COMMENTS ON RECENT STUDIES OF HIGH-TEMPERATURE PLASMAS AT THE NCBJ IN POLAND

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This invited lecture presents comments on the most important results of high-temperature plasma studies which have been carried out at the NCBJ, Poland, since the ICPPCF-2014. The main scientific tasks concerned studies of fast electrons, ions, neutrons, and x-rays emitted from different research facilities of the PF-, RPI-, ICF- and Tokamak-type as well as investigations of high-temperature plasma streams and their interactions with various solid targets. The first part presents the authors' opinion about experimental studies of the fast runaway electrons generation in the COMPASS (Prague) and FTU (Frascati) tokamaks. The second part presents the comments on applications of nuclear track detectors for studies of fast ions and products from $p^{11}B$ nuclear reactions at the PALS (Prague) experiment. The next part presents the comments on measurements of the X-rays, ions and electrons from PF-type discharges. The last part summarizes OES studies of plasma-streams interactions with W-targets in the PF-1000U facility and with CFC-targets in the RPI-IBIS machine. These comments are followed by proposals of future theoretical and experimental studies.

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INTRODUCTION

In Poland the experimental and theoretical studies of hot plasmas were initiated about 65 years ago and conducted at the Institute of Nuclear Research (IBJ, later IPJ) in Swierk. In 2011 the institute was up-grated to the National Centre for Nuclear Studies (NCBJ), and in 2012 the Department of Plasma Physics and Materials Engineering (PV) at NCBJ was split into the Plasma/Ion Beam Technology Division (FM2) and Plasma Studies Division (TJ5). The results of research on high-temperature plasma and controlled fusion have been presented at many international conferences, as well as in Alushta and Kharkov [1-5].

The main aim of this invited talk was to comment on results of the recent studies of high-temperature plasma at the NCBJ, which have been obtained after the previous conference ICPPCF-2014 [5] and to presents some new proposals.

1. RESEARCH ON FAST ELECTRONS IN VARIOUS TOKAMAKS

Studies of fast (ripple-born and run-away) electrons deliver important information about dynamics of plasma in tokamaks. Therefore, such studies have been performed at the NCBJ in frames of the EURATOM and EUROfusion programmes. A control of intense high-energy electron beams, which can damage the first wall, plays also a significant role because it enables to avoid or to mitigate disruptions. Studies performed in order to determine conditions of the runaway electrons generation, and to investigate their mitigation techniques, were started in a frame of the international cooperation at the IPP ASCR in Prague in 2014, as a part of the MST-2 EUROfusion project. Such studies were also continued in 2015. The NCBJ team proposed to apply Cherenkov probes, because of their high spatial- and temporal-resolution. New single- and multi-channel Cherenkov detectors were installed within the COMPASS tokamak. During the 2015-spring campaign, using a single-channel detector, very short Cherenkov signals were recorded in addition to usually observed long signals. During the 2015-autumn campaign a new multichannel Cherenkov detector was installed. It was equipped with three radiators made of CVD diamond crystals, which were covered by different filters in order to establish various energy detection thresholds (58, 145, and 221 keV) and some measurements of runaway electrons were performed. Signals from the Cherenkov probe channels were correlated with the photo-neutrons and hard x-rays, but in many shots electron-spikes were recorded in the Cherenkov channels only (Fig. 1).

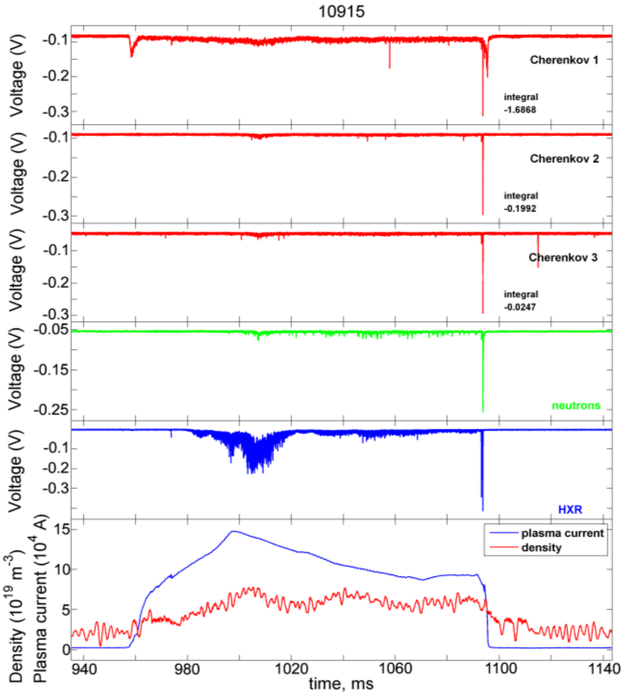

Fig. 1. Electron-produced Cherenkov signals and spikes recorded during the Compass experiment

