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Deuterated fibre Z-pinch on the S-300 generator

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Abstract
Dense Z-pinch experiments were carried out on the S-300 generator (3.5 MA, 100 ns, 0.15 Ω) at the Kurchatov Institute in Moscow. The experiments were performed at a peak current of 2 MA with a rise time of about 100 ns. The Z-pinch was formed from a deuterated polyethylene fibre of 100 μm diameter and 1 cm length. The optical emission began early in the discharge and the coronal plasma expanded with a radial velocity of about 2×10^6 cm s^{-1}. The optical and XUV emission continued for several hundreds of nanoseconds. The peak power of sub-keV radiation reached 30 GW near the maximum current. The total emitted energy exceeded 5 kJ. The neutron yield from the D-D reaction reached 2×10^7 per shot. The mean energy of neutrons obtained from time-of-flight analysis in the axial (downstream) direction was near 2.45 MeV.

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1. Introduction

The dense Z-pinches initiated from cryogenic deuterium fibres were investigated in the 1980s and 1990s in connection with the research of controlled thermonuclear fusion and radiative collapse [1–4]. The plan was to heat and ionize the fibre from frozen deuterium and to confine the high density and high-temperature plasma column within a small diameter. Fibres from deuterated polymer were also employed [5–8] because their discharge behaviour was roughly the same (cf [4]) and at the same time they were easily available and could be handled much easier than the frozen deuterium ones. Unfortunately, the development of MHD instabilities and global expansion of a pinch column were observed from the very beginning of the discharge and so the idea of the fibre Z-pinch as a fusion reactor was abandoned.

The purpose of our fibre experiments on the S-300 generator was (i) to compare results with the wire array implosion onto a central fibre [9, 10] and (ii) to study the generation of XUV and x-ray radiation together with neutron production which gives insight into the acceleration of ions and hence into the processes taking place in Z-pinches.

2. Apparatus and diagnostics

2.1. Current generator and Z-pinch load

So far most experiments with dielectric fibres have been pursued on high impedance (about 1 Ω) pulsed power generators since they are better optimized to drive currents into a high-impedance load, which a dielectric fibre surely is (cf [11]). Despite this, however, we carried out fibre Z-pinch experiments on a low impedance S-300 generator (3.5 MA, 100 ns, 0.15 Ω) at the Kurchatov Institute in Moscow. The experiments were performed at a current level of 2 MA with a rise time of about 150 ns. The Z-pinch was formed in a vacuum chamber from a deuterated polyethylene fibre of 100 μm diameter and 1 cm length.

2.2. Diagnostics

In order to study the dynamics of a Z-pinch plasma, an extensive set of diagnostic tools was used. The diagnostic set-up is displayed in figure 1.

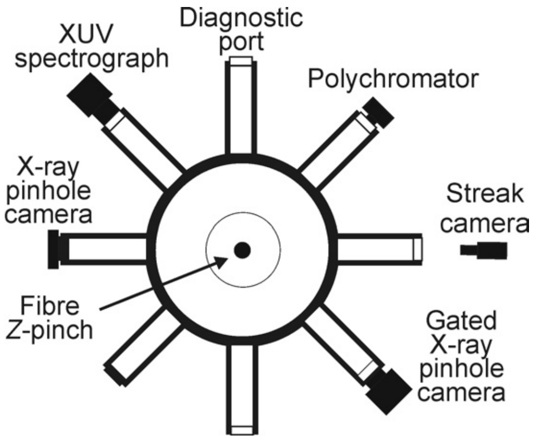

Figure 1. Diagnostic set-up on the S-300 generator, Moscow.

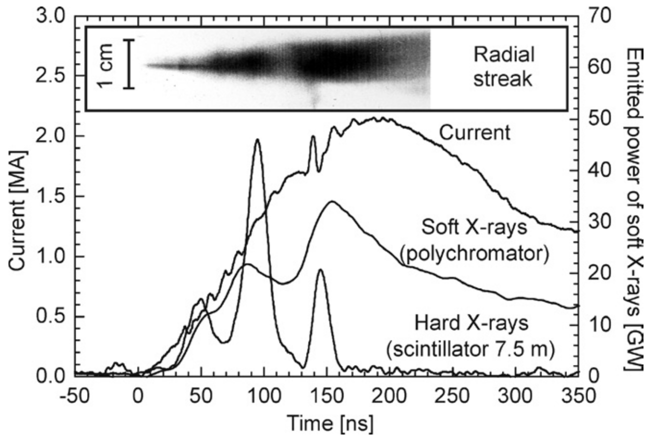

Figure 2. Current waveform, emitted power of soft x-rays, hard x-ray signal and streak photograph, shot number 030606-1.

