the Air Force Office of Scientific Research (AFOSR), and by CU Aerospace internal research

and development funds. The authors would like to acknowledge the contributions of: T. Madden (Air Force Research Laboratory); G. Hager (University of New Mexico); M. Kushner (Iowa St. Univ.); L. Sentman (Univ. of Illinois); T. Rawlins and S. Davis, (PSI); M. Heaven and K. Morokuma (Emory Univ.); G. Perram (Air Force Institute of Tech.); M. Berman (AFOSR); J. Mulroy and J. Kotora (MDA); B. Otey (USA/SMDC); A. Ionin (P.N. Lebedev Physics Inst.); and T. Rakhimova and Yu. Mankelevich (Lomonosov Moscow State Univ.). We also thank B. Wheaton and A. Roberts for their technical assistance.

REFERENCES

1. W. McDermott, N. Pchelkin, D. Benard, and R. Bousek, *Appl. Phys. Lett.*, **32** (8), pp. 469–470, 1978.
2. D. L. Carroll, J.T. Verdeyen, D.M. King, B.S. Woodard, L.W. Skorski, J.W. Zimmerman, and W.C. Solomon, *IEEE J. Quant. Elect.*, **39** (9), pp 1150–1159, 2003.
3. D. L. Carroll, J.T. Verdeyen, D.M. King, B. Woodard, J. Zimmerman, L. Skorski, and W.C. Solomon, AIAA Paper 2003–4029.
4. J. Schmiedberger, S. Hirahara, Y. Ichinoche, M. Suzuki, W. Masuda, Y. Kihara, E. Yoshitani, and H. Fujii, *SPIE* **4184**, 2001.
5. A. E. Hill, *Proc. Int. Conf. Lasers 2000*, V. Corcoran and T. Corcoran, Eds., McClean, VA, pp. 249–258, 2001.
6. A. A. Ionin, Y. M. Klimachev, A. A. Kotkov, I. V. Kochetov, A. P. Napartovich, L. V. Seleznev, D. V. Sinityn, and G. D. Hager, *J. Phys. D: Appl. Phys.*, **36**, pp. 982–989, 2003.
7. T. V. Rakhimova, A. S. Kovalev, K. S. Klopovsky, D. V. Lopaev, Yu. A. Mankelevich, A. N. Vasilieva, O. V. Braginsky, N. A. Popov, O. V. Proshina, and A. T. Rakhimov, AIAA Paper 2005–4918.
8. T. V. Rakhimova, A. S. Kovalev, D. V. Lopaev, O. V. Proshina, Yu. A. Mankelevich, Yu. V. Kolobyani, O. V. Braginsky, K. S. Klopovsky, N. A. Popov, A. T. Rakhimov, and A. N. Vasilieva, AIAA Paper 2006–3762.
9. W. T. Rawlins, S. Lee, W. J. Kessler, L. G. Piper, and S. J. Davis, AIAA Paper 2005–5299.
10. Yu. V. Kolobyani, A. A. Adamenkov, Yu. A. Adamenkov, V. V. Bakshin, V. V. Buzoverya, L. A. Vdovkin, B. A. Vyskubenko, L. Goryachev, V. Efremov, S. Ilyin, A. Kalashnik, E. Kudryashnov, G. Rogozhnikov, and Yu. Savin, AIAA Paper 2005–4920.
11. A. Hicks, Y. Utkin, W.R. Lempert, J.W. Rich, and I.V. Adamovich, AIAA Paper 2006-3754.
12. A. A. Ionin, A. P. Napartovich, and N. N. Yuryshev, *Laser Physics*, **16** (1), 155-172, 2006.
13. O. V. Braginskiy, A.N. Vasilieva, K.S. Klopovskiy, A.S. Kovalev, D.V. Lopaev, O.V. Proshina, T.V. Rakhimova, and A.T. Rakhimov, *J. of Physics D: Applied Physics*, **38**, 3609-3625, 2005.
14. O. V. Braginskiy, A.N. Vasilieva, A.S. Kovalev, D.V. Lopaev, Yu. A. Mankelevich, T.V. Rakhimova, and A.T. Rakhimov, *J. of Physics D: Applied Physics*, **38**, 3625-3634, 2005.
15. D. L. Carroll, J. T. Verdeyen, D. M. King, J. W. Zimmerman, J. K. Laystrom, B. S. Woodard, N. Richardson, K. Kittell, and W. C. Solomon, *Appl. Phys. Lett.*, **85** (8), pp. 1320–1322, 2004.
