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Selected methods of electron- and ion-diagnostics in tokamak scrape-off-layer

Marek J. Sadowski

Abstract. This invited paper considers reasons why exact measurements of fast electron and ion losses in tokamaks, and particularly in a scrape-off-layer and near a divertor region, are necessary in order to master nuclear fusion energy production. Attention is also paid to direct measurements of escaping fusion products from D-D and D-T reactions, and in particular of fast alphas which might be used for plasma heating. The second part describes the generation of so-called runaway and ripple-born electrons which might induce high energy losses and cause severe damages of internal walls in fusion facilities. Advantages and disadvantages of different diagnostic methods applied for studies of such fast electrons are discussed. Particular attention is paid to development of a direct measuring technique based on the Cherenkov effect which might be induced by fast electrons in appropriate radiators. There are presented various versions of Cherenkov-type probes which have been developed by the NCBJ team and applied in different tokamak experiments. The third part is devoted to direct measurements of fast ions (including those produced by the nuclear fusion reactions) which can escape from a high-temperature plasma region. Investigation of fast fusion-produced protons from tokamak discharges is reported. New ion probes, which were developed by the NCBJ team, are also presented. For the first time there is given a detailed description of an ion pinhole camera, which enables irradiation of several nuclear track detectors during a single tokamak discharge, and a miniature Thomson-type mass-spectrometer, which can be used for ion measurements at plasma borders.

Key words: diagnostics • electrons • ions • fusion products • probes • tokamak

M. J. Sadowski
Plasma Studies Division (TJ5),
National Centre for Nuclear Research (NCBJ),
7 Andrzeja Soltana Str., 05-400 Otwock/Swierk, Poland
and Division of Magnetised Plasma,
Institute of Plasma Physics and Laser Microfusion (IPPLM),
23 Hery Str., 01-497 Warsaw, Poland,
Tel.: +48 22 718 0537, Fax: +48 22 779 3481,
E-mail: marek.sadowski@ncbj.gov.pl

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Introduction

It is well known that high-temperature plasma in tokamaks is never completely stable [1]. One can observe different instabilities, e.g. sawtooth oscillations [2], Alfven eigenmodes [3], etc. There also appear various internal turbulences [4]. As a result, the transport of heat and particles in tokamak plasmas happens more quickly than expected from a classical theory. It means that this transport is strongly turbulent [5]. Therefore, the controlling turbulence is necessary to reduce losses of heat and particles from tokamaks.

In general, turbulences in tokamaks as well as in astrophysical plasma can be described by a gyrokinetic theory, i.e. kinetic theory averaged over the fast Larmor motion (gyro-motion) of charged particles [5, 6]. It enables plasma behaviour in chosen cases to be simulated, as shown in Fig. 1.

One can easily notice that the plasma torus of a circular or D-shaped cross section, which is produced within a tokamak, is usually separated from chamber walls by a near-wall region (so-called scrape-off-layer), as shown in Fig. 1 (right). Since impurity ions originate mostly from the internal parts of tokamak-chamber (e.g., limiters, antennas or walls), the scrape-off-layer (SOL) can be used

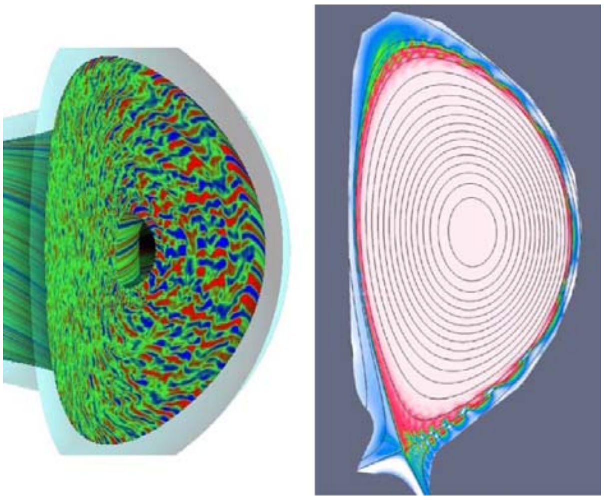

Fig. 1. (Left) Computer simulations of turbulence in a D-shaped tokamak (adapted from [6]); (right) the image of plasma in the vertical cross section of the ITER chamber, showing magnetic field surfaces, a scrape-off-layer and a divertor region. (Picture by G. Huijsamans, ITER organization).

