RECENT ACHIEVEMENTS OF PLASMA RESEARCH AT IPJ, SWIERK, POLAND

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This invited lecture describes the most important results of experimental and theoretical studies in the field of plasma physics and technology, which were obtained at the IPJ in Swierk during recent two years. The main topics were as follows: Selected problems of plasma theory; Investigation of plasma phenomena in pulse discharges of Plasma-Focus (PF) and Z-Pinch type; Development of the selected methods of plasma diagnostics; Research on experimental facilities for basic studies and industrial applications; Modification of material surfaces by means of pulse plasma-ion streams. Particular attention is paid to results obtained within a frame of the international scientific collaboration.
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1. INTRODUCTION

The progress in plasma research in Poland was reported in several papers presented at the previous Ukrainian Conference, which was held in Alushta in 2000 [1-3], as well as in many papers presented at the International Symposium PLASMA-2001,which was held in Warsaw in 2001. Recent research activities were also reported at the 20[th] SPPT held in Prague and at the GPPD held in Greifswald this year. The main aim of this paper was to summarize the achievements of the recent two years and to report on the newest plasma research.

2. SELECTED PROBLEMS OF PLASMA THEORY

Within a frame of theoretical studies the numerical modeling of discharges in IPD-type coaxial plasma-accelerators was continued, and there were found conditions good for the evaluation of Rayleigh-Taylor instabilities upon the current sheath surface [4]. Computational studies of plasma dynamics have significantly increased the understanding of plasma phenomena in the IPD accelerator [5].

Another aim of theoretical studies was a quasi-classical model of the six-electron p-shell of noble gas atoms. On the basis of the known laws of classical dynamics and electrodynamics, an algorithm for the numerical integration of moving electrons was formulated, and a solution has been found, which is supposed to represent collective motion of the considered p-shell [6].

In theoretical studies particular attention was paid to the numerical modeling of ion motion in PF discharges [7]. To explain angular distributions of fast deuterons emitted from PF discharges, as observed in numerous experiments, it was necessary to take into account a filamentary structure of the pinch column. Numerical computations of deuteron trajectories, which were carried out for the “flower-like” configuration of current filaments, gave the deuteron angular distribution with a local minimum in a qualitative agreement with experimental data (Fig. 1).

Recently, in the ion-motion modeling attention has been brought to an influence of electrical fields induced by the radial movement of the current filaments during the radial compression and expansion phases [8]. The computations have been performed for various numbers and spatial

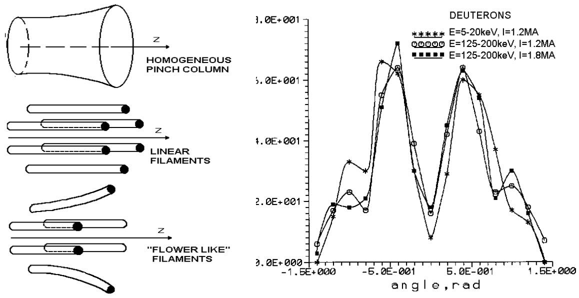

Fig. 1. Three configurations considered for modeling of trajectories of ions emitted from a PF pinch column and an angular distribution of deuterons, as computed for a flower-like pinch column with 6 filaments of αz^2 shape.

distributions of current filaments, and varfor different starting points and initial velocities (energies) of protons and deuterons. The obtained results are in a good agreement with the observed angular distributions of ions (Fig. 2).

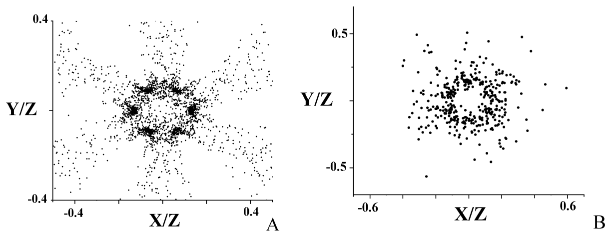

Fig.2. Ion tracks upon the Y-X plane, corresponding to angular distributions of deuterons emitted from a PF pinch column, obtained for different filamentary structures.

