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Status of a mega-joule scale Plasma-Focus experiments

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Abstract This paper presents results of the recent plasma-focus (PF) experiments carried out with PF facilities, which was operated at energies ranging from 0.5 MJ to about 1 MJ. Particular attention has been paid to pinch evolution, the emission of pulsed X-ray, fast electron beams, and fusion produced neutrons. Some theoretical models of the initial breakdown, which occurs at the insulator surface, are compared. It is pointed out that modeling of the breakdown is sensitive to kinetics of ionization processes and transport coefficients. Progress in experimental studies of the axial acceleration phase is unsatisfactory. Important experimental data have been collected, but new measurements are still needed. For the radial collapse phase, it was shown that the MHD modeling is efficient until the maximum compression, but plasma instabilities require more sophisticated approaches. The pinch phase was investigated by means of different diagnostics. Fusion neutron yields were measured in different experiments, but some discrepancies in scaling must still be explained. The conclusions concern directions for further studies and optimization of large-scale high-current PF facilities.

Key words Plasma Focus • dense magnetized plasma • neutron yield

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Introduction

Plasma-focus (PF) device belongs to the family of the dynamic, non-cylindrical Z-pinches and is based on the pulsed high-current discharge between two coaxial electrodes placed in a working gas (Fig. 1). The development of PF discharge can be divided into a number of phases. The first phase constitutes an initial breakdown of the working gas upon the surface of an insulator separating the coaxial electrodes, and the formation of a dense ionized plasma layer (current sheath). During the second phase, the current sheath is driven off the insulator surface and is accelerated towards the open end of the electrodes. During the consecutive phases (i.e. radial compression, column creation and column disruption), the current sheath collapses rapidly toward the axis of the inner electrode where a dense pinch column is formed. The micro instabilities and turbulences of dense magnetized plasma compressed inside the pinch lead to the generation of powerful electron and ion beams, large emission of electromagnetic radiation and of fusion neutrons when deuterium is applied as a working gas. In general, the PF device can be considered as a power transformer in which the energy stored in the magnetic field is abruptly converted into the energy of the pinch plasma. The propagation time from the breakdown to the pinch formation takes usually a few microseconds. The final stages of PF phenomena are much shorter and they last from several tens to several hundreds of nanoseconds (it depends on PF device scale).

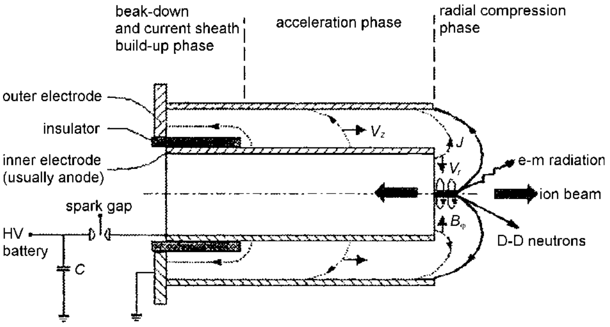


Fig. 1. Plasma-focus device (Mather-type) – general layout and principle of operation.

During the last years, the interest in PF devices has increased, because they are one of the most efficient sources of pulsed neutron emission. The scaling laws for the neutron yields, as formulated at the beginning of the PF studies, were very promising. Later investigations, however, which were performed with larger devices, suggested that there is a certain energy limit above which the scaling law is not valid [1]. Hence, the essential problem to be solved in PF research has always been to discover the physics which dominates the plasma formation, especially for a large device. This question is closely related to neutron production mechanisms, plasma dynamics and physics of different phases of such plasma discharges [2, 3]. It means, in turn, that on the basis of such a kind of information the optimization of PF device working conditions in order to achieve higher and higher neutron yield could be easier and more feasible.

Apparatus and experimental set-up

The experimental studies of high-current PF discharges have been continued in Warsaw with a large plasma-focus (PF-1000) facility [4–6], which can be operated up to 1 MJ.

