PROGRESS IN LARGE-SCALE PLASMA-FOCUS EXPERIMENTS

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This invited talk presents the most important results of theoretical and experimental studies of high-current Plasma-Focus (PF) discharges, as performed recently in a frame of the scientific collaboration of IPJ and IPPLM, Poland. Progress in studies of the breakdown and axial acceleration phase was achieved. Numerical computations showed that a modified MHD model is satisfactory until the maximum compression. In experimental studies the use was made of different diagnostic techniques. Correlations of X-ray pulses with other PF phenomena were analyzed, and differences in polarization of X-ray spectral lines were explained. Fast electron-beams (emitted through the axial channel) were analyzed, and energetic ions (emitted in the forward direction) were measured. Anisotropy of fusion neutrons was investigated and its temporal changes were analyzed. For the first time an optical spectrometer with a high temporal resolution was applied to study the evolution of spectral lines. The main issues of PF studies were also considered.

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1. INTRODUCTION

High current PF-type discharges are sources of the powerful VR and X-ray emission, energetic ions, fast electron-beams, and intense streams of fusion reactions products, e.g. fast protons and neutrons from shots with deuterium. Investigations of such discharges are of importance not only for high-temperature plasma physics, but also for numerous applications. Therefore, extensive studies and optimization tests of various PF facilities have been carried out in various laboratories since many years. Different PF experiments, as performed in Poland, were reported at many international conferences [1-8].

Fig.1. Experimental chamber of the PF-360 device

Extensive PF studies, as carried out by joint research teams of IPJ and IPPLM during recent years, delivered new important data. Hence, the main aim of this talk was to report and discuss the theoretical and experimental results, as obtained in the recent two years.

2. EXPERIMENTAL FACILITIES

In recent years the PF studies in Poland have mostly been performed with the MAJA-PF and PF-360 facilities in Swierk and with the PF-150 and PF-1000 facilities in Warsaw. Some experiments have been performed within the frame of the international scientific collaboration, in particular with the Czech and Ukrainian partners. Details of these experimental facilities have been described in the previous papers [1-8]. Pictures of the PF-360 and PF-1000 facilities are shown in Figs.1 and 2.

The both PF facilities were equipped with numerous diagnostic tools: HV- and current-probes and fast storage oscilloscopes for measurements of voltage- and current-waveforms, high-speed cameras for recording of 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), as well as scintillation- and activation- detectors for measurements of fusion-produced neutrons, etc. [3, 5]. The location of some diagnostic equipment is shown in Fig. 3.

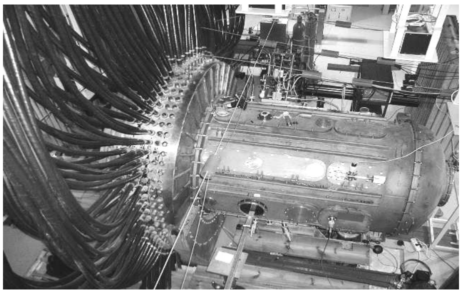


Fig.2. Large experimental chamber of PF-1000 facility

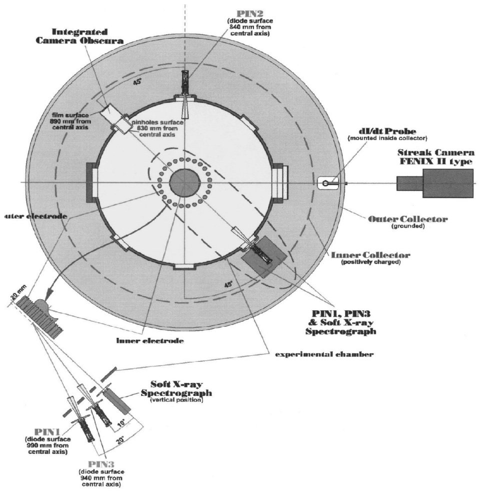


Fig.3.Arrangement of the diagnostic equipment in the chosen cross-section plane of the PF-1000 chamber

During the experiments reported here the PF-360 device was operated up to about 125 kJ, at the charging voltage of 31.5 kV and the maximum current of 1.85 MA. The initial pressure was varied within the range 5.5-8.0 hPa D_2. The PF-1000 facility was investigated up to the energy level of 1 MJ, but most experiments were performed at 800 kJ and the peak current of 2.3 MA. The initial filling pressure was changed from 4 to 8 hPa D_2.

