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Electric Oxygen-Iodine Laser Performance Enhancement using Larger Discharge and Resonator Mode Volumes

J. W. Zimmerman,[1] G. F. Benavides,[1,2] B. S. Woodard,[1] M.T. Day,[1] D. L. Carroll,[3]
A.D. Palla,[4] J. T. Verdeyen,[5] and W. C. Solomon[6]

University of Illinois at Urbana-Champaign, Urbana, IL 61801

CU Aerospace, Champaign, IL 61820

The authors observed 95% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine for only a 50% increase in gain length (5.1 cm to 7.6 cm), flow rates, and discharge input power, making use of a large volume 16-mm gap transverse discharge. A gain of 0.26% cm^{-1} was obtained and the laser output power was 55 W in a stable resonator with two 5 cm (2-in.) diameter, 0.9970 reflective mirrors. A longer gain length cavity permits use of lower reflectivity resonator mirrors that reduce diffractive spill losses, and thereby extract power from the gain medium more efficiently. The outcoupled power was increased to 92 W by increasing the mirror diameter to 10 cm (4-in.), demonstrating that significantly higher power was available in the electric oxygen-iodine laser gas flow which could be extracted by tailoring the cavity design. Two 4-mirror folded resonator configurations using 5 cm optics were also demonstrated, a stable "Z-resonator" with a z-shaped optical path having six roundtrip passes through the gain medium, and a stable "X-resonator" having four roundtrip passes through the gain medium. The best measured outcoupled powers for these folded designs were 102 W and 109 W for the Z-resonator and X-resonator, respectively. Continued expansion of the operating envelope to higher flow conditions, pressures, and gain length of the laser cavity, plus the addition of an iodine pre-dissociator discharge are expected to provide significant increases to the gain and laser power. The results presented herein represent more than two orders of magnitude improvement in gain and laser power since the initial demonstration in 2005.

I. Introduction

The electrically driven oxygen-iodine laser (ElectricOIL) that was first demonstrated by Carroll *et al*.[1,2] operates on the electronic transition of the iodine atom at 1315 nm, $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ [denoted hereafter as I^* and I respectively]. The lasing state I^* is produced by near resonant energy transfer with the singlet oxygen metastable $O_2(a^1\Delta)$ [denoted hereafter as $O_2(a)$]. Since the first reporting of a viable electric discharge-driven oxygen-iodine laser system (also often referred to as EOIL or DOIL in the literature), there have been a number of other successful demonstrations of gain[3,4,5] and laser power,[4,5,6] as well as a recent demonstration of gain and lasing from an air-helium discharge.[7] Computational modeling of the discharge and post-discharge kinetics[8,9,10] has been an invaluable tool in ElectricOIL development, allowing analysis of the production of various discharge species [$O_2(a^1\Delta)$, $O_2(b^1\Sigma)$, O atoms, and O_3] and determination of the influence of NO_X species on system kinetics. Ionin *et al*.[11] and Heaven[12] provide comprehensive topical reviews of discharge production of $O_2(a)$ and various EOIL studies. As of approximately one year ago[13], the highest reported gain in an ElectricOIL device was 0.22 % cm^{-1}, with an output power of 28.1 W.

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[1] Res. Assistant, Univ. of Illinois at Urbana-Champaign, 104 S. Wright, Urbana, IL 61801, Student Member AIAA.
[2] Senior Engineer, CU Aerospace, 2100 S. Oak St. – Ste 206, Champaign, IL 61820, Member AIAA.
[3] Vice President, CU Aerospace, 2100 S. Oak St. – Ste 206, Champaign, IL 61820, Associate Fellow AIAA.
[4] Senior Physicist, CU Aerospace, 2100 S. Oak St. – Ste 206, Champaign, IL 61820, Senior Member AIAA.
[5] Senior Scientist, CU Aerospace, 2100 S. Oak St. – Ste 206, Champaign, IL 61820.
[6] Prof. Emeritus, Univ. of Illinois at Urbana-Champaign, 104 S. Wright, Urbana, IL 61801, Fellow AIAA.

One of the significant remaining questions regarding the ElectricOIL system is: why is the amount of laser power extracted so much lower than the available power carried by the $O_2(a)$? For example, for the ElectricOIL configuration reported in Ref. 14, the laser output power of 12.3 W was extracted from a flow having approximately 210 W carried downstream by $O_2(a)$. While the BLAZE model[9,10] has demonstrated good agreement with the experimental measurements for production of various discharge species and laser gain, Fabry-Perot laser simulations with the BLAZE model indicate that for this case over 160 W in laser power should be extracted, 13x higher than the experimental measurement. The two possible causes that seem the most likely suspects: (i) optical losses that dissipate power before it is outcoupled, and (ii) an unidentified chemical kinetic process that is somehow inhibiting (slowing) the power extraction process.

Carroll and Verdeyen[15] explored the possibility that Fraunhofer diffraction that occurs off the edges of the supersonic cavity (which effectively act as an aperture) could create a significant optical loss mechanism for the ElectricOIL experiments to date which have employed mirrors with very high reflectivity (typically > 0.9999). They made a conservative estimate that the expansion angle in recent experiments is $\sin\theta \cong \theta = \lambda/d = 1.315$ μm/2.54 cm = 5.2×10^{-5} radians. They then estimated the amount of beam area from diffractive expansion that could be clipped by the apertures; this estimate comes out to be a loss of approximately 0.00056 per restricting aperture for the geometry studied. While this number seems at first glance to be very small, when one considers the number of passes the photons make through a high reflectivity resonator, then even small intracavity losses may have a significant effect. Carroll and Verdeyen[15] concluded that a small diffractive loss would have a significant effect on ElectricOIL performance and recommended more experiments to verify the hypothesis. In this paper, this possibility is further examined with comparisons to experimental data using a longer gain length cavity, which enables the use of lower reflectivity mirrors.

The kinetics aspects of power extraction were addressed by measurements of gain recovery downstream of an operating laser cavity, reported in Ref. 16 (using the same discharge/cavity configuration from Ref. 14). Modeling of these experiments showed that reducing the forward and backward pumping rates by an effective factor of approximately 4 to simulate a competing mechanism results in the computational modeling matching the experimental gain recovery measurements, and improved agreement between the measured and modeled laser power extraction. Note that the work in Ref. 16 does not suggest that the established pumping rates are in error, only that there is an additional competing process that is occurring in the ElectricOIL system kinetics due to additional species not present in classic COIL. These experiments suggested that a larger volume resonator that extends further downstream in the flow direction may be able to extract more power from the ElectricOIL gain medium. Some experiments described in this paper have focused on validating this hypothesis, including gain recovery measurements in the new cavity configuration, and laser power extraction experiments using larger optics and folded-path resonator designs.

Additional improvements to the heat exchanger design used between the discharge and laser cavity were also made. The design applied to the new ElectricOIL configuration Cav6 was based on the analysis described in Ref. 13. The thermal power extracted from the flow exiting the discharge was measured by the heating of the cooling water passed through the heat-exchanger. Comparison of this and the flow temperature measurements suggests that a significant amount of O-atom recombination occurs in the heat-exchanger device. A method of temperature measurement using the $O_2(a)$ ro-vibrational spectra has also been applied to recent measurements in ElectricOIL experiments, which should aid in future analysis and design work.

II. Laser Power Extraction Experiments

The increase in gain length (and correspondingly the flow rates) was motivated by the desire for more understanding of the system. Recent theoretical investigations have indicated that the combination of short gain length (5.1 cm) with gain < 0.25% cm^{-1} (which requires highly reflective mirrors for lasing) results in significant diffractive losses inside the laser hardware that thereby reduce the extracted power from the gain medium.[15] To help alleviate this problem the 5.1 cm gain length of the prior fifth generation "Cav5" laser cavity, reported on in Ref. 13, was increased to 7.6 cm in the new sixth generation "Cav6" laser cavity discussed herein. Longer gain length enables lower reflectivity mirrors to be used for the resonator, which reduces the number of passes a photon makes within the resonator, and thereby lowers the amount of energy lost to diffractive spill (or equivalently increases the fraction of power extracted from the gain medium). Longer gain lengths than 7.6 cm were considered for design and fabrication, but cost and possible vacuum pumping limitations led to selection of 7.6 cm as a gain length that would give significant support to the above proposition. With the new "Cav6" design, some experiments using larger volume resonator designs were conducted in order to establish that there was more power available in the flow which was not being extracted with 2-in. optics. The two approaches used were (i) increased mirror diameter to 10 cm (4 in), and (ii) folded path resonator designs using 5-cm (2 in.) mirrors. Both approaches resulted in accessing larger gain volume in the supersonic flow and were successful in extracting significantly higher power.