The PF-1000 plasma-focus facility, constructed and operated at the Institute of Plasma Physics and Laser Microfusion (IPPLM), is equipped with a large condenser bank of the total capacity equal to 1347 μF. This bank can be charged up to 40 kV, what corresponds to 1.2 MJ of electrical energy. The problem is how to transmit this energy to plasma discharges effectively. Recently, the PF-1000 facility has been modernized, and new experiments (aimed at the optimization of PF discharges) have been carried out. The mega-joule PF-1000 facility, equipped with a 3.5 m long experimental chamber, is shown in Fig. 2.

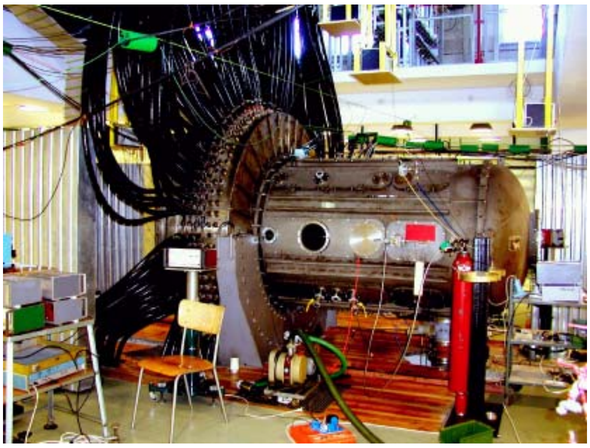


Fig. 2. View of the present experimental arrangement with the large PF-1000 chamber.

This facility was equipped with various diagnostic tools: equipment for measurements of voltage- and current-waveforms, high-speed cameras recording VR and X-ray images of plasma, X-ray pinhole cameras and crystal spectrometers, ion pinhole cameras and sets of nuclear track detectors (NTDs) for measurements of fast primary ions (mostly deuterons) and protons from DD reactions, as well as scintillation- and activation-detectors for measurements of fusion-produced neutrons, etc. All these tools were used for numerous experimental studies, which have been performed by international teams within the frame of the International Center for Dense Magnetized Plasmas (ICDMP) operated at IPPLM in Warsaw.

Complexity of PF phenomena requires a detailed qualitative and quantitative analysis. For this purpose, the data obtained with a given diagnostic technique should easily be related to those obtained with other methods (even after a long time). Therefore, all the PF discharge phases should still be studied in more detail and more systematically.

Status in studies of breakdown

The initial breakdown occurs at the insulator surface, and the final PF pinch-column is formed at the electrode outlet. These two stages, which are separated by the axial acceleration and radial collapse phases, can in fact be optimized in different ways. A current-sheath layer, as formed at the insulator, cannot be accelerated within the inter-electrode gap effectively at a very low gas pressure. An appropriate amount of gas must be delivered to enable effective "snow-plough" process. Numerical simulation of the breakdown phase was performed by researchers [5] and the results of such computations agree relatively well with results of experimental observations, as shown in Fig. 3.

Unfortunately, an accurate quantitative model, taking into account complexity of the current sheath formation phase, is still missing. In particular, the influence of a status of the insulator surface should be taken into consideration. Active experiments with planned modifications of the insulator surface have not been performed so far. A localized gas puffing has also been under consideration.

The well known difficulties in the operation of PF facilities at large energy are probably connected with a lack of the optimization of different parts and/or procedures. It should be reminded that in the POSEIDON facility [1] the replacement of a glass insulator by a ceramic one shifted the so-called neutron saturation limit and it made possible the operation at higher energy and higher neutron yields. As regards the breakdown phase in the PF-1000 facility, it is a pity that no experi-

