RECENT ATTAINMENTS OF RESEARCH ON PLASMA PHYSICS AND TECHNOLOGY AT IPJ, POLAND

M.J. Sadowski[1,2]

[1] The Andrzej Soltan Institute for Nuclear Studies (IPJ), 05-400 Otwock-Swierk, Poland;
[2] Institute of Plasma Physics and Laser Microfusion (IPPLM), 00-908 Warsaw, Poland,
E-mail: msadowski@ipj.gov.pl

This invited lecture presents the most important achievements of the IPJ team in theoretical- and experimental-studies in the field of plasma physics and technology during recent years. The main efforts concentrated on the development of diagnostic techniques and studies of plasmas in Plasma-Focus (PF) facilities and Multi-Rod Plasma Injectors (RPI). Other efforts concerned diagnostics of fast electrons in selected Tokamaks (CASTOR, ISSTOK, and TORE-SUPRA), fusion protons in TEXTOR, and fusion neutrons in JET (EURATOM). Separate efforts concerned technological applications, e.g. modeling of an IPD accelerator for the material engineering, the use of UHV arc-discharges to deposit superconducting Nb layers on RF cavities and superconducting Pb photo-cathodes in electron injectors (EC CARE).

PACS: 52.50.Dg; 52.58.Lq; 52.59.-f; 52.70.-m; 52.77.-j.

1. INTRODUCTION

Studies of hot plasmas have been performed at the Soltan Institute (initially IBJ, now IPJ) in Swierk n. Warsaw since mid 50s. Now these studies are carried out at the Dept. of Plasma Physics & Technology (P-V) in collaboration with the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw, and foreign labs in Cadarache, Culham, Kharkov, Juelich, and Praque. The most important results of those studies were presented at many international conferences, including those at Alushta [1-3]. The main aim of this lecture was to report on progress in plasma studies during recent two years.

In the recent years the main research activities of Dept. P-V concerned studies of phenomena in dense magnetized plasmas, development of methods for high-temperature plasma diagnostics (mainly for EURATOM program), and a research on new plasma technologies, e.g. the ultra-high vacuum (UHV) arc-technique, and on the optimization of the IPD plasma accelerator.

2. STUDIES OF X-RAYS AND PARTICLES BEAMS IN PF-TYPE DEVICES

Experimental studies of PF-type discharges have been performed with three different facilities: MAJA-PF and PF-360 devices at IPJ in Swierk, and a large PF-1000 facility at IPPLM in Warsaw [1-2]. Since 2006 the important task has been a study of X-ray pulses correlations with pulsed electron- and other corpuscular-beams. The analysis of the ion- and electron-beams, as well as of 2.45-MeV neutron pulses from MAJA-PF and PF-360 devices, was presented in a PhD thesis [4]. It was shown that these emissions depend strongly on physical processes in a PF-pinch column. Another task concerned the elaboration of results obtained from previous studies of the X-ray emission in MAJA-PF facility. Studies of He-like Ar-lines were performed using a collisional-radiative model, taking into account strong electric fields and high electron densities in "hot-spots" [5]. Intensities of the resonance, inter-combination, and forbidden lines were computed. It was shown that the computed spectral lines are similar to the ArXVII lines recorded in the experiments, as shown in Fig. 1.

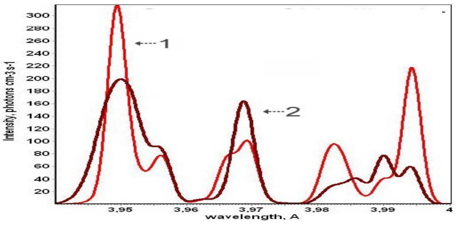

Fig.1. Profiles of ArXVII (He-like) lines computed from the collisional-radiative model with the self-absorption for different plasma parameters [5]

In a frame of another task, detailed measurements of the X-ray spectra were undertaken with a new XEUV spectrometer, which is operated in a 12-72 nm range [6].

3. STUDIES OF X-RAYS AND FAST E-BEAMS IN TOKAMAKS

Analyses of problems connected with measurements of fast electron beams in the TORE-SUPRA facility at CEA-Cadarache, as performed by the IPJ team in the previous years, made possible to design a new 4-channel Cherenkov-type detector, shown in Fig. 2.