to extract them along magnetic field surfaces to the a divertor system, where they can be neutralised and pumped out. Achieving conditions in which a positive energy balance can be obtained, requires maintaining plasma at high density and temperature for a few hours or even in steady state. Therefore, the active control of plasma instabilities, which cause energy losses or bring the hot plasma in close contact with the chamber walls, is necessary. The respective plasma regimes of operation must also ensure that the heat produced in the plasma is redistributed on the walls and divertor targets by radiation, and too large localised heat loads are avoided. Hence, in some cases there is applied an injection of deuterium and a heavy-gas admixture (e.g., nitrogen) in order to moderate the divertor temperature [7]. It should here be noted that heat-exhaust systems in future tokamaks must be capable of withstanding the large heat and particle fluxes expected in a fusion power plant.

In general, the understanding of turbulence phenomena is of primary importance and it requires development not only theory and computer simulations, but also experimental measurements of fast electrons and ions escaping from tokamak plasma.

Considering energetic ions, another important problem is connected with charged fusion-products generated in tokamak discharges, and in particular fast protons, ^{3}He, tritons (from D-D reactions) and alphas (from D-T fusion). The performed computer calculations showed that the confinement of alphas for further plasma heating can be realized under specific conditions in large tokamaks only [1]. To estimate efficiency of fast ion confinement, the simulations require analysis of multi-dimensional distribution functions for multi-species plasma and they take many computer hours. In any case, one needs also experimental studies of the fusion products escaping from plasma.

This paper describes selected diagnostic techniques which can be applied for measurements of fast electrons and ions in tokamak experiments.

Studies of fast ripple-born and runaway electrons

The initial generation, heating and confinement of plasma in tokamaks are achieved by driving a current inside a ring-shaped vacuum chamber filled with a working gas (e.g. deuterium or deuterium–tritium mixture) under a low pressure. The induced toroidal electric field leads also to the generation of so-called runaway electrons, since for electrons of high energy the friction of collisions with plasma does not compensate the externally induced electrical force [8]. Therefore, some electrons may be accelerated and run away in the phase space, and escape from the magnetic trap. Another mechanism of the fast electrons generation is connected with imperfections of the toroidal magnetic field, which are responsible for so-called ripple-born electrons [9].

During tokamak experiments intense streams of fast electrons can induce significant damages of chamber walls, as observed in the Tore Supra facility, France [9]. For these reasons the generation of high-energy runaway electrons has been a subject of extensive experimental studies, e.g., by observations of electron-induced X-rays or synchrotron radiation [10]. The main disadvantage such techniques has been non-local character of measurements, i.e. impossibility to determine places where the fast electron streams appear.

During recent years a modern electron diagnostic technique, which was based on use of the Cherenkov effect, has been developed [11]. This technique has made it possible to perform direct observations of fast electron streams, with an excellent spatial and temporal resolution. A prototype Cherenkov probe was designed and successfully applied by the NCBJ team for electron measurements in the small CASTOR tokamak in Prague [12]. That probe had a quartz-rod radiator placed inside a metal shielding and coupled optically with a fast photomultiplier. Considerable differences were observed in the Cherenkov signals recorded for high-density and low-density discharges. Interesting results obtained in Prague were additional motivation for the construction and use of Cherenkov detectors in the ISTTOK tokamak in Lisbon [13, 14]. Different models of the Cherenkov-type probe have been designed and manufactured especially for ISTTOK experiments, as shown in Fig. 2.

The most important results of fast electron measurements, which were performed in the ISTTOK tokamak, have been reported in several papers, e.g. [13, 14]. Similar to the earlier observations in the CASTOR tokamak, the Cherenkov signals recorded in the ISTTOK facility, at different radial positions of the probe, have not always been correlated with the hard X-ray signals, which were measured with other detectors, as shown in Fig. 3.

One can easily notice that the Cherenkov signals (i.e. the fast electron beams) were recorded mostly at instants when a discharge current was amounting the maximal value or was decreasing considerably.

The Cherenkov probes, which were initially used in the CASTOR and ISSTOK experiments, have subsequently been modernized and adopted for multi-channel measurements. In particular, a 4-channel

Fig. 2. Different versions of the Cherenkov-type detectors designed especially for fast electron measurements within the ISTTOK tokamak; (top) a single-channel detector with an AlN radiator; (middle) a 4-channel detector with AlN radiators, (bottom) a new single-channel detector with a diamond radiator.