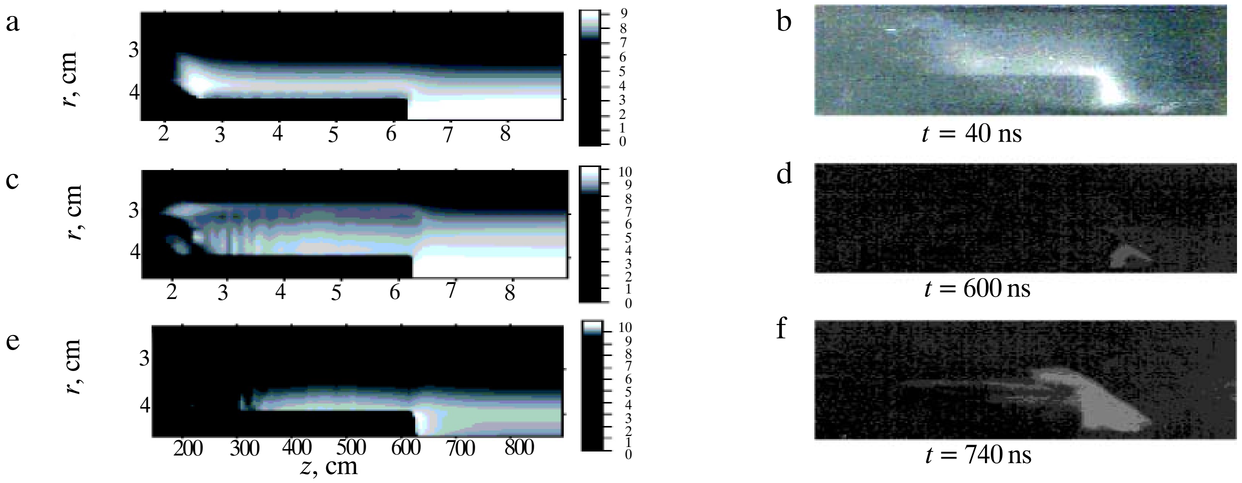


Fig. 3. Comparison of computed density distributions with high-speed camera pictures showing relatively good agreement.

mental optimization of the main insulator material and configuration has been made so far.

Status of research on radial collapse and pinch phase

To perform modeling of the radial acceleration phase different approaches were applied. The most popular and effective appeared to be the 2-fluid MHD model using plasma continuity, momentum and energy equations, Maxwell equations and the electrical circuit equation. In general, the modeling is very sensitive to kinetics of the ionization and transport coefficients. The computer simulation must of course be specified for the chosen electrode configuration and gas conditions. For the PF-1000 experiment simulation, use was made of the Braginski transport coefficients [7]. The ionization process was described by the known formula $dn_e/dt = n_e(n_0 - n_e)\,S - \alpha_r n_e^2 - \beta_{3B} n_e^3$, where values of coefficients S, α_r and β_{3B} were assumed according to the Braginski theory. Anomalous resistivity of plasma was also taken into account.

The performed computations have proved that the MHD modeling of the collapse phase is efficient until the maximum compression occurs. After that, the development of different plasma instabilities requires more sophisticated approaches. Nevertheless, using an extended MHD model described above, some valuable computer simulations of the collapse phase were carried out. Some examples are shown in Fig. 4.

The dynamics of the radial collapse phase has been extensively investigated with high-speed cameras. Numerous VR pictures were collected and analyzed by a comparison with some model computations. Those calculations were performed simultaneously on the basis of the extended MHD model described above. In general, the recorded VR pictures are in good qualitative agreement with results of the performed simulations, as shown in Fig. 5.

One can easily see that the development of local MHD instabilities can be simulated, but their location in the real experiment cannot be indicated synonymously, due to their stochastic character.

