Generation of extended plasma channels in air using femtosecond Bessel beams

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Abstract: Extending the longitudinal range of plasma channels created by ultrashort laser pulses in atmosphere is important in practical applications of laser-induced plasma such as remote spectroscopy and lightning control. Weakly focused femtosecond Gaussian beams that are commonly used for generating plasma channels offer only a limited control of filamentation. Increasing the pulse energy in this case typically results in creation of multiple filaments and does not appreciably extend the longitudinal range of filamentation. Bessel beams with their extended linear foci intuitively appear to be better suited for generation of long plasma channels. We report experimental results on creating extended filaments in air using femtosecond Bessel beams. By probing the linear plasma density along the filament, we show that apertured Bessel beams produce stable single plasma channels that span the entire extent of the linear focus of the beam. We further show that by temporally chirping the pulse, the plasma channel can be longitudinally shifted beyond the linear-focus zone, an important effect that may potentially offer additional means of controlling filament formation.

OCIS codes: (320.2250) Femtosecond phenomena; (320.7110) Ultrafast nonlinear optics; (350.5400) Plasmas

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1. Introduction

Since the original report on generation of extended plasma channels by intense femtosecond laser pulses in air [1] this phenomenon has been the subject of active research motivated by various potential applications such as remote spectroscopy [2], generation of few-cycle optical pulses [3], lightning control [4], and generation of THz radiation [5]. The fundamental mechanisms responsible for the stable self-guided propagation of the ultrafast high-intensity laser pulses in Kerr media are now well understood, although particular details can still be puzzling due to the richness and complexity of the highly nonlinear physics involved [6].

It has been found by numerical simulations and later confirmed experimentally that only a small fraction of the intensity of the ultrafast laser beam is confined in the plasma channel, while the remaining portion of the beam is propagating in the close to linear regime and thus is subjected to ordinary diffraction. However, this linear photon bath is instrumental to the self-guided propagation of the plasma channel, as it continuously supplies energy expended into the plasma generation and heating [7, 8].

Of particular practical interest in remote spectroscopy and lightning control is the creation of extended filaments. In theoretical and experimental studies, it is common to use fundamental Gaussian beams for the initiation of plasma channels, but Gaussian beams allow for only limited control of filamentation. In particular, in order to create a longer filament with a Gaussian beam the focusing of the beam has to be weakened, but then the wavefront distortions that are

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inevitably present in the beam cause spontaneous creation of filaments in the hot spots of the beam and not on the geometrical beam axis. Increasing the energy of the laser pulse in this case only leads to creation of multiple filaments instead of extending the propagation of a single filament. Furthermore, the multiple filaments are randomly distributed within the laser beam and their locations fluctuate on the pulse-to-pulse basis. The fluctuating multi-filament pattern can be stabilized by introducing aberrations, e.g. by weakly focusing the beam with a tilted lens [9].

It has been known for quite some time that optical beams with transverse profiles in the form of a Bessel function propagate in free space in a diffraction-free manner [10]. Instead of having a localized longitudinal range where the optical intensity is high (such that the Raleigh range for a Gaussian beam), Bessel beams have an extended linear focus. The extent of the linear focus is determined by the size of the (typically truncated) input Bessel beam.

The diffraction-free nature of Bessel beams has been utilized in diverse applications of linear optics such as illumination and imaging [11, 12] and optical trapping [13]. The use of Bessel beams in nonlinear optics in general and in the light string science in particular has been explored to a much lesser extent. Such beams have been previously used for creating few centimeter-long high-density plasma channels for particle acceleration and X-ray generation [14]. Various experiments on filamentation in condensed media (fused silica and water) with ultrafast Bessel beams have also been reported [15, 16, 17]. It has been pointed out to us by one of the reviewers of this paper that an experiment on filamentation in air using a femtosecond Bessel beam has been very recently reported in a conference presentation [18]. In [18], a 50 fs-long pulse with 8 mJ of energy was focused with an axicon lens in air and created a $\sim$1 m-long plasma channel.

In this paper, we report experiments on generating plasma channels in air by femtosecond Bessel beams at 800 nm center wavelength, and with various pulse energies and durations. In our experiments, the extended linear focus of the Bessel beam is 2.25 m-long. We found that for 50 fs-long pulses with energies of up to 14.5 mJ, the created plasma channel spans the entire linear focus zone of the beam. In the range of pulse energies attainable in the experiments, only the central peak of the beam has sufficient intensity to create a filament while the peripheral rings are not strong enough to initiate filamentation on their own. As a result, the single stable filament is pinned to the geometrical axis of the beam and its location experiences negligible pulse-to-pulse fluctuations. This behavior is compared with the case of filamentation of weakly focused Gaussian beams, in which increased pulse energy is shown to create multiple filaments.