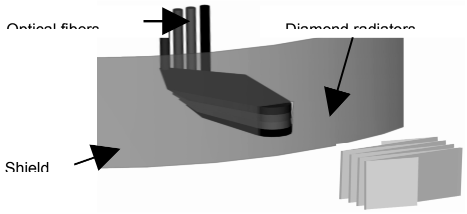

Fig. 2. Arrangement of diamond radiators and optical fibres in a Cerenkov-type detector for TORE-SUPRA

The construction and appropriate selection of constructional materials ensured a good transfer of heat deposited upon the Cherenkov-probe. To reduce a thermal load the French team at the CEA-Cadarache prepared a special mobile shaft, which will enable the Cherenkov-probe to be exposed for short periods only, but several times during a single discharge. Tests of the whole Cherenkov-probe are to be performed in 2008.

To get experience in fast electron measurements the IPJ team constructed a new Cerenkov head, adopted especially for experiments in small tokamaks. That head, was installed and used at the CASTOR facility at IPP in Prague. Cherenkov signals, which were recorded with the temporal resolution of 1 µs, were compared and analyzed [7]. Electron measurements, which were carried out at different toroidal magnetic fields ranging from 0.8 T to 1.4 T, and at the plasma discharge currents varied from 5 kA to 15 kA, showed that the character of the signals depends very strongly on the detector position and plasma density. The obtained results confirmed that the Cherenkov signals, recorded in CASTOR facility, were induced by fast electron streams of energy >50 keV [7-9].

Since in 2008 the TORE-SUPRA facility was not ready for Cherenkov measurements, the IPJ team accepted an invitation from the IST in Lisboa in a frame of the EURATOM collaboration. A new Cherenkov-type probe was installed in the ISSTOK facility, and electron measurements were carried out, as shown in Fig. 3.

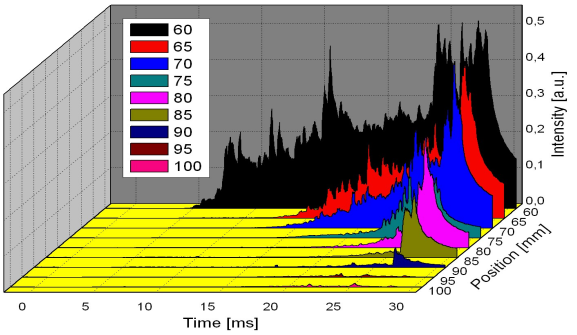

Fig. 3. Time–resolved electron signals from the Cherenkov-detector placed inside ISSTOC chamber [10]

4. APPLICATION OF TRACK DETECTORS FOR STUDIES OF FUSION-PROTONS IN PF

Another task concerned research on the emission of 3-MeV protons from discharges in PF-1000 and PF-360 devices. For time-integrated angular- and spatial-measurements of the fusion protons the use was made of miniature pinhole cameras equipped with PM-355 track detectors [11]. The first set of such cameras was used for measurements of the fusion protons in the vertical plane at different angles Θ to the z-axis, and the second set was situated at different azimuthal angles γ around the z-axis.

The irradiated detectors were etched and analyzed with an optical microscope. Those measurements made it possible to obtain images of the fusion reactions, as well as to determine angular distributions and numbers of fusion protons. Some proton images are shown in Fig. 4.

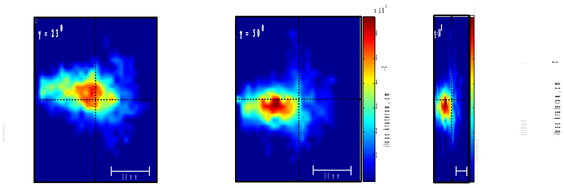

Fig. 4. Pinhole images of plasma micro-regions emitting the fusion protons, as measured at chosen angles around the discharge axis in PF-360 experiment [12]

Detailed analyses showed that the proton images at different γ angles differ considerably, and it might be explained by the appearance of so-called current filaments (and strong local magnetic fields) inside the PF pinch.

