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Laser induced air breakdown using 0·355, 0·532, and 1·06 μm radiation

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Abstract. Studies of breakdown threshold intensity for air at various pressures in the range of 24–760 torr using 0·355, 0·532 and 1·06 μm radiation are reported. We observe $p^{-0.8}$ scaling of I_{th} at 1·06 μm and a weak scaling of $p^{-0.4}$ at 0·532 and 0·355 μm radiation. Strong dependence of breakdown spot size on laser power but weak dependence on air pressure is observed.

Keywords. Lasers; air breakdown; pressure scaling; plasma.

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1. Introduction

Since the first report of laser induced breakdown (Maker *et al* 1963) of air in 1963, there has been an enormous growth of understanding of the phenomenon (Pendleton and Guenther 1965; DeMichelis 1969; Grey Morgan 1974). By focussing a laser beam in gas it is possible to obtain a high-temperature, high density plasma. Various properties of the gaseous plasma created by focussing laser radiation have also been studied. Laser produced plasmas have been used as source for high intensity X-rays (Brown *et al* 1987) and VUV continuum in rare gases (Laporte *et al* 1987). Sensitive techniques to measure UV radiation using gas breakdown have also been developed (Kopeika *et al* 1977). Lasers have been used to trigger electrical discharge between electrodes in vacuum and in gases in spark gap switches (Guenther and Bettis 1978). Detailed calculations of the gas breakdown threshold caused by laser irradiation have been carried out by Kroll and Watson (1972). Buscher *et al* (1965) were the first to study the breakdown threshold intensity of rare gases at wavelengths 1·06, 0·69, 0·53 and 0·35 μm. They found that the threshold intensity for each rare gas studied, first increases to a maximum and then decreases with decreasing wavelength. Alcock *et al* (1972) reported the breakdown of nitrogen, methane and rare gases using a ruby laser of pulse width 20 ns and its second harmonic, in agreement with Buscher *et al* (1965). Krasyuk *et al* (1970) studied the breakdown threshold of nitrogen, helium and argon using *ps* pulses of ruby laser in the pressure range $2 \leqslant p \leqslant 10^4$ torr. The results show a weak dependence on the pressure for $p \leqslant 10^3$ torr in He and Ar and $p \leqslant 300$ torr in N_2, characteristic of multiphoton absorption. At higher pressure in He and Ar there is a pronounced pressure dependence, indicating the occurrence of collisional ionization by inverse bremsstrahlung absorption, however for N_2 the pressure dependence is less pronounced. Gamal and Harith (1981) and Weyl and Rosen (1985) have done theoretical calculations of laser induced breakdown thresholds of atomic and molecular gases as a function of pressure of the gas, pulse width of laser, using the equation of growth of electrons, and including the effects of both multiphoton and cascade ionization. In this paper we report the studies on air breakdown by focussing the Nd:YAG laser and its harmonics at various pressures, in the range of 24–760 torr. It is assumed that intensity distribution remains gaussian in the focal plane. The lens aberration function (Born and Wolf 1964) is less than one wavelength of the radiation (Evans and Norgan 1968) used. Dependence of the size of visual spark as a function of laser power is also studied.

2. Experimental set-up

A Nd:YAG laser (DCR-4, Spectra physics) with Gaussian limited mode structure, and its harmonics delivering 900 mJ in 2·5 ns (FWHM) at fundamental with a repitition rate of 10 pps, was focussed with a quartz lens ($f = 12$ cm) in to the centre of a vacuum chamber. The chamber was evacuated to $< 10^{-2}$ torr with a rotary pump. Laser energy was varied by varying the voltage on the laser amplifier. No significant variation in mode pattern was observed at different energies. The energy of the laser was measured with a laser power meter (Ophir Model No. 30A), by placing the power meter in the path of the main beam. The output power of the laser was stable within $\pm 7\%$. The beam divergence being less than 0·5 mrad. The pulse width for harmonics at 0·532 and 0·355 μm scales as 1·06 μm pulse width divided by $\sqrt{2}$. Threshold energy was measured only when the breakdown spark, seen visually through the window, was modulated at 10 pps.

