Conference Paper

# Terahertz Radiation of a Low-inductance Discharge in Vacuum with Laser-plasma Initiation

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## Abstract

The results of the study of terahertz radiation, which is generated by the plasma of a low-inductance discharge with micropinchs, are presented in this paper. The discharge was initiated by focused radiation from a pulsed Nd:YAG laser (pulse duration is 10 ns, pulse energy is 0.8 J). The energy that was stored in the capacitor of the discharge system was ~ 40 J. The principal role of micropinch for the generation of THz radiation was proposed. The oscillogram of the diode current was obtained to visualize the presence of micropinch plasma. The power of the THz source was calculated and an experimental study of the spectrum of this source was carried out.

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## 1. Introduction

The tasks of detecting and identifying explosives, explosive devices which are based on them and also search for other items that can be used as weapons are very important in modern conditions. THz radiation can be used to search for explosives and implementation inspection activities at airports, post offices, etc. [1-2]. At the same time, there is an obvious interest in creating powerful, fairly compact, and relatively inexpensive THz radiation generators. The frequencies of THz radiation vary in the interval $10^{11}$ - $10^{13}$ Hz, the wavelength range 1 - 0.03 mm, respectively.

It is assumed that more intense generation of THz radiation than in the case of thermal radiation can occur during micropinching of a vacuum discharge. There are several mechanisms for generating THz radiation from micropinch plasma that differ in the nature of their origin: thermal radiation, *bremsstrahlung*, and radiation that is emitted due to instabilities (oscillations) that are generated in the periodic micropinch structure by electron beams. Due to the fact that the hot micropinch plasma is a source of intense soft and hard X-ray radiation, it is necessary to exclude the X-ray radiation by a system of filters that simultaneously pass THz radiation well.

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## 2. Description of the installation

An installation was designed to carry out experiments to obtain THz radiation from a laser triggered vacuum spark with micropinchs. The installation is a vacuum high-current diode. The installation scheme is shown in Figure 1.

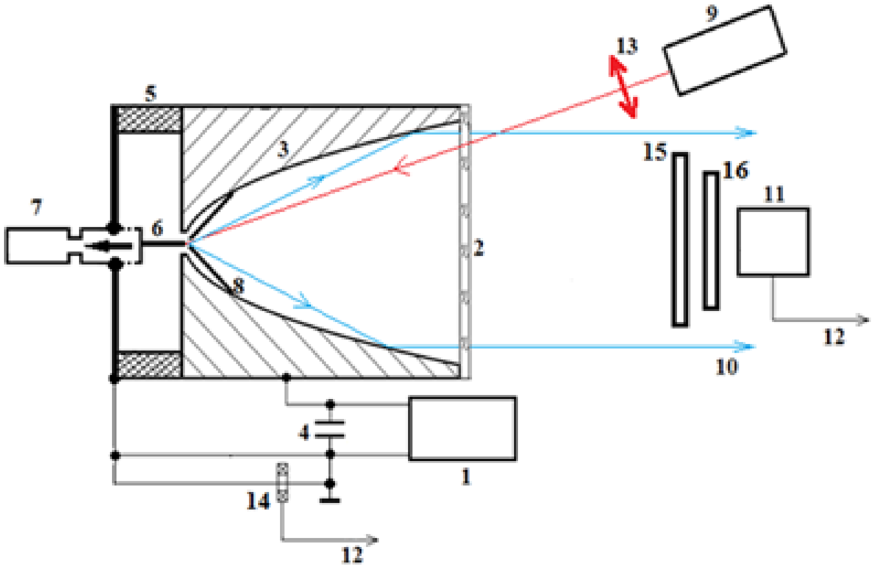


**Figure** 1: Experimental installation: 1 - source of high voltage; 2 - fused quartz window; 3 - parabolic chamber; 4 – low-inductance capacitor; 5 - insulator; 6 - cathode with a pumping channel; 7 - pumping system; 8 - molybdenum electrodes; 9 - laser; 10 - THz radiation; 11 - pyroelectric detector; 12 - cable to the oscilloscope, 13 - optical lens, 14 - Rogowski coil, 15 - THz band-pass filter, 16 - fluoroplastic filter.