Since in many PF experiments there were observed two fusion–neutron bursts emitted from a single PF discharge, it has been suspected that the first neutron pulse might be partially produced by the thermonuclear mechanism, while and the second pulse is rather caused by beam-target interactions of high-energy deuterons. Energy spectra of fusion protons can be determined from histograms of the recorded track diameters taking into account detector calibration diagrams [13]. An example of the measured energy spectrum is shown in Fig. 5.

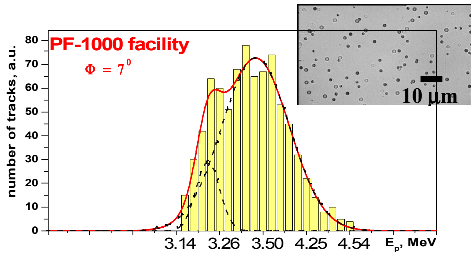

Fig. 5. Histogram of proton tracks vs. proton energy [13]

5. CALIBRATION AND APPLICATIONS OF NUCLEAR TRACK DETECTORS

Calibration measurements of nuclear track detectors (NTD) have been continued at IPJ for several years. Samples were irradiated with mono-energetic protons and analyzed with a microscope to determine track diameters as a function of proton energy and etching time. The calibrated detectors were used to measure 3 MeV fusion reaction protons emitted from the TEXTOR tokamak in Juelich, and to study characteristics of high energy proton beams emitted from laser produced plasmas in Palaiseau.

Measurements within TEXTOR were carried out by means of a small ion pinhole camera, equipped with a detector and placed below the plasma ring, with an input oriented in the ion-drift direction [14]. That detector was irradiated with protons during discharges supplied by ICRF (2 MW) and NBI (1.3 MW). Unfortunately, the detector showed a low track density, because the fusion neutron (and proton) emission amounted to ~10^{12} neutrons/day only. Therefore, it was not possible to measure the track distribution upon the whole detector surface. Nevertheless, histograms of track diameters were determined [15]. The proton energy spectrum, which was obtained from those measurements, is presented in Fig. 6.

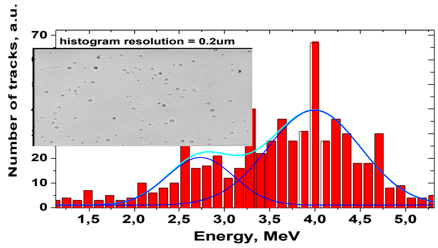

Fig. 6. Energy spectrum obtained on the basis of proton track diameter histogram, as measured in TEXTOR [14]

In experiments performed with the LULI 100-TW laser facility, a 15-J/350-fs pulse irradiated a 1-3 µm PStarget or that covered with a thin (< 0.2 µm) Au-layer. The laser pulse intensity on the target was $2 \cdot 10^{19}$ W/cm^2. Proton beams were measured with ion collectors, NTD and radio-chromic films. It was shown that laser-irradiated targets can emit very intense proton beams (MA currents and TA/cm^2 current densities).

6. APPLICATION OF ACTIVATION METHOD FOR NEUTRON STUDIES

To test possibility of using new materials for multi-foil neutron activation measurements, some dedicated experiments were performed with the PF-1000 facility used as a source of neutron pulses [16]. Other tests were carried out within JET facility in Culham. It was shown that, apart from indium, other materials (such as ^{89}Y, ^{167}Er, ^{204}Pb, ^{180}Hf, ^{111}Cd), which have a suitable high reaction threshold and a large reaction cross-section in the energy range (0.5–16 MeV), can also be used for measurements delivering more accurate information about fusion-produced neutrons [17]. Those materials have not been used for activation measurements earlier because they produce some short-living nuclides. To investigate them the IPJ-IPPLM team proposed modifications of the JET activation system. It was tested in summer 2008.

7. STUDIES OF PLASMA DISCHARGES BY MEANS OF OPTICAL SPECTROSCOPY

In 2007 there was finished the elaboration of papers on studies performed within PF-1000 facility, e.g. on interactions of pulsed plasma streams with different solid targets (e.g. C-W ones). Results of those studies were reported in papers presented at the international conference PLASMA-2007 [18-19]. Examples of the recorded spectra are shown in Fig. 7.

