NUKLEONIKA 2002;47(1)31–37

ORIGINAL PAPER

Results of large scale Plasma-Focus experiments and prospects for neutron yield optimization

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Abstract This paper summarizes results of the recent Plasma-Focus (PF) studies carried out with different PF facilities in Poland, which were operated at energies ranging from 100 kJ to about 1000 kJ. Particular attention has been paid to current-sheath (CS) dynamics, the emission of pulsed X-rays, fast electron beams, energetic ion beams, and fusion-produced neutrons. Some efforts, undertaken in order to increase the neutron emission, have been described. In particular, nuclear targets made of D_2O-ice layers, which were deposited upon special cryogenic devices, have been applied in the PF-360 machine. An increase in the neutron yield from 2.4×10^{10} up to 3.8×10^{10} neutrons per shot has been achieved in 130-kJ discharges. With the PF-1000 machine, for the first time the well-formed plasma pinch columns were obtained in PF discharges performed at 1 MJ, and the neutron yield of 2×10^{11} neutrons per shot was achieved.

Key words neutron yield • nuclear target • optimization • plasma focus

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Received: 11 June 2001

Introduction

Investigations of PF discharges were started in Poland in the 60s. The first PF-20 and PF-150 machines of the Mather-type, with nominal energies from 20 kJ to 150 kJ, were constructed at the Institute for Nuclear Research (IPJ) at Swierk, and later on they were investigated at the Military Academy of Technology (WAT) in Warsaw. Those early PF devices were used to study basic PF phenomena and to gain experience in experimenting with dense magnetized plasmas. In particular, there were investigated the deuterium discharges and fusion-produced neutron pulses [2, 15].

In the late 70s, at the IPJ at Swierk, there was constructed the PF-360 facility of the nominal energy of 360 kJ, at 50 kV charging. The device was used to study dynamics of PF discharges and to optimize the fusion neutron yield [11, 14, 24]. Basing on that experience, the IPJ team designed a new megajoule PF-1000 facility, which was put in the operation at the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw in 1994, initially at lower energies only [32]. Meanwhile, at Swierk the old MAJA-RPI device was converted into the MAJA-PF machine, which could be operated up to 60 kJ. The modified device was designed especially for studies of the X-ray emission [12] and measurements of relativistic electron beams (REBs) [13].

In recent years the dense magnetized plasma (DMP) studies in Poland have been concentrated on the MAJA-PF and PF-360 machines at Swierk, and on the PF-150 and PF-1000 facilities in Warsaw [26]. Some DMP experiments have been performed within a frame of the international scientific collaboration. Numerous PF experiments, which were carried out by joint research teams from IPJ and IPPLM, were reviewed at the 3rd Symposium on Current Trends in International Fusion Research [27]. Therefore, the main aim of this invited talk was to report and discuss only the newest experiments with the PF-360 and PF-1000 machines, which were carried out during the recent two years.

Experiments with PF-360 machine

Several series of PF experiments were performed with the PF-360 facility operated at Swierk. The machine was equipped with Mather-type electrodes made of thick-wall copper tubes of 170 mm and 120 mm in diameter, and 300 mm in length. The basis of the inner electrode was embraced with the insulator tubing made of an alumina-based ceramics, which was selected on the basis of the optimization studies [11, 14]. The device was mostly operated at 122 kJ/30 kV or 166 kJ/35 kV. To investigate dynamics of the visible radiation (VR) and X-ray emission, the use was made of a multi-frame imaging system consisted of two VR measuring channels and two X-ray framing modules, which were placed side-on the main experimental chamber, as shown in Fig. 1.

The VR and X-ray frames were synchronized in pairs, and their exposition times were <1 ns. All electrical signals were stored within the TDS784A digital oscilloscope, and frames were elaborated with an automatic image capturing and processing system. The VR pictures and corresponding X-ray images demonstrated good correlation of fine structures formed within the pinch column.

