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Photodetachment as a Control Mechanism for Diffuse Discharge Switches

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TABLE I
ERROR ESTIMATE ($|\omega_r - \omega_0|/\omega_0$) OF RAY TRACING IN 100-keV PLASMA

Mode	T_e	At Resonance	After Passing Through Resonance
O	100 keV	9%	0.2%
X	100 keV	7%	5%

nary and the extraordinary modes, respectively, for $T_e = 100$ keV. For the ordinary mode, the ray is directed from the low field side, and for the extraordinary mode, the ray is injected from the high field side of the torus. The parameters are chosen such that no mode conversion can occur. Because of the high temperature, single pass absorption of 100 percent is achieved for both cases. Specifically, the ordinary mode is absorbed near the center of the torus and the extraordinary mode is absorbed about half way before it reaches the center of the torus. The absorption regions are spread over several wavelengths so that ray tracing is still valid. We see that the warm plasma trajectories are almost identical to the cold ray paths. The difference is even smaller for $T_e = 300$ eV and $T_e = 10$ keV. The errors in ray trajectories are monitored by substituting the local values of $\boldsymbol{k}$ and $\boldsymbol{r}$ into the local dispersion relation which is then solved numerically for the complex ω. ω_r, the real part of ω, is compared with the heating frequency ω_0 which, of course, does not change throughout the ray path. For the cold ray tracing, the accuracy is good to roundoff. For the warm ray tracing, the error is typically a few percent (see Table I). The error is computed using the formula: error $\approx (|\omega_0 - \omega_r|/\omega_0) \times 100$ percent.

CONCLUSIONS

In conclusion, we find that for temperature of interest to tokamak research, ray tracing with cold plasma dielectric tensor is quite sufficient as long as the validity of ray tracing are met [1]. But for temperatures in the hundreds of kiloelectronvolts range, such as those encountered in bumpy torus and tandem mirror, the general approach by Friedland and Bernstein [1] must be used. The absorption of the wave energy, of course, must be calculated with the warm plasma dielectric tensor.

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Abstract—**Photodetachment is considered as a control mechanism for diffuse discharge switches. Experiments have been performed on photodetachment of ions in the flowing afterglow of a dc glow discharge in oxygen. Experiments with different laser wavelengths and the dependence of the optogalvanic signal on the laser energy flux indicate that O^- is the dominant negative ion. For an energy flux of 35 mJ/cm^2, 50 percent of the O^- ions can be photodetached.**

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I. INTRODUCTION

RECENTLY, externally controlled diffuse discharge opening switches have been considered for applications in inductive energy storage systems [1]. The discharges have to fulfill the requirement of low resistance during the conduction phase and high resistance during the opening phase. For fast opening times, which, in general, require rapid depletion of the electron density, the discharge has to be attachment-dominated in the opening phase. In optically controlled diffuse discharges the influence of the light can either be to enhance or to decrease the conductivity. For processes that increase the conductivity, the opening effect is achieved when the laser is turned

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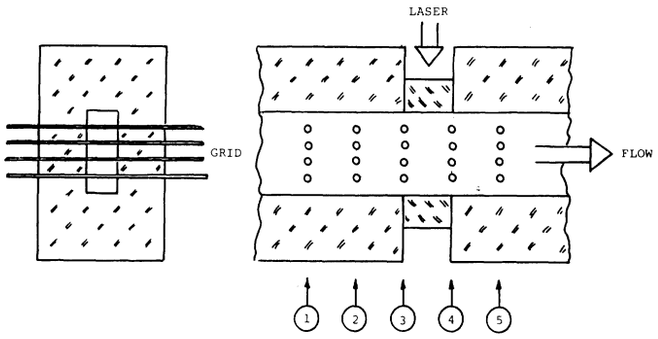

Fig. 1. Experimental setup for photodetachment experiments. Although only four are shown for clarity, ten parallel wires were used for each grid, as discussed in the text.

off. Photodetachment has been considered as a conductivity-enhancing process [2]. Using photodetachment, a strong change of the conductivity of the discharge should be possible, if without photodetachment the negative ion density is much larger than the electron density, and if the electrons of the existing negative ions can be mostly detached by means of photodetachment.

To investigate the feasibility of photodetachment for optically controlled diffuse discharge switches we chose the negative ion O^- for several reasons.