A. Experimental Laser System Setups

$O_2(a)$ was produced using transverse capacitive radio-frequency (rf) electric discharge ignited in a flowing O_2-He-NO mixture. The gas flow passes through the discharge where $O_2(a)$ is excited, then passes through a cross-flow heat exchanger, and then is mixed with molecular iodine and chilled nitrogen. The combined flow then expands through a Mach 2 supersonic nozzle to a lower flow temperature, and then passes through the laser cavity situated at the nozzle exit. Two discharge configurations having similar $O_2(a)$ production performance were applied: (i) a single transverse discharge ignited in a 1.6 cm x 7.5 cm rectangular cross-section channel, and (ii) a 6-tube array of transverse discharges ignited in 1.6 cm I.D. circular cross-section quartz tubes. A block diagram and photograph of the experimental laser setup with the rectangular discharge are shown in Figs. 1a and 1b, respectively. The plasma zone filled the transverse gap of 1.6 cm and was 50.8 cm long (the gap between the parallel plate electrodes, the outside dimension of the flow channel, was 2.2 cm, i.e. the quartz tube walls were 0.3 cm thick).

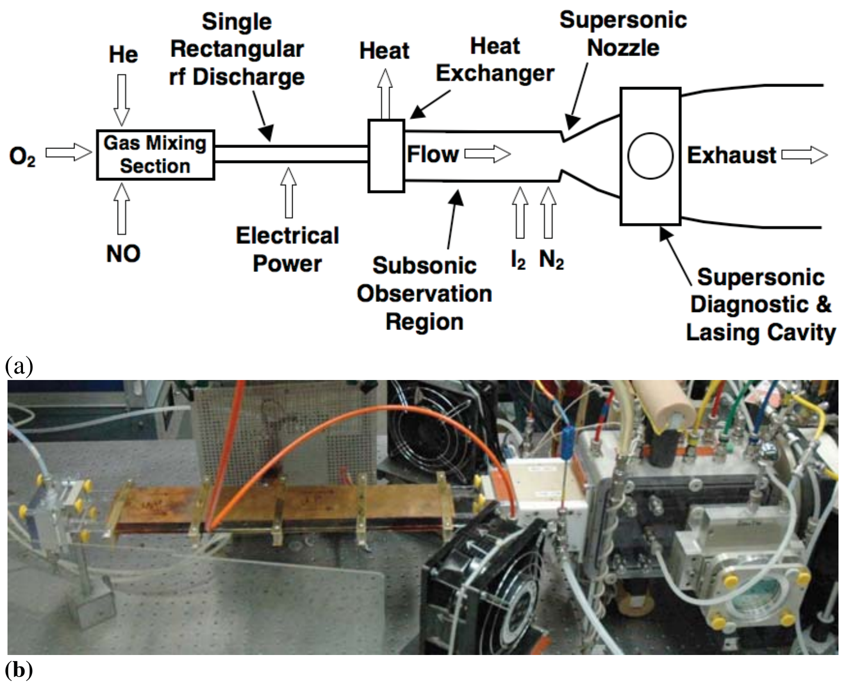


Figure 1. Experimental laser setup with rectangular discharge: (a) block diagram and (b) photograph.

In prior experiments[13,14], single and multiple 1.6 cm internal diameter discharge tubes were utilized that resulted in substantially increased discharge stability at higher pressure while maintaining significant $O_2(a)$ yields. More information related to the performance of the transverse electric discharge sustained in an O_2-He-NO gas mixture used in the experiments presented herein can be found in Woodard *et al.*[17] and Zimmerman *et al.*[13]. The disadvantage to these smaller tubes is that they limit the amount of gas flow that can be flowed through them without creating substantial pressure rises in the discharge [detrimental to $O_2(a)$ yield performance[17]]. As such, a high aspect ratio rectangular discharge channel (Fig. 1) was chosen to simultaneously maintain the good discharge characteristics with a small discharge gap while at the same time permitting higher flow rates without any increase in discharge pressure. An alternative approach was to add more tubes to the array of discharges while maintaining the flow rate per tube, as was done in the configuration shown in Fig. 2. The total cross-sectional areas of the 6-tube array (Fig. 2) and the single rectangular tube (Fig. 1b) are equivalent (12 cm^2).

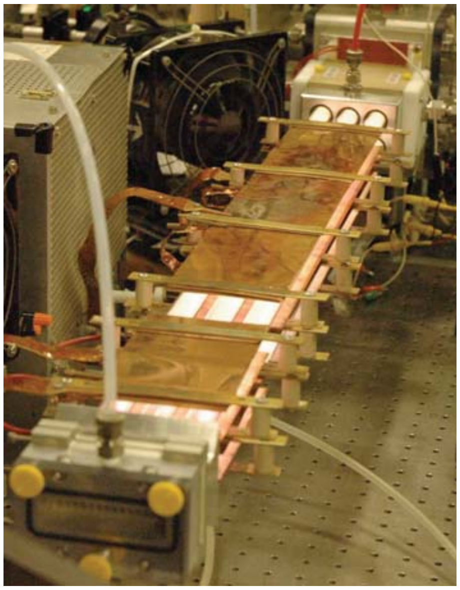


Figure 2. Discharge configuration using six 1.6-cm I.D. quartz tubes, with flow entering the Cav6 laser cavity. The plates between the tubes are at high voltage, while the top and bottom plates are grounded. The discharge array is driven by two 13.56 MHz rf supplies, one supply excites the upstream portion of the tubes referred to as the "primer" discharge, and the other excites the longer "primary" discharge section. For best laser operation, 40% of the total rf power was input to the "primer" section. This configuration (with higher power density in the upstream "primer" section promoted a uniform glow discharge throughout the flow channel sections between the electrodes.

The supersonic diagnostic cavity has a Mach 2 nozzle with purged optical mounts into which can be placed either wedged windows for measurement of the gain or high-reflectivity mirrors for laser oscillation. The gain length of the Cav6 laser cavity is 7.6 cm. Supersonic bank blowers, flowing in the same direction as the gain medium gases, were added to the Cav6 design at the sides of the gain medium to provide better gas flow confinement. The bank blowers eliminate recirculation regions that could absorb photons and prevent contamination of the laser mirrors.

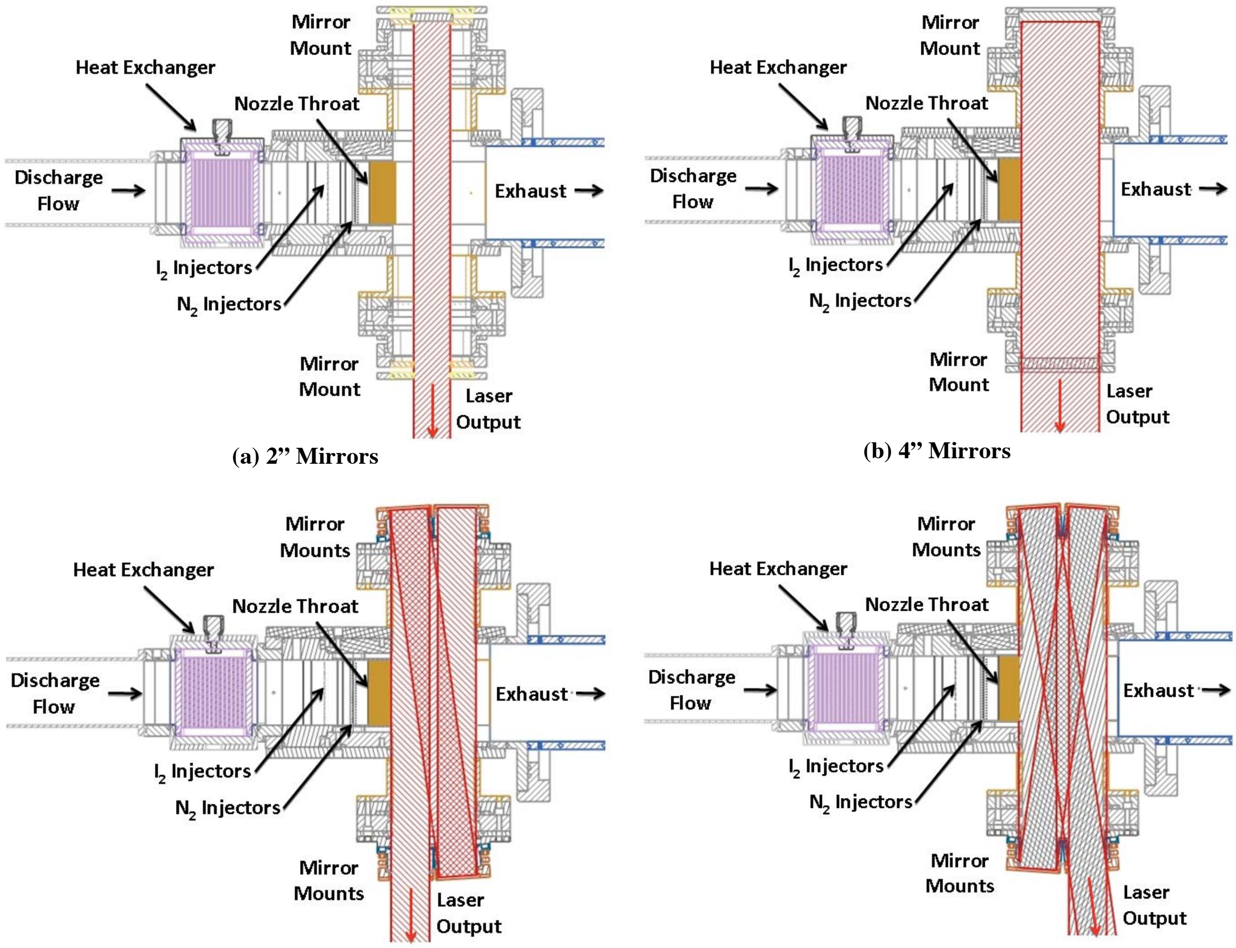
Micro-Motion CMF and Omega FMA mass flow meters were used to measure the flow rates of the gases, including the gaseous I_2. Pressure in the subsonic and supersonic flow regions were measured by capacitance manometers from MKS and Leybold.

