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Anisotropy of the neutron emission from PF-360 facility operated without and with solid-state targets

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Abstract The paper reports on detailed studies of an anisotropy of the fusion-produced neutrons emitted from the modernized PF-360 facility [10], which has been operated with a pure deuterium-gas filling, without and with some additional solid-state targets containing deuterium atoms. Under standard operational conditions, anisotropy of the neutron yield from the PF-360 facility is similar to that observed in other PF devices. For the first time the neutron emission anisotropy has been measured in the PF experiments performed with a planar cryogenic target covered with a heavy-ice (D_2O) layer. Changes in the $Y_n(\Phi)/Y_n(90°)$ ratio, particularly for angles $\Phi = 0–60°$, have been explained by the known features of the angular distribution of fast deuterons.

Key words anisotropy • beam-target mechanism • Dense Plasma Focus • neutron yield • thermal mechanism

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Introduction

Dense Plasma Focus (DPF) discharges have been investigated since the late 50s, and those studies have been stimulated by their relative simplicity and capabilities to produce intense pulses of electromagnetic and corpuscular radiation [2, 5]. If a DMP facility is filled up with pure deuterium, accelerated deuterons can react with a dense hot plasma volume and produce fusion neutrons. The neutron yield (Y_n) ranges from 10^6 per shot in kilojoule-scale devices, up to about 10^{12} per shot in the largest megajoule facilities, and it usually follows a power law: W_0^2 or I_p^4, where W_0 is the energy supplied, and I_p is the pinch current. Unfortunately, with an increase in W_0 and I_p above some critical values, the neutron yield saturates or even decreases [3, 8]. Also an anisotropy of the neutron emission depends on constructional parameters and experimental conditions.

During recent years, a considerable progress has been achieved in DPF research in many laboratories [12]. Although some research projects still consider the scaling of DPF facilities up to nuclear fusion breakdown experiment [1], most of the recent studies are motivated by ongoing interest in the generation of intense X-ray and/or fast-neutron pulses. The main aim of this work was to study an anisotropy of the neutron emission from the modified PF-360 [10] facility operated without and with additional solid-state targets used for the optimization of the neutron yield [4, 9].

Measuring set-up

The measuring system consisted of two scintillator-photomultiplier (pmt) probes and eight activation-counters with silver foils. The silver-activation counters were prepared according to the standards known from earlier studies and numerous publications. Each activation counter contained a Geiger-Muller (GM) tube of the STS-6 type, which was wrapped by a pure silver foil of 0.1 mm in thickness, and of 160 mm in width. Every wrapped GM-tube was placed inside a paraffin block of 145 mm in diameter, and of 220 mm in width.

In order to make possible studies of an angular anisotropy of fast neutrons, which originated from D-D fusion reactions occurring within the PF-360 facility, all the silver-activation counters were distributed around the main experimental chamber. They were located at different angles, but at the same distance from the center of the electrode ends. The measurements of the neutron yield were performed at the angles as follows: φ_1 = -20.4°, φ_2 = 0°, φ_3 = 30°, φ_4 = 56°, φ_5 = 90°, φ_6 = 124°, φ_7 = 150°, and φ_8 = 180°. The distances of the individual counters from the electrode end center were equal to 345 cm. Due to the safety reasons, the PF-360 experimental chamber was surrounded with an appropriate paraffin shield wall, it appeared impossible to distribute all the activation counters in the same plane crossing the electrode axis. Therefore, five activation counters were placed in the plane perpendicular to the ground level, and three counters (SAC_3, SAC_5, and SAC_6) were located in the horizontal plane, at different angles to the z-axis, as shown in Fig. 1.

All the activation counters have been calibrated by a comparison of their yields with the yields of a reference activation counter (SAC_6), which was placed nearby each tested counter during subsequent PF discharges. Those test discharges were performed under identical operational conditions within the PF-360 device.

Absolute values of the neutron yield have been determined by means of two reference model counters, which were calibrated some time ago with a standard Pu-Be source emitting neutron flux of 1.2×10^6 fast neutrons per second. During those calibration measurements, the radioactive source was placed inside the experimental chamber, at the z-axis, and near the electrode outlet, i.e. in the region emitting most fusion neutrons.

