PROGRESS IN PLASMA RESEARCH AT IPJ AND IPPLM, POLAND

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The most important results of theoretical and experimental studies of plasmas, which have been achieved at the IPJ in Swierk and IPPLM in Warsaw recently, are presented. Studies of physical phenomena in PF discharges, development of diagnostic techniques and research on new plasma technologies, as performed at IPJ, have been summarized. Studies of dense magnetized plasmas, investigation of physics and applications of laser-produced plasmas; and research on the development of advanced diagnostic techniques for the EURATOM fusion program, as performed at IPPLM, are also described.

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1. INTRODUCTION

Studies of high-temperature plasmas were initiated in Poland about 50 years ago, when multi-rod plasma injectors (RPI) were built in Warsaw and Swierk. The IPJ (initially IBJ) was established in Swierk (about 30 km from Warsaw) in 1955. Now it is divided into 10 depts, subordinated to Ministry of Industry (MI) and supported by Ministry of Science and Education (MSE). Studies of hot plasmas are performed at Dept. of Plasma Physics & Technology (P-V). Some research on plasma technology is carried out in Dept P-IX, and theoretical studies are performed at Dept. P-VIII in Warsaw.

The largest plasma research center in Poland is the IPPLM situated in Warsaw. It was established in 1976, and currently it is carrying out research on plasma physics and applications in cooperation with many domestic and foreign laboratories. It is also subordinated to MI and supported by MSE. It is now divided into two research divisions: Magnetized Plasma Physics Division (MPPD) and Laser Plasma Physics Division (LPPD).

Studies on dense magnetized plasmas carried out at the both research centers were described in previous papers [1-3]. The main aim of this talk was to report on progress in plasma studies achieved recently in the both institutes mentioned above.

2. PLASMA RESEARCH AT IPJ IN SWIERK

The Dept. of Plasma Physics & Technology (P-V) is divided into several groups, as described in the IAEA World Survey. The main research directions are as follows: studies of physical phenomena in pulsed discharges producing dense magnetized plasma; development of methods and tools for high-temperature plasma diagnostics (mainly for EURATOM fusion program); and research on new plasma technologies, particularly on the deposition of thin superconducting layers by means of ultra-high vacuum arc-discharges.

2.1. STUDIES OF PHENOMENA IN PF DISCHARGES

The main phases of PF-type discharges are well known, but mechanisms of the acceleration of primary ions as well as of the generation of intense pulses of X-rays, electron beams and fusion products (fast neutrons and protons from D-D reactions) are not explained satisfactorily. Therefore, research on these phenomena has been continued for many years.

At IPJ experimental studies of physical phenomena in high-current pulse discharges of the Plasma-Focus (PF) type are carried out within two facilities. A general view of a 50-kJ MAJA-PF device is shown in Fig.1.

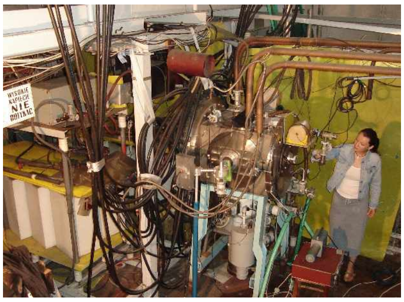

Fig.1. MAJA-PF experimental facility at IPJ in Swierk

The MAJA-PF facility has been used mainly for studies of the fast electron-beams, which are emitted through the tubular central electrode in the upstream direction, and the emission of X-rays. Recently, particular attention has been paid to the correlation of pulsed e-beams and hot spots, as well as to temporal changes in the polarization of different X-ray spectral lines [4].

The larger PF-360 facility of nominal energy equal to 360 kJ, operated in Swierk, is shown in Fig.2.