Prior to gain and laser experiments, flow tube measurements of the optical emission from $O_2(a)$ at 1268 nm and $O_2(b^1\Sigma)$ [denoted hereafter as $O_2(b)$] at 762 nm were made downstream from the exit of the rectangular discharge in a purged subsonic observation region. A Roper Scientific Optical Multi-channel Analyzer (OMA-V) with a 1024-element InGaAs LN_2 cooled array interfaced to an Acton Research SP-2300i monochromator was used for measurements of $O_2(a)$ at 1268 nm. A thermoelectric-cooled Apogee CCD was used to measure spectra of the $O_2(b)$ transition about 762 nm. Both instruments were fiber-coupled to enable instrument positioning flexibility and excellent measurement repeatability. The measurements indicated an $O_2(a)$ yield of ≈ 12.5% at 4000 W of rf power (similar for both discharge configurations). $O_2(b)$ measurements downstream of the rectangular discharge indicate a flow temperature of ≈ 550 K, which drops to ≈ 325 K after the flow passes through the water cooled heat exchanger, with less than one yield percent loss in the $O_2(a)$ (similar to results from Zimmerman *et al.*[13]).

Measurements of gain (or absorption) were made prior to operating the system as a laser using the Iodine-Scan Diagnostic (ISD) developed by PSI[18]. Since the ISD uses a narrow band diode laser, measurements of the lineshapes can also be used to determine the local temperature from the Voigt profile. The windows on the sides of the cavity when using the gain diagnostic were wedged and anti-reflection coated to minimize etalon effects. A single pass configuration (7.6 cm path length) was used in the supersonic diagnostic section.

Various sets of mirrors purchased from AT Films were used in the laser power trials. Laser power measurements were made with Scientech Astral™ model AC5000 and UC150HD40 calorimeters interfaced to a pair of Scientech Vector™ model S310 readouts. An Infrared (IR) Detection Card from New Focus, Model 5842, with response between 800-1600 nm, was also used to observe the intensity profile of the beam. The beam profile was also captured by burning black polycarbonate plates.

The four resonator configurations tested with Cav6 are illustrated in Fig. 3. The only cavity system components that change for each case are the mirror mounts and optics. The standard resonators were tested with the rectangular discharge tube (Fig. 1), while the Z and X-resonators were tested using the 6-tube discharge array (Fig. 2). As discussed by Woodard *et al*.[19], the two discharge configurations had very similar O_2(a) production as a function of rf power input. However, it was found in laser experimentation that the 6-tube array required roughly 35% more power than the rectangular setup to maximize the laser power performance. This likely has to do with the differences in oxygen atom production between the two systems and the influence that O-atoms have on iodine kinetics, but the reason has not been resolved conclusively.



(a) 2" Mirrors **(b) 4" Mirrors**

(c) Z-resonator with 2" Mirrors **(d) X-resonator with 2" Mirrors**

Figure 3. Various resonator configurations tested with the Cav6 hardware, standard stable resonators with (a) 2" diameter optics, (b) 4" diameter optics, and multi-pass designs with four 2" optics, (c) stable Z-resonator, and (d) stable X-resonator. (Note: the Z-resonator and X-resonator configurations were tested with a 6-tube discharge rather than a rectangular discharge).

B. Cav6 Performance with Rectangular Discharge and 5 cm optics

The flow conditions for these gain and laser power experiments with the single rectangular primary discharge are 45 mmol/s of O_2 which is diluted with 150 mmol/s of He and 0.23 mmol/s of NO. A secondary stream of ≈ 0.30 mmol/s of I_2 with 46 mmol/s of secondary He diluent was injected 26.7 cm downstream from the exit of the primary discharge. A tertiary flow of 312 mmol/s of cold N_2 gas (≈100 K) was injected further downstream to lower the temperature, improve mixing, and improve the performance of the nozzle in our vacuum system. The pressures in the discharge region and in the supersonic diagnostic cavity were 45.0 Torr and 4.0 Torr, respectively.

Gain was measured for the above flow conditions at a total of 4000 W of primary rf discharge power coupled into the flow over a discharge length of 50.8 cm. Figure 4 shows the gain at line center which peaks at 0.26% cm^{-1} with the rectangular primary discharge. For comparison, the best gain previously observed was 0.22% cm^{-1} (Ref. 13), using four 1.6-cm I.D. primary discharge tubes and roughly two-thirds of the flow rates at 53 Torr total pressure (4.7

Torr in the supersonic diagnostic cavity). Since the discharge flow conditions and discharge power per O_2 molecule were approximately the same, no major changes in gain for these Cav6 experiments as compared to the Cav5 experiments were anticipated. However, an 18% enhancement in gain was observed, most likely due to improvements in flow uniformity with the rectangular discharge and better flow confinement in the laser cavity when using the supersonic bank blowers. The lineshapes indicate temperatures of ≈ 125 K in the laser cavity.

The lowest reflectivity set of mirrors used was a 0.9896 and 0.9970 combination, the middle reflectivity set was a 0.9896 and 0.99997 combination, and the highest reflectivity combination was a pair of 0.9970 mirrors. All of the mirrors used had a 2-m radius of curvature and the pair formed a stable optical cavity. In the standard 2-mirror configuration, the mirrors were separated by approximately 41.9 cm and were located with an optical axis 7.4 cm downstream from the throat of the nozzle.

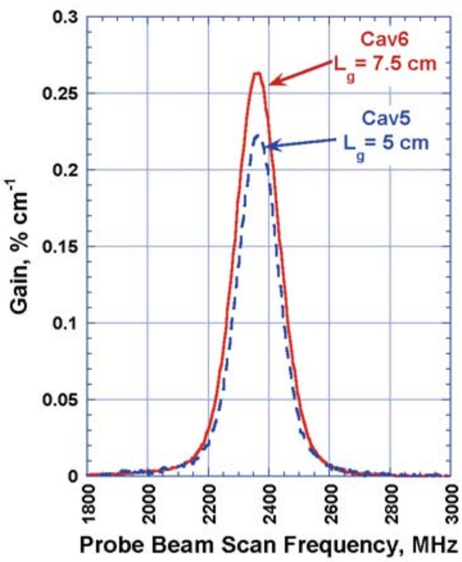


Figure 4. Gain lineshapes in the supersonic cavity as a function of probe beam scan frequency for the 5.1 cm gain length Cav5 (Ref. 13) and the 7.6 cm Cav6 hardware (Ref. 20).

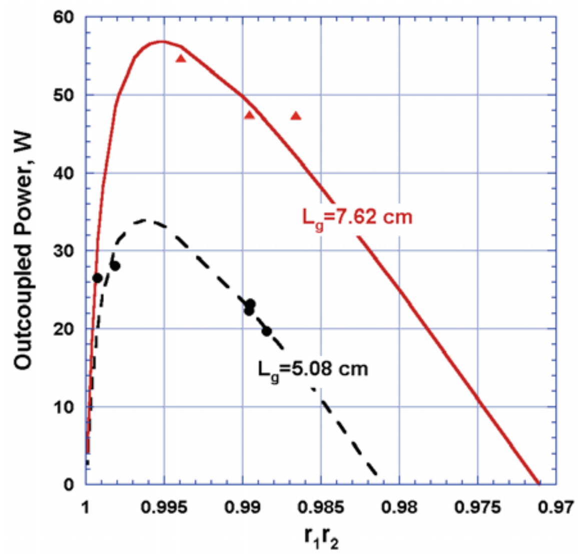


Figure 5. Outcoupled laser power data as a function of the product of the mirror reflectivities for the 5.1 cm gain length Cav5 (Ref. 13) and the 7.6 cm Cav6 hardware (Ref. 20). Rigrod theory with a diffraction loss term is illustrated for comparison with Rigrod parameters I_{sat}=650 W/cm^2, average g_o=0.0020 cm^{-1}, A=8.87 cm^2, a_1=a_2=a=0.00002, t=1-r-a, δ_1=δ_2=δ=0.00056, for two gain lengths L_g=5.08 and 7.62 cm.

