PLASMA DIAGNOSTICS

HIGHLIGHTS OF DENSE MAGNETIZED PLASMA RESEARCH IN POLAND

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This invited lecture presents the most important achievements of theoretical and experimental studies which concerned dense magnetized plasmas and were performed in Poland during recent few years. Those studies were concentrated on high-current pulse discharges within the large mega-joule PF-1000 facility, which was operated at the IPPLM in Warsaw and investigated by researchers from the IPJ and IPPLM. The machine was operated mainly with a pure D_2 filling, and the peak discharge current amounted to 1,5...1,8 MA. Theoretical studies concerned motions of accelerated primary deuterons and fusion-produced protons. Experimental investigations included a multi-frame laser interferometry, measurements of neutron yields, optical spectroscopy of plasma streams, diagnostics of fast electron- and ion-streams, and measurements of an angular distribution of fusion protons.

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2. INTRODUCTION

Investigation of high-temperature plasmas in Poland, which was initiated at IPJ about 55 years ago, has been continued mainly within two institutes: IPJ and IPPLM for many years [1]. This investigation included studies of basic plasma physics and fusion-oriented research on magnetic confinement fusion (MCF) as well as inertial confinement fusion (ICF). The most important results of these studies were presented at many international conferences, including those held in Alushta [2-4].

The main aim of this lecture was to present highlights of research on dense magnetized plasmas, which was carried out in a frame of a close scientific collaboration of IPJ and IPPLM teams after the previous Alushta-2008 conference. That research was concentrated on theoretical and experimental studies connected with the large mega-joule plasma focus PF-1000 facility, shown in Fig. 1.

Fig. 1. General view of PF-1000 experimental chamber

2. THEORETICAL STUDIES

In previous years theoretical analysis concerned mainly the modeling of a current sheath dynamics using an extended 2D-MHD model. It was shown that such an approach describes the axial acceleration and radial compression of the current sheath satisfactory [2]. In particular the computed plasma density and electron temperature distributions were reasonable and consistent with other experimental results until the maximum compression of the pinch column. An example of the computation results is presented in Fig. 2.

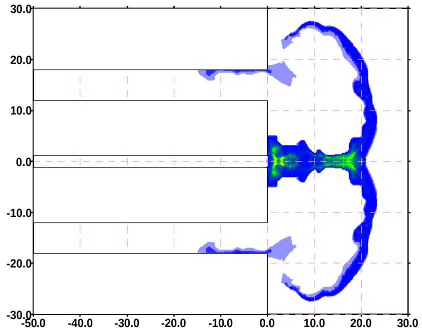

Fig. 2. Plasma density distribution in PF-1000 during the radial collapse phase , as computed by M. Scholz et al. for t = 10 μs after the discharge beginning [2]

In the next analysis attention was paid to modeling of motions of the primary deuterons and fusion-produced protons. As regards the accelerated primary particles, computations for the uniform pinch showed that the fast (>50 keV) deuterons (emitted at small angle to the z-axis) should form a concentric image.

The next theoretical approach took into account that the PF pinch column is never a uniform one and at the pinch end there is usually formed a quasi-spherical region of higher density plasma, as shown in Fig. 3.

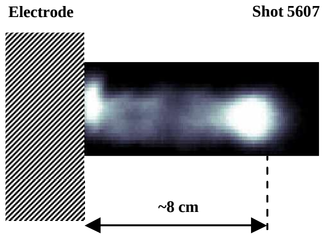

Fig. 3. X-ray pinhole image showing the formation of dense plasma at the end of the PF-1000 pinch column

The computer modeling of the deuteron emission, which took into account influence of such dense plasma, suggested that the deuteron angular distribution should have a local minimum at the z-axis, as shown in Fig. 4.