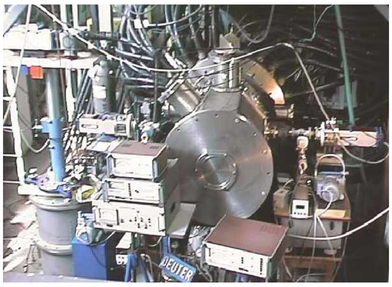

Fig.2. Experimental chamber of the PF-360 facility

The PF-360 facility was used for research on dynamics of PF-type discharges and the investigation of emission characteristics. The dynamics of discharges was investigated by means of high-speed cameras recording the VR or X-ray images [5]. There were also investigated fast e-beams escaping through the tubular inner electrode, and accelerated primary ions emitted mainly along the z-axis [6]. Other studies concerned the microstructure of the ion beams. It was investigated with pinhole cameras equipped with nuclear track detectors coated with different absorption filters [7]. Particular attention was paid to studies of the correlation of fast neutrons (from D-D reactions) with other corpuscular and x-ray pulses (emitted from plasma), because it is of great importance for understanding physical phenomena of the PF pinch phase. Detailed studies were performed within MAJA-PF and PF-360 facilities [8]. An example is shown in Fig.3.

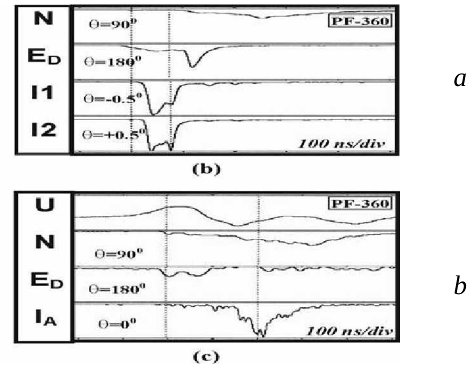

Fig.3. Time-resolved signals from the PF-360 experiment: (a) at 121 kJ and $Y_n = 6.5 \times 10^9$; (b) at 113 kJ and $Y_n = 5.9 \times 10^9$. Notations: N – neutrons; U – voltage; E_D – e-beams signals; I – ions; I_A – 600-keV deuteron-signals

Those studies enabled a sequence of the emission phenomena in PF discharges to be determined as a function of the experimental conditions.

2.2. DEVELOPMENT OF DIAGNOSTIC METHODS

In the scope of this topic particular efforts were directed on characteristics of new nuclear track detectors (NTD) and their application for studies of fusion protons in PF facilities. The calibration measurements of NTDs of the PM-355 type were performed using different proton beams. The calibrated detectors were first used for measurements of fast protons from D-D reactions, which were emitted from the PF-360 facility in Swierk [9]. Using miniature ion-pinhole cameras and the calibrated NTDs it was possible to record proton images and to determine the proton emission sources, as shown in Fig.4.

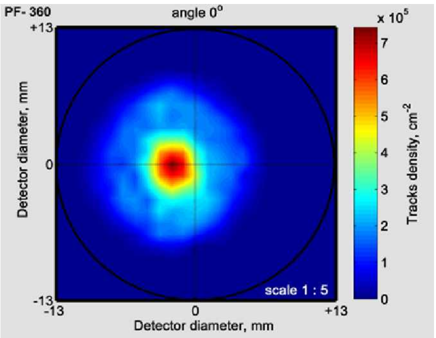

Fig.4. End-on image of regions emitting fusion-produced protons in the PF-360 facility [9]

Other efforts concerned the application of NTD for measurements of fusion-reaction protons emitted from Tokamak experiments (in a frame of the EURATOM collaboration with ERM in Brussels and FZ in Juelich). Samples of new PM-355 type detectors were irradiated with mono-energetic protons from an accelerator, and the etched proton tracks were analyzed with an optical microscope. The obtained calibration diagrams (showing track diameters vs. proton energy and etching time) could be used to estimate energy spectra of fusion protons. An ion-pinhole camera, adapted especially for the TEXTOR facility, was designed at IPJ and used at FZ-Juelich [10]. An example is presented in Fig.5.

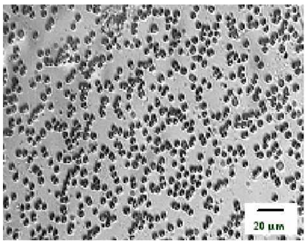

Fig.5. Picture of tracks produced by 3-MeV fusion protons, as obtained in the TEXTOR experiment

The obtained results were used for analysis of fast proton trajectories in the TEXTOR magnetic field. Preliminary computations of proton trajectories were performed with a so-called Gourdon code [11].