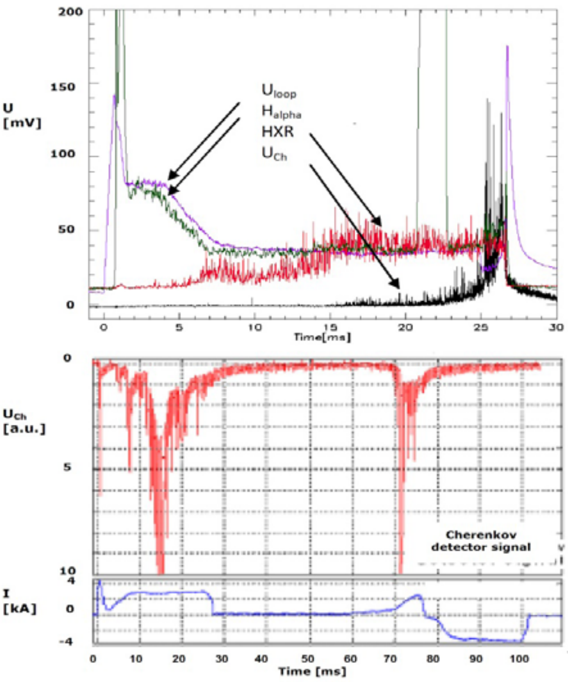

Fig. 3. (Top) Comparison of Cherenkov signals (U_{Ch}) with hard X-ray emission recorded in the old CASTOR experiment; (bottom) a comparison of the Cherenkov signals with the discharge current measured in the ISTTOK experiment.

Cherenkov probe with diamond radiators has been designed especially for TORE-SUPRA experiment in Cadarache [15]. Some results are presented in Fig. 4.

The Cherenkov probes, which were used within the TORE-SUPRA tokamak, have shown macroscopically reproducible electron-induced signals at the determined probe positions (during its downwards and upwards motion). This observation could

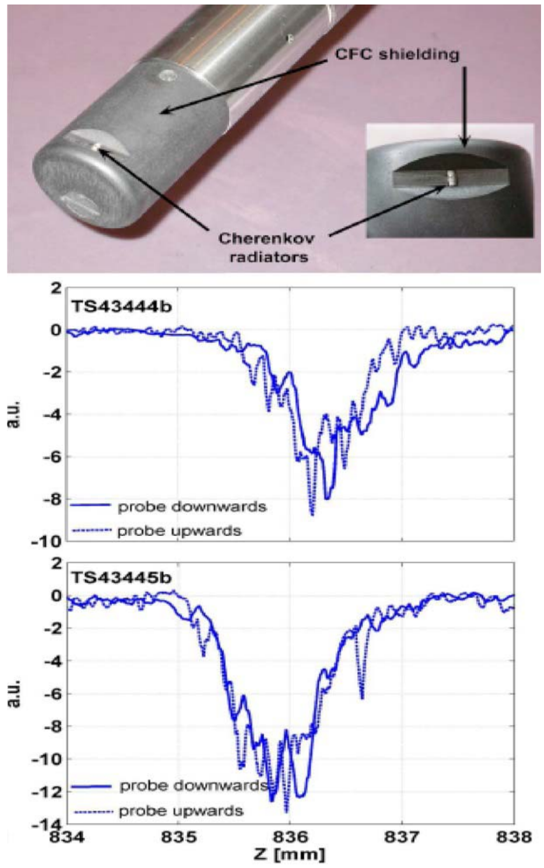

Fig. 4. Cherenkov-type probe with four diamond radiators, which was used for fast electron measurements during TORE-SUPRA experimental campaign in 2008 (top), and electron signals recorded in one measuring channel for two successive discharges, during the probe insertion and withdrawal, which were converted into a dependence of the signal amplitude on the probe position.

be interpreted as a result of the appearance of fast electrons in the TORE-SUPRA scrape-off-layer (SOL), when a level of the lower hybrid heating (LHH) and ion cyclotron resonance heating (ICRH) was high enough. It was, however, noted that the applied Cherenkov probe (called the DENEPR) could not record the whole electron stream because of geometrical limitations (the radiators were located in a slit cut side-on the probe shielding). The detailed description of theoretical interpretation and experimental observations can be found in a paper [16].