However, unlike in [3], the anode was made in this installation in the form of a flange with an internal parabolic surface placed on it. The focus of the parabolic surface is located in the place of formation of spark. Three molybdenum electrodes were fixed on the walls of the inner surface. They are directed toward the cathode, the gap between the cathode and the electrodes is $\sim$ 4 mm. The idea of manufacturing an anode of this form is to ensure a more quality collection of THz radiation from micropinch plasma.

Vacuum pumping was carried out inside the chamber space to a pressure of $\sim 10^{-4}$ Torr. The focusing laser initiation system was tuned to focus the radiation of a pulsed Nd:YAG laser in the middle of the cathode surface. The capacitor chain has Rogowski coil for measuring of the discharge current.

Parameters of the Nd:YAG laser: wavelength is 1.06 μm, pulse duration is 10 ns, pulse energy is 0.8 J and power density at the target is $10^{11}$ W/cm$^2$.

# 3. Experimental results

The following experiments were conducted to determine the characteristics of the diode discharge current and the spectrum of THz radiation.

Plasma was created between the cathode and the anode with the help of focused radiation from a pulsed laser. High voltage ($\sim$ 11 kV) was supplied to a low-inductance capacitor with value of 0.6 μF and an inductance of about 8 nH. The choice of the low-inductance capacitor is due to the desire to create conditions for faster pinching of plasma with a rise time of $\sim$ 150 ns. In this case, higher plasma temperatures can be achieved, which can provide a proportionately higher power of generated THz radiation due to the thermal channel. The energy stored in the capacitor is $\sim$ 40 J. The current of the vacuum diode was registered with the help of Rogowski coil. The oscillogram of the current is shown in Fig. 2.

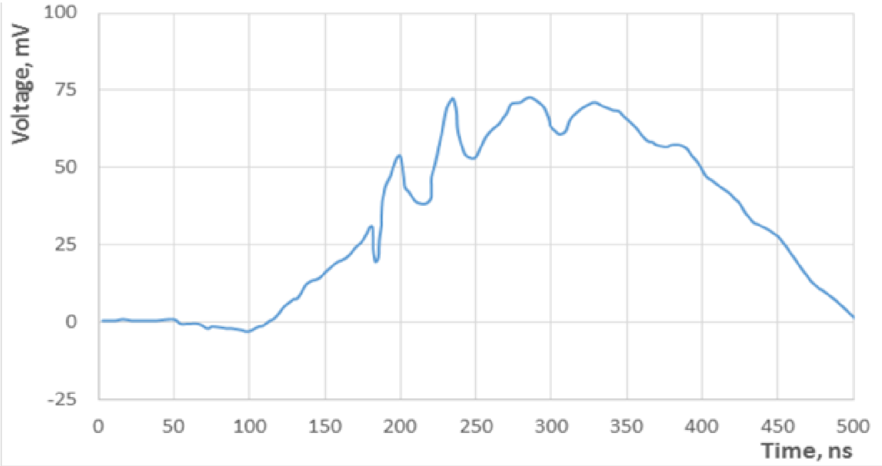


**Figure** 2: Oscillogram of the current of the vacuum diode.

The areas of the current recession are visible on the oscillogram (at times 220 ns and 250 ns). This indicates that there are micropinches in the discharge and the plasma is compressed in these places. Similar recessions were observed in [4]. The anomalous resistance of the plasma, which can become turbulent due to the presence of electrostatic instabilities, is considered as a possible cause of their appearance [5]. The discharge plasma at pinching is a powerful source of hard X-ray radiation. It is necessary to create a filtration system so that X-rays radiation are absorbed as much as possible, and THz radiation enters the detector only with a slight attenuation. Window of crystalline quartz was set in the chamber. This window strongly absorbs X-ray quanta and well passes THz radiation. Fluoroplastic plates of different thickness were used as attenuators of X-ray radiation. Plates slightly absorb THz radiation, but also strongly absorb X-ray.