Other important diagnostic study concerned the development of new equipment for measurements of fast-electron beams in Tokamaks (in a frame of the EURATOM collaboration with IPP-Praque and CEA-Cadarache). To measure fast electrons the IPJ team proposed to apply Cerenkov-type detectors with special radiators. An analysis of the experimental conditions within the CASTOR facility, operated at IPP in Prague, was performed and a prototype Cerenkov-detector system for this experiment was manufactured, as shown in Fig.6.

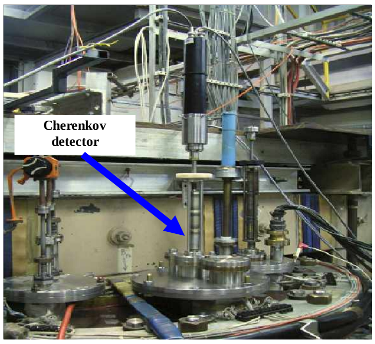

Fig.6. Cerenkov detector head mounted upon the diagnostic port of the CASTOR device in Prague

The developed Cerenkov-type detector was used for measurements of fast electrons during the CASTOR experiment [12]. Possibility to measure ripple-born electron beams by means of Cerenkov detectors was analyzed for experimental conditions observed in TORE SUPRA facility at CEA-Cadarache. It was known that the spectrum of such electrons spreads from about 50 keV to about 300 keV, and their power flux amounts up to 1 kW/cm^2. A new Cerenkov detector system with four energetic channels was designed, using diamond radiators covered with molybdenum filters of different thickness. Diamond radiators were chosen due to their high refractive index (enabling to observe electrons of energy above 50 keV) and their very good thermal conductivity (enabling heat from the detector surface to be dissipated). Such a detector will be manufactured until end of 2006.

2.3. RESEARCH ON NEW PLASMA TECHNOLOGIES

Separate efforts concerned the development of new plasma technologies. For this purpose the use was made of several experimental facilities, and in particular of the IBIS-RPI facility, which is shown in Fig.7.

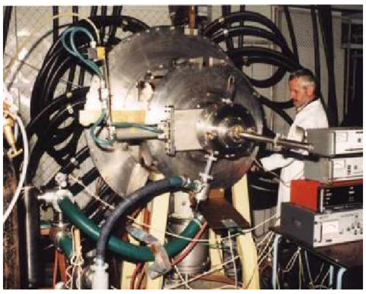

Fig.7. Experimental chamber of the IBIS-RPI facility

Recently, experimental studies have concerned diagnostics of deuterium-plasma streams emitted from RPI-IBIS discharges [13]. Particular attention was paid to research on the dependence of the spatial structure of emitted plasma-ion streams on the operational mode of the applied experimental facility. Using a Thomson-type analyzer, energy spectra of deuterons were determined under different operational conditions. Using ion pinhole cameras and NTDs covered with thin absorption filters, it was possible to investigate the spatial structure of the emitted plasma-ion streams, as shown in Fig. 8.

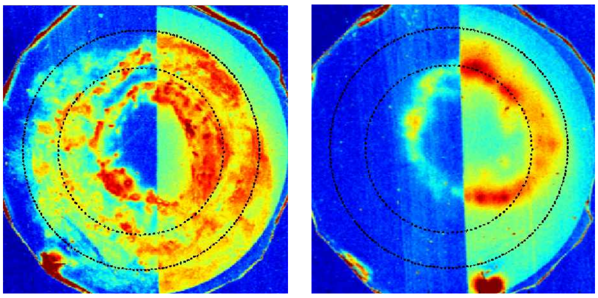

Fig.8. Structure of deuteron beams emitted along the z-axis of RPI-IBIS in so-called fast mode (on the left) and slow mode (on the right). Left parts of the detectors were covered with an Al-foil eliminating deuterons < 80 keV. Broken lines show projections of electrode ends [13]

Information collected from RPI-IBIS discharges is of importance for physics and applications of pulsed plasma-ion streams for modifications of different materials.