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Detailed electron measurements with Cherenkov probes were performed within the ISTTOK facility in Lisbon, Portugal, and recently particular attention was focused on a mutual influence of such probes [6].

The Cherenkov probes were also applied for studies of fast electrons within the FTU tokamak in Frascati, Italy [7]. During recent studies in the FTU facility a new kind of modulated signals was found and explained as results of the magnetic island rotation (Fig. 2).

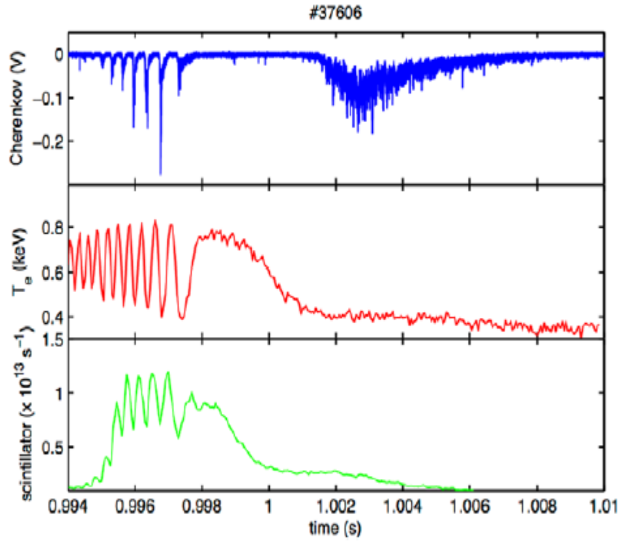

Fig. 2. Correlation of Cherenkov signals (top) with oscillations of electron temperature (middle) and D-D fusion neutrons (bottom) in the FTU experiment #37606

During more detailed studies at the FTU machine, the Cherenkov signals were compared with data collected from many other diagnostics, which included X- and gamma-rays, the electron cyclotron emission and signals from Mirnov coils (recording MHD instabilities), as well as from fusion- and photo-neutron detectors. In fact these were the first observations of the correlation between runaway electrons and evolution of magnetic islands [8]. In addition there were also recorded disruptions caused by injections of deuterium pellets.

The summary of NCBJ research on the construction of Cherenkov probes and their application for studies of fast electron beams (in the CASTOR, ISTTOK, TORE-SUPRA, and FTU facilities) was presented at the ECPD-2015 [9]. Another paper about the development of the Cherenkov probes was presented at a SPIE meeting [10].

Our comments about the studies described above can be formulated as follows: 1. It was shown that the Cherenkov detectors deliver direct and immediate information about the emission of fast electrons and plasma dynamics; 2. Particular attention should be focused on the application of multi-channel Cherenkov probes for research on correlations of electron pulses with signals from Mirnov coils which can inform about instabilities, e.g., motion of magnetic islands; 3. New probes should be designed to study directional characteristics of the fast electron beams; 4. New efforts should be undertaken to perform computer simulations by means of gyro-kinetic codes.

2. STUDIES OF FAST IONS AND FUSION PRODUCTS FROM LASER-EXPERIMENTS

In 2014 and 2015 another NCBJ team was engaged in measurements of laser-produced ions at the PALS facility in Prague. Particular efforts concerned investigation of products from $^{11}B(p,2\alpha)\alpha$ fusion reactions, i.e. fast alpha particles [11, 12]. In the described experiments the use was made of thin and thick silicon targets saturated with hydrogen and implanted with boron (so-called Si-H-B). Those targets were irradiated by intense laser pulses to produce fast protons, which could undergo reactions with boron atoms and produce fast alpha particles (of the total energy equal to 8.7 MeV). To measure the emission of such alphas several nuclear track detectors (NTDs) of the PM-355 type were placed at different angles, at a distance of 50 cm from the target. The irradiated detectors were etched and analysed with an optical microscope to discern tracks produced by the escaping protons and alphas.

