COMMENTS ON RESULTS OF RECENT HIGH-TEMPERATURE PLASMA STUDIES AT NCBJ (FORMER IPJ) IN POLAND

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This invited lecture presents the most important results of high-temperature plasma studies, which were performed at the NCBJ in Otwock-Swierk, Poland, since 2012. The presentation contains comments on the performed studies and suggestions of future investigation. The first part concerns studies of corpuscular streams in tokamaks, and particularly measurements of run-away electrons within ISSTOK in Lisbon, Portugal, and FTU in Frascati, Italy, by means of Cherenkov-type probes. The second part describes possible applications of solid-state nuclear track detectors (NTDs) for measurements of fast ions and fusion-products in tokamaks, and particularly within COMPASS in Prague, Czech Republic. The third part presents new diagnostic tools for ion measurements in various facilities (including tokamaks and stellerators). The fourth part describes experimental studies of pulsed plasma streams within different Plasma-Focus (PF) and multi-rod plasma injector (RPI) facilities, during a free propagation and interactions with targets made of materials of importance for fusion technology. The last section reports on other activities at the NCBJ Plasma Studies Division (TJ5). In summary there are also some proposals for future plasma studies, which might be performed at domestic and foreign research centres, in frames of the international scientific collaboration.

PACS: 52.50.Dg; 52.55.Fa; 52.58.Lq; 52.59.Hq; 52.65.Cc; 52.70.-m.

INTRODUCTION

Research on high-temperature plasma in Poland was initiated at the Institute of Nuclear Research (IBJ) in Swierk about 60 years ago. About 35 years ago plasma studies were also undertaken at the Institute of Plasma Physics and Laser Microfusion in Warsaw. In 1989 the IBJ in Swierk was converted in the Institute of Nuclear Problems (IPJ), and in 2011 it was up-grated to the National Centre for Nuclear Studies (NCBJ).

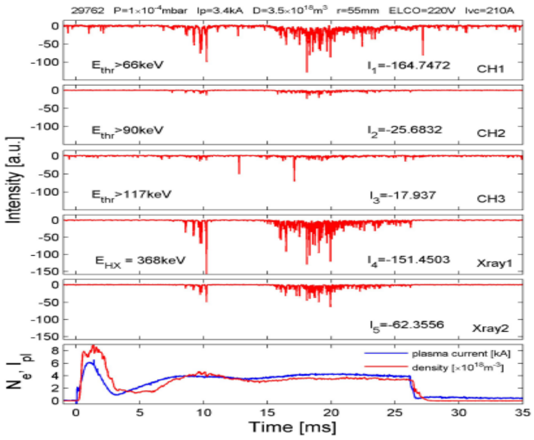
On January 1, 2012, the previous Department of Plasma Physics and Technology (PV) at NCBJ was split into the Low-Temperature Plasma and Ion Technology Division (FM2) and Plasma Studies Division (TJ5), which is continuing high-temperature plasma and fusion research. The most important results of studies concerning this research have already been reported at many international conferences, including those held in Alushta [1-4].

The main aim of this invited talk has been to comment on results of high-temperature plasma research at NCBJ, which have been obtained after the previous Alushta-2012 conference [4]. The paper presents some new proposals.

1. INVESTIGATION OF FAST ELECTRONS IN TOKAMAKS

Studies of fast (ripple-born and run-away) electrons were continued in a frame of the EURATOM programme. To perform local measurements of such electrons in different tokamaks the NCBJ team developed a convenient diagnostic technique basing on a Cherenkov effect, as reported in previous papers [4-5].

In a frame of the international collaboration extensive studies of fast electrons were performed in the ISSTOK tokamak in Lisbon, using a single- and four-channel. Cherenkov detectors [5-6]. To perform measurements in different electron energy ranges, the Cherenkov radiators were shielded with thin molybdenum layers of different thickness [6]. Particular attention was paid to correlations of electron beams and hard X-rays in the ISTTOK tokamak [7], as shown in Fig. 1.



