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Fast-ion measurements with neutron and gamma-ray spectroscopy in thermonuclear plasmas: recent results and future prospects

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Summary. — A high-performance thermonuclear plasma is a strong source of nuclear radiation, which includes neutron emission from the main fusion reactions and gamma-rays born from the interaction of supra-thermal ions and plasma impurities. Spectroscopic measurements of both types of radiation are an indirect probe of the distribution function of the fast ions leading to nuclear emission. In this paper we present a selection of recent results obtained with neutron and gamma-ray spectroscopy as a means to study the energy distribution of supra-thermal particles in high-performance thermonuclear plasmas. We focus in particular on the advancements made possible by the combination of dedicated instrumentation and detailed models based on the nuclear physics behind the emission. Future developments are finally addressed, especially regarding the availability of compact detectors with spectroscopy capabilities, which open up to a full tomographic reconstruction of the fast-ion velocity space.

1. – Introduction

The goal of controlled thermonuclear fusion research is to use nuclear reactions between hydrogen isotopes to produce energy. The most promising process is $\mathrm{t(d,n)}\alpha$ that can occur between deuterons and tritons in a deuterium-tritium (DT) plasma confined by the magnetic fields of a tokamak. The plasma parameters that need to be obtained for a self sustaining process are quite demanding: the DT plasma mixture must be heated up to about 15 keV (*i.e.* 100 million degrees) and kept confined at a pressure slightly higher than 8 atm. Transport processes must be tamed so as the energy released by the fusion reactions in the plasma core remains confined for about 1 s before it diffuses out to the first wall of the device, typically just at a few meter distance from the core. The simultaneous achievement of these three conditions will eventually have to be demonstrated in an economically sustainable and industrially reliable device.

While the availability of a commercial fusion power plant is still several decades away, an extended amount of research has been and is being carried out to understand fusion plasma behaviour. Among the different aspects of this very diverse and multidisciplinary field of research, the development of experimental techniques to measure the distribution function of the fuel ions and charged products of the fusion reactions plays an essential role. For example, a key requirement for the self-sustainment of a DT fusion plasma is that α particles born from the fusion reactions are well confined, which in turn demands to develop suitable diagnostic systems for their study.

As fusion research matures enabling the construction of high-performance, large-size devices, the diagnostic techniques developed for fuel ion and fusion product studies are experiencing a paradigm shift. In mid-size devices, where operations are entirely based on deuterium plasmas and understanding plasma physics rather than fusion performance is the driver of operations, diagnostics that can directly probe the fast-ion energy distribution to an unprecedented level of detail have been developed. These involve, for example, the detection of light from charge exchange reactions induced by the injection of beams of neutral particles in the plasma [1], or the direct measurement of ions escaping the plasma by means of edge probes [2, 3]. The significantly harsher measurement conditions of a high-performance plasma in a large-size device, both in terms of edge temperatures and neutron radiation bombardment, however, makes the application of these type of techniques extremely challenging, if not impossible. On the other hand, a high-performance plasma is a very strong source of nuclear radiation, which includes neutrons from the main fusion reactions and gamma-rays from the interaction of charged fusion products and plasma impurities. Exploiting this spontaneous nuclear emission for diagnostic purposes may be the only viable way to determine the distribution function of fuel ions and fusion products in a plasma approaching reactor conditions, although it is an indirect measurement that requires advanced, dedicated detectors and nuclear-physics–based models to relate measurements to parameters of the underlying ion distribution functions.

In this paper we briefly summarise the status of neutron and gamma-ray emission spectroscopy (NES and GRS) research in high-power fusion plasmas, with focus on the instrumentation and on the relation between measurements and parameters of the fast-ion energy distribution. Future opportunities enabled by the recent availability of spectrometers combining compact size and good energy resolution are finally illustrated, with emphasis on the potential they offer for a tomographic reconstruction of the energetic-ion velocity space.