The same TJ5 team investigated the influence of soft x-rays on characteristics of the NTDs [13] and changes in the sensitivity of PM-355 after a long storage [14].

Our comments about the studies described above can be formulated as follows: 1. Measurements of charged particles produced from the $^{11}B(p,2\alpha)\alpha$ reactions should be supplemented by accurate measurements by means of mass- and energy-analysers; 2. Studies of calibration characteristics and aging effects of NTDs are time-consuming, but they should be performed before any application of such detectors for accurate investigation of the primary ions and fusion products.

3. TUDIES OF X-RAYS, IONS AND FUSION PRODUCTS FROM RPI- AND PF-FACILITIES

Another NCBJ-TJ5 team was engaged in measurements of X-rays and ions (including fusion products) from plasma discharges performed in the Rod-Plasma-Injector (RPI) and Plasma-Focus (PF) facilities.

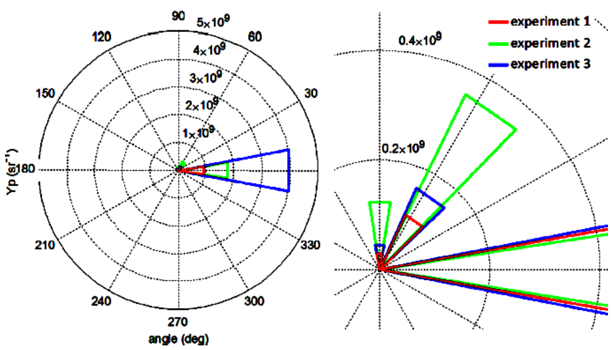

Fig. 3. Anisotropy of the fusion-produced neutrons (left) and protons (right) from 3 experiments. The numbers of tracks are given after normalization to a stereo-radian

In 2015 this team published a paper on anisotropy of fusion-produced protons and neutrons emitted from high-current plasma discharges. These studies were performed by means of so-called “sandwich-detectors”, composed of an absorption Al-filter and two PM-355 nuclear track detectors separated by a converter of neutrons into protons, which was made of a polyethylene [15]. The detailed measurements performed within a modified PF-1000U facility enabled the investigated anisotropy to be determined (Fig. 3). The results of earlier measurements of fast ion beams emitted from discharges in the PF-1000U facility were analysed [16]. Those ion beams were recorded by means of a pinhole camera equipped with a PM-355 track detector, and their microstructure was studied (Fig. 4).

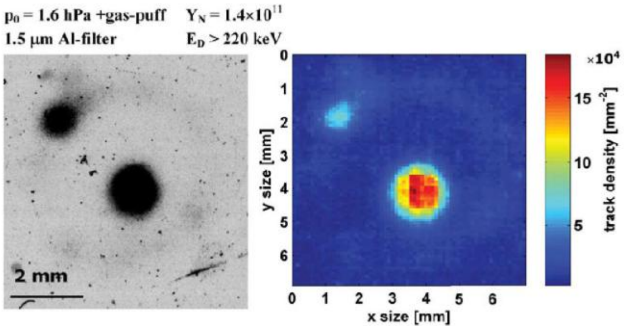

Fig. 4. Image and density map of deuteron beams of energy > 220 keV emitted from a PF-1000U discharge

Energy distributions of the emitted ions were determined also by means of a small Thomson-type analyser [17].

The earlier energy- and time-resolved measurements of fast ions from the PF-1000U facility, which were performed with the Thomson analyser, equipped with miniature scintillation detectors and placed at a distance 135 cm from the electrodes outlet, were also analysed. [18]. Signals, which were obtained from different energy channels, were compared to determine periods of the fast deuterons emission (Fig. 5).