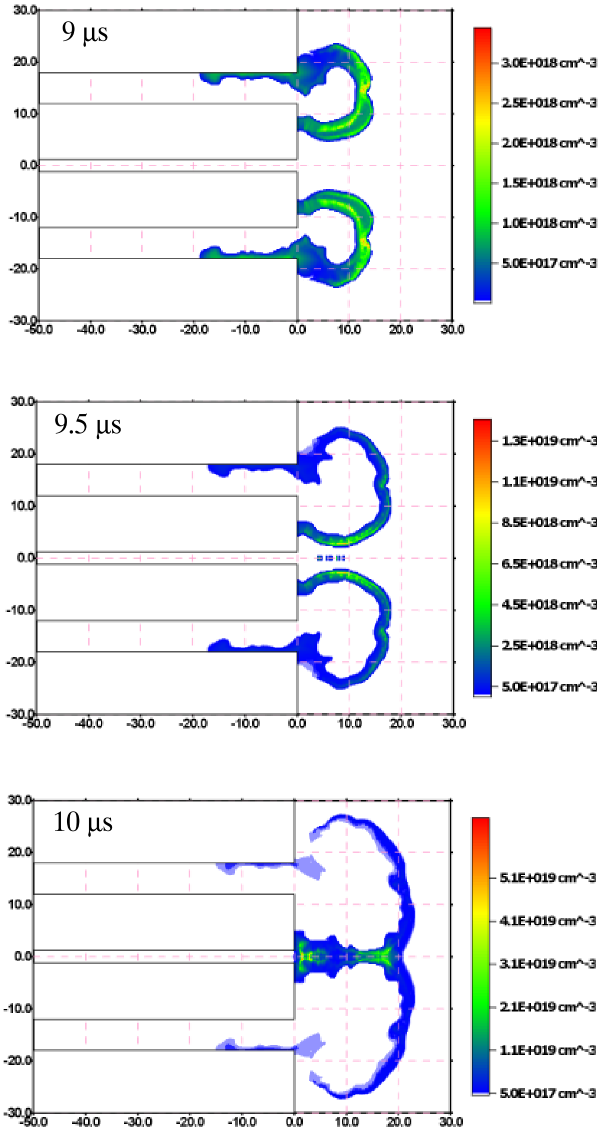
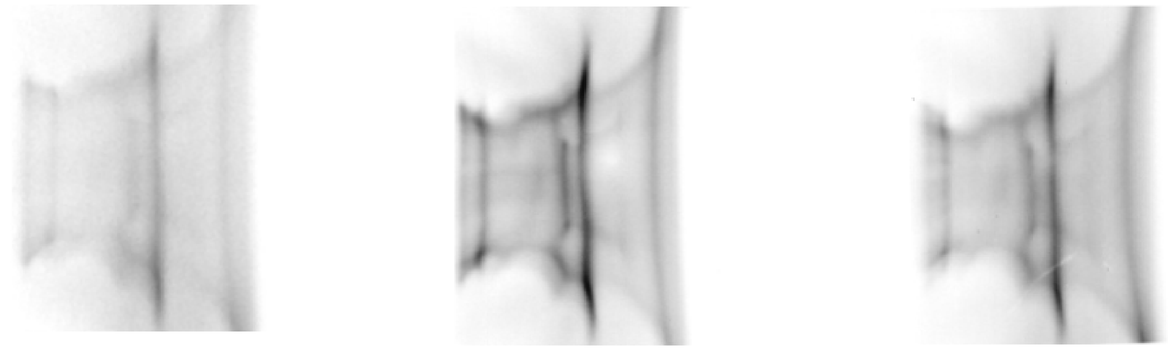


Fig. 4. Plasma density distribution during the radial collapse, as computed for the PF-1000 experiment [7] and different instants: 9, 9.5 and 10 µs after the discharge beginning.



−178 ns −168 ns −148 ns

Fig. 5. High-speed frame camera pictures of the radial collapse phase, as taken in the PF-1000 experiment performed at p_0 = 4 hPa, U_0 = 33 kV and I_{max} = 1.7 MA. Time is expressed in relation to the maximum compression.