2. – Neutron spectroscopy measurements in thermonuclear plasmas

Since the early days of thermonuclear fusion research, NES was proposed as a way to determine the plasma temperature from measurements of the Doppler broadening of the peak from deuterium-deuterium (DD) and deuterium-tritium (DT) reactions in plasmas. The first analytical calculation of the relation between temperature and peak width was published in 1960 [4], but it took more than twenty years before a proof of principle measurement of this relation could be demonstrated [5]. The temporal gap between the theoretical work and the experimental verification was due to the time required to generate a fusion plasma with high enough neutron yield allowing for spectral measurements at sufficient statistics.

With the boost of fusion plasma performance in the early '90s and the corresponding availability of large-size machines, such as the Joint European Torus (JET) in the UK, neutron-spectroscopy–based measurements have gained increasing importance. New, dedicated detectors have been developed, with the aim of improving the energy resolution, stability, counting rate capability and dynamic range of the measurements. The

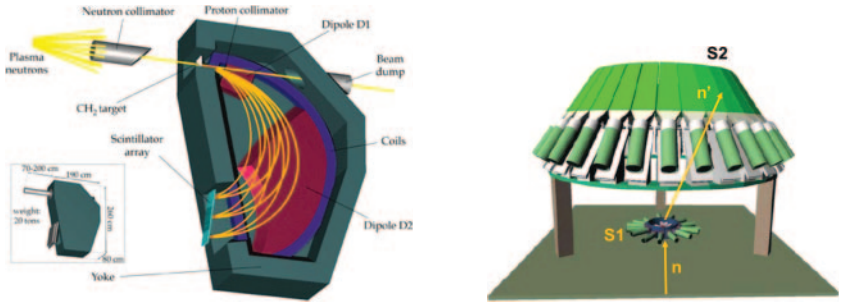

Fig. 1. – Schematics of the MPR (left) and TOFOR (right) spectrometers for neutron measurements in DT and DD plasmas at JET.

most advanced devices developed so far are the magnetic proton recoil (MPR) (fig. 1 left) [6] and the Time Of Flight Optimised For Rate (TOFOR) (fig. 1 right) [7] neutron spectrometers, for DT and DD plasmas, respectively. MPR is based on elastic scattering of neutrons impinging on a CH_2 foil and energy selection of the recoil protons by a magnetic field. In TOFOR, instead, incoming neutrons that scatter on a pile of start detectors (S1 in the figure) are measured by an umbrella of stop detectors (S2) arranged on a sphere at constant time of flight. The recorded distribution of time of flights between S1 and S2 is then related to the energy spectrum of the incoming neutrons. Both MPR and TOFOR are in operation at JET and, thanks to their advanced design and performances, they have significantly extended the scope of NES measurements in thermonuclear plasmas so that spectrometers of a similar type are now under operation in the most recent tokamak devices [8, 9]. Besides the determination of the bulk plasma temperature, nowadays NES is a driver diagnostic for studying supra-thermal components in the fuel ion distribution function of high-performance plasmas in the framework of the research on "fast-ion physics" effects in fusion devices [10]. These studies are made possible by the observation of fine (at the level of 10^{-2}–10^{-4} with respect to the main thermal peak) features of the spectrum [11, 12] that are related to the contribution of supra-thermal components of the fuel ion distribution functions to neutron emission.

A recent, extreme example of the role played by supra-thermal fuel ions in neutron emission was obtained in an experiment where radio frequency (RF) waves tuned to the third harmonic of the fundamental ion cyclotron frequency were injected in the plasma and coupled to a beam of deuterons for heating purposes [13-15]. The distribution function generated in this scenario is highly non Maxwellian (see fig. 2 left) with a sharp cut-off in the MeV range that depends on details of the coupling of the RF wave to the deuteron beam. Figure 2 right shows the corresponding neutron spectrum measured with TOFOR. A clear cut-off in the spectral shape can be seen, which has been used to determine the distribution function shown to the left.

