Interferometry of the plasma focus equipped with forehead cathode

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Abstract. The PF-1000 plasma-focus facility in Warsaw, equipped with Mather-type coaxial electrodes working with a deuterium filling, was modified by the addition of a cathode disk in front of the anode front-plate at a distance of 3 cm. The plasma was diagnosed with temporal resolved interferometry and neutron diagnostics. The modified electrode configuration showed an increase of the current in the pinch phase and a decrease of the total neutron yield. The lower total neutron yield is caused by a lower energy of deuterons producing the observed neutrons and by a decrease of the velocity of transformations of the structures in the pinch column.

Key words: interferometry • neutron diagnostics • plasma focus discharge

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Received: 13 October 2011
Accepted: 30 November 2011

Introduction

The z-pinch facilities are simple and efficient sources of neutrons and protons produced from deuterium-deuterium (D-D) reactions [1, 5]. The plasma focus PF-1000 device in Institute of Plasma Physics and Laser Microfusion (IPPLM, Warsaw, Poland) is a convenient facility for the study of mechanisms of the D-D reactions due to its relatively high neutron yield (above 10^{10}) and unique X-ray, neutron and interferometry diagnostics [2]. The position of scintillation detectors in the upstream direction at distances 7–84 m from the pinch makes it possible the use of the time-of-flight (TOF) method and determining the time of neutron production and distribution of their energy in axial direction. From the neutron energy spectra, the mean energy of deuterons producing observed neutrons can be evaluated [4]. The system of mirrors splits the laser pulse into 16 beams passing the plasma. From the interferograms created, we can estimate the plasma structures and density distribution during the neutron production.

The hard X-rays (HXRs) and neutrons are produced in temporal correlation with the formation and disintegration of spherical-like dense structures, plasmoids. These plasmoids are the dominant source of fusion reactions as well. It was estimated that each intense neutron pulse was produced by about 10^{17} fast deuterons with an energy range of 100–200 keV and with total energy of 3–8 kJ [2]. This high energy of deuterons confirms the beam-target origin of the neutrons. The small cross-section of the fusion D-D reaction ($\sim 10^{-30}$ m^{-2}) for the above-mentioned deuteron energy and for electron densities 2–4 × 10^{24} m^{-3} is a reason for the low probability of neutron production by deuteron catch ~ 1:1 000 000. Therefore, practically the total energy of fast deuterons escapes from the pinch. At the ion temperature of this plasma (about 1 keV), only about 1% of the thermonuclear neutrons is produced. To increase this temperature and thermonuclear neutron output, it is necessary to have available a higher plasma density together with a lower energy of fast deuterons. Under these conditions, the fast deuterons can be effectively confined in the plasma and more of their energy can be absorbed in plasma through Coulomb interactions.

This paper presents results which were obtained after placement of an additional cathode disc in front of the anode end. This modification was motivated by two aims: to form the electrode configuration more similar to the classical z-pinch and to obtain a higher energy density within the pinch region.

Experimental results

The PF-1000 facility is equipped with Mather-type coaxial electrodes, and it operates at the charging voltage of 24–27 kV, stored energy about 400–500 kJ, and the current during the pinch phase 1.2÷1.8 MA. The initial pressure of the deuterium filling was 150÷300 Pa. The scheme of electrode configuration with a disk of 3 cm in the front of the anode of 23 cm in diameter is depicted in Fig. 1.

The voltage, current and current derivative signals were measured at the current collector near the main insulator. The soft X-ray (SXR) pulses in the range of 0.6÷15 keV were recorded with a silicon PIN detector shielded by means of a Be-foil of 10 μm in thickness. The time-resolved measurements of hard X-rays and neutrons were made with a set-up of scintillation detectors coupled with fast photomultipliers. The energy of registered HXR passing through the chamber wall was above 100 keV. The detectors were situated side-on and upstream in order to estimate the neutron energy spectra in more detail using the TOF analysis. The interferometric measurements were performed with a Nd:YLF laser working at the second harmonics (527 nm). One laser pulse (lasting below 1 ns) was split by a set-up of mirrors into 16 separated beams, penetrating through a Mach-Zehnder interferometer. The plasma region was investigated with a time delay ranging from 0 ns to 220 ns. The total neutron yield was calculated from the data recorded with silver-activation