In a frame of plasma technology research other efforts concerned the deposition of superconducting films by means of arc discharges performed under ultra-high vacuum (UHV) conditions, as proposed several years ago [14]. Recent activities have been concentrated upon the Nb-film deposition technology based on linear (cylindrical) arc or the planar filtered arc (in collaboration with Tor Vergata University in Rome). A general view of the UHV facility at IPJ is shown in Fig.9.

Recently, particular attention has been paid to the application of the UHV arc technology for the deposition of a Pb-film needed for the formation of a photocathode inside an RF electron-injector [15].

Fig.9. Modified UHV linear-arc facility constructed at IPJ for the deposition of thin super-conducting layers and the axial cut of the RF cell coated with a pure Nb-layer

3. PLASMA RESEARCH AT IPPLM IN WARSAW

The main research directions at IPPLM are as follows: studies of dense magnetized plasmas produced by pulsed discharges of the PF- and Z-pinch type; investigation of physics and applications of laser-produced plasmas; the development of advanced diagnostic techniques applicable for the EURATOM fusion program; and studies of some theoretical problems of magnetic confinement fusion (MCF).

3.1. STUDIES AT MPPD

Experimental studies at MPPD are carried out mainly with the large mega-joule PF-1000 facility, but some research is performed also with smaller PF-type machines (DPF-6 and PF-150). A general view of the PF-1000 facility is shown in Fig.10.

Fig.10. Large experimental chamber of PF-1000 facility

Extensive PF studies with the PF-1000 device, which were carried out by joint research teams of IPJ and IPPLM, have already been reported at various conferences and described in earlier publications [1-4]. Therefore, this paper presents only the most important results obtained recently. Studies of pinch dynamics in PF-1000 discharges have been performed by means of fast-streak- and frame-cameras [16], as shown in Fig.11.

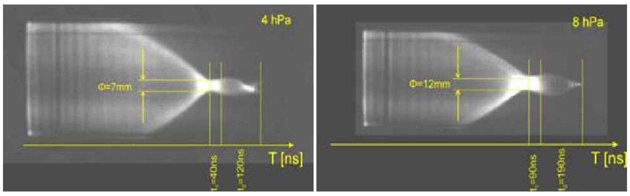

Fig.11. Examples of the streak pictures, which were taken for PF-1000 experiments at different initial pressures (4-8 hPa) and show a phenomenon of the double pinch

Particular attention was paid to the study of the neutron emission from PF-1000 discharges [17]. Two or three peaks in hard X-ray signals and the subtle structure of neutron-induced signals were observed in many discharges.

The PF-1000 facility was also used for studies by means of optical spectroscopy during the free propagation of pulsed plasma streams and their interactions with different targets [18]. An example is presented in Fig. 12.

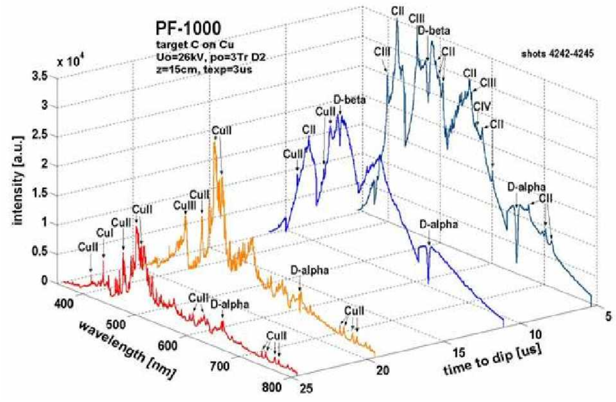

Fig.12. Optical spectra recorded for different phases of PF-1000 discharge interacting with a C-Cu target placed 15 cm from the electrode outlet

The elaboration of time-resolved spectroscopic measurements of pulsed plasma streams in the PF-1000 facility and their interaction with various targets was performed [19]. Spectroscopic studies of the VR emission were also performed for PF-1000 shots with deuterium, helium and a mixture of deuterium and helium [20-21].

3.2. STUDIES AT LPPD

Experiments at LPPD are carried out with three Nd:glass laser systems: a single-shot terawatt system (≤ 2 J, 1.2 ps), a single-pulse system (≤ 10 J, 1 ns) and a new repetitive system (≤ 0.6 J, 3.5 ns, the repetition ≤ 10 Hz).

