Polarimetric investigations of nonthermal electrons in a high-current vacuum spark

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Abstract. The investigation of nonthermal electron beams in a high-current vacuum spark by Bragg polarimetry of continuous radiation from discharge plasma is reported. Movement features of electron beams inside and outside of contraction region of the discharge plasma are revealed.

1. Introduction
Among X-ray sources of various types for technological and diagnostic applications, a special place belongs to pinched discharges. A characteristic feature of these is that the radiation spectrum contains photons with energies significantly exceeding the difference of potentials between electrodes. The origin of this radiation is related to high-energy electron beams formed during local pinching of the plasma column to micron dimensions (micropinch). Information concerning the directional and energy characteristics of such electron beams is important for understanding the mechanism of their formation and controlling the radiation parameters.

This report presents the results of our investigation of nonthermal electron beams formed in plasma of a high-current low-inductance vacuum spark, which was based on an analysis of the polarization of X-ray emission from the discharge plasma.

2. Experimental setup
The experiments were performed on a Zona-2 micropinch machine (National Research Nuclear University MEPhI, Moscow). A discharge was occurred out between a pointed anode and a plane cathode separated by a gap of 5 mm. Both electrodes were made of iron. The residual pressure in the vacuum chamber was \( p \approx 3 \times 10^{-5} \) Torr. At the discharge voltage of 15 kV, the amplitude of the discharge current reached 150 kA. The period of discharge current oscillations was 8.5 \( \mu \)s. The X-ray emission spectrum was measured by two identical FSSR-1D focusing spectrographs with a spatial resolution in the direction perpendicular to the dispersion plane. The spectrographs were arranged so that the dispersion plane of one spectrograph was perpendicular, while that of the other spectrograph was parallel to the discharge axis. The spectra were recorded on an X-ray sensitive photographic film. For the adopted adjustment, the system monitored a spectral interval of 1.83–1.88 Å.

Densitograms of the emission spectra integrated over the entire discharge gap are presented in the figure 1. Symbols w and y indicate positions of the resonance and intercombination spectral lines of...
helium-like iron ions, respectively; symbol j indicates the satellite of the resonance line. As can be seen, the characteristic lines of multiply charged ions are observed on the background of a rather intense continuum. The intensity of the continuum with a predominantly perpendicular component $I_\perp$ (curve 1) is higher than that of the parallel component $I_\parallel$ (curve 2). The spatial region of continuous emission occurs between the point of micropinch localization and the anode.

![Figure 1. Integral densitograms of the emission spectra recorded by spectrographs with the dispersion planes oriented (1) parallel and (2) perpendicular to the discharge axis.](image)

3. Discussion

The electron temperature in the micropinch reaches $T_e > 1$ keV. When electrons with these energies interact with atoms and ions in the surrounding plasma, the main contribution to continuous emission is due to bremsstrahlung radiation, which carries direct information on the directional motion of electrons. Model calculations [1] showed that the degree of polarization of the X-ray bremsstrahlung at a given electron beam energy $E_0$ can vary depending on the photon energy from $P_B(\nu) = 1$ at low frequencies ($\nu \to 0$) to $P_B(\nu) = -1$ at high frequencies ($\nu \to E_0$), in accordance with the following formula:

$$P_B(\nu) = \frac{I_\perp(\nu) - I_\parallel(\nu)}{I_\perp(\nu) + I_\parallel(\nu)}$$

where $I_\perp(\nu)$ and $I_\parallel(\nu)$ are the intensities of emission components at frequency $\nu$ polarized perpendicular and parallel, respectively, to the discharge axis.

In the spectral interval studied ($\nu \approx 6.6 - 6.7$ keV), the intensities of continuous emission components reconstructed from the results of measurements correspond to $P_B \approx 0.2$. That is, the given spectral interval corresponds to a low-frequency part of the bremsstrahlung radiation spectrum and, hence, is related to the axial flow of super thermal electrons with energies $E_0$ much greater than the energy of radiation photons detected by the spectrograph, i.e., with $E_0 \gg 7$ keV. This estimation agrees with our previous data [2] about the presence of electrons with an equivalent temperature of $T_e > 20$ keV (for the Maxwell velocity distribution). The formation of a beam of super thermal electrons is probably related to the development of an anomalously high resistance of plasma in the region of pinching, accompanied by the appearance of a strong longitudinal electric field.
Analogous measurements were recently performed in [3]. Data obtained in the same spectral range were indicative of a negative polarization of bremsstrahlung within \(-1 < P_B << 0\). This is evidence for the axial propagation of an electron beam with energy \(E_0\) on the order of the energy of detected photons (i.e., \(E_0 \sim 8\) keV), in agreement with data on the temperature of high-energy electrons determined for the same system by the “gray” filter technique. We believe that the low energy part of electrons in the axial beam was related to the used system of discharge initiation, which was located away from the discharge gap behind the anode. In this case, it is possible to form the current channels out of the compression region. This leads to decrease in the efficiency of pinching and, hence, in the magnitude of the generated axial electric field.

It has been proved in experiment that the polarization of bremsstrahlung emission from high-current low-inductance vacuum spark depends on the ratio of energies of the detected photons and beam electrons. This allows one to determine the energy of superthermal electrons from the degree of polarization of bremsstrahlung continuum in a given spectral range.

References
[1] Gluckstern R L and Hull M H 1953 Phys. Rev. 90 1030
[2] Averin M S, Baykov A Y, Bashutin O A, Vovchenko E D, Dmitrusenko A S, Savjolov A S and San-Wei L 2006 Instr. and exp. techniq. 49 265
[3] Dolgov A N, Klyachin N A and Prokhorovich D E 2014 Plasma Phys. Rep. 40 733