Experimental measurements of the THz radiation characteristics were carried out at the next stage of the work. To do this, a pyroelectric detector with set of various filters were installed opposite the camera's window. In the course of the experiments oscillograms of the signals from the pyroelectric detector were obtained. Amplitudes of voltage signals from the oscilloscope were converted into power. The conversion factor of the detector is $k = 5{\cdot}10^4$ V/W. The obtained values of the THz radiation power are presented in the form of a diagram (Figure 3), in which the color of the column corresponds to the frequency of the THz Band Pass filter, and the column type is the thickness of the fluoroplastic filter.

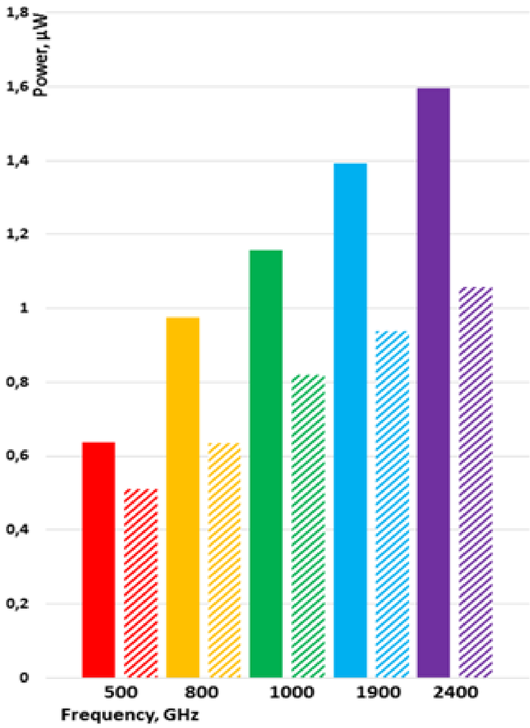


**Figure** 3: The diagram of pulse power for different bandwidths of THz filters with fluoroplastic filters of two thicknesses: solid type – 5 mm, striped type – 10 mm.

The measurements of the spectrum in Fig. 3 were conducted with THz Band Pass filters at 500, 800, 1000, 1900 and 2400 GHz with a bandwidth of 60-280 GHz at half-height. Two measurements were made for each filter: with a fluoroplastic plate 5 mm thick and 10 mm thick. Thus, ten measurements were carried out. As mentioned above the most difficult task was to cut off hard X-rays.

A comparative calculation of the energies was carried out for several mechanisms of generating X-ray radiation to determine the maximum energy of the radiation quantum, which can be obtained from micropinch plasma.

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The quantum energy obtained in the case of a resonant transition of hydrogen-like iron ions with wavelength

$$\lambda \approx 1.85 \text{ or } h\nu \approx 6.7 keV [6]. \quad (1)$$

In the case when the quantum is due to synchrotron radiation during electron transitions between Landau levels in a strong azimuthal magnetic field of the current in the state of maximum compression and heating of the plasma [7]:

$$\begin{aligned} h\omega = mc^2 (\alpha\beta)^{\frac{1}{2}} \gamma^2 \left(\frac{T_e}{mc^2}\right)^{\frac{3}{4}} \left(\frac{eI}{mc^3}\right)^{\frac{1}{2}} \approx 3.6\ keV,\ \alpha = \frac{1}{137}; \\ \beta = \frac{\upsilon}{c},\ \upsilon\ \sim\ 0.3c;\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ T_e \sim 20\ keV,\ e = 4.8 \bullet\ 10^{-10} esu \end{aligned} \quad (2)$$

The maximum energy of a quantum that occurs as a result of electron deceleration against the anode wall can be obtained from the maximum accelerating voltage of 11 kV. Consequently,

$$h\nu \approx 11 keV. \quad (3)$$

It can be seen from the estimates (1)-(3) that the largest energy of X-ray radiation that can be obtained in the setup is hv ≈ 11 keV. On the basis of these data, the transmission coefficient of X-ray radiation with an energy of 11 keV was calculated in the case of a quartz window 5 mm thick (transmittance ~ $3 \cdot 10^{-7}$) and fluoroplastic plates with thicknesses of 5 and 10 mm.