3. – Gamma-ray spectroscopy measurements in thermonuclear plasmas

Supra-thermal components of the fuel ion distribution function are not the only population of energetic ions in a high-performance plasma. An even more important contribution is represented by charged products of the fusion reactions, where a dominant role is played by α particles born from $t(d,n)\alpha$ reactions in DT plasmas. Besides, energetic populations of non-fuel ions can be introduced on purpose to enhance the efficiency of

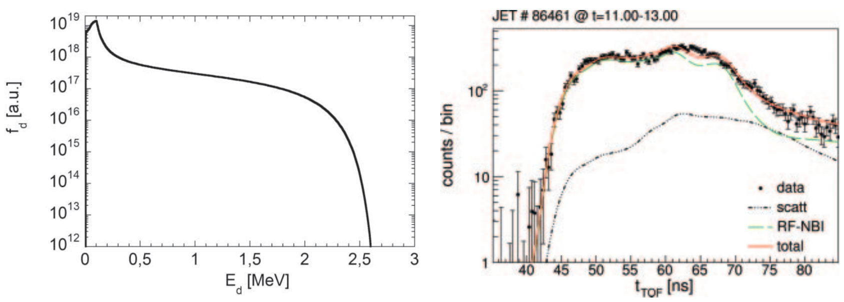

Fig. 2. – Left: deuteron distribution function inferred from neutron measurements in a recent JET discharge with RF heating at the third ion cyclotron harmonic. Right: time-of-flight neutron spectrum measured by TOFOR in the same discharge. The time of flight t_{TOF} is related to the neutron energy E_n by $t_{TOF} \propto E_n^{-1/2}$ so that shorter flight times indicate higher neutron energies. $t_{TOF} = 65$ ns corresponds to $E_n = 2.45\,\text{MeV}$. The lines shown in the right figure are a fit to the experimental data based on the distribution shown to the left (dashed line) and the effect of neutron energy degradation along their path from the plasma to the detector (dashed-dotted line).

certain heating schemes. An example is ^{3}He minority heating in a bulk deuterium plasma ((^{3}He)D), where RF waves are used to accelerate ^{3}He ions by tuning the antenna to the first harmonic of the ^{3}He cyclotron frequency [16].

Apart from few processes of the second order based on nuclear elastic scattering [17], in most cases non-fuel fast ions do not directly lead to neutron emission and a different diagnostic method needs to be adopted. A particularly successful technique is gamma-ray spectroscopy (GRS) [18], which is based on nuclear reactions between fast ions and plasma impurities (^{9}Be, ^{12}C) naturally found in the plasma depending on the material composition of the tokamak first wall. These processes lead to the formation of a compound nucleus, often in an excited state and that decays by emission of characteristic gamma-ray lines. The most important example is provided by $^9\text{Be}(\alpha,\text{n}\gamma)^{12}\text{C}$ which leads to the emission of 4.44 MeV gamma-rays from de-excitation of the first excited state of ^{12}C and that can be used to determine parameters of the α-particle energy distribution in DT plasmas.

Similarly to neutron spectroscopy, the recent application of high-resolution detectors (for example high-purity germanium or LaBr_3 scintillators [19, 20]) to these type of measurements has significantly broadened the diagnostic capabilities of the technique. Early GRS observations were limited to counting rates of few kHz and were mostly aimed at assessing the presence of fast ions exceeding the energy threshold associated to many of the gamma-ray reactions of interest, which is done by identifying the energy of the corresponding full energy peaks in the emission spectrum. Present-day detectors have better resilience to neutron background and enable operations up to a few MHz [20]. Besides, and most importantly, the quality of their measurements at high resolution has allowed observing the Doppler broadening of the peak spectral shape due to the fast-ion kinematics, which can be exploited to determine parameters of the fast-ion energy distribution. Figure 3 shows a recent example of a GRS measurement for the (^{3}He)D plasma scenario with RF heating described above. The measured spectrum shows a certain complexity, as it is made by several peaks corresponding to either different reactions between fast ^{3}He and plasma impurities, or by decays from different excited states of the

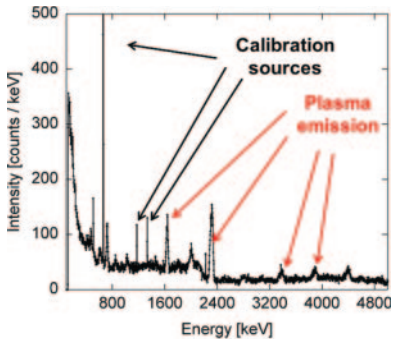

Fig. 3. – Gamma-ray energy spectrum measured with a high-purity germanium detector in a (^{3}He)D plasma at JET with RF heating at the fundamental cyclotron harmonic of ^{3}He. The arrows indicate full-energy peaks arising from gamma-ray emission due to nuclear reactions in the plasma, as well as due to laboratory sources placed in the vicinity of the detector and used for energy calibration purposes. A clear shape broadening is visible for lines from plasma emission.

