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# Neutron emission parameters from the collapse of the condensed Z-pinch*

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**Abstract.** The parameters of neutron emission from the neck of the condensed Z-pinch, were measured at an S-300 installation (2 MA, 100 ns). Profiled loads with central parts made from microporous deuterated polyethylene (with a density of 100 mg/cm$^3$) were used in the experiments. Neutron emission parameters were measured by the time-of--flight (TOF) method. Neutrons were registered using four flight bases with 10 scintillation detectors which were placed at two axial and two radial directions. It was found that the mean neutron energy, determined by the TOF method, turned out to be anisotropic. The average energy of neutrons emitted along the axis towards the cathode, was shifted to higher energy (2.6–2.8 MeV) and the average energy of neutrons emitted towards the anode, was shifted to lower energy (2.1–2.3 MeV) compared to the d-d reaction neutron energy 2.45 MeV. The average energy of neutrons, emitted in two opposite radial directions, was close to 2.45 MeV. The half-width of the energy distributions reconstructed for all directions was 400–500 keV. The analysis of the experimental results demonstrated that the found phenomena could be explained by a slowly decaying high energy tail in the energy distribution of colliding deuterons. The maximal neutron yield was of $6 \times 10^9$.

**Key words:** neutrons • energy distribution • fast Z-pinch

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## Introduction

Proposals to create a plasma with thermonuclear parameters, based on the maximum implication of the mode $m = 0$ instability using the current flow $I >$ 10 MA through a profiled cylindrical target made from a D-T mixture, have initiated studies of the plasma compression and dynamics in fast Z-pinches [9, 12]. The solid deuterium is an ideal substance for modelling of the D-T mixture compression. In works [1, 2] the currents smaller than 3 MA were used for modelling of the compression dynamics in fast Z-pinch microporous substances with small densities, 30–100 mg/cm$^3$. At such densities the effective matching generator with a load has been realized. In experiments with agar-agar loads $CD_2$ atoms were implemented in the load structure) a hot plasma formation with the size up to 50 μ was observed. The appearance of the hot plasma formation was accompanied by a short neutron pulse with the duration < 10 ns [3]. The maximal neutron yield, observed in this experiment, was $10^8$.

A more promising load substance is low-density microporous deuterated polyethylene ($CD_2$). It has essentially more homogeneous deuterium atom distribution in a target and a smaller content of elements with larger

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*Z* numbers. In this article we present experimental results for neutron emission from a neck of a fast Z-pinch. The experiments were carried at an S-300 generator with currents up to 2 MA and the 100 ns rise time. The neck of the load was produced from the heterogeneous deuterated polyethylene, its density varied between 50 and 100 mg/cm$^3$ [4]. Parameters of neutron radiation were measured by a time-of-flight (TOF) method. The Monte-Carlo (MC) method has been used for neutron spectra reconstruction [6, 7].

## Experimental setup

Studies of neutron emission characteristics were carried out at an S-300 eight-module high-current generator with a 2 MA current and a 100 ns rise time. Experiments were performed with a profiled microporous load. The load consisted of two agar-agar columns of 5 mm diameter and 30 mg/cm$^3$ density. Between the agar-agar columns, a cylindrical neck of 1 mm diameter and 1 mm length was installed to enhance the energy concentration. The neck was produced from deuterated polyethylene with a density of 100 mg/cm$^3$. The load was placed in an anode-cathode gap of the target unit. The inter electrode distance could varied between 7.5 and 10 mm.

Neutron energies were measured by the TOF method. Detector positions are shown in Fig. 1. Neutrons were recorded at four flight bases by 6 scintillation detectors SSDI-8 and 4 detectors based on a Hamamatsu photo multiplier R1828-01. Two pairs of detectors of the same type were installed in two axial directions at distances 2.6 m and 5.1 m from the load (over the anode) and 2.6 and 7.4 m (under the cathode), three detectors were installed in opposite radial directions (at 90° angle with respect to the load axis) at distances 2.6, 5.1, 8.3 m. The time resolutions of the SSDI-8 detectors and R1828-01 photo multipliers were 8–10 ns and 4–6 ns, respectively. For protection of detectors against hard X-ray radiation (HXR), the detectors were located in lead containers with a 12 cm wall thickness. The total yield of neutrons from the plasma, formed in the neck, was measured using the activation method [5]. Corresponding detectors have been made on the basis of the counter STS-5 (or STS-6) of the Geiger-Muller type. These detectors were installed above the anode at a 115 cm distance from the load and at a 22° angle with respect to its axis. Neutron spectrum in the axial and radial directions was restored from time-resolved neutron signals which were recorded by several detectors in one direction at different distances. In our work the MC method [6] was used and subsequently improved. Our improvement was based on the fact that it was possible to use neutron detectors in mutually opposite direction [5].