It has been proved that the 3-D model, which takes into consideration the realistic funnel-like configuration of current filaments as well as their motion and particle collisions, describes behavior of different (trapped and run-away) ions in PF discharges.

3. INVESTIGATION OF THE PLASMA-FOCUS (PF) AND Z-PINCH DISCHARGES

Within a frame of experimental studies there were investigated different phenomena, which occur in high-current pulse discharges of the PF and Z-Pinch type. The studies within the MAJA-PF device concerned mainly the formation of micro-regions (hot spots) of high electron concentration (~10^{20} cm^{-3}) and relatively high electron temperature (ranging up to several keV). Particular attention was paid to the correlation between X-ray pulses emitted from the hot spots and the emission of pulsed electron beams, ion beams, and the pulsed neutron fluxes [9-10]. The formation of many (up to dozen) hot spots in a single discharge was observed. Also observed was their motion with a relatively high velocity. Those phenomena influenced a spectrum of the X-ray emission from individual hot spots. It was found that the values of the local electron temperature and concentration were higher when the observed hot spots were formed close in space and time. The measured pulsed electron beams of energy ranging several hundreds keV were evidently emitted from different hot spots (Fig.3).

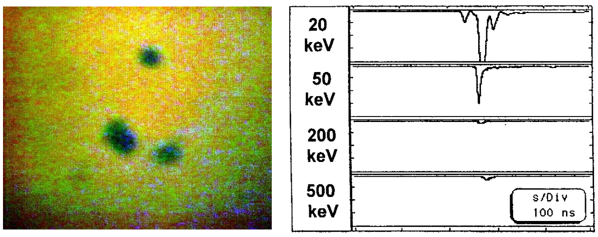

Fig.3. Ion pinhole image, which shows tracks produced by the pulsed ion beams, and the electron-induced signals, which were recorded during the same PF discharge within the MAJA-PF device.

The measured ion (deuteron) beams, as recorded with track detectors, were emitted mostly along the z-axis. Different groups of the ion tracks, as observed after their etching, were identified as ion beams emitted from different hot spots. An optical analysis of the ion tracks showed ion fluxes ranging 10^{12} deuterons/stereo-radian. A study of polarization of some X-ray lines was also continued, and space-resolved measurements of He-like argon lines were performed. The X-ray spectra, as obtained with two crystal spectrometers, showed that the He-like resonance line is polarized perpendicular to the Z-axis, what confirmed the preferential polarization of He-like ions during their de-excitation [11].

There were also continued experimental studies of plasma discharges in the PF-360 facility, which was operated with additional nuclear targets made of D_2O-ice or gas-puffed D_2 (Fig.4).

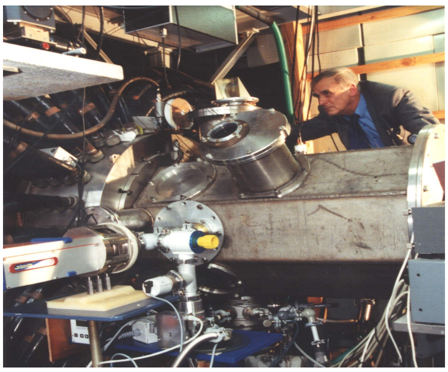

Fig.4. Experimental chamber of the PF-360 facility.

The recent investigation was concentrated on the planar solid target covered with a D_2O-ice layer. The use was made of the four-channel ultra-high speed camera, which was equipped with two visible radiation channels and two soft X-ray modules. It was observed that the dynamics of the current sheath layer has not been disturbed considerably at different target positions and various initial gas conditions in the vacuum chamber. Disturbances have been negligible for the optimal position of the target at a distance of 225 mm [12-13].

