Investigation of THz radiation generation in a laser spark of axicon discharge

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***Abstract*—Results of experimental investigations and theoretical modeling of THz pulse generation in a laser spark of axicon discharge are presented. Experimental results demonstrate define evidence of Cherenkov cone in radiation pattern of THz radiation, what is in favor of the idea that radiation is generated in the region of ionization front, moving with superlight velocity. Polarization features in generated radiation and weak reaction to the applied external dc electric field give rise to the idea that THz radiation is generated due to internal low frequency electric field excited in the process of laser discharge. The main discrepancy between theoretical expectations and experimental results is a rather low frequency of generated THz radiation which means low ionization rate of ambient air in the generation region and is a matter of theoretical simulations.**

I. INTRODUCTION AND BACKGROUND

At present intensive investigations of new ways of THz radiation generation and detection draw attention to gaseous (and plasma) media irradiated by femtosecond laser pulses [1-5]. Generation in a specific plasma of axicon discharge, proposed in [6] and further developed in [7] may possess high efficiency only under extreme conditions, but under conventional conditions there is a lot of interesting fundamental physics, concerning the dynamics of optical discharge and related to it intrinsic low-frequency electric field.

In our communication we present experimental results on THz radiation generation in the plasma of axicon optical discharge, obtained at the specialized laser facility «Spitfire», operating at the Institute of Applied Physics (RAS). The system is capable to deliver 3 mJ pulses at the wavelength 795 nm with pulse duration about 50 fs and the repetition rate about 1 kHz; laser beam aperture being about 1 cm. Linearly polarized laser pulses were focused by an axicon lens with the convergence angle 15 deg. According to ideas developed in [6], it is also possible to apply a dc electric field for outer excitation of plasma oscillations which may serve as additional source of THz radiation.

For investigation parameters of generated THz pulses two independent diagnostics techniques are used. One is based on the classical sampling technique using ZnTe EO crystal in which THz radiation is focused by external mirrors to EO crystal together with probe laser pulses produce in principle both the waveform and the spectrum of THz pulses. In order to get minimal THz spot in front of the mirror system there was a teflon axicon lens which forms cylindrical wave structure before the mirror system. Other diagnostics has been designed for investigation the radiation pattern and polarization properties of THz radiation; it is based on the use of small diaphragm (hole in absorbing screen) scanning in the plane transverse to the discharge axis and InSb bolometer measuring the power penetrating through the diaphragm.

II. EXPXPERIMENTAL RESULTS

After exceeding some threshold value of laser pulse energy in the focus of axicon lens filament discharge of about 15 mm in length is generated. Even without external electric field the generation of THz radiation is observed. The dependence of generated THz power on the averaged power of femtosecond radiation is presented in Fig.1. It is obtained with InSb bolometer capturing all the focused THz radiation.

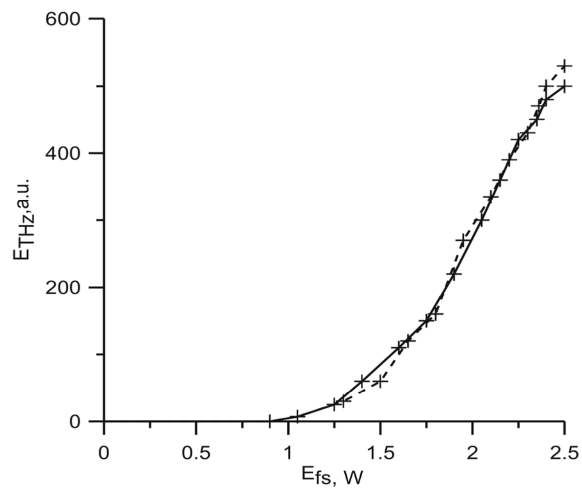

Fig.1

The generation threshold is apparently related to the ionization threshold. The increase in the optical pulse duration without change of the pulse energy results in the decrease of conversion efficiency from optical pulse to terahertz one. It should be mentioned also that the change from linear polarization to the circular one results in the shift of threshold value to essentially higher optical power.

Typical waveform and amplitude spectrum of THz pulses obtained with replacing of bolometer by ZnTe detector are presented in Figs. 2 and 3. It is clearly seen that the wave form consists mainly of one THz field period which is about 1 ps, independent of the intensity of optical radiation. Water absorption lines are definitely observed in the spectra. If try to relate the observed frequency of THz radiation to plasma frequency in axicon discharge, the ionization rate in the emitting region of the discharge should be estimated as 10^{-3}.

