EXPERIMENTAL STUDIES OF THE INTERACTION OF ION- AND PLASMA-STREAMS WITH CARBON-BASED TARGETS PLACED NEAR A CATHODE OF PLASMA-FOCUS FACILITY

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The paper presents measuring techniques and results of experiments performed within the PF-1000 Plasma-Focus facility in order to investigate the interaction of high-energy deuteron beams (of E_D >100 keV) and deuterium plasma streams (of $v_{str} \geq 10^7$ cm/s) with carbon-based materials, designed for the first wall of a future thermonuclear reactor of the ICF or MCF type. Particular attention was paid to the verification of diagnostic techniques, which might be used for time- and space-resolved studies of the interaction of ion- and plasma-streams with the targets placed near the cathode outlet inside the experimental device.

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1. INTRODUCTION

In order to test different materials, which might be used for the construction of a future thermonuclear reactor, it is necessary to study behavior of these materials during the interaction of high-energy deuteron beams and energetic plasma streams. The main aim of the recent studies at the IPPLM in Warsaw, Poland, was to verify applicability of different measuring techniques and to investigate some selected targets, e.g. those of the (Cu + C) type.

2. EXPERIMENTAL SET-UP

In the experiments to be described the use was made of the PF-1000 facility [1-2]. Energy stored in the condenser bank was varied from 600 kJ to 800 kJ. The peak discharge current amounted to 2.3 MA. The working gas was pure deuterium under the initial pressure changed from 400 to 600 Pa.

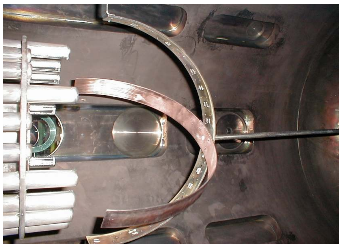

Fig. 1. Internal view of the PF-1000 experimental chamber, which shows a semicircle support with a rotating shield

The investigated targets were placed upon a semicircle support, which was placed inside the main experimental chamber and had an electrical contact with walls, as shown in Fig. 1. A distance between the anode and investigated targets was equal to 15 cm. The plasma-ion flux density upon the target reached 10^{10} W/cm^2 and the interaction period was 0.1-1.0 μs.

3. STUDY OF DIAGNOSTIC METHODS

The first measuring technique was based on the recording of the plasma visible radiation (VR) observed through a slit perpendicular to the discharge axis, which was placed at a distance of 3 cm from the anode outlet. That method enabled the "quality" of successive discharges to be determined as regards the plasma stream velocity, its compression and symmetry. It made possible to discern "good shots" (i.e. fast, symmetrical and high-compression discharges) from "weak shots" (i.e. slow, unsymmetrical and low-compression ones), as it is shown in Fig. 2.

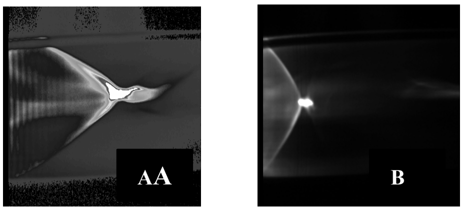

Fig. 2. Streak-camera pictures of the collapsing plasma sheath: A - a "weak shot", B - a "good shot"

The spatial- and temporal-analysis of such smear pictures made it possible to determine the radial implosion velocity of the plasma-current sheath (PCS). It appeared that during the final stage of the plasma collapse near the axis the PCS velocity was ca. 10^{7} cm/s for "weak shots" and 3-5Ч10^{7} cm/s for good ones.

The second measuring technique applied a four-frame high-speed camera, which was used for the observation of the VR from the PF-pinch column as well as that from plasma produced between the pinch and the investigated target. It made possible:

1) to determine geometry and velocity of the plasma collapse process, as well as velocity of plasma streams (jets) emitted along the discharge axis and shock waves formed in front of the pinch,
2) in some cases to observe the structure of fast ion beams emitted from the PF-facility and to estimate their speed,
3) to evaluate a velocity of the expansion of a secondary plasma produced by fast ions and plasma jets at the surface of the irradiated target.

An example of a sequence of four pictures, which was taken for a single shot during the plasma collapse phase, is shown in Fig. 3.