A particularly interesting outcome of our experiments is an observed longitudinal shift of the filamentation region beyond the linear focus zone that occurs for a certain value of the temporal chirp introduced into the laser pulse. The effect is found to be independent of the sign of the chirp. At the optimum pulse length (found to be in the 500 fs range) the filament is shifted beyond the linear Bessel zone by as much as 50 cm. A similar effect in the case of a Gaussian beam was previously described in [19], where existence of an optimum pulse duration that maximizes the length of the filament was theoretically predicted. The experimentally observed longitudinal extension of the plasma channel by pulse chirping may offer additional means of control over filament formation.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The high-energy femtosecond pulses are generated by a commercial Ti:Sapphire laser system that operates at a pulse repetition rate of 10 Hz and delivers up to 25 mJ of energy in a sub-50 femtosecond pulse, at 800 nm wavelength. The output beam has a diameter of 11 mm ($1/e^2$ intensity), with a beam-quality factor, M^2, of 1.5 as specified by the manufacturer. The nearly Gaussian output beam is transformed into a

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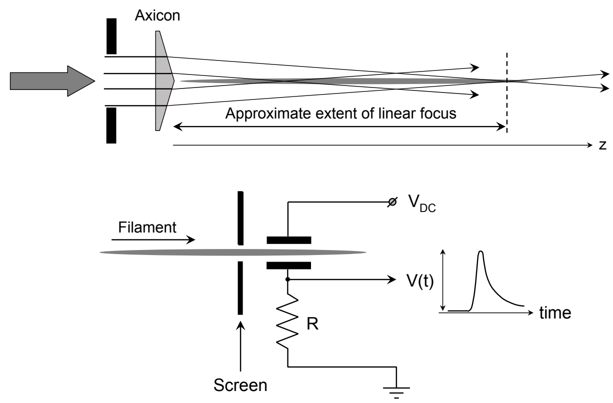

Fig. 1. Schematic of the experiment. Top: Filamentation with apertured femtosecond Bessel beam. Bottom: Setup for probing local charge density in the plasma channel.

Bessel beam using an axicon lens with an apex angle of 179.48°. The axicon is preceded by an iris with a diameter of 9.2 mm. Using the iris is necessary in our case in order to fit the beam into the finite-aperture axicon without using a telescope, as well as to confine the filamentation inside the laboratory space.

The approximate extent of linear focus for an apertured beam focused by an axicon lens is given by the following expression:

$$z_0 = \frac{r_0}{(n-1)\tan(90^\circ - \alpha/2)} \tag{1}$$

where r_0 is the radius of the circular aperture limiting the transverse dimension of the incident laser beam, n is the index of refraction of the lens material, and α is the tip angle of the axicon. In our experimental geometry z_0 equals 2.25 m. In the linear regime, at propagation distances larger than z_0 the beam diffracts in a form of an expanding ring with a central dark region so that the on-axis intensity beyond z_0 is close to zero.

The energy of the linearly polarized laser pulses can be continuously varied using an attenuator based on a half-wave plate followed by a polarizer. After the aperture and the axicon, the maximum pulse energy attainable from our system is 14.5 mJ, and the duration of the pulses is (50$\pm$5) fs as derived from a measurement with a single-shot intensity autocorrelator.

In order to access the local charge density along the filamentation path we use a simple setup shown in the bottom part of Fig. 1. In this system, two flat 3.75 cm-long electrodes are charged to 1 kV from a DC-voltage source. The distance between the electrodes is 1.5 mm. In the absence of the plasma channel between the electrodes no current flows in the system, thus the voltage drop across the 1 MΩ load resistor connected in series with the plates is zero. As the femtosecond laser pulse creates a filament between the electrodes, the freed electric charges in the filament are accelerated by the DC electric field. The majority of the freed charges recombine. However, a small fraction of the charges reaches the electrodes causing a spike of electric current through the circuit. The amplitude of this impulse of current is measured by recording the impulse voltage drop across the load resistor with a self-triggered storage oscilloscope.

Direct exposure of the electrodes to the laser light is prevented by placing a flat metal screen with a 1 mm-wide slit in front of the electrodes. The screen is positioned immediately before the electrodes so that the filament passing through the slit reaches the gap between the electrodes undisturbed by the screen.

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The above technique yields a direct measure of the total linear charge density in the plasma channel that is spatially averaged along the 3.75 cm-long electrodes. We experimentally verified that the amplitude of the electrical signal recorded by this system is linear in applied electric field (i.e. it is linearly proportional to the applied DC voltage and inversely proportional to the distance between the electrodes). In addition, the measurement is relatively insensitive to the exact location of the filament in the transverse plane between the electrodes. To reduce the uncertainty associated with the pulse-to-pulse fluctuations of the laser intensity, at each data point the measurement was averaged over $\sim$100 pulses.

