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Measuring fast ions in fusion plasmas with neutron diagnostics

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Abstract

Fast ions in fusion plasmas often leave characteristic signatures in the neutron emission from the plasma. In this paper, we show how neutron measurements can be used to study fast ions and give examples of physics results obtained on present day tokamaks. The focus is on measurements of the neutron energy spectrum, either with dedicated neutron spectrometers or with compact neutron detectors used in each channel of neutron profile monitors.

A measured neutron spectrum can be analyzed in several different ways, depending on the physics scenario under consideration. Gross features of a fast ion energy distribution can be probed by applying suitably chosen thresholds to the measured spectrum, thus probing ions with different energies. With this technique it is possible to study the interaction between fast ions and MHD activity, such as toroidal Alfvén eigenmodes and sawtooth instabilities. Quantitative comparisons with modeling can be performed by a direct computation of the neutron emission expected from a given fast ion distribution. Within this framework it is also possible to determine physics parameters, such as the supra-thermal fraction of the neutron emission, by fitting model parameters to the data. A detailed, model-independent estimate of the fast ion distribution can be obtained by analyzing the data in terms of velocity space weight functions. Using this method, fast ion distributions can be resolved in both energy and pitch angle by combining neutron and gamma-ray measurements obtained along several different sightlines.

Fast ion measurements of the type described in this paper will also be possible to perform at ITER, provided that the spectrometers have the dynamic range required to resolve the fast ion spectral features in the presence of the dominating thermonuclear neutron emission. A dedicated high-resolution neutron spectrometer has been designed for this purpose.

1 Introduction

The most relevant reactions for the fusion research program are the $D(d,n)^3He$ and $T(d,n)^4He$ fusion reactions. These reactions are commonly referred to as the DD and DT reactions, respectively. Neutrons are produced in both reactions, which means that neutron measurements can be used to obtain information about the fuel ions in a fusion reactor. In this paper we consider neutron measurements from tokamak fusion experiments, which are sources of intense neutron emission. At the JET tokamak neutron rates of $5.5 \cdot 10^{16}$ s^{-1} and $5.7 \cdot 10^{16}$ s^{-1} have been achieved in D and DT plasmas, respectively.

The alpha particles (^4He) produced in the DT reaction carry 20 percent of the released fusion energy and will be

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an important source of plasma heating in a future burning fusion reactor. In a tokamak, this “self-heating” is supplemented by externally applied heating methods, such as neutral beam injection (NBI) [1] and electromagnetic wave heating in the ion cyclotron range of frequencies (ICRF) [2]. These heating methods rely on energy transfer to the bulk plasma during the slowing down of energetic ions with energies significantly higher than the average thermal energy. Such supra-thermal ions are commonly referred to as “fast ions”, and their confinement in the plasma is of great importance in order to have effective plasma heating and high fusion performance. The physics of fast ions in fusion plasmas is therefore a topic of intense research [3, 4, 5].

This paper presents recent advances in the field of neutron based fast ion measurements. The aim is to give a coherent overview of this topic and connect results that have previously been presented separately. The paper is organized as follows. Section 2 contains a brief description of the measurement techniques relevant for this paper. In Section 3 we present the theoretical basis for neutron-based fast ion measurements. Section 4 contains a presentation and discussion of selected physics results. In Section 5 a brief outlook about fast ion measurements at ITER is given. A summary and concluding remarks are presented in Section 6.

2 Neutron measurement techniques

The focus of this paper is measurements made with neutron spectrometers and neutron profile monitors (commonly called neutron cameras). In particular, most of the physics results discussed below are obtained at JET with the time-of-flight spectrometer TOFOR [6] and with the neutron camera [7]. Several other neutron spectrometers and cameras have been used on various tokamaks over the years. This includes dedicated spectrometer systems such as the magnetic proton recoil spectrometer at JET [8] and the time-of-flight spectrometer TOFED at EAST [9]; compact spectrometers based on diamond detectors [10, 11] and scintillator detectors [12, 13, 14]; and neutron cameras at MAST [15], TFTR [16] and JT-60U [17].

Of key importance when analyzing data from any of the above instruments is the knowledge of the instrument response function, i.e. the expected measured signal due to a given neutron emission from the plasma. Depending on the instrument, the response function can be determined by particle transport modeling, measurements at a well characterized neutron source, or a combination of measurements and modeling. For a more detailed discussion about the response function of a specific instrument, the reader is referred to references [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] given above.

3 Fast ion signatures in the neutron emission from a fusion plasma

In a given fusion reaction, the energy, emission direction and reaction probability of the emitted neutron depends on the momenta of the reacting fuel ions and on the angular differential cross section of the reaction [18]. Hence, the energy spectra and spatial emissivity profiles of DD and DT fusion neutrons are determined by the phase space distribution of the D and T ions. Fast ions often have distributions that are distinctly different from that of the thermal bulk plasma and therefore give rise to characteristic signatures in the neutron emission. These fast ion signatures can be used as the basis for diagnostics.