1. The photodetachment cross section of O^-, $\sigma_{p.d.}$, is well matched to our Nd:YAG-based laser system, in that $\sigma_{p.d.}$ has a threshold at a photon energy of $h\nu = 1.47$ eV and reaches a plateau at a photon energy of 2 eV. Thus the 1.06 μm (1.17 eV) fundamental of the laser should produce no photodetachment of O^-, whereas visible radiation, such as is obtained by frequency doubling or by pumping a dye laser, should produce strong photodetachment.

2. O^- can easily be produced in discharges containing O_2, SO_2, N_2O, or other oxides.

3. From O_2 glow discharges it is well known that the negative ion density N_- can be much larger than the electron density N_e [4].

II. Experimental Setup

The experimental setup for our experiment is shown in Fig. 1. The flow tube has a rectangular cross section with dimensions 3×14 mm^2. Five grids, separated from each other by 2 mm, are placed perpendicular to the flow axis. Each grid is made of 10 individual Pt wires with 0.127-mm diameters. For photodetachment experiments in the flowing afterglow, a discharge was operated between grid 1 (cathode) and grid 2 (anode), with each wire of the cathode grid separately ballasted for discharge homogeneity. The region between grid 2 and grid 3 was generally kept nearly field-free, although for discharges with small admixtures of O_2, a small negative voltage was applied to grid 3 to achieve zero current through grid 3 in dc operation. Between 3 and 4 a voltage of 5-100 V was applied to collect the photodetached electrons. The optogalvanic signal was detected by measuring the voltage across a resistor of between 1 kΩ and 1 MΩ in series with grid 3. The fifth grid did not play an important role in the experiments described here, but was available to establish an exit condition for charged species passing through grid 4. Also, by establishing a discharge between grids 2 and 5, photodetachment effects within the discharge could be monitored using grids 3 and 4. The light source was a Quanta-Ray PDL dye laser pumped by the Q-switched, frequency-doubled output of a Quanta-Ray DCR-1, Nd:YAG laser. The dye laser delivered pulses of about 50 mJ energy in 7 ns.

TABLE I
Important Processes in O_2 Discharges

		Reaction		Charged Product	
Attachment	(1)	$e + O_2 \rightarrow O^- + O$		O^-	
	(2)	$e + 2\,O_2 \rightarrow O_2^- + O_2$		O_2^-	
Ion Molecule Reactions	(3)	$O^- + O_2 \rightarrow O_2^- + O$		O_2^-	
	(4)	$O^- + 2\,O_2 \rightarrow O_3^- + O_2$		O_3^-	
Photo-detachment	(5)	$O^- + h\nu \rightarrow O + e$	($h\nu > 1.47$ eV)	e^-	[3]
	(6)	$O_2^- + h\nu \rightarrow O_2 + e$	($h\nu > 0.434$ eV)	e^-	[7]
	(7)	$O_3^- + h\nu \rightarrow O_3 + e$	($h\nu > 2.103$ eV)	e^-	[8]
Photo-dissociation	(8)	$O_3^- + h\nu \rightarrow O^- + O_2$	($h\nu > 1.7$ eV)	O^-	[9]
	(9)	$O_3^- + h\nu \rightarrow O_2^- + O$	($h\nu > 2.7$ eV)	O_2^-	[10]

III. Experimental Results

In a discharge containing O_2, several different attachment processes and subsequent ion-molecule reactions are possible. For these, the important ions are O^-, O_2^-, and O_3^-, and the processes with large reaction rates are shown in Table I. The dominant attachment process in the range ($E/p \leqslant 2$ V $\cdot$ cm^{-1} $\cdot$ torr^{-1}) is the three-body attachment (reaction 2), while for higher values ($E/p \geqslant 2$ V $\cdot$ cm^{-1} $\cdot$ torr^{-1}), the dissociative attachment (reaction 1) dominated [5]. Among the ion-molecule reactions, reaction (3), which produces O_2^-, is important at higher values of E/p, while reaction (4), which produces O_3^-, dominates at lower E/p values [6]. The important photo-induced processes for these ions are also given in Table I. Of these, the Nd:YAG fundamental ouput with a photon energy of 1.17 eV can induce only reaction (6).