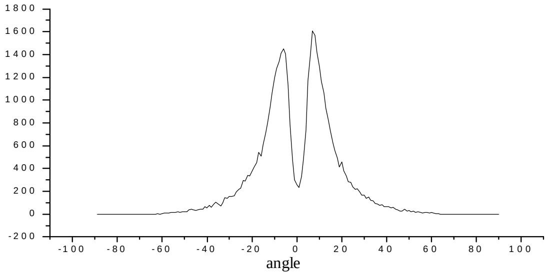

Fig. 4. Computed angular distribution of the deuterons accelerated (to >50 keV in the PF-1000 experiment

That theoretical result was consistent with experimental data collected within the PF-1000 experiments [2-4], but there appeared another problem connected with a micro-structure of the pinch column. In many Z-pinch and PF experiments inside the pinch column there were observed so-called current filaments. Strong local magnetic fields, which surround such filaments, can modify motions of charged particles considerably. Therefore, the recent theoretical analyses were concentrated on studies of an influence of the pinch micro-structure. Different models of the pinch column were considered, as shown in Fig. 5.

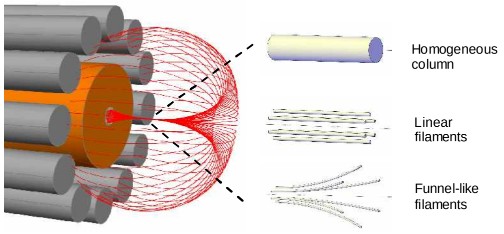

Fig. 5. Various configurations of the pinch column and current filaments, as considered for PF-1000 discharges

Detailed computations were performed particularly for fast (about 3 MeV) fusion-protons [5-6]. It was shown that their trajectories depend strongly on the configuration of the current filaments [6-7], as presented in Fig. 6.

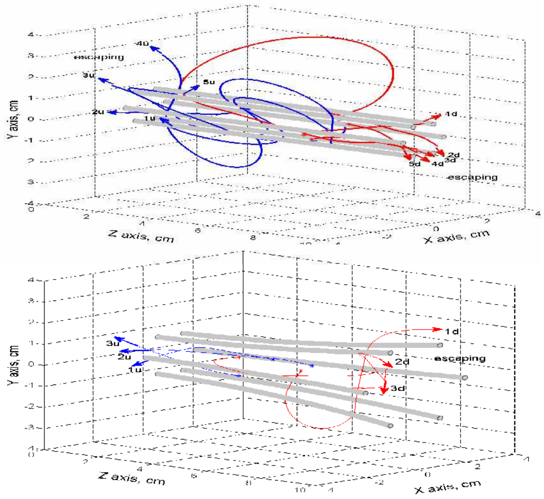

Fig. 6. Trajectories of fast fusion-produced protons, as computed for different configurations of PF-1000 pinch

It should be noted that, due to local magnetic fields, some fusion-protons could be emitted also in the upstream direction. The described computer modeling of proton trajectories enabled also an azimuthal distribution to be calculated [6-7]. Detailed computations showed that the azimuthal distribution of the fusion protons can have a number of distinct peaks corresponding to the number of the current filaments, as shown in Fig. 7.

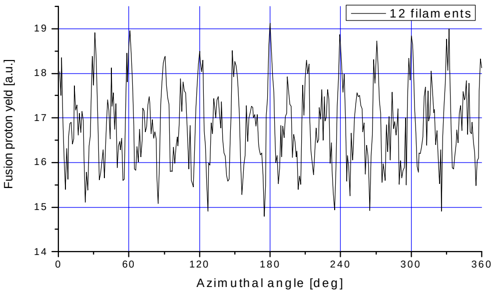

Fig. 7. Azimuthal distribution of fusion-protons around the PF-1000 axis, which was computed under assumption of the appearance of 12 linear filaments

The results of the theoretical considerations could be compared with results of experimental measurements, as described below.

3. EXPERIMENTAL STUDIES

The recent experimental studies were concentrated first of all detailed on measurements by means of a multi-frame laser interferometer [8-9]. Due to the application of a special splitter and interferometer arrangement, which was designed by M. Paduch, it was possible to get 16 interferograms from a single PF-1000 shot. A quantitative analysis of those inteferograms enabled the distributions of isodensity lines and corresponding electron densities to be determined [9], as shown in Fig. 8.