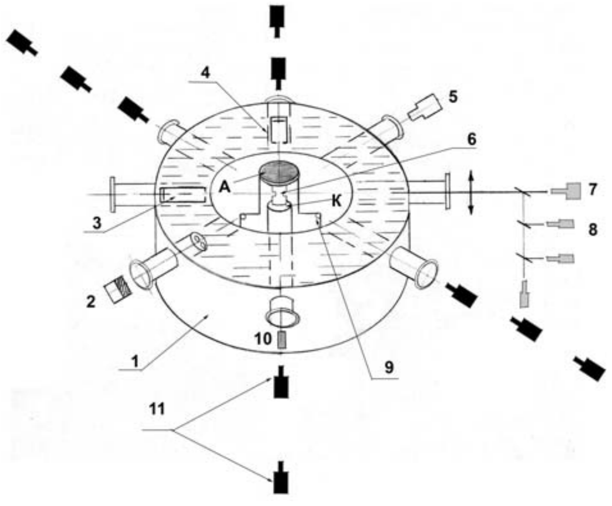

**Fig. 1.** Diagnostic complex: 1 – system of formation of high--voltage pulses with water isolation; 2 – four frame X-ray image camera; 3 – pinhole camera; 4 – slit camera; 5 – X-ray vacuum diode; 6 – Z-pinch; 7 – optical streak camera; 8 – optical image tube; 9 – magnetic probes; 10 – semiconductor detectors; 11 – scintillation detectors.

In all experiments the spatial-time parameters of the plasma formed in the neck were studied by the diagnostic complex of the installation S-300. Plasma dynamics in the neck was recorded with a time resolution of 0.75–1.0 ns by using an optical streak camera with a 50 μm wide slit oriented along the load axis (Fig. 1). Three optical image tubes were used to photograph the neck with a frame exposure of 6 ns. Photographs on the soft X-ray radiation (SXR) and extreme ultraviolet (XUV) spectral ranges were taken using a microchannel plate (MCP) X-ray image tube, which allowed to image four frames with an exposure of 3–5 ns (Fig. 1). To increase a spatial resolution of the integrated photography in the energy range 1–15 keV the slit camera with a step attenuator, was used [1]. The slit of 50 μm width was placed at the right angle to the load, at a 90 cm distance from the load. Spatial resolution along the axis was 15 μm. SHR emission in the range 1–10 keV was recorded with a time resolution of 1–2 ns by using photoemissive X-ray diodes and semiconductor detectors equipped with X-ray filters. The load current, its derivative and the voltage at the input of the target unit of the installation, was recorded with magnetic probes and the voltage divider.

## Experimental results

As it was already mentioned above, the parameters of neutron emission were measured by the TOF technique. Figure 2 shows the waveforms of HXR and the neutron emission recorded by scintillation detectors in two axial and radial directions during the discharge through a profiled deuterated load. This figure also shows waveforms of voltage applied to the target unit, the current through the load and pulses of SHR. The first HXR pulse in the oscillograms registered by scintillation detectors corresponds to electron leakages in a vacuum concentrator of the installation. The electron leakages appeared as a result of the installation of the magnetic isolation in the vacuum lines of the concentrator. The second HXR pulse with a photon energy ≥ 100 keV appears in the signal from some detectors at a time of 160 ns. Simultaneously, a small negative peak appeared in the voltage signal and the high-frequency oscillations were observed in the current waveform. From the analysis of results of the processing of the neutron pulses received with the help of TOF measurements, it follows that this pulse appears at the moment of neutron generation. The neutron generation was accompanied