.Fig. 1. Comparison of electron-induced Cherenkov signals (CH1-CH3) and hard X-ray detectors signals with waveforms of current and plasma density in ISSTOK

Other examples of applications of Cherenkov-type probes were reported in a paper [8]. A new Cherenkov probe for ISTTOK experiments, which was equipped with an 8 mm-dia., 1.5 mm-thick diamond, is shown in Fig. 2.

Fig. 2. Single-channel Cherenkov probe for ISTTOK

The main motivation for development of Cherenkov measuring heads were earlier observations of fast (mainly ripple-born) electrons in the TORE-SUPRA facility in Cadarache, France [9]. To enable more accurate studies of electron beams, a new Cherenkov probe (with 4 diamond radiators fixed at the top of the probe body) was designed and manufactured. The use of that probe enabled to prove that in TORE-SUPRA there was formed a large zone of intense electron streams [9].

Detailed studies of fast electrons within the ISTTOK tokamak were also continued. A comparison of different Cherenkov-type probes used so far was performed and reported in a paper [10]. New data about electron beams and hard X-ray emissions in the ISTTOK were obtained by means of a special measuring head equipped with two identical diamond radiators, which enabled to record fast electrons arriving from both direction in the horizontal plane (during successive discharges) [11]. It was shown that outside a plasma torus one can detect fast runaway electrons, and both Cherenkov radiators (placed at a 5-mm distance) can record electron-induced signals, which are correlated with hard X-rays measured outside the tokamak chamber. When the probe was immersed into the plasma ring too deeply, electron-signals became un-correlated, since the probe played a role of an a local limiter. That observation induced more detailed studies. Using two Cherenkov probes, placed at different positions around the ISTTOK chamber, it was possible to study a mutual influence of these probes, and their influence on other detectors and behaviour of plasma [12].

The Cherenkov-probe technique was also applied for measurements of fast electrons within the FTU tokamak in Frascati, Italy. A new probe contained a small cylindrical diamond radiator fixed at the top of a stainless-steel shielding. That radiator was coated with a thin Mo-layer, which determined an electron detection threshold at 58 keV. The probe was placed inside the FTU chamber at variable radial positions, but mostly in a shadow of a limiter. It was proved that the detector was insensitive to the background electro-magnetic radiation such a visible-, synchrotron- and gamma-emission Comparing the Cherenkov signals with those obtained from other diagnostics, an evident correlation of them with MHD instabilities was found., as shown in Fig. 3.

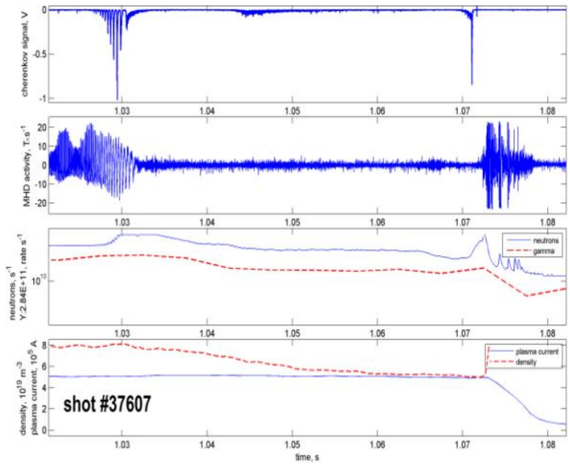


Fig. 3. Comparison of Cherenkov signals with MHD instabilities and neutron signals in the FTU tokamak

The modulated character of the signals resulted probably from a rotation of magnetic islands around of the tokamak torus. That hypothesis was confirmed by correlations of Cherenkov signals with those from a neutron/gamma camera. Results of this research are to be presented at the FEC-2014 [13].

