PASSIVE CORPUSCULAR DIAGNOSTICS OF CHARGED PARTICLES EMISSION FROM HIGH-TEMPERATURE PLASMA EXPERIMENTS

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This invited lecture presents results of research on charged particles emitted from high-temperature plasmas, which was performed by means of corpuscular-diagnostic techniques at NCBJ (former IPJ) during recent years. The studies were performed by joint teams at different facilities, e.g. RPI-IBIS and PF-360 machines at NCBJ, and PF-1000 facility at IFPiLM. To study spatial and energetic structure of fast ion streams emitted from RPI- and PF-type discharges the use was made of nuclear track detectors (NTDs), ion pinhole cameras and Thomson-type analyzers. The appearance of many ion micro-beams was confirmed and detailed mass- and energy-analysis of them was carried out. For time-resolved ion measurements the use was made of miniature scintillation detectors coupled with fast photomultipliers. Fast electrons from RPI- and PF-facilities were investigated with a magnetic analyzer, and energy spectra of them were determined. Time-resolved measurements of fast electrons were also performed in some tokamaks by means of Cherenkov-type detectors. Recently, new probes have been designed for ion studies in MCF experiments, e.g. COMPASS-U tokamak in Prague. Some research on passive corpuscular diagnostics of plasma was realized in a frame of the Polish-Ukrainian scientific collaboration.

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INTRODUCTION

A development of appropriate diagnostic techniques is of primary importance for basic plasma studies and fusion-oriented research. Particular role is played by passive corpuscular measurements, because they can deliver information about fast electrons and ions (including fusion products) without disturbing plasma itself. Efforts connected with the development and applications of different diagnostic techniques are often realized in frames of international scientific collaboration programs. The scientific collaboration between the IPJ (now NCBJ) in Swierk, Poland, and the KIPT in Kharkov, Ukraine, was initiated in the 60s and it has been run for many years [1-5].

The main aim of this lecture, given at the International Seminar in Kharkov, on Jan. 16-17, 2013, in memory of Prof. V.I. Tereshin, has been to present some important results of research on passive corpuscular diagnostics of high-temperature plasmas. Results of the collaboration in the field of the optical spectroscopy of plasma have been reported in another talk.

1. STUDIES OF FAST ION EMISSION FROM RPI FACILITIES

Multi-Rod Plasma Injectors (RPI) have been developed and studied in Poland for many years [1, 6]. Such facilities are equipped with coaxial electrodes composed of many thin parallel rods, and operated usually with the working gas puffing at a low initial pressure. They can produce pulsed plasma-ion streams which contain relatively small amount of impurities, and can be used for fusion studies as well as for material engineering.

A general view of an RPI device, which has been used at NCBJ for many years, is presented in Fig. 1.

Fig. 1. Experimental chamber of the RPI-IBIS facility

To study the spatial and energetic structure of fast ion streams emitted from RPI facilities the use is often made of nuclear track detectors (NTDs). Such detectors are placed directly upon appropriate supports or inside ion pinhole cameras and Thomson-type analyzers. The NTDs are very convenient diagnostic tools, because they are selectively sensitive to ions, which produce in these detectors tracks (micro-craters) visible after appropriate chemical etching. To make the NTDs applicable for accurate ion measurements they should be calibrated with appropriate ions, e.g. by means of an accelerator. Since calibration characteristics can differ considerably, the calibration measurements must be performed for each detector batch [7].

Recent studies have shown that track diameters depend not only on ion parameters and etching conditions, but also a temperature of the NTDs during exposition and processing [8]. Therefore, the NTDs must be protected against over-heating, e.g. by the use of cooled supports.

During experimental studies with the RPI-IBIS facility there were performed detailed studies of the ion emission, and particular attention was paid to a micro-structure of the emitted plasma-ion streams [9-10], as presented in Fig. 2.
On the basis of ion images recorded behind different absorption filters it was possible to determine energies of the investigated ion beams. Recently, to investigate mass- and energy-spectrum of the ions emitted from the RPI-IBIS the use was made of a miniature Thomson spectrometer [10-11]. The measurements proved that the amount of impurity ions, e.g., Mo+ from the electrodes, is very low and the deuteron energy spectrum extends from a few keV to about 700 keV, with the maximum at about 40 keV. A new aim appeared to be time-resolved measurements of the ions (mostly deuterons). They have been performed by means of miniature scintillation detectors placed in different places upon the deuteron parabola. The recorded signals showed that the deuterons of the chosen energy are emitted not as a single pulse, but as several spikes [6, 12], as shown in Fig. 3.