3. STUDIES OF BREAKDOWN PHASE

The breakdown in PF facilities is the important initial phase which determines the development of discharges. It usually occurs upon the surface of the inner insulator. A current-sheath layer, which is formed during the breakdown, cannot be accelerated within the inter-electrode gap effectively at a very low gas pressure. Therefore, some amount of gas must be gathered by the so-called "snow-plough" process. Theoretical simulations of the breakdown were performed [3, 5] and the results of the numerical computations agree relatively well with experimental data, as shown in Fig.4.

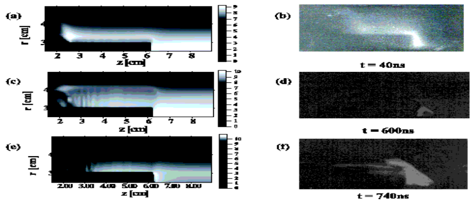


Fig.4. Computed plasma density distributions and corresponding high-speed camera pictures, which show a relatively good agreement

Unfortunately, an accurate quantitative model, taking into account complexity of the current sheath formation phase, is still missing. In particular, influence of a status of the insulator surface has not been taken into account. It should be reminded here that in the POSEIDON facility the replacement of a glass insulator (by an alumina ceramic tube) made it possible to operate at higher energy and higher neutron yields. Therefore, new experiments with modified insulators have to be performed soon. It is considered to apply also the working gas puffing.

4. STUDIES OF AXIAL ACCELERATION

In order to analyze the axial acceleration phase there was applied a modernized 2-fluid MHD model using equations of plasma continuity, momentum and energy balance, the Maxwell equations and the electrical circuit equation. The computer simulations were specified for the PF-1000 electrode configuration and gas conditions. That modeling was sensitive to kinetics of the ionization and transport coefficients. Therefore, the use was made of the Braginski transport coefficients [5]. Anomalous resistance of plasma was also taken into account. Some results of such computations are presented in Fig.5.

No new experimental data on the axial acceleration phase have been collected recently, but new probes and spectroscopic measurements are under preparation. A role of non-uniformities and quasi-radial filaments (in the moving current sheath) has to be explained satisfactorily.

5. STUDIES OF RADIAL COLLAPSE PHASE

The model described above has also been applied for numerical computations of the radial collapse phase [5]. It was shown that the obtained results are reasonable until the maximum compression of the pinch column. Some examples of such simulations are presented in Fig. 6.

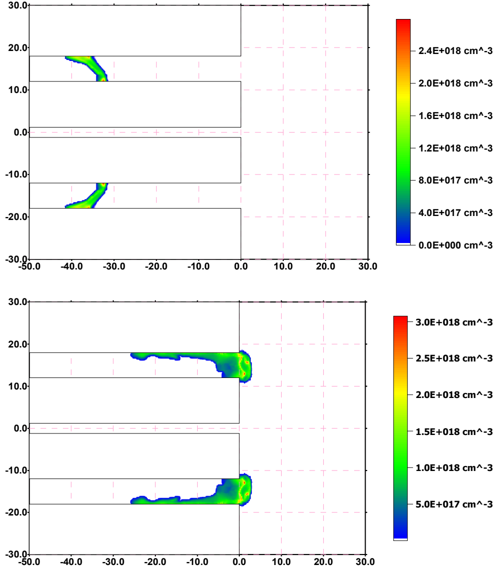


Fig.5. Plasma density distribution in the accelerated current-sheath, as computed for PF-1000 and different instants: 3 μs and 7 μs after the discharge beginning