Different diagnostic techniques were applied to study time-integrated and time-resolved characteristics of charged particles and neutrons from the PF-360 machine [25]. It was

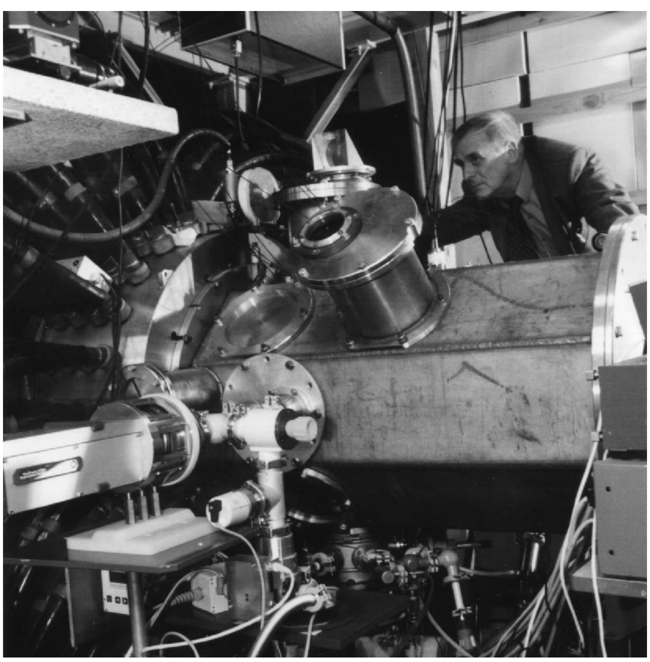

Fig. 1. General view of the PF-360 vacuum chamber and some diagnostic equipment. The X-ray and neutron counters were placed above and side-on the chamber. X-ray pinhole cameras were located at different angles to the z-axis, and two X-ray framing modules were fixed to opposite sides of the vacuum chamber.

known from numerous experiments [6, 9, 17, 18, 20–25, 37] that even a moderate (e.g. 70 kJ) PF discharge can emit above 10^{15} fast deuterons of energy above 300 keV. Such energetic deuteron beams, emitted mainly in the downstream direction, could be used for the production of additional neutrons from D-D reactions within a target containing deuterium. For the sake of simplicity it was decided to use first the solid-state target made of a heavy-ice (D_2O) layer. For this purpose a special cryogenic system was designed. It consisted of a metal cylinder and a thick copper plate cooled down by an internal flow of a liquid nitrogen stream [28, 29]. To ensure the deposition of the D_2O-ice layer on the target plate only, other surfaces of the applied target system were covered with an additional thermal shield. The planar cryogenic target could be positioned at different distances from the PF-360 electrode outlet, as shown in Fig. 2.

To facilitate the formation of the D_2O-ice layer on the target plate, the PF-360 experimental chamber was equipped with an additional vacuum valve, which could inject a chosen amount of heavy water. Changing the amount of the injected heavy water and cooling medium flow, it was possible to vary the thickness of the D_2O-ice layer within a range from 0.3 mm to 2 mm.

Several series of PF shots were performed with the use of the described planar cryogenic target, at different distances from the electrode ends and at various experimental conditions. When the target was placed not too close to the electrode outlet, the formation of the PF pinch column and the X-ray emission have not been changed considerably, as shown in Fig. 3.

The most important observations were measurements of fast neutron yields, which were carried out with eight silver-activation counters and two scintillation detectors, at different positions of the D_2O-ice planar target, and at various filling pressures changed from 6 hPa to about 12 hPa D_2. The neutron yields were averaged over the series of successive PF shots, performed under the identical experimental conditions. At the determined experimental conditions: $p_0 = 8.0$ hPa D_2, $U_0 = 30$ kV, and $W_0 = 130$ kJ, there was observed a considerable increase in the average neutron yield from 2.4×10^{10} to 3.8×10^{10} per shot. The performed measurements showed that the optimal position of the planar cryogenic target was at a distance $l_0 = 225$ mm from the electrode ends, as shown in Fig. 4.

Simultaneously with the time-integrated measurements, there were also performed time-resolved studies of the neu-

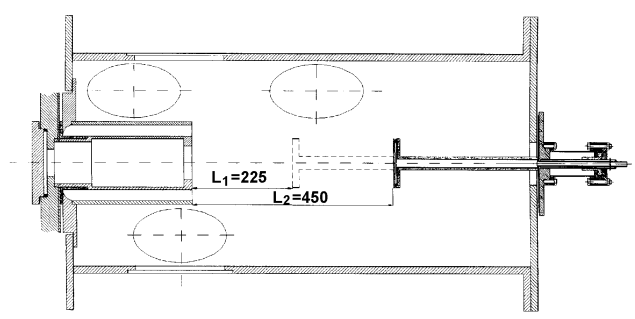

Fig. 2. Positions of the planar cryogenic target inside the main experimental chamber of the PF-360 facility.