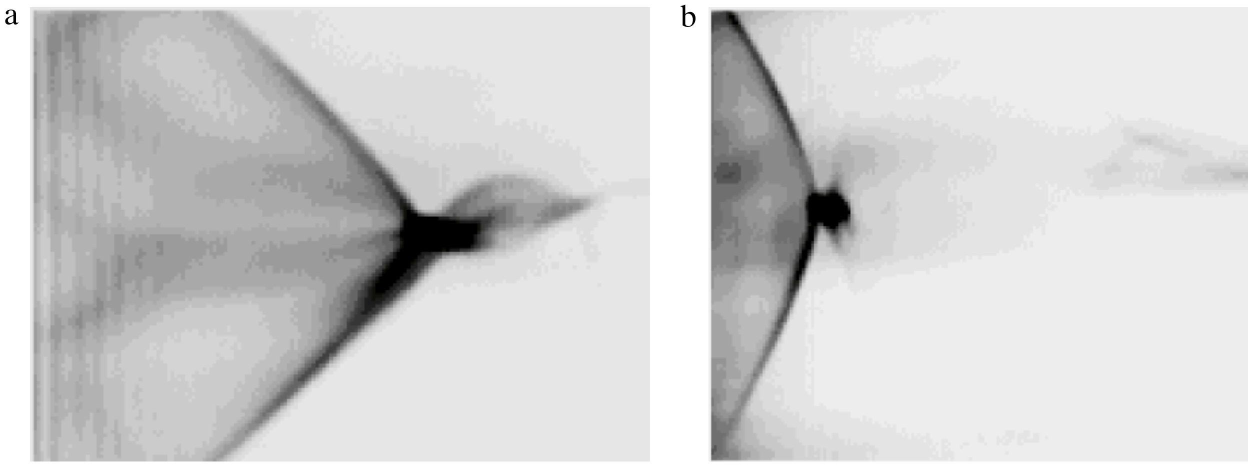


Fig. 6. Streak-camera pictures made for shots with low (a) and high (b) neutron yield.

Our investigations of the current sheath (CS) collapse dynamics performed by means of a streak camera for the shots with low and high neutron yield are presented in Figs. 6a and 6b, correspondingly. One may see easily two main features distinguishing the "good" shot from the "poor" one: very different implosion velocities of CS and the degree of their symmetry. Both are much better in the case of high neutron yield (Fig. 6b). As for the speed we have received the best figure equal to 5×10^7 cm/s. But in any good shot the velocity of a shock wave and the current sheath (SW + SC) at the final stage of the pinch collapse was not less than 2×10^7 cm/s.

Another problem is some disagreement between the computed and recorded current waveforms, as shown in Fig. 7. These differences could be induced by wrong values of the circuit parameters, which were taken for the modeling of PF-1000 discharges, but one cannot exclude the case that the applied model does not work sufficiently. This question must still be investigated experimentally and theoretically.

The pinch phase of PF discharges has also been investigated extensively. The use was made mostly of high-speed streak- and frame-cameras and the other diagnostic tools described above. Some examples of the recorded traces and high-speed VR pictures are shown in Fig. 8.

The filtered frame camera recorded emission in a narrow window of 589 nm. In this range, any intense optical lines were not observed in the plasma. Then the emission – bremsstrahlung – depended on the square of electron density and thus the intensity of the pictures depended also on the plasma density. The frames in Fig. 8 image evolution of the pinch phase in the time of the neutron production. At this time, one was able to see the start of the right part of the downstream zipper effect of the radiating (dense) part up to a distance of 6 cm in front of the anode. This phase finished at t = 0, in the time of the peak of soft X-rays and in the time of

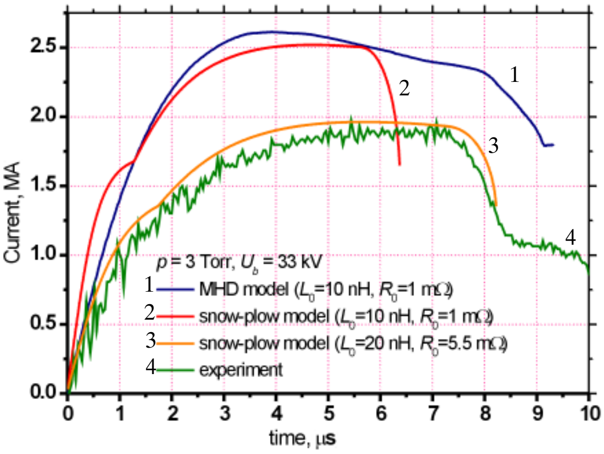


Fig. 7. Discrepancies between computed current-waveforms and experimental traces, as observed in the PF-1000 experiment.