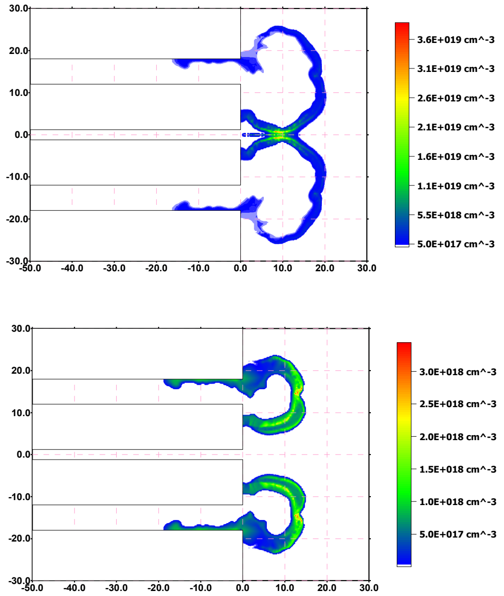
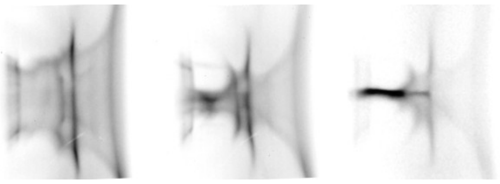


Fig.6. Plasma density distribution during the radial collapse, as computed for PF-1000 and different instants: 9 μs and 9.7 μs after the discharge start

The radial collapse phase has been extensively investigated experimentally [3, 5-8]. High-speed camera pictures were collected and compared with computations performed on the basis of the MHD model. The recorded pictures remained in a qualitative agreement with results of the numerical simulations, as shown in Fig.7.



-148 ns - 49 ns - 5 ns

Fig.7. High-speed camera pictures of the radial collapse phase, as taken in the PF-1000 experiment performed at p_o = 4 hPa, U_0 = 33 kV and I_{max} = 1.7 MA. Time is counted in relation to the maximum compression

Using the improved MHD model one could also simulate the development of local MHD instabilities, but their appearance in the real experiment could not be predicted because of their stochastic character.

It should be noted that during the simulations performed so far there was some disagreement between computed and real discharge current waveforms [5, 8]. These differences have possibly been induced by the assumption of wrong values of the circuit parameters.

6. STUDIES OF THE PINCH PHASE

The pinch phase of PF discharges was investigated experimentally very extensively [3-8]. The use was made of different diagnostic techniques described above. Some examples of the recorded waveforms and high-speed VR pictures are shown in Figs. 8 and 9.

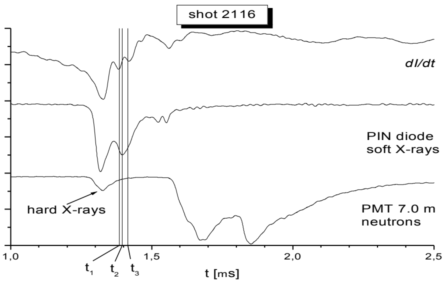
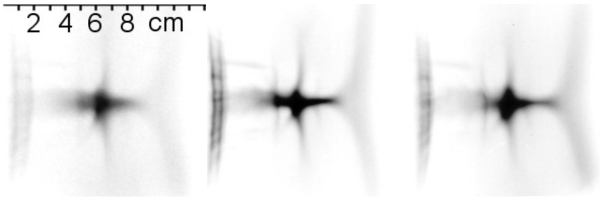


Fig.8. Time-resolved traces recorded for the PF-1000 experiment performed at p_o = 4 hPa D_2, W_o = 734 kJ and I_{max} =1.66 MA



t_1 = 57 ns t_2 = 67 ns t_3 = 87 ns

Fig.9. High-speed camera pictures of the pinch column correspond to instants marked in Fig.8

The analysis of the pinch phase could not be performed with the MHD model because of the appearance of different non-linear phenomena. Although no satisfactory theoretical model of this phase has been developed so far, numerous experimental studies supplied valuable information about dynamics of the pinch and its basic parameters.

