Comparison of ions mass-spectra and terahertz radiation from low-inductive vacuum sparks with laser initiation

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Abstract. The relationship between the parameters of the ion component of vacuum spark plasma with a laser initiation and the power of the studied plasma terahertz radiation was experimentally investigated. For this purpose, ion fluence was studied using a time-of-flight mass spectrometer with a magnetic analyzer. Analysis of the ion mass spectra suggested a non-linear power-law dependence of the terahertz radiation power on the electron concentration in the spark plasma. The experimental results are compared with the results of studying the generation of terahertz radiation in beam-plasma experiments.

1. Introduction
Vacuum spark with laser initiation can serve as one of the possible sources of broadband Terahertz radiation (THz-waves). It is possible to offer several mechanisms of generation of THz-waves by plasma of the vacuum spark differing in the nature of emergence: thermal (Planck) radiation, electron radiation in the magnetic field of the high-current discharge (cyclotron mechanism) and radiation due to rapidly developing instabilities arising in the structure of the micropinch.

The approximate THz-waves spectrum generated by a vacuum spark in the frequency range $f=400–2400$ Hz is shown in [1]. As follows from this experiment, the power of THz-waves approximately depend on frequency as a linear function Thus, the nature of THz-waves in a vacuum spark is mainly not thermal, since the spectral power density in the black body approximation, according to the Rayleigh-Jeans law, is proportional to the square of the radiation frequency.

Another mechanism of THz-waves generation is studied in experiments on beam-plasma interaction, in which a high-energy (about 1 MeV) electron beam is injected into the plasma, leading to heating and strong plasma turbulence [2–5]. In this case for a dense plasma a beam-excited turbulence can be considered as an efficient source of electromagnetic radiation at the fundamental plasma frequency $\omega_p$ and its second harmonic.

For the electron density range of the plasma $n_e=(0.2–5)\times10^{15}$ cm$^{-3}$, considered in [2, 3], the terahertz frequency range falls second harmonic radiation corresponding to the upper boundary of $n_e$. In this case, the radiation power increases as $P_T\sim n_e^{3/2}$ with an increase in the plasma density at a fixed turbulence energy. For high-power beams injected into plasma with $n_e=3\times10^{15}$ cm$^{-3}$, $P_T\approx 1$ MW cm$^{-3}$ is predicted. Such terahertz radiation can be very attractive for various applications, since it is possible to change the frequency of radiation by changing the plasma density.

In this paper, we studied the mass spectra of ions emitted from the plasma of a vacuum spark with laser initiation. According to the intensity of the ion current peaks and the ion charge distribution, the
calculation in relative units of the number of \( N_e \) electrons involved in ionization acts was performed. Comparison of the value of \( N_e \) with the level of measured terahertz radiation of \( R_T \) generated by the vacuum spark discharge plasma made it possible to establish the type of dependence of \( R_T = f(N_e) \). Assuming that the value of \( N_e \) is proportional to the electron density \( n_e \), a functional relationship between \( R_T \) and \( n_e \) can be found.

2. The experimental setup

The experimental setup consists of two functional systems: a vacuum discharge system with laser plasma initiation and a time-of-flight mass spectrometer with a magnetic analyzer. The scheme of experimental setup is shown in figure 1.

2.1. Vacuum-discharge system with laser initiation of plasma

A vacuum spark discharge with laser initiation and energy \( E_D \approx 17 \) J, initially stored in a capacitive storage with operating voltage \( U_{dK} = 12.5 \) kV, was used to generate the plasma. The laser pulse with variable energy \( E_L = 8\text{–}110 \) mJ at duration \( \tau \leq 20 \) ns was focused on the anode of the discharge system, which is in a vacuum chamber with a residual pressure of \( 10^{-2} \) Pa.

Vacuum spark plasma is a source of intense ion flows of different charge, electrons and electromagnetic radiation, covering the range from X-ray emission to THz-waves. Evaluation of its electron temperature \( T_e \approx 1 \) keV and density \( n_e \leq 10^{17} \) cm\(^{-3} \) was obtained using X-ray absorption filters and laser interferometry.