same compound nucleus formed in a given process. From the figure we also note that there is a remarkable difference between peaks due to plasma emission and those from laboratory radioactive sources left in the vicinity of the detector for energy calibration purposes. The former are significantly broader as a result of the fast-ion kinematics [21].

A zoom in the energy region around one of the peaks at mean energy $E_\gamma = 1635\,\mathrm{keV}$ (fig. 4 left) from $^{12}\mathrm{C}(^3\mathrm{He},\mathrm{p}\gamma)^{14}\mathrm{N}$ reveals that its spectral shape is non trivial, which mirrors the more complex nuclear physics behind gamma-ray emission from reactions leading to compound nucleus formation compared to the $\mathrm{d}(\mathrm{d},\mathrm{n})^3\mathrm{He}$ and $\mathrm{t}(\mathrm{d},\mathrm{n})\alpha$ fusion reactions responsible for neutron emission.

This is confirmed by a detailed, quantitative analysis of the spectral shape and aimed at establishing the relation between peak width and the tail temperature of the ^{3}He ions driven to high energies by the RF waves (fig. 4 right). Unlike NES, for which broadening of the thermal peak is related to the square root of the bulk plasma temperature, it is

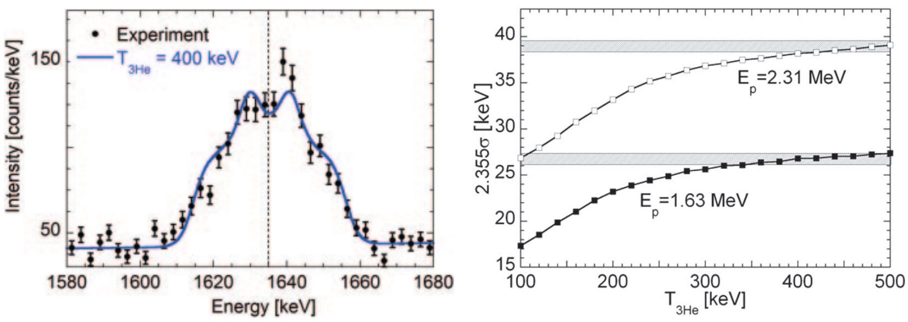

Fig. 4. – Left: spectral shape of the $E_\gamma = 1635\,\mathrm{keV}$ peak from $^{12}\mathrm{C}(^3\mathrm{He},\mathrm{p}\gamma)^{14}\mathrm{N}$ reactions in a (^{3}He)D plasma with RF heating. The solid curve is a fit to the spectral shape based on a model of gamma-ray emission from this reaction. Right: relation between broadening of the 1635 keV and 2313 keV peaks from $^{12}\mathrm{C}(^3\mathrm{He},\mathrm{p}\gamma)^{14}\mathrm{N}$ reactions and the tail temperature of fast ^{3}He ions accelerated by RF waves.

seen here that there indeed is a change of the peak width with the ^{3}He tail temperature, but this saturates for $T_{^3\mathrm{He}} > 300\,\mathrm{keV}$, so that a determination of $T_{^3\mathrm{He}}$ based on the peak broadening alone becomes experimentally very challenging in this range. On the other hand, we can still infer a temperature value from the measured spectrum by combining information on peak broadening with other parameters of the emission, such as its intensity and the ratio between lines at different energies arising from the same reaction. An important point to highlight in this context is that the quantitative relation between the fast-ion distribution function and the parameters of characteristic gamma-ray emission peaks (width, intensity, ratio) depends on details of the cross sections of each emission process, including their anisotropy [22], and needs to be studied case by case. In this sense, although the detectors required for GRS are simpler than those of NES, the interpretation of measurements is comparably more involved due to the underlying nuclear physics and the larger variety of reactions that are of interest for diagnostic applications.