Figures 4 a), b) show the transmittance of X-ray radiation for fluoroplastic plates with thicknesses of 5 mm and 10 mm.

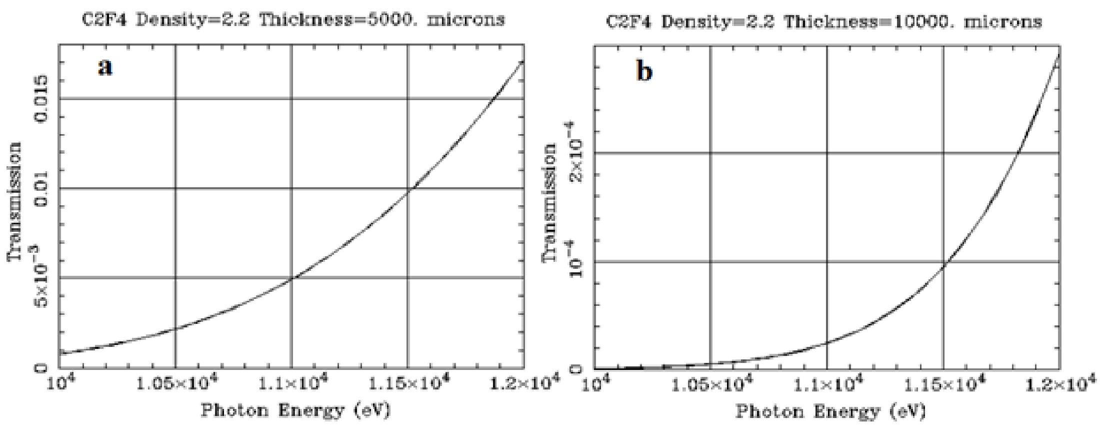


**Figure** 4: Transmission coefficient of X-ray radiation with a quantum energy of 11 keV for fluoroplastic plates: a)5 mm thick, b)10 mm thick.

It can be seen from the graphs (Fig. 4 a), b)) that the transmission coefficient of X-ray radiation with a quantum energy of 11 keV for a 5 mm fluoroplastic plate is ~

$5 \cdot 10^{-3}$, and for a 10 mm plate the transmission is $\sim 2 \cdot 10^{-5}$. The difference is 250 times. However, the diagram (Figure 3) shows that the difference in the amplitudes of the signals is 15 - 35%. This indicates that the received signal from the detector is not caused by X-ray radiation. We can draw a conclusion from the obtained dependence of the signal power on the transmission frequency of the THz Band Pass filter (Fig. 3), that it is recorded terahertz radiation in the experiment. Based on the results of the diagram of the power spectral distribution (Fig. 3), a calculation was made to estimate the total pulse power. The total absorption coefficient of THz radiation for the filtering system was determined, which amounted to $k_1$ = 0.85. The ratio of the apertures of the output window and the receiving device was $k_2$ = 220. Thus, the total value of the radiation pulse power in the frequency range 0.5 - 2.4 THz in the developed THz source was $P \approx 40$ mW.

## 4. Conclusions

It is possible to assume several mechanisms of THz radiation generation from a laser triggered vacuum spark (from micropinch plasma) that differ in the nature of their origin: thermal radiation, electron deceleration in the ion field, and radiation emitted through instabilities (oscillations) that are generated in the periodic micropinch structure by electron beams. If radiation is predominantly thermal, then the spectral power density in the *blackbody* approximation is described by the Rayleigh-Jeans formula:

$$u = kT\frac{\omega^3}{4\pi^2 c^2}$$

However, based on the experimental data (Figure 3), the dependence is close to linear. Thus, it can be concluded that the nature of THz radiation of micropinch plasma is predominantly not thermal. As you can see additional studies are needed to determine its nature.

The pulse power of the developed THz source in the range 0.5 - 2.4 THz was $P \approx 40$ mW.

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