PLASMA DIAGNOSTICS

PROGRESS IN HIGH-TEMPERATURE PLASMA RESEARCH AT NCBJ (FORMER IPJ) IN POLAND

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This invited lecture presents the most important results of theoretical and experimental studies of high-temperature plasma, which were performed at the NCBJ (former IPJ) in Otwock-Swierk, Poland, during recent two years. The research activity included: Studies of fast electrons and X-rays in Z-pinch and Tokamak devices; Research on applications of solid-state nuclear track detectors for detection of fast ions and neutrons emitted from plasma in experimental facilities of Z-pinch, Tokamak and ICF type; Investigations of high-temperature plasma streams and their interactions with solid targets; Ultra-high vacuum arc deposition of thin metallic films; Selected studies on plasma engineering of solid surfaces. The formation of the NCBJ (on Sept. 1, 2011) and its successive reorganization (on Jan. 1, 2012) led to the separation of the Division of Plasma Studies (TJ5) which is concentrated on high-temperature plasmas within frames of domestic and international research programs.

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INTRODUCTION

Studies of high-temperature plasma in Poland, which were initiated at IPJ in the mid 50s, have been continued mainly within two institutes: IPJ and IFPiLM. They included studies of plasma physics as well as fusion-oriented research on magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). The most important results were presented at many international conferences, including those in Alushta [1-3].

The main aim of this lecture was to present the most important results of research, which was carried out at NCBJ (former IPJ) after the previous Alushta-2010 conference.

1. STUDIES OF FAST ELECTRONS AND HARD X-RAYS IN TOKAMAKS

The 1st task concerned the design and construction of probes for direct measurements of fast electrons in tokamaks within a frame of the EURATOM fusion programme. Strong electrical fields in tokamaks can lead to the generation of „runaway electrons". Another mechanism is connected with ripples of the toroidal magnetic field, which generate "ripple-born electrons" [4]. Studies of the fast electrons emission are motivated by several reasons. Fast electron beams can influence the plasma behaviour because they carry a substantial part of the plasma current. Sometimes they can improve the plasma confinement, but in some cases energetic e-beams can cause severe damages of internal walls in fusion facilities. Therefore, efforts to measure the emitted fast e-beams were undertaken at IPJ (now NCBJ) several years ago [4].

The IPJ team developed special probes for direct measurements of fast e-beams inside tokamaks. The probes were based on the Cherenkov effect, i.e. the emission of the intense radiation by fast electrons in appropriate radiators. Such probes made possible to perform direct, spatially well-defined and instantaneous measurements of the fast e-beams [4-5].

In 2011 a new Cherenkov-type probe equipped with four radiators made of modified AlN crystals was designed and manufactured , as shown in Fig. 1.

Fig. 1. New version of the 4-channel probe with AlN radiators of 10 mm in dia. and 2 mm in thickness [5]

Some examples of the electron-induced signals from the ISTTOK experiment (performed in Lisbon) are presented in Fig. 2.

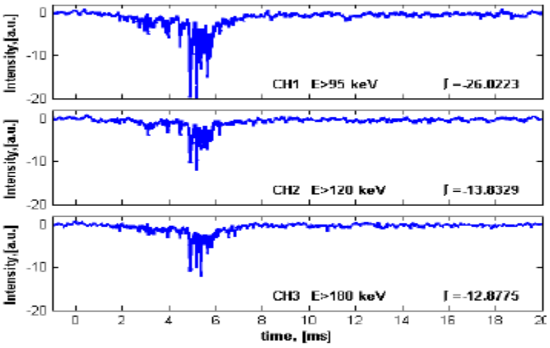

Fig. 2. Electron-induced signals from different channels of the Cherenkov-type probe used in the ISTTOK [4-5]

It can be easily seen that the largest amount of fast electrons was recorded by the CH1 channel. It means that the runaway emission from ISTTOK was dominated by electrons of energy 90 keV. During recent experiments with ISTTOK measurements of the fast e-beams were accompanied by measurements of hard X-rays (HXR). The use was made of two sets of measuring heads equipped with NE102A scintillators and placed behind different Cu-filters outside the tokamak chamber. Taking into account the absorption coefficients it was found that energy of HXR amounted to about 350 keV [6-8].

A comparison of the electron-induced signals with the HXR signals from ISTTOK showed a good temporal correlation and evident proportionality. It might be explained by strong interactions of the fast e-beams with the limiter and chamber wall.