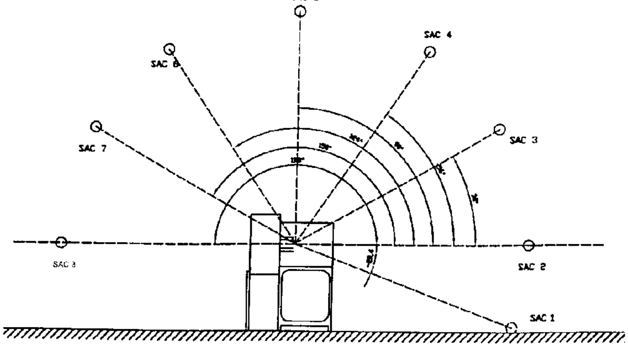

Fig. 1. Positions of the neutron activation counters in relation to the z-axis of the PF-360 experimental chamber.

Experimental results

Studies of a neutron emission anisotropy have been carried out under typical operational conditions of the PF-360 facility [10]. Simultaneously, voltage- and current-waveforms, X-ray signals, fast electron pulses, and pulsed ion beams have been measured. Time-resolved measurements of hard X-rays and neutron pulses have been performed with two scintillator-photomultiplier sets placed at different angles. Time-integrated neutron measurements have been carried out with the silver activation counters (SAC) described above. During each PF discharge with the pure deuterium filling, the use was made of all the activation counters. Control of these counters has been realized by means of a special system shown in Fig. 2.

During the studied PF discharges the synchronization unit (1) triggered the opto-electronic receiver (2), which in turn initiated a control unit (3). The control set, which used appropriate electric relays, switched on all the silver-activation counters (5), and after a chosen delay time (of about half second) it sent subsequent signals: "Stop", "Reset", and "Start again". The measurement period was usually equal to 100 seconds, and it was determined with the acting electronic scalers. When indications of the counters were read out, the initial state (of waiting) was restored with a push-button "Erase". The electrical separation of the counters and electronic scalers appeared to be necessary because of a strong electromagnetic interference of high-current discharges within the PF-360 facility. Therefore, the switching of all the measuring circuits was realized with a delay of 0.1 second after the main discharge.

Results of the neutron yield measurements, which were carried out under the chosen experimental conditions, have been averaged over the performed series of PF shots. A diagram, which shows a dependence of the $Y_n(0°)/Y_n(90°)$ ratio on the initial filling pressure (p_0), is presented in Fig. 3. The ratio of the neutron yields $Y_n(\Phi)/Y_n(90°)$, which was measured as a function of the angular position of the SAC at different operational pressures, is shown in Fig. 4.

Analogous measurements have also been performed within the PF-360 facility during experiments with additional cryogenic targets [4, 9]. Since the highest neutron yield was achieved with the planar cryogenic target, when it was placed at the distance of L_0 = 225 mm from the electrode outlet [4, 9], particular attention is paid to that configura-

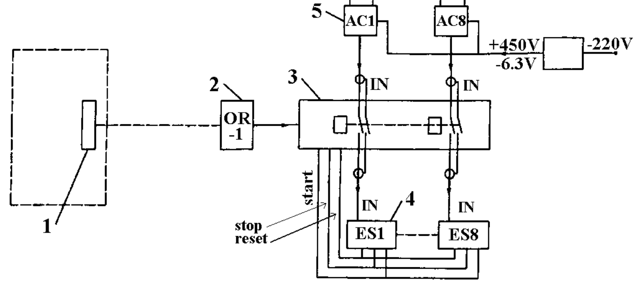

Fig. 2. Electronic control system used for the operation of neutron activation counters placed around the PF-360 experimental chamber. 1 – synchronization unit, 2 – opto-electronic receiver, 3 – central unit, 4 – electronic scaler, 5 – activation counter.

