Aspects of Air-Breakdown with a High-Peak Power Passively Q-Switched Nd:YAG/Cr^{4+}:YAG Laser

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Abstract: A passively Q-switched Nd:YAG/Cr^{4+}:YAG laser is used to investigate the air breakdown in a static chamber. The characteristics of the transmitted laser pulse are measured and the energy transfer from the pulses to plasma is evaluated. As the air pressure increases inside the chamber the amount of transferred energy from pulse to plasma increases.

OCIS codes: (140.0140) Lasers and laser optics; (140.3440) Laser-induced breakdown; (140.3540) Lasers, Q-switched; (120.1740) Combustion diagnostics

1. Introduction

Laser induced ignition could be an alternative to the conventional electrical method. Advantages of this ignition technique include the possibility to choose the position of the ignition point inside the combustion chamber whereas lean air-fuel mixtures can be ignited. Various laser systems were used to start the combustion process for different types of fuel, such as methane-air mixtures [1], hydrogen [2], propane and jet fuel [3], or gasoline [4]. However, for this new method to be implemented on real internal combustion engines one of the major conditions were to have a laser system with dimensions comparable with that of an electrical spark-plug [5]. Compact passively Q-switched Nd:YAG/Cr^{4+}:YAG laser systems were built as spark-induced igniters [6,7], and Taira *et al.* presented in 2013 the first automobile that was run only with laser igniters [8].

Several studies regarding the effects on ignition resulting from the variation of pulse energy and focusing parameters of the laser beam have been reported. Srivastava *et al.* have investigated the effects of laser pulse energy on the engines performance and emissions [9]. Kawahara *et al.* performed experiments for laser-induced breakdown in air; it was concluded that both the plasma growth time and the plasma volume were proportional to the energy deposited by the laser [10]. Recently, Lorenz *et al.* developed a quantitative measurement technique for analyzing spatially and temporally the energy transfer from a laser pulse to the plasma induced in air [11]. This technique was applied with a passively Q-switched Nd:YAG/ Cr^{4+}:YAG laser yielding high (8 to 12 mJ) energy per pulse and short (ns level) to long (3.4 ns) pulse duration.

A Renault engine was operated recently with high-peak power Nd:YAG/Cr^{4+}:YAG laser-spark devices developed in our group [12]. In the presented work the technique developed by Lorenz *et al.* [11] was used to evaluate the transferred energy from the laser pulse to the plasma induced in air from our passively Q-switched Nd:YAG/Cr^{4+}:YAG laser. Global energy deposition and local energy deposition, as well as plasma evolution during laser induced air breakdown were investigated in static chamber from vacuum to up to 9 bar air pressure.

2. Experimental setup

A general view of the experimental set-up is presented in Fig. 1a and a spark-plug like Nd:YAG/Cr^{4+}:YAG laser is shown Fig. 1b. The measurements were realized with a Nd:YAG/Cr^{4+}:YAG laser prototype [12] that delivered pulses with energy up to 4.0 mJ and short pulse duration of 0.9 ns.

The laser was mounted on an optically accessible vacuum pressure chamber that was filled with air at different values of pressure (up to 9 bar pressure). Experiments were performed at room temperature. The laser beam was focused inside the chamber using three different aspheric lenses, with focal lengths of 11.0, 13.8 and 18.4 mm. A lens located after the gas chamber was used to collimate the transmitted laser beam. The collimating beam was sent to a filter box, for spatial filtering. A second lens was used to focus the laser beam on a fast UPD-35-IR2-P photodiode (Alphalas, Germany) with a short (<35 ps) rise time. The profile of the transmitted pulse was recorded with a digital storage oscilloscope (Wavemaster 8Zi-A, LeCroy).

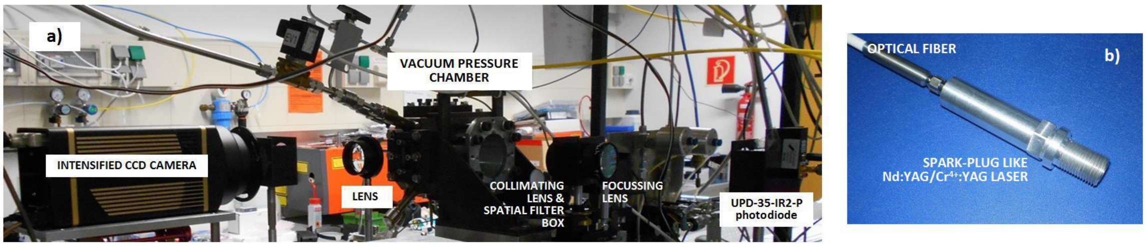

Fig. 1. a) The experimental setup used for measuring the global energy deposition, the local energy deposition and the plasma evolution is presented. **b)** A laser spark plug used in the experiments is shown.