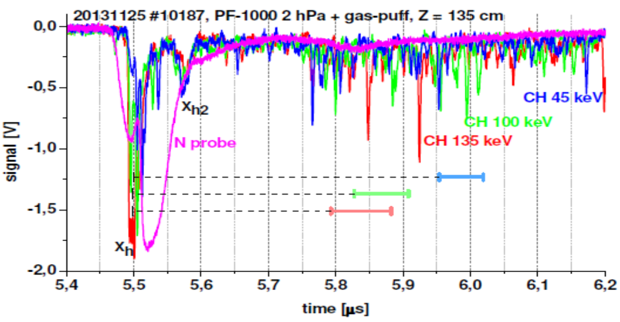

Fig. 5. Comparison of deuteron signals from 3 energy channels of the Thomson analyser and a signal from the x-ray and neutron probe. Straight solid lines show periods when the deuterons could be emitted

Different methods of electron- and ion-diagnostics, applied in various PF studies and applicable also for measurements in tokamaks, were compared. Particular attention was focused on various Cherenkov-type probes and new ion probes. There was also described an ion pinhole camera, which enables irradiation of several NTDs during a single tokamak discharge, and a miniature Thomson-type spectrometer, which can be used for ion measurements at plasma edge [19].

The most important problems, which have to be solved before construction of future thermonuclear reactors, were also analysed, discussed at the PME conference and described in a review paper [20].

During the whole 2015 the joint NCBJ-IFPiLM team has continued also experimental studies of the x-ray emission from PF discharges. Results of the earlier measurements of soft X-rays from the PF-1000U facility were analysed and summarized. Attention was paid to x-ray pinhole images which demonstrated the appearance of plasma filaments and so-called “hot-spots” [21].

The team analysed also results of the time-resolved measurements performed with four PIN diodes located behind filtered pinholes, which observed different regions of a dense plasma column (Fig. 6).

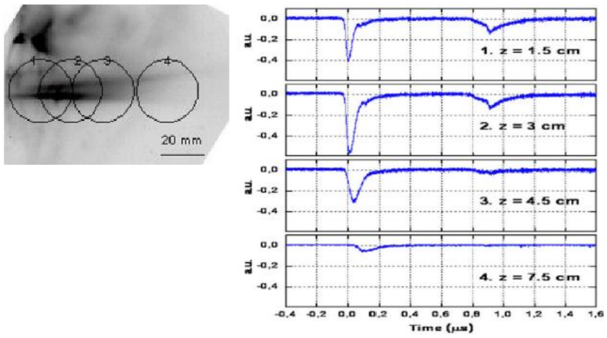

Fig. 6. Time-integrated X-ray image (with the marked observation fields) and time-resolved x-ray signals from PIN diodes, as recorded forPF-1000U shot #10333

The most important results of the studies performed by the NCBJ-IFPiLM team were presented in a paper [22].

Many efforts were also devoted to measurements of fast electron beams emitted from a modified PF-360U facility, mostly in the upward direction through a central channel in the anode. The use was made of magnetic analysers equipped with miniature Cherenkov- or scintillation-detectors [23]. The most important result was the observation that the fast electron beams are often emitted as narrow pulses in different energy channels (Fig. 7).

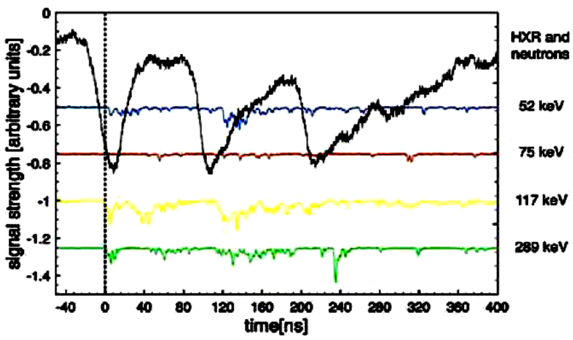

Fig. 7. Hard x-rays and neutrons signals (from a scintillation probe) and electron signals (from different spectrometer channels) recorded in a PF-360U device

Our comments on the studies described above can be formulated as follows: 1. Time-integrated soft x-ray images obtained with appropriate filters can provide information about the structure of a PF pinch column; 2. Space- and time-resolved X-ray measurements enable dynamics of the local sources (filaments and hot-spots) to be investigated; 3. Energy- and time-resolved studies of electron beams give important information about their emission characteristics.

The recent study of x-rays was focused on estimations of plasma electron temperature [24, 25]. It is proposed to continue more accurate space-, time- and energy-resolved measurements of x-ray emissions.

4. STUDY OF VISIBLE RADIATION FROM HOT PLASMA STREAMS AND THEIR INTERACTIONS WITH SOLID TARGETS

At the beginning of 2015 the earlier experimental studies, which concerned physics and applications of plasma streams produced by plasma-focus discharges and were performed within a frame of the international collaboration, were summarized in a paper [26].