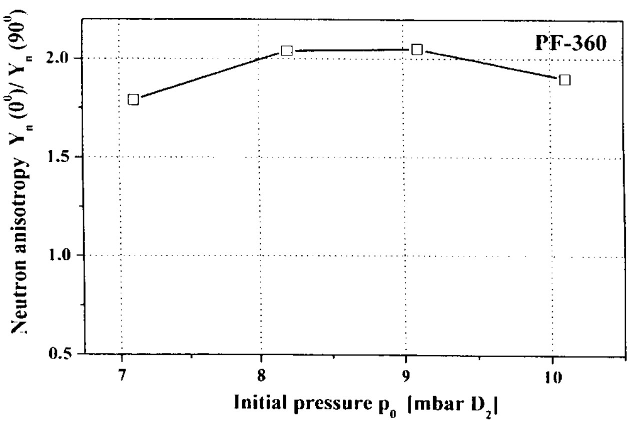

Fig. 3. Neutron emission anisotropy as a function of the deuterium filling pressure within the PF-360 experimental chamber.

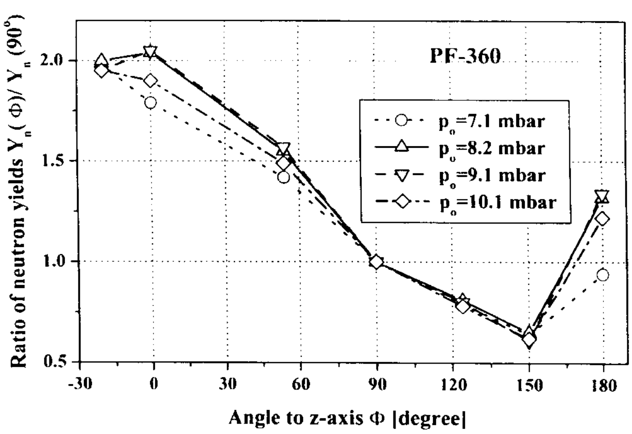

Fig. 4. Neutron anisotropy as a function of angle measured in relation to the z-axis of the PF-360 experimental chamber.

tion. Diagrams, showing the $Y_n(\Phi)/Y_n(90°)$ ratio *versus* the angular position (Φ) for different experimental conditions, are presented in Figs. 5 and 6.

Analysis of results

The observed anisotropy of the neutron emission from the PF-360 facility gives evidence that accelerated primary deuterons, responsible for the D-D reactions, have some privilege direction of their average motion, similarly as in other PF facilities [12]. The highest neutron anisotropy $Y_n(0°)/Y_n(90°)$ of the order of 2.0 (see Fig. 3) was measured at the optimal operational pressures (ranging from 8 mbar to 9 mbar D_2), when the highest neutron yields were achieved. It proves that the thermal mechanism of the neutron generation in the PF-360 facility plays a secondary role, and the beam-target interactions are of primary importance under the considered experimental conditions.

The measured dependence of the $Y_n(\Phi)/Y_n(90°)$ ratio on the angular position (Φ), as shown in Fig. 4, seems very similar to the results of other PF experiments. Taking as a reference value $Y_n(90°)$, the highest neutron yield (almost 2 times higher) was observed on the z-axis (at Φ = 0°) at all the investigated operational pressures. It can be explained by an important role played by fast deuteron beams emitted mainly along the z-axis. The lowest values of Y_n were registered at angles Φ = 100–160°, which says that the population of fast deuterons emitted in these directions is relatively small. It should, however, be noted that the local minimum at Φ = 150° could result from the scattering of neutrons by the main collector plates and shieldings, as well as by HV coaxial cables connected with the PF-360 experimental chamber. An increase in the Y_n value at Φ = 180° is in agreement with results of computations of deuteron trajectories [6, 7], which showed the propagation of some deuterons in the upstream direction.