According to the EURATOM programme in 2010 another modified measuring head, equipped with four diamond Cherenkov-radiators, was prepared also for the TORE-SUPRA facility (in Cadarache). It enabled new experimental data to be collected. They showed a significant contribution of electrons with energies ranging up to 150 keV [9]. Details of these studies and a new equipment for calibration of the Cherenkov detectors are presented in another paper [10].

2. STUDIES OF IONS AND NEUTRONS BY MEANS OF SSNTD AND ACTIVATION TECHNIQUES

This task concerned the calibration of solid-state nuclear track detectors (SSNTD) of the PM-355 type and their application for measurements of fast ions in PF-type experiments, fusion-produced protons in the TEXTOR facility in Juelich, and fast ions emitted by laser-produced plasma in the PALS system in Prague.

SSNTD have been investigated and used at IPJ (now NCBJ) for many years. In order to make these detectors more relevant for accurate ion measurements each detector batch has been calibrated by means of chosen ions from an accelerator. Since in various plasma experiments the SSNTD must operate under harsh conditions (e.g. high-temperature, heat fluxes, intense X-rays and fast electrons) more detailed studies of their behavior have been performed. The main aim of these studies was to determine a role of such conditions for the track formation process in the SSNTD of the PM-355 type [11-13].

In 2011 the PM-355 detectors were also used for monitoring neutrons during radiotherapy treatments with a Varian Clinac-2300 accelerator. The studies were performed at the Oncology Centre in Warsaw. For a comparison the use was also made of an activation detector based on nuclear reactions ^{58}Ni(n, p)^{58}Co. Both detectors were calibrated with a ^{252}Cf neutron source. Some results of this calibration are presented in Fig. 3.

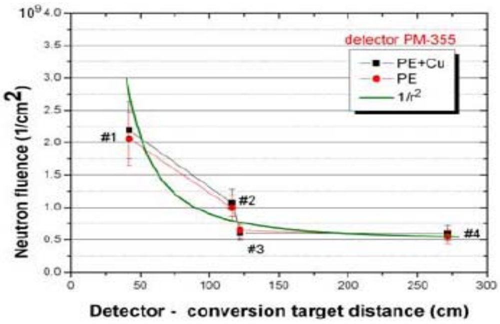

Fig. 3. Total neutron fluences recorded by thePM-355 samples vs. the distance from the conversion target

The results obtained with both detectors appeared to be consistent with an acceptable error of < 30%.

In 2011 the detailed analysis of fusion neutron measurements from the recent JET experiments in Culham was also performed. The neutron data were obtained by means of the multi-foils activation technique using selected targets placed inside the 3U-JET activation channel. The chosen materials had high cross-sections for neutrons in various energy ranges, and reaction products were analyzed with a HPGe gamma spectrometer. The measured neutron fluence was related with the total neutron yield by applying calibration factors K, which were determined by the neutron transport calculations (a modified MCNP code) [14]. The performed calculations showed that the total neutron yield from JET discharges was ~ 14% higher that was thought hitherto.

3. STUDIES OF PLASMA-ION STREAMS FROM PF- AND RPI-TYPE FACILITIES

The next task concerned studies of a spatial structure of the intense plasma-ion streams emitted from PF- and RPI-type experiments, as well as mass- and energy-analysis of the ion components. Those studies embraced also measurements of fast electron-beams, as well as optical emission spectroscopy of free-propagating plasma streams and plasma produced during interactions of such streams with solid targets made of materials interesting for fusion technology, e.g., graphite, tungsten and CFC.

In 2010-2011 all the experimental results collected previously within the PF-1000 facility in Warsaw were summarized and published [15-16]. Attention was paid to research on behavior of materials important for fusion technology, e.g. tungsten, boron nitrate, Al_2O_3 ceramics and carbon-fiber composites within the PF-1000, QSPA Kh-50 in Kharkov and RPI-IBIS in Swierk [17-19]. It was demonstrated that these facilities are applicable for material studies, as shown in Fig. 4.

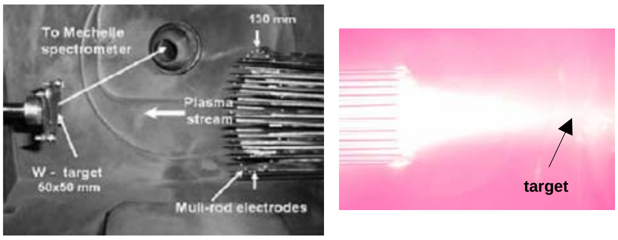

Fig. 4. RPI-IBIS experiment and picture of a plasma-ion stream interacting with a solid target [19]

Attention was paid to experiments on simulation of ITER-like edge-localized plasma modes and their impacts on material surfaces in available plasma accelerators. In a frame of the Polish-Ukrainian collaboration some experiments were performed with a 2.4 MJ/cm^2 plasma stream in the QSPA Kh-50 [20].