Firstly, to provide time and space resolved information about visible emission, an optical streak camera was used. The streak camera was performed in the radial mode, i.e. with a slit parallel to the Z-pinch axis.

Secondly, x-ray radiation was detected with two x-ray pinhole cameras, XUV grazing incidence spectrograph, and 11-channel soft x-ray polychromator. One x-ray pinhole camera, which was gated, recorded four frames with 2 ns exposure and 10 ns inter-frame separation. All four frames were filtered with 24 μm thick beryllium. The other pinhole camera, time integrated and differentially filtered (without a filter, and with 5 μm and 24 μm mylar), was used to observe the plasma in various spectral ranges with a spatial resolution of 100 μm. Even better spectral information was obtained by a time integrated XUV grazing incidence spectrograph which recorded carbon K-shell lines. Time resolved studies of soft x-ray emission were conducted using an 11-channel polychromator. The various combinations of glancing incidence mirrors, transmission filters, and semiconductor detectors enabled the detection of photons in channels of 50, 80, 120, 180, 270, 365, 600, 800, 1000, 1200 and 2200 eV.

Finally, as far as neutrons are concerned, a time-of-flight analysis of neutrons was made possible by two axially positioned SSDI-8 scintillators at distances of 2.70 m and 7.45 m (downstream). The neutron yield was measured by an indium activation counter. Since the activation counter has not been calibrated *in situ* and since we have some experimental evidence that the yield was underestimated by one order of magnitude, it is possible that the neutron yields should be multiplied by 10 throughout this paper and [9, 10].

3. Experimental results

3.1. Current waveform and x-ray emission

The results of a number of diagnostic tools from the discharge number 030606-1 are shown in figures 2–5.

In figure 2, we present the current waveform, optical streak photograph and some x-ray characteristics. Time $t = 0$ corresponds to the start of the current at the fibre. The streak photograph shows that the optical emission began early in the discharge. The optical emission continued for several hundreds of nanoseconds and its intensity was modulated by several peaks. Similarly, the soft x-ray power (measured by the 11-channel polychromator) peaked more than once. The peak power of sub-keV radiation reached 30 GW near the maximum current. The total emitted energy exceeded 5 kJ.

Also, it could be observed that the pinch consisted of several distinct layers. We could distinguish a low-density coronal plasma and higher-density interior layers. The coronal plasma was expanding with the radial velocity of about 2×10^6 cm s^{-1} (see figure 2). Interior layers were displayed by the x-ray pinhole cameras (see figure 3).

The time integrated soft x-ray images (figures 3(a) and (b)) show a radiating sub-millimetre core. Several bright spots were observed near the cathode and anode. Some of them were smaller than 100 μm in diameter, i.e. smaller than the spatial resolution of the pinhole camera. At the peak of the soft x-ray pulse (figures 3(d) and (e)), the ‘harder’ radiation came from several bright spots near the anode. (Note of the fact that the detection efficiency varied between sections of MCP detector. For that reason the decreasing emission recorded by the pinhole camera (figures 3(c)–(e)) did not correspond to the increasing power of soft x-rays (figures 2).) Another noticeable feature in figure 3 is the radiation from the anode which indicates runaway electrons in the outer regions. On the basis of other experiments [8], we assume that the strong radiating plasma near the cathode (figure 3(c)) was the expanding electrode material.

Figure 4 presents the temporally and spatially integrated spectrum in the 200–600 eV spectral range where K-shell lines of carbon ions occurred. The plasma parameters determination is somewhat problematic since the opacity effects with space- and time-dependence have to be taken into account. To simulate the spectrum with one temperature and one density was therefore impossible. Nevertheless, most features of the obtained spectrum were simulated with the ‘integrated’ electron temperature T_e of 120 eV (cf the synthetic spectrum in figure 4). The estimation of the electron density n_e was ambiguous owing to its dependence on the choice of the optical path length l_Ω. The only feature that was not included in the synthetic spectrum was the strong continuum of He-like ions. This continuum could have originated from the part of plasma volume with higher density