Other experimental studies, which concerned high-power plasma streams interactions with samples made of different tungsten grades and were carried out in a frame of the Polish-Ukrainian scientific collaboration, were also summarized in a paper [27].

Many experimental efforts have concerned an analysis of data obtained during optical emission spectroscopy (OES) of plasma streams generated in a PF-1000U facility without and with the additional gas puffing. The detailed analysis of the recorded spectra enabled changes in the D_α line profile to be determined (Fig. 8) and used for estimates of changes in the electron concentration [28].

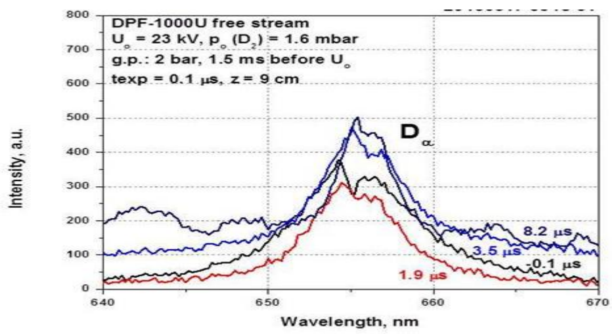

Fig. 8. D_α-line profiles observed at different instants after the current dip for a PF-1000U experiment performed with the gas-puffing (1.5 ms before discharge initiation)

Results of other experimental research on intense plasma streams interactions with targets made of tungsten, those were obtained within the PF-1000U facility, were analyzed by a joint Polish-Ukrainian team. Particular attention was focused on identification of tungsten spectral lines and determination of mass-losses caused by the irradiation of the investigated W-samples [29].

The Polish-Ukrainian team elaborated also results of OES measurements performed during a free propagation of plasma streams within the PF-1000U facility and during their interactions with CFC-samples. Many CII and CIII spectral lines were recorded (Fig. 9) and enabled the erosion dynamics to be estimated [30].

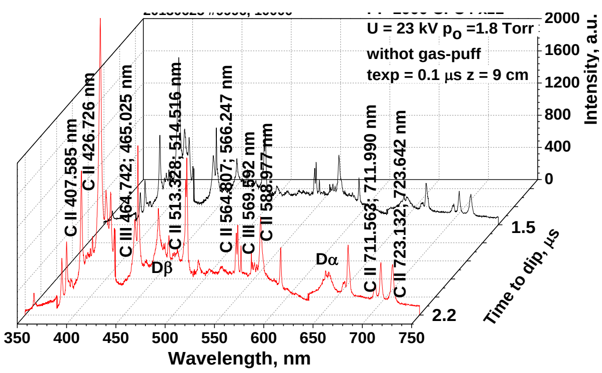

Fig. 9. Temporal changes in the optical spectrum measured near the CFC-target surface in the PF-1000U

Optical emission spectra from plasma streams and plasma produced from different targets in the PF-1000U experiments were also presented at a Joint ICTP-IAEA Advanced School in Trieste [31].

Another task concerned research on interactions of plasma streams with CFC targets within an RPI-IBIS facility. In addition to optical spectra there were investigated surface changes of the irradiated targets.

To study morphology of the irradiated CFC samples, their surfaces were analysed also by means of an energy dispersive spectroscopy (EDS) technique. The obtained EDS images showed that upon the irradiated target surface there are deposited also many impurity ions, e.g., ions from the applied metal electrodes [32].

The results of the earlier studies of plasma interactions with pure (99.95 %) tungsten targets, those were obtained in the PF-1000U facility, were summarized and analysed. Particular attention was focused on comparison of different parts of the optical spectra (Fig. 10).

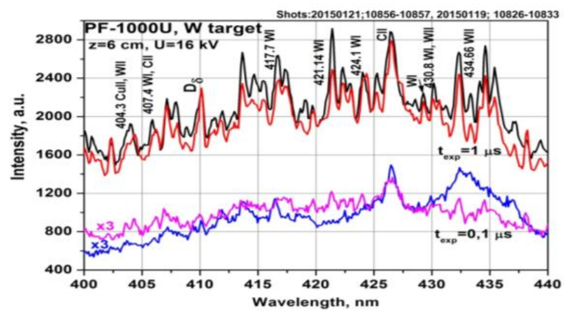

Fig. 10. Optical spectra in the range of λ = 440...480 nm, recorded near the irradiated W-target surface at different exposition times (0.1 and 1 μs), and obtained during 4 plasma discharges (marked by different colours)

To investigate changes in the target surface morphology, which were induced by plasma streams, an additional analysis was performed by means of an optical microscope [33].