Commenting on applications of Cherenkov-type probes in tokamak studies, it can be stated that: 1. It was proved by various experiments (CASTOR, ISTTOK, TORE-SUPRA, FTU) that such probes deliver valuable information not only about fast electrons, but also about behaviour of plasma in tokamaks; 2. Although different Cherenkov-type probes were constructed and applied, new versions should be designed and tested, taking into account specific requirements of large tokamak facilities; 3. It seems reasonable to apply this diagnostic technique also for electron measurements in stellarators; 4. A new design of the Cherenkov-type probe should made it possible to explore also directional characteristics of the Cherenkov radiation.

2. STUDIES OF FAST IONS AND FUSION REACTION PRODUCTS

In order to make possible accurate measurements of primary ions and charged fusion products, detailed calibration studies of selected solid-state nuclear track detectors (SSNTD) were performed and elaborated. In particular different characteristics of the PM-355-type detectors were determined, i.e. their energy resolution for α-particles and protons, sensitivity function, etching rates, etc. [14, 15]. In 2013 a simple ion-pinhole camera and a manipulator, as designed especially for ion measurements in the COMPASS tokamak in Prague, Czech. Republic, were manufactured, as shown in Fig. 4.

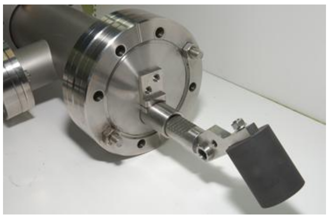


Fig. 4. Simple ion-pinhole camera fixed upon the manipulator prepared for COMPASS experiments

The ion measurements within the COMPASS facility are planned to be performed in 2014.

In 2013 also the results of earlier experimental and theoretical studies of fast ions, as performed in plasma facilities of the RPI-, PF- and MCF-type, were analyzed [8]. In particular, there was summarized research on the spatial and energetic structure of fast ion streams from RPI-IBIS, PF-360 and PF-1000 devices, which were investigated by means of nuclear track detectors, ion pinhole cameras and Thomson-type analyzers. Particular attention was paid to mass- and energy-analysis of the fast ion beams emitted from RPI-type plasma discharges, which were investigated by means of a modified Thomson analyzer [16, 17].

Commenting on studies described above, one should notice that : 1. Accurate calibration of new SSNTD is necessary, because there appear some differences in characteristics of such detectors from different producers and supplies; 2. Tools for mass- and energy-analysis of primary ions and fusion products should be developed continuously.

3. DEVELOPMENT OF NEW PLASMA DIAGNOSTICS EQUIPMENT

Other efforts of the NCBJ team concerned the development of new diagnostic tools for ion studies under extreme thermal loads expected in future fusion reactors. Those studies were performed in a frame of the national program the „Studies and development of technology for controlled thermonuclear fusion". In 2013 detailed technical projects of new ion probes were completed., and two probes, i.e. an ion pinhole probe with a rotated support for placement of several SSNTD, and a probe with a small Thomson-type analyzer, were manufactured. A picture of the first one is shown in Fig. 5.

Fig. 5. Parts of the ion pinhole camera equipped with a rotated drum for several nuclear track detectors

There was also designed and manufactured an universal manipulator for fixing exchangeable measuring heads. After the assembling the both measuring heads and their testing in a high-vacuum stand, there were carried out detailed laboratory tests of the complete probes in plasma facilities available at the NCBJ. A picture, as taken during such tests, is shown in Fig. 6.

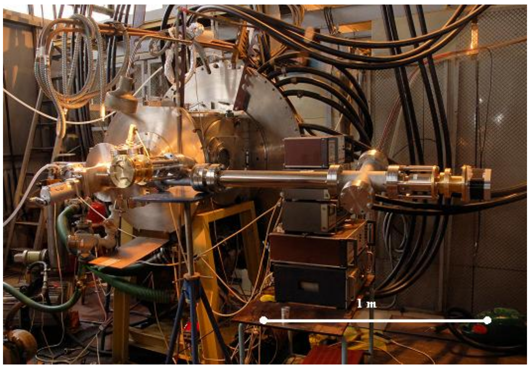


Fig. 6. Completed ion probe during its tests within the RPI-IBIS facility

Those tests proved that the new probes can be applied for fast ion measurements inside intense plasma-ion streams [17]. An example is presented in Fig. 7.