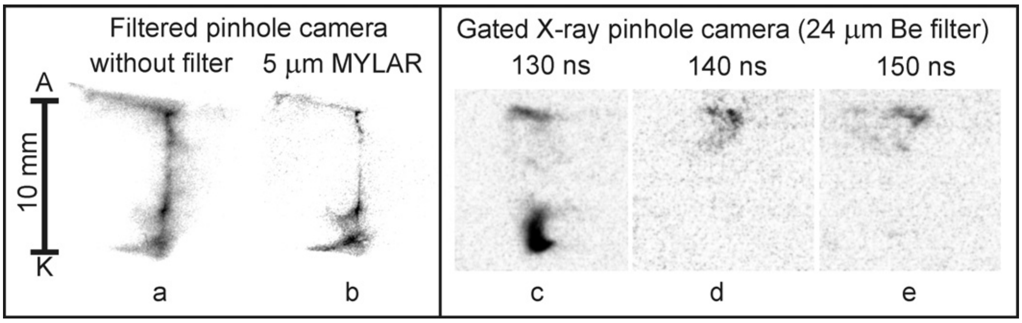

Figure 3. Time integrated x-ray pinhole images and the sequence of gated x-ray images, shot number 030606-1.

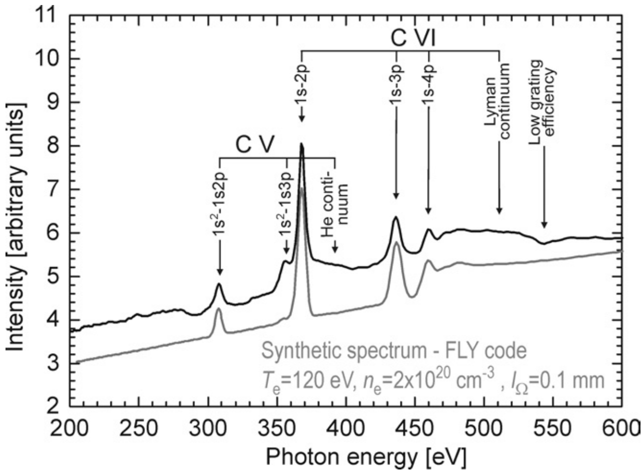

Figure 4. XUV spectrum in the 200–600 eV spectral range, shot number 030606-1.

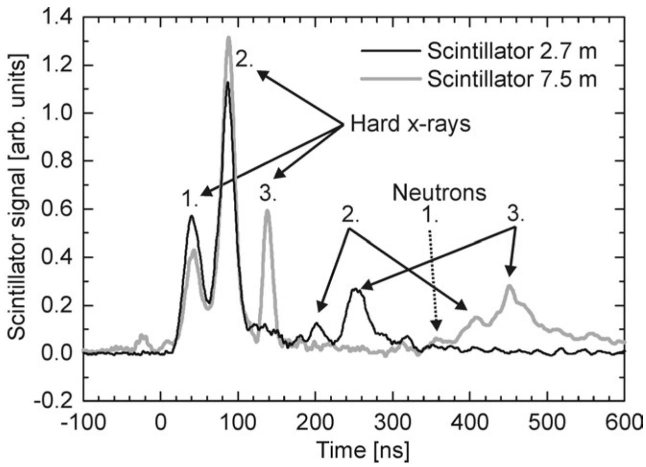

Figure 5. Scintillator signals in shot number 030606-1, neutron yield 2×10^7.

($n_e > 10^{21}\,\mathrm{cm}^{-3}$) and lower temperature ($T_e < 120\,\mathrm{eV}$). As regards the emitted energy of the carbon Lyman-α line, the 365 eV channel of the polychromator measured the total energy of about 30 J.

3.2. Neutron measurements

The results of neutron measurements are demonstrated on shot number 030606-1 that was described above. In this shot, an indium activation counter detected the modest neutron yield of 2×10^7. The yield was calculated assuming isotropic emission over a sphere.

Furthermore, we determined the production time and mean energy of neutrons from two time-of-flight scintillators situated at distances of 2.70 and 7.45 m away from the pinch. The output from these two scintillators is shown in figure 5. To clarify the graph in figure 5, x-ray pulses from both scintillators were placed over each other. The time-of-flight of x-rays and the delay of photomultiplier were included. Time $t = 0$ corresponds to the start of the current and hence the time axis is the same as in figure 2.