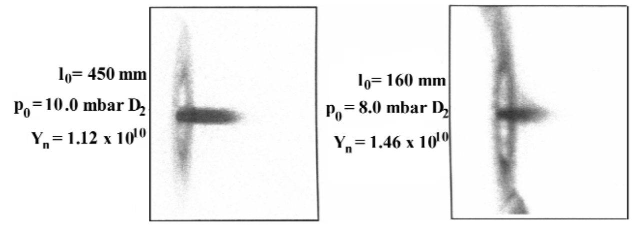

Fig. 3. X-ray pinhole pictures taken side-on the PF-360 experimental chamber, at different positions of the planar cryogenic target. Both the PF shots were performed at U_0 = 30 kV and W_0 = 130 kJ. On the left – the picture taken for the target placed far from the electrode outlet. On the right – the picture taken for the target covered with a D_2O-ice layer and placed close to the pinch region.

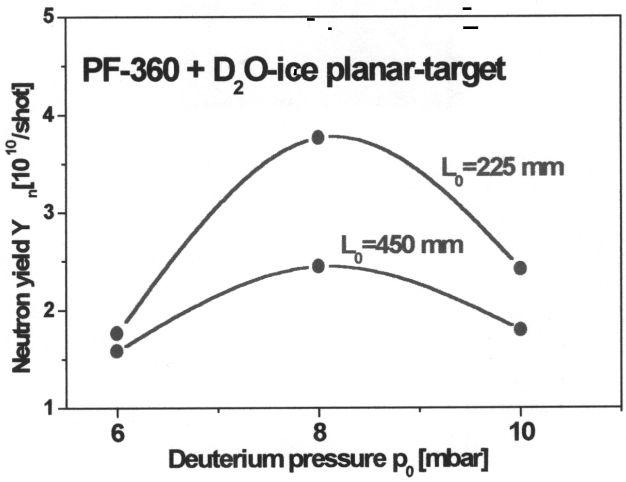

Fig. 4. Average neutron-yield *vs.* the initial pressure in PF-360 facility operated with the planar cryogenic target, as registered for several series of 130-kJ shots performed at different target positions and various initial pressures.

tron emission. The measurements by means of scintillation detectors confirmed that the fusion-originated neutrons are emitted in one or two main pulses, correlated with the discharge current peculiarity and hard X-ray pulses, as shown in Fig. 5.

The first peaks of the neutron signals from the two scintillation detectors, placed at different positions near the PF-360 machine, were shifted in time in relation to the X-ray-induced peaks, because of a time of flight of fast neutrons [40]. The observed time shift, which was equal to about 190 ns, corresponded to the time-of-flight of about 2.5 MeV neutrons.

An important result was delivered by detailed studies of the neutron emission anisotropy [7]. They were performed with 8 silver-activation counters placed at different angles to the z-axis, but at the same distance from the center of the electrode ends. All the activation counters were calibrated by a comparison of their yields with the yield of the reference activation counter, which was placed nearby each tested unit during the subsequent PF shots. Absolute values of the neutron yield were determined by means of two reference units, which were calibrated some time ago with standard Pu-Be source emitting the known flux of fast neutrons. The anisotropy measurements were carried out under typical operational conditions. The electrical separation of the counters and electronic scalers appeared to be necessary, because of strong electromagnetic interference from high-current discharges. Therefore, switching of all the measuring circuits was realized by means of an automatic control system with some delay after the main discharge.

The anisotropy, defined as the ratio of the neutron yields $Y_n(\Phi)/Y_n(90°)$, was determined for PF shots without the cryogenic target and compared with that measured for shots with the use of the planar D_2O-ice target, as shown in Fig. 6.