An actual problem for the ion-beams studies appears to be a detailed quantitative analysis of the ion parabolas and a performance of time-resolved measurements with an increased number of miniature detectors, to be placed upon parabolas corresponding to different ion species.

Another aim is a computer simulation of the ion emission from RPI-discharges. So far, some computer modeling of electric- and magnetic-fields, as well as ion trajectories in the RPI-IBIS facility, has been performed on the basis of a single particle model and Monte-Carlo method [13-14]. Exemplary results are presented in Figs. 4 and 5.

An important aim is also the computer simulation of ion images for the chosen distances from the electrode outlets. To compute the real ion images one must take into account a micro-structure of the ion streams, what requires a 3D approach.

In general, additional experimental studies of the ion emission from the RPI-facilities and more detailed theoretical analyses are needed.

2. STUDIES OF ION AND ELECTRON EMISSION FROM PF FACILITIES

The second group of investigated devices constituted Plasma-Focus (PF) facilities which are known as sources of intense electromagnetic and corpuscular pulses. In fact, the PF machines have been investigated in Poland for many years. A picture of an old (but still used) PF-360 facility is shown in Fig. 6.

An important aim is also the computer simulation of ion images for the chosen distances from the electrode outlets. To compute the real ion images one must take into account a micro-structure of the ion streams, what requires a 3D approach.

In fact, the studies of the ion emission were started many years ago [1], and the recent important results were reported in several papers, e.g. [15-17].

Fig. 2. Ion pinhole image recorded on PM-355 detector with (right part) and without (left part) 0.75-μm Al filter for the RPI-IBIS discharge in a so-called fast mode

Fig. 3. Correlation of deuteron pulses with the voltage waveform from the RPI-IBIS experiment

Fig. 4. Distribution of electric- and magnetic field lines in the RPI-IBIS facility

Fig. 5. Computed trajectories of 200-keV deuterons inside the RPI-IBIS facility [14]

Fig. 6. Experimental chamber and some diagnostic equipment at the PF-360 facility
Recently, to investigate plasma-ion streams from the PF-360 facility the use was made of new ion-pinhole cameras equipped with NTDs and some absorption filters. An example of the ion image is presented in Fig. 7.

![Ion pinhole image obtained in PF-360 experiment with and without an absorption filters (left), and a profile of the ion stream measured along the broken-line](image)

During recent PF-360 experiments attention has been paid to time-resolved ion measurements by means of miniature scintillation detectors located in the image plane of the new pinhole camera [17]. An example is shown in Fig. 8.

![Signals from an X-ray and neutron detector in a comparison with the X-ray- and ion-signals from two scintillators in the pinhole camera, that was placed 50 cm from the PF-360 electrode outlets, at 45° to the z-axis](image)

Attention has also been brought to an explanation of the time-integrated ion images, and a comparison of ion pinhole images from PF-1000 and PF-360 experiments, as shown in Fig. 9.

![Ion pinhole images from PF-1000 (left) and PF-360 (right), taken without and with an absorption filter](image)

The analyzed ion pinhole images confirmed that the fast ions are emitted in many micro-beams along the z-axis and at some angles to that. Considering the actual problems, the complex (multi-spike) character of the ion emission [11] and its quasi-periodical structure (shown in Fig. 9) must still be investigated in more details.

As regards the electron emission, measurements were performed by means different magnetic analyzers, e.g. in the old MAJA-PF machine the use was made of a 180° magnetic analyzer, and the electron energy spectrum from a few keV to about 600 keV was recorded.

For time-resolved measurements of electrons in PF-1000 experiment small scintillation detectors were located in different points of the image plane, and electron signals from those measuring channels were recorded [18], as shown in Fig. 10.

