

# **ElectriCOIL: An Advanced Chemical Iodine Laser Concept**

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## **ABSTRACT**

Advanced chemical iodine laser technology will logically include novel all gas phase generation techniques for an iodine energy donor and the injection of atomic rather than molecular iodine. Candidate methods are discussed for the creation of an all gas phase energy donor as well as for injecting atomic iodine. This research will lead directly to designs that will be fabricated and tested extensively with detailed diagnostics to evaluate the chosen design's performance attributes. Preliminary analysis and modeling of the ElectriCOIL system concept is presented. ElectriCOIL will reduce weight and simplify both military and commercial chemical iodine laser systems. Potential cost and weight savings are also envisioned as the massive quantities of liquid chemicals will be completely eliminated from the device operation.

Keywords: ElectriCOIL, COIL, chemical oxygen iodine laser, iodine laser, electrical singlet oxygen generation, iodine dissociation.

## **1. INTRODUCTION**

Several dramatic changes to gain generator technologies are needed to allow chemical oxygen-iodine laser (COIL) systems to achieve their full potential as efficient producers of 1.3  $\mu$ m laser beams. These include: 1) Highly improved nozzle mixing efficiencies; 2) Carefully designed media and beam quality properties; 3) Higher pressure recovery potential; and 4) Radically new the  $O_2(^1\Sigma)$  generator subsystems. This paper addresses the fourth issue, innovative improvements in generation of excited states of both oxygen and iodine. The development of gas phase  $O_2(^1\Sigma)$  generator subsystems will also have a direct impact on technological improvements needed in under items 1 and 3.

The Chemical Oxygen-Iodine Laser (COIL) was developed first by the United States Air Force in 1978 [McDermott, 1978]. Since that initial demonstration COIL technology has undergone numerous improvements [Truesdell, 1992] and chemical efficiencies as high as 27-30% using helium diluent have been demonstrated [Rittenhouse, 1999; Yang, 1997]. Much of the COIL technology development to date has focused on the singlet-oxygen generator (SOG) and the liquid SOG technology has developed to a fairly mature state; major improvements to the aqueous system are less likely to occur, especially in terms of efficiency as expressed by power to weight ratios. The basic COIL design has changed little over the past decade. However, an all gas phase system offers a new exciting pathway. One approach is to exploit the recent findings at the Air Force Research Laboratory (AFRL) with the NCI ( $^1\Sigma$ ) all gas phase chemical system [Henshaw, 2000]; a second is to provide the necessary atomic Iodine and  $O_2(^1\Sigma)$  purely by electrical means.

AFRL has recently demonstrated that significant quantities of excited iodine atoms can be produced using an all gas phase generator [Henshaw, 2000]. The excited species which transfers to Iodine atoms, in this case, NCI( $^1\Sigma$ ), can be produced without a liquid phase generator. This is the first major breakthrough in energy donor generator technology in ten years. This Air Force research provides a roadmap for future work in the field. The Air Force Research Laboratory at Albuquerque demonstrated lasing with this concept [Henshaw, 2000]. As their research proceeds, a number of opportunities subsequently open up. The potential which intrigues CU Aerospace and the University of Illinois is presented in this paper. We believe that it is possible to construct a highly efficient electric generation scheme to provide the precursor energy donor species,  $O_2(^1\Sigma)$ . A new kind of cw COIL laser which is an Electrically assisted Chemical Oxygen Iodine Laser, (**ElectriCOIL**) would subsequently be achievable, see Figure 1. Workers in Japan [Itami, 1999; Fujii, 2000] and Russia [Ivanov, 1999] have shown that flowing discharge tubes containing ground state oxygen can produce significant quantities of the desired,  $O_2(^1\Sigma)$  precursor molecules. This paper suggests how one can transform such research into a practical all gas phase system. Atomic iodine injection is also an integral part of the proposed program. Figure 1 illustrates the limitations of existing COIL technology as well as the possible improvement from the implementation of ElectriCOIL technology. Such an

electronically produced  $O_2(^1\Sigma)$  generator could be even more effective if implemented simultaneously with an atomic iodine augmentation technique.

