RAPID COMMUNICATIONS

PHYSICAL REVIEW E VOLUME 60, NUMBER 4 OCTOBER 1999

Formation of a conducting channel in air by self-guided femtosecond laser pulses

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(Received 16 February 1999; revised manuscript received 13 July 1999)

We report a drastic reduction of air resistivity following the passage of a self-guided femtosecond pulse from a Ti:sapphire laser system at 800 nm with energies per pulse between 1 and 14 mJ and a pulse duration of 120 fs. Connected plasma filaments with a length that can exceed 150 cm are created by these pulses. The presence of a conducting plasma channel results from multiphoton ionization of air molecules in the filament core. [S1063-651X(99)51210-5]

PACS number(s): 52.40.Nk

A very unusual propagation of light has been observed recently [1–4]. Intense ultrashort laser pulses launched in air self-organize into filaments, which persist over very long distances. This self-guiding effect is interesting in several ways. From a fundamental point of view, long-range self-guided propagation is a beautiful example of strong nonlinear responses conspiring to establish a quasistable dynamic regime. It also suggests interesting applications. For instance, one might use these filaments to trigger and guide an electric discharge. The peak intensity of the pulse inside the filament can reach $10^{14}\,\mathrm{W/cm^2}$ [5], a value sufficient to ionize air molecules by multiphoton transitions. Hence, a channel of weakly ionized plasma should be formed after passage of the pulse that could perhaps act as a precursor for lightning [6]. However, evidence for the existence of such a plasma filament has so far been indirect [1–3,7,8]. In this paper, we present direct evidence that a conducting channel is indeed created by self-guided pulses. Using as little as 14 mJ of laser energy, a plasma column extending over a distance of more than 100 cm is observed. Similar electric conductivity experiments performed in Jena have been published recently [9].

The experiment setup, shown in Fig. 1, is simple in principle. To detect the presence of a conducting column, we measure the change of resistivity of air between two electrodes after passage of a filament. The initial laser pulse is delivered by a Ti:S oscillator followed by a CPA amplifier system. The pulse wavelength is 800 nm, its duration is 120 fs, and its energy can reach 50 mJ. At the output of the compressor stage, the beam profile is nearly Gaussian, with a Gaussian parameter of $w_0 = 12\,\mathrm{mm}$. The beam goes through a diaphragm of variable diameter D and is focused in air with a thin lens of focal distance $F=1$ or 2 m. This converging beam geometry reduces the distance necessary for the formation of a self-guided pulse, allowing one to perform experiments in a laboratory of restricted dimensions [10].

The filament traverses a first copper electrode through a pinhole drilled in its center. The diameter of the pinhole (1 mm) is a compromise. A smaller diaphragm would destroy most filaments before they reach the second electrode, because of fluctuations in their position from shot to shot. On the other hand, with a larger diaphragm the electric signal diminishes rapidly, due to the high resistivity between the ionized core of the filament and the edge of the electrode. As a first electrode, we have also used a polished stainless steel mirror set at grazing incidence in the vicinity of the filament. The beam then impinges on the second electrode, consisting of a plain copper block or, for short electrode separation $d < 2$ cm, a replica of the first electrode with its pinhole on the axis. A dc voltage of typically 1000 V is applied between both electrodes. One measures the current circulating through the plasma column by recording the voltage induced across a resistance. The electric discharge is non-self-sustained, giving a pulse with a rise time and decay time less than 3 ns across a 100-Ω resistance, limited by the response time of the detection system (see inset of Fig. 3). A more sensitive detection of the presence of free carriers is obtained with an electrometer, which integrates over many laser shots the charges flowing to one electrode.

In Fig. 2, the average charge per laser shot collected by the electrometer is shown as a function of distance L between the geometric focus and the first electrode, keeping the separation between the two electrodes constant at $d = 1.5\,\mathrm{cm}$. Curve (*a*) is for a filament produced by a beam with a diameter limited by the diaphragm to 8 mm. The initial energy of the pulse (before the lens) is about 3 mJ. The lens has a focal distance F of 1 m. Curve (*b*) refers to a diaphragm of 18 mm. The pulse energy is 14 mJ and the lens has a focal distance of 2.24 m. Under these last conditions, shot-to-shot fluctuations were more important, with the filament breaking sometimes in a multifilamentary structure. Careful alignment of the laser reduced the tendency to multifilamentation by improving the transverse mode structure of the laser beam. Nevertheless, fluctuations in position of the filament by a few mrad were still present.

As can be seen in Fig. 2, the self-guided pulse forms an ionized track over a distance of at least 150 cm. In Fig. 3, the peak of the voltage signal, detected across an 8.2-kΩ resis-

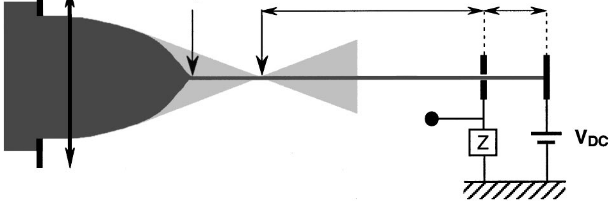

FIG. 1. Experiment setup (see text).