![Neutron signal from a detector placed 8 m down-stream in the PF-1000 facility and electron signals from different scintillation detectors of the magnetic analyzer](image)

Recently, more accurate measurements of the electron beams have been performed up-stream and down-stream the PF-1000 facility [16]. Those measurements proved that electrons emitted in the upstream direction have energies from about 60 to about 600 keV, while weaker electron beams emitted in the downstream direction have energies ranging to 200 keV only.

For time-resolved measurements of electrons in MAJA-PF and PF-1000 experiments the use was also made of Cherenkov-type detectors. Using different radiators (e.g. diamonds or Rutile crystals) with various metal filters it was possible to investigate temporal correlations of the e-signals with other phenomena in PF-discharges [19]. Considering the actual problems one should perform more detailed investigation of the ion- and electron-beams emissions in both directions along the symmetry axis of PF facilities.

3. DEVELOPMENT OF ELECTRON AND ION PROBES FOR MCF EXPERIMENTS

A very important diagnostic problem appeared to be measurements of fast “ripple-born” and “run-away” electrons in tokamaks [20]. For this purpose the NCBJ team elaborated special probes equipped with Cherenkov-type detectors. An example of such a probe is shown in Fig. 11.

The developed Cherenkov probes were successfully used in several tokamak experiments, e.g. CASTOR in Prague [21], ISSTOK in Lisbon [22], and TORE-SUPRA in Cadarache [23]. An example of the electron signals, as recorded in the TORE-SUPRA [24], is shown in Fig. 12.
The development of the Cherenkov probes was reported in details at the Alushta 2012 conference [11]. The NCBJ team is now preparing new Cherenkov probes for the next series of experiments. As regards the present problems, the Cherenkov signals from different tokamaks should be analyzed theoretically in order to explain population and localization of the observed electron streams.

For different tokamak experiments the separate aim was to develop corpuscular diagnostics of ions, and in particular charged fusion products, e.g. fast protons from D-D reactions. Several years ago some efforts were undertaken to design and use an ion pinhole camera for TEXTOR experiments [25]. An example of those measurements is shown in Fig. 13.

In 2011 the NCBJ team started to realize a domestic contract concerning the construction of two new probes for ion measurements in tokamaks. The first probe should contain an ion pinhole camera with a rotating drum and several NTDs, those could be irradiated during a single tokamak discharge. After etching of the irradiated NTDs one might obtain information about temporal changes in the ion emission. The second probe should contain a miniature Thomson-type spectrometer in order to perform mass- and energy-analysis of the ions investigated at the plasma boundary inside a tokamak chamber. Simplified schemes of the both probes were presented at the 1st NCBiR Seminar in Cracow [26] and the Alushta-2012 conference [11].

Attention has been paid to an analysis of the expected exploitation conditions for such probes, i.e. dimensional and mobility requirements, estimated thermal loads and shielding against electro-magnetic interference. Possible laboratory tests of such probes in accessible tokamaks have also been considered. A detailed analysis has been carried out for the COMPASS-U tokamak in Prague [27], according to a request of our Czech partners. High-vacuum connectors and electro-mechanical drives, those are needed for positioning of probes inside the tokamak chamber, have been designed, as shown in Fig. 14.

Recently, to prepare for the use of the new probes in tokamak experiments some efforts have been undertaken to perform computer simulation of ion trajectories under determined experimental conditions in COMPASS-U. An example of the computer modeling is presented in Fig. 15.
Other efforts have concerned the computer simulation of the ion images to be recorded with a pinhole probe in the COMPASS-U. An example is presented in Fig. 16.

![Fig. 16. Pinhole camera and computed efficiency of 3 MeV protons on the chosen detector sector](image)

If plasma discharges with deuterium are not performed in the COMPASS-U, new measurements of fusion protons will be carried out in another tokamak. The actual problem is to construct the new movable probe with measuring heads (according to the design), and to perform some laboratory tests in available experimental facilities.