The studies revealed that the anisotropy of the axial neutron emission from the PF-360 machine, similar to other PF experiments, changed from 1.7 to 2.0 as a function of the initial filling pressure. For PF shots without the additional target measurements of $Y_n(\Phi)$, as a function of the Φ angle to the z-axis, revealed that the highest neutron yield was observed on the z-axis, and the lowest values of Y_n were registered at angles Φ = 100°–160°. Those observations confirmed an important role of the beam-target mechanism at the standard operational conditions [10, 11]. Analogous measurements for PF shots with the use of the additional target showed some evident differences, particularly at angles Φ = 0°–60°. The local minimum at Φ = 0°, as well as the local maximum at Φ = 60°, could be explained by the known characteristic wings in the angular distribution of fast deuterons emitted from the PF pinch column [22, 23]. In both cases, the observed differences in the neutron yield and its anisotropy could be caused by different mechanisms of the neutron production.

Within a frame of the optimization studies within the PF-360 machine, there were also performed investigations of the neutron emission from PF discharges with the use of a needle-like cryogenic target [3] and D_2 gas-puffed targets [36]. In the first case a thin D_2O-ice layer was deposited upon a needle-like "cold nose", which could be inserted into the PF pinch region. In the second case the D_2 gas cloud was formed in front of the central electrode end by means of a fast acting gas valve, which was placed inside that electrode. Some increase in the average neutron yield was observed in both the cases under the determined experi-

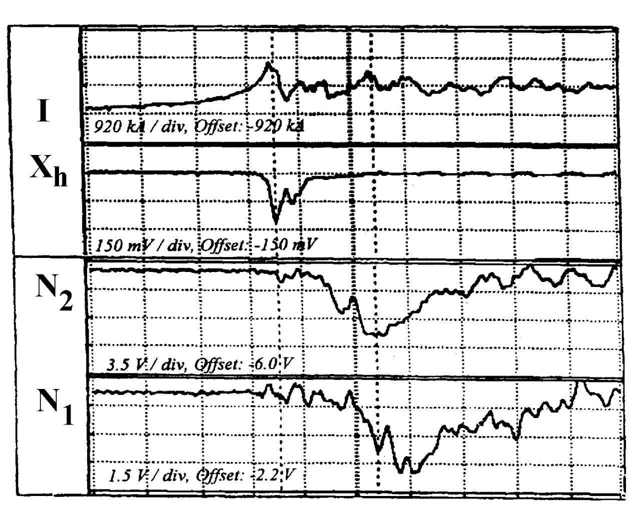

Fig. 5. Time-resolved waveforms of the discharge current (I), hard X-rays (X_h), and neutron signals (N_1 and N_2) obtained from two scintillation detectors placed at different positions. The measurements were performed with the PF-360 facility operated with the D_2O-ice planar target, at the initial charging U_0 = 30 kV and W_0 = 130 kJ. The time basis was 100 ns per division.

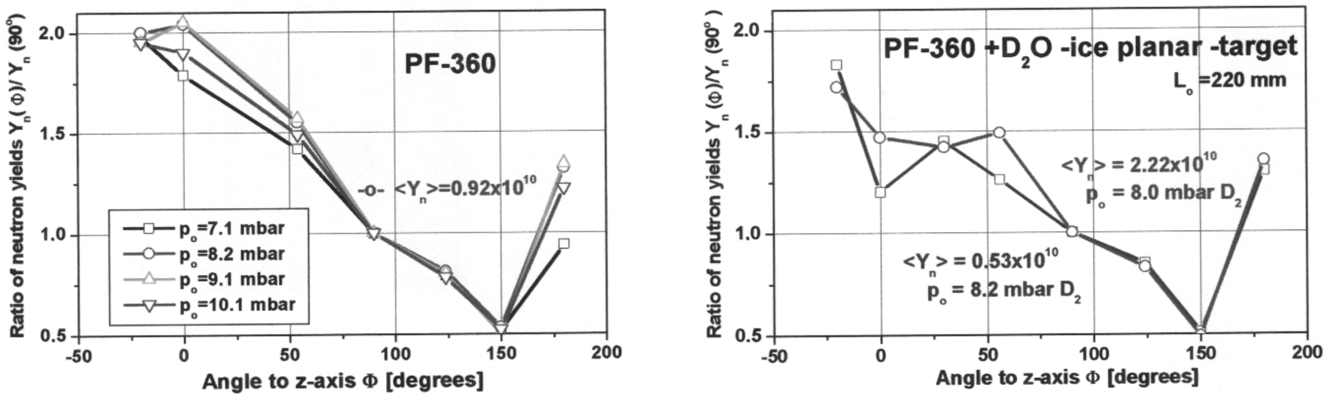

Fig. 6. Anisotropy of the neutron emission, as measured in the PF-360 facility for shots without and with the additional cryogenic target.

mental conditions [3, 36], but the best results have so far been obtained with the use of the D_2O-ice planar target described above.