4. – Towards velocity space tomography with nuclear diagnostics and compact detectors

NES and GRS measurements at high resolution have so far been based on optimised detectors observing the plasma along a single collimated line of sight (LOS). These detectors are however rather bulky and their application for observations along multiple LOSes is impractical. On the other hand, since the first years of JET operations, a system made of multiple collimated lines of sight (called camera) has been built and used to reconstruct the spatial profile of neutron emission by tomographic inversion of the measurements. The detectors used in this system, which is still under operation and has recently undergone a refurbishment, are liquid scintillators, thus compact and suitable for applications in a camera system, where space limitation is a significant empirical constraint. Liquid scintillators, however, offer poor energy resolution and a quite complex response function, which make the extraction of spectral information from the measurements extremely challenging, if not even impossible in certain scenarios. Similarly to neutron profile measurements, gamma-ray yield observations along multiple chords have also been successfully attempted [23] in plasmas with moderate yields, resulting in kHz counting rates at the detector position. These measurements, however, had similarly to rely on low-resolution CsI detectors, which did not allow observing and identifying characteristic peaks, but only integrating the emission in predefined energy windows where gamma-ray reactions were supposed to occur. Clearly, the possibility to combine good energy resolution and compact detectors would be highly desirable.

The latest developments in the technology for nuclear detectors can nowadays make this possible. An important achievement in the field of neutron spectroscopy is the availability of synthetic, single-crystal diamond detectors (SDD) that, compared to formerly used natural diamonds [24], have superior electrical properties, besides being more reproducible and significantly less expensive. SDD have a different response function to DD an DT neutrons [25]. In the first case, the response is similar to that of liquid scintillators, thus generally not suitable for high-resolution applications, although SDD offer significantly improved stability and intrinsic MHz capabilities. In case of 14 MeV neutrons from DT, instead, the response function features a peak at an energy resolution (about 3%) better than MPR and TOFOR [26], making SDDs suitable for high-resolution applications, but with a more limited dynamic range up to 2–3 orders of magnitude down the thermal peak (compared to 3–5 for MPR and TOFOR). Figure 5 left shows a picture of an SDD detector with an example of measured spectrum for the same discharge of fig. 2,

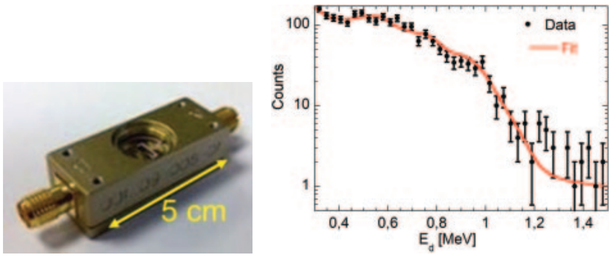

Fig. 5. – Left: picture of a single-crystal, synthetic-diamond detector (SDD). Right: neutron energy spectrum measured in the same experiment of fig. 2 by the SDD detector. E_d is the energy deposited in the detector by neutrons of energy E_n and is related to E_n by the detector response function.

shown to the right [15]. Although the spectrum comes from a DD plasma, where SDD have some spectral limitations, in this extreme case data are comparable with those of TOFOR in fig. 2 and can be understood based on the same model for the distribution function.

Concerning gamma-ray spectroscopy with compact detectors, an important advancement is made possible by the development of silicon photo-multipliers (SiPM, also commercially known as multi-pixel photon counters) that can replace photo-multiplier tubes (PMT) when insensitivity to magnetic fields and space limitations are the driver of the detector development, such as in multi-chord systems. The electronic performances of SiPMs are rapidly growing and have been almost a revolution in other fields of applied physics, for example for Positron Emission Tomography applications [27], where there is need to measure the two 511 keV gamma-rays emitted back to back by positron annihilation from the β decay of a radioactive nucleus. GRS of fusion plasmas is a more difficult application, as there is here need to detect peaks from different reactions in the MeV range and at MHz counting rates. However, by a suitable adaptation of the SiPM readout circuit, experimental results show that a comparable energy resolution and signal length can be obtained with SiPM and PMT coupled to $LaBr_3$ crystals [28], opening up to the development of compact SiPM-based gamma-ray spectrometers for fusion plasma applications at good energy resolution.