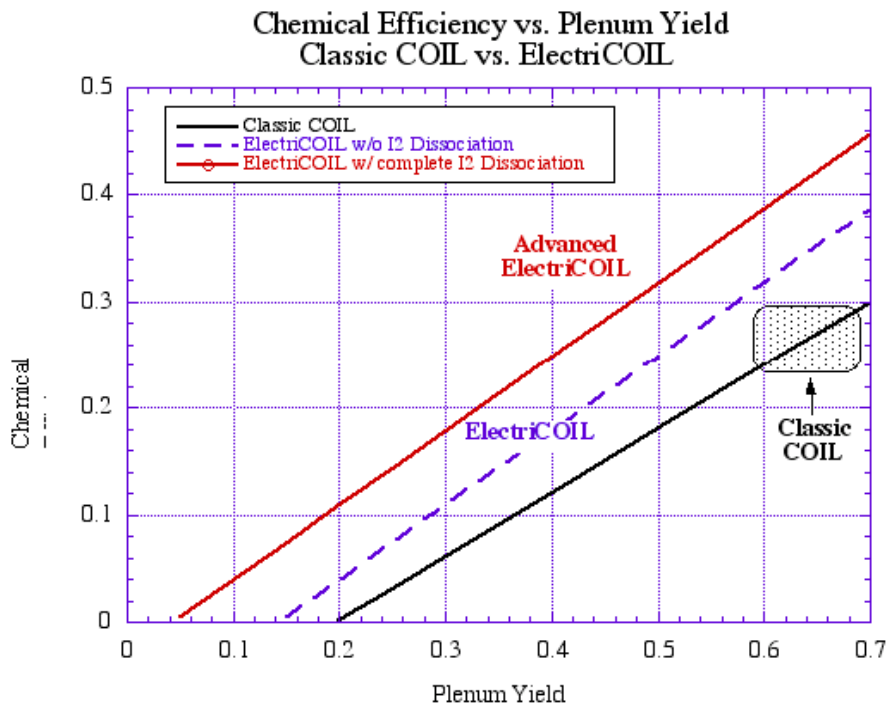


Fig. 1. Using a heuristic equation, a comparison between classic COIL technology and the performance possibilities for an ElectriCOIL device are illustrated. While ElectriCOIL may not be able to match the plenum yield of today's COIL system, significantly smaller yields are capable of matching current chemical efficiencies.

We believe the ElectriCOIL concept will be a major breakthrough in high power laser technology. The impact of this technology is summarized below:

- ***Dramatically reduce the overall energy donor and gain generator tankage requirements by eliminating the aqueous chemicals needed for generation of  $O_2(^1\Sigma)$  in today's COIL systems.***
- ***Eliminate the need to constantly re-supply an advanced version of a military or commercial COIL system with exotic aqueous fluids which are inherently difficult to handle. Advanced laser support hardware will largely consist of power conditioning equipment and a small tank of liquid oxygen.***
- ***Take advantage of research in aircraft power generation systems to provide the necessary power to supply an airborne ElectriCOIL laser system.***

## 2. BACKGROUND

Low pressure discharges in electronegative gases are the basis for plasma processing in micro electronics. The plasma of the dc low pressure discharge in a long cylindrical tube with the electric field directed along the axis is convenient for experimental study. A high degree of both non-equilibrium and non-uniformity with the radius along the axis is an important feature of these discharges. In pure oxygen the major active particles are atomic oxygen and the oxygen metastable  $O_2(^1\Sigma)$ . Modeling of the electric discharge phenomena has shown that oxygen atoms and  $O_2(^1\Sigma)$  account for the volume processes within the discharge [Ivanov, 1999]. It has also been found experimentally that excitation of molecular oxygen in a glow discharge at around 1 torr provides significant quantities of  $O_2(^1\Sigma)$  [Ivanov, 1999]. Concentrations of  $O_2(^1\Sigma)$  on the order of  $2 \times 10^{15}$  molecules/cc were observed [Ivanov, 1999] employing emission spectroscopy of the 1268 nm band for the transition  $O_2(^1\Sigma, \nu=0) \rightarrow O_2(^3\Sigma, \nu=0)$ .