The Cav6 supersonic gain medium was used as the active medium for the stable resonator. For the above 45 Torr flow conditions, total laser output powers of 47.8 W, 47.3 W, and 54.8 W were obtained for the three aforementioned mirror sets in order of increasing product of reflectivity, respectively, Fig. 5. The 54.8 W result is a 95% improvement to laser power relative to the 28.1 W result from (Ref. 13) for only a 50% increase in gain length, flow rates, and discharge input power. The beam shape was rectangular with rounded corners and had a length of ≈ 4.45 cm in the flow direction and a height of ≈ 2.5 cm (the same dimensions as the clear aperture of the mirror mounts in the flow direction and the height of the nozzle at the center of the beam in the vertical direction).

Also plotted in Fig. 5 are the Rigrod curves modified to include a diffractive loss term δ, Eq. (1); the details of the derivation are not included here for brevity, but can be found in Carroll and Verdeyen[15].

$$P_{out} = I_{sat} A \frac{(1-\delta_1)t_1\sqrt{(1-\delta_2)r_2} + (1-\delta_2)t_2\sqrt{(1-\delta_1)r_1}}{\left(\sqrt{(1-\delta_1)r_1} + \sqrt{(1-\delta_2)r_2}\right)\left(1-\sqrt{(1-\delta_1)(1-\delta_2)r_1 r_2}\right)}\left[g_o L + \ln\sqrt{(1-\delta_1)(1-\delta_2)r_1 r_2}\right]. \tag{1}$$

Figure 6 shows the gain and laser power as a function of input rf power for Cav6 with 2" optics and a 7.6 cm gain length. The best gain and laser power occur at 4 kW input, while the gain threshold occurs at 600 W, and the laser power threshold is near 2 kW.

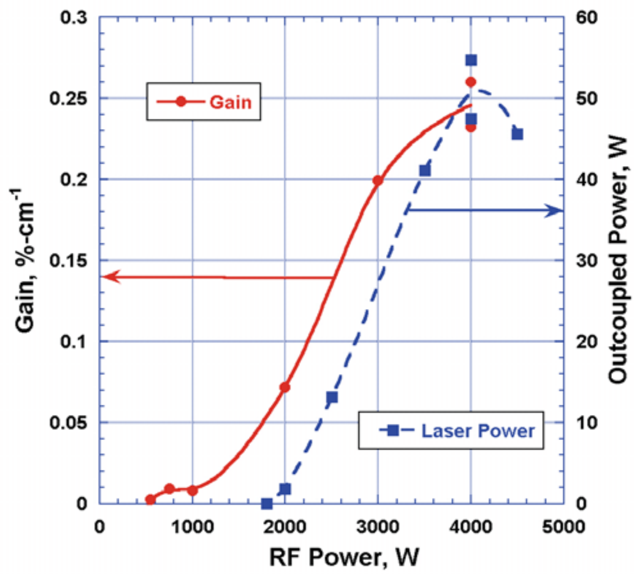


Figure 6. Gain and laser power as a function of rf discharge input power for the 7.6 cm gain length Cav6 hardware. 5-cm (2 in.) diameter mirrors each having a reflectivity of 0.997 were used to obtain the laser data shown.

C. Cav6 Performance with 6-tube Array Discharge and Increased Mode Volume Resonators

There appear to be unidentified kinetic processes that are occurring in the ElectricOIL system that are creating a competing (but not quenching) effect with the pumping reaction (see for example Rawlins *et al.*[20]; Zimmerman *et al.*[16]]. It was hypothesized that it may be possible to engineer around this competing kinetic effect by using a larger mode volume resonator[21], i.e., by extending the resonator further downstream to extract more of the available power being carried by the O_2(a). In an effort to understand the resonator size effects three other resonators were investigated (see Fig. 3), (i) a simple stable resonator with 4" diameter mirrors (rather than 2" diameter mirrors), (ii) a Z-Resonator, and (iii) a X-Resonator.

The experimental setup was very similar to that discussed in Sect. II.B using the Cav6 hardware, with the exception of replacing the rectangular discharge with a 6-tube configuration using 1.6-cm i.d. discharge tubes (Fig. 2) Additionally, the 6-tube configuration required the use of two discharges (one upstream and one downstream) with the upstream discharge necessary to initiate discharge uniformity in all the tubes. Flow rates and pressures were approximately the same as those in Sect. II.B, however total discharge powers were approximately 35% higher to obtain the same laser output power with 2-in. diameter optics; this strongly indicates that the rectangular discharge tube configuration is desirable for the future in terms of electrical efficiency of the system.

Figure 7 compares data from the four different mirror configurations (Fig. 3) as a function of the product of the mirror reflectivities (r_1r_2 for the configurations shown in Figs. 3a and 3b, and $r_1r_2r_3r_4$ for the "Z" and "X" configurations shown in Figs. 3c and 3d). The Rigrod curve fit (Eq. 1) for the folded resonators includes three times the gain length for the six-pass (roundtrip) "Z" configuration and twice the gain length for the four-pass (roundtrip) "X" configuration. The diffraction loss $\delta = 9\text{x}10^{-4}$ (Eq. 1) was assumed in both "Z" and "X" cases, and I_{sat} was chosen to match the peak experimental output power. The use of different saturation intensities compared to the 4-in. optics case to match the peak outputs of the Z and X resonators may indicate problems with effective gain volume or may point to issues associated with modeling the diffraction loss. For example, the Z-resonator data would be better replicated by instead using I_{sat} = 495 W-cm^{-2} and L_g = 17.5 cm, while the X-resonator data would be better replicated by instead using I_{sat} = 495 W-cm^{-2} and $\delta = 4.0\text{x}10^{-4}$. This may indicate that more power can be extracted by stretching the Z or X resonators along the flow direction, increasing the effective mode volume sampled by the resonator.

The peak measured output power for 4-in. mirrors was 92.0 W. The Z-resonator peak measured power was 102.5 W. The X-resonator peak measured power was 109.0 W. Thus, by using a larger mode volume resonator the output power has been improved by 99% (from 54.8 W with 2-in. optics) thereby proving that (i) there is still a considerable amount of power still available in the ElectricOIL flow, and (ii) there are ways to extract this power as useful laser energy.