Valuable information from the ISTTOK and TORE-SUPRA experiments with the use of prototype Cherenkov probes, has motivated the NCBJ team to design and use 4-channel probes equipped with radiators, which might be protected with absorption filters of different thickness. Such Cherenkov probes made it possible to perform a rough energy analysis of the investigated electron streams, as shown in Fig. 5.

One can easily see that the 4-channel Cherenkov probe has proved capability to obtain information about fast electrons in different energy ranges simultaneously. In the considered case the similarity and close correlation of the electron signals from all channels could be treated as a confirmation of the theoretical model assuming the generation

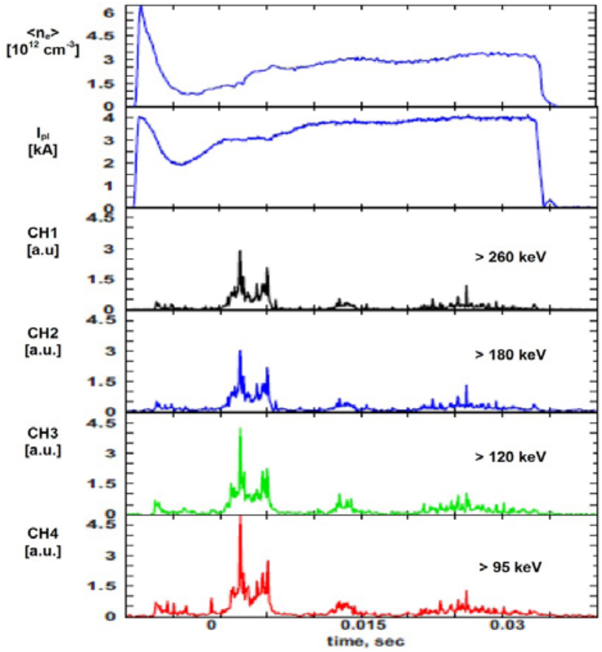

Fig. 5. (From top to bottom). Averaged plasma density, discharge current and electron-induced signals from four different channels of the Cherenkov-type probe, as recorded during one cycle of a discharge within the ISTTOK tokamak [14].

of quasi-mono-energetic electron streams due to the Dreicer mechanism [14]. It should, however, be mentioned that recent experiments within the ISTTOK tokamak have shown that using several Cherenkov probes (at different angular and radial positions) one must take into consideration their mutual interactions. A probe inserted too deeply into the plasma region can overtake a role of a limiter.

The described measuring technique is still under development, and new versions of the Cherenkov probes are under construction and calibration. One can conclude that such probes can be applied not only in tokamaks, but also in stellarators.

Studies of charged fusion products

In order to investigate fast primary ions and charged fusion products, which have relatively high energies, one can apply different diagnostic techniques, e.g., Thomson scattering, charge–exchange recombination spectroscopy, pellet technique, etc. To measure ions in tokamak boundary plasma one can also use different probes, e.g. retarding field analysers, Sniffer probes, plasma ion-mass spectrometers, etc. [17]. Considering different corpuscular diagnostic methods one should also mention active techniques, which use appropriate ion beams for plasma probing, but such systems are relatively complex and difficult to be applied within large tokamaks.

It should be noted that very useful diagnostic techniques appeared to be electric probes, which have been designed and applied for the CASTOR tokamak [18]. In that case the use was made of 1D- and 2D-arrays of Langmuir probes which are particularly applicable for spatially resolved measurements of the edge turbulence, and of the ball-pen- and emissive-probes useful for direct measurements of plasma potential. There were also developed and applied a so-called tunnel probe (for fast measurements of electron and ion temperature) and a Gundestrup-type probe (for measurements of parallel and perpendicular ion flows) [18]. Those probes enabled an efficient corpuscular diagnostics, which is necessary to understand physics of processes occurring within tokamaks at a plasma edge, such as the formation of transport barriers, the appearance of edge plasma turbulence, and the occurrence of plasma–wall interactions. Results of the experiments with small tokamaks have suggested that the probe techniques might be applied also for experimental studies in large fusion facilities, but in that case one must take into consideration high thermal loads upon probe surfaces. An additional issue is the correct and synonymous interpretation of electric probe measurements in the presence of strong magnetic fields.