Our comments on the studies reported above can be formulated as follows: 1. The OES measurements are very useful to observe dynamics of plasma radiation and to identify various ion species; 2. The plasma density can be estimated from an analysis of selected spectral lines if re-absorption effects can be neglected; 3. To estimate a density of dense and multi-component plasma, which is formed at a surface of the irradiated target, one should use other methods e.g. laser interferometry; 4. To study plasma interactions with solid targets one should apply different diagnostic methods, e.g. AFM, SEM and EDS.

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, as developed at the NCBJ and used in several tokamaks, might also be applied for fast electron measurements in stellarators; 2. NTDs are convenient tools for recording fast ions (including fusion products), but these detectors require time-consuming calibration measurements; 3. The OES methods are widely applied in different plasma experiments, but to determine an electron density in multi-species plasmas at surfaces of the irradiated targets one should use other techniques, e.g. laser interferometry.

The described plasma studies, as performed in a frame of the scientific collaboration of the NCBJ, IFPiLM and KIPT teams, supplied important information about plasma-streams and plasma-interactions with various materials. Hence, this collaboration should be continued.

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НАИБОЛЕЕ ЗНАЧИМЫЕ РЕЗУЛЬТАТЫ ПО ИЗУЧЕНИЮ ВЫСОКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ В НЦЯИ ПОЛЬШИ

M.J. Sadowski, J. Żebrowski

Представлены самые важные результаты экспериментов по изучению высокотемпературной плазмы, которые проводились в НЦЯИ Польши с 2014 года. Основные научные цели – это изучение быстрых электронов, ионов, нейтронов, рентгеновского излучения на различных плазменных установках, таких как PF-, RPI-, ICF-токамаки, а также исследования высокотемпературных плазменных потоков и их взаимодействия с различными материалами. Первая часть представляет мнение авторов об экспериментальных изучениях генерации убегающих быстрых электронов в токамаках Compass (Прага) и FTU (Fraskati. Вторая часть включает комментарии по применению детекторов ядерных частиц для изучения быстрых ионов и продуктов ядерной реакции $p^{11}B$ в экспериментах на установке PALS (Прага). Следующая часть – это описание измерений рентгеновского излучения, ионов и электронов в установках типа плазменный фокус (ПФ). Последняя часть суммирует исследование взаимодействия плазменных потоков с вольфрамом на установке PF-1000U и CFC на RPI-IBIS. Далее следуют предложения о дальнейших теоретических и экспериментальных исследованиях.

НАЙБІЛЬШ ВАГОМІ РЕЗУЛЬТАТИ З ВИВЧЕННЯ ВИСОКОТЕМПЕРАТУРНОЇ ПЛАЗМИ В НЦЯД ПОЛЬЩІ

M.J. Sadowski, J. Żebrowski

Представлено найважливіші результати експериментів по вивченню високотемпературної плазми, що проводились в НЦЯД Польщи з 2014 року. Основні наукові цілі – це вивченя швидких електронів, іонів, нейтронів, рентгенівського випромінювання на різних плазмових пристроях, таких як ПФ-, RPI-, ICF-токамаки, а також дослідження високотемпературних плазмових потоків та їх взаємодії з різними матеріалами. Перша частина представляє думку авторів щодо експериментальних вивчень генерації швидких електронів в токамаках Compass (Прага) та FTU (Frascati). Друга частина включає коментарії із застосування детекторів ядерних часток для вивчення швидких іонів та продуктів ядерної реакції $p^{11}B$ в експериментах на пристрої PALS (Прага). Наступна частина – це опис вимірювань рентгенівського випромінювання, іонів та електронів в пристроях типу плазмовий фокус (ПФ). Заключна частина підсумовує дослідження взаємодії плазмових потоків з вольфрамом на ПФ-1000U та CFC на RPI-IBIS. Далі йдуть пропозиції щодо наступних теоретичних та експериментальних досліджень.