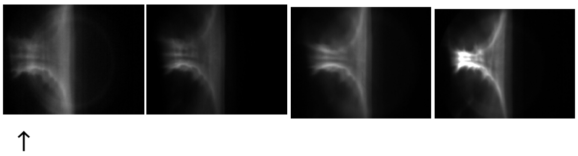

Fig. 3. The sequence of four VR frames taken during a single shot, which demonstrate the formation of the pinch column. The arrow shows the anode end-plane

Taking into consideration the spatial- and temporal- calibration of the picture it was found that for the considered shot the collapse speed was of the order of 5Ч10^{7} cm/s, what coincided with the previous measurements performed with the streak-camera. Other frame pictures, which show the characteristic cases mentioned above, are presented in Fig. 4.

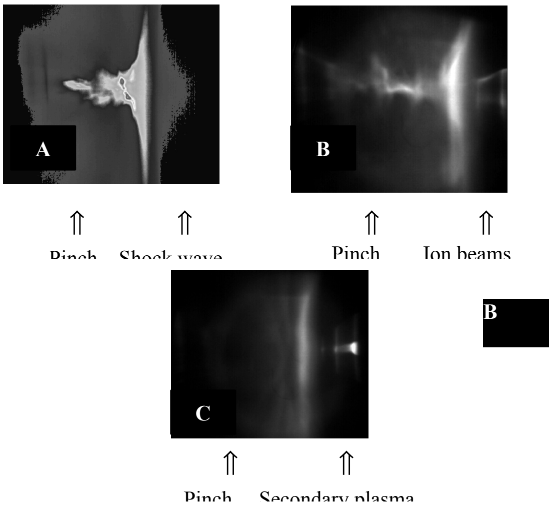

Fig. 4. Selected VR frames showing different phases

Fig.4A presents the formation of the shock wave by the emitted cumulative plasma jet, Fig.4B shows the emission of fast ion streams from the pinch column, and Fig.4C visualizes the formation of the secondary plasma in front of the irradiated target.

Taking into account time intervals between the recorded frames (usually 10 ns), it was possible to determine the shock wave velocity (and consequently the cumulative jet speed of the order of 6-10Ч10^{7} cm/s), to visualize structure and to estimate velocity of the fast ion streams (above 3Ч10^{8} cm/s), and to measure the speed of secondary plasma emitted from the irradiated target (about 10^{7} cm/s). The both techniques were used to estimate the duration of the interaction of each stream (plasma and fast ion beam) on the target surface, their power flux density and a sequence of their interaction with the samples.

The third measuring technique, which was used in the reported studies, applied a four-frame camera recording soft X-rays (SXR). It appeared to be useful especially for determination of the spatial- and temporal-localization of the hottest parts of studied plasma. Some examples are shown in Fig. 5.

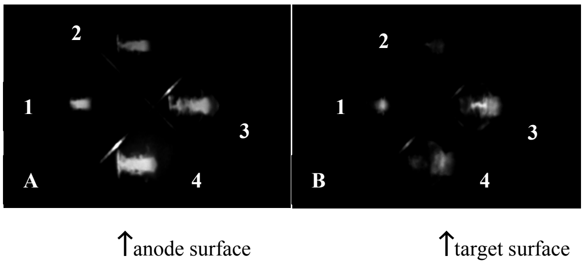

Fig. 5. The first set (A) presents SXR frames showing the evolution of the hottest parts of the pinch, and the second set (B) - the formation of secondary plasma at the irradiated target

It should be noted that all the above described techniques have temporal resolution of the order of 1 ns. Their spatial resolution, as determined by lenses and geometry in cases of VR observations and by an input diameter of the pinhole camera in the case of SXR measurements, was about 100 micrometers.

The fourth measuring technique was based on the use of solid-state nuclear track detectors [3]. That technique delivered information about fast ion (proton and/or deuteron) beams emitted from the PF-1000 facility. Since the nuclear track detectors were placed upon the semicircular support, and the rotating shield was removed during the investigated shots (Fig. 1), the obtained ion track images (after their etching) delivered information about the angular distribution of the fast ions from chosen shots and their energy spectrum. The ob[redacted]results have supported optical pictures recorded ans of the 4-frame VR camera (Fig. 4b). It has been found that the emitted fast deuteron stream has a conical-like structure with the divergence angle (measured to the pinch axis) equal to about 20^0. The measured ion-energy distribution, together with information about the beam configuration and pulse duration (taken also from four-frame pictures), made it possible to estimate the ion power flux density.

