Current structure of a plasma focus during generation of fast particles

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A complex structure of the localized regions of generation of fast particles in the MeV range in a plasma focus as a result of azimuthal destruction of the current sheath was observed experimentally. The acceleration of particles is associated with dynamic dissipation of the magnetic field as a result of interchanging the magnetic lines of force. Such effect can explain the acceleration mechanism of neutron generation in classical linear pinches.

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As mentioned earlier,[1] an intensive acceleration of charged particles to high energies is observed in a plamsa focus (PF) in the "runaway" regime of the current sheath when an anode with a recessed center is used. The experiments on recording of such deuterons in photographic emulsions using several combinations of the pinhole-camera method with an additional magnetic deflection of the charged particles made it possible to determine the localization of the acceleration regions and the current structure of the PF during generation of fast particles. The setup for the first set of experiments is shown in Fig. 1. The specifications of the setup and the parameters of the discharge were given in Ref. 1. The deuterons accelerated in the PF (P) are transmitted through a system consisting of a hole (4) and a slit (6) to photographic emulsion (7) after being deflected in a transverse magnetic field H. To prevent a direct exposure of the emulsion to the luminous radiation of the discharges, we covered the area of the emulsion near the axis with a 2-μm Al filter (8). To reduce the deuteron scattering, the evacuated drift tube (3) was opened only during the discharge of the system's capacitor bank, which was triggered by the electromagnetic valve (5). A 0.1 to 0.2-mm-wide slit (6) made of 10-μm Al was used to record the soft x-ray picture of the discharge around the axis, if it was transmitted through the slit. Figure 2 shows typical pictures of the energetic deuterons obtained by FT-41 photographic emulsion. The investigated energy interval is bounded below by the instrument's aperture and by the magnetic field H. A fraction of the discharge was accompanied by generation of a hard deuteron flux with a complex structure. In addition to the small (frequently <1 mm) cross-sectional dimensions of the source, we should call attention to the monochromaticity

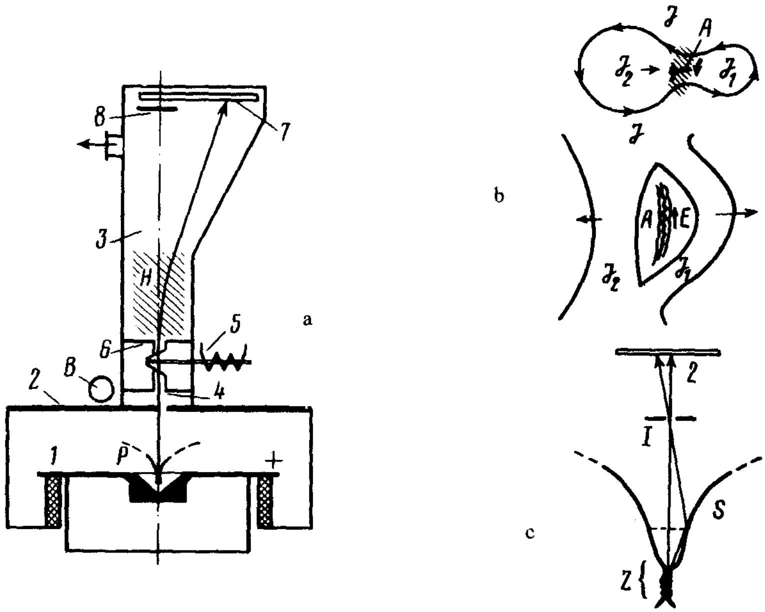

FIG. 1. (a) Experimental setup and beam-deflection system; (b) current filamentation system; (c) recording of the reflection of deuterons from the plasma sheath.

of the individual elements that were pointed out in Ref. 2 in analyzing the Z pinch. These groups correlate stably with the reading of the STA-5 (B) counter which recorded the γ activity resulting from the β decay of Al^{28} obtained from the $Al^{27}(dp)Al^{28}$