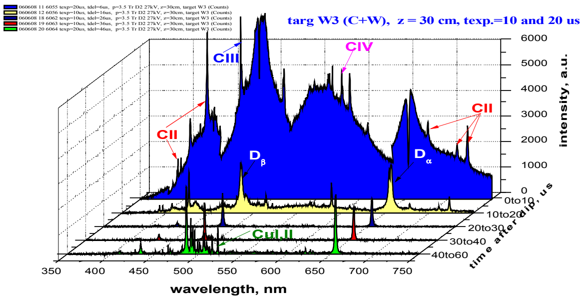

Fig. 7. Time-resolved spectroscopic studies of plasma-streams interaction with a C+W target in PF-1000

Particular efforts were devoted to the application of optical spectroscopy methods to investigations of pulsed plasma streams generated in the RPI-IBIS device, which is used for studies in the field of material engineering A separate task was the detailed study of different operational modes in the RPI-IBIS facility, which was performed in a frame of the Polish-Ukrainian scientific collaboration and reported at SAPP-2007 [20]. Analyses of results obtained from spectroscopic measurements of plasma, which was produced by the bombardment of a tungsten target with laser beams, were reported in papers presented at PPLA-2007 [21-22].

There was also performed an experiment with plasma produced in the MAJA-PF facility equipped with a central electrode containing a W-insert. The main aim was to investigate a spectrum of the visible radiation emitted from dense plasma containing W-ions. An analysis of the recorded optical spectra was reported at PLASMA-2007 [23]. Examples of the recorded spectra are shown in Fig. 8.

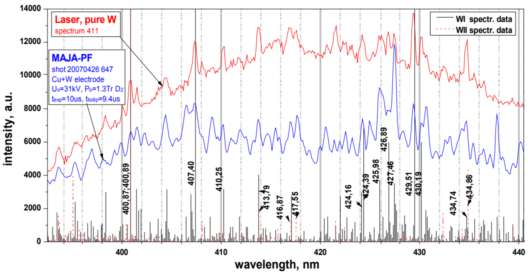

Fig. 8. Comparison of a spectrum from laser-target experiment (upper curve), with that measured in PF-MAJA (lower curve), and W-lines taken from NIST [23]

In 2007 the IPJ team performed also new series of spectroscopic measurements at IPPLM to investigate the interaction of pulsed YAG-laser beams with solid targets made of different materials (C, W and Ti), which are of interest for fusion reactors (e.g. ITER). The C-target was taken from the TEXTOR in Juelich, and the aim was to study efficiency of a removal of deuterium absorbed in that material during previous discharges. There were also performed observations of the erosion of a W-target [24], and the deuterium desorption from a Ti-target, which was previously saturated with that gas [25].

8. STUDIES OF PLASMA DISCHARGES BY MEANS OF CORPUSCULAR DIAGNOSTICS

In 2007 there was finished the calibration of PM-355 track detectors for low-energy deuterons (from 30 keV to about 500 keV) [26]. In a frame of further studies particular attention was paid to measurements of pulsed streams of hydrogen- and deuterium-plasmas by means of ion pinhole cameras (equipped with PM-355 and different absorption Al-filters), as well as Thomson-type mass- and energy-analyzers. Spatial and energetic distributions of pulsed plasma-ion streams were investigated particularly in the RPI-IBIS facility. In addition to the previous calibrations for deuterons, there were studied responses of the PM-355 track detectors to low-energy protons (from 30 keV to about 500 keV). In the subsequent research, using the determined calibration diagrams, it was possible to investigate energy distributions of the proton beams. Results of those studies were reported in two papers, which have been presented at the IC SSD-15 [27-28].

There were also continued measurements with a miniature Thomson-type analyzer, which might be applied for mass- and energy-analysis of ions inside vacuum chambers of different experimental facilities. To check the operation of that miniature analyzer, there were performed measurements of the plasma-ions within the RPI-IBIS facility [29], as shown are shown in Fig. 9.