The fifth diagnostic technique was based on the application of the optical spectroscopy. It enabled a density and temperature of plasma produced from the irradiated targets to be estimated. The recording equipment consisted of a collimator and quartz light-pipe coupled to the MECHELLE ®900 spectrometer, which enabled the optical spectra to be recorded with the exposition time variable from 100 ns to 200 ms. The applied system had the spatial resolution equal to about 10 mm. An example of the recorded spectrum is shown in Fig.6.

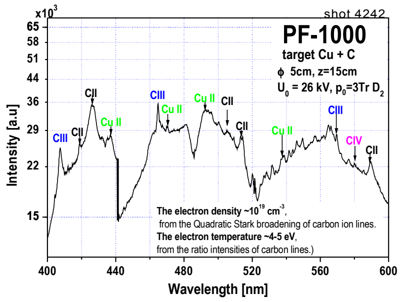

Fig. 6. Optical spectrum with the identified lines of C-ions, as obtained from the PF-1000 experiment

For estimates of the plasma density in the near target region the use was made of the known Inglis-Teller formula, which determines a shift of boundary serial and gives the minimum N_e values [4]:

$$\lg N_e = 23.26 - 7.5 \times \lg n_{max}$$

where n_{max} is the general quantum number for the last Balmer line, which is observed as an isolated one (e.g. if D_β - n = 4, if D_α - n = 3, etc.).

Qualitative information about the temporal behavior of the plasma density might be obtained from the continuum intensity, taking into account that is proportional to N^2. An example is presented in Fig. 7.

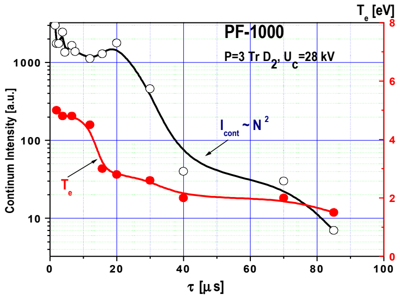

Fig. 7. Temporal evolution of the continuum and electron concentration in PF-1000 experiment

Temporal changes in the continuum intensity (in arbitrary units), as presented in Fig.6, were measured (taking into account the exposition time) at the region λ ~ 700 nm. It should be noted that the region λ ~ 400 nm showed a similar temporal dependence.

The electron temperature (T_e) values were also estimated and analyzed. The T_e estimates were performed using the ratio of intensities of the CIV spectral lines (doublet 580.1 nm, 581.1 nm) and CIII line (multiplet 465.1 nm), assuming the LTE conditions (due to high N_e values). Using all these data and the Saha formula, it was possible to reconstruct "the ionization distribution" for carbon ions.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ВЗАИМОДЕЙСТВИЯ ИОННЫХ И ПЛАЗМЕННЫХ ПОТОКОВ С УГЛЕРОДНЫМИ МИШЕНЯМИ, РАСПОЛОЖЕННЫМИ ВБЛИЗИ КАТОДА УСТАНОВКИ ПЛАЗМЕННЫЙ ФОКУС

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В работе описаны измерительная техника и результаты экспериментов, проведенных на плазменном фокусе PF-1000, направленных на изучение взаимодействия высокоэнергетичных пучков дейтронов (E_D >100 кэВ) и потоков водородной плазмы ($v_{str} \geq 10^7$ см/с) с материалами на основе углерода, разработанными для использования в качестве первой стенки будущего термоядерного реактора, на основе инерциального или магнитного удержания. Особое внимание было уделено проверке работоспособности диагностического оборудования, используемого для исследования с временным и пространственным разрешением взаимодействия ионных и плазменных потоков с мишенями, расположенными вблизи торца катода экспериментальной установки.

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ ІОННИХ І ПЛАЗМОВИХ ПОТОКІВ З ВУГЛЕЦЕВИМИ МІШЕНЯМИ, РОЗТАШОВАНИМИ ПОБЛИЗУ КАТОДА УСТАНОВКИ ПЛАЗМОВИЙ ФОКУС

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У роботі описані вимірювальна техніка і результати експериментів, проведених на плазмовому фокусі PF-1000, спрямованих на вивчення взаємодії высокоенергетичних пучків дейтронів (E_D >100 кэВ) і потоків водневої плазми ($v_{str} \geq 10^7$ см/с) з матеріалами на основі вуглецю, розробленими для використання в ролі першої стінки майбутнього термоядерного реактора на основі інерціального або магнітного утримання. Особлива увага була приділена перевірці працездатності діагностичного устаткування, використовуваного для дослідження з тимчасовим і просторовим дозволом взаємодії іонних і плазмових потоків з мішенями, розташованими поблизу торця катода експериментальної установки.