Ring-shaped formations in the corona of an electrically exploded wire

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(Submitted 28 December 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 3, 111–114 (10 February 1985)

Time-resolved x-ray photographs show that the development of the constrictions is preceded by the appearance of superheated ring-shaped structures. The origin of these structures is explained in terms of the formation of current sheets.

The formation of "hot points" as a result of the explosion of a wire in the diode of a high-power (10^{11}–10^{12}-W) source of a relativistic electron beam is a well-known effect. Mosher *et al.*[1] reported in 1973 that hot formations appear in the plasma channel resulting from the explosion of a wire of a high-Z material, and the channel becomes subject to the MHD sausage instability.

We have now carried out several experiments on the Triton accelerator to determine the nature of these hot points. In these experiments, a plasma channel is formed by passing a current pulse $\tau_{1/2} \simeq 50$ ns long with an amplitude $\lesssim 200$ kA through tungsten wires 10 and 50 μm in diameter and 12 mm long. Two-frame images of the

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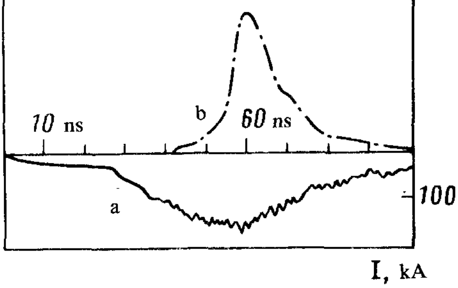

FIG. 1. a—Oscilloscope trace of the current through the wire; b—soft x radiation detected by a vacuum photoemission detector with a 3-μm polyester filter.

plasma channel are recorded in the spectral range $\varepsilon \gtrsim 0.5$ keV by nanosecond x-ray module image converters[2] with a resolving time ~ 5 ns. Integrated images are recorded by means of multiple-hole x-ray pinhole cameras with a set of absorbers. At the same time, we measure the time-resolved absolute spectrum of soft x radiation.[3]

Analysis of the signals from the electronic detectors, with allowance for the inductive component, shows that roughly the same load, 0.5–4 Ω, is produced during the electrical explosion of the wires 10 and 50 μm in diameter. The ultrasoft x-ray signals ($E \lesssim 10$ keV; Fig. 1b) arise at the same time as the high-frequency oscillations appear on the current signal (Fig. 1a). The images of the plasma channel obtained with the help of the image converter near the maximum of the ultrasoft x-ray signals show an inhomogeneous tubular structure with an external diameter ~ 400 μm near the cathode. This diameter increases toward the anode; the thickness of the tube wall is $\lesssim 80$ μm (i.e., we are at the limit of the spatial resolution). The plasma of the skin layer is optically transparent to the intrinsic emission and has a temperature $T_e = 500$–800 eV. In the structurally complex corona, we can identify some relatively bright ring-shaped structures, which are mostly concentrated near the cathode. On the image-converter photographs, these structures appear as spots (shown by the arrows in Fig. 2a) in the tube wall, as is shown by photography from various angles at azimuthally symmetric points with respect to the tube axis. The process by which the hot points form is a rather complicated one, which can apparently take different paths, but we can assert that in the explosion of wires 10 μm in diameter in the present experiments there are high-temperature formations at the axis. These formations appear through a decrease, in a time < 10 ns, of the diameter of the plasma channel in the superheated regions in the rings. This decrease in diameter proceeds to the limit of the spatial resolution of the image converters (Fig. 2b). This process occurs during different time intervals of the discharge in different points in the plasma.

The corresponding integrated x-ray pinhole photographs recorded in the same spectral range show superimposed images of the coronal tube and transverse bands between parts of the tube wall (Fig. 3a). On the harder integrated pinhole photographs

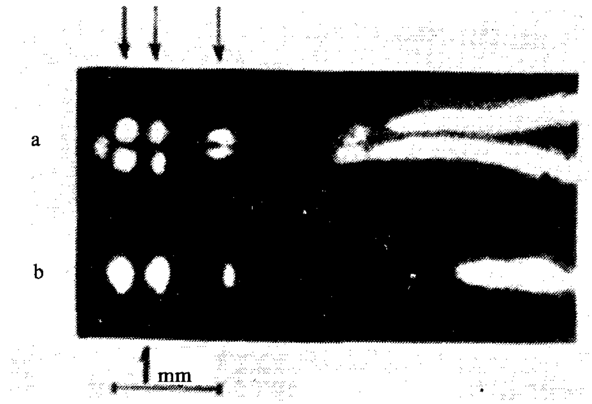

FIG. 2. a, b—Image-converter photographs of the plasma channel resulting from the explosion of a wire. The arrows show ring-shaped formations. The time interval between frames is 10 ns.