Experiments with the RPI-IBIS facility concerned observations of the visible radiation, measurements of ion-plasma streams and detailed studies of the optical emission spectra. Measurements of the ion beams were of primary importance because of erosion effects which can be induced by high-power pulsed ion beams. On the basis of ion images recorded behind different absorption filters it was possible to determine energy distribution of fast ions emitted from plasma discharges. An example of deuteron energy spectrum measurements, which were performed with a miniature Thomson spectrometer constructed and used at NCBJ, is presented in Fig. 5.

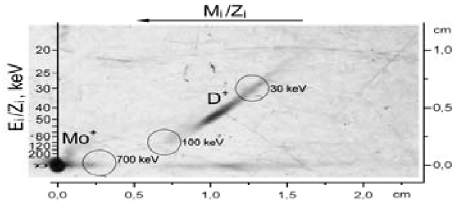

Fig. 5. Thomson parabolas of fast deuterons and impurity ions (Mo+) emitted from the RPI-IBIS facility [21]

The operation of the RPI-IBIS facility under conditions, which ensured the emission of deuterium-plasma streams with a small amount of impurities, an energy flux from 3 to 7 J/cm^2, and a relatively high power density enabled studies of a W-target irradiated by chosen plasma loads [21]. Examples of the optical spectra, are shown in Fig. 6.

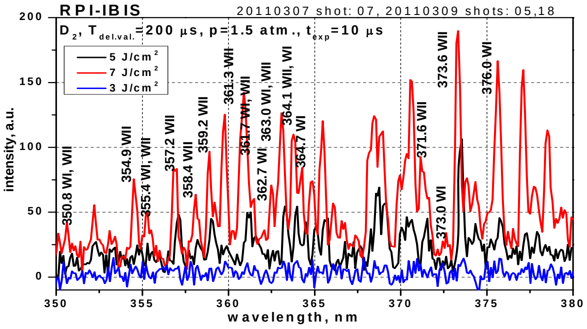

Fig. 6. Comparison of the optical spectra recorded in experiments with a W-target in the RPI-IBIS facility [21]

It was found that the erosion of the irradiated W-target (see WI- and WII-lines) depends considerably on the irradiation power when the energy flux is > 3 J/cm^2.

Recently, new spectroscopic studies have been performed in the PF-1000 facility equipped with a modified anode [22].

4. SPACE- AND TIME-RESOLVED STUDIES OF HIGH-ENERGY ION BEAMS FROM PF DISCHARGES

In a frame of this task all earlier measurements of electron and ion beams emitted in the upstream- and downstream-direction from the PF-1000 facility were analyzed and published [23]. Some new experimental studies of high-energy ion beams emitted from the PF-360 facility were also carried out. Time-integrated ion measurements were performed with pinhole cameras equipped with nuclear track detectors and placed at different angles to the z-axis, as shown in Fig. 7.

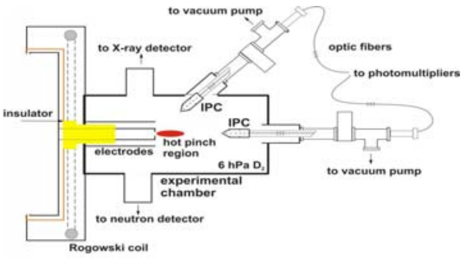

Fig. 7. Scheme of the PF-360 experiment showing positions of two ion pinhole cameras (not to scale)

The time-integrated ion pinhole images confirmed that the fast ions are emitted in many micro-beams. Simultaneously, an experimental evidence was gained that the ion micro-beams emitted at some angles to the z-axis have a periodical structure [24], as shown in Fig. 8.