Nevertheless, different probes have been developed and successfully applied in various tokamak experiments. In fact, most of the earlier time-resolved measurements of charged fusion products were done using solid-state surface barrier diodes, which could identify the ion species by measuring energy spectrum of the ions in the pulse-height analysis mode. Such detectors successfully identified the escaping 3-MeV protons, 1-MeV tritons and 14-MeV protons. Conventional semiconductors, however, could not be used for D-T alphas detection due to their relatively low neutron threshold equal to about 10^{12} neutrons/cm^2. To eliminate this difficulty, the use of a thin scintillation (phosphor) detector to measure alpha loss in D-T tokamaks was proposed many years ago [19].

In order to investigate charged fusion products in the TEXTOR facility, the IPJ (now NCBJ) team designed and used a pinhole camera with exchangeable solid-state nuclear track detectors (NTD), which could be placed upon a movable and cooled support [20], as shown in Fig. 6.

The placement of the described pinhole camera within the TEXTOR facility was chosen by taking into account computer simulations of D-D fusion products trajectories, an particularly those of the fast fusion-produced protons. The described pinhole camera was equipped with an NTD sample and fixed on the top of the water-cooled support, which was inserted into the TEXTOR chamber. It enabled the applied NTD samples to be irradiated at the chosen experimental conditions. Those samples were later-on etched under the standard conditions, and the obtained ion images were analysed with an optical microscope. Taking into consideration dimensions of the recorded ion tracks, and the known calibration characteristics of the applied NTD, it was possible to determine an energy distribution of the investigated fusion-protons, as shown in Fig. 7.

The described measurements delivered important information about the fusion-protons generation in the TEXTOR tokamak [20]. It should here be noticed that the NTD have well known advantages, e.g., they are selectively sensitive to ions and insensitive to electrons and electromagnetic radiation (up to very high doses), they enable quantitative

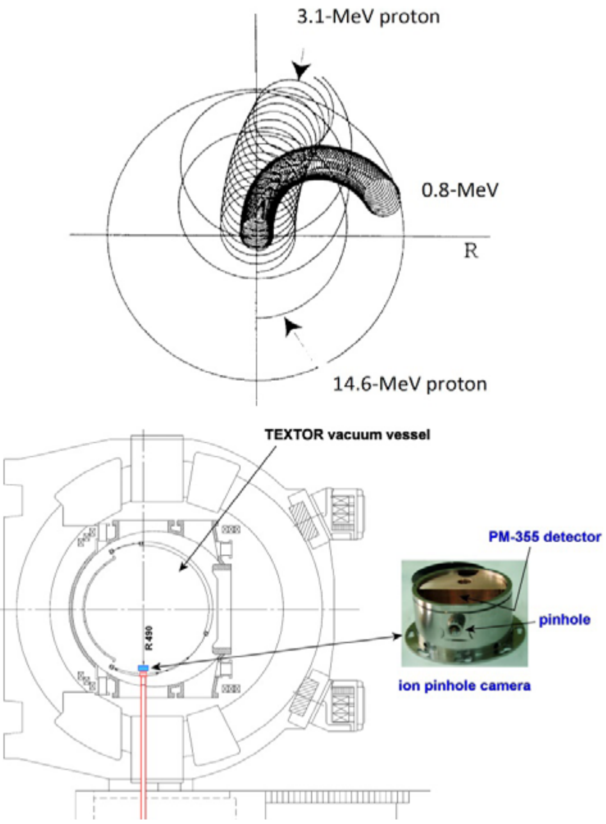

Fig. 6. (Top) Computed trajectories of 3.1-MeV and 14.6-MeV protons, and 0.8-MeV ^{3}He ions, which could reach plasma boundary in TEXTOR; (bottom) a cross section of the TEXTOR chamber and the position of an ion pinhole camera used for detection of the fusion products.