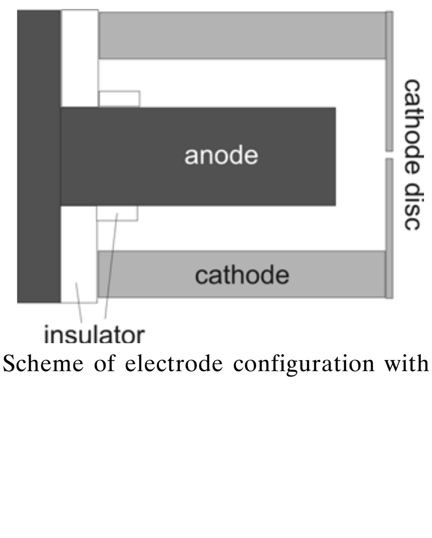

Fig. 1. Scheme of electrode configuration with cathode disk.

counters, which were placed at different angles to the discharge z-axis. The first peak of the PIN detector signal was assigned as $t = 0$.

We compared 28 shots with the cathode disc and 45 without it. The experimental results differ considerably. The registered maximum of the discharge current was without change, but the current at the time of the pinch phase was higher, by about 20% than in the configuration without the disk. By contrast, the dip of the derivative of the current in time and maximal voltage decreased to 60%. The total inductance of the electrode system and the pinched column decreased by about 10–20%. Then, we can estimate the change of energy E delivered to the plasma using the equation

$$E = UI\Delta t - L\,I\frac{dI}{dt}\Delta t \tag{1}$$

where the waveforms of voltage U current I and current derivative dI/dt are registered at the collector. On average, this energy is only about 70% of that delivered without the disk, yet the length of the pinch of 3 cm is more than two times lower than that without the disk. Therefore, the energy density obtained in configuration with the disk should increase above 40%.

The neutron yield decreased, on average, to 30%. In Fig. 2, we can see the waveforms registered at the same distance of 7 m, one upstream (7u) and the second side-on (7r), which are shifted with TOF method using energy of 2.45 MeV to the centre of the pinch. In shots without the disk, the peaks of signals registered upstream were imaged 20–30 ns after the side-on peaks. In Fig. 2, the temporal difference of both waveforms is not evident. Consequently, the anisotropy of neutron energies in both directions is small. Another important feature of the signals depicted in this figure, long neutron emission, has a duration of 200 ns.

The waveforms registered at a distance of 7 m show a picture of temporal distribution of the neurons produced. More precise determination of energy distribution can be obtained from the most distant detector at 83.7 m. In Fig. 3, we can compare signals from the nearest and most distant detectors shifted by the TOF method, similarly as in Fig. 2. The mean energy value of neutrons upstream is 2.2 MeV, close to the 2.45 MeV in comparison with the mean energy of neutrons (2.0–2.1) MeV registered in the shots without the disk. Then, the axial component of deuteron energy in the range of 40–80 keV (with the disc) is lower than (100–200) keV obtained without the

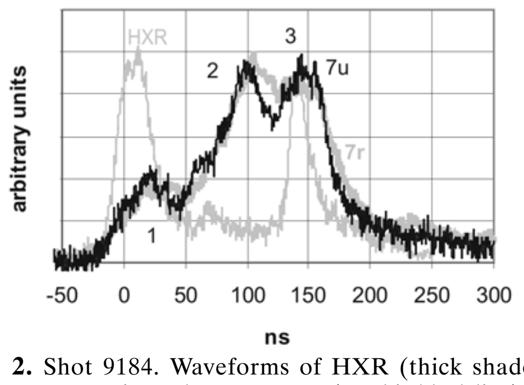

Fig. 2. Shot 9184. Waveforms of HXR (thick shadow) and neutrons registered 7 m upstream (7u, thin black line) and 7 m side-on (7r, thick shadow). The numbers mark a number of the HXR and neutron pulse in the shot.