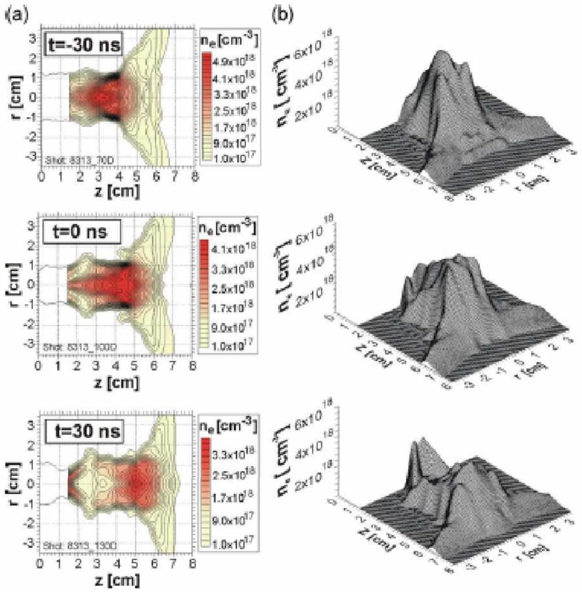

Fig. 8. Isodensity lines from interferograms and the electron density distributions, as determined for t=-30, 0 and 30 ns (in relation to the maximum compression)

The interferometric measurement delivered valuable information about plasma dynamics and density distributions during different phases of the PF pinch formation and decay [8-9]. They informed also about transformations of the PF-1000 pinch column structure during the periods of the fusion-neutron emission [10].

Measurements of fusion-neutrons within the PF-1000 facility have in fact been carried out for many years [2-3]. In recent years there were carried out detailed time-integrated and time-resolved measurements of fusion-neutrons simultaneously with the laser interferometry studies [10-14]. The time-integrated measurements of the neutron yield were performed with a set of silver-activation counters and scintillation detectors placed at different distances from the PF-1000 pinch column, as shown in Fig. 9.

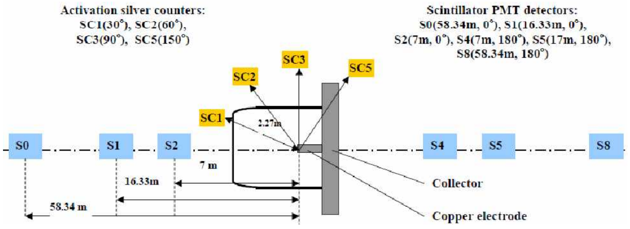

Fig. 9. Arrangement of the activation and scintillation detectors for neutron measurements at PF-1000

There were performed time-integrated measurements with so-called “bubble chambers”. The measured total neutron yields were compared with results of earlier PF experiments performed in different labs. The best neutron yield from PF-1000 shots carried out at 550 kJ, and the maximum current equal to 1,95 MA, amounted to about 6 x 10^{11} neutrons. It was comparable with a result of a large Los Alamos experiment LA3.

Some theoretical considerations suggested that the neutron yield scaling should be proportional to I^4, i.e. to the fourth power of the current flowing through the pinch column. In reality, all PF experiments performed so far have demonstrated some saturation of the neutron yield with an increase in the discharge current and energy [1, 14]. That effect was the main motivation to perform detailed studies of time-resolved the neutron pulses in correlation with other signals, as presented in Fig. 10.

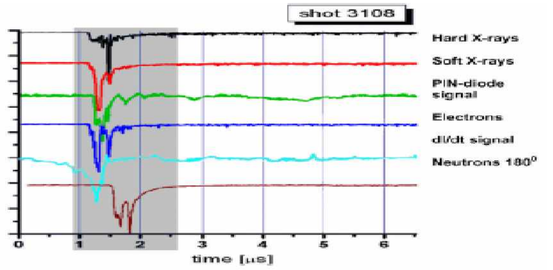

Fig. 10. Signals of X-rays, visible radiation (recorded with a PIN diode), fast electrons, current derivative dI/dt and fusion neutrons (measured at 180^0) from PF-1000 at 734 kJ/33 kV and the peak current of 1.7 MA [1]

Recently attention was paid to the scaling of the total neutron yield from PF-1000 versus the current flowing through the pinch column during the maximum compression. That current was measured by means of miniature magnetic probes situated at different radii (12 and 40 mm) at the anode end [14]. It was observed that the total neutron yield is proportional to I^4 measured with the probe placed at r = 40 mm, as shown in Fig. 11.