THz-waves come out of the vacuum chamber through a window of Mylar film (50 microns) and are detected by a pyroelectric detector based on lithium tantalate (LiTaO\(_3\)) with a sensitivity of \( 5\times10^4 \) V·W\(^{-1}\). THz-detector is placed near the plasma above the discharge electrodes, as shown in figure 1. To protect both against infrared radiation and bremsstrahlung used teflon filter with a thickness of 3 mm.

2.2. A time-of-flight mass spectrometer

A time-of-flight mass spectrometer with a magnetic analyzer was used to study the emission of ions from the vacuum spark discharge plasma (see figure 1). First, ion flows pass through the time-of-flight tube of the mass spectrometer, which has a sufficiently long length of \( \sim 3.5 \) m. This allows us to study
the mass and charge spectrum of ions in a large energy range [6]. After selection in the magnetic analyzer, a secondary electronic multiplier detects the ion beam. Then the pulse signal was amplified and transmitted to the computer on the analog-to-digital converter having a time resolution of 25 ns. The table 1 below shows some characteristics of the mass spectrometer.

Table 1. Some characteristics of the mass spectrometer.

| Analyze mass of the ions (amu) | Mass spectrometer resolution (m/Δm) | Ion energy (keV) | Adjustable magnetic field (mT) |
|--------------------------------|------------------------------------|-----------------|--------------------------------|
| 1–300                          | 300                                | 1–250           | 0–100                          |

3. Experimental results and analysis

During the experiment, the mass spectra of plasma ions of a vacuum spark were simultaneously recorded and the intensity of the terahertz signal was measured. Several series of measurements of the ion mass spectra were done for two values of the currents of the magnetic analyzer for anodic initiation of a vacuum discharge: \( I = 71.2 \) mA and \( I = 139.1 \) mA. The choice of the magnitude of the current of the magnetic analyzer makes it possible to detect more energetic ions for a strong current and less energetic ions for a weak current.

The mass spectra obtained under identical conditions were conditionally divided into 2 groups (for each current of the magnetic analyzer) according to the magnitude of the TR intensity: 1 – the magnitude of the terahertz signal \( P_{T1} \approx 500 \) mV; 2 – the magnitude of the terahertz signal \( P_{T2} \approx 50 \) mV (this corresponds to the noise level). Figure 2 shows the averaged mass spectra of anode discharge plasma for the current of a magnetic analyzer \( I = 71.2 \) mA.

![Figure 2](image)

Figure 2. Averaged mass spectra of anode discharge plasma ions for different values of TR power. The current of the magnetic analyzer is 71.2 mA.

A plasma with a higher ion concentration, i.e. with a higher electron concentration, corresponds to a more powerful TR signal it is clear from figure 2. The situation is similar with the mass spectra of ions at 139.2 mA current of a magnetic mass analyzer.

Figure 3 shows the results of processing several series of measurements of mass spectra for two magnitudes of the current of a magnetic analyzer: \( I = 71.2 \) mA (a) and \( I = 139.2 \) mA (b). Mass spectra were selected by the amplitude of the TR and then averaging was performed. In figures 3ab the distribution curve 1 corresponds to the intensity of the TR \( P_{T1} = 500 \) mV and the curve 2 corresponds
to the intensity $P_T = 50$ mV. The type of these distributions is obviously determined by the energy and geometry of the discharge system, the state of the electrode surface, the dynamics of development, and the temperature of the discharge plasma.

Figure 3. Charge distributions of discharge plasma ions for cases with TR generation (curve 1) and without TR generation (curve 2). The results of the processing of mass spectra for two magnitudes of the current magnetic analyzer: $I = 71.2$ mA (a) and $I = 139.2$ mA (b).