Recent experiments with PF-1000 facility

The optimization studies were also carried out with the largest PF-1000 facility operated in Warsaw [26, 32]. The preliminary investigations were performed with the old Mather-type electrodes of 100 mm and 150 mm in diameter, and about 330 mm in length. Dynamics of a CS layer was investigated by means of high-speed cameras. Using an X-ray pinhole camera, there was studied the formation of hot spots within the pinch column. Also studied were fast (>80 keV) ion beams emitted along the z-axis. The registered ion images confirmed the emission of bunches of fast ion beams. Particular attention was paid to spectroscopic studies of the X-ray emission from highly stripped Ar admixture-ions. Since the old electrodes were too small, the PF-1000 machine was operated below a 400 kJ level. Those investigations were reviewed in several papers [1, 26, 29, 32]. During those studies the use was made of different diagnostic equipment, as shown in Fig. 7.

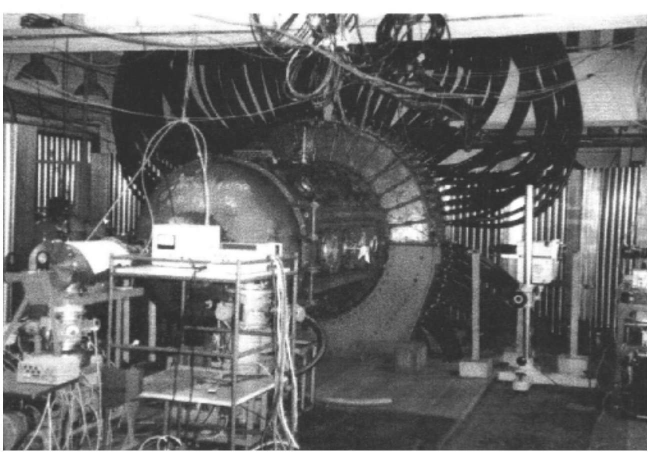

Fig. 7. General view of the PF-1000 facility and the diagnostic equipment used for measurements of X-rays, ions, and neutrons. Dynamics of the CS layer was observed with high-speed cameras placed side-on the main experimental chamber. X-rays were measured with a pinhole camera (from the top) and a crystal spectrometer (fixed to a diagnostic port on the opposite side). Ion beams were registered with nuclear track detectors placed inside the chamber or in the Thomson-type analyzer, which was adjusted along the z-axis.

In order to investigate the neutron emission at higher energy levels, the PF-1000 facility was equipped with new larger coaxial electrodes of the Mather-type [33]. The inner electrode was made of the thick-wall copper tubing of 231 mm in diameter, equipped with an end plate with a central 30-mm-diameter hole. The outer electrode consisted of 24 stainless-steel rods of 32 mm in diameter, which were distributed symmetrically around a cylinder of 400 mm in diameter. The free ends of those rods were connected with a stainless-steel ring. Both the electrodes were 600 mm in length. The main insulator tubing was made of the same ceramic material as the insulator of the PF-360 machine, but it had appropriately larger dimensions.

After modernization of the PF-1000 facility, the first experiments were performed at energy levels from 500 kJ to 800 kJ [33]. Dynamics of the CS layer was studied with high-speed cameras, as shown in Fig. 8.

To obtain time-integrated X-ray images of the PF pinch column, the use was made of a pinhole camera with two 100-μm-diameter pinholes, covered with Be-filters of 10 μm and 25 μm in thickness, respectively. The registered soft X-ray images showed the formation of distinct "hot spots", especially in shots performed with an argon admixture. In order to study fast ion beams emitted along the z-axis, there