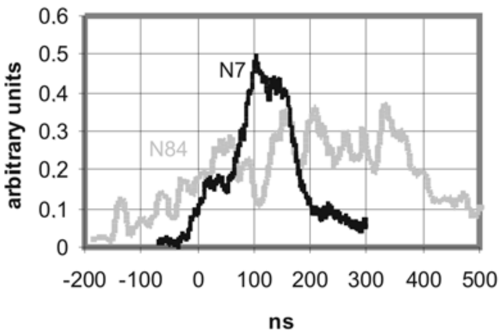

Fig. 3. Shot 9184. Waveforms of neutrons registered in 7 m (N7, black) and 84 m upstream (N84, shadow), temporarily shifted by TOF to centre of the pinch.

disk. As a result, we can infer that in the presence of the disk, a lower energy of fast deuterons is observed.

The interferometry images show the dependence of the line densities of the plasma along the path of diagnostic beam on its distance from the axis. This value can be transformed into radial distribution of densities under the assumption of radial symmetry using the Abel inversion. In the case of deuterium in fusion conditions, the electron density is equal to the ion density. In Fig. 4 we see the distribution of deuteron densities at four different times: at the onset and maximum of the first neutron pulse and at the start and the end of the third pulse. These images document the emission of neutrons during the creation and disintegration of spherical-like structures with a dense centre (electron density above 5×10^{24} m^{-3}). With the disk electrode modification, a lower velocity of transformations of structures is observed. Specifically, the evolution of constriction is considerably moderated, while its implosion usually correlates with an increase of the density in the column surface. It is probable that the breakdown occurs here and switches a part of the current going through the constriction. The smaller transportation velocity of structures can be a reason for the lower energy of fast deuterons and lower total neutron yield. The cross-section of the D-D reaction for deuterons with an energy of 150 keV is 5–6 times higher than for 75 keV.

Knowing the diameter of a plasmoid column of about 1 cm and the current in the pinch of about 1 MA, we can evaluate the mean magnetic field in the pinch about 10–20 T and estimate the energy of fast deuterons confined in the plasmoid. This upper limit should be 20–30 keV. Then, the deuterons with energy below 20 keV can be confined by the magnetic field, and the neutrons produced by these deuterons can have isotropy distribution of energies. The deuterons with energy above 30 keV can be confined only partially and energy of neutrons produced by these deuterons (above 2.65 MeV) has an anisotrophy distribution with the dominant direction downstream.

Similar results were obtained in a plasma focus device with the compact cathode plate without holes [3]. The decrease of the neutron yield, voltage, energy of HXR and neutrons in the range of 30–80 keV, together with an increase of isotropy of neutron production were obtained in similar positions of the plate a few cm in the front of the anode.

Increase of the erosion of the ions from the anode and the disk was a disadvantage of this adapted elec-