Fujii [Fujii, 1994] reported good success, 17% yield of  $O_2(^1\Sigma)$ , with a small RF generator. More recently, workers in Japan provided evidence that they could produce 21%  $O_2(^1\Sigma)$  in a microwave discharge [Itami, 1999] and 32% using an RF discharge [Fujii, 2000]. They studied the yield sensitivity of  $O_2(^1\Sigma)$  in the presence of various compositions of  $O_2$ ,  $N_2$ ,  $NO$ , and  $NO_2$  and showed added gases gave improved results. The experiments were carried out in subsonic axial flow at 2 torr in

a 30 cm long tube with window attachments for observation. Their paper leads one to believe that they are expecting to conduct lasing experiments in the near future employing an upgraded system with a more efficient discharge.

### 3. PRELIMINARY ANALYSIS

To investigate important technology issues related to the COIL lasers, it is useful to employ the COIL heuristic equation developed by Hon *et al.* [Hon, 1996], which is given by,

$$\eta_{chem} = U_{Cl2} (Y_{plen} - Y_{diss} - Y_{th} - Y_{deact}) \eta_{mix} \eta_{geom} \eta_{ext} \eta_{res} \quad (1)$$

where  $\eta_{chem}$  is the chemical efficiency,  $U_{Cl2}$  is the utilization of chlorine in the singlet oxygen generator (SOG),  $Y_{plen}$  is the yield in the plenum region just upstream of iodine injection,  $Y_{diss}$  is the loss of singlet delta oxygen due to dissociation of the iodine molecules,  $Y_{th}$  is the threshold yield representing the minimum  $O_2(^1\Delta)$  fraction necessary for positive gain,  $Y_{deact}$  is the loss of yield due to deactivation reactions,  $\eta_{mix}$  is the mixing efficiency defined as the ratio of the accessed  $O_2(^1\Delta)$  to the total  $O_2(^1\Delta)$  in the flow,  $\eta_{geom}$  represents the fraction of the flow interrogated by the resonator,  $\eta_{ext}$  is the optical extraction efficiency, and  $\eta_{res}$  is the flow residence time efficiency. The yield is defined as the ratio of excited  $O_2(^1\Delta)$  to total oxygen in the flow.

Table 1 and Figure 1 present a preliminary examination of the implementation of an ElectricoIL concept using the heuristic equation [Hon, 1996]. The classic COIL case compared with is the baseline RADICL condition with helium diluent, 0.50 moles/s of  $Cl_2$ , 4:1 diluent ratio, and a titration ratio of 1.7%; there is a substantial amount of reported data for this condition [Helms, 1994; Tate, 1995]. For ElectricoIL preliminary estimates it is assumed that the  $\eta_{mix}$ ,  $\eta_{geom}$ ,  $\eta_{ext}$  and  $\eta_{res}$  terms remain the same as with classic COIL [Truesdell, 1996], that the  $Y_{deact}$  term is zero, and  $Y_{th}$  has a 150K cavity temperature ( $Y_{th}=0.044$ ); with these assumptions, Eq. (1) reduces to:

$$\eta_{chem} = 0.6962 (Y_{plen} - Y_{diss} - 0.044) \quad (2)$$

Table 1. Estimated effects of different conditions on RADICL performance.