In 2013 there were also continued computer simulations of trajectories of fast protons, tritons and ^{3}He ions, which might be measured e.g. in the COMPASS tokamak. Also computed were efficiencies of the detectors to be used in future experiments [18]. There were also performed measurements and computer simulations of fast ions from plasma accelerators of the RPI-type. The detailed results obtained for the RPI-IBIS facility were summarized in a Ph.D. thesis and a paper [19].

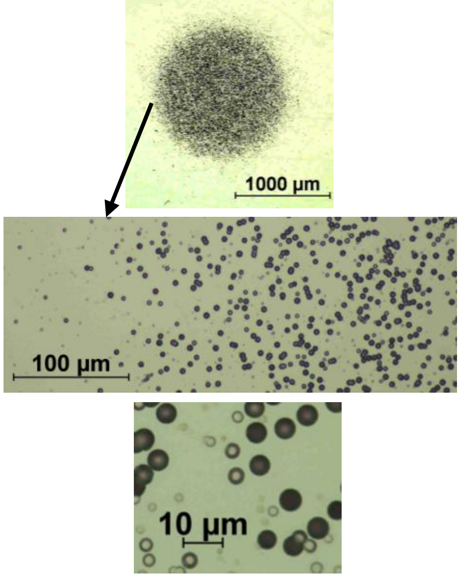


Fig. 7. Ion image obtained within the RPI-IBIS by means of the pinhole camera with a rotated drum and SSNTD

Commenting on the studies described above it might be stated that: 1. For passive corpuscular diagnostics of plasma in a tokamak scrape-off layer one needs probes resistant to high-thermal loads, and constructional materials must be selected very carefully; 2. If probes are designed for a fast immersion and withdrawal, optical contacts between radiators and light-pipes (cables) must be reliable during fast motions of these probes.

4. OPTICAL EMISSION SPECTROSCOPY OF FREE-PROPAGATING PLASMA STREAMS AND THEIR INTERACTIONS WITH SOLID TARGETS

In 2013 the results of earlier experimental studies of plasma produced from a carbon target irradiated by laser pulses, as performed by means of the optical emission spectroscopy (OES), were summarized in a paper [20]. Detailed OES measurements of free-propagating plasma streams and plasma, which is produced during interactions of such streams with solid targets in the RPI-IBIS and modified PF-1000U facilities, were summarized in another paper [21].

In subsequent spectroscopic studies particular attention was paid to interactions of intense plasma streams with tungsten and CFC targets, which were irradiated in the modified PF-1000U facility [22]. An example of the recorded spectra is shown in Fig. 8.

In the PF-1000 facility there were also performed studies of interaction intense plasma-ion streams with SiC targets. The OES measurements made it possible to determine dynamics of plasma emission and to identify ion species in plasma streams and plasma produced at the target surface. Some results of such studies in PF-1000 facility were presented in a paper [23]. Recently, analogous studies of SiC targets have been carried out within the modified PF-360U facility, as reported in another paper [24].

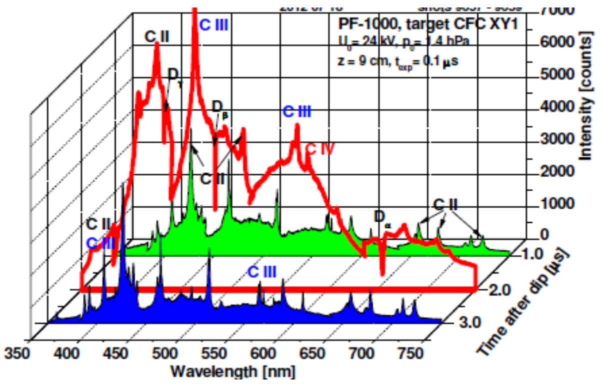


Fig. 8. Evolution of optical spectra of plasma produced from a CFC target in the PF-1000 device

In a frame of the scientific collaboration of the **NCBJ, the IPiLM and KIPT, there were also performed** studies on behaviour of tungsten samples irradiated by intense plasma streams emitted from different plasma accelerators [25, 26]. A dependence of tungsten erosion, e.g. surface cracks, on the heat load and the number of plasma shots was investigated.