The need for detectors combining a compact size and spectral capabilities is not only beneficial to improve the reconstruction of the spatial profile of NES and GRS, but is also of interest from a theoretical point of view as it in principle opens up to velocity space tomography (VST) [29]. The principle upon which VST is based is that different instruments observing the same distribution function may be sensitive to different parts of its velocity space, depending on the emission process they adopt, for example neutron or gamma-ray emission. Moreover, even when the same emission process and the same channel in the energy spectrum of the emission are considered, the velocity space regions to which this is sensitive depend on the angle of observation, so that spectroscopy observations with multiple sight-lines tilted to different angles with respect to the same plasma volume provide complementary information. The idea is better illustrated with reference to fig. 6 [30]. Here we consider the channel at energy 4424 keV in the full-energy peak of the gamma-ray emission spectrum arising from the ${}^{9}\mathrm{Be}(\alpha, \mathrm{n}\gamma){}^{12}\mathrm{C}$ reaction. The figure illustrates the velocity space regions observed by this channel when the measurement is performed along a line of sight tilted by an angle $\phi = 30^\circ$ (top) and $\phi = 90^\circ$ (bottom)

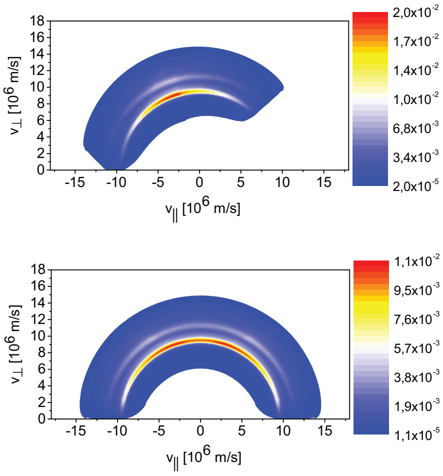

Fig. 6. – Velocity space regions observed by the channel at 4424 keV in the gamma-ray spectrum from the ^{9}Be$(\alpha, n\gamma)^{12}$C reaction when the line of sight is tilted by 30° (top) and 90° (bottom) with respect to the magnetic field. A slowing down α-particle distribution was assumed in these calculations.

with respect to the magnetic field and when α particles are described by a slowing down distribution function. By comparing the two panels it is clear that the same distribution function is weighted differently in the two cases by events falling in the same 4424 keV channel of the spectrum. While in the $\phi = 90°$ case particles with positive and negative parallel velocities have equal weights, in the $\phi = 30°$ case there is instead a stronger bias for anti-parallel velocities. Formally, we can repeat the calculations behind fig. 6 for each channel in the spectrum of a gamma-ray or neutron measurement and for each available tilting angle so to derive the corresponding weight matrices in the velocity space. This set of matrices describes how the whole velocity space is weighted by a given diagnostic along a specified line of sight. From their knowledge, tomographic inversion techniques can then in principle be applied to neutron or gamma-ray emission spectroscopy data along multiple LOSes to derive the underlying fast-ion distribution function in high-performance plasmas. VST has so far been attempted in mid-size devices and using diagnostics based on the emission of visible light. The first results obtained are very encouraging and motivate its application to nuclear diagnostics [31].

5. – Conclusion

Neutron and gamma-ray spectroscopy at high resolution are key diagnostics to investigate the distribution function of fast ions in high-performance fusion plasmas. The most recent neutron emission spectroscopy (NES) results were obtained with dedicated, advanced detectors that could reveal small-amplitude, high-energy components in the emission spectrum and that are associated to supra-thermal populations of the fuel ion distribution function. Gamma-ray spectroscopy (GRS), on the other hand, is based on reactions between fast ions and plasma impurities arising from erosion of the machine first wall. It requires comparably simpler instrumentation but is based on a more complex nuclear physics so that the quantitative relation between measurements and the underlying fast-ion distribution function is more involved and different for each specific reaction. As for NES, high-resolution GRS detectors have allowed measuring the peak Doppler broadening from the fast-ion kinematics and to use this piece of information to infer the tail temperature of the fast ions.