The important role of beam-target mechanisms has been also confirmed by the results of the neutron measurements in experiments performed with additional cryogenic targets. From data presented in Fig. 5, one can easily see that the introduction of the planar target, even without its coating with a heavy-ice (D_2O) layer, induces an evident decrease in Y_n at angles Φ = 0–60°. This effect seems to be weaker

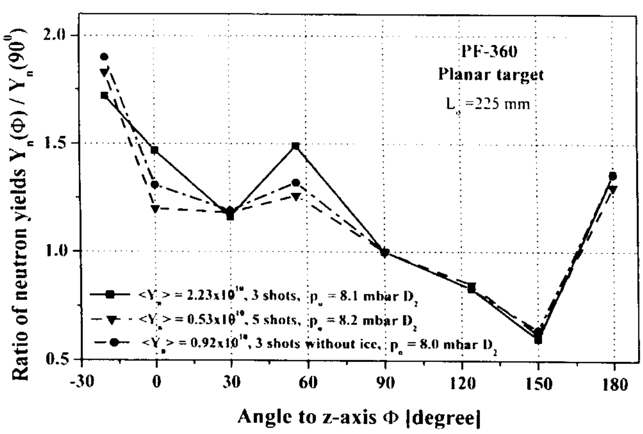

Fig. 5. Neutron anisotropy as a function of angle in relation to the z-axis, as measured in the PF-360 facility for shots at U_0 = 30 kV, W_0 = 122 kJ, which performed with the planar cryogenic target without and with a D_2O-ice layer.

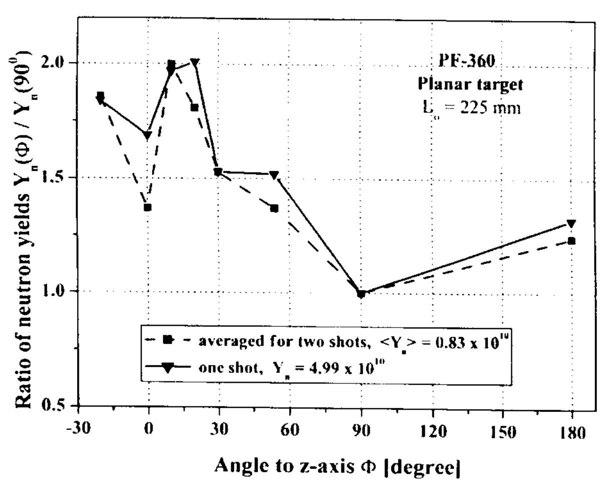

Fig. 6. Neutron anisotropy as a function of angle in relation to the z-axis, as measured in the PF-360 facility for "good" shots at higher initial pressure p_0 = 9.9 mbar D_2, U_0 = 30 kV, and W_0 = 122 kJ, which performed with the planar cryogenic target covered with a D_2O-ice layer.

when the operational pressure is optimized, and the highest neutron yields ($Y_n = 2.2\times10^{10}$) are achieved. Some rise of Y_n at $\Phi = 30–70°$ can be explained by wings in the angular distribution of fast deuterons, which were measured in previous studies of the fast ion emission [11].

It should be noted that an influence of the local minimum in the deuteron angular distribution, which usually appears along a symmetry axis of the pinch column [6, 7, 11], may be stronger marked for better PF shots with higher neutron yields, as one can see in Fig. 6. This effect can be explained by a dominant role of beam-target interactions under the considered experimental conditions.

Summary and conclusions

The main results of the studies described in this paper can be summarized as follows:

- The anisotropy of the neutron emission from he PF-360 facility, similar to other DPF experiments, changes within range of 1.7–2.0 as a function of the initial filling pressure.
- For the first time the neutron emission anisotropy has been measured in the PF experiments with additional cryogenic targets, which is of the importance not only for practical applications but also for future theoretical analysis.
- The use of the planar cryogenic target, which was placed in front of the electrode outlet, considerably changed the neutron yield and its anisotropy, in particular at angles $\Phi = 0–60°$, which was explained by the known features of the deuteron angular distribution.
- Differences in the neutron yield and its anisotropy could be explained by different mechanisms of the fusion neutron production, which might be strongly influenced by beam-plasma interactions.

Since for many applications it is not important, which is the generation mechanism of the produced neutron pulses, it is reasonable to increase the neutron emission by the application of additional targets. In order to reduce the neutron emission anisotropy, however, some additional measures have to be undertaken.

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