Measurement of Spatial Distribution of Plasma Emission from Femtosecond Laser filament

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The spatial plasma distribution of femtosecond laser filament is measured by using fiber optic spectrometer (FOS). Firstly, we chose the maximum peak intensity of each spectrum to get the full spectrum of laser filament and verify this spectrum is a Gaussian distribution. Secondly, we chose the full width half maximum intensity of each Gaussian fitted spectrum to do the same work as the first step. Gaussian fitting of two methods have been analyzed and compared.

Abstract: femtosecond, laser filament, plasma spatial distribution, Gaussian fitting

I INTRODUCTION

Filamentation of femtosecond laser pulses has been the subject of interest and attracted a wide range of attention of researches both experimentally and theoretically [1]. Filamentation is the result of a dynamic competition between two main effects, the Kerr-effect and multiphoton ionization. The first one induces laser self-focusing and the second one creates the plasma. The filament has an almost constant narrow waist over propagating lengths much longer than the corresponding Rayleigh range. Filamentation of femtosecond laser beams has been found practical applications. It can be used as a terahertz radiation sources [2], triggering high-voltage discharges in megavolt switches [3], and guide microwave radiation [4]. Thus, characterizing the laser generated plasma filament in a quantitative manner is quite important for both the fundamental understanding of the nonlinear optical pulse propagation and applications [19].

For filamentation, it is always assumed that its plasma emission of is a kind of Gaussian distribution. In this paper, we measured the plasma emission at different angles to verify this assumption.

The dominant relaxation processes of the decay of the plasma are electron recombination and electron attachment to neutral oxygen molecules. The decay processes occur on a nanosecond time scale and are functions of plasma parameters such as electron density and temperature. Measuring those parameters is difficult due to fast relaxation (~1 ns), small filament diameter (~100μm) as well as the high laser intensity in the filament (~1013-1014 W/cm2). A number of approaches have been used for the characterization of the low-density laser-generated plasma filament, such as imaging of the cross-section, detection of fluorescence, measurement of resistivity, diagnostics of acoustic, and shadowgraphy [19], plasma conductivity [5], interferometry [6], holography [7],
and recently microwave diagnostics [9]. All of the abovementioned methods demand delicate alignment, filament propagation.

In this paper, we propose a method based on fiber optic spectrometer to detect the plasma spatial distribution of the femtosecond filament. The system is a single-filament regime and the expected approach is based on measuring and comparing the propagating radiation of the plasma filament. Fiber optic spectrometer is used to detect the spectrum at different angles from -15 to 15. After the experiment, we use the direct-peak method and Gaussian distribution fitting method to get the peak of spectrum at different angles.

II METHOD DESCRIPTION AND PRINCIPLE

We used a Ti-Sapphire laser with single pulse energy 1mJ and central wavelength 800 nm as the major light source. The laser path is directed and focused by a plano convex lens with focal length 5cm. The detailed experimental equipment is listed in Table. 1. FIG. 1 shows the schematic diagram of this experiment.

Tab.1 Equipment parameters and functions for measuring the plasma spatial distribution.

<table>
<thead>
<tr>
<th>Instrument and Equipment</th>
<th>Function and Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main laser</td>
<td>Ti-Sapphire Femtosecond laser with single-pulse laser energy 1mJ, central wavelength is 800nm, pulse width 70fs, and repetition frequency 1kHz.</td>
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<tr>
<td>CCD</td>
<td>Imaging femtosecond laser filament</td>
</tr>
<tr>
<td>Fiber optic spectrometer</td>
<td>Forward spectrum measurement</td>
</tr>
<tr>
<td>Flat mirror</td>
<td>Direct laser beam(M1, M2, M3, and M4)</td>
</tr>
<tr>
<td>Plano convex lens</td>
<td>Convergence laser beam(Focal length 5cm)</td>
</tr>
<tr>
<td>Universal stage</td>
<td>Adjusting the position of fiber optic spectrometer(With angle scales in the bottom).</td>
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</tbody>
</table>
The Femtosecond Laser will self-focus because refractive index of air will change with the light intensity of incident light, as equation (1) shows, when laser pulse transfer in the air\(^20\).

\[
\eta = \eta_0 + \eta_2 I
\]  

(1)

Where \(\eta\) is the refractive index of air, \(\eta_0\) is the linear refractive index, \(\eta_2\) is the coefficient of the relation of laser intensity and refractive index, and \(I\) is the laser intensity\(^{21,22}\).