In our experiment, the ions can either be produced in the discharge itself, where the value of E/p varies in the range of $5 \leqslant E/p \leqslant 27$ V $\cdot$ cm^{-1} $\cdot$ torr^{-1} (as determined by the discharge conditions), or in the nearly field-free drift region between grid 2 and 3. To learn which ions are the dominant species under various discharge conditions, we performed optogalvanic experiments using either visible light ($h\nu \approx 2.2$ eV) from the dye laser, or the Nd:YAG fundamental at 1.17 eV.

Some experimental results are shown in Table II. They indicate that for the range of discharge conditions we investigated, O_2^- is produced best in pure O_2 discharges at pres-

TABLE II
OPTOGALVANIC SIGNAL FOR DIFFERENT DISCHARGE CONDITIONS AND PUMP FREQUENCIES

Discharge I=15 mA / Laser	p = 10 torr He : O_2 = 20:1	p = 0.3-0.8 torr O_2 only	p = 3-10 torr O_2 only
Dye Laser 560 nm 10mJ	strong OGS	medium OGS	medium OGS
Nd-YAG Laser 1060 nm 100mJ	weak OGS	weak OGS	medium OGS

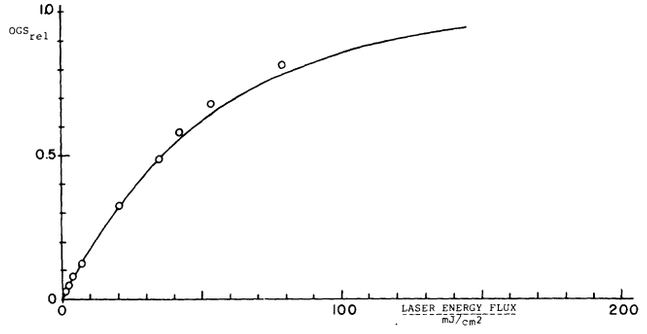

Fig. 2. Relative optogalvanic signal depending on laser energy flux. Discharge current was 1.5 mA in 10:3 He:O_2 mixture at 10 torr.

sures above 3 torr. We found that O_2^- production was not a strong function of the voltage across the drift region (between grid 2 and 3), indicating that the attachment processes occur mainly in the discharge. Since the E/p values for all discharge conditions are such that reaction (1) strongly dominates, we conclude that the production of O_2^- at O_2 pressures above 3 torr results from reaction (3) in the discharge. Consistent with our experimental observation this reaction should preferably occur at E/p values above 10 V · cm^{-1} · $torr^{-1}$ [6] and at the highest O_2 pressures.

To distinguish between optogalvanic signals caused by O^- and O_3^- we note that for $h\nu > 2$ eV photodissocitation (reactions (8) and (9)) has been found to be the dominant photo process in O_3^- [8]. Of these, only reaction (8) is possible with the photon energies produced by our dye laser source ($h\nu \approx 2.2$ eV). The cross section for reaction (8) has a spectral structure [9] which we did not observe in our experiments when the laser was tuned through the range 2.18-2.28 eV. We therefore conclude that the dominant optical electron generation mechanism in our experiment is direct photodetachment of O^-.

To investigate whether the existing negative ions can be completely detached we performed saturation experiments in which the dependence of the optogalvanic signal strength on laser energy flux was determined. These results are shown in Fig. 2. The solid line shows the calculated result, assuming a photodetachment cross section of $\sigma = 6.5 \times 10^{-18}$ cm^2, and the circles indicate the result of our measurement. Since the optogalvanic signal is only measured in arbitrary units, the scale of the experimental curve was adjusted so that the slopes of the two curves agreed in the linear region (<10 mJ/cm^2). These results indicate that only 35 mJ/cm^2 of light energy flux is needed to photodetach 50 percent of the O^- ions.

IV. CONCLUSION

Our experiments demonstrate that photodetachment may be an attractive control mechanism for optically controlled diffuse discharge switches in systems where the negative ion density is much larger than the electron density. Assuming a time constant for attachment $t_a \approx 10^{-8}$ s, for a gas mixture in a discharge producing O^-, a power of 3.5 MW/cm^2 is necessary to reduce the steady-state negative ion density by a factor of 0.5. Work is continuing to determine the optogalvanic response of the discharge to photodetachment.

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