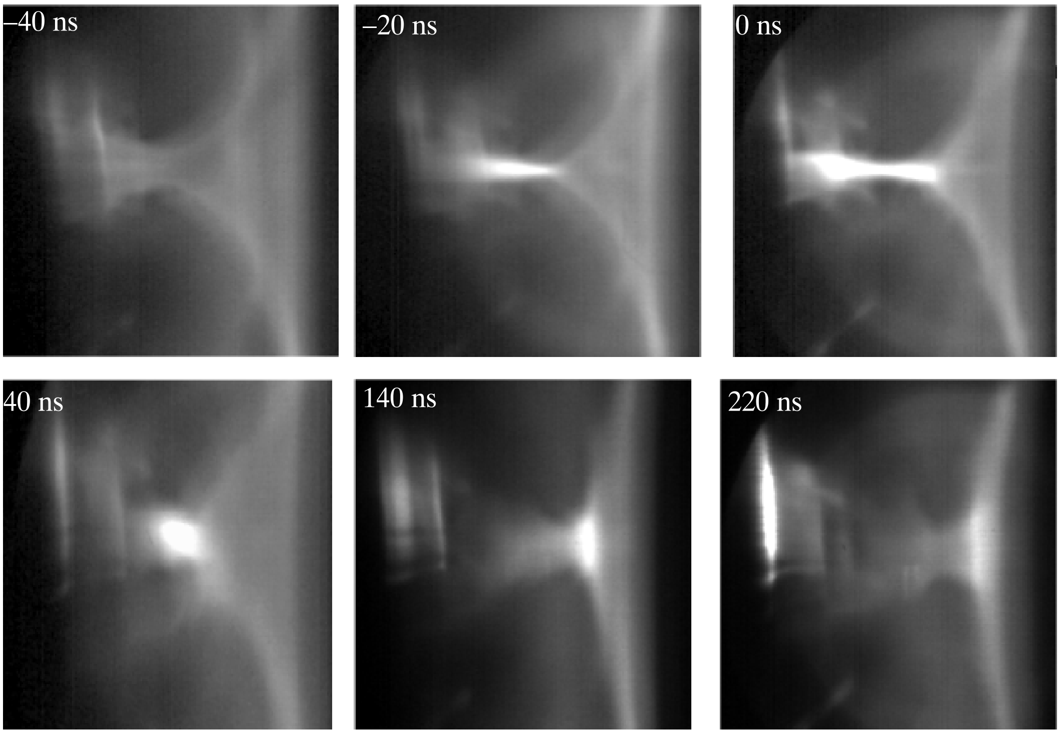


Fig. 8. High-speed pictures of the pinch phase in the PF-1000 experiment performed at p_0 = 4 hPa, W_0 = 734 kJ 1.66 MA. The images correspond to instants indicated by broken lines.

the narrow radiating part of the focus with the minimum diameter of ~ 5 mm and 5 cm in length. At the $t = 0$ we observed a continuing of the zipper effect – movement of the left boundary of the radiating pinch downstream, while the right boundary stayed practically without motion. This phase ended with a creation of dense spherical structure of ~ 1 cm in diameter. The spherical structure was situated 6–8 cm in front of the anode in the top of the focus at the bottom of the dilated current sheath. Its lifetime was about 30–50 ns. The period of the plasma column evolution lasts about 200 ns.

In the PF scheme one relies on the development of self-consistent phenomena occurring after maximum compression during the evolution of the plasma column. Anomalous microscopic effect are probably responsible for particle heating, while instabilities create a favorable situation for the onset of relaxation processes of the magnetized plasma, which lead to the formation of the plasma configuration.

Its lifetime exceeds by an order of magnitude the transit time of reacting particles. In such a case, the efficiency of energy transfer from the source of the magnetic energy stored in the system, as the distribution of current densities in the plasma column, are of paramount importance.

PF emission characteristics

The start of X-rays, electrons and neutrons correlated with forming of the intensively radiating part of the pinch located 2 cm in front of the anode top (Fig. 8). The production of neutrons correlates with X-ray activity (Fig. 9), mainly with hard X-rays above a few tens keV. The first neutron pulse starts together with the X-rays, i.e. 20–30 ns before the X-ray peak. The maximum of neutrons is observed ~ 30 ns after the X-ray peak. The FWHM of the first pulse is 50–70 ns.