	Classic COIL	Early ElectricoIL w/ I <sub>2</sub> Injection	Early ElectricoIL w/ I atom Injection	Mid-stage ElectricoIL w/ I atom Injection	Advanced ElectricoIL w/ I atom Injection
Conditions	$Y_{plen}=0.60$ $Y_{diss}=0.10$ H <sub>2</sub> O $T_{cav}=170K$	$Y_{plen}=0.20$ $Y_{diss}=0.10$ <b>No H<sub>2</sub>O</b> <b><math>T_{cav}=150K</math></b>	$Y_{plen}=0.20$ $Y_{diss}=0.0$ No H <sub>2</sub> O $T_{cav}=150K$	$Y_{plen}=0.30$ $Y_{diss}=0.0$ No H <sub>2</sub> O $T_{cav}=150K$	$Y_{plen}=0.40$ $Y_{diss}=0.0$ No H <sub>2</sub> O $T_{cav}=150K$
Heuristic Equation	24.1%	3.9%	10.9%	17.8%	24.8%

Table 1 shows that the heuristic equation predicts a nominal chemical efficiency of 24.1% for the given classic COIL RADICL case. Switching to an early stage ElectricoIL in which it is assumed that a 20% yield can be obtained (as demonstrated by Japanese researchers [Itami, 1999]), all of the water is removed from the flow, the expected performance is a mere 3.9% chemical efficiency.

Discussed above was the possibility of injecting atomic, rather than molecular, iodine. For this situation  $Y_{diss}=0$ . The heuristic equation indicates that this alone results in a significant performance improvement when the dissociation term is zero, Eq. (2), Table 1. Because of the large potential performance enhancement, we feel the investigation of iodine pre-dissociation schemes is an important issue. Conceptually, the ideal ElectricoIL design appears to be one that injects atomic iodine into a waterless primary flow with singlet delta oxygen generated electrically, provides complete mixing by the end of the optical extraction region, and gives a low cavity temperature of around 150 K. The heuristic equation indicates that such an advanced ElectricoIL concept could realistically provide chemical efficiencies of around 25%, comparable to today's classic COIL, Table 1, and potentially provide even higher chemical efficiencies if the plenum yield can be increased above roughly 40%, Fig. 1. Even an ElectricoIL that provides 24% chemical efficiency is an enormous improvement to the classic COIL design because it will lead to a significant reduction of weight per kW of the Airborne Laser (ABL) and simpler operation procedures.

Preliminary calculations using the Blaze II chemical laser model [Sentman, 1977; Carroll, 1995; Carroll, 1996] support the qualitative conclusions drawn from the heuristic equation. Fig. 2 illustrates Blaze II results that are comparable to those shown in Fig. 1, which was based upon the heuristic equation. The advantage of the ElectricoIL concept is

immediately realized when examining the gain curve with and without molecular iodine pre-dissociation, Fig. 3. The gain curve, with a 20% yield and no pre-dissociation, is very low and would not make a useful laser. However, when the molecular iodine is completely pre-dissociated, then the gain curve, even with a 20% yield, compares very favorably with the classic COIL type gain curve having a 67% yield. Note that the classic COIL curve is for a VertiCOIL case that was baselined to power data, not gain data; historically, when Blaze is baselined to power data the gain curve underpredicts gain data.

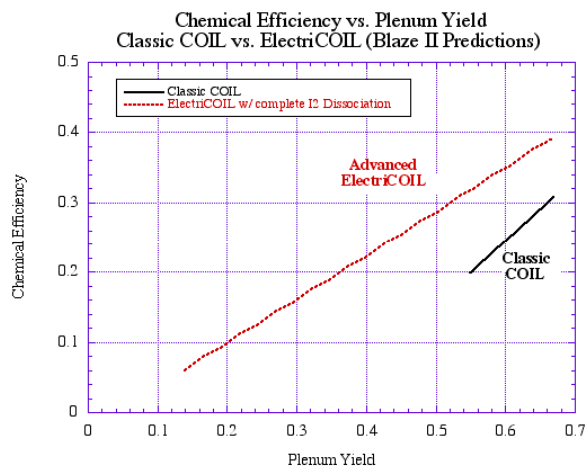


Figure 2. Blaze predictions comparing classic COIL technology and the performance possibilities for an ElectriCOIL device are illustrated. While ElectriCOIL may not be able to match the plenum yield of today's COIL system, significantly smaller yields are capable of matching current chemical efficiencies.