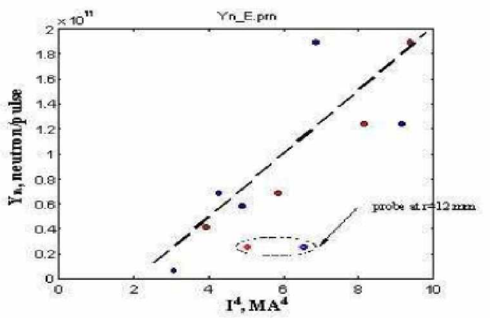

Fig. 11. Neutron yield from PF-1000 as a function of the pinch current, which was measured by means of miniature magnetic probes [14]

During recent years particular attention was paid to detailed time-resolved measurements of the neutron signals [12-14]. An example of the time-resolved signals from scintillation detectors is shown in Fig. 12.

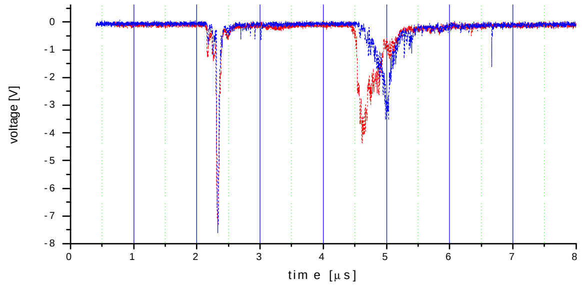

Fig. 12. Signals from scintillation detectors placed at 180^0 and at 0^0 to the discharge axis, both a distance of 8 m from the pinch center

The first peaks were well correlated and showed X-ray pulses, while the next peaks presented neutron-induced peaks: the earlier peak (from 0^0) corresponded to 2.88 MeV neutrons, and the later one (from 180^0) corresponded to 2.14 MeV neutrons. The difference in neutron energies, as obtained from the time-of-flight measurements, showed that reacting deuterons could move along the z-axis with velocities corresponding even to about 120 keV.

Recently, particular efforts concerned measurements of neutrons with very high temporal resolution, using new scintillation probes BETA equipped with ultra-fast scintillators and photomultipliers [14]. The new probes showed a multi-peak structure of the recorded signals and some shift in their maxima, as presented in Fig. 13.

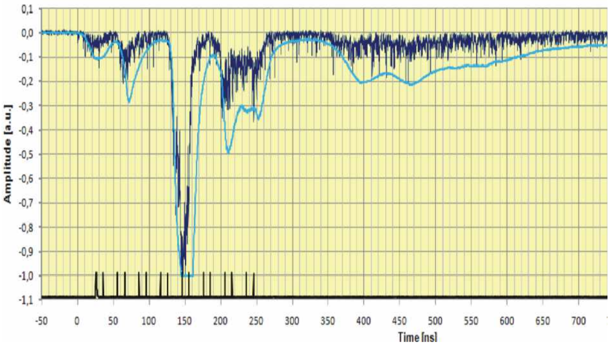

Fig. 13. Comparison of X-ray and neutron signals from the standard probe BRAVO (bright line) and a new ultra-fast probe BETA (dark line), recorded for the same shot

Some PF-1000 discharges were also investigated by means of the optical emission spectroscopy. A plasma stream was observed during its free propagation, and during its interactions with solid targets [15-16]. The use was made of an optical Mechelle®900 spectrometer, which was situated as shown in Fig. 14.