In figure 5, three hard x-ray pulses emitted in shot number 030606-1 can be seen. The time-of-flight analysis proved that each of x-ray pulses was accompanied by neutron production. The x-ray pulse number 1, 2 and 3 corresponded to neutron pulses number 1, 2 and 3, respectively. Most of the neutrons were emitted at the third hard x-ray pulse. As figure 2 shows, the third x-ray pulse corresponded both to the peak of soft x-rays and to the noticeable change in the current waveform. The mean neutron energy (measured in the axial, downstream direction) of all three pulses was $2.45 \pm 0.05\,\mathrm{MeV}$ which corresponds to the D-D reaction.

4. Discussion

The experimental results presented in this paper are similar to other fibre Z-pinch experiments. There was no indication of globally collapsing pinch although the Pease–Braginskii current (600 kA for polyethylene fibres) was exceeded. This rapid expansion is usually explained by the anomalous resistivity in a low-density corona [12] and/or turbulent heating arising from MHD instability growth [13]. As for MHD instabilities in our experiment, the evidence of an $m = 0$ mode was given by the x-ray pinhole camera which recorded bright spots.

The key issue of our experiment was the modest neutron yield of about 10^7 per one shot. In contrast, neutron yields of between 10^9 and 10^{10} were typical in other fibre Z-pinches even with a lower current [1–8]. One of the possible explanations for that could be the diameter of the fibre used. Stephanakis reported that neutron yield decreased with increasing fibre diameter [5, 6]. For instance, 100 μm diameter fibres produced ten times fewer neutrons than fibres of 20 μm diameter. Another fact that could play an important role is the current generator. At this point, we could mention the disappointing results and the modest neutron yield reported by Decker and Kies on a 'low' impedance SPEED 2 generator [3].

Another significant result we obtained was the mean energy of neutrons, which was near the value of 2.45 MeV. In addition to that, the time of neutron production corresponded to soft x-ray emission (cf figures 2 and 5) and hence the detected neutrons could be of thermonuclear origin. This result would be consistent with the Z-pinch experiments initiated from thicker ($>40\,\mu$m) fibres on the Gamble II [2] and Kalif [7] generators. Such a conclusion seems to be more optimistic than the beam–target mechanism reported on the Poseidon [1] and MAGPIE [8] generators. However, the shift from 2.45 MeV could be too small to be identified. Therefore it is still feasible that the neutron yield was caused by beam–target interactions at the relatively slow motion of dense plasma regions. The beam–target mechanism is also supported by the 'integrated' electron temperature of 120 eV that is too low even for the modest neutron yield produced by the thermonuclear method. This discrepancy was also observed by the HDZP group in Los Alamos National Laboratory. The explanation they proposed was the model of instability heating in which the ion temperature T_i was substantially higher than the temperature of electrons T_e [13]. Ion temperature T_i higher than the electron temperature T_e was also observed during the stagnation in wire-array Z-pinches and was ascribed to ion viscous heating within fine-scale interchange instabilities [14]. Another explanation of how to reconcile the observed neutron yield with a low electron temperature is that only a small part of the plasma volume was heated to a sufficiently high temperature. Then the bulk of the plasma could remain cold. But even if the fusion mechanism were thermonuclear, it would still hold that the neutron yield was modest in our experiment and that the yield higher than 10^{10} has not been reported by other research groups.

Finally, we compare our fibre Z-pinch with the implosion of a wire array onto a deuterated fibre. Both experiments were carried out on the same current generator S-300 with similar deuterated fibres and currents [9, 10]. We found that the neutron yield was one order of magnitude higher in the case of implosion of a wire array. Another difference we observed was a slight shift of the neutron mean energy from 2.45 MeV towards higher energies [10].

5. Conclusion

The dense Z-pinch formed from a deuterated polyethylene fibre was studied on the 'low' impedance S-300 pulsed power generator at the Kurchatov Institute. The majority of the observed phenomena were in agreement with other fibre Z-pinch experiments carried out on 'higher' impedance generators. The important result was obtained by the time-of-flight analysis which determined the mean neutron energy of about 2.45 MeV. However, the modest neutron yield of 2×10^7 per shot was one order of magnitude lower than in our experiments with the implosion of a wire array onto a fibre.

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