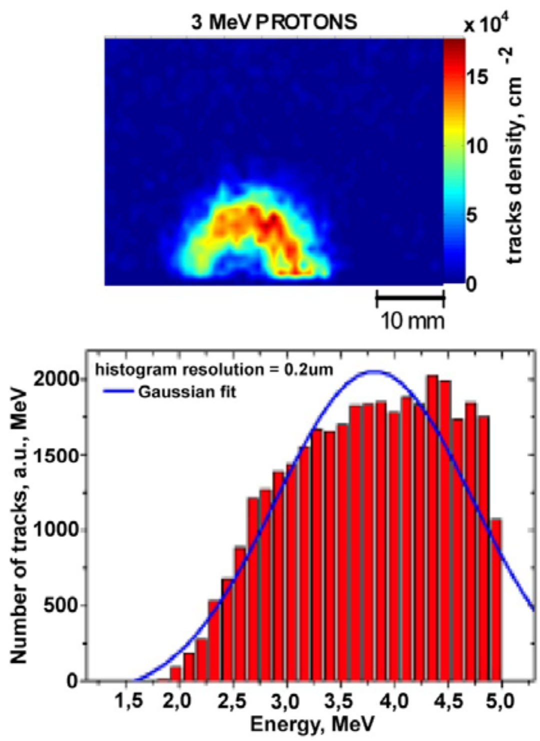

Fig. 7. (Top) Colour-enhanced image of the etched tracks of fusion protons recorded by means of the pinhole camera within the TEXTOR tokamak; (bottom) the proton energy distribution determined on the basis of tracks dimensions and calibration characteristics of the applied NTD.

measurements by counting ion tracks (above the determined energy threshold, and below the saturation limit), and they make it possible to estimate energy of ions by mean of appropriate absorption filters. Unfortunately, they have also some disadvantages, e.g., they require a relatively long-lasting etching procedure and time-consumable analysis with an optical microscope. The important disadvantage of the fusion products measurements with use of the NTD is their time-integrating character.

Taking into account that tokamak discharges can last relatively long time, several years ago [11] the author proposed to apply a pinhole camera with a rotating drum and several NTD samples, which might be exposed during a single discharge and etched after the experiment in order to get information about changes of the ion emission. Later on, for more accurate mass- and energy-analysis of ions it was also proposed to apply a miniature Thomson-type analyser with an appropriate magnetic shielding, which might be introduced into the SOL region. The construction of such ion probes is shown in Fig. 8.

Basing on the principles described above, the NCBJ team designed two miniature ion probes [21] and an universal manipulator [22], which could be equipped with a chosen probe. In the first step there was elaborated a detailed for-design documentation of the both measuring heads. The analysis concerned experimental conditions expected for the probes operation in different tokamaks, as well as Plasma-Focus facilities which might be used for preliminary tests of the ion probes. There were determined detailed requirements as regards the probe dimensions and their displacements during plasma experiments. Attention was paid to expected thermal loads upon the designed probes, as well as the selection of ap-

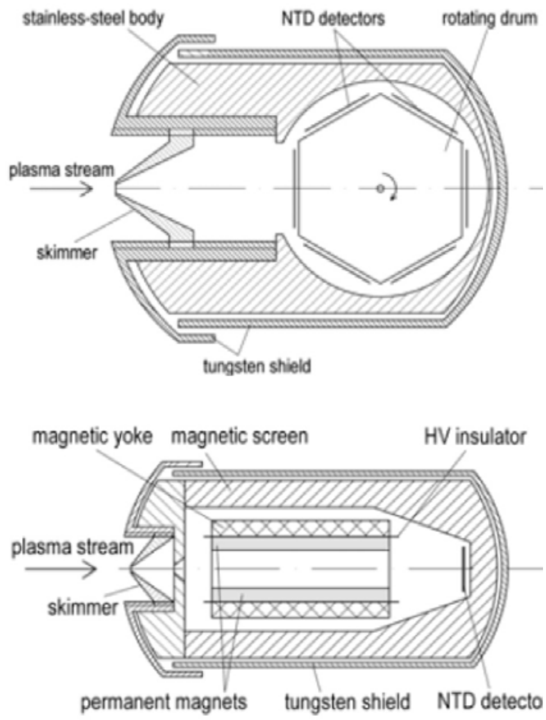

Fig. 8. Schematic drawings of the ion pinhole camera enabling exposition of several NTD during a single discharge (top) and of a miniature Thomson-type analyser (bottom).

propriate constructional materials, and other exploitation requirements (for laboratory tests and future tokamak experiments). Particular attention was also paid to an analysis of the exploitation conditions of the NTD during the planned ion measurements, as well as to limitations connected with strong electromagnetic interferences occurring during high-current plasma discharges. It was taken into consideration that the designed probes should have relatively small dimensions (to reduce disturbances of investigated discharges), appropriate electromagnetic screening of electrical circuits as well as magnetic shielding of the miniature Thomson analyser.

