32. ON OPPORTUNITY OF BESSEL BEAM BREAKDOWN APPLICATION TO AIRCRAFTS DRAG REDUCTION

S.S. Bychkov, L.Ya. Margolin, L.N. Pyatnitsky
Institute for High Temperatures of Russian Academy of Sciences, 13/19 Izhorskaya Str., 127412 Moscow, Russia

Abstract. Gas breakdown by laser Bessel beam of almost constant longitudinal field distribution and radial one corresponding to Bessel function, results in long continuous plasma channel. The discharge peculiarities are high conductivity (10V voltage may be commutated in atmospheric air up to 1m distance) and unique geometry (in laboratory 1m length and 100 microns diameter) of the channel. Owing to the attributes the Bessel beam breakdown is promising in fundamental research and applications. In particular, the spark channel looks like being able for energy transportation with a goal of flight drag reduction by gas heating in front of aircraft.

The report deals with Institute for High Temperatures research results on plasma channels formation by gas breakdown in laser Bessel beams. Characteristics of optical elements providing for required laser beams transformation are under consideration. Calculations and experiments data on determination of the spark creation conditions and the plasma channel properties are presented.

Introduction

A concept of aircraft drag reduction by utilizing focused energy deposition into the flow looks like very promising for application. For example, blunt body case simulation [1] leads to the drag reduction up to 50% and more. The most convenient way for the energy carriage is laser spark utilizing. Experiments on energy deposition by spherical lens focused laser radiation [2], also have shown about 50% drag reduction. But relatively low laser efficiency should result in high rate (in energy spending and weight being in flight) for each Joule of deposited energy. To diminish the rate we propose two stages for energy deposition: during the first stage extended high conductive channels will be formatted by means of laser breakdown; at the second stage main amount of low rate energy (High Frequency Radiation or Direct Current Source) will be delivered by the channels.

The problem of distant generation of high conductive channels is considered in the report. It based on results obtained in Bessel beam breakdown investigations carried out in Institute for High Temperatures of RAS since 1983.

The research directions were as follows:
1. Technique development for Gaussian laser beams transformation to Bessel beams of fiber or tubular configurations.
2. Laboratory experiments and numerical simulations on exploration of plasma channel properties arose under optical breakdown of gases by powerful Bessel beams.
3. Creation of basis for practical applications of the channels.

Bessel Beams Formation

Bessel beams are formed by focusing Gaussian laser beams to produce beams with a conical front. A conical lens – axicon may be used for the goal. In the case radial field distribution is described by zero order Bessel function, and fiber Bessel beam (zero order Bessel beam) is generated [3]. In case the axicon is added by special component known as phase screw the radial field distribution described by high order Bessel function, and Bessel beam with tubular configuration (high order Bessel beam) is generated [4]. The phase screw represents a transparent plate whose optical thickness varies: variation, in a plane perpendicular to the axis, of the azimuthal angle from 0 to 2\(\pi\) proportionally increases the optical thickness simultaneously for all values of the radius and at the azimuthal angle 2\(\pi\) there is a jump by integer number of laser wavelengths.

Axicons were produced by abrasive treatment to have conical surfaces with accuracy better then quarter of laser wavelength. The elements for high order Bessel beams formation were fabricated by photolithography etching. The produced kinoform formers possessed of eight level surface microrelief and efficiency about 50%.

The illustration is given in Fig.1. Fig.1a presents optical scheme and cross-section intensity distribution for a case of Gaussian beam formation by laser radiation focusing with a spherical lens; Figs 1b and 1c present those for cases of zero order Bessel beam formation by axicon and high order Bessel beam formation by phase screw and axicon combination, respectively. In Bessel beam cases longitudinal intensity distribution was practically constant along the whole region of the beam propagation.

Powerful single-mode multi cascade Nd-glass laser with several nanoseconds pulse duration and 10-20 J pulse energy was used as a source of heating radiation.
Plasma Channels Properties

Commutative ability

There is side delivering of heating radiation to each point of Bessel beam focal region. This is a reason for creation of continuous plasma channel. The channel conductivity looks like that of copper. The experiments in atmospheric air proved the channel ability to commutate such a low voltage as 10V at 1m distance [5].
Illustrations of the channel creation and its commutation ability are given in Figs. 2 and 3 respectively. Powerful Bessel beam was formed by axicon (2° base angle) focusing of 1μm radiation of 10GW Nd-glass laser (20 J energy, 2ns pulse duration, 5cm beam diameter). Fig.2 presents photo of 1m long laser spark in pure atmospheric pressure air without any preparation [6]. Photo was taken by open shutter camera. The channel body looks like continuous along the whole spark extending. Fig.3 presents the channel commutation ability (triangle marked 3 on the picture) in comparison with that of high voltage discharge (solid curve marked 1) and Gaussian laser spark (circle marked 2) [7]. The conductivity of Bessel beam breakdown looks like three order better then that of other discharges.

**Fig.3**

*Dynamics of the plasma channel parameters in radial direction*

The plasma formed by the breakdown of noble gases and air at atmospheric pressure was studied experimentally and modeled numerically [8]. Frame and streak-cameras, CCD-cameras, grating spectrometers for visual, IR and UV regions were used as diagnostic tool in experiments. Numerical modeling was performed with 1D code SPARK combining a hydrodynamic description and a calculation of the kinetics of the ionization of a gas in the field of zero or fifth orders Bessel beams.