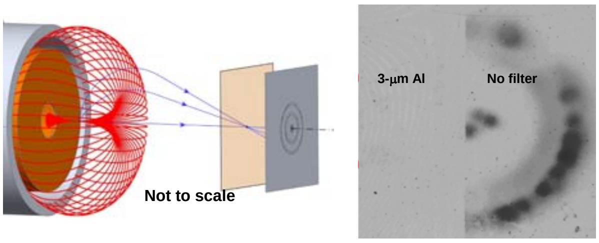

Fig. 8. Explanation of the pinhole image formation and time-integrated pinhole image of deuteron micro-beams recorded behind a thin Al-foil (left part) and without any filter (right part) for 8 shots in PF-360 facility

Detailed studies of the spatial- and energetic-characteristics of fast ion beams were performed by means of cascade pinhole cameras, in those some ion beams could penetrate through a small hole in the first detector and be recorded upon the second detector. It enabled to observe the divergence of micro-beams and to study the fine structure of the ion emission [25]. An analysis of the recorded ion images, as performed by means of an optical microscope, made it possible to determine ion flux densities in different places of the detection plane, as shown in Fig. 9.

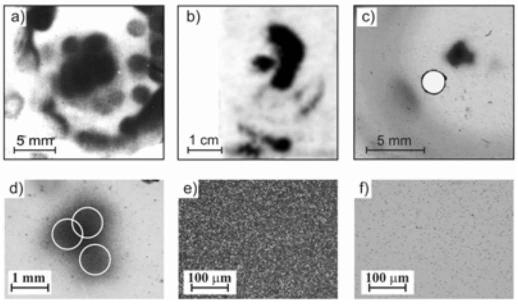

Fig. 9. Ion images from earlier PF-20 experiments (a), from the previous PF-360 experiments (b) and from the recent PF-360 experiments (c). Bottom row shows the (c) image enlargement, which shows 3 micro-beams (d), ion tracks taken in the micro-beam centre (e) and outside (f)

The most important issues of high-current plasma experiments of the Z-pinch and PF-type were also analyzed [26]. To perform time-resolved measurements of the fast ions the use was made of pinhole cameras equipped with miniature scintillation detectors of the NE102 type, which were coupled with fast photo-multipliers (see Fig. 7) [27]. To record ions of different energies, the SSNTD were shielded with filters made of pure Al foil of different thickness (e.g., 1.5 μm or 3 μm), which allowed to record deuterons of energies above 220 and 380 keV, respectively. The time-resolved ion signals showed that high-energy ions (e.g. 400…600 keV deuterons) are emitted in a few bunches and they correlate with hard X-ray pulses, as shown in Fig. 10.

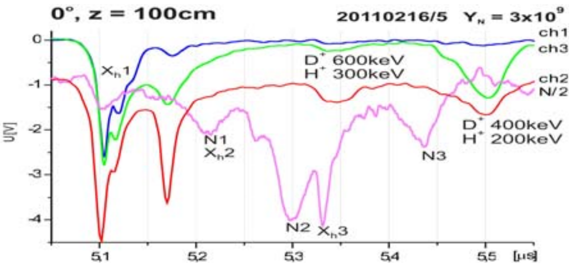

Fig. 10. X-ray and ion signals, as obtained from three measuring channels (ch1-ch3) in the pinhole camera placed 100 cm from the PF-360 electrode ends, in comparison with signals from a neutron detector [27]

5. DEVELOPMENT OF NEW TECHNIQUES FOR PLASMA DIAGNOSTICS UNDER EXTREME CONDITIONS

In September 2011 two teams from the NCBJ started to realize two different tasks of an NCBiR contract: a development of two diagnostic probes adapted for extreme experimental conditions which will occur in fusion-reactors, and the modernization of the PF-360 facility for testing the new plasma diagnostic tools.

The first probe was designed as an ion pinhole camera equipped with a rotating drum and several SSNTD to be irradiated during a single plasma discharge. After appropriate etching of the irradiated detectors and their quantitative analysis, it should be possible to obtain data about dynamics of the ion emission (including the charged fusion products) to be obtained. A simplified scheme of such a probe is shown in Fig. 11.

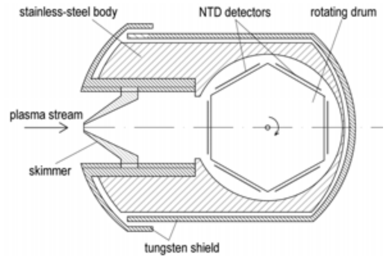

Fig. 11. Scheme of an ion pinhole camera with a rotating drum and SSNTD.

The second probe was designed as a miniature Thomson-type analyzer and an appropriate SSNTD or CCD. This probe should enable mass- and energy-spectra of the emitted ions to be recorded inside an experimental chamber of the fusion facility, e.g. tokamak. A simplified scheme of such a probe is shown in Fig. 12.