Particular attention was paid to measurements of spatial characteristics of the neutron emission from D-D reactions. The angular distribution of fusion neutrons was measured by means of eight silver-activation counters, and the time-resolved measurements were performed by means of four scintillation-based neutron probes [14-15]. To study the anisotropy the use was made of the two neutron probes, which were placed side-on and end-on. The measurements have enabled to determine the anisotropy coefficient values for the subsequent neutron peaks (Fig.5).

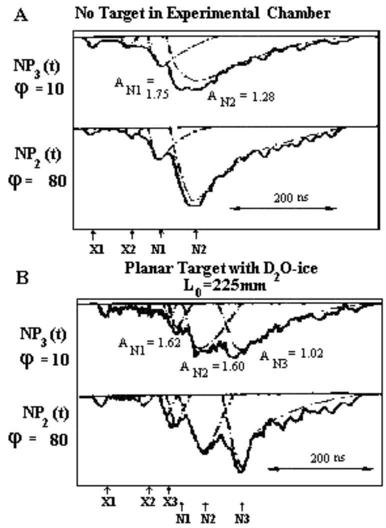

Fig.5. Time-resolved neutron signals from the NP_3 and NP_2 probes, as registered at different experimental conditions in the PF-360 experiment. A – without any target, p_o = 8.0 mbar D_2, U_o = 30 kV, Y_n = 1.82 x 10^{10}; B – with the D_2O-ice target, p_o = 9.85 mbar D_2, U_o = 30 kV, Y_n = 1.67 x 10^{10}. Numbers A_N give values of the anisotropy coefficient for the subsequent neutron peaks.

Usually there were observed two distinct neutron peaks, but (with the planar target) in some cases there were observed three peaks. It was concluded that the second neutron peak, which for the PF shots performed with the use of the planar cryogenic target shows higher anisotropy, is produced mainly by the beam-target mechanism Recent studies within PF-360 facility concerned dynamics of the interaction PF discharge with the solid targets [16-17]. The optimal conditions for the planar solid target positioning have been found.

In the frame of the collaboration with the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw there were performed neutron and X-ray measurements within the modernized PF-1000 facility operated at energy of about 1 MJ [18-19]. The main aim of those experiments was to study the neutron emission mechanism [20]. The problem of the neutron emission emerged many years ago, but some questions have been unexplained so far [21]. Important information could be deduced from the neutron emission characteristics. Therefore, in the PF-1000 experiments the neutron yield, angular distribution, energy spectra and neutron source location were investigated as a function of discharge parameters, e.g. the D_2-filling pressure, discharge current, initial voltage and energy supplied. For neutron measurements there were applied four silver- and two indium-activation counters (placed at different angles to the z-axis). For time-resolved measurements the use was made of three scintillation-probes, which were placed upstream, at the discharge axis, but at different distances (15, 40 and 85 m) from the plasma focus region. It made possible to determine dynamics of the neutron emission and to estimate energy spectra of the fusion neutrons (Fig.6).

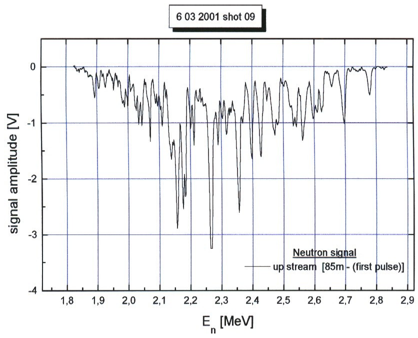

Fig.6. Neutron energy spectrum determined on the basis of a signal from the scintillation probe placed at a distance of 85 m from the PF-1000 electrode outlet.