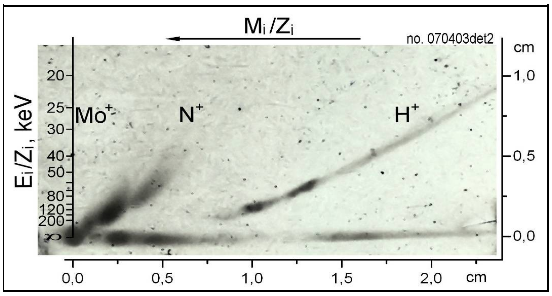

Fig. 9. Proton- and impurity-ions parabolas recorded with the miniature Thomson analyzer [29]

9. RESEARCH ON PLASMA STREAMS AND THEIR INTERACTIONS WITH MATERIALS

In a frame of this task there was performed a detailed analysis of experimental results from measurements of pulsed plasma streams, which were carried out previously within the PF-1000 facility. Particular attention was paid to measurements of pulsed beams of fast electrons (emitted mostly in the upstream direction, i.e. towards the anode) and fast ions (emitted mainly along the z-axis), as well as their correlations with fusion-produced neutrons. The most important result of that analysis was the conclusion that inside a dense magnetized plasma (DMP) there are formed miniature plasma diodes, which cause the acceleration of electrons and ions (in opposite directions). The second conclusion was that the neutron production is caused mainly by interactions of fast deuteron beams with dense plasma [30].

10. STUDY OF CURRENT FILAMENTS IN PF EXPERIMENTS

Basing on experimental results, as collected with different PF facilities at IPJ, IPPLM and several foreign laboratories, there was performed a detailed analysis of various physical issues of research on DMP phenomena. Different phases of PF-type discharges were analyzed. In the breakdown- and formation-phases of a current sheath, attention was paid to plasma non-uniformities and current filaments. In the next phase (the axial acceleration) particular attention was paid to cases when distinct quasi-radial filaments were observed in the inter-electrode gap and to the fact that such phenomena cannot be described by 2D MHD-models. In the third phase (i.e. the radial compression) there were also observed the intense current filaments, which may exist even during the maximal compression of the plasma column, as shown in Fig. 10.

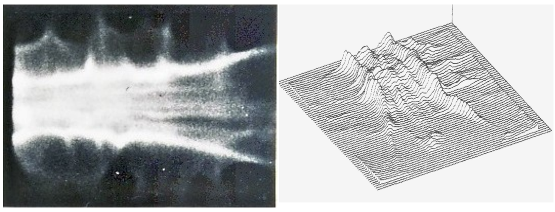

Fig. 10. X-ray pinhole picture of a PF pinch and the 3D intensity-diagram showing the distinct current filaments

There were also considered so-called hot-spots and (connected with them) emissions of X-ray pulses as well as pulsed beams of fast electrons and ions. Simple models of the filamentary structure of a plasma column and connected physical effects were considered, and results of that analysis were presented in at the 28th ICPIG [31-32]. Analyses of the filamentation in PF-discharges were also presented at ICDMP [33-34] and SPPT [35].

11. MODELING OF IPD ACCELERATOR

The IPD (Impulse Plasma Deposition) process is used for surface modifications of different materials, e.g. coating with oxides, diamond-like C, TiN or multi-component metallic layers. To improve the understanding of this process the computational studies of plasma flow phenomena have been performed using an MHD approach. Equations have been solved numerically for the chosen experimental conditions. It was shown that the current sheath spreads both in the inter-electrode gap and at the electrode outlet. Due to high electrical fields in front of the electrode ends, there is generated an electron stream which induces strong erosion of the inner electrode surface (emitting metal ions). Results of the computations showed considerable differences in the process dynamics for negative and positive polarization of the central electrode [36-37]. Conditions for mixing of materials from the electrode and working gas were analyzed.

12. DEPOSITION OF SUPERCONDUCTING FILMS BY MEANS OF UHV ARC METHOD

In a frame of another technology-oriented task there were continued experimental and theoretical studies of UHV arc discharges. An experimental UHV facility equipped with a cylindrical Nb cathode was assembled. It was equipped with a neutral-gas flow-chamber and used for deposition of thin superconducting Nb layers upon inner walls of RF accelerator cavities (made of pure Cu). Single copper cavities, delivered from the CEA-Saclay, were coated inside Nb-layers, and test coating of a 3-cell cavity was performed [38-39], as shown in Fig. 11.

Fig. 11. UHV linear-arc facility and end-on view of a test 3-cell cavity coated with Nb

Laboratory tests have however shown that the adhesion of the deposited layers is too low to withstand high-pressure water rinsing (HPR at 10^7 Pa), and it must still be improved. Detailed measurements of Nb/sapphire samples showed an increase in bias voltage (i.e. ion energy) improves the film hardness. At the -70 V bias the RRR value achieved value of 44. Some samples, which were earlier treated chemically, could withstand HPR.