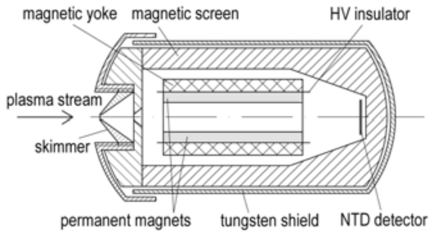

Fig. 12. Scheme of an ion probe equipped with a miniature Thomson-type spectrometer and SSNTD.

In 2011 the main efforts concerned an analysis of experimental conditions expected during exploitation of the new probes and the determination of requirements as regards their dimensions and motions. Possibilities of laboratory tests of such probes in accessible plasma experimental facilities were also analyzed.

The second task concerned the modernization and adaptation of the PF-360 facility for tests of the new diagnostic probes. In particular all sections of the current pulse generator have been investigated technically. It has been decided that all the HV spark-gaps must be regenerated and equipped with new charging resistors. New schemes of the PF-360 current-pulse generator and its control unit have also been elaborated. The main results of the tasks described above have been presented at the 1st Scientific Seminar on the NCBiR Project, which was held at the IFJ PAN in Cracow, Poland [28].

SUMMARY AND CONCLUSIONS

Before summarizing this review it should be noted that the former IPJ Dept. of Plasma Physics and Material Engineering (N-5) was engagedin research on selected plasma technology problems, e.g. applications of UHV-arc devices for the deposition of thin super-conducting Nb-layers and Pb-photocathodes needed for particle accelerators. After the formation of the NCBJ (on Sept. 1, 2011) and successive reorganizations (performed on Jan. 1, 2012), the Dept. N-5 became split into the Division of Plasma and Ion Technology (FM2) and the Division of Plasma Studies (TJ5). The last one concentrates all studies of high-temperature plasmas, which are carried out at NCBJ within frames of domestic (e.g., NCBiR) and international (e.g., EURATOM) research programs.

The most important achievements of research on high-temperature plasma, which were obtained by the NCBJ (former IPJ) team, can be summarized as follows:

1. Special Cherenkov detectors of fast electrons were constructed and electron-induced signals were recorded in tokamaks (CASTOR, ISSTOK and TORE-SUPRA).
2. Studies of fast ions and neutrons in various experiments were performed by means of SSNTD and activation techniques.
3. Detailed studies of intense plasma-ion streams emitted from PF- and RPI-type experiments were performed with corpuscular and optical diagnostics.
4. New diagnostic probes, which might operate under extreme conditions in fusion-reactors, were designed.

Research on the fast electrons and ions should be continued to elaborate detection systems for different plasma experiments (e.g. ASDEX, JET) and future ITER. In particular studies of ion-plasma streams should be continued to understand interactions of plasma with materials interesting for fusion technology. It is expected that the reported plasma studies will be continued in a frame of the Polish-Ukrainian scientific collaboration.