In the PF-1000 experiment there were also performed other measurements, e.g. current sheath dynamics was studied by means of a fast two-frame camera and a high-speed streak camera placed side-on. The time-resolved soft X-ray signals were registered with a PIN diode with a 10-μm Be-filter, and fast ion beams were recorded with nuclear track detectors of the PM-355 type, which were placed inside the PF-1000 chamber. The highest neutron yield obtained so far has been 3×10^{11} neutrons/shot [21]. In so-called "good shots" the current sheath had a cylindrical symmetry along the electrode axis, and it imploded with the radial velocity of about 1.7×10^7 cm/s. When the discharge current was not adjusted to the filling pressure (when it was too small or too high), there appeared so-called "bad shots" with the current sheath asymmetric and disturbed by MHD instabilities. In such cases a considerably lower neutron emission was obtained.

Intensity of the soft X-ray emission, recorded as a function of the discharge current, was proportional to the total neutron yield. It suggested that a large portion of fast neutrons from D-D reactions was of the thermonuclear origin. Similar conclusion could be drawn from the observed neutron emission anisotropy; at a high discharge pressure it appeared to be lower than that expected for the pure acceleration mechanism. Moreover, the neutron energy spectra, as determined at a low filling pressure, showed the maximum at energy of 2.2–2.3 MeV, i.e. at the value lower than that deduced from the D-D reaction energy balance. It suggested that at low-pressure discharge the acceleration mechanism could prevail [22-23].

The fast ion (deuteron) beams were recorded with the nuclear track detectors only for shots performed at a relatively low discharge pressure value (1-2 Torr). An optical analysis showed that the ion crater densities on the irradiated and etched samples ranged from 10^6-10^7 craters/cm^2 up to the saturation level. Taking into account detector calibration characteristics, it was estimated that the deuterons had energies ranging from about 100 keV to about 1.5 MeV.

Particular attention was also paid to combined experiments with a foam liner and a metal wire placed in the plasma focus region [24]. It was found that XUV and soft X-ray pulses (with FWHM = 80-200 ns) were generated mainly at a surface of the compressed liner, and the insertion of the wire did not influence hart X-ray and neutron yield considerably.

Within a frame of the international collaboration detailed measurements of the corpuscular emission from various plasma systems were performed. The publications on the spatial- and energetic-characteristics of ions emitted from a small PF device in Tandil (Argentina), and on measurements low-energy ions, were finished [25-26]. The paper on influence of diaphragms was also ended [27]. In the collaboration with IPP in Prague (Czech Republic) the analysis of the X-ray and ion emission was performed within the Prague Capillary Pinch (PCP) system [28-29]. It was demonstrated that the fast capillary discharge emits not only the intense visible and soft X-ray radiation, but also the strong corpuscular flux (Fig.7).

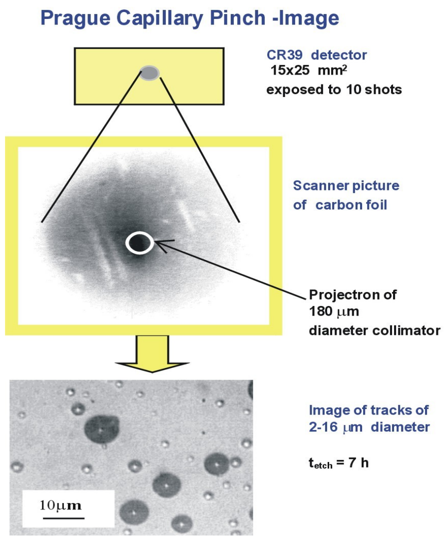

Fig.7. Images registered with a CR-39 track detector, which was irradiated during 10 successive shots in PCP system. Top picture - the whole detector surface after irradiation, middle - a scanned image of the detector surface with a thin C-layer, bottom - an enlarged image of a central part of the detector.

Taking into account the energy threshold of the CR-39 nuclear-track detector, it was concluded that energy of the registered ions was higher than 80 keV. From an optical analysis of the recorded tracks it was estimated that the time-integrated particle flux, as measured at a distance of 20 cm from the collimator outlet, was about 3.5×10^7 particles/cm^2/pulse.