To compare filamentation of the Bessel beam with that of a Gaussian beam, the conductivity measurements were first performed on a filament created by focusing the beam with an ordinary fused-silica lens. The focal length of the lens was 1.3 m which was chosen such that the locations of the maximum intensity for the lens and for the axicon approximately coincided in the linear propagation regime.

3. Results and discussion

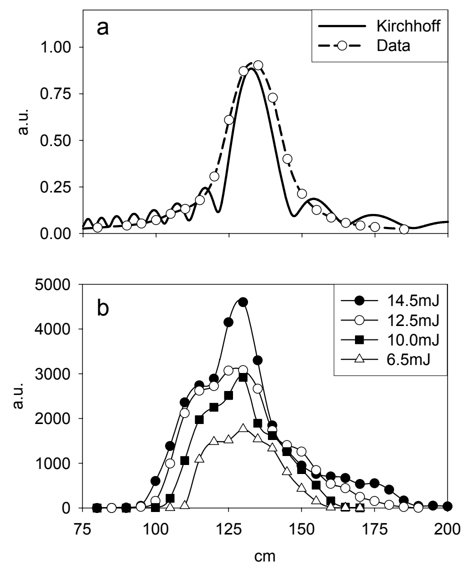

Fig. 2. Case of focusing with a lens with focal length of 1.3 m. a: On-axis intensity in the linear propagation regime (low intensity). Experimental data is shown with circles, solid line is a calculation based on the Kirchhoff diffraction integral. b: Plasma density along the filament probed with the flat-electrode setup. Different curves correspond to four different values of the pulse energy as specified in the inset.

The experimental results obtained by focusing with the lens are shown in Fig. 2. In Fig. 2(a), the linear on-axis intensity is plotted as a function of the longitudinal position along the beam path. The linear intensity was measured using a photodetector with a 100μm pinhole in front of the detector. To ensure a linear regime of propagation, the laser beam was strongly attenuated using the polarization-based attenuator and several neutral density filters placed in the beam path. The results of this measurement are in good agreement with the calculation based on the Kirchhoff diffraction integral.

In Fig. 2(b), we plot the results of the conductivity measurements obtained with the setup described above, in the case of focusing with the ordinary lens. The measurements were per-

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formed at four different values of pulse energy. It is evident from the data that in all four cases the longitudinal onset of filamentation occurs slightly ahead of the linear beam waist of the weakly focused beam, and the filamentation ends right after the beam starts to diverge due to diffraction.

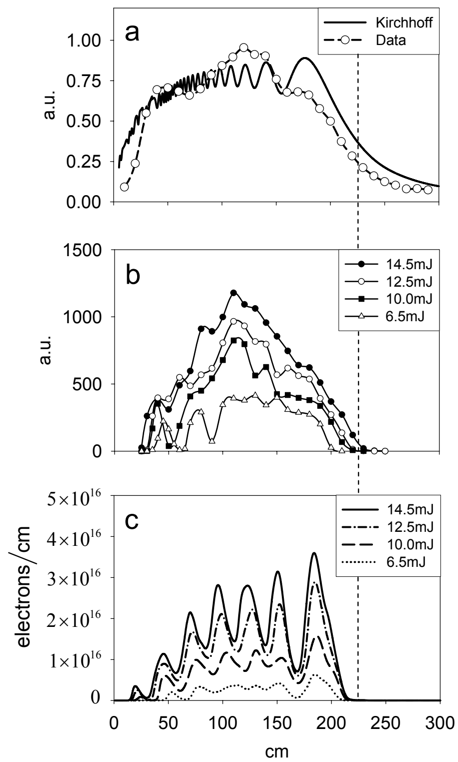

Fig. 3. Filamentation initiated by the apertured Bessel beam with pulse duration of 50 fs. a: Linear on-axis intensity fitted by calculation based on the Kirchhoff diffraction integral. b: Plasma density measured for different values of pulse energy. Units on the vertical axis are same as in Fig. 2(b). c: Results of the numerical simulations for the total charge integrated over the entire cross-section of the beam, for different input pulse energy. The linear plasma density is shown in units of the number of electrons per centimeter.

In Fig. 3 we show the results for the case of focusing with the axicon. The approximate extent of the linear focus as given by equation (1) ($z_0 = 2.25\,\mathrm{m}$) is indicated by the dashed vertical line. Fig. 3(a) is a plot of the on-axis intensity in the linear propagation regime. The experimental data is in close agreement with the calculation based on the Kirchhoff diffraction integral.