Extensive studies of the PF emission characteristics have been carried out. The emission of X-rays was investigated in details and temporal correlations of the X-rays and other PF characteristics were analyzed. Considerable differences in the polarization of various X-ray spectral lines were observed [9]. They were explained as a result of directed e-beams, which are generated within dense high-temperature plasma micro-regions (“hot spots”) [10]. Intense e-beams, as emitted through the axial channel within the inner electrode, were measured [11-12], as shown in Fig. 10.

In order to investigate the correlation of the pulsed e-beams with other PF phenomena, attention was paid to time-resolved measurements by means of different techniques [12-15], as shown in Figs. 11 and 12.

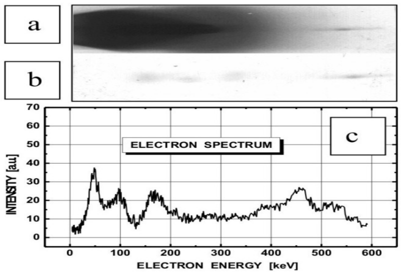


Fig.10. Electron energy spectrum, as obtained with a magnetic analyzes for a single 40-kJ shot in the MAJA-PF device: a) recorded on the first emulsion layer; b) recorded behind a filter, c) measured with a photometer

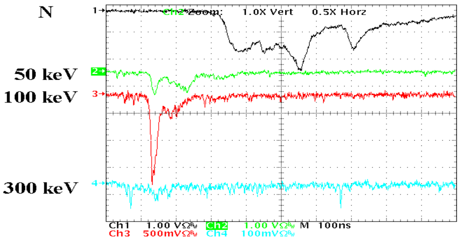


Fig.11. Time-resolved electron signals, as obtained in different energy channels of the magnetic analyzer for a single shot in the PF-1000 facility. For a comparison there is also shown a signal of fusion-produced neutrons

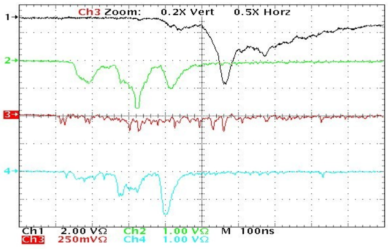


Fig.12.Pulsed e-beams recorded with a Cerenkov-type detector (4) in a correlation with hard X-rays (2), soft X-rays (3) and neutron-induced signal (1); $Y_n = 3.2 \times 10^{10}$

Accelerated primary ions, those are emitted mainly in the down-stream direction (along the discharge axis), have also been investigated [16-21]. There were observed mostly deuterons, because an amount of impurity ions is low in regular PF discharges.

Angular distributions of the emitted ions, those were measured with NTD samples placed at various angles, are shown in Fig.13.

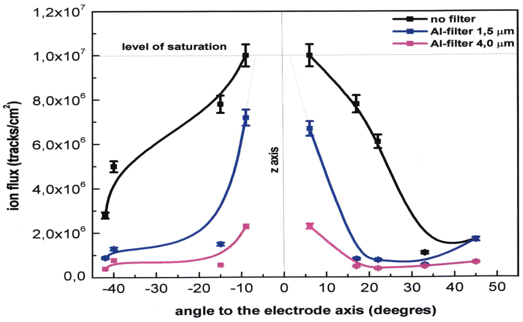


Fig.13. Ion angular distribution in the PF-1000 facility, as measured by means of NTDs with different filters [18]

During PF experiments particular attention has been paid to measurements of fast neutrons originated from the D-D fusion reactions [17, 21-23]. The total fusion neutron yield was measured within the PF-1000 facility at different experimental conditions, as shown in Fig.14.