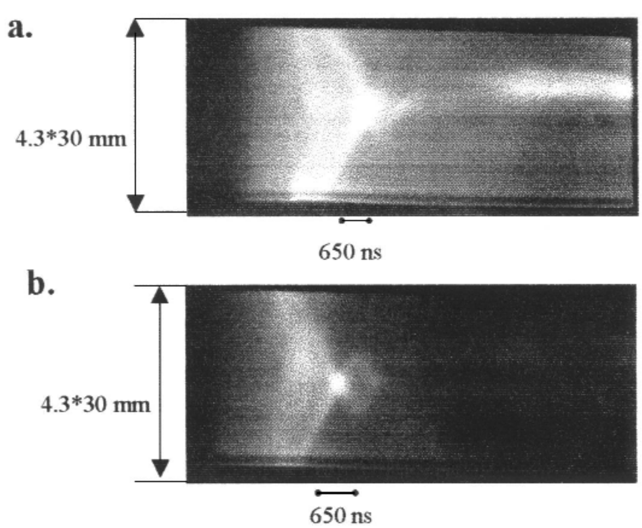

Fig. 8. Streak pictures of the collapsing current-sheath in PF-1000 facility, as taken through a radial slit, at p_0 = 3.9 mbar D_2, U_0 = 30 kV, and W_0 = 600 kJ.

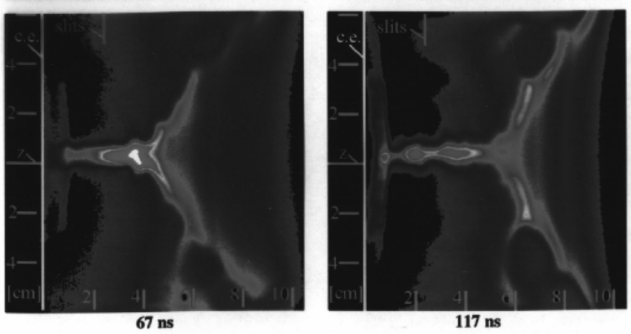

Fig. 9. High-speed frames of the pinch column within PF-1000 facility, as registered for a 970-kJ shot with the neutron yield $Y_n = 2.0\times10^{11}$.

was used a pinhole camera equipped with nuclear track detectors. The obtained ion pinhole images confirmed the emission of intense ion beams of energies higher than 80 keV. Also measured were neutron yields emitted in different directions. Since at that time the PF-1000 machine was not conditioned enough, the neutron yields were relatively low [33, 34].

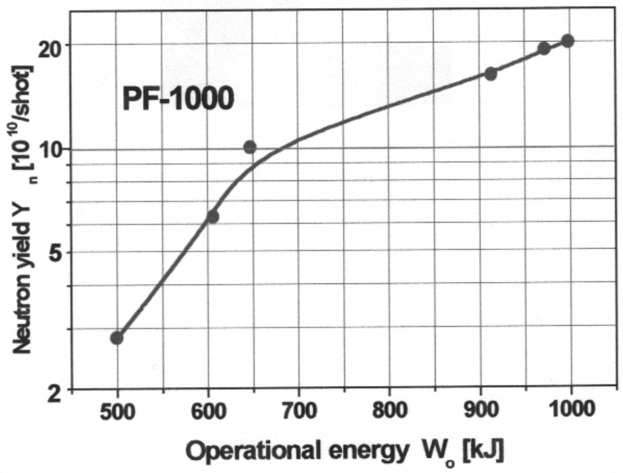

Fig. 10. Average neutron yield versus the initial energy stored in the condenser bank of the PF-1000 facility, as measured during several series of experiments performed at different charging voltage values. The initial pressure, depending on the operational energy level, was varied within the range from 3 hPa to 7 hPa D_2.

In order to check the scaling laws, next series of experiments with the PF-1000 facility were carried out at energies ranging from 500 kJ to about 1000 kJ [35, 38]. For the first time there were also performed shots above 1 MJ. Measurements with high-speed cameras showed the formation of the distinct PF pinch column, as presented in Fig. 9.

Details of the recent PF-1000 experiments are described in two invited papers presented at the 4th Symposium on Current Trends in International Fusion Research [31, 35]. Here it should be noted that during these experiments, performed without long lasting conditioning of the machine, it was possible to obtain $Y_n = 2\times10^{11}$ neutrons per shot [30]. The scaling of the neutron yield, which was observed during the recent series of experiments with the PF-1000 machine, has been presented in Fig. 10.

