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Fusion Neutrons Produced in Wire-Array Z-Pinch at S-300 Facility

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INTRODUCTION

Z-pinches are nowadays the most intensive laboratory sources of soft X-rays and this is also the main reason why they are studied [1]. Whereas a large number of papers are devoted to studies of EUV, soft and hard X-ray radiation, and in some cases electrons, information about fast ions is rather rare. At this point we can mention the recent measurement of an ion temperature in wire-arrays at the Z-machine. The Doppler-width of iron spectral lines indicated that the ion temperature exceeded 200 keV [2]. Such a result suggests that also fusion neutron measurements could provide invaluable data for Z-pinch physics since they give insight into the acceleration of fast ions. For that purpose we carried out Z-pinch experiments in which a wire-array imploded onto a deuterated fibre. Experimental results with standard aluminium wire-arrays were published in [3]. In this paper, we focus on experiments with conical tungsten wire-arrays.

EXPERIMENTAL SET-UP AND DIAGNOSTICS

Wire-array experiments were performed on the S-300 Z-pinch generator (Kurchatov Institute in Moscow [4]) at a peak current of about 2 MA with a rise time of 100 ns. The diameter of a conical wire-array was 10 mm and 7 mm at the anode and at the cathode, respectively. Wires were inclined at an angle of 15° to the array axis. The conical wire-array consisted of about 30 tungsten wires of 7 μm in diameter. The deuterated polyethylene fibre with a diameter between 80 and 120 μm was placed on the axis of the wire-array.

In order to observe Z-pinch dynamics, various diagnostic tools were used: e.g. an optical streak camera, a 4-frame X-ray pinhole camera, a differentially filtered time integrated pinhole camera, and 5-frame laser shadowgraphy. The neutron emission was measured with an indium activation counter (for neutron yield measurements) and seven scintillator-photomultiplier tubes (for time of flight analysis [5]). This diagnostic set-up enabled us to obtain the following experimental results.

EXPERIMENTAL RESULTS

Typical results of the implosion of the conical tungsten wire-array onto the deuterated polyethylene fibre are displayed in Fig. 1. Fig. 2 shows the neutron spectrum obtained in the axial direction behind the cathode (i.e. downstream).

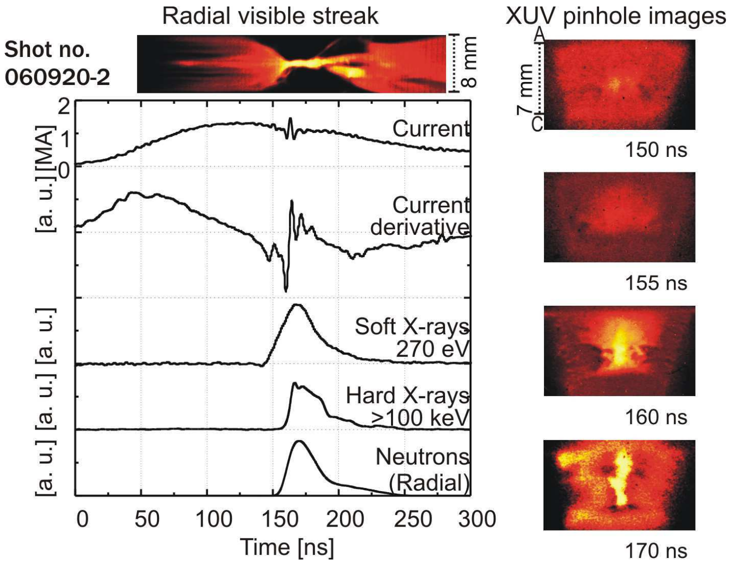

Figure 1. Waveforms of current, current derivative, X-ray and neutron emission together with XUV pinhole and streak images recorded in discharge no. 060920-2, neutron yield of 4×10^8.

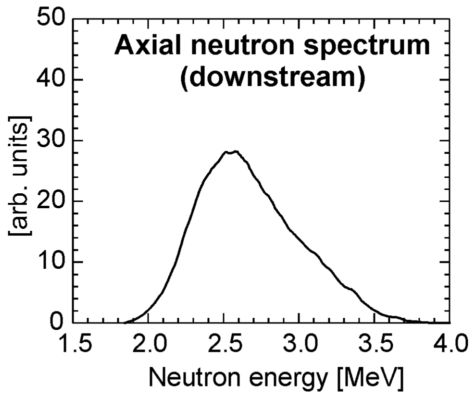

Figure 2. Axial neutron energy spectrum emitted in shot no. 060920-2, neutron yield of 4×10^8.