The experimental data for the plasma density measured with the flat-electrode setup is shown in Fig. 3(b), for four different values of pulse energy. Note that the scale of the vertical axis in Fig. 3(b) is the same as that in Fig. 2(b). From the data, the plasma density in this case is lower than that in the case of focusing with the lens; the created continuous filament is longer and spans the entire extent of the linear focus. A single stable filament is produced up to the highest pulse energy attainable from the laser system, contrary to the case of the lens focusing in which three filaments were observed at the highest pulse energy.

In Fig. 3(c) we show the results of numerical simulations of the experiment based on the Unidirectional Pulse Propagation Equation (UPPE) [20] and a phenomenological model of air [6, 21]. In the figure, the linear plasma density (i.e. the integral of the total number of the

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generated electrons over the entire cross-section of the beam) is plotted against the propagation distance. The simulations qualitatively support our experimental observations, although there are differences. In particular, the simulations show oscillatory behavior of the linear plasma density along the entire filamentation region. Such oscillations are present in the experimental data, but only in the beginning of the filament and at low pulse energies. The discrepancy may be attributed to the non-ideal profile of the input beam used in the experiments.

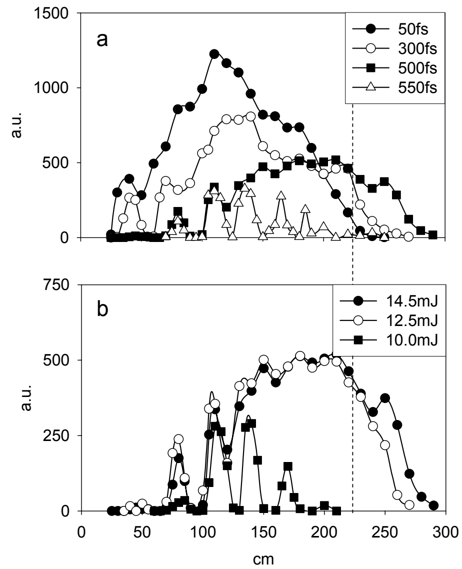

Fig. 4. a: Linear plasma density for temporally chirped femtosecond Bessel beams. Pulse energy is 14.5 mJ in all cases. Different curves correspond to different pulse widths as specified in the inset. b: Same for 500 fs–long pulse. Different curves correspond to three different values of the pulse energy as specified in the inset. Units on the vertical axes of both graphs are same as in Figs. 2(b) and 3(b).

The results described so far were obtained using the shortest pulses attainable from our system (50 fs). In what follows, we will discuss filamentation with temporally chirped Bessel beams. We found that by chirping the pulses the filamentation region can be longitudinally shifted beyond the linear-focus zone.

The experimental results with chirped femtosecond Bessel beams are summarized in Fig. 4. The dashed vertical line indicates the approximate extent of the linear focus (1). In all cases shown, the on-axis intensity in the linear propagation regime is the same as that shown in Fig. 3(a). In Fig. 4(a), we show the linear plasma density for the highest pulse energy of 14.5 mJ, but at different durations of the chirped pulse. From the data, chirping the pulse reduces the amount of generated plasma and gradually shifts the filamentation region in the propagation direction. The longitudinal extent of filamentation is at a maximum when the pulse length equals 500 fs, and the filamentation rapidly disappears for longer pulses. We experimentally confirmed that this effect is independent of the sign of the chirp. Furthermore, the extended filamentation shows a threshold-like behavior with respect to the pulse energy, as shown in Fig. 4(b).

Shifting the filamentation zone by pulse chirping is a practically important effect as it may potentially offer additional means of controlling filament formation. A similar phenomenon has been predicted in [19] for the case of Gaussian beams. In [19], the existence of the optimum pulse duration that maximized the length of the plasma channel resulted from the interplay between the multi-photon absorption that is higher for shorter pulses and avalanche ionization that kicks in once the pulse duration exceeds the electron collision time in air ($\tau_c \sim 350\,\mathrm{fs}$) [6]. In the case of a Bessel beam, additional effects may be responsible for extension and longitudinal shift of the filament. In particular, the shift may be related to the formation of a strong on-axis wave component at the pump wavelength, an effect that has been previously reported in condensed Kerr medium [22]. If the energy in this on-axis component reaches the critical threshold for self-focusing, it will initiate filamentation that may prolong the plasma channel formed by the primary Bessel beam.

4. Conclusion

We reported experimental results on filamentation of truncated femtosecond Bessel beams in air. Our experiments show that the use of Bessel beams allows for the creation of extended and stable plasma channels, thus it may be beneficial in various practical applications of filaments such as remote spectroscopy and lightning control. Additional spatial control of filamentation is possible by chirping the pulses.

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