Fig.4 illustrates calculation results for argon, fifth order Bessel beam, 3° inclination of heating rays to the axis and heating energy exceeding the threshold value by 10%. The temporal profile of laser pulse and the plasma parameters evolution in a transverse section of the channel are presented in Fig. 4a and Figs.4b-4f accordingly. After 5ns from the start of a laser pulse a plasma with an annular configuration and electron temperature and concentration 5.5eV and 3×10^19cm^-3, respectively, is formed near the main field maximum having 80μm diameter. Towards the end of the pulse (6ns), the electron temperature and concentration increase to 15eV and 10^20cm^-3, respectively. During this period, the heavy component is heated and two fronts of a shock wave with velocities of 10^6 cm s^-1 are formed; they correspond to compression towards the axis and expansion outside. After ~8ns , the inner shock wave collapses, forming an axial plasma filament with the electron parameters of ~6eV and ~4×10^20cm^-3 and a density exceeding almost by two orders of magnitude the initial gas density.

**Fig.4**

Experimental results confirm those of calculation.

**Longitudinal structure of the plasma channel**

In most cases of the spark realization the plasma channel has a quasi-periodic longitudinal structure which may limit its potential applications. This circumstance provided the stimulus for investigating the mechanisms of the appearance of such a structure and for the development of suitable models. Moreover, the structure looks like a result
of very interesting physics: namely, interaction of oblique heating radiation with plasma. And this is an additional argument for the structure exploration.

Examples of the streak and framing photographs of the corresponding sections of the plasma channel are presented in Fig.5, which also includes a characteristic oscillogram of a heating pulse [9]. The photographs in Fig.5a were obtained in scattered light and those in Fig.5b in the plasma's own radiation. The three highest streak photographs were also taken in scattered light and the lowest was obtained in the plasma's own radiation. The two highest streak photographs illustrate the influence of aerosols on the structure when the aerosol is near the axis of the caustic (the highest streak photograph) and outside the caustic (the second from the top). Under the experimental conditions, the scans in the presence of aerosols were recorded an order of magnitude less frequently than the clean scans. The difference in the dynamics between the foci constituting the periodic structures and of those induced by the aerosols can be readily seen and the independence of the quasi-periodic structures of the type of aerosol is also evident.

Fig.5

One of the most important results of our investigation is the observation of the homogeneous component of the scattered radiation throughout the laser pulse. This shows that the plasma forms initially and it exists throughout the pulse within the volume of the caustic. The brighter regions (foci) develop against the background of the relatively homogeneous plasma.

A model was developed to describe generation of periodic structures in the plasma channel of an extended laser spark [10]. This model is based on inhomogeneous refraction of the heating radiation when the electron concentration exceeds the critical value for a given inclination angle.

Possible Applications of the Plasma Channels

Plasma channels created by gas breakdown in Bessel beam are promising to apply for a number of practical problems.

1. Wave guiding of intense laser pulses [11,12]. The application deals with laser-driven plasma accelerators problem. Waveguiding operation is based on getting of channel configuration with decreasing radial profile of refractive index with maximum value on the channel axis. Investigations on the application are carrying out in Maryland University (USA), Institute for High Temperatures of RAS (participated within the frame of joint Project of American Civilian Research and Development Foundation ).

2. Short wavelength generation [13,14]. The long narrow optical discharge in gases (up to one meter long and a few tens of microns in diameter) created by laser B-beams produces an aligned column of hot dense plasma considered as a promising X-ray lasing medium. Moreover, this new-type plasma object is characterized by a possibility to vary its geometrical configurations (tubular or fiber shape of radial profile) and target conditions (pressure and kind of gases), allowing various pumping schemes to be realized and thus to achieve high efficiency.

3. High current, high speed switching [5,15]. The application is based on unique conductivity of the plasma channel. Low time required to form the channel leads to high speed of commutation (delay time about 1ns). The experiments on the problem were carried out in IHT RAS and in Princeton University (USA), as well. On the base of experimental results high speed switchers were fabricated in IHT RAS.

4. Drag reduction in flight. Distant making of conductive channels gives a possibility of energy deposition in front of an aircraft. So, the
two stage scheme mentioned above (see Introduction) looks like to be easy for solving. At the same time the necessary equipment possesses a feature being complicated for realizing within frames of the applications, namely tremendous sizes and weight of the laser, using as a source of heating radiation. To prove a possibility of the application development we investigated usage of lasers units with lower requirements to the heating radiation, then was used in main part of experiments. Accordingly, sizes and weight of the units were rather suitable for the application. Table-top Nd-glass laser with telescopic final amplifier and ring configuration of the output beam and multi-mode ruby laser were used in additional experiments. Characteristics of the plasma channel arose (length and continuous character) were practically identical as those for single-mode multi cascade Nd-glass laser usage.

The work is partially supported by Russian Foundation for Basic Researchers (Project 99-02-16007) and Federal Program “Integration” (Project A1101).

References