(taken with filters with a cutoff energy of 2 keV) we do not find the image of the corona, and in place of the bands we see hot points $\lesssim 80\ \mu m$ in diameter (the resolution of the pinhole cameras; Fig. 3b). These results mean that the temperature of the ring-shaped formations, which leave a "signature" in the form of perpendicular bands inside the coronal tube in the course of the compression, reaches a maximum in the final stage of the compression. The temperature estimated for the hot points by the absorber method is 1–2 keV.

During the explosion of a wire 50 μm in diameter, the integrated pinhole photographs in the corresponding range also show the image of bands inside the coronal tube, but the hot points are not found on the pinhole photographs with the harder filter.[4] Consequently, during the explosion of a wire 50 μm in diameter, there is no substantial compression of the superheated ring-shaped formations.

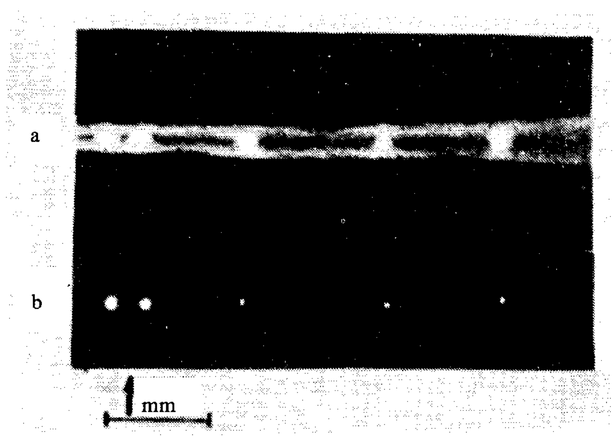

FIG. 3. a, b—Time-integrated x-ray pinhole photographs of the plasma channel resulting from the explosion of a wire. These images were obtained in different spectral ranges.

At present, opinion is divided on the nature of the events leading to the high-temperature local plasma formations in high-current discharges. Furthermore, these processes can apparently have distinctive features in different experiments. Well-known models have been proposed for the development of constrictions, with various mechanisms stabilizing the final dimension.[5,6] For pinches in which the current shell breaks up into filaments, it has been hypothesized that hot points form as a result of the linking up of these filaments.[7] The experimental data reported here show that there may be a process in which a hot plasma forms at certain points as a result of the compression of ring-shaped formations that initially arise in the corona of the plasma channel during the stage of the maximum intensity of the ultrasoft x-ray emission.

Let us examine the possible appearance of such ring-shaped formations in the corona. If we assume that the greater part of the current is flowing through the corona, we can work from the temperature and the equality of the magnetic and thermal pressures to find the ratio of the current velocity to the Alfvén velocity: $v_c/v_A \sim (R/\delta)(\sqrt{T}/I)$. Substituting the numerical values, we find $v_c/v_A \gtrsim 3$.

If the current velocity is substantially higher than the Alfvén velocity, the perturbation of the magnetic field would be described by the equation $(\partial H_\varphi/\partial t) + AH(\partial H_\varphi/dz) = 0$, which describes breaking waves.[8-11] The scale time for this process is $\tau \sim \lambda/v_A$ (λ is the perturbation wavelength), from which we find $\tau \sim 10^{-9}$ s with $\lambda \sim R$. The breaking may be stabilized by the finite conductivity. Accordingly, in pinches with a high current velocity ($v_c > v_A$), the formation of the constrictions may be preceded by a stage in which ring-shaped current shells form in the skin layer. In these shells, the current is directed along r and Z. We believe that these are the events that occurred in the experiments described here.

We wish to thank L. I. Rudakov and V. P. Smirnov for interest in this study and V. V. Yan'kov for very useful discussions of this study.

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Translated by Dave Parsons
Edited by S. J. Amoretty