Other OES measurements were carried out during depositions of coatings obtained by means of the impulse plasma deposition (IPD) process. The measurements were performed at the Warsaw University of Technology. An example of the recorded and identified spectral lines is shown in Fig. 9.

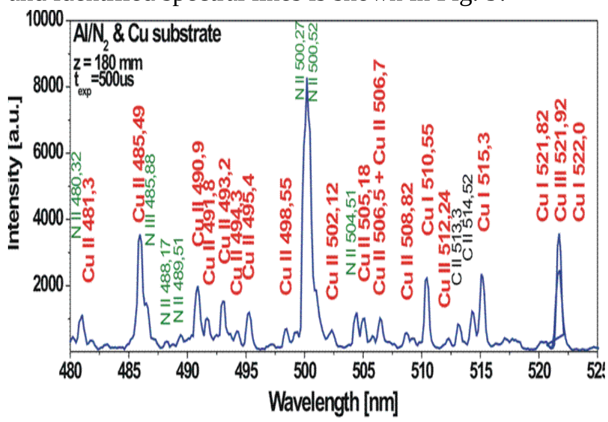


Fig. 9. Part of the optical spectrum recorded for Al/N_2 pulsed plasma interacting with a Cu target

It should here be noted that a characteristic feature of the IPD method is intense and strong excitation of the substrate surface (by heat and defects), which is solely induced by the impact of pulsed plasma. Using this technique the layers deposited upon unheated and un-polarized substrates showed very good adhesion. The detailed results of those studies were presented in a paper [27].

Commenting on OES studies of high-temperature plasmas, one should to note that: 1. The optical spectroscopy is a very convenient method to observe dynamics of plasma radiation and to identify different ion species; 2. An estimation of the plasma density can be performed on the basis of selected spectral lines if re-absorption effects can be neglected; 3. To estimate a density of dense and multi-component plasma, which is usually formed at a surface of the irradiated target, one should apply other techniques, e.g. laser interferometry.

5. OTHER PLASMA RESEARCH ACTIVITIES

Some members of the NCBJ-TJ5 team participated also in other research activities. An example is research on computational modelling of discharges within IPD accelerator equipped with a gas valve, which is of importance for material engineering [28]. A laser-removal of a deuterium deposit from graphite samples, which is of interest for tokamak design and engineering, was investigated in a frame of the bilateral collaboration of the NCBJ and IFiPLM [29]. In the same collaboration there was studied the application of selected radio-nuclides for monitoring of D-D reactions occurring in a dense plasma-focus device [30].

6. SUMMARY AND CONCLUSIONS

The detailed comments on described research activities have been given in the previous sections. The most important ones seem to be as follows: 1. The Cherenkov-type probes of different constructions, as developed at the NCBJ, have already been used in several tokamaks, and in author's opinion they might also be used for fast electron measurements in stellarators; 2. SSNTD are very convenient tools for selective recording ions (including fusion products), but these detectors require very careful and cumbersome calibration measurements; 3. To use SSNTD for time-resolved measurements one can apply a probe with an ion pinhole camera equipped with a rotated drum, which enables exposition of several detectors during a single discharge; 4. The OES methods are widely applied in different plasma experiments, but in order to determine an electron density in a dense multi-species plasma produced at surfaces of irradiated targets one needs other techniques, e.g. laser inteferometric systems.

The reported plasma studies (in frames of the scientific collaboration of the NCBJ, IFPiLM and KIPT teams) have already enabled to collect important information about plasma-streams and plasma-interactions with various materials. This collaboration should be continued.