In order to reduce costs of the diagnostic equipment it was decided to design an universal manipulator, which might be used for fixing exchangeable measuring heads (probes). It has been equipped with an axially movable shaft driven with an electric step-motor. Inside that shaft there were located a rotating rod, which (in the case of the installation of the ion pinhole camera) could be driven by the second step-motor. To ensure high-vacuum conditions the use was made of stainless-steel parts, all-metal washers and high-vacuum feed-throughts, as shown in Fig. 9.

Simultaneously with the completing and assembling of the universal manipulator and both measuring heads, there was also performed an analysis of

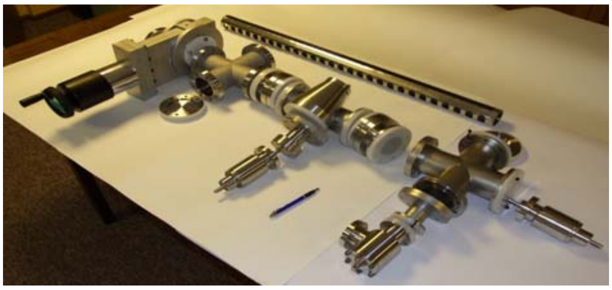

Fig. 9. Picture of mechanical parts collected before the assembling of an universal manipulator which was designed for positioning of the ion probes (measuring heads) inside an experimental chamber.

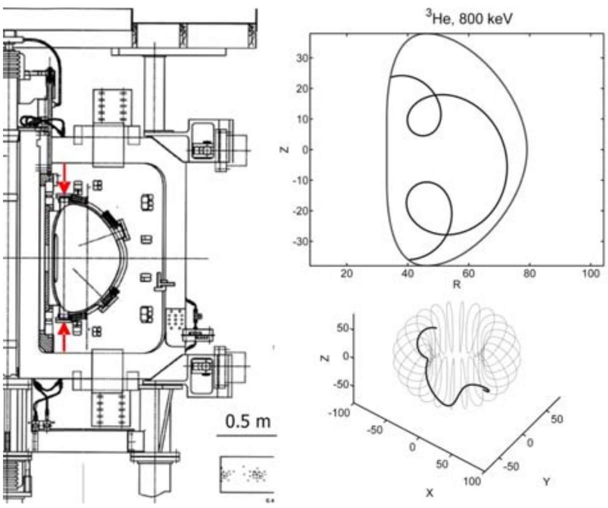

Fig. 10. (Left) Vertical cross section of the COMPASS facility and diagnostic ports (marked by arrows), which might be used for insertion of the ion probes; (right) projections of trajectories of 800-keV ^{3}He-ions, which might be generated by D-D fusion reactions in this tokamak [23].

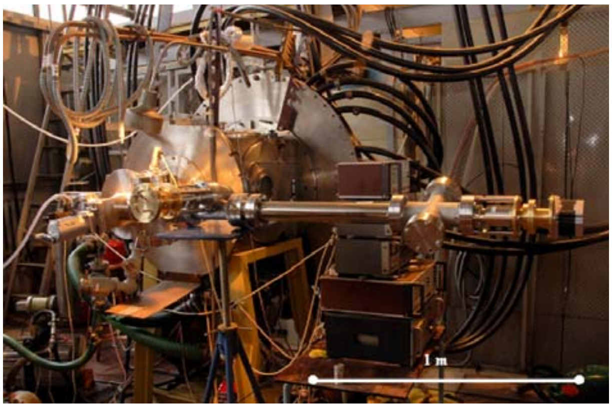

Fig. 11. Picture taken during laboratory tests of the universal manipulator and the ion pinhole camera at the RPI-IBIS facility which can generate intense plasma–ion streams.

possible applications of the constructed ion probes, e.g., in the COMPASS facility. The configuration of this tokamak was considered, some diagnostic ports were chosen, and corresponding computer simulations of fusion-products trajectories were carried out [22, 23], as shown in Fig. 10.

The performed analysis has shown that the ion pinhole probe might be applied in the COMPASS tokamak, provided that deuterium discharges are carried out and D-D reactions are sufficiently efficient.

In order to prepare the described ion probes for future experiments, they have been subsequently installed and tested in available experimental plasma facilities, which are operated at the NCBJ, as presented in Fig. 11.