4. DEVELOPMENT OF SELECTED METHODS FOR PLASMA DIAGNOSTICS

Within a frame of plasma diagnostics development particular attention was paid to optical spectroscopy of pulsed plasma-ion streams and to research on an influence of initial gas conditions on the neutron yield. The emission of ion beams, as well as its coincidence with the soft X-ray radiation and the emission of H_β and H_γ spectral lines, was studied in the RPI-IBISEK device [30]. The studies included measurements of ion beams (as a function of energy) and determination of the ion current density. Simultaneously, there were performed measurements of soft X-ray pulses, as well as of their correlation with time-resolved waveforms of the H_β and H_γ lines. The studies (of a hydrogen plasma) showed the appearance of two mechanisms of the discharge development, producing two different types of plasma [31]. Detailed spectroscopic measurements were carried out by means of the MECHELLE-900 spectrometer, operating within the wavelength range from 200 nm to 1100 nm. The measurements were performed at different time-delays (τ = 130-320 μs) between the gas puffing and the application of a high-voltage pulse, and recording of the optical spectrum was carried out at different exposition times (5 μs and 100 μs). Particular attention has been paid to the H_α 656.279 nm, H_β 486.133 nm, and CIII 418 nm spectral lines (Fig.8).

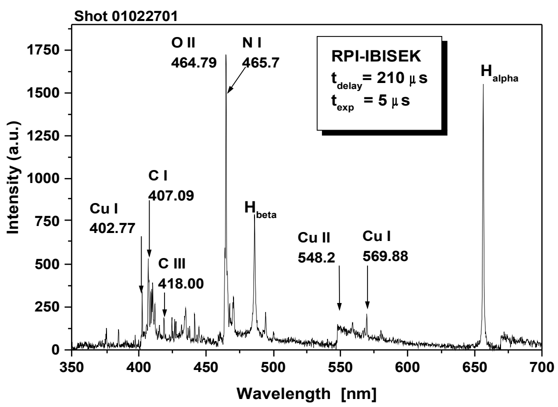

Fig.8. Optical spectrum of plasma, as obtained from a single discharge in the RPI-IBISEK device operated at U_0 = 28 kV, τ = 210 μs, with the exposition 5 μs.

The main aim of the spectral measurements was to check whether plasma achieves the LTE state and what are ion temperatures (T_i) at different gas conditions. The estimates of T_i have been based on the Doppler effect measured for the selected spectral lines [32]. In the RPI-IBISEK device the temperature, as estimated for hydrogen- and carbon-ions, achieved 10^6 K [33]. More detailed spectroscopic measurements were performed within the IBIS-RPI device [34]. Spectral lines from the working gas (i.e. D_α, D_β and D_γ) as well as from the electrode material (i.e. Mo-lines), were recorded and analyzed.

Another direction of diagnostics was the calibration and use of different solid-state nuclear track detectors (SSNTD). In particular low-energy ions dosimetry by means of such detectors was developed [35]. Studies of responses of SSNTD, which were initiated several years ago, were also continued [36-38]. The investigated PM-355 detectors were applied in the PF-1000 experiments (within a frame of the collaboration with IPPLM) in order to determine angular distributions of the fast ions emitted from the plasma-focus region [39-40]. For this purpose the detector samples were fixed on a semi-circular support at the electrode outlet (Fig.9).

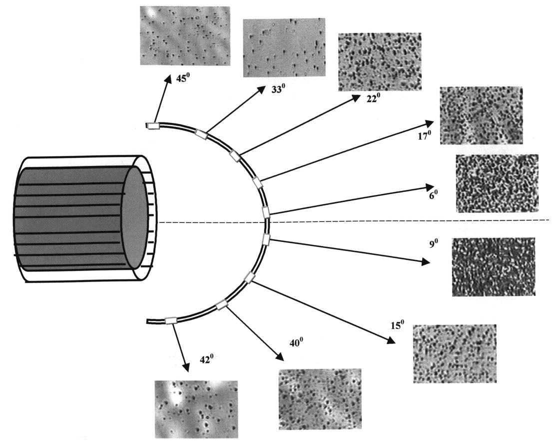

Fig.9. Ion track images, as recorded during studies of ion angular distribution within the PF-1000 facility.