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REFERENCES

1. M.J. Sadowski, et al. // *PAST. Series «Plasma Phys».* 2006, № 12, p. 213-235.
2. M.J. Sadowski // *PAST. Series «Plasma Phys».* 2008, №. 14, p. 90-94.
3. M.J. Sadowski, M. Scholz // *PAST. Series «Plasma Phy.s».* 2010, №.16, p. 194-198.
4. M.J. Sadowski// *Nukleonika* 2011, v. 56, № 2, p. 85-98.
5. L. Jakubowski, et al.// *Nucl. Instr. Meth. A* 2010, v. 623, p. 686-689.
6. M. Rabiński, et al.// *PAST. Series «Plasma Phys.».* 2011, №17, p. 164-166.
7. L. Jakubowski, et al.// *PAST. Series «Plasma Phys.».* 2011, №.17, p. 170-172.
8. L. Jakubowski, et al. // *Nukleonika* 2012, v. 57, №2, p. 177-181.
9. L. Jakubowski, et al.// *Measurements of fast electrons in the TORE-SUPRA tokamak – Submitted for RSI.*
10. J. Zebrowski, et al.// *Proc. Alushta-2012 Int. Conf. & School on PP&CF*, Alushta, Sept. 16-19, 2012, Oral 9-02.
11. A. Malinowska, et al.// *Nucl. Instr. and Meth.* B 2012, v. 281, p. 56-63.
12. A. Szydlowski, et al.// *Radiat. Meas.* 2012 - In print.
13. A. Malinowska, et al.// *Nucl. Instr. and Meth. B* 2012 – in print.
14. R. Prokopowicz, et al.// *Nucl. Instr. Methods A* .2011, v. 637, p. 119-127.
15. K. Jakubowska, et al.//*Acta Technica CSAV* 2011, v. 56, p. T107-T112.
16. E. Składnik-Sadowska, et al.// *Contrib. Plasma Phys.* 2011, v. 51, p. 288-292.
17. K.. Jakubowska, et al.// *Nukleonika* 2011, v. 56, № 2, p.125-129.
18. V.A. Gribkov, et al.// *Physica Scripta*. 2011, v. 83, 045606.
19. M.S. Ladygina, et al.// *Fusion Sci. Technol.* 2011, v. 60, p. 27-33.
20. V.A. Makhlaj, et al.// *Physica Scripta* 2011, v. T145, 014061.
21. E. Skladnik-Sadowska, et al.// *Nukleonika* 2012, v. 57, № 2, p. 193-196.
22. E. Skladnik-Sadowska, et al.// *Proc. Alushta-2012 Int. Conf. & School on PP&CF*, Alushta, Sept. 16-19, 2012, Oral 9-04.
23. R. Kwiatkowski, et al.// *Nukleonika* .2011, v. 56, № 2, p. 119-123.
24. M.J. Sadowski // *Proc. 11th Kudowa School Towards Fusion Energy,* Kudowa, June 11-15, 2012, Invited IL-15.
25. R. Kwiatkowski et al. // *Nukleonika*. 2012, v. 57, № 1, p. 67-74.
26. M.J. Sadowsk i// *Nukleonika*. 2012, v.57, №.1, p. 11-24.
27. R. Kwiatkowski et al.// *Nukleonika*. 2012, v. 57, № 2, p. 211-214.
28. M. Rabiński, M.J. Sadowski, J. Żebrowski, et al. http://www.ifj.edu.pl/pro/fuz_termo_sem.php?lang=pl

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ПРОГРЕСС В ВЫСОКОТЕМПЕРАТУРНОЙ ПЛАЗМЕ, ИССЛЕДОВАННОЙ В НЦЯИ (БЫВШИЙ ИЯП) В ПОЛЬШЕ

M.J. Sadowski

Представлены наиболее важные результаты теоретического и экспериментального исследований высокотемпературной плазмы, которые были получены в НЦЯИ (бывший ИЯП) в Отвоцк-Шверке, Польша, за последние два года. Исследовательская деятельность включала в себя: исследования быстрых электронов и рентгеновского излучения в устройствах типа Z-пинч и токамаках; исследования по применению твердотельных трековых детекторов для регистрации быстрых ионов и нейтронов, испускаемых плазмой в экспериментальных установках Z-пинч, токамаках и установках инерциального термоядерного синтеза; исследования высокотемпературных плазменных потоков и их взаимодействия с твердыми мишенями; сверхвысокого вакуумно-дугового осаждения тонких металлических пленок; некоторые исследования по плазменной инженерии твердых поверхностей. Образование НЦЯИ (1 сентября 2011) и его последующая реорганизация (1 января 2012) привела к отделению Секции плазменных исследований (TJ5), работа которой направлена на изучение высокотемпературной плазмы в рамках внутренних и международных научно-исследовательских программ.

ПРОГРЕС У ВИСОКОТЕМПЕРАТУРНІЙ ПЛАЗМІ, ДОСЛІДЖЕНІЙ В НЦЯД (КОЛИШНІЙ ІЯП) У ПОЛЬЩІ

M.J. Sadowski

Представлені найбільш важливі результати теоретичного та експериментального дослідження високотемпературної плазми, які були отримані в НЦЯІ (колишній ІЯП) в Отвоцк-Шверк, Польща, за останні два роки. Дослідницька діяльність включала в себе: дослідження швидких електронів і рентгенівського випромінювання в пристроях типу Z-пінч і токамаках; дослідження по застосуванню твердотільних трекових детекторів для реєстрації швидких іонів та нейтронів, що випускаються плазмою в експериментальних установках Z-пінч, токамак і установок інерціального термоядерного синтезу; дослідження високотемпературних плазмових потоків та їх взаємодії з твердими мішенями; надвисокого вакуумно-дугового осадження тонких металевих плівок; деякі дослідження по плазмовій інженерії твердих поверхонь. Утворення НЦЯІ (1 вересня 2011) та його подальша реорганізація (1 січня 2012) призвела до відокремлення Секції плазмових досліджень (TJ5), робота якої спрямована на вивчення високотемпературної плазми в рамках внутрішніх та міжнародних науково-дослідницьких програм.