16. D. L. Carroll, J. T. Verdeyen, D. M. King, J. W. Zimmerman, J. K. Laystrom, B. S. Woodard, G. F. Benavides, K. Kittell, and W. C. Solomon, *IEEE J. Quant. Elect.*, **41** (2), pp. 213–223, 2005.
17. W. T. Rawlins, S. Lee, W. J. Kessler, and S. J. Davis, *Appl. Phys. Lett.*, vol. 86, pp. 051105–1–3, 2005.
18. D. L. Carroll, J. T. Verdeyen, D. M. King, J. W. Zimmerman, J. K. Laystrom, B. S. Woodard, G. F. Benavides, K. Kittell, D. S. Stafford, M. J. Kushner, and W. C. Solomon, *Appl. Phys. Lett.*, **86**, 111104–1–3, 2005.
19. D. L. Carroll, J. T. Verdeyen, D. M. King, J. W. Zimmerman, J. K. Laystrom, B. S. Woodard, G. F. Benavides, N. R. Richardson, K. W. Kittell, and W. C. Solomon, *IEEE J. Quant. Elect.*, **41** (10), pp. 1309–1318, 2005.
20. J. T. Verdeyen, D. L. Carroll, D. M. King, J. K. Laystrom, G. F. Benavides, J. W. Zimmerman, B. S. Woodard, and W. C. Solomon, *Appl. Phys. Lett.*, to be published, 2006.
21. D. S. Stafford and M. J. Kushner, *J. of Appl. Phys.*, **98** (5) pp. 2451–2465, 2004.
22. D. S. Stafford and M. J. Kushner, *J. of Appl. Phys.*, **98**, 073303-1-12, 2005.
23. R. Arakoni, D. S. Stafford, N. Y. Babaeva, and M. J. Kushner, *J. of Appl. Phys.*, **98**, 073304-1-7, 2005.
24. A. D. Palla, D. L. Carroll, J. T. Verdeyen, and W. C. Solomon, *J. of Appl. Phys.*, to be published, 2006.
25. T.V. Rakhimova, A.P. Palov, Yu.A. Mankelevich, N.A. Popov, and D.L. Carroll, “Mixing of Post-discharge O₂/He Flow with NO₂/He Flow: 3D Modeling of Experimental Data,” Proc. of the GCL-HPL 2006 Conf., Gmunden, Austria, 2006.
26. W.T. Rawlins, S.J. Davis, S. Lee, M.L. Silva, W.J. Kessler, and L.G. Piper, AIAA Paper 2003-4032.
27. S.J. Davis, M.G. Allen, W.J. Kessler, K.R. McManus, M.F. Miller, and P. Mulhall, *SPIE* Vol. **2702**, 195, 1996.
28. D. M. King, D. L. Carroll, J. T. Verdeyen, J. K. Laystrom, G. F. Benavides, A.D. Palla, J. W. Zimmerman, B. S. Woodard, and W. C. Solomon, AIAA Paper 2006-3756.
29. M.C. Heaven, private communication, 2001.
30. V.N. Azyazov, I. Antonov, S. Ruffner, and M. Heaven, “Quenching of I(²P_{1/2}) by O₃ and O(³P),” *SPIE* Vol. **6101**, 61011Y, 2006.
31. G.D. Hager, C.A. Helms, K.A. Truesdell, D. Plummer, J. Erkill, and P. Crowell, *IEEE J. Quant. Elect.*, **32** (9) 1525, 1996.
32. J. W. Zimmerman, D. King, A. Palla, J. Verdeyen, D. Carroll, J. Laystrom, G. Benavides, B. Woodard, W. Solomon, W. Rawlins, S. Davis, and M. Heaven, “Important kinetic effects in the ElectricOIL system,” *SPIE* Vol. **6261**, 62611R1-12, 2006.
33. F. Kaufman, *Proc. Roy. Soc. A*, **247**, 123, 1958.
34. R. Atkinson, D. Baulch, R. Cox, R. Hampson, Jr., J. Kerr, M. Rossi, and J. Troe, *J. of Phys. and Chem. Ref. Data*, **26**, 3, 1997.
35. L. H. Sentman, M. Subbiah, and S. W. Zelazny, S. “Blaze II: a chemical laser simulation computer program,” Bell Aerospace Textron, Buffalo, NY, Tech. Repp. H-CR-77-8, 1977.