The laboratory tests have proved that the described diagnostic equipment might be operated successfully and it is possible to record pinhole images of fast ions, which can be analysed quantitatively, as shown in Fig. 12.

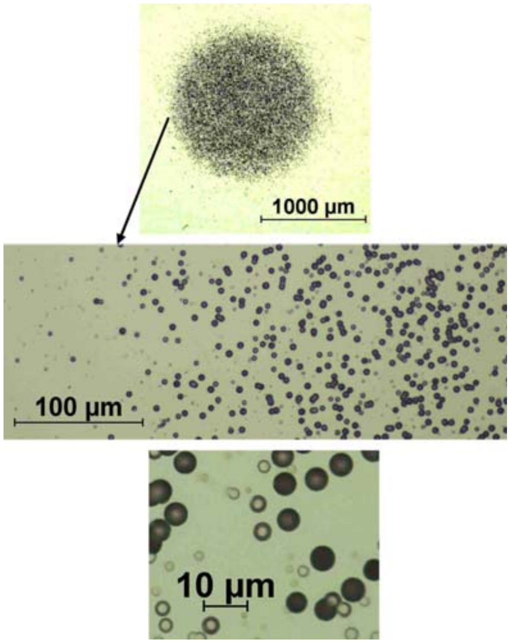

Fig. 12. Ion image (observed at different magnification), which was obtained within the RPI-IBIS facility by means of the ion pinhole camera with a rotated drum and nuclear track detectors.

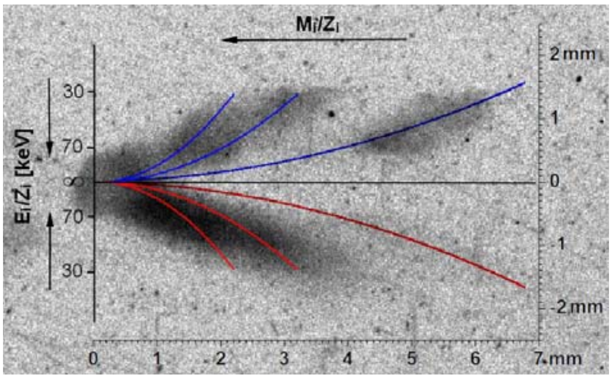

Fig. 13. Ion parabolas recorded by means of a miniature Thomson-type probe during its tests within the RPI-IBIS facility. These ion parabolas are deflected upwards and downwards because two successive discharges were investigated at the opposite polarization of Thomson electrodes.

The reported tests were performed subsequently in two different plasma facilities: the RPI-IBIS and PF-360 devices, which can generate intense plasma streams containing fast ion beams. Similar tests were also carried out with the probe equipped with the miniature Thomson spectrometer. Some examples of the recorded ion parabolas are presented in Fig. 13.

A quantitative analysis of tracks on the obtained ion parabolas can deliver information about ion species (e.g., the primary deuterons and impurity ions) as well as their energy spectra. Although during the reported laboratory tests it was unnecessary to cool down the investigated probes, a water-cooling circuit can easily be added. An open question is efficiency of magnetic shielding of the probes (particularly of the miniature Thomson analyser) against strong magnetic fields occurring in tokamaks, but it must be tested *in-situ*. There was also considered possibility of a replacement of the NTD by detectors of another type, e.g., a CCD matrix. It would, however, require considerable changes in the construction of the measuring heads and a lot of time for testing of electronic circuits. It should also be mentioned that the described ion-probes were designed and constructed taking into account requirements of COMPASS experiments [21–23], but if this facility is unavailable in proper time these probes might be used to measure charged fusion-products in another tokamak. The adaptation of these probes for large fusion experiments will require appropriate constructional changes and further laboratory tests.

Summary and conclusions

This paper described some diagnostic techniques applicable for fast electron measurements in tokamaks, and in particular the use of Cherenkov-type probes, which have already been applied in several tokamak experiments. Different constructions of the Cherenkov-type probes have been compared and examples of Cherenkov measurements have been discussed. Measurements of fast ions, and in particular of charged fusion-products, have also been described. New miniature ion probes, which have been designed for tokamak experiments, have been described for the first time in details. For the first time there are presented some results of the performed laboratory tests. In authors opinion the developed electron- and ion-probes can be used not only in tokamaks, but also in stellerators.

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