The second neutron pulse is dominant with 3–10 times higher number of neutrons than the first one. The onset of the pulse is not as sharp as the first one. The FWHM of the second pulse is 70–100 ns.

Recent neutron measurements, performed for the PF-1000 machine with new electrodes, have shown some discrepancy in absolute values (by factor of 2), as deter-

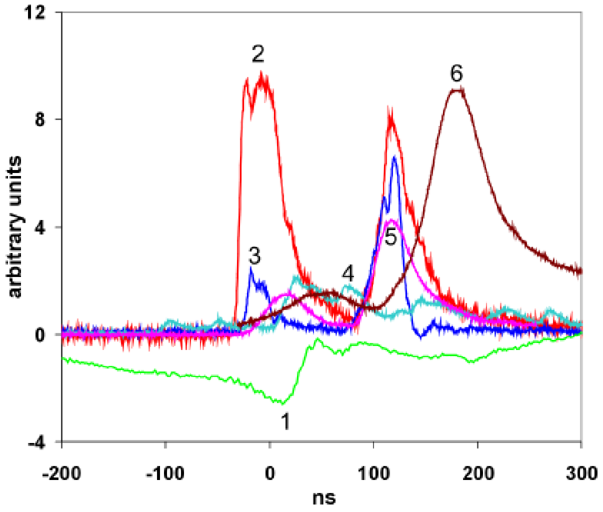


Fig. 9. Records of signals of current derivative (trace 1), soft X-rays above 4 keV (trace 2), electrons 180 deg with energies above 70 keV (trace 3), electrons 90 deg (trace 4), hard X-rays 100 keV (trace 5), and neutrons (trace 6).

mined by means of different measuring techniques. This effect must still be investigated and explained. Recently, particular attention has also been paid to measurements of neutron anisotropy and fusion-produced fast protons. These experiments must be continued.

In general, PF discharges with the highest neutron yields are not necessarily the ones with the strongest anisotropy. High neutron yields were observed in some large-scale PF experiments, when the first predominant neutron pulse was characterized by a reduced anisotropy. In order to optimize the operation of the chosen PF facility and to estimate the possibilities for an increase in the fusion neutron yield, one should analyze the whole circuit of the PF discharge. For this purpose, one should consider energy (W_{in}) supplied to the system, energy cumulated within the pinch ($W_{\text{pinch-internal}}$) which can be divided into two components: thermal (W_{th}) and fast beam ($W_{\text{fast-ion}}$). Such an analysis, which should be performed for realistic experimental parameters, may deliver valuable information how to increase the total neutron production.

Summary and conclusions

The most important conclusions from this review can be formulated as follows:

1. The PF-1000 facility has been operated at the energy level exceeding 1 MJ, with a regular and reproducible neutron emission of the order of 10^{10}–10^{11} neutron/shot, but optimization of PF machine operation, analysis and optimization of the fusion yield is needed.
2. The highest neutron yield registered so far has achieved about 3.5×10^{11}, but it is expected that higher emission will appear after appropriate conditioning of the insulator and electrode surfaces.
3. A two dimensional approach to describe initial formation of the current sheath near the insulator (breakdown phase) has been proposed. This model is based on the continuity equations for electron and ions, Poisson's equation and the Townsend formula for ionization coefficient. The results of calculations from the model agree relatively well with the results of experimental observations to study the breakdown phase, an improved model should be developed and the dedicated experiments should be run with special pre-formed insulators or localized gas puffing.
4. The soft X-ray emission, as measured with PIN diode equipped with a pinhole covered with a 10 μm Be-foil, seems to be proportional to the neutron yield.
5. In case of high neutron yields from PF-1000, the typical neutron signal usually shows a double structure with the second pulse more intense than the first one (Fig. 9).
6. The first pulse correlates with soft X-ray and the second pulse corresponds to the beam emission. This can be interpreted that the first pulse contains mainly thermal neutrons and the second one – neutrons produced by the beam target mechanism.
7. It has been shown that the sheath structures of experimentally recorded plasma images are at least in qualitative agreement with the results taken by MHD numerical modeling. However, further improvements of numerical modeling are necessary. A role of current-sheath symmetry and uniformity must be investigated.

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