Comparison with previous PF experiments

It is known that, to obtain higher neutron yields, some PF experiments with a mixture of deuterium and tritium were performed and the record yield of 6×10^{12} (14 MeV) neutrons/shot was reported [8]. Since the D-T experiments appeared to be danger because of the tritium radioactivity, the majority of PF experiments was carried out with the deuterium filling. The maximum neutron yield from D-D reactions in a 0.5-MJ PF experiment was reported to be 10^{12} neutrons/shot [39], but that result has never been repeated. In several large-scale (above 0.5 MJ) PF experiments with the deuterium filling, there were achieved average yields of about 2×10^{11} neutrons/shot [4, 5, 11]. On the basis of numerous measurements of the neutron yields (Y_n), as performed within a large range of pinch currents (I_p), there was deduced an experimental scaling law $Y_n \propto I_p^{3.3}$ [4]. Many PF experiments showed that such a scaling holds on for discharges with pinch currents below 2×10^6 A, but at higher pinch currents there appears some saturation of the neutron yield [5, 11].

In the recent PF-1000 experiments described above the saturation of the neutron scaling appeared at energies above 600 kJ, as shown in Fig. 10. It should, however, be noted that the PF-1000 facility has not been so far optimized as regards the electrode dimensions and operational conditions. Therefore, the maximum current values in the PF-1000 machine, as well as the obtained neutron yields, were lower than one could expect for energy cumulated within

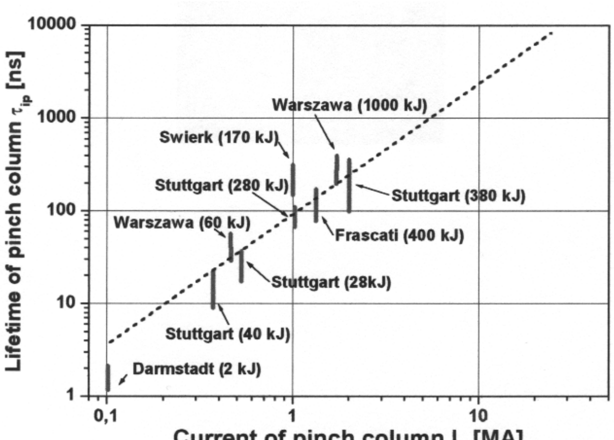

Fig. 11. Dependence between a lifetime of the pinch column and the maximum pinch current value, as observed in different PF experiments.

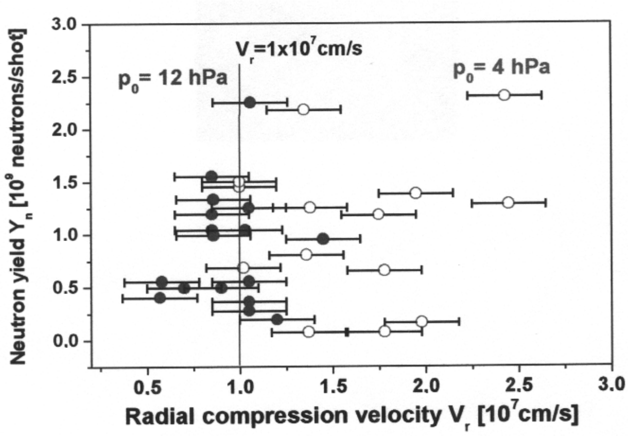

Fig. 12. Neutron yield *vs.* the radial compression velocity as measured for about 100-kJ PF shots performed at two different initial filling pressures.

the condenser bank. Nevertheless, for the first time the well-formed pinch plasma columns were produced in the PF discharges at the 1 MJ level, as shown in Fig. 9.

The general features of the PF discharges performed within the PF-1000 machine are similar to characteristics of other large-scale experiments, and in particular to those of the POSEIDON facility [10, 11]. Dynamics of the CS layer depends considerably on the operational conditions. The "good shots" are characterized by the strong compression of the symmetric pinch column, which remains stable during a relatively long period. In this case there is observed an intense emission of X-rays and corpuscular pulses. The "bad shots" demonstrate disturbances of the collapsing CS layer and an unstable pinch column, which is formed off the symmetry axis. In such cases, instead of the distinct radiation pulses, one can register some oscillations and very low neutron yields.