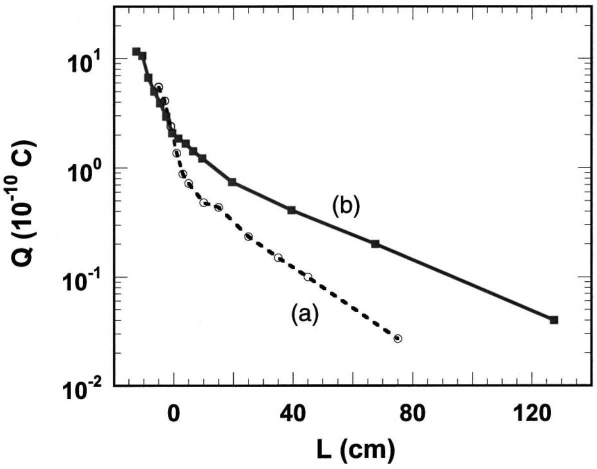

FIG. 2. Integrated electric charge measurements over 100 laser shots, normalized to a single laser shot, made by use of an electrometer connected to the rear electrode. The electrode spacing is 1.5 cm. Curve (*a*) is obtained with 3 mJ energy per pulse and a duration of 120 fs. Curve (*b*) is for 14 mJ energy per pulse. The applied voltage is 1000 V dc.

tance, is plotted as a function of *L* for the case of a 14-mJ pulse. Single shot detection now allows one to discriminate amplitudes of signals. In the plot of Fig. 3, only those signals of large amplitude corresponding to well connected single filaments are registered. The presence of a plateau of constant conductivity extending beyond the geometric focus to a distance of about 40 cm, which was buried in the averaging procedure of Fig. 2, is now revealed.

The current has also been measured as a function of electrode separation in the plateau region, up to a distance $d = 50$ cm. It reveals a linear dependence of the current with $1/d$, for a fixed applied dc voltage (see Fig. 4), or with applied voltage between 500 and 2500 V for a fixed separation *d*. This in turn indicates that we are in an Ohmic regime, with the current directly proportional to the applied field. The peak current in the plateau, measured with a 100-Ω resistance, is at least 10 mA.

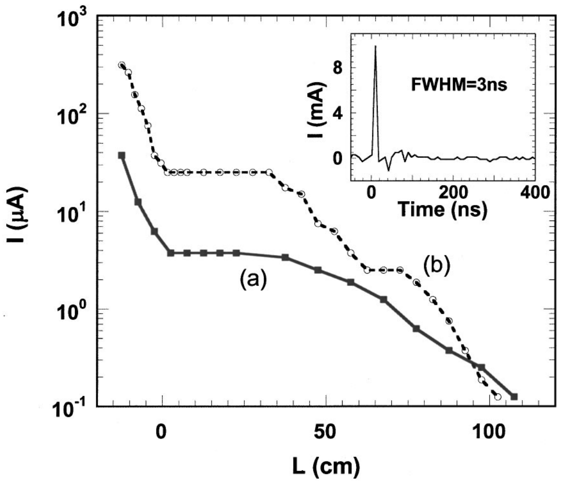

FIG. 3. Single shot electric current measurements as a function of the distance *L*. The applied voltage is 1000 V dc across the electrodes with spacing (a) $d = 11.5$ cm and (b) $d = 3$ cm. The energy per pulse is 14 mJ and the external resistance is 8.2 kΩ. The origin of *L* corresponds to the geometric focus of the lens. The inset shows the shape of the transient voltage, measured across a 100-Ω resistance, with an applied voltage of 1500 V. The signal is recorded in a single shot with a numerical oscilloscope (Tektronix TDS 544A) of 500 MHz bandwidth.

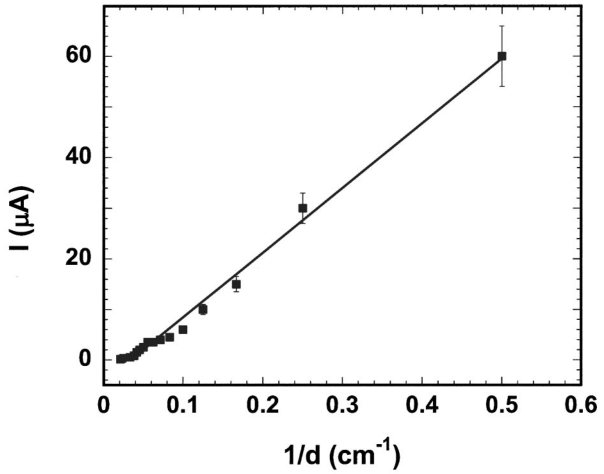

FIG. 4. Electric current measurements as a function of $1/d$, in the plateau region. The first electrode is at $L = 0$. The incident energy per laser pulse is 14 mJ. The applied field is 1000 V. The external resistance is 8.2 kΩ.