Approximately the number of electrons was calculated in per-units by the equation (1) for the distributions shown in figure 3

$$N_e = \sum N_i Q$$

where $Q$ – ion charge, $N_i$ – number of ions with charge $Q$. The calculation results were recorded in the table 2.

| Mass spectrum registration conditions | Number of electrons $N_e$ (pu) (with TR generation) | Number of electrons $N_e^T$ (pu) (without TR generation) |
|--------------------------------------|-----------------------------------------------|-------------------------------------------------|
| $I = 71.2$ mA                        | 0.95                                          | 2.8                                            |
| $I = 139.2$ mA                       | 1.3                                           | 5.9                                            |

The equation (2) is performed for the anode discharge in both cases, as can be seen from table 2.

$$\frac{N_e^T}{N_e} = 3–4$$

where $N_e^T$ – the number of electrons in the discharge in the case of generation of TR, $N_e$ – the number of electrons in the discharge in the case without generation of TR.

The energy in the pulse TR is approximately 500 mV for the case of generation of TR and in the opposite case is 50 mV. A value of 50 mV corresponds to the noise of the TR measuring system. We can assume a power dependence taking into account the equation (2) since $P_T/P_T^2 \approx 10$, then

$$P_T \sim (N_e^T)^x$$

where $x \geq 2$.

It can be assumed that TR generation is of a threshold nature. The condition for the effective generation of TR is a substantial concentration of electrons in the plasma if there is a sufficiently strong magnetic fields. All the foregoing is true if the cyclotron mechanism is considered the main mechanism for the generation of microwave radiation and TR.
In our case, when the radius of the current channel 500 \( \mu \text{m} \) and the peak value of the discharge current is 10 kA the magnetic field is 2 T. Then the cyclotron frequency is \( \omega_c = 1.76 \times 10^{11} \times B \text{ rad s}^{-1} \), where \( B \) is the magnetic field (in units of T). The cyclotron frequency is \( \omega_c = 0.35 \times 10^{12} \text{ rad s}^{-1} \) if the magnetic field is 2 T. This is a small value in terms of approaching the terahertz range. If there is a deep pinch mode, then local magnetic fields can be equal to \( B \geq 20 \text{ T} \), then the cyclotron frequency is equal to \( \omega_c = 3.5 \times 10^{12} \text{ rad s}^{-1} \). Either another TR generation mechanism prevails.

Equation (3) can be rewritten in the form (4) if we assume the mechanism for the conversion of plasma oscillations into the energy of electromagnetic radiation in a vacuum discharge plasma

\[
P_T \sim (\omega_p^2)^x
\]

where \( x \geq 2 \), \( \omega_p \) – plasma frequency. The dependence of the power of terahertz radiation on the magnitude of the plasma frequency is indirectly confirmed by studies of a similar dependence in the beam-plasma generation of TR.

4. Summary

The nature of the generation of terahertz radiation by a vacuum spark is of a combined nature: there is a contribution from the cyclotron mechanism, there is a contribution from the mechanism of plasma oscillations conversion to the energy of TR, and there is some contribution from the thermal mechanism.

The contribution of the cyclotron mechanism depends on the magnitude of the generated spontaneous magnetic fields. For the terahertz range, fields of \( B \geq 20 \text{ T} \) are needed. This may be, for example, with a deep pinch of the discharge.

It can be assumed that the dependence of the TR power on the electron concentration in the plasma is power: \( P_T \sim (n_e)^x \), where \( x \geq 2 \). It is based on the results of mass spectrometry studies of the plasma of a vacuum spark. That is, in our case, the contribution of the mechanism of beam-plasma generation of TR is significant.

This conclusion is confirmed by the results of research on the beam-plasma generation of TR, in particular, in BINP – Budker Institute of Nuclear Physics.

5. Conclusion

An experimental study of the generation of TR by a vacuum spark with laser ignition was carried out. Intensive terahertz radiation was observed much more often during anodic ignition of the discharge than during cathodic ignition. Using the mass spectra of ions of different charge, the density of electrons (per-units) in the plasma of a vacuum spark was approximately calculated using a combined time-of-flight mass spectrometer with a magnetic analyzer. It is shown that the dependence of the TR intensity on the electron concentration is of a threshold nature and varies nonlinearly with it according to a power law.

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