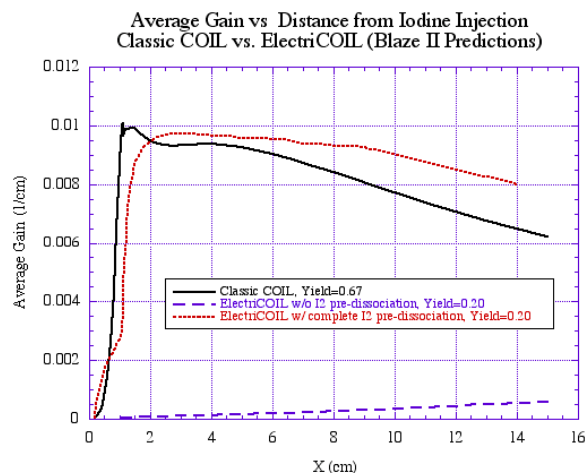


Fig. 3. Blaze predictions of the average gain as a function of distance from the iodine injection position for classic COIL with a yield of 0.67, ElectriCOIL with and without molecular iodine pre-dissociation. Helium diluent was used for these calculations.

Figures 2 and 3 illustrate the innovative concept of combining both electrically produced singlet delta oxygen and pre-dissociated iodine. Each of these concepts have been demonstrated individually, but not in combination; when both ideas are implemented together it is possible to obtain significant gain and laser power with a mere 20% yield; this yield has already been generated in experiments conducted by Itami [Itami, 1999]. More recently, Fujii [Fujii, 2000] obtained 32% yield using an RF discharge; this result is particularly encouraging. Experimental work in the area of iodine pre-dissociation has been conducted by Endo and Fujioka's group in Japan [Endo, 1999]. They reported nearly total dissociation from interaction of an Iodine/N<sub>2</sub> stream within the microwave cavity. Experiments with subsonic injection, sonic injection and supersonic injection of the atomic iodine stream were conducted. Due to experimental difficulties, only the transonic injection mixing nozzle showed the expected increase in laser efficiency. In this case, about a 10% increase in laser efficiency was noted by Endo. This is probably a lower bound on the efficiency increase since it was difficult to insure that recombination in the injectors was negligible. Iodine pre-dissociation has also been investigated using three-dimensional CFD computations by Madden *et al.* [Madden, 1998]; Madden's results indicated that the injection of atomic iodine slightly downstream of the throat would enhance the power output. Thus it should be possible to demonstrate a 10-15% chemical efficiency with today's electrical generation technology. Improved methods of generating higher yields should lead to even higher chemical efficiencies.

#### 4. CONCLUDING REMARKS

We believe that the key performance enhancements to COIL technology are the combination of electrically generated O<sub>2</sub>(<sup>1</sup>Δ) and the injection of pre-dissociated iodine with an appropriately redesigned nozzle [Carroll, 2000] that uses the atomic iodine efficiently in the laser region. The principle candidate being considered for creating excited oxygen in the primary flow is an RF discharge. For the ElectriCOIL concept we are focused on either RF discharge [Vagin, 1995], microwave discharge [Sugimoto, 1999] or photolytic pumping for creating atomic iodine to inject into the primary flow. Based upon experimental results of Fujii [Fujii, 2000] that obtained a 32% yield of O<sub>2</sub>(<sup>1</sup>Δ), analysis predicts that the ElectriCOIL concept should be able to obtain a chemical efficiency of at least 18%; assuming further enhancements the RF generator would enable a yield of 40%, analysis predicts that a chemical efficiency of around 25% should be achievable.

## ACKNOWLEDGEMENTS

This work was supported by the Air Force Research Laboratory SBIR contract F29601-00-C-0086.

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