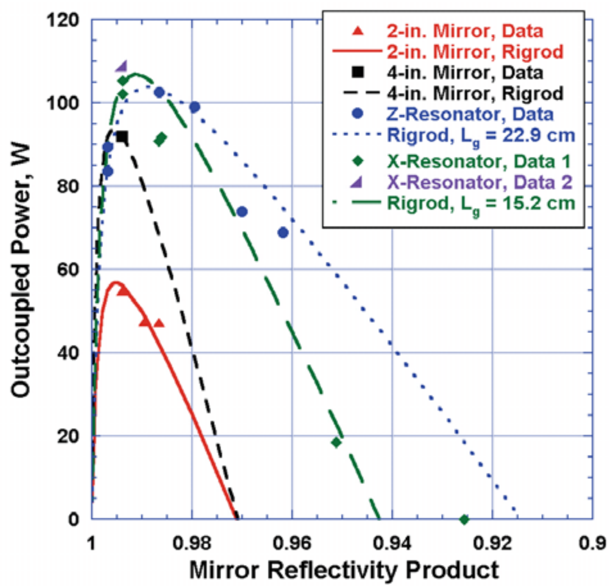


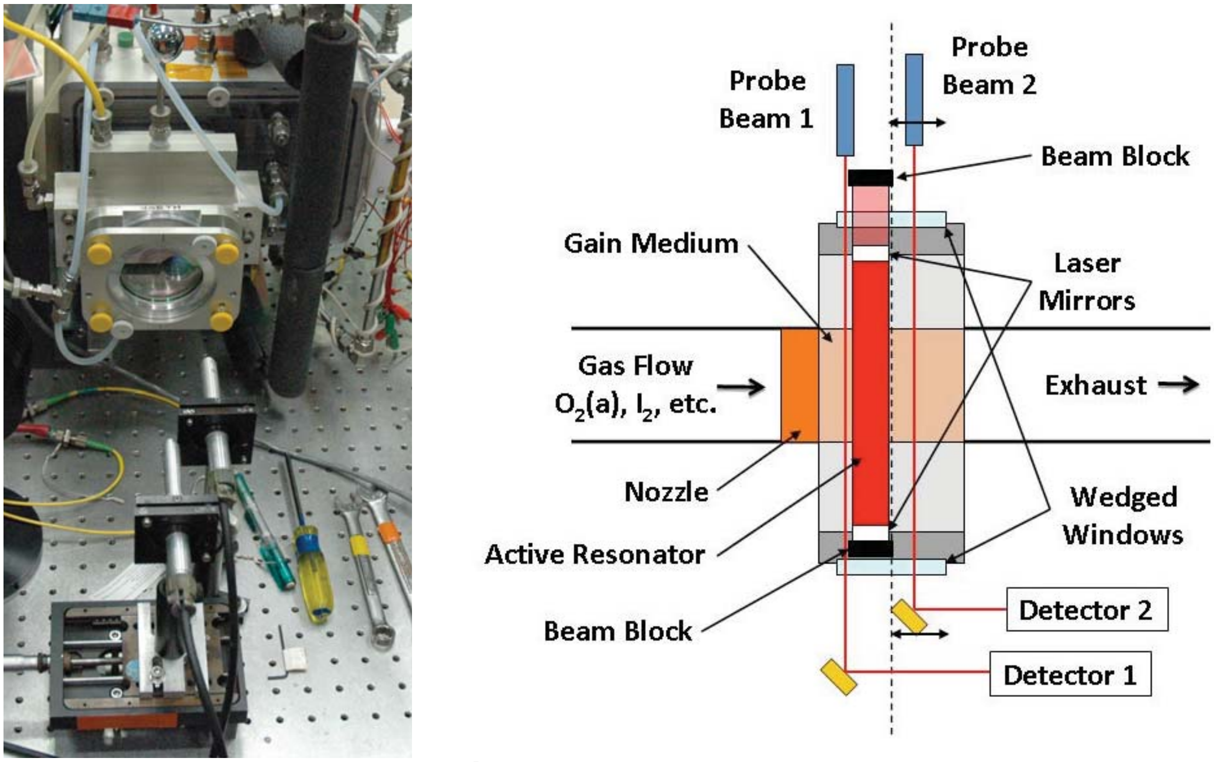
Figure 7. Outcoupled power as a function of resonator configuration (Fig. 3) with Cav6 hardware. The second data set (Data 2) for the X-resonator used improved alignment technique, and achieved slightly higher output power. Modeling of outcoupled power using Rigrod theory (Eq. 1) is also shown. The 2-in. Rigrod inputs are as in Fig. 5. The 4-in. case uses Rigrod inputs g_o=0.0020 cm^{-1}, A=18.4 cm^2, a=2x10^{-5}, δ= 4.5x10^{-4}, L_g=7.6 cm, I_{sat}=495 W-cm^{-2}. The Z-resonator case is compared to the (2-mirror) Rigrod assuming inputs g_o=0.0020 cm^{-1}, A=8.87 cm^2, a=2x10^{-5}, δ= 9x10^{-4}, L_g=22.9 cm, I_{sat}=348 W-cm^{-2}. The X-resonator case is compared to the (2-mirror) Rigrod assuming inputs g_o=0.0020 cm^{-1}, A=8.87 cm^2, a=2x10^{-5}, δ= 9x10^{-4}, L_g=15.2 cm, I_{sat}= 580 W-cm^{-2}.

III. Gain Recovery Experiments

Work reported in Ref. 16 suggested that the forward and backward pumping rates of I + O_2(a) ⇆ I*+ O_2(X) were being effectively slowed by some competing mechanism. This was concluded by observing the gain (proportional to [I*] – 0.5[I]) as a function of position in the region downstream of an active resonator (using 1-in. mirrors). Measurements were taken at two different cavity operating temperatures, ~115 K (using chilled N_2 diluent) and ~164 K (using room-temperature N_2 diluent). The gain measurements in the cavity (without a resonator) were 4.5x10^{-2} %-cm^{-1} and 1.1x10^{-2} %-cm^{-1} respectively for the cold and warm diluent cases. In both conditions, the spatial gain measurements downstream of the resonator were consistent with the effective forward/backward rates being ~4x slower, when compared to the calculations from the BLAZE model.[16] As ElectricOIL development continued, and levels of gain and system flow rates increased, a measurement of gain recovery in conditions of best power extraction performance became desirable. Therefore, an experiment similar to the one performed in Ref. 16 was devised using the new 7.6-cm gain length Cav6 configuration hardware discussed in Sect. II.

A. Experimental Setup

Spatial measurements of gain (proportional to [I*]-0.5[I]) were made downstream of an active resonator using a specially designed optical configuration in the new ElectricOIL cavity referred to as "Cav6". The configuration is similar to the one used in the Cav5 experiments described in Ref. 16. In the new optical configuration, a specialized insert which fits into the 4-in. optical mounts was constructed. This insert holds a 1-in. mirror under vacuum off-center inside of a 3-in. diameter wedged window (anti-reflection coated to minimize etalon effects). With one of these specially designed inserts installed at either side of the Cav6 gain medium, an active resonator can be produced between the 1-in. mirrors, and a gain probe beam can be passed through the gain medium upstream and downstream of the active resonator. A photograph of the experimental setup is shown in Fig. 8a, and a sketch illustrating the experimental technique and setup is shown in Fig. 8b. Measurements of gain were made using both the probe and reference beam of the Iodine-Scan Diagnostic (ISD) developed by PSI.[18]



(a) **(b)**

Figure 8. Setup used to measure recovery of gain downstream of an active resonator in ElectricOIL Cav6: (a) photograph of probe beam launches and optical mount, and (b) diagram of diagnostic setup (not to scale).

B. Spatial Gain Measurements

Gain recovery was measured in a variety of conditions in ElectricOIL Cav6, summarized in Table 1. The best power extraction in these cases using two 1-in. high-reflectivity mirrors was 9.6 W, while 29.2 W was obtained with a pair of 0.997 reflectivity mirrors (better than half of what was obtained with 2-in. optics at similar reflectivity). The power extracted without NO in the flow (case 3) was low, ~0.2 W, and the laser operated near threshold. For all cases shown, the input power to the rectangular cross-section discharge (Fig. 1) was 3.5 kW.

Table 1. Operating Conditions for Gain Recovery Measurements in Cav6

Case	Primary Flow Rates			Secondary Flow Rates		Tertiary Flow Rate	Discharge Pressure	Nozzle Pressures			Laser Power	Mirror Reflectivity	
	[mmol/s]			[mmol/s]		[mmol/s]	[Torr]	[Torr]			[W]	[frac.]	
	O_2	He	NO	He	I_2	N_2	p_0	p_1	p_2	p_3		r_1	r_2
1	45	150	0.26	38	0.38	302	49	5.3	3.8	3.1	9.6	0.99997	0.99995
2	45	150	0.054	38	0.30	306	55	5.7	3.6	2.8	4.4	0.99997	0.99995
3	45	150	0	39	0.23	306	67	6.0	3.2	2.8	0.2	0.99997	0.99995
4	45	150	1.2	39	0.36	297	57	5.7	3.4	3.0	3.2	0.99997	0.99995
5	45	150	0.19	39	0.21	292	59	5.7	3.4	2.5	29.2	0.997	0.997

The experimental procedure consisted of tuning and detuning the laser cavity mirrors (by manual mirror mount adjustment) such that the gain at each position downstream of the mirrors could be measured with and without the active resonator. Examples of the data obtained are shown in Fig. 9 for Case 1 and Fig. 10 for Case 2. Without the resonator tuned, the gain upstream and downstream of the resonator is similar, changing little with position. When the resonator is tuned and laser power is extracted, the gain in the resonator is reduced to the value near threshold (~0 %/cm in Case 1 and 2); downstream of the resonator, the gain increases from zero, and recovers to a significant percentage of the value measured with the resonator detuned (63% in Case 1, 68% in Case 2). Interpretation of the data obtained in these experiments is difficult without a detailed model of the kinetics. As was done with the Cav5 experiments in Ref. 16, the data obtained were analyzed using the BLAZE model. The detailed analysis of this data (Cases 1-5 in Table 1) and discussion of potential mechanisms which may explain the observed behaviors is given by Palla *et al.*[21] in a concurrent publication. Two important conclusions can be drawn from this data (i) the amount of gain recovered is significant meaning that a significant amount of extractable power remains in the flow, and (ii) the rate of gain recovery is slower than expected (from modeling with accepted kinetics). These data explain why the use of larger volume resonators described in Sect. II.C. led to significantly higher power extraction, which scaled approximately with the volume of the resonator in the flow direction.