Present progress in NES and GRS for fusion plasmas is concentrating on the development of compact devices, benefiting from the latest achievements in nuclear detector technology, such as single-crystal, synthetic-diamond detectors for NES and silicon photo-multipliers for GRS. The goal is to enable spectroscopic capabilities in NES and GRS systems based on observations along multiple collimated lines of sight, which can in principle open up to a velocity space tomography of the fast-ion distribution function in high-performance plasmas.

REFERENCES

[1] Geiger B. *et al.*, *Plasma Phys. Control. Fusion*, **53** (2011) 065010.
[2] Garcia-Munoz M. *et al.*, *Nucl. Fusion*, **53** (2013) 123008.
[3] Garcia-Munoz M. *et al.*, *Plasma Phys. Control. Fusion*, **55** (2013) 124014.
[4] Faust W. R. and Harris E. G., *Nucl. Fusion*, **1** (1960) 62.
[5] Fisher W. A., Chen S. H., Gwin D. and Parker R. R., *Phys. Rev. A*, **28** (1983) 3121.
[6] Sjöstrand H. *et al.*, *Rev. Sci. Instrum.*, **77** (2006) 10E717.
[7] Gatu Johnson M. *et al.*, *Nucl. Instrum. Methods A*, **591** (2008) 417.
[8] Zhang X. *et al.*, *Nucl. Fusion*, **54** (2014) 104008.
[9] Zhang X. *et al.*, *Rev. Sci. Instrum.*, **85** (2014) 043503.
[10] Gorelenkov N., Pinches S. and Toi K., *Nucl. Fusion*, **54** (2014) 125001.
[11] Tardocchi M., Nocente M. and Gorini G., *Plasma Phys. Control. Fusion*, **55** (2013) 074014.
[12] Nocente M. *et al.*, *Nucl. Fusion*, **54** (2014) 104010.
[13] Hellesen C. *et al.*, *Nucl. Fusion*, **53** (2013) 113009.
[14] Eriksson J. *et al.*, *Nucl. Fusion*, **55** (2015) 123026.
[15] Nocente M. *et al.*, *Rev. Sci. Instrum.*, **86** (2015) 103501.
[16] Nocente M. *et al.*, *Nucl. Fusion*, **51** (2011) 063011.
[17] Nocente M. *et al.*, *Nucl. Fusion*, **53** (2013) 053010.
[18] Kiptily V. G. *et al.*, *Nucl. Fusion*, **42** (2002) 999.
[19] Nocente M. *et al.*, *Rev. Sci. Instrum.*, **81** (2010) 10D321.
[20] Nocente M. *et al.*, *IEEE Trans. Nucl. Sci.*, **60** (2013) 1408.
[21] Tardocchi M. *et al.*, *Phys. Rev. Lett.*, **107** (2011) 205002.
[22] Proverbio I. *et al.*, *Rev. Sci. Instrum.*, **81** (2010) 10D320.
[23] Kiptily V. G., Cecil F. E. and Medley S. S., *Plasma Phys. Control. Fusion*, **48** (2006) R59.
[24] Krasilnikov A. V. *et al.*, *Nucl. Instrum. Meth. A*, **476** (2002) 500.
[25] Cazzaniga C. *et al.*, *Rev. Sci. Instrum.*, **85** (2014) 11E101.
[26] Cazzaniga C. *et al.*, *Rev. Sci. Instrum.*, **85** (2014) 043506.
[27] Roncali E. and Cherry S. R., *Ann. Biomed. Eng.*, **39** (2011) 1358.
[28] Nocente M. *et al.*, *Rev. Sci. Instrum.*, **85** (2014) 11E108.
[29] Salewski M. *et al.*, *Plasma Phys. Control. Fusion*, **57** (2015) 014021.
[30] Salewski M. *et al.*, *Nucl. Fusion*, **55** (2015) 093029.
[31] Salewski M. *et al.*, *Nucl. Fusion*, **54** (2014) 023005.