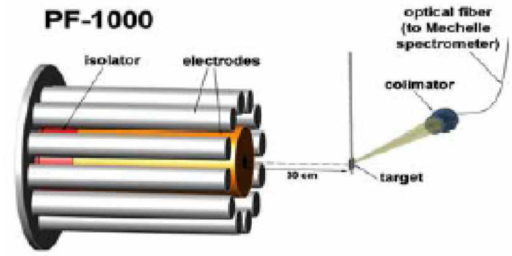

Fig. 14. Experimental arrangement for optical spectroscopy measurements within PF-1000

It was shown that one can determine experimental conditions when a relatively pure deuterium plasma stream arrives to the plane (z), as shown in Fig. 15.

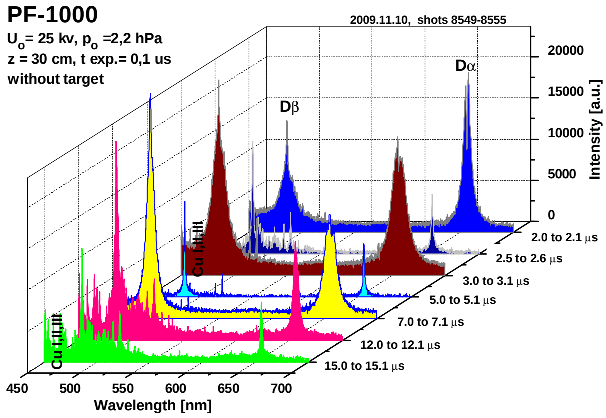

Fig. 15. Changes of spectrum in the 450…700 nm range, as recorded for different instants after the current peculiarity, with the exposition equal to 0.1 μs

These measurements were of importance for studies of targets made of materials to be used in fusion reactors, e.g. tungsten [16]. Details of such studies are presented in another paper at this conference [17].

Recent experimental efforts concerned also the corpuscular diagnostics of fast electron- and ion-beams emitted from the PF-1000 facility. To measure energy spectra of electrons the use was made of a magnetic analyzer equipped with a shielded X-ray film [18]. It was shown that the electron beams, which are emitted from deuterium discharges supplied from a 21…27 kV, 290…480 kJ condenser bank, have energies ranging up to about 800 keV. To investigate the ion beams there were applied small pinhole cameras equipped with shielded PM-355 track detectors [19]. Mass- and energy-analysis of the emitted ions was performed by means of a miniature mass-spectrometer of the Thomson type [20]. It was shown that for the experimental conditions described above the emitted ion streams consist of many deuteron micro-beams of energies ranging up to > 700 keV. It has been confirmed by the first time-resolved measurements of the deuteron beams. The appearance of such energetic deuterons is explained as an effect of non-linear phenomena occurring in a pinch column. Details of the ion measurements are presented in another paper at this conference [21].

Recently, particular attention has also been paid to measurements of an angular distribution of fast fusion-produced protons by means of pinhole cameras and shielded PM-355 detectors [22], as shown in Fig. 16.

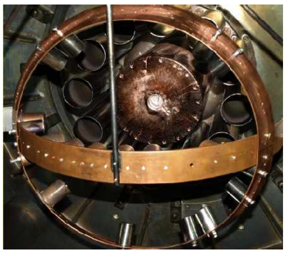

Fig. 16. Experimental arrangement for measurements of angular distributions of the fusion-produced protons

The pinhole images of the fusion protons, which were recorded at different azimuthal angles around the z-axis, have shown considerable differences, as shown in Fig. 17.

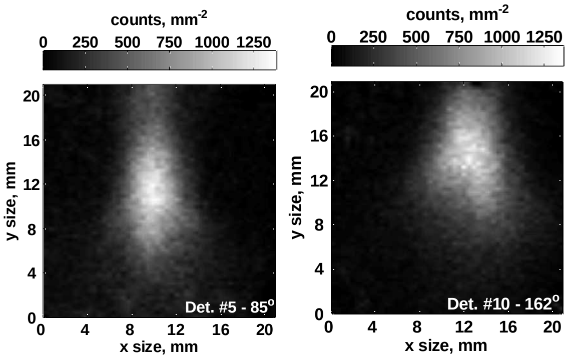

Fig. 17. Examples of the scanned images of protons recorded at different angles around the pinch axis

A quantitative analysis of the fusion-proton images (i.e. the counting of the recorded tracks) made possible to determine the azimuthal distribution, which demonstrated a quasi-periodic character, as shown in Fig. 18.