The main research topics at LPPD are as follows: study and application of plasma produced by high-power lasers; research on interaction of ultra-short laser pulses with matter (EC COST P14 program); development of modern diagnostic systems (partially supported by EURATOM), and technological applications of plasma-matter interactions (EURATOM and STREP 6).

Study and application of plasma produced by high-power lasers has been performed mainly within the PALS facility operated in Prague, as shown in Fig.13.

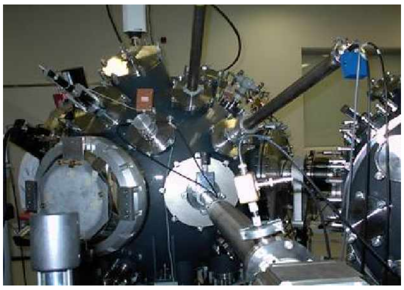

Fig.13. Experimental chamber of the PALS facility with some diagnostic equipment delivered by IPPLM

To determine properties of laser-produced ions the use was made of ion collectors, a cylindrical electrostatic ion analyzer and NTDs. The laser-produced ions were implanted into different samples (polymers, C, Si and Ti) placed at various angles and distances [22]. Energy spectra of heavy (Cu, Ag and Ta) ions were investigated with an electrostatic analyzer [23], as shown in Fig.14.

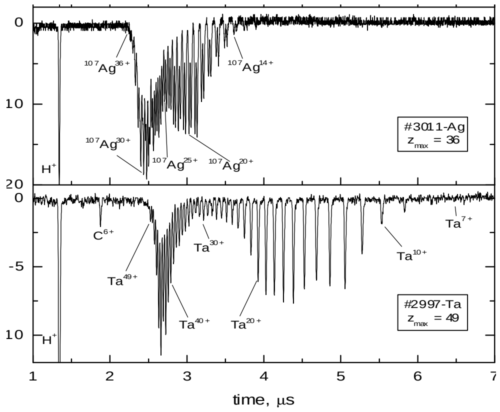

Fig.14. Highly-ionized species obtained from Ag- and Ta-targets bombarded by 200-J laser pulses, as recorded by means of an electrostatic analyzer and TOF method [23]

Studies of indirect interactions of a PALS beam with solid targets were also performed [24]. An example is shown in Fig.15.

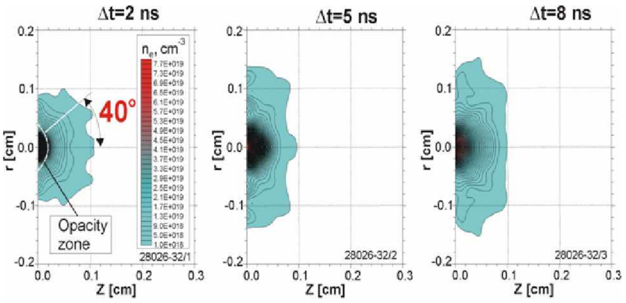

Fig.15. Measurements of plasma produced from a thin (11-µm) Al-disk placed in front of a solid Al target, as performed with a laser interferometer [24]

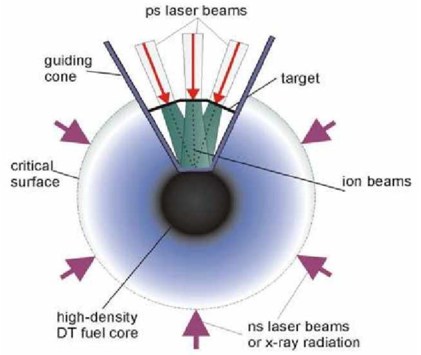

Fig.16. Proton fast ignition (PFI) scenario proposed for a future European High Power Laser Facility [27]

Particular attention was paid to the generation of intense plasma streams (jets) during the interaction of a laser beam with planar solid targets [25]. Other studies concerned the interaction of ultra-short laser pulses with matter and fast ion beam production (COST P14 program)

[26]. Numerical simulations of the generation of proton beams by laser pulses of intensity > 3 x 10^{18} W/cm^2 were performed and it was shown that intense particle beams are generated, which might be used for the fast ignition of thermonuclear fusion [27], as shown in Fig.16.