We now address the question of the origin of the conducting structure. One can reject an interpretation based on the presence of a stream of fast electrons ejected from one electrode and collected by the other from the fact that a second electrode with a pinhole gives essentially the same results as a plain electrode. We have also compared signals obtained by inverting the polarity between the two electrodes. Results are shown in Fig. 5. No significant change of the magnitude of the signal is detected with polarity, except in a small region before the geometric focus of the beam, and for small interelectrode spacing only ($d < 5$ cm).

A more plausible physical origin for the presence of con-

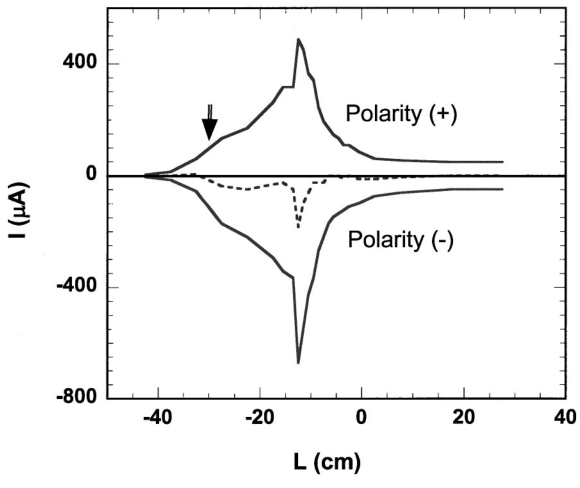

FIG. 5. Electric current measurements as a function of the distance *L*. The applied voltage is 1000 V for the polarity (+) and −1000 V for the polarity (−). Electrode spacing is $d = 1.5$ cm. The dotted curve is the difference between the signals for each polarity. The pulse energy is 14 mJ. The arrow indicates the calculated position of the beginning of the filament.

ducting charges is multiphoton ionization, a process playing a crucial role in pulse self-guiding [1–3,10]. We have confronted our measurements with the numerical results of a three-dimensional (3D) propagation code with initial conditions close to those of the experiment. According to the simulation, the birth of the filament should occur 30 cm before the geometric focus. This displacement of the onset of filamentation from the geometric focus is understood simply [11]: the focal point of the beam sweeps back from the geometric focus along the propagation axis z during the ascending part of the laser pulse. This sweep forms an ionized track as well, extending from the geometric focus inward up to a distance shown as an arrow in Fig. 5. This position is close to the measured onset of conduction in Fig. 5.

One can also compare the calculated electron density in the conducting core of the filament with values extracted from the measurements. The simulation yields a laser field clamped to a maximum on the order of $10^{14}\,\mathrm{W/cm^2}$ by the rapid surge of ionization [12]. At this field value, the ionization rate is of the order of 10^{-3} and only singly ionized atoms are formed. In the corresponding conducting core with a diameter estimated by the numerical code to lie between 40 and 100 μm (full width at half maximum), an average free-electron density ranging between 3×10^{16} and $2\times10^{17}\,\mathrm{cm^{-3}}$ is expected.

To evaluate the free-electron density from the measurements, we rely on the reported current density per ion, $i=3\times10^{-14}\,\mathrm{A/cm^2}$, quoted in Ref. [13], for air at atmospheric pressure with an applied field of similar magnitude. Taking a filament size of 40 μm diam, we obtain in the plateau region a minimum average peak current flux of 800 $\mathrm{A/cm^2}$ and a plasma resistivity less than 1.2Ω cm. From this, we estimate a free-electron density of $3\times10^{16}\,\mathrm{cm^{-3}}$ [14]. At such densities, the decay of the plasma is expected to be predominantly due to recombination of electrons at the parent ions, following a law $dn/dt=-bn^2$. Assuming a value $b=2.2\times10^{-7}\,\mathrm{cm^3/s}$ from the literature [6], one finds that the majority of carriers disappear within 5 ns, in agreement with the duration of the electric signal $t<3$ ns. More accurate measurements of the decay are now in progress.

In conclusion, using laser pulses of modest energy, we observe the presence of a conducting plasma column over distances exceeding one meter along the track of self-guided filaments. Such a plasma column could be useful for the study of electric lightning, since it may provide an artificial precursor of uniform carrier density, circumventing the complex initial stage of streamer formation preceding electric breakdown of air.

We are thankful to Professor R. Sauerbrey for a private communication of his results on similar measurements before publication.

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[14] After submission of this manuscript, a paper was published where initial free-carrier densities exceeding $n=10^{15}\,\mathrm{cm^{-3}}$ have been estimated in a laser-induced filament by interferometry [B. La Fontaine *et al.*, Phys. Plasmas **6**, 1615 (1999)].