Evidently, the streak image shows the radiation from the fibre and/or precursor plasma already at 70 ns. At about 140 ns, the tungsten wire-array started to implode. The most intense soft X-rays were emitted at about 170 ns during the stagnation of imploded tungsten wires onto the fibre. The power of soft X-rays (between 0.1 and 10 keV) reached 100 GW. The maximum spectral power density was measured at a photon energy of 120 eV. The radiation was close to the radiation of a black body with a temperature of 40 eV.

Hard X-ray emission started during the stagnation of the wire-array onto the fibre. The rise-time of the hard X-ray signal was very short and usually did not exceed 3 ns. In all shots, this rapid rise of the X-ray emission corresponded to a sharp dip in the *dI/dt* signal. After that, the hard X-ray emission lasted for about 30 ns, i.e. during the stagnation and expansion phase.

As regards neutron emission, it temporally correlated with hard X-rays within 5 ns accuracy. On average, downstream neutron energy spectra peaked at 2.65 MeV and the full width at half maximum (FWHM) of neutron energy spectra was 350 keV. In the radial direction, the peak neutron energy was 2.48 MeV with 450 keV FWHM. Such a result indicates that neutrons were produced mainly by deuterons with the mean axial component of kinetic energy of about 60 keV while the mean radial component was about 40 keV. Therefore the average kinetic energy of deuterons which produced fusion neutrons was 100 keV.

DISCUSSION

During the past 60 years, the plasma theory and modelling were improved to such a degree that it was possible to explain gross dynamics of the discharge as well as a lot of fine phenomena of Z-pinches. However, several key-points such as the mechanism of neutron production have remained unresolved. In order to explain the acceleration mechanism in our experiment, one can exclude the model of a moving boiler towards the cathode since the observed shift to 2.65 MeV requires an unreasonable high velocity of plasma. Besides that, the zippering was seen in the opposite direction, i.e. from the cathode towards the anode (cf. XUV images in Fig.1). Even though the observed neutron energy anisotropy could be also the result of the anisotropy of target deuterons (i.e. higher number of target deuterons near the anode), we suppose that the anisotropy was caused by fast deuterons which were directed towards the cathode. It would indicate that the beam target mechanism played an important role. However, because of the 450 keV FWHM of radial neutron spectra, trajectories of deuterons producing fusion reactions seemed to be strongly influenced by a magnetic field and thus the classical linear beam target model did not occur. Instead of rectilinear motion, fast deuterons could move similarly as described by Bernstein et al. [6]. The deuteron movement described in [6] could explain observed neutron spectra. However, it is still not clear how these deuterons were accelerated especially when fusion neutrons were produced at the end of the stagnation and at the beginning of the expansion phase. Also the fast onset and a relatively long duration of neutron emission deserve more detail research.

Recently, we have prepared a deuterium gas-puff in order to interpret experimental results and to compare them with those obtained on the Z-Machine at SNL [7,8]. We expect that the interpretation of Z-pinch experiments with pure deuterium will be more straightforward in comparison with a heterogeneous mixture of tungsten, carbon and deuterium ions. In addition to that, neutron yields could be higher with pure deuterium because deuterons will not be slow down so rapidly as in the case of a high number of electrons bounded in tungsten ions.

As regards thermonuclear reactions, the significant fraction (above 10%) of thermal neutrons cannot be ruled out. In the axial (downstream) direction, these thermonuclear neutrons could be hidden among scattered neutrons. According to obtained neutron spectra, a relatively large number of thermonuclear neutrons could originate from a small localities with >10 keV temperature rather than from the plasma bulk of 2 keV temperature.

CONCLUSION

The implosion of a conical wire-array Z-pinch onto a deuterated polyethylene fibre was studied on the S-300 pulsed power generator at the Kurchatov Institute. The study of neutron emission in these experiments was focused mainly on the estimation of neutron emission time and neutron energies. The knowledge of neutron spectra at different directions relative to the Z-pinch axis provided important information about the energy of deuterons which produced fusion reactions.

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