Consider a fast fast D population at a particular energy and pitch (i.e. $v_{\|}/v$) in a thermal D plasma. The temperature of the plasma is such that the typical thermal energies are small compared to the fast ion energy. The neutron energy spectrum resulting from the fast ion population reacting with the bulk plasma depends on (i) the fast ion energy, (ii) the fast ion pitch and (iii) the angle of observation. This is illustrated in Figure 1, where neutron energy spectra for different cases have been calculated according to the procedure described in [18]. The spectrum from thermonuclear reactions is well approximated by a Gaussian [19], while the spectra from reactions between the fast ions and the bulk plasma typically cover a broader energy range and have a characteristic “double-humped” shape. This feature is a result of the Doppler shift caused by the cyclotron gyration of the fast ions, and at a given energy it is most pronounced when the fast ions have $v_{\|}/v = 0$ and are observed perpendicularly to the plasma magnetic field.

The spectrum calculations demonstrated above can be used to generate a complete map of the relationship between the fast ion velocity coordinates and the neutron energy spectrum. The result can be visualized in the form of velocity space weight functions, a practice routinely used for FIDA [20, 21] and CTS measurements

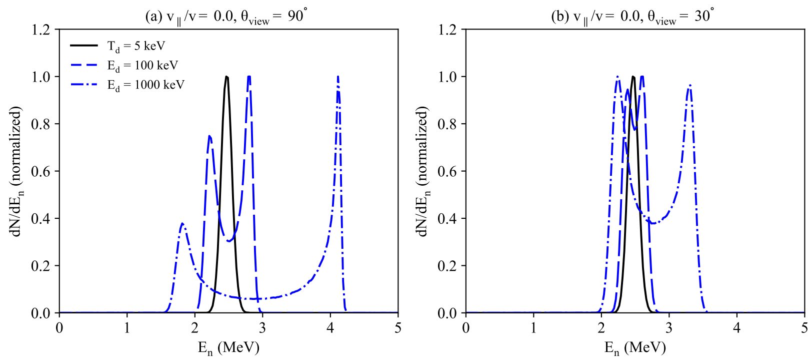

Figure 1: Calculated neutron energy spectra for reactions between different mono-energetic D distributions and a 5 keV bulk plasma (blue broken lines). The spectrum from purely thermo-nuclear reactions is also shown. The fast ion pitch is zero and the viewing angles relative to the magnetic field are 90° in panel (a) and 30° in panel (b).

[22], which has recently been applied also to neutron diagnostics [23] and gamma-ray diagnostics [24, 25]. Once the relevant weight functions have been computed, the neutron energy spectrum corresponding to reactions between an arbitrary fast ion distribution and the bulk plasma can be obtained by multiplying the weight functions with the fast ion distribution and integrating over the phase space coordinates. In practice this typically reduces to a number of matrix multiplications that can be rapidly evaluated. The instrument response function can also be taken into account in this process [26].

The neutron emission calculation techniques demonstrated above, in combination with the response function for the instrument under consideration, forms the basis for the interpretation of all neutron measurements presented in this paper.

4 Overview of recent results

4.1 Threshold analysis

As a first basic example of how fast ion information is obtained from neutron measurements we consider TOFOR spectrometer data from JET discharges 85372 and 85375. Data from two 1s time windows during these discharge are shown in Figure 2a. It is clearly seen that the TOFOR spectrum extends down to significantly lower times-of-flight for discharge 85372. Shorter time-of-flights correspond to higher neutron energies, and higher neutron energies is a sign of more energetic deuterons in the plasma (c.f. Figure 1). Based on the knowledge of the response function of TOFOR and from the kinematics of the fusion reactions between fast ions and the bulk plasma, it is possible to relate a given time-of-flight to a minimum deuteron energy [26]. This relationship is shown in Figure 2b. For instance, for JET discharge 85372 shown in Figure 2a the TOFOR data extends down to $\sim$ 50 ns, which is direct evidence of the presence of deuterons with energies up to at least 1 MeV in the plasma. For discharge 85372, this result is attributed to ICRH acceleration of deuterons at the second harmonic of their cyclotron frequency [27]. For discharge 85375 on the other hand, no ICRH accelerated deuterons are observed; the data only extends down to about 58 ns (apart for some scattered points due to random background). Neutrons with this time-of-flight can be generated by deuterons with energies around 100 keV, i.e. the NBI energy at JET.