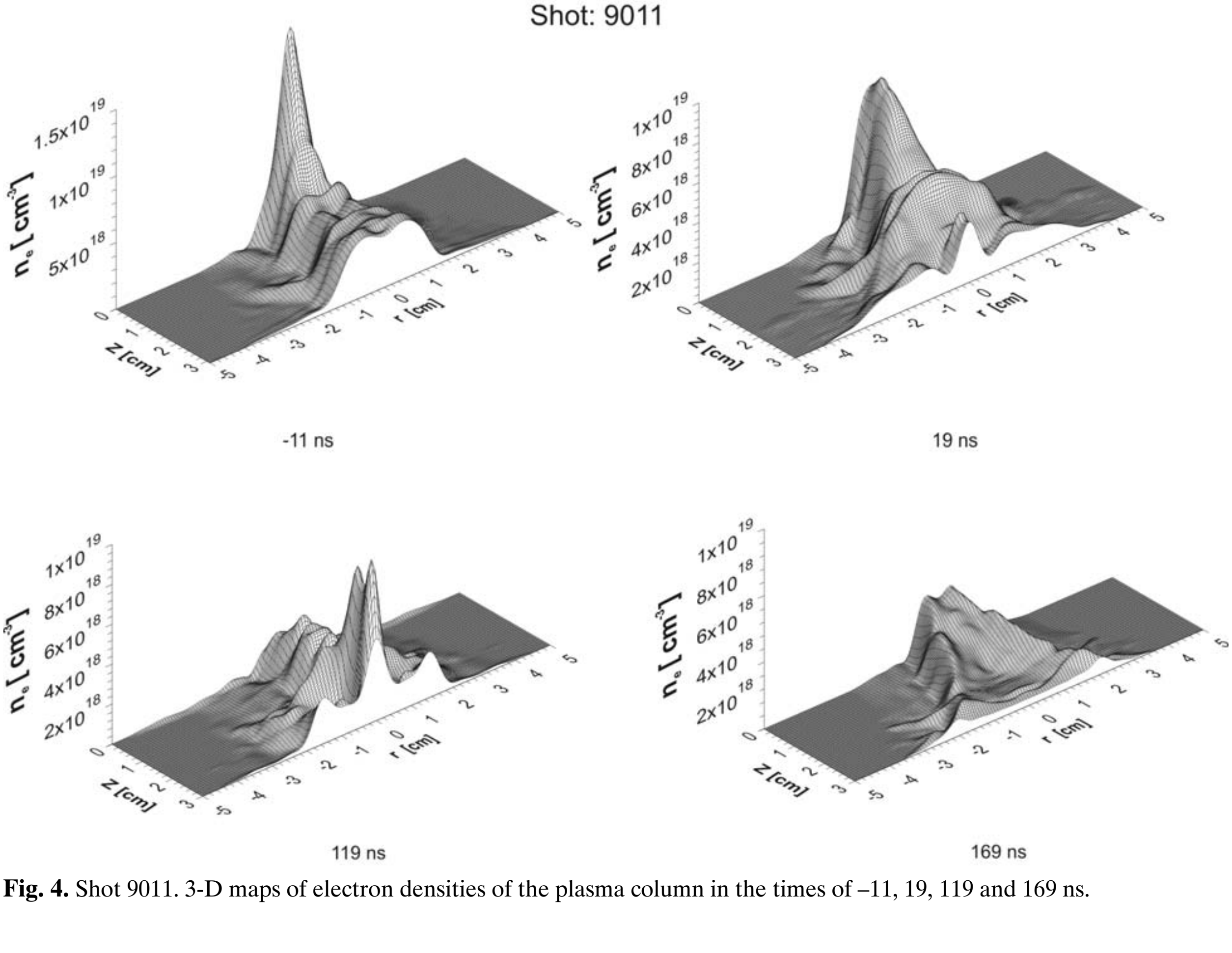

Fig. 4. Shot 9011. 3-D maps of electron densities of the plasma column in the times of –11, 19, 119 and 169 ns.

trode configuration, specifically for interferometry due to the opacity of the diagnostic window during the above 4–5 shots.

Summary and conclusions

The cathode disk placed 3 cm in the front of the anode face in a PF-1000 device has an important influence on the characteristics of the plasma and neutron production, which can be summarized as follows:

1. The current in the pinch phase was increased by about 20%. The depth of the current derivative and the peak of voltage were depressed to 50–60%, but the energy density in the pinch increased by about 40%.
2. The neutron yield was decreased to 30% and the mean energy of deuterons producing neutrons was depressed below 100 keV. The decrease of the neutron yield was caused by the stronger decay of cross-section of the D-D fusion reaction for lower energy of fast deuterons.
3. The velocity of transformations, evolution of instabilities and formation of the plasmoids was also depressed.
4. The changes mentioned above enabled better confinement of the fast deuterons in the magnetic field and heating of the electrons and ions in the pinch due to Coulomb interactions. The upper energy boundary for confinement of fast deuterons in the pinch was evaluated as 20–30 keV.

Acknowledgment. This research has been supported by the research programs of the Ministry of Education (grant nos. LA08024, ME09087, LC528), the IAEA (grant no. RC14817), the CTU (grant no. SGS10/266/OHK3/3T/13) and the National Science Centre, Poland (no. 0661/B/H03/2011/40).

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