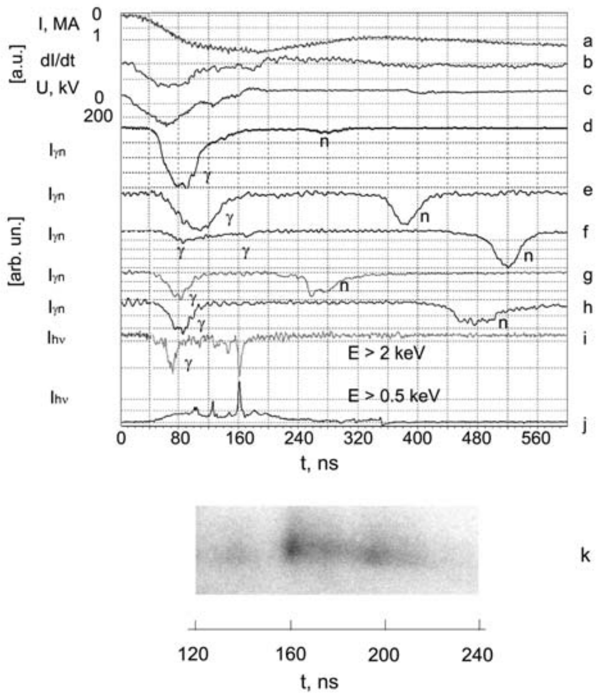

**Fig. 2.** (a) Waveform of the current ($I$); (b) derivation ($dI/dt$), (c) voltage ($U$); pulses: of HXR and neutrons ($I_{\gamma n}$), recorded by scintillation detectors, installed in the radial directions, at distances of 2.6 m (d), 5.1 mm (e) and 8.3 m (f), and in the axial directions, at distances of 2.6 m (g) and 7.4 m (h) (under cathode), SXR signal ($I_{h\nu}$) recorded by the semiconductor vacuum X-ray diodes in the energy range $E > 2$ keV (i) and $E > 0.5$ keV (j) and an optical streak camera image of plasma luminescence in the field of neck, obtained in axial direction (k).

by short SHR pulses with 2–4 ns FWHM (full width and half maximum) and energies $E > 0.5$ keV and $E > 2$ keV, which were registered by vacuum photoemissive and semiconductor diodes. From the optical streak images, one can see that the radiating local plasma formation (LPF) occurs during the constriction. The intensity of the luminescence (LPF) increased to the 160 ns. Time correlations between the appearance of LPF and pulses of SHR and HXR are observed.

In Fig. 3 the restored neutron spectra obtained in one of the experiments are shown, for axial and radial directions. In the cathode direction the maximum of the neutron energy distribution is $E_{\max} = 2.6$ MeV with FWHM $D_{1/2} = 0.5$ MeV, in the anode direction the distribution maximum is shifted to $E_{\max} = 2.25$ MeV with $D_{1/2} = 0.65$ MeV and in the radial direction the distribution maximum is close to $E_{\max} = 2.45$ MeV with $D_{1/2} = 0.25$ MeV. From the results of processing of all series of experiments from 30 shots, it follows that in the cathode direction the average neutron energy is equal to 2.6 MeV, in the anode direction –2.1 MeV and in the radial direction it is close to the value 2.5 MeV. Thus, anisotropy of the average neutron energy was observed in the axial direction.

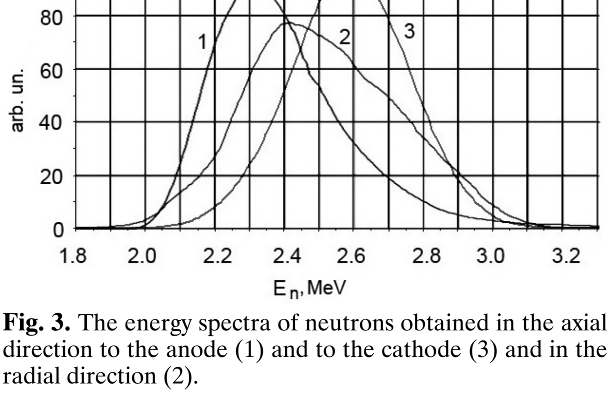

**Fig. 3.** The energy spectra of neutrons obtained in the axial direction to the anode (1) and to the cathode (3) and in the radial direction (2).

Plasma images of the Z-pinch neck, obtained by the X-ray pinhole camera in the energy range 10–300 eV, are collected in Fig. 4. From Fig. 4, one can see that the load own luminescence in the spectral range 10 eV, is registered from 35 ns and the brightest luminescence is observed on the neck periphery. To 100 ns at the neck axis the compact plasma formation is formed. The hot spots (HSs) of a size of 50–100 μm for the neck area energies 1.5 keV, have been observed in the integrated X-ray obscures. Using a slot-hole chamber, the estimation of the HS minimum size was made for energies $E > 1.5$ keV. The minimum HS size was 30–50 μm. The load photographing in a visible light has allowed to obtain information on the peripheral plasma dynamics in the neck area. From these images, one can see that LPF's were observed against the background of the feebly glowing residual material of the neck (Figs. 4c and 4d).