A more elaborate example of how this kind of threshold analysis can be used to study fast ions is provided by [28]. Here, TOFOR data from a JET discharge heated with a combination of deuterium NBI and ICRH tuned to the third harmonic of the deuterium cyclotron frequency was studied. With this heating scheme it was possible to accelerate deuterons up to several MeV, which provided many opportunities to study fast ion physics. In particular, it was possible to study the interaction between the fast deuterons and toroidal Alfvén eigenmodes (TAEs) by integrating the TOFOR data below various time-of-flight thresholds, thus probing fast deuterons above different deuteron energy levels. It was observed that the signal from fast deuterons with energies above ~1 MeV decreased significantly during periods of strong TAE activity – indicating that these ions were transported away from the plasma core – while deuterons with energies below ~0.5 MeV were not affected by the TAEs. This energy dependent redistribution of the deuterons was found to be consistent with the expected location of different

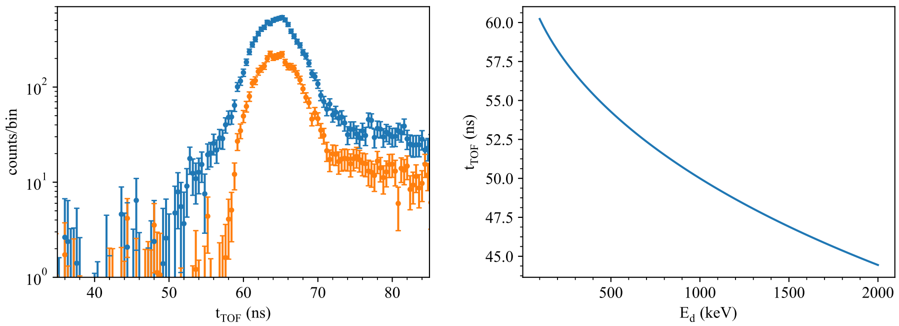

Figure 2: (a) Example TOFOR data from JET discharges 85372 (blue points) and 85375 (orange points). (b) The relationship between fast deuteron energy and the minimum possible time-of-flight values in the TOFOR data.

resonances between the deuterons and the TAE modes.

A similar analysis as above has recently been carried out with the JET neutron camera. In this case, the focus of the analysis was the behavior of deuterons during sawtooth instabilities. The plasmas scenario studied was the same as in the example discussed above, i.e. third harmonic ICRH and NBI. By applying thresholds to the spectra measured by the different camera detectors it was possible to study the energy dependent redistribution of fast ions during sawtooth events. The observations are summarized in Figure 3, which shows data from the JET neutron camera before and after a sawtooth crash, using different thresholds for the energy deposited by the neutrons in the detectors. The lower threshold ($E_{\text{dep}} = 2$ MeV) effectively probes deuterons of all energies, while the higher threshold ($E_{\text{dep}} = 4$ MeV) only probes deuterons with energies above $\sim$1 MeV. It is observed that the relative difference between the pre and post sawtooth data is significantly smaller for the higher threshold setting, indicating that energetic deuterons (which are expected to be mainly trapped for this plasma scenario with strong ICRH acceleration) are less prone to be redistributed during a sawtooth event than ions with lower energies, in qualitative agreement with theory [29]. A more detailed account of this study will be the topic of a future paper.

4.2 Model validation and parameter fitting

The analysis presented above relies only on basic considerations about fusion kinematics, along with knowledge of the response function of the neutron spectrometers under consideration. In order to perform more quantitative fast ion studies, one option is to use the methods described in Section 3 to calculate the neutron emission expected from a certain theoretical model or modeling code, and compare the calculations to the experimental data. Ideally, the calculations should be compared with as many different diagnostics as possible, in order to validate different aspects of the modeling. This is done e.g. in [30], where a fast D distribution computed with the ASCOT code [31] coupled to the RFOF library [32] is validated against several neutron and gamma-ray measurements. A summary of the results is presented in Figure 4, which shows the ASCOT fast D distribution and the comparison of the corresponding neutron spectra with data from the TOFOR spectrometer and an NE213 spectrometer. TOFOR has a vertical line-of-sight, viewing the plasma perpendicularly to the magnetic field, while the NE213 spectrometer has a horizontal line-of-sight that is quasi-tangential with respect to the magnetic field. As described in the paper, this combination of diagnostics allows for validating the distribution obtained from the ASCOT-RFOF simulation in both energy and pitch, which would not have been possible with only one diagnostic. The plasma scenario under consideration is once again the 3rd harmonic ICRH scenario considered above and the ASCOT-RFOF simulations indicate that this scenario results in deuterons accelerated to energies up to about 2 MeV by the ICRH, with pitch values driven towards zero (c.f. Figure 4). The neutron spectra computed from this distribution agree well with the experimental data from both TOFOR and the NE213, which gives confidence in the modeled distribution.

A similar example of this kind of model validation has recently been carried out at MAST. In this case, a set of complementary fast ion diagnostics, including the MAST neutron camera, were used in conjunction with modeling to study fast ion behavior during TAEs and fishbone instabilities [33, 34].