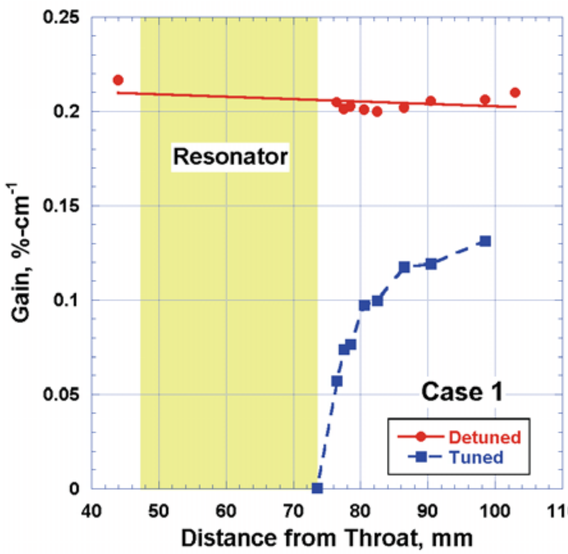


Figure 9. Gain as a function of position in Cav6 gain recovery experiment without and with a tuned laser cavity. Flow conditions are those for Case 1 in Table 1.

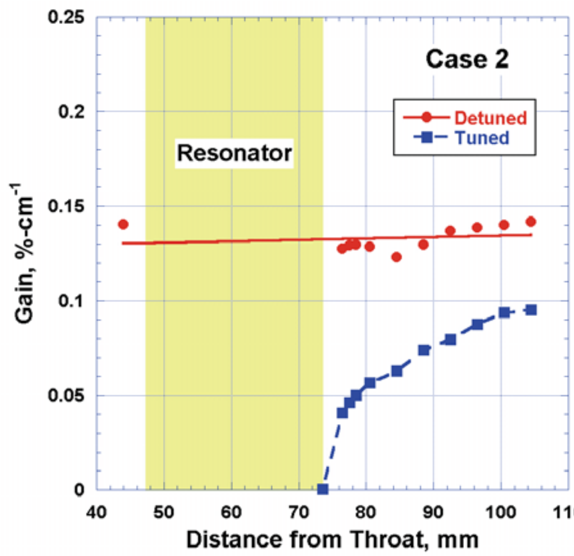


Figure 10. Gain as a function of position in Cav6 gain recovery experiment without and with a tuned laser cavity. Flow conditions are those for Case 2 in Table 1.

IV. Thermal Management

In the ElectricOIL devices, the discharge exit flow temperature is typically in the range of 450 to 600 K. Because the equilibrium between the forward and backward reactions between O_2(a) and I* is temperature dependent, it is preferable to reduce the temperature to approximately 300 K or less (a temperature comparable to classical COIL) before entering the supersonic nozzle and lasing cavity. Therefore it is important to properly engineer post-discharge thermal management solutions. A temperature as low as 200 K provided by a heat exchanger at the discharge exit, which would result in a resonator temperature close to 100 K, could be favorable, but in designing such a heat exchanger, there is a tradeoff between exit temperature and loss of O_2(a) yield which must be considered.

Issues related to an EOIL heat exchanger are complex. Heat exchangers function by introducing a fluid to a substantially cooler surface with preferentially a very great surface area to maximize heat transfer. However, with oxygen-iodine lasers, like any gaseous laser, the role of wall deactivation on laser performance must be considered as well. In the case of EOIL, increases in surface area result in increased quenching of the desired O_2(a) state, thereby reducing laser performance. From the standpoint of preserving O_2(a), minimizing surface area and resonance time between the discharge and resonator is ideal. Clearly the goals of maximizing heat removal and minimizing O_2(a) loss conflict in a real apparatus. However, since reducing the flow temperature ultimately reduces the O_2(a) threshold yield, so long as the usable concentration of O_2(a) above threshold increases more than the concentration lost due to wall deactivation, significant benefit can be obtained. The new Cav6 heat exchanger design is based on the work in Ref. 13, using the Cav5 ElectricOIL lasing cavity which established the tradeoff between temperature performance and O_2(a) yield losses.

The work in Ref. 13 showed that significant heat extraction was attainable from the post discharge flow, while simultaneously forcing a significant reduction in the oxygen atom population; both highly desirable effects for an EOIL device. The temperature dropped by as much as 150 K. More importantly, it was found that various Al 6061 heat exchanger configurations resulted in an acceptably small percentage of O_2(a) quenching across the heat exchanger given the favorable reduction in flow temperature. The O_2(a) yield in the experimental setup varied between 9.4% and 8.2% depending on the heat exchanger configuration. The O_2(a) yield without a heat exchanger being at the high end of that range, and a highly complex heat exchanger being at the low end. Under current best lasing conditions, the yield is closer to 13%. However, due to the limitations of the experimental setup, which require analysis of the flow far downstream from the heat exchanger exit, where the flow becomes uniform, reported yields were less.[13]

A. Cav6 Heat Exchanger Design

The Cav6 ElectricOIL device, like the Cav5 device, utilizes a water cooled heat exchanger to provide active thermal management of the post discharge flow. The Cav6 device, however, has been improved over its predecessor to further reduce the flow temperature, while also incurring a reduced pressure drop across the heat exchanger, resulting in a lower discharge pressure. The flow temperature at the discharge exit under current lasing conditions is about 550 K. After passing through the Cav6 heat exchanger, the flow temperature drops to about 325 K compared to about 400 K with Cav5, resulting in a population inversion between O_2(a) and I* that more strongly favors I*. The pressure drop given flow conditions described later is approximately 5 torr (typically, discharge pressure of 47 torr and nozzle plenum total pressure of 42 torr).

The Cav6 heat exchanger is an aluminum 6061-T6 unibody design. The body consists of 112 1/8-in. diameter ducts in the flow-wise direction with a length of 3.5 inches. Perpendicular to the flow are 45 1/8-in. channels carrying water at approximately 55º C (328 K). The heat exchanger was designed with insulating side walls on all 6 sides to force all heat transfer solely into the coolant for diagnostic purposes. The only openings in the insulation are for the primary gas flow and the water cooling. The insulation is constructed using PTFE and PEEK. Contact resistance and air gaps have also been integrated into the design to further aid in thermal isolation. Testing indicates that the insulation is providing good thermal isolation as intended.

B. Cav6 Heat Exchanger Measurements

To measure the heat transferred out of the primary flow into the cooling water, T-type thermocouples were mounted in the input and exit cooling line. The water flow rate was continuously measured with a turbine style liquid flow meter. The gas temperature at the discharge exit, just prior to the heat exchanger, was determined from the O_2(b) rotational spectral emission at 762 nm using an Apogee E47 CCD camera coupled to a Roper Scientific/Acton Research 150-mm monochromator. The detector was repositioned to a diagnostic port just downstream of the heat exchanger to determine the post heat exchanger flow temperature.

Using flow conditions that correspond to current optimal lasing conditions, 45 mmols/s oxygen, 150 mmols/s helium, and 0.5 mmols/s nitric oxide, with a varying rf electrical input power in the 6-tube discharge configuration (Fig. 2), heat exchanger performance data was taken for Cav6. Figure 11 shows the reduction in temperature over a wide range of rf power. The temperature drop is substantially improved from the data reported by Ref. 13 for the Cav5 predecessor. O_2(a) loss in the heat exchanger has yet to be experimentally determined for Cav6 design, yet given that Cav6 uses a ducted design similar to the 1/8-in. ducted design reported in Ref. 13, an O_2(a) loss of approximately 10 to 15 percent is to be expected with a reduction in oxygen atoms of approximately one order of magnitude.

The power change in the flow attributed solely to a temperature change is calculated by

$$Gas\ HeatFlux = \dot{m}_{gas} C_{P,gas} \Delta T_{gas}, \tag{2}$$

where $\dot{m}_{gas}$ is the mass flow rate of oxygen and helium, $C_{P,gas}$ is the specific heat of the oxygen-helium mix, and ΔT_{gas} is the temperature difference across the heat exchanger determined from the O_2(b) spectra. The additional power stored in the coolant water after passing through the heat exchanger is calculated by

$$Coolant\ HeatFlux = \dot{m}_{w} C_{P,w} \Delta T_{w}, \tag{3}$$

where $\dot{m}_w$ is the mass flow rate of water, $C_{P,w}$ is the specific heat of water, and ΔT_w is the difference in water temperature between the input and exit fittings on the heat exchanger. Values calculated from data using Eqns. 2 and 3 are summarized in Fig. 12.