3. Results and discussion

Figure 1 shows the dependence of threshold intensity on pressure of air for different laser wavelengths. It is observed that threshold intensity increases with the decrease of pressure. At low pressures the collision frequency is low and sufficient ionization can be maintained by increasing the probability of ionization at each collision (i.e. the electron velocity) and thus the electric field associated with laser radiation should be high. Hence threshold intensity increases as pressure decreases. Breakdown threshold intensity of air at 1·06 μm shows a pronounced pressure dependence, characteristic of collisional ionization by inverse Bremsstrahlung absorption. The threshold intensity scales with pressure as $p^{-0.8}$. However, weak dependence on pressure $p^{-0.4}$ is observed at 0·532 and 0·355 μm indicating the occurrence of multiphoton absorption. Thus the breakdown of air at visible and shorter wavelengths may be initiated with multiphoton absorption and then proceed due to cascade processess.

Figure 2 exhibits the dependence of breakdown threshold intensity on wavelength of laser radiation at different pressures of air. At 380 torr the threshold intensity decreases with the increase of wavelength. However at atmospheric pressure of air it is observed that the threshold intensity first decreases to a minimum and then increases with increase in wavelength, in contradiction to Buscher's result. Breakdown

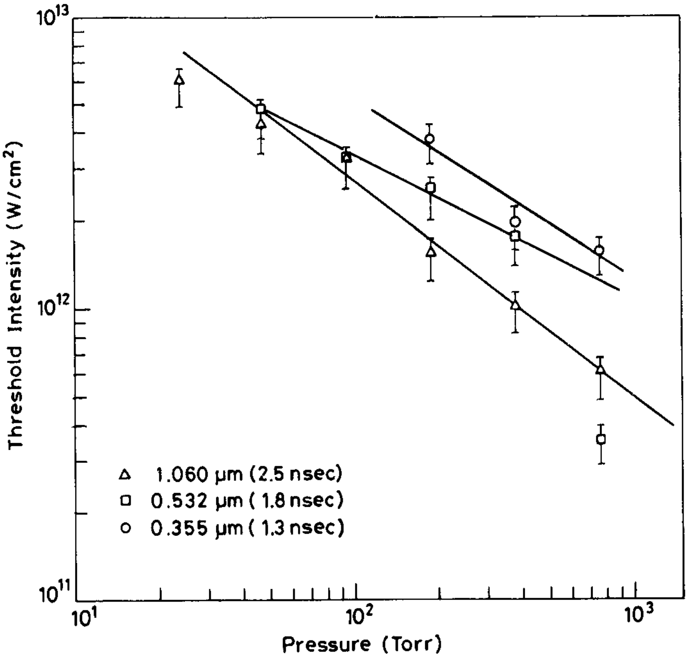

Figure 1. Dependence of breakdown threshold intensity on pressure of air. The pulse widths of various wavelengths used are shown in parantheses.

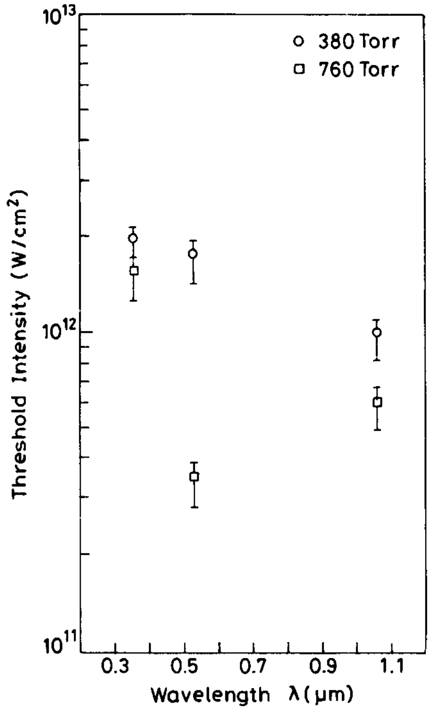

Figure 2. Dependence of breakdown threshold intensity on wavelength of radiation for two pressures.

threshold intensity was measured for atmospheric air inside and outside the chamber. It is observed that threshold intensity is less outside the chamber as compared to inside the chamber. It is expected since breakdown threshold intensity can be reduced for dusty air as compared to the case of still air inside the chamber. The variation of the length of visible spark with 1·06 μm laser energy radiation at atmospheric pressure shows that length of the visible spark increases with the increase of laser energy. As the energy contained in the beam waist increases, length of visible spark increases due to increased absorption in the focal volume. No appreciable change of spot size (length or width) was observed with the pressure of air with 1·06 μm radiation.

In conclusion, air breakdown was observed visually with Nd:YAG laser and its harmonics at various pressures, in the range of 24–760 torr. Breakdown threshold intensity was found to be dependent on wavelength and pressure. Visible breakdown spot size is strongly dependent on the laser radiation and weakly dependent on the pressure of air.

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