The temporal shape of the laser beam after plasma was measured with a fast SIR5-FC photodiode (Thorlabs; rise time <50 ps). The plasma evolution was recorded with an intensified CCD camera (Princeton Instruments).

3. Results and discussions

In order to evaluate the global energy deposition, the profiles of the transmitted pulses were recorded in the case of each focusing lens, from vacuum up to 9 bar pressure in the chamber. Vacuum was realized in order to have no air breakdown.

Typical measurements were performed at 5-Hz laser repetition rate. In addition, an investigation was done at several values of the pressure (1 bar, 3 bar, 5 bar, 7 bar and 9 bar) versus the laser pulse repetition rate up to 40 Hz. As an example, Fig. 2a shows the shapes of the laser pulses transmitted from chamber after air-breakdown initiation with the lens of 18.4-mm focal length. From such curves the energy transferred from the laser pulse to plasma was determined (as shown in Fig. 2b). Transfer efficiency in excess of 60% was evaluated for this lens and pressure higher than 8 bar. A change of the transfer efficiency for different laser pulse repetition rate was not detectable in the conditions of our experiments.

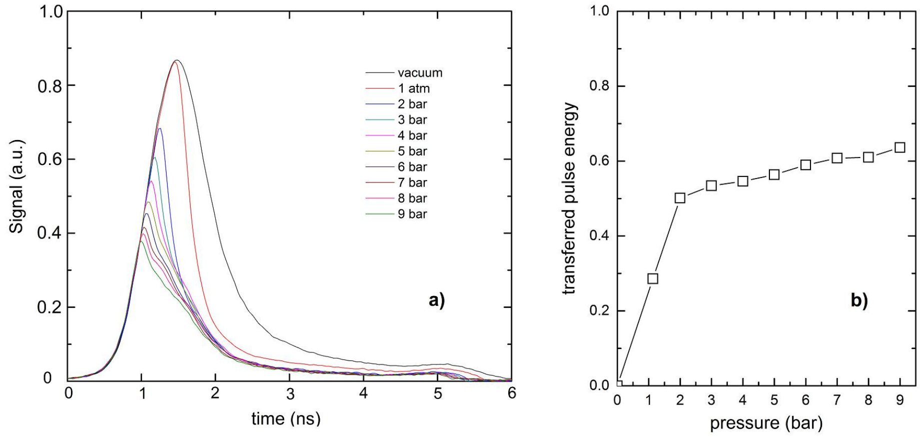

Fig. 2. a) Temporal pulse profiles for different air pressure, focusing lens with 18.4-mm focal length, 5-Hz repetition rate. **b)** The transferred energy of the laser pulse during air-breakdown plasma initiation.

Information about what spatial part of the laser pulse contributes firstly to the breakdown can be obtained from local energy deposition. The temporal profiles of the laser pulses were measured, as described in Ref. [11], by placing circular filters in the way of the collimated beam after the chamber. Figure 3 shows such temporal profiles that were recorded for the lens with18.4-mm focal length and pressure in the static chamber of 3.2 bar. Within the pressure range used in the experiments and considering the measurement accuracy, conclusion was that air-breakdown is induced simultaneously by all spatial parts of the laser pulse (similar to Ref. [11]).

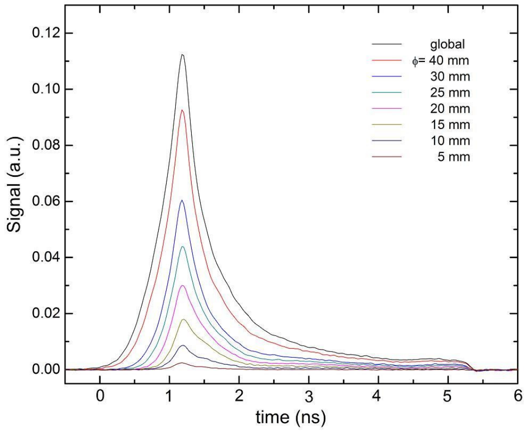

Fig. 3. Temporal pulse profile recorded by placing spatial filters with different diameter (ϕ) in the collimated laser beam after the static chamber; lens with 18.4 mm focal length. 3.2-bar pressure of the air.

4. Conclusions

A passively Q-switched Nd:YAG/Cr^{4+}:YAG laser prototype that yields moderate (4 mJ) energy per pulse with duration around 1 ns is used for air breakdown in a combustion chamber. The energy transfer characteristics from the laser pulses to plasma are estimated by evaluating the global energy deposition and the local energy transfer.

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5. References

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