For the "good shots" in the PF-1000 machine there are observed intense X-ray pulses correlated with the discharge current peculiarity. Also observed are fast ions (mostly deuterons), which are emitted mainly in the downstream direction. They have a characteristic angular distribution, showing a local minimum at the z-axis and relatively wide wings [22, 38]. The fusion-produced neutrons are usually emitted in two or three pulses, which are shifted in time depending on the experimental conditions.

The pinch columns formed within the PF-1000 machine appear, however, to be relatively stable during 150–400 ns. Therefore, it is of interest to compare these characteristics with those obtained in other PF experiments. A comparison of lifetimes of the pinch column, which were registered in various PF experiments carried out in Germany, Italy and Poland [6, 9, 11, 14, 17, 20–24, 32, 37], gives an interesting scaling shown in Fig. 11.

It was found that the pinch lifetimes achieved in the PF-150 and PF-360 machines in Poland were relatively longer than those observed in the other PF experiments. It could be induced by the fact that those machines were well optimized and conditioned. It was stated at the comparison of the PF-360 machine operated at Swierk and the POSEIDON facility, which was operated in Stuttgart [10, 11]. This statement does not concern the recent PF-1000 experiments, since the optimization tests have just been started.

Prospects of further optimization of PF discharges

The extrapolation of the PF neutron yield up to the scientific break-even requires first the elimination of the neutron saturation effect observed at energies above 600 kJ. Several years ago it was shown [11] that a considerable increase in the neutron yield could be achieved by the replacement of the Pyrex-glass insulator by ceramic one, used also in the PF-360 and PF-1000 machines. It seems that a further improvement might be achieved by the use of other special materials.

From the beginning of the PF studies it was suspected that the neutron yield depends on the quality and radial compression velocity of the CS layer. Numerous experiments showed that the compression velocity could be increased by the operation at lower pressures, but it does not increase the neutron yield, as shown in Fig. 12.

In general, it is very difficult to influence the quality (e.g. uniformity) of the CS layer, but one could apply special techniques, e.g. those based on the injection of a working gas at the main insulator surface.

At higher currents and faster PF discharges the formation of current filaments inside the pinch column was observed [16, 21]. Local magnetic fields, coupled with the current filaments, influence ion and electron trajectories considerably [19]. Some attention should be paid to the optimization of the current filaments and the fast ion emission. The fast deuteron beams, emitted mainly in the downstream direction, can be used for the production of additional fusion neutrons within special solid- or gaseous-targets containing deuterium or tritium.

Summary and conclusions

The most important results of the studies described above can be summarized as follows:

1. The PF facilities remain convenient and relatively inexpensive machines making possible the production of dense magnetized plasmas of thermonuclear interest. They emit intense electromagnetic and corpuscular radiation pulses, including numerous fusion-produced neutrons.
2. The scaling of a fusion neutron yield versus the input energy has been checked in different PF machines up to about 1 MJ. For the first time in Mather-type experiments the 1 MJ level has been achieved, although the PF-1000 facility has not been optimized so far.
3. The optimization studies should include not only changes in the electrode configuration and variations of the initial gas conditions, but also the application of additional nuclear targets, e.g. analogous to those used in the PF-360 machine.
4. In order to increase the total neutron yield one could effectively utilize fast deuterons escaping from a PF pinch column, e.g. by the application of nuclear targets containing more deuterium or tritium.
5. It would be reasonable to base on the scaling of the neutron yield versus the pinch current, but it is difficult aim to determine the current values correctly. Some special measures should, however, be undertaken to determine and to optimize the current flowing through the pinch column.
6. The observed lifetimes of a PF pinch do not scale exactly versus energy supplied, but a relative long lifetime of the PF pinch column is an optimistic feature of the PF-1000 machine.

An effective international scientific collaboration is needed for the further optimization of PF machines. Some new opportunities are offered at the International Center for Dense Magnetized Plasma (ICDMP), which is equipped with a large PF-1000 facility and operated under auspices of the National Atomic Energy Agency, Poland (PAA) and UNESCO.

Acknowledgments This paper presents an invited talk given at the 4th Symposium on Current Trends in International Fusion Research, which was held in Washington, D.C., U.S.A., on March 12–16, 2001 [31]. The authors wish to express their thanks to all the colleagues and coworkers from both Institutes, which were engaged in the described experiments performed with the PF-360 and PF-1000 facilities.

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