ACKNOWLEDGEMENTS

The studies of tokamaks were performed as a task of the program supported by the EURATOM Community under the contract with the Association EURATOM-IPPLM, Poland (Contract No. FU07-CT-2007-00061), and by the Ministry of Science and Higher Education, Poland, under contract 2498/7.PR EURATOM/2012/2 and 2861/7.PR EURATOM/2013/2. The opinions expressed herein do not necessarily reflect those of the EC. The development of new diagnostic tools was performed in a frame of the task № 2 of the research project realized under the contract №. SP/J/2/143234/11 of the NCBiR with the NCBJ, Poland.

REFERENCES

1. M.J. Sadowski, E. Skladnik-Sadowska, M. Scholz, J. Wolowski // *PAST*. 2006, № 6, p. 213-235.
2. M.J. Sadowski // *PAST*. 2008, № 6, p. 90-94.
3. M.J. Sadowski, M. Scholz. // *PAST*. 2010, № 6, p. 194-198.
4. M.J. Sadowski // *PAST*. 2012, № 6, p. 238-242.

5. M. Rabinski, L. Jakubowski, J. Zebrowski, et al // *PAST*. 2012, № 6, p. 246-248.
6. V.V. Plyusnin, L. Jakubowski, J. Zebrowski, et al. // *Rev. Sci. Instrum.* 2012, v. 83, p. 083505.
7. L. Jakubowski, V.V. Plyusnin, K. Malinowski, et al // *Contrib. Plasma Phys*. 2013, v. 53, p. 615-622.
8. M.J. Sadowski, K. Czaus, R. Kwiatkowski, et al. // *PAST*. 2013, № 1, p. 252-257.
9. L. Jakubowski, M.J. Sadowski, J. Zebrowski, et al. // *Rev. Sci. Instrum.* 2013, v. 84, p. 016107.
10. L. Jakubowski, M.J. Sadowski, J. Żebrowski, et al. // *Phys. Scripta*. 2014, v. T161, p. 014011.
11. L. Jakubowski, V.V. Plyusnin, K. Malinowski, et al. // *Phys. Scripta*. 2014, v. T161, p. 014012.
12. F. Causa, G. Pucella, P. Buratti, et al.// *Proc. FEC 2014*, St. Petersburg, Russia, Oct. 13-18, 2014, EX/P2-49.
13. A. Szydlowski, A. Malinowska, M. Jaskola, et al. // *Radiat. Measur.* 2013, v. 50, p. 258-260.
14. A. Malinowska, A. Szydlowski, M. Jaskola, et al.// *Rev. Sci. Instrum.* 2013, v. 84, p. 07351.
15. K. Czaus, E. Skladnik-Sadowska, et al // *PAST*. 2013, № 1, p. 261-263.
16. M.J. Sadowski// *Proc. 12th Kudowa Summer School, Kudowa Zdroj, Poland, June 9-13, 2014*, CD issue.
17. R. Kwiatkowski, K. Malinowski, M.J. Sadowski // *Phys. Scripta*. 2014, v. T161, p. 014013.
18. K. Malinowski, M.J. Sadowski, E. Skladnik-Sadowska // *Phys. Scripta.* 2014, v. T161, p. 014054.
19. A. Czarnecka, M. Kubkowska, E. Skladnik-Sadowska, et al. // *PAST*. 2013, № 1, p. 258-260.
20. E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, et al. // *PAST*. 2013, № 1, p. 279-283.
21. M. Kubkowska, E. Skladnik-Sadowska, R. Kwiatkowski, et al. // *Phys. Scripta*. 2014, v. T161, p. 014038.
22. E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, et al. // *Phys. Scripta*. 2014, v. T161, p. 014039.
23. E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, et al. // *Proc. ICPPCF-2014*.
24. V.A. Makhlaj, I.E. Garkusha, N.N. Aksenov, et al. // *Phys. Scripta*. 2014, v. T159, p. 014024.
25. V.A. Makhlaj, I.E. Garkusha, N.N. Aksenov, et al.// *Phys. Scripta.* 2014, v. T161, p. 014040.
26. K. Nowakowska-Langier, K. Zdunek, R. Chodun, et al. // *Phys. Scripta.* 2014, v. T161, p. 014063.
27. M. Rabinski, R. Chodun, K. Nowakowska-Langier, K. Zdunek // *Phys Scripta*. 2014, v. T161, p. 014049.
28. M. Kubkowska, E. Skladnik-Sadowska, K. Malinowski, et al. // *J. of Phys.: Conf S.* 2014, v. 508, p. 012015.
29. S. Jednorog, A. Szydlowski // *J. Radioanal. Nucl. Chem.* 2014, v. 300, № 2, p. 1-7.