The proposed scenario assumes that high-energy ns-laser (or X-ray) beams compress DT fuel to density about 1000 times higher than that of the solid, and penta-Watt ps-laser beams produce high-density proton beams, which heat a small portion of the dense DT fuel core to about 10keV, igniting the nuclear fusion reactions.

Other efforts of LPPD concerned the development of diagnostic systems for EURATOM program, e.g. matrix semiconductor detectors for measurement of the X-ray emission from the MAST facility in UK. Other activities concerned the application of laser pulses for the removal of deposited deuterium/tritium from in-vessel components (UT1 project Association EURATOM–IPPLM) [28].

4. SUMMARY AND CONCLUSIONS

The most important recent achievements of IPJ have been as follows: New valuable data about dynamics and parameters of pulsed plasma-ion streams were collected by means of optical spectroscopy during their free propagation and interaction with different targets. Images of sources emitting fusion-protons were recorded in different PF systems and their asymmetry was explained by the filamentary structure of high-current discharges. The technology of the deposition of superconducting layers by means of UHV arc-discharges was improved, the test coating of an RF cavity was performed and different macro-droplets filters were tested.

The most important recent achievements of the IPPLM have been as follows: New data about dynamics and emission characteristics of PF discharges were collected by means of different diagnostic techniques and they were used for a comparison with model calculations. An interesting effect of the emission of narrow plasma-ion jets from solid targets irradiated by intense (100 J, 400 ps) laser pulses was observed experimentally and its theoretical explanation has been proposed. Theoretical computations of the interaction of PW-ps laser pulses with matter were performed, which showed that such pulses generate collimated proton beams of current density reaching TA/cm^2, which can be used for the fast ignition of fusion targets.

Results obtained by researchers from IPJ-Swierk and IPPLM-Warsaw are documented by many publications (see IPJ and IPPLM web pages and Annual Reports). Many studies were performed in the collaboration with different foreign research centers, e.g. CVUT in Prague, Tor-Vergata University in Rome, Messina University and INFN-LNS in Catania, Kurchatov Institute in Moscow and IPP KIPT in Kharkov. Polish teams have also been engaged in the EURATOM fusion program in cooperation with several foreign laboratories, and particularly with IPP in Prague, ERM in Brussel, CEA-Cadarache and IPP FZ-Juelich .

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РАЗВИТИЕ ПЛАЗМЕННЫХ ИССЛЕДОВАНИЙ В IPJ И IPPLM В ПОЛЬШЕ

М. Садовский, Е. Складник-Садовская, М. Шольц, Е. Воловский

Представлены наиболее важные последние результаты теоретических и экспериментальных исследований плазмы, которые получены в Институте ядерных исследований им. А. Солтана (IPJ) в Шверке и в Институте физики плазмы и лазерного микросинтеза (IPPLM) в Варшаве. Приведены результаты выполненных в JPJ исследований физических явлений в разрядах с плазменным фокусом и развития методов диагностики и новых плазменных технологий. Описаны также результаты проведенных в IPPLM исследований плотной замагниченной плазмы, по физике и применению лазерной плазмы; разрабатывались и исследовались новые методы диагностики для программы управляемого синтеза ЕВРОАТОМа.

РОЗВИТОК ПЛАЗМОВИХ ДОСЛІДЖЕНЬ В IPJ І IPPLM В ПОЛЬЩІ

М. Садовський, Е. Складнік-Садовська, М. Шольц, Є. Воловський

Подано найбільш важливі останні результати теоретичних і експериментальних досліджень плазми, які були одержані в Інституті ядерних досліджень ім. А. Солтана (IPJ) в Швєрку та в Інституті фізики плазми і лазерного мікросинтезу (IPPLM) в Варшаві. Доведені результати виконаних в IPJ досліджень фізичних явищ в розрядах з плазмовим фокусом та розвитку методів діагностики і нових плазмових технологій. Також описані результати виконаних в IPPLM досліджень щільної замагніченої плазми, по фізиці та застосуванню лазерної плазми; розроблялися та вивчалися нові методи діагностики для програми керованого синтезу ЄВРОАТОМа.