Separate efforts concerned the deposition of pure Pb (upon Nb) for photo-cathodes in SRF electron injectors. An influence of micro-droplets on the photo-emission quantum efficiency (QE) was investigated [40] and measurements (performed in foreign labs) showed that it is possible to obtain high QE [41-42].

13. SUMMARY AND CONCLUSIONS

The recent achievements of the IPJ team have been reported. Correlations of pulsed e-beams with other emissions were studied in more details. There were performed measurements of fast electrons in tokamaks (CASTOR and ISSTOK) with Cherenkov detectors, and studies of fusion-protons in PF- and Tokamak-discharges by means track detectors. Activation methods for neutron measurements were improved and detailed studies of pulsed plasma-ion streams (during their free propagation and interactions with different targets) as well as studies of current filaments in PF discharges were carried out. In technology-oriented research the recent achievements concerned the UHV-arc deposition of superconducting Nb-layers inside RF accelerator cavities, and that of superconducting Pb photo-cathodes in electron injectors.

The described attainments are documented by numerous publications (see IPJ web pages and Annual Reports). Many studies were and are performed in the collaboration with different foreign research centers. The IPJ team can continue studies in a frame of EURATOM and EuCARD programs, as well as bilateral agreements.

REFERENCES

1. M.J. Sadowski// *Probl. of Atom. Science and Technology. Ser.”Pl. Phys.”(4).* 2002, N 7, p. 118-122.
2. M.J. Sadowski, M. Scholz // *Probl. of Atom. Science and Technology. Ser.”Pl. Phys.”(1).* 2005, N 10, p. 81-85.
3. M.J. Sadowski et al.// *Probl. of Atom. Science and Technology. Ser.”Plasma Phys.”(6).* 2006, N 12, p. 213-217.
4. J. Zebrowski. Studies of corpuscular radiation and X-rays emission from discharges of the PF type// *PhD Thesis.* IPJ, Swierk, 2006.
5. E.O. Baronova et al.//*AIP CP.* 2008, v. 993, p. 271-274.
6. K. Nowakowska-Langier et al.// *IPJ-PV Internal Report 2007.*
7. L. Jakubowski et al.// *ECA.*2007, v. 31F, P-5.097.
8. J. Zebrowski et al.// *AIP CP.* 2008, v. 993, p. 255-258.
9. L. Jakubowski et al. *// AIP CP.* 2008, v. 996, p. 219-223.
10. V.V. Plyusnin et al.// *Proc. 17th Top. Conf. HTPD, Albuquerque, May 2008/ RSI.* 2008, N2.
11. A. Malinowska et al.// *Radiat. Measur.* 2008, v. 43, S295-S298.
12. A. Malinowska et al.// *AIP CP.* 2008, v. 993, p. 353-356.
13. A. Malinowska, Research on emission of fusion reaction protons emitted from PF facility// *PhD Thesis./* IPJ, Swierk, 2007.
14. A. Szydlowski et al.// *Radiat. Measur.* 2007, v. 43, S290–S294.
15. A. Szydlowski et al.// *AIP CP.* 2008, v. 993, p. 247-250.
16. M. Scholz, et al. // *AIP CP.* 2008, v. 993, p. 345-346.
17. R. Prokopowicz et al.// *AIP CP.* 2008, v. 993, p. 251-254.
18. E. Skladnik-Sadowska et al.// *AIP CP.* 2008, v. 993, p. 365-368.
19. V.A. Gribkov, et al.// *AIP CP.* 2008, v. 993, p. 361-364.
20. E. Skladnik-Sadowska et al.// *Proc. SAPP-2007, Podbanske.* P64.
21. M.J. Sadowski et al.// *Proc. PPLA-2007, Scilla.* O7.
22. E. Skladnik-Sadowska et al.//*Proc. PPLA-2007, Scilla.* P2.
23. K. Malinowski et al.//*AIP CP.* 2008, v. 993, p.357-364.
24. E. Skladnik-Sadowska et al.// *Proc. IC PSI-2008, Toledo,Spain,May 2008.* p. 386; *J. Nucl. Mat.* 2008.
25. K. Malinowski et al.// *Proc. 23rd SPPT, Prague, June 2008.* p. 55.
26. K. Malinowski et al.// *Radiat. Measur.* 2007, v. 43, S286-S289.
27. E. Skladnik-Sadowskaet al.//*Proc. 15th IC SSD, Delft, July 2007,* PVII-23.
28. K. Malinowski et al.//*ibid.* PVII-24.
29. K. Czaus et al.//*AIP CP.* 2008, v. 993, 159-162.
30. V.A. Gribkov et al.//*J. Phys. D: Appl. Phys.* 2007, v. 40, p. 3592-3607.
31. M.J. Sadowski, M. Scholz; *Proc. 28th ICPIG, Prague, 2007.* G05; *PSST.* 2008, v. 17, 024001.
32. P. Kubes et al.//*ibid.* p. 1473-1475.
33. M.J. Sadowski; *Proc. ICDMP-2007 Workshop, Warsaw.* Inv. Mo8.
34. P. Kubes et al.//*ibid.* Inv. Mo09.
35. W. Stepniewski et al.//*Proc. 23rd SPPT, Prague.* 2008, p. 48.
36. M. Rabinski, K. Zdunek// *Proc. EUROCON-2007, Warsaw.* p. 2177-2183.
37. M. Rabinski, K. Zdunek// *AIP CP.* 2008, v. 993, p. 117-120.
38. M.J. Sadowski et al.//*Proc. SAPP-2007, Podbanske.* IL12.
39. P. Strzyzewski et al.//*Proc. 1st NC Nanotechnology, Wroclaw, April 2007.* P. 218.
40. P. Strzyzewski et al.//*Proc. 20th SPIE Symp., Wilga, May 2007.*
41. J. Sekutowicz et al.//*Proc. PAC07, Albuquerqu.*TUPMN021.
42. M.J.Sadowski et al.//*Proc. EUROCON-2007,Warsaw.* P. 1162-1169.