### SUMMARY AND CONCLUSIONS

This lecture can be summarized as follows:

1. During studies of the ion and electron emission from different RPI and PF-type facilities, as operated at NCBJ (former IPJ) in Swierk and KIPT in Kharkov, various diagnostic methods were developed, and in particular passive corpuscular diagnostic techniques.

2. Successful applications of these techniques enabled to determine characteristics, those of primary importance for basic plasma physics and application-oriented research, e.g. information about spatial structure of pulsed ion streams, their mass- and energy-distributions, etc.

3. The Polish-Ukrainian scientific collaboration delivered valuable data reported in joint presentations at international conferences and numerous publications in various scientific journals, e.g. [1-6, 16-17].

4. Recently, efforts have been undertaken to develop new probes for MCF experiments and it would be reasonable to continue the scientific collaboration of research teams from NCBJ and KIPT.

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### REFERENCES


ПАССИВНАЯ КОРПУСКУЛЯРНАЯ ДИАГНОСТИКА ЭМИССИИ ЗАРЯЖЕННЫХ ЧАСТИЦ
В ВЫСОКОТЕМПЕРАТУРНЫХ ПЛАЗМЕННЫХ ЭКСПЕРИМЕНТАХ

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Представлены результаты исследований заряженных частиц эмиттированных из высокотемпературной плазмы, которые в течение последних лет были получены с помощью корпускулярно-диагностической техники в НЦЯФ (предыдущий ИЯП). Исследования были выполнены объединенными группами на различных установках, например, RPI-НИИС и PF-360 в НЦЯФ, и установке PF-1000 в ИФПиЛМ. Изучение пространственной и энергетической структуры потоков быстрых ионов, испускаемых из разрядов в RPI и PF, было проведено с помощью ядерных трековых детекторов (ЯТД), пин-хол-камер и анализаторов Томсона. Было подтверждено появление многих ионных микропучков и выполнены детальный массовый и энергетический анализ. Для ионных измерений с разрешением во времени изготовлен миниатурный сцинтилляционный детектор, соединенный с быстрым фотоумножителем. Были определены энергетические спектры быстрых электронов. Исследования проводились на RPI и PF с помощью магнитных анализаторов. В некоторых токамаках также были выполнены измерения быстрых электронов с разрешением во времени с помощью детекторов Черенкова. Недавно новые зонды были разработаны для исследования ионов в экспериментах МУС, например, для токамака COMPASS-U в Праге. Некоторые исследования пассивной корпускулярной диагностики плазмы реализованы в рамках польско-украинского научного сотрудничества.

ПАСИВНА КОРПУСКУЛЯРНА ДИАГНОСТИКА ЭМИСІЇ ЗАРЯДЖЕНИХ ЧАСТИЦ
У ВИСОКОТЕМПЕРАТУРНИХ ПЛАЗМОВИХ ЕКСПЕРИМЕНТАХ

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Представлено результаты досліджень заряджених частинок, емітованих з високотемпературної плазми, які протягом останніх років були отримані за допомогою корпускулярно-діагностичної техніки в НЦЯФ (колишній ІЯП). Дослідження були виконані об’єднаними групами на різних установках, наприклад, RPI-НИИС і PF-360 у НЦЯФ, і установці PF-1000 в ИФПиЛМ. Вивчення просторової і енергетичної структури потоків швидких іонів, що випускаються із розрядів в RPI і PF, були проведено за допомогою ядерних трекових детекторів (ЯТД), пін-хол-камер і аналізаторів Томсона. Була підтверджена появи багатьох іонних микропучків та виконано детальний масовий і енергетичний аналіз. Для іонних вимірювань з роздільною здатністю в часі був виготовлений мініатурний сцинтилляційний детектор, з’єднаний з швидким фото- помножувачем. Були визначені енергетичні спектри швидких електронів. Дослідження проводились на RPI і PF за допомогою магнітних аналізаторів. У деяких токамаках також були виконані вимірювання швидких електронів з дозволом у час за допомогою детекторів Черенкова. Недавно нові зонди були розроблені для дослідження іонів в експериментах МУС, наприклад, для токамака COMPASS-U у Празі. Деякі дослідження пасивної корпускулярної діагностики плазми були реалізовані в рамках польсько-українського наукового співробітництва.