Maximum of the radiation power measured by vacuum diodes ($E > 0.5$ keV) and semi-conductor detectors ($E > 2$ keV) was $\sim 10^{10}$ W and $10^{8}$ W, correspondingly, and the energy of the 3 ns SHR pulse (measured at the same energy interval) was $\sim 100$ J and few Joules, respectively. If we assume that the electron component of an HS is in thermal equilibrium and, accordingly, the intensity of SHR emission decreases exponentially

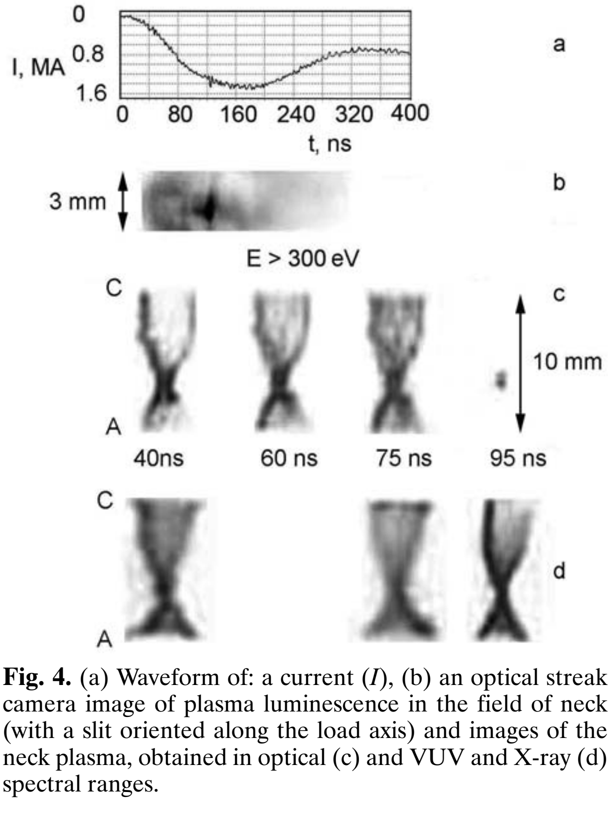

**Fig. 4.** (a) Waveform of: a current ($I$), (b) an optical streak camera image of plasma luminescence in the field of neck (with a slit oriented along the load axis) and images of the neck plasma, obtained in optical (c) and VUV and X-ray (d) spectral ranges.

with increasing energy, then electron temperature $T_e$ can be estimated from the SHR intensities measured in two spectral ranges [13]. Estimates show that $T_e$ is close to 1 keV. The maximal neutron yield at the current amplitude of 1.5 MA was $6 \times 10^9$.

## Discussion

Our experiments have shown that the formation of HS's in the Z-pinch necks made from microporous deuterated polyethylene was accompanied by neutron emission. HS's with a temperature of 1 keV and a characteristic size of 100 μm were observed. The hot spots emit short soft X-ray pulses with the duration of 2–4 ns. The average neutron energies measured by TOF method in the anode and cathode directions, were 2.1 ± 0.2 MeV and 2.6 ± 0.1 MeV respectively, and those measured in radial directions were close to 2.5 ± 0.1 MeV. The spectrum peaks of neutrons restored by the MC method were shifted in the cathode and anode directions to the energies 2.6–2.8 MeV, and 2.1–2.3 MeV, correspondingly. The time in which a neutron with a mean energy was generated, coincided within 10 ns with the appearance of SHR and HXR pulses. From the reconstructed neutron spectra, information about the deuteron kinetic energies, which produce fusion neutrons, has been obtained. The average kinetic energy of the fast deuterons was about 100–150 keV. FWHM of the neutron spectra produced both in the radial and axial directions, was 0.4–0.65 MeV. The broad wide spectrum is connected to a feature of the ion energy distribution formation in the Z-pinch [11]. Analysis of the simulation results, within the limits of the two-dimensional magnetohydrodynamics (MHD), shows that the main mechanism for ions to acquire the energy, is the plasma acceleration under the influence of the $\mathbf{j}\times\mathbf{H}$ force [10]. The plasma is accelerated differently in different regions of the pinch. This is the reason why the accelerated ions have smooth energy spectra. Thus, in the process of the neck formation the full spectrum of ions is a result as a thermal motion in a high-temperature plasma of the neck and the deuteron acceleration during the process of the MHD instability development. The ion energy spectrum in Z-pinches differs from the Maxwell one because the number of fast ions is essentially larger than in the Maxwell distribution. With increasing energy, the number of fast ions decreases as $\sim E^{-k}$, where the exponent $k$ is in the range 2–4. The presence of a power-low tail in the energy distribution of deuterium ions accounts for a rather large width of the neutron spectrum even at relatively low (< 1 keV) temperatures of plasma [11].

The observed neutron energy anisotropy in axial directions can be connected to the deflection of fast ions moving in the transverse magnetic field of the pinch. As a result, the deuterons begin to move preferentially towards the cathode [10]. As it was shown in [8], this effect is sufficient to explain the anisotropy of colliding ions and the anisotropy of neutron emission from the Z-pinch.

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