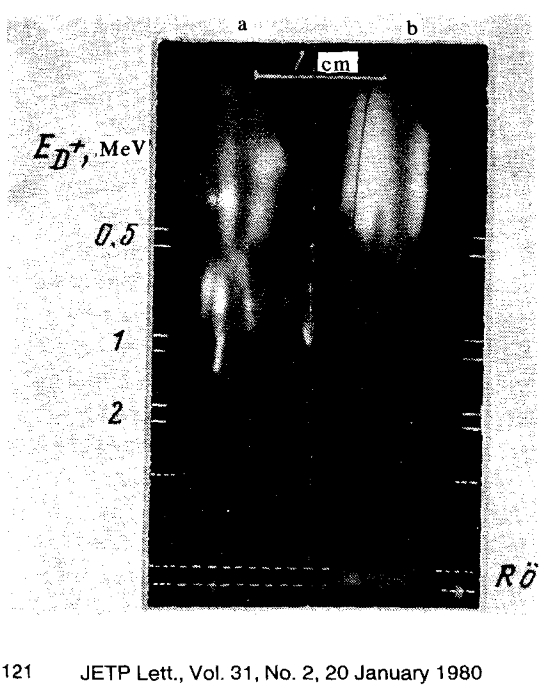

FIG. 2. Different energy distributions of fast deuterons obtained according to the scheme in Fig. 1a at 1.4-kOe magnetic fields (a) and (b).

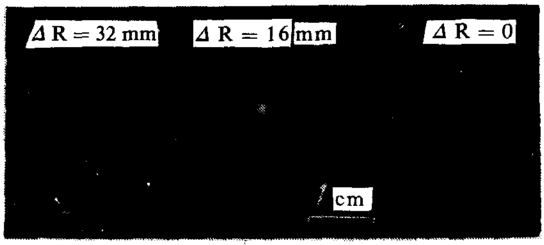

FIG. 3. Images of the deuteron generation zone obtained simultaneously through the axial hole and through two holes shifted 16 and 32-mm with respect to the radius.

reaction on the Duralumin cover of the chamber (2). The experiments showed no evidence of a correlation between the soft x-ray picture of the axial zone of the discharge and the spectral distribution of the fast deuterons.

The axial position of the acceleration zone was determined by analyzing the pinhole camera pictures photographed through the three holes ϕ 0.1. mm (without filters), two of which were moved 16 mm and 32 mm from the axis of the chamber. After processing a large number of photographs such as those shown in Fig. 3, we saw that the acceleration region is located in the anode cavity 2 to 3 cm below the anode surface and its cross-sectional dimensions are $\leqslant 1$ mm. Using Fig. 3a, we can reconstruct the geometry of the current-plasma sheath (CPS) during generation of the fast deuterons according to the scheme in Fig. 1c. In addition to the axial (direct) group of deuterons accelerated in the acceleration zone only those deuterons which were reflected from the narrow annular zone (S) of the CPS can be transmitted through the holes of the camera (1). Thus, we obtain from the geometry of the experiment $\phi\, S = 7.5$ mm and $S - Z = 10$ mm. Such annular images are produced for discharges that do not accompany the activation of Al. For discharges generating a large number of hard deuterons the pinhole camera photographs have an irregular structure similar to that in Fig. 3b, which indicates that a solid plasma sheath cannot be maintained near the acceleration region.

We can see from magnetic deflection of the deuterons transmitted through the pair of holes of the pinhole camera (Fig. 4a, $H = 810$ Oe) that exposure of the emul-

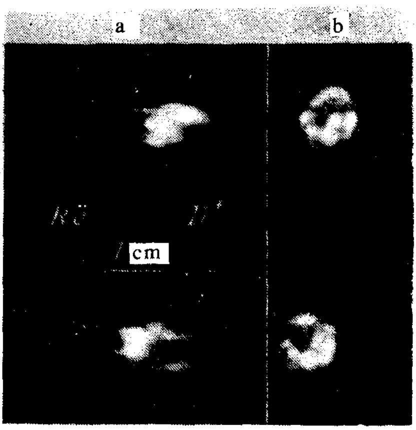

FIG 4. Images of the deuteron generation zone obtained simultaneously through two holes shifted 6 mm from the axis in the opposite directions, with a deflecting magnetic field (a) and without the field (b).