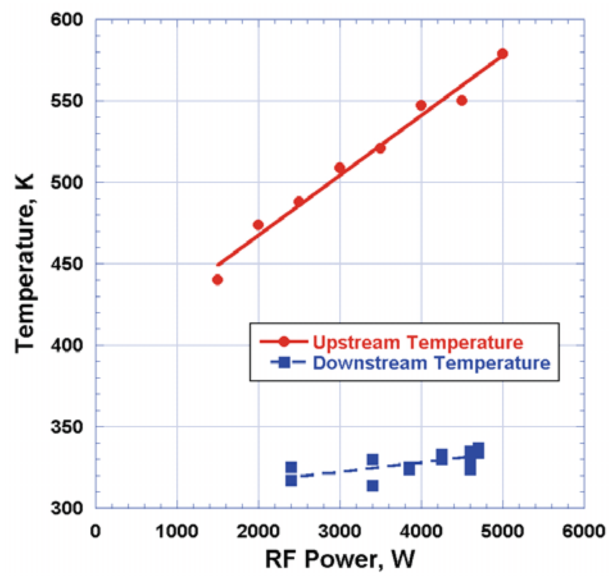


Figure 11. Pre- and post-discharge flow temperature determined from O_2(b) spectra versus rf input power.

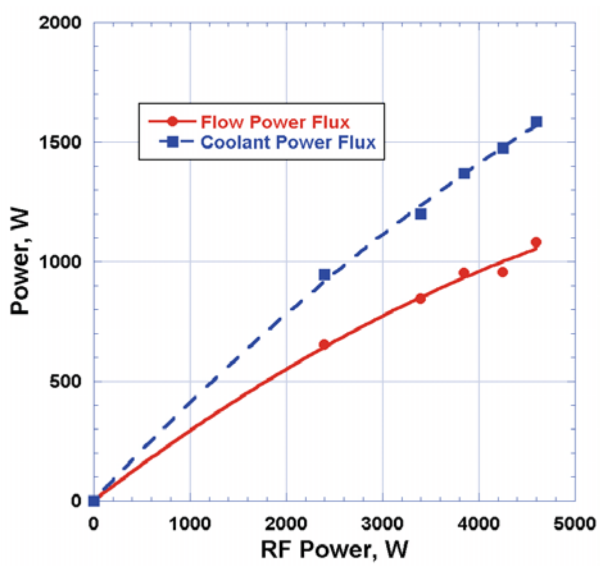


Figure 12. Comparison of power extracted by heat exchanger to power reduction of primary ElectricOIL flow attributed solely to temperature change. The power difference is attributed to thermalizing of energy stored as dissociated oxygen.

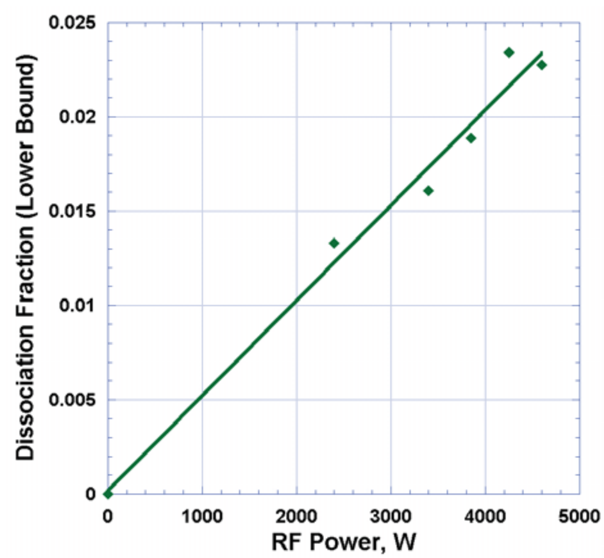


Figure 13. Dissociation fraction determined by comparison of power extracted by heat exchanger to power reduction of primary ElectricOIL flow attributed solely to temperature change.

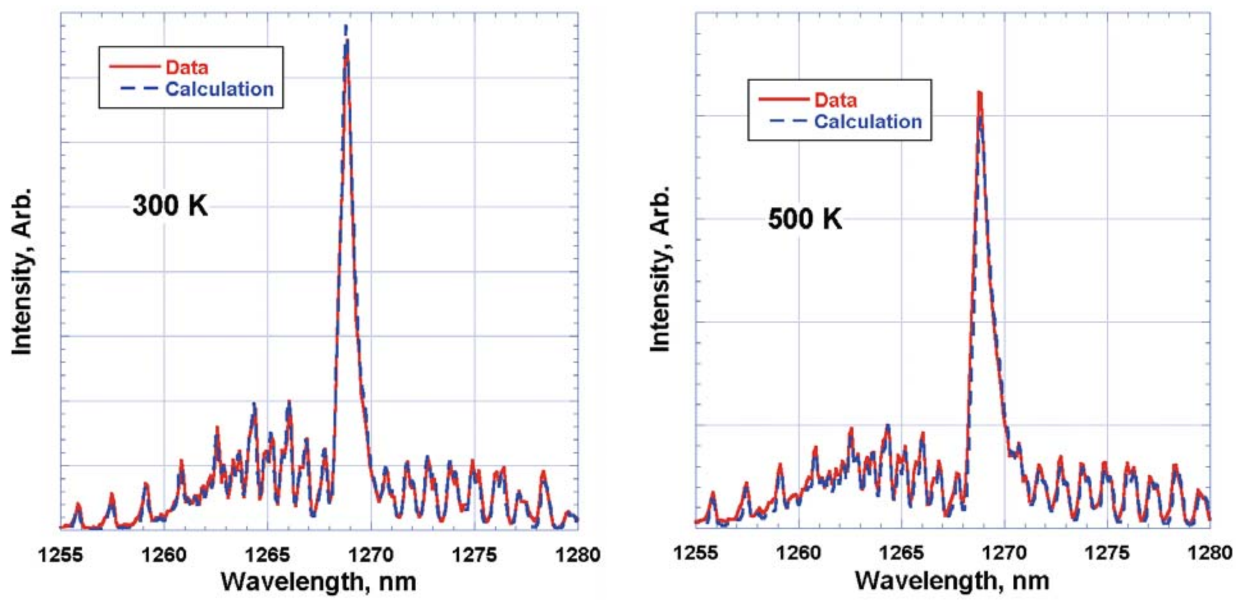
The heat transferred into the coolant is contrasted with the power difference calculated by measuring the primary flow temperature before and after the heat exchanger. Notice that the two powers are considerably different. The cooling water has removed more heat from the gas flow than the temperature drop of the gas flow deems possible. This can be explained by recalling that oxygen atoms are recombined and thermalized while passing through the heat exchanger. While only a small percentage of the O_2(a) is deactivated in the heat exchanger, the majority of oxygen atoms are recombined, resulting in substantial heating of the flow. The difference in the power fluxes shown in Fig. 12 can be used to determine a lower bound of the oxygen atoms exiting the discharge, as shown in Fig. 13.

The Cav6 heat exchanger implements advancements in cooling researched with the Cav5 predecessor. Cooling of the flow has been further improved from the Cav5 design, likely due to improvements that provide a more uniform wall temperature throughout the heat exchanger. Otherwise, the Cav6 design is highly similar to the 1/8-in. ducted design tested with Cav5 and discussed by Ref. 13. Experimental data has been taken with Cav6 that demonstrates significant energy being extracted from the flow beyond that corresponding directly to the heat flux. The primary source of this energy is the thermalization of the largely undesirable oxygen atom population. Given that the primary flow temperature has nearly approached the coolant temperature at the heat exchanger exit, where heat removal efficiency becomes poor, some reduction in the heat exchanger size may be warranted. This may reduce the O_2(a) quenching and improve overall performance. In short, heat exchangers integrated into the EOIL design are now providing flow exit temperatures comparable to classical COIL, yielding substantial improvement in system performance.

C. Temperature Deduced from O_2(a) Spectra

Typically, the flow temperature has been determined using either the ro-vibrational spectra of O_2(b) (Fig. 11) or the gain lineshape (Fig. 4). However, these methods are not always useful depending on the experimental conditions. For example, when analyzing the flow downstream of the discharge, the level of O_2(b) is sometimes very low due to quenching by O-atoms, and the measured spectra has poor signal-to-noise ratio. This is often further complicated by the presence of O-NO airglow near the O_2(b) emission at 762 nm. In the case of analyzing the cavity flow, it is often desirable to know temperature near gain or laser threshold where interpretation of temperature from the gain signal is difficult, and the use of the 762 nm emission is prohibited due to low O_2(b) density. Therefore, the method developed by Rawlins *et al*.[22] for deducing temperature from the ro-vibrational spectra of O_2(a) was implemented. Because O_2(a) density is sufficiently high throughout the system, use of the O_2(a, v"=0$\rightarrow$v'=0) spectra at 1268-nm to determine temperature is a convenient diagnostic tool that can be applied.