The diameter of laser beam decreases due to self-focusing and then laser intensity increases. The air is ionized when laser intensity increase to \(10^{13}\text{-}10^{14}\text{W/cm}^2\), which forms a large amount of plasma\(^{23,24}\). At the same time, plasma defocuses the laser beam\(^{20}\). As a balance is reached between self-focusing and plasma defocusing, laser filament is achieved in the air.

In our experiment, laser is converged by a plano convex lens after reflected by four flat mirror. We measured 30 plasma spatial distribution with different angles ranging from 15° to 45° (30° corresponds to the central spectrum) by 1° each time. We put attenuation slices in front of fiber optic spectrometer to prevent damage from fiber optic spectrometer, which has high intensity.

III SELECTED RESULTS

We used two methods to deal with the data to get a plasma spatial distribution of the laser filament. For the first method, we chose the maximum intensity of each spectrum with wavelength ranging from 760nm to 790nm. FIG.2 shows the Gaussian fitting of the data chosen with total error 260.78, relative error 0.0478. We can see that there are two peaks, where the first peak is what we are expecting. Theoretically, the ionization of the air is mainly the first order ionization of nitrogen atoms, of which the central wavelength is 777 nm. The highest intensity should occur at central position, while both of sides decay, respectively. However, the second peak is inconsistent with the above analysis. The distribution is fairly symmetric about -0.392° around the first peak, and it is well distributed as a Gaussian shape.

FIG.1 Schematic diagram for measuring the plasma spatial distribution.

FIG.2 Gaussian fitting of the plasma spatial distribution by choosing the data of the maximum
intensity of each angle with the wavelength of the spectrum ranging from 760nm to 790nm.

For the second methods, we made Gaussian fitting of all the angles with spectrum wavelength ranging from 765-785nm. FIG.3 shows the Gaussian fitting result with total error 217.51, relative error 0.0439. While we have neglected the points of -1°, 1°, and 7°, since these points do not fit well. FIG. 4[(a), (b), and (c)] shows the Gaussian fitting of plasma distributions at -1°, 1°, and 7° respectively.

FIG.3 Gaussian fitting of the plasma spatial distribution by choosing the data of full width full maximum intensity of each angle with the wavelength of the spectrum ranging from 760nm to 790nm.

FIG. 4 Gaussian fitting of the plasma spatial distribution at angles -1°(a), 1°(b), and 7°(c) with the wavelength of the spectrum ranging from 760nm to 790nm.

In FIG. 4(c), we can only see one peak. Then we amplified the peak as shown in FIG. 5. There is also a small peaks at 777nm wavelength, which corresponds

1 Corresponding author(writing paper).
2 Processing data.
3 Background and frontier(introduction).
4 Equipment design.
to the first order ionization of nitrogen atoms.

FIG. 5 Amplified figure of the peak in FIG. 4(c).

Comparing the two methods we have used to get the Gaussian fitting of the plasma spatial distribution, the total error is 16.59% smaller in the second method (Full width full maximum intensity). The relative error is 8.16% smaller than the first method (Choose the maximum intensity).

IV DISCUSSION

In FIG. 2 and FIG. 3, we can both see two peaks. While the first peak centers at 0° considering the allowed error, which corresponds to the plasma spatial wave peak. And the plasma distribution is a Gaussian distribution according to our fitting. The second peak centers at 5° ~ 7°. In FIG. 4, the first peak centers at 700~750nm, which corresponds to the wavelength of the plasma spatial wave.

In the process of dynamic interaction of laser and plasma, the high electric field of laser will ionize the air molecules. The ionized electrons during this process give off or absorb electromagnetic wave when they jump between different energy level. If there is some physical process happening many times during this process, which will create a peak with high peak value at some specific wavelength and show in the spectrum. The proportion of peak value is equal to the proportion of physical process. In FIG. 4, the second peak value occurs at around wavelength of 770~780nm. These results due to primarily ionization peak of nitrogen-atom, while its theoretical value is 777nm.

CONCLUSION

In this experiment, we have got the plasma spatial distribution of laser filament at different angles. We have used two methods to verify the plasma spatial distribution is a Gaussian distribution and analyzed the cause of the peak formation at wavelength around 770-780nm.

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[19] Zuo-Qiang Hao, Filamentation Nonlinear Optics of Intense Femtosecond Laser Pulses in Air