Article received 22.09.08.

ПОСЛЕДНИЕ ДОСТИЖЕНИЯ В ИССЛЕДОВАНИЯХ ПО ФИЗИКЕ ПЛАЗМЫ И ТЕХНОЛОГИИ В ИЯП, ПОЛЬША

М. Садовский

Представлены наиболее важные достижения коллектива ИЯП в теоретических и экспериментальных исследованиях в области физики плазмы и технологии за последние годы. Основные усилия были сконцентрированы на разработке диагностической техники и исследованиях плазмы в плазменных фокусах (ПФ) и многостержневых плазменных инжекторах. Развита диагностика быстрых электронов на некоторых токамаках (CASTOR, ISSTOK, и TORE-SUPRA), термоядерных протонов на TEXTOR и нейтронов синтеза на JET (ЕВРАТОМ). Технологические приложения включали моделирование ИПН ускорителя для материаловедения, использование сверхвысоковакуумных дуговых разрядов для напыления сверхпроводящих Nb слоев на РЧ- резонаторы и сверхпроводящих Pb фотокатодов для инжекторов электронов (EC CARE).

ОСТАННІ ДОСЯГНЕННЯ В ДОСЛІДЖЕННЯХ ПО ФІЗИЦІ ПЛАЗМИ І ТЕХНОЛОГІЇ В ІЯП, ПОЛЬЩА

М. Садовський

Представлено найбільш важливі досягнення колективу ІЯП у теоретичних і експериментальних дослідженнях в області фізики плазми і технології за останні роки. Основні зусилля були сконцентровані на розробці діагностичної техніки і дослідженнях плазми в плазмових фокусах (ПФ) і багатострижневих плазмових інжекторах. Розвито діагностику швидких електронів на деяких токамаках (CASTOR, ISSTOK, й TORE-SUPRA), термоядерних протонів на TEXTOR та нейтронів синтезу на JET (ЄВРАТОМ). Технологічні прикладення включали моделювання ІПН прискорювача для матеріалознавства, використання надвисоковакуумних дугових розрядів для напилювання надпровідних Nb шарів на РЧ-резонатори і надпровідних Pb фотокатодів для інжекторів електронів (EC CARE).