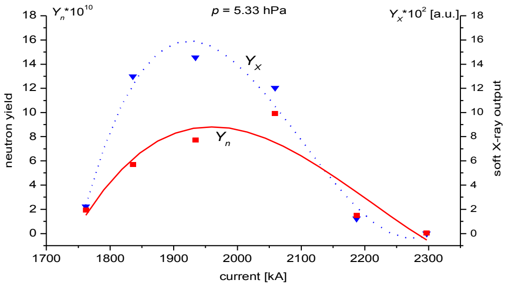


Fig.14. Total neutron and X-ray yields from experiments performed at constant initial pressure, but at different discharge currents in the PF-1000 facility equipped with the old (version I) electrodes [3]

It was shown that the total neutron yield as a function of the discharge current in the PF-1000 facility (at the initial pressures varied from 1.3 hPa to 8.0 hPa D_2) behaves according to the scaling law $Y_n \sim I_{tot}^{1.49}$ [3, 8]. Recent neutron measurements, performed for a new set of electrodes, have shown some discrepancy in absolute values determined by means of different techniques [21-23]. It must still be investigated and explained.

It was shown that to optimize the operation of the chosen PF facility one must analyze the whole electrical and plasma circuit. For this purpose one should consider energy supplied to the system and energy cumulated within the pinch (that can be divided into two parts: thermal- and fast-beam-component), since the total fusion yield is determined both by thermo-nuclear processes and beam-target interactions. To get information how to increase the total neutron emission one should perform such an analysis for realistic experimental parameters.

In order to collect more data about the fusion mechanisms, angular anisotropy of the fusion-produced neutrons was investigated in PF-360 and PF-1000 experiments. It was confirmed that PF discharges with the highest neutron yields are not necessarily the ones with the strongest anisotropy. Temporal changes of the neutron anisotropy were also analyzed [22], as shown in Fig.15.

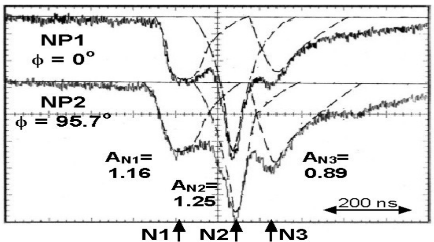


Fig.15. Time-resolved signals from two (NP1 and NP2) neutron probes, those were located at the PF-1000 facility, at a distance of 7 m from the electrode outlet. Three neutron pulses, as obtained at p_0 = 5.3 hPa, W_o = 486 kJ, $Y_n = 2.9 \times 10^{10}$, have been analyzed and their anisotropy factors (A_N) have been determined

Differences in anisotropy of the successive neutron pulses, as observed in the both PF-experiments, can be explained by different mechanisms those contribute to the subsequent neutron-peaks production.

To get more information about plasma regions, where the most nuclear fusion reactions occur, measurements of fusion-originated fast protons have been undertaken [24]. Some results of the preliminary measurements of fusion protons, as obtained within the PF-1000 facility, are shown in Fig. 16.

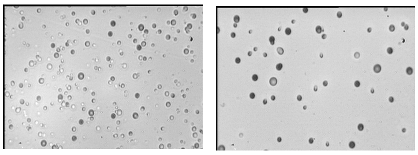


Fig.16. Pictures of fusion-produced proton tracks recorded on PM-355 detectors, those were placed side-on (A) and end-on (B) the PF-1000 electrode ends. The tracks were developed during 4-hour etching

In recent PF-360 and PF-1000 experiments, for the first time, there was applied an optical spectrometer with a high temporal resolution that enabled to study evolution of different spectral lines [25-30], as shown in Fig. 17.