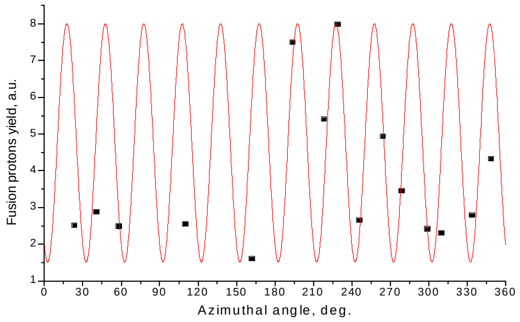

Fig. 18. Total yields of fusion-protons, as recorded around the PF-1000 z-axis during one experimental campaign and fitted to the 12-peaks sinusoid

One can easily notice that the measured azimuthal distribution of the fusion protons is consistent with predictions of theoretical simulations performed for the filamentary pinch column.

SUMMARY AND CONCLUSION

The most important achievements of dense magnetized plasma studies in Poland can be summarized as follows: evident progress in theoretical analysis of PF discharges (based on MHD and single-particle models); considerable progress in experimental studies, and in particular the mastering of a multi-frame laser interferometry, studies of fast fusion-neutrons, applications of time-resolved optical spectroscopy, measurements of ion- and electron-beams, and measurements of fast fusion-protons.

It might be concluded that intense theoretical and experimental studies of dense magnetized plasmas should be continued in order to understand all physical phenomena and to explain the experimental data.

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ОСНОВНЫЕ ДОСТИЖЕНИЯ В ИССЛЕДОВАНИЯХ ПЛОТНОЙ ЗАМАГНИЧЕННОЙ ПЛАЗМЫ В ПОЛЬШЕ

M.J. Sadowski, M. Scholz

Представлены наиболее важные результаты теоретических и экспериментальных исследований плотной замагниченной плазмы, которые проведены в Польше в течение последних нескольких лет. Эти исследования в основном касаются сильноточных импульсных разрядов на большой мегаджоульной установке ПФ-1000, действующей в ИФПЛМ в Варшаве, исследуемой совместно учеными ИЯИ и ИФПЛМ. Установка работает, в основном, с напуском чистого дейтерия, максимальный разрядный ток достигает 1,5...1,8 МА. Теоретические исследования связаны с изучением динамики ускоренных дейтронов и протонов термоядерного происхождения. Экспериментальные исследования включали многокадровую лазерную интерферометрию, измерения нейтронного выхода, оптическую спектроскопию плазменных потоков, диагностику пучков быстрых электронов и ионов и измерения распределения по углам термоядерных протонов.

ОСНОВНІ ДОСЯГНЕННЯ В ДОСЛІДЖЕННЯХ ГУСТОЇ ЗАМАГНІЧЕНОЇ ПЛАЗМИ В ПОЛЬЩІ

M.J. Sadowski, M. Scholz

Представлено найбільш важливі результати теоретичних і експериментальних досліджень густої замагніченої плазми, що проведено в Польщі протягом останніх декількох років. Ці дослідження в основному стосуються потужнострумових імпульсних розрядів на великий мегаджоульній установці ПФ-1000, що діє в ІФПЛМ у Варшаві, досліджуваної спільно вченими ІЯИ і ІФПЛМ. Установка працює, в основному, з напуском чистого дейтерію, максимальний розрядний струм досягає 1,5...1,8 МА. Теоретичні дослідження зв'язані з вивченням динаміки прискорених дейтронів і протонів термоядерного походження. Експериментальні дослідження включали багатокадрову лазерну інтерферометрію, виміри нейтронного виходу, оптичну спектроскопію плазмових потоків, діагностику пучків швидких електронів і іонів і виміру розподілу по кутах термоядерних протонів.