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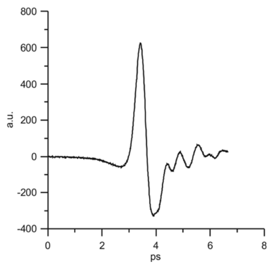

Fig.2

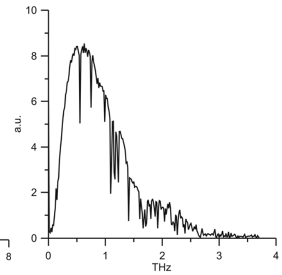

Fig.3

Applying of the external dc electric field up to 15 kV/cm results in not very much essential increase (1.5 – 2 times) in THz generation efficiency. This means that intrinsic electric fields in plasma may be significantly higher.

Figs. 4 and 5 demonstrate distribution of THz field intensity and polarization in the plane transverse to the axis of the discharge.

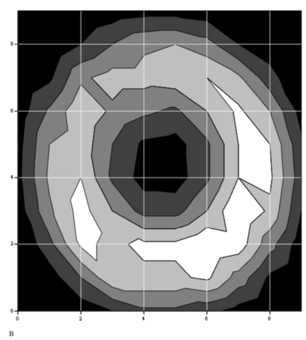

Fig.4.

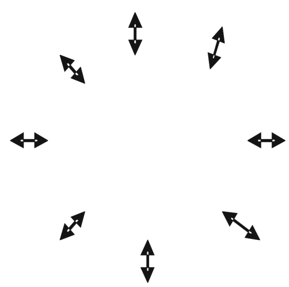

Fig.5.

Maximum of THz field intensity is concentrated in the vicinity of Cherenkov cone, while its polarization is linear and radially directed in the intensity maximum. Such kind of polarization distribution may result from both longitudinal (with respect to discharge axis) radiating current and from axially symmetric distribution of radial currents. The measured polarization distribution implies great uncertainty into results of EO diagnostics because in the case of absolute axial symmetry the response from the detector should be zero. This means that both wave forms and spectra are registered only due to some misalignment of the whole system, and the absolute values of registered field cannot be used for estimations of generation efficiency.

III. THEORETICAL MODELLING

There are three main stages in theoretical modeling. The first one includes investigation of self-consistent evolution of plasma radiation in non-stationary plasma with the density rapidly varying due to tunnel ionization. For the description of wave field dynamics we use Shroedinger equation for the field complex amplitude:

$$2ik_o \frac{\partial E}{\partial z} + \Delta_\perp E - k_0^2 \frac{n_i}{n_{cr}} E = 0,$$

while the plasma density is governed by the equation:

$$\frac{\partial n_i}{\partial t} = 4 n_0 \omega_H \exp\left(-\frac{2E_H}{3|E|} \right)$$

where n_i is current plasma density, n_c is the critical plasma density for laser frequency, n_0 is the neutral density, ω_H and E_H are characteristic atomic frequency and atomic electric field correspondingly. It is assumed that the wave packet is propagating in z-direction. Numerical simulation demonstrates that the refraction of laser radiation tends to essential decrease of maximum plasma density in the discharge.

The second stage is the investigation of excitation of low-frequency oscillations of plasma column. To describe this process we use the set of hydro-dynamical equations for electrons in high-frequency field:

$$\frac{\partial \rho}{\partial t} + div\boldsymbol{j} = 0, \quad \frac{\partial \boldsymbol{j}}{\partial t} + \frac{e^2}{m} n_i (\nabla\Phi + \nabla\varphi) = 0, \quad \Delta\varphi = -4\pi\rho$$

where ion distribution (n_i) is considered to be fixed, ρ and $\boldsymbol{j}$ are electron charge and current density correspondingly, and $\Phi = \dfrac{e^2 |E|^2}{4m\omega^2}$ is the pondero-motive potential describing averaged action of laser radiation to the plasma.

The final stage is the calculation of THz radiation following from this current. In the case of axi-symmetric pondero-motive potential radial plasma oscillations are excited at the frequency, corresponding to plasma density at the discharge axis. This results in THz wave generation with Cherenkov cone radiation pattern and radial distribution of polarization fully in accordance with the experimental results obtained. Another possibility is related to the excitation of transverse dipole oscillations of plasma column, which may be excited for example due to applying the external dc electric field or as a result of instability of rectilinear propagation of the mass-center of laser pulse under conditions of self-focusing. The radiation should be linearly polarized in a fixed direction and the radiation pattern should have the same Cherenkov cone structure. At present polarization for this case is under current investigation.

IV. ACKNOWLEDGEMENT

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