Article received 17.09.2014

КОММЕНТАРИИ К РЕЗУЛЬТАТАМ НЕДАВНИХ ВЫСОКОТЕМПЕРАТУРНЫХ ПЛАЗМЕННЫХ ИССЛЕДОВАНИЙ В NCBJ (РАНЕЕ IPJ) В ПОЛЬШЕ

M.J. Sadowski

Представлены наиболее важные результаты высокотемпературных плазменных исследований, которые были проведены в NCBJ в Отвоцк-Шверке (Польша) с 2012, а также комментарии к проведенным исследованиям и предложения на будущее. Первая часть касается изучений корпускулярных потоков в токамаках и частично измерений убегающих электронов в ISSTOK в Лисабоне (Португалия) и FTU в Фраскати (Италия) с помощью черенковских детекторов. Вторая часть описывает возможные применения твердотельных ядерных трековых (NTDs) детекторов для измерений быстрых ионов и продуктов синтеза в токамаках, частично в COMPASS в Праге (Чешская Республика). Третья часть представляет новые диагностические инструменты для ионных измерений на разных установках (включая токамаки и стеллараторы). Четвертая часть описывает экспериментальные изучения импульсных плазменных потоков в разных плазма-фокусах (ПФ) и многостержневом плазменном инжекторе (RPI) в свободном потоке и при взаимодействии с мишенями, сделанными из материалов, важных для технологий синтеза. Последняя часть – наша деятельность в Отделе плазменных исследований NCBJ (TJ5). В заключение есть несколько предложений для будущих плазменных исследований, которые могут быть представлены в домашних и иностранных исследовательских институтах в рамках международного научного сотрудничества.

КОМЕНТАРІ ДО РЕЗУЛЬТАТІВ НЕЩОДАВНІХ ВИСОКОТЕМПЕРАТУРНИХ ПЛАЗМОВИХ ДОСЛІДЖЕНЬ В NCBJ (РАНІШЕ IPJ) У ПОЛЬЩІ

M.J. Sadowski

Представлено найбільш важливі результати високотемпературних плазмових досліджень, які були проведені в NCBJ в Отвоцк-Шверку (Польща) з 2012, а також коментарі на проведені дослідження та пропозиції на майбутнє. Перша частина стосується вивчень корпускулярних потоків у токамаках та частково вимірювань електронів, що тікають в ISSTOK у Лісабоні (Португалія) та FTU у Фраскаті (Італія), за допомогою черенковських детекторів. Друга частина описує можливість застосування твердотільних ядерних трекових детекторів (NTDs) для вимірювань швидких іонів та продуктів синтезу в токамаках, частково у COMPASS у Празі (Чеська Республіка). Третя частина представляє нові діагностичні інструменти для іонних вимірювань на різних установках (включаючи токамаки та стелларатори). Четверта частина описує експериментальні вивчення імпульсних плазмових потоків у різних плазма-фокусах (ПФ) та багатостержневому плазмовому інжектор (RPI) у вільному потоці та при взаємодії з мішенями з матеріалів, важливих для технологій синтезу. Остання частина – про нашу діяльність у Відділі плазмових досліджень NCBJ (TJ5). У висновку є декілька пропозицій для майбутніх плазмових досліджень, які можуть бути проведені у домашніх та іноземних дослідницьких центрах у рамках міжнародної наукової співпраці.