The ion measurements were also performed with In another experiment several miniature ion pinhole cameras. The result confirmed strong anisotropy of the ion emission from PF-1000 discharges. The detectors covered with Al-filters registered also large numbers of tracks, what proved that accelerated primary deuterons could reach energies above several hundreds keV.

5. RESEARCH ON EXPERIMENTAL FACILITIES FOR BASIC STUDIES AND INDUSTRIAL APPLICATIONS

In the frame of technological studies, investigation of electromagnetic compatibility (EMC) was continued. An analysis of the European Union Directives and harmonized standards was performed. Since medical and scientific equipment is produced at IPJ also for export purposes, the analysis was extended also to foreign standards. A method of producing, measuring and calibration of weak magnetic fields (at frequency of 50 Hz) has been elaborated for the EMC immunity testing purposes [41-42]. Recent efforts have been devoted to special requirements of EMC tests [43]

6. MODIFICATION OF MATERIAL SURFACES BY MEANS OF PULSE PLASMA-ION STREAMS

In the collaboration with KIPT in Kharkov (Ukraine) characteristics of TiN-coated surfaces and of plasma-treated constructional steels were investigated [44-45]. Also investigated were shielding properties of a reversible getter ($Zr_{55}V_{40}Fe_5$ alloy) under the irradiation with high-power plasma streams [46]. In cooperation with HCEI in Tomsk (Russia) the use of low-pressure arc discharges for plasma treatment of different materials was studied [47]. Within the collaboration with Tor-Vergata University in Rome (Italy), new samples were coated with thin Nb-layers, and the construction of a new experimental setup (with two arc sources) was initiated [48]. A new experimental system with a linear arc and cylindrical Nb-cathode was designed in the collaboration with DESY (Germany) [49] (Fig.10).

Fig.10. New UHV stand with cylindrical Nb-cathode.

Other studies on plasma-ion techniques applicable for material engineering were carried out in the cooperation with the Dept. of Material Studies (P-IX). There were investigated metallic (Ti) ions eroded from RPI-electrodes and thermal processes in solid targets irradiated with pulse plasma streams [50]. Also studied were palladium profiles in titanium foils treated by high-intensity plasma pulses. Several research contracts were realized for various industrial laboratories [50].

7. SUMMARY AND CONCLUSIONS

This invited review lecture can be summarized as follows. The most important achievements of the Dept. P-V in 2001 were: 1. Investigation of a neutron emission anisotropy as a function of time and the proof that the fusion neutrons are produced by different mechanisms; 2. Collection of new information about dynamics and emission characteristics of discharges in the PF-1000 facility operated at energy ranging 1 MJ (in collaboration with IPPLM); 3. Deposition of high-quality super-conducting layers by means of arc discharges, and the construction of new technological devices (in collaboration with partners in Italy and Germany). In 2002 evident progress was achieved in all directions of research run at the Dept. P-V, in spite of limited funds. The most important results were reported at the Symposium on Plasma Physics and Technology (held in Prague on June 10-13, 2002) and at the German-Polish Conference on Plasma Diagnostics for Fusion and Applications (held in Greifswald on Sept. 4-6, 2002). Selected results were presented at other international conferences.

One can conclude that a further development of plasma theory is needed to explain unsolved phenomena. Also needed are further experimental studies of PF and Z-Pinch facilities as well as RPI (IONOTRON) devices. In the first case particular attention should be paid to combined experiments with the use of liners, nuclear targets and gas-puffing. In the RPI devices particular attention should be to space- and time-resolved studies of X-rays and ion beams.

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