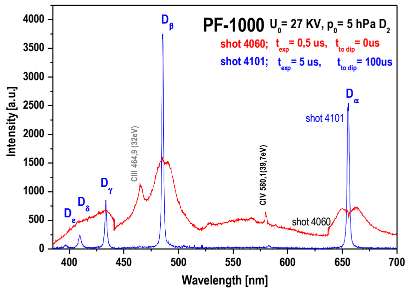


Fig.17. Optical spectra of plasma produced in the PF-1000 facility, as recorded for two different shots performed at the same energy value

An influence of CD_2 fiber on the compression of the current sheath (CS) in the PF-1000 facility was also investigated [31-32]. There were also initiated studies of the application of fast ion beams for the activation or modification of different targets [33-34].

7. SUMMARY AND CONCLUSIONS

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

1. The theoretical simulation of the PF breakdown phase gave good results, but the model applied has still to be improved, and new experiments with special insulators or gas puffing should be performed.

2. The axial acceleration phase of PF discharges was well described by the extended MHD model, but new experiments (e.g. with segmented electrodes and gas puffing) are still needed.
3. The radial collapse phase was also well described by the same modified MHD model, but it is necessary to study a role of current-sheath symmetry and uniformity. Also the development of plasma instabilities within the PF pinch requires more sophisticated approaches.
4. The pinch phase of PF discharges was studied extensively, but further optical, X-ray and corpuscular measurements with good spatial- and temporal-resolution are still needed.
5. Fusion reaction yields (fast neutrons and protons) have been measured under different experimental conditions, but they still require the optimization.

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ПРОГРЕСС В ЭКСПЕРИМЕНТАХ НА КРУПНОМАСШТАБНЫХ ПЛАЗМЕННЫХ ФОКУСАХ

М.Садовский, М. Шольц

В работе представлены наиболее важные результаты теоретических и экспериментальных исследований разрядов в плазменном фокусе (ПФ), проводимых в последнее время в рамках сотрудничества между IPJ и IPPLM (Польша). Достигнут прогресс в изучении пробоя и фазы ускорения. Численные исследования показывают, что модифицированная модель МГД является удовлетворительной до момента максимальной компрессии. В экспериментальных исследованиях было использовано различное диагностическое оборудование. Была исследована корреляция рентгеновского излучения с другими эффектами в ПФ, а также отмечено различие в поляризации рентгеновских спектральных линий. Исследовались потоки быстрых электронов (излученных через аксиальный канал), и измерены потоки энергетических ионов (излученных в обратном направлении). Была исследована анизотропия термоядерных нейтронов и проанализированы их временные изменения. Впервые для изучения эволюции спектральных линий был использован оптический спектрометр с высоким временным разрешением. Рассмотрены также основные проблемы изучения ПФ.

ПРОГРЕС В ЕКСПЕРИМЕНТАХ НА ВЕЛИКОМАСШТАБНИХ ПЛАЗМОВИХ ФОКУСАХ

М. Садовський, М. Шольц

У роботі представлені найбільш важливі результати теоретичних і експериментальних досліджень розрядів у плазмовому фокусі (ПФ), проведених останнім часом у рамках співробітництва між IPJ і IPPLM (Польща). Досягнуто прогрес у вивченні пробою і фази прискорення. Чисельні дослідження показують, що модифікована модель МГД є задовільною до моменту максимальної компресії. В експериментальних дослідженнях було використано різне діагностичне устаткування. Була досліджена кореляція рентгенівського випромінювання з іншими ефектами у ПФ, а

також відзначено розходження в поляризації рентгенівських спектральних ліній. Досліджувалися потоки швидких електронів (випромененних через аксіальний канал), і виміряні потоки енергетичних іонів (випромененних у зворотному напрямку). Була досліджена анізотропія термоядерних нейтронів і проаналізовані їхні часові зміни. Уперше для вивчення еволюції спектральних ліній був використаний оптичний спектрометр із високим часовим дозволом. Розглянуті також основні проблеми вивчення ПФ.