The method has been applied to some recent data, determining the temperature by matching the experimental spectra at 1268-nm with theoretical spectra. The theoretical spectra were created using data from the HITRAN database.[23] A computer code consisting of two components was constructed: (i) a component that calculates the theoretical spectra from the HITRAN data, and (ii) a component that determines the theoretical spectra that best fit the experimental spectra. The two parameters that are varied to form the theoretical spectra are temperature and resolution. Increasing or decreasing the flow temperature leads to changes in intensity values of the various transitions as the population of upper rotational states redistributes. The resolution affects the peak and valley heights (e.g. a high resolution leads to more distinct peaks). The code therefore determines a best fit between the peak-to-peak and peak-to-valley ratios of the experimental and theoretical spectra. Figure 14 compares the experimental and calculated O_2(a) spectra at two temperatures: 300 and 500 K. Application of this temperature diagnostic technique should aid in development of future ElectricOIL designs.



(a) **(b)**

Figure 14. Comparison of experimental and calculated spectra of O_2(a, v"=0→v'=0) at 1268-nm at two temperatures: (a) 300 K, and (b) 500 K.

V. Concluding Remarks and Future Work

One of the significant remaining questions regarding the ElectricOIL system is: why is the amount of laser power extracted so much lower than the available power in the O_2(a)? In this paper, two factors that could help answer this question were investigated: (i) optical losses, and (ii) kinetic effects. Considering these two factors in the Cav6 design and testing has allowed a considerable increase in the extracted power.

An improved heat exchanger design applied in Cav6 has allowed more heat to be removed from the flow exiting the discharge (compared to previous designs applied in Cav5). Analysis of the Cav6 experiments has shown that significant levels of oxygen atoms produced in the discharge are being recombined within the heat exchanger, considered beneficial to the system performance as O-atoms are a quencher of O_2(a) and I*. The application of a method which deduces the flow temperature from the spectra of O_2(a), should be a useful tool in future ElectricOIL design and analysis.

New measurements of gain recovery in the Cav6 nozzle have shown that in the current operating regime of the laser, there is still an unidentified mechanism that competes with the re-pumping of I* by O_2(a). Determining the mechanism which causes the slow re-pumping, and determining a way to remove the effect of this mechanism would allow for better power extraction.

In conclusion, the authors observed a 95% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine through the use of a longer gain length laser cavity and a rectangular discharge for only a 50% increase in gain length, flow rates, and discharge input power. A gain of 0.26% cm^{-1} was obtained and the laser output power was 54.8 W in a stable cavity with two 2-in. diameter 0.9970 reflective mirrors. The implementation of a longer gain length cavity permits use of lower reflectivity resonator mirrors that reduce diffractive spill losses, and thereby more efficiently extract power from the gain medium. An output power of 92.0 W was obtained with two 4-in. diameter 0.9970 reflective mirrors (reflectivity product = 0.9940), 102.5 W was obtained with a folded "Z-resonator" configuration using a combination of four 2-in. diameter mirrors (reflectivity product = 0.9865), and 109.0 W was obtained with a folded "X-resonator" configuration using a combination of four 2-in. diameter mirrors (reflectivity product = 0.9939). Thus, the use of a larger (approximately a factor of 2) mode volume resonator enabled a further increase of 99% in outcoupled power and efficiency. A continued expansion of the operating envelope to higher flow conditions, pressures, and gain length of the laser cavity, plus the addition of an iodine pre-dissociator[24] are expected to provide significant increases to the gain and laser power. The results presented herein represent more than two orders of magnitude improvement in gain and laser power since the initial demonstration[2] in 2005.

These results better illustrate the important role that diffraction can play inside the resonators of small scale ElectricOIL systems. As the gain and gain length of such systems are increased, the diffractive effects will become much less pronounced. Further, as the mode volume of the resonator increases, it is possible to compensate for competing kinetic effects in the gain region. In effect, as the ElectricOIL system is scaled to larger sizes it can become dramatically more efficient.

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References

[1]Carroll D L, Verdeyen J T, King D M, Zimmerman J W, Laystrom J K, Woodard B S, Richardson N, Kittell K, Kushner M J and Solomon W C (2004) *Appl. Phys. Lett.* **85** 1320.

[2]Carroll D L, Verdeyen J T, King D M, Zimmerman J, Laystrom J, Woodard B, Benavides G, Kittell K, Stafford D, Kushner M J and Solomon W C (2005) *Appl. Phys. Lett.* **86** 111104.

[3]Rawlins W T, Lee S, Kessler W J and Davis S J (2005a) *Appl. Phys. Lett.* **86** 051105.

[4]Verdeyen J T, Carroll D L, King D M, Laystrom J K, Benavides G F, Zimmerman J W, Woodard B S, and Solomon W C (2006) *Appl. Phys. Lett.* **89** 101115.

[5]Hicks A, Tirupathi S, Jiang N, Utkin Yu, Lempert W R, Rich J W and Adamovich I V (2007) *J. Phys. D: Appl. Phys.* **40** 1408.

[6]Bruzzese J, Cole A, Nishihara M, and Adamovich I V (2009) "Gain Distribution and Output Power Measurements in a Scaled Electric Discharge Excited Oxygen-Iodine Laser," *AIAA Paper* 2009-4061.

[7]Woodard B S, Zimmerman J W, Benavides G F, Carroll D L, Verdeyen J T, Palla A D, Field T H, Solomon W C, Davis S J, Rawlins W T, and Lee S (2008a) *Appl. Phys. Lett.* **93** 021104.

[8]Stafford D S and Kushner M J (2004) "$O_2(^1\Delta)$ production in He/O_2 mixtures in flowing low pressure plasmas." *J. Appl. Phys.* **96** 5

[9]Palla A D, Carroll D L, Verdeyen J T and Solomon W C (2006). *J. Appl. Phys.* **100** 023117.

[10]Palla A D, Zimmerman J W, Woodard B S, Carroll D L, Verdeyen J T, Lim T C and Solomon W C (2007) *J. Phys. Chem. A* **111** 6713.

[11]Ionin A A, Kochetov I V, Napartovich A P and Yuryshev N N, (2007). *J. Phys. D: Appl. Phys.* **40** R25.

[12]Heaven, M.C. (2010). "Recent advances in the development of discharge-pumped oxygen-iodine lasers," *Laser and Photonics Review* (published online, Feb. 8, 2010).

[13]Zimmerman J W, Benavides G F, Woodard B S, Carroll D L, Palla A D, Verdeyen J T, and Solomon W C (2009) "Measurements of Improved ElectricOIL Performance, Gain, and Laser Power," AIAA Paper 2009-4059.

[14]Zimmerman J W, Woodard B S, Benavides G F, Carroll D L, Verdeyen J T, Palla A D and Solomon W C (2008) *Appl. Phys. Lett.* **92** 241115.

[15]Carroll D L, and Verdeyen J T (2009) *Applied Optics* **48** 6035.

[16]Zimmerman J W, Benavides G F, Palla A D, Woodard B S, Carroll D L, Verdeyen J T, and Solomon W C (2009) "Gain recovery in an electric oxygen-iodine laser," *Appl. Phys. Lett.* **94** 021109 (2009a).

[17]Woodard B S, Zimmerman J W, Verdeyen J T, Carroll D L, Field T H, Benavides G F, Palla A D, Solomon W C (2008b) "Improved production of $O_2(a^1\Delta)$ in transverse radio-frequency discharges," *SPIE* Vol. **7005**, 70051L.

[18]Davis S J, Allen M G, Kessler W J, McManus K R, Miller M F and Mulhall P A (1996). *SPIE* Vol. **2702** 195.

[19]Woodard B S, et al. *AIAA LASE-PDL* 2010 (to be presented)

[20]Benavides G F, Zimmerman J W, Woodard B S, Carroll D L, Palla A D, Day M T, Verdeyen J T, and Solomon W C (2008) "Enhancements of electric oxygen-iodine laser performance using a rectangular discharge and longer gain length," *Appl. Phys. Lett.* **95** 221112.
[21]Palla A D, Carroll D L, Verdeyen J T, Zimmerman J W, Woodard B S, Benavides G F, Day M T and Solomon W C (2010) "Modeling of Recent ElectricOIL Gain Recovery Data," *AIAA paper* (to be presented at *41st AIAA Plasmadynamics and Lasers Conf., Chicago, IL 28 June – 1 July. 2010*).
[22]Rawlins W T, Lee S, Kessler W J, Oakes D B, Piper L G and Davis S J (2005) "Advanced Diagnostics and Kinetics of Oxygen-Iodine Laser Systems," *AIAA paper* 2005-5299.
[23]Rothman L S, Gordon I E, Barbe A, Benner D C, Bernath P F, et al., (2009) "The HITRAN 2008 molecular spectroscopic database," *Journal of Quantitative Spectroscopy & Radiative Transfer* **110** 533-572.
[24]Benavides G F, Zimmerman J W, Woodard B S, Carroll D L, Verdeyen J T, Field T H, Palla A D, and Solomon W C (2008) "Gain and continuous-wave laser power enhancement with a secondary discharge to predissociate molecular iodine in an electric oxygen-iodine laser," *Appl. Phys. Lett.* **92** 041116.