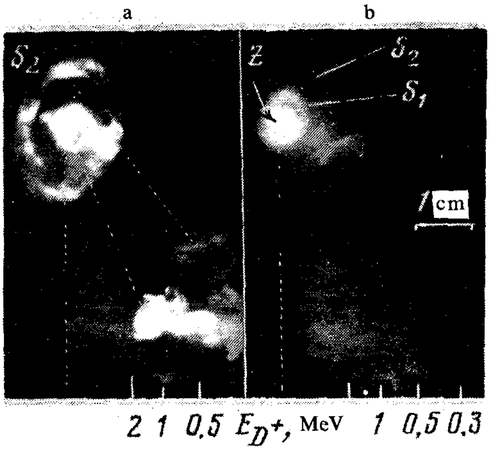

FIG. 5. Images of the deuteron generation zone obtained simultaneously through two holes near one of which a deflecting magnetic field is applied. In case (a) a generation of fast particles is observed.

sion to photon radiation of the discharge is much smaller than its exposure to corpuscular radiation, which is attributable to the large gap that prevents a contact between PF and the metal surface. Figure 4b ($H=0$) illustrates the complex structure and the size of the acceleration region. The space-energy structure of the deuteron source can be examined by applying a magnetic field near one of the holes of the stereo pinhole camera. Figure 5 shows photographs of two discharges: (a) one with a large number of hard deuterons and (b) one without them. Here we see the acceleration zone (Z), the first reflection zone of the CPS (S_1), and the second zone (S_2), which is apparently associated with the double structure of the sheath. The magnetic deflection indicates that the energy of the deuterons reflected from the first sheath is close to their energy in the direct beam, whereas the energy of the deuterons after they pass through the first sheath and are reflected from the second sheath, decreases from $E = 1.3$ MeV to 0.8 MeV (Fig. 5a).

The experimental data confirm the idea expressed by Syrovatskiĭ[5] that fast particles can be generated as a result of dynamic dissipation of the magnetic field. The initial compression of the region of current constriction ($m=0$) or of the focus region is determined by the relationship between the magnetic pressure and the inertial forces of the CPS and by the counterpressure of the trapped volume of hot plasma. Further evolution of the PF is associated with the longitudinal flow of the substance along the discharge axis and with the possible radial expansion or even ruptures in the current sheath, which were recorded experimentally by Gribkov[3] using the LV-2 apparatus. In the short PF (flat anode) the main loss of the substance occurs in the axial direction; however, in the long PF (anode with a central gap), in which the axial discharge is suppressed, the CPS breaks in the "weakest" places. A neutral current sheet A whose decay accelerates the ions in the direction of the electric field in the region with $H=0$ is produced as a result of reconstructing the magnetic lines of force of the current J after breaking it down into separate filaments (two filaments in Fig. 1b).

If the filamentation is weak and does not spread far along the axis of the PF, then the part of the CPS that conserved its symmetry gives almost ring-shaped reflections

(Figs. 3a and 5b) and in this case there is no acceleration of particles at energies below the MeV range. When the gaps in the CPS are large, the filamentation extends far on the current lines along the axis of the PF and a complex combination of reflected and direct beams of hard deuterons is recorded on the film (Figs. 2a and 2b, 3b, and 5a). It should be noted that x-ray radiation in the MeV range of hardness corresponding to acceleration of electrons toward the anode is also observed in the last case. The neutron yield from the PF in the case of generation of fast deuterons is usually smaller due to an earlier destruction of the focus as a result of radial breaking of the sheath.

The acceleration mechanism described above is even more suitable for linear Z pinch where it can be the main source of fast particles and neutron radiation. The axial discharge is greatly suppressed here due to a long pinch zone, and the radial breaks are initiated by the initial "uneven strength" of the sheath due to a highly developed azimuthal structure at small (20–50 mTorr) initial pressures of the gas. In 1956, the author performed experiments in which the initial pressure of deuterium was reduced below 5–8 mTorr.

The breakdown of the gas space was achieved by shorting with a copper rod ϕ 14 mm the interelectrode gap of the cylindrical chamber shown on p. 238 of Ref. 4. Thus, a series of successive neutron pulses was observed regularly in each discharge after each compression–expansion cycle of the pinch, although the axial part of the chamber, which was occupied by the rod, could not be the generation zone of fast particles.

The experiments show that there is a direct correlation between the current filamentation and the generation of fast particles in the MeV energy range in the plasma focus. The fast particles generated in this way do not determine the neutron yield of the plasma focus but are at the same time the main source of generation of hard radiation from the linear Z pinch.

The mechanism analyzed above also determines the generation of powerful electron beams by establishing a contact between the PF and the anode. The lesser hardness (70–300 keV) of the produced x-ray radiation is attributable to a slower development of gaps and of the reconnection process in the heavy metallic plasma.

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