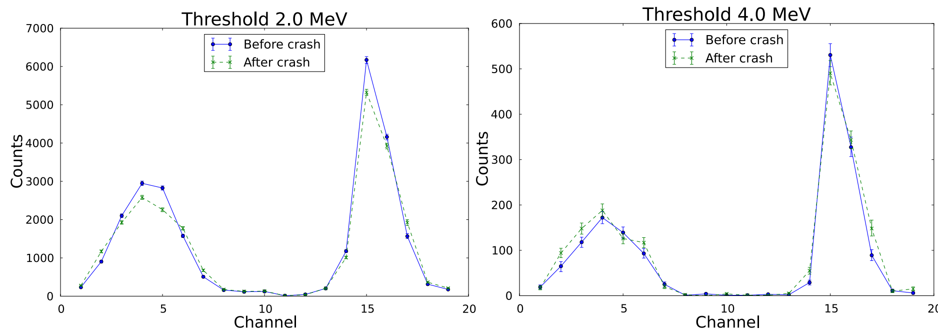

Figure 3: (a) Number of counts measured by each of the 19 JET neutron camera channels in a 90 ms time interval right before (line) and after (line) the sawtooth crash, for an energy deposition threshold of 2 MeV. With this threshold, deuterons of any energy can contribute to the neutron signal. (b) Same as in (a), but for an energy deposition threshold of 4 MeV. With this threshold, only deuterons with energies above ∼1 MeV can contribute to the neutron signal.

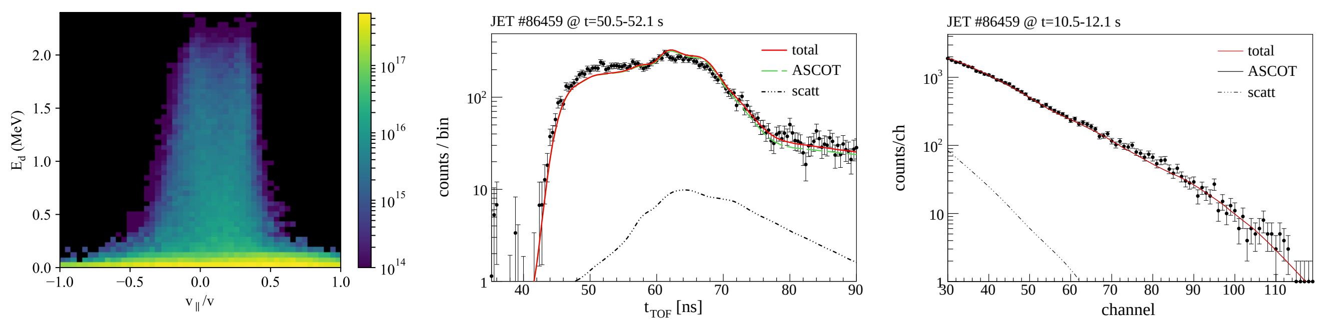

Figure 4: (a) Fast D distribution obtained from the ASCOT-RFOF code. (b) The neutron spectrum computed based on this distribution compared to measurements with the TOFOR spectrometer (vertical/perpendicular sightline). (c) The corresponding comparison with data from the NE213 spectrometer (horizontal/quasi-tangential sightline).

Another possible analysis procedure is to start from a parameterized model of the deuterium distribution in the plasma and estimate the model parameters from a fit to the experimental data. For example, the thermal bulk ion distribution is commonly modeled as a Maxwellian distribution, while distributions resulting from NBI and ICRH can be modeled e.g. with the Fokker-Planck equation described in [2]. The overall normalization factors of the various distributions are typically taken to be free parameters in the fit. When this kind of model is fitted to a measured neutron spectrum, it is thus possible to deduce the relative contribution that NBI ions and/or ICRH accelerated ions make to the neutron emission. This analysis technique has been extensively used in recent years e.g. to check for consistency between plasma heating codes and neutron measurements [35, 36, 37].

4.3 Weight function analysis

In the previous section it was described how neutron measurements can be used to validate modeled fast ion distributions, as well as to determine free parameters of a given model through a fitting procedure. A useful complement to these analysis methods is to use the velocity space weight functions described in Section 3 in order to obtain a model-independent estimate of the fast ion distribution. The basic idea of this method is to use the weight functions, each of which represents a well localized region in the fast ion phase space, as "building blocks" for the measured spectra, and iteratively adjust the weight of each building block until the best match with the experimental data is found.

Any neutron measurement represents a volume integral over the viewing cone of the measuring instrument, which means that the weight functions should in principle be resolved in both space and velocity. As described in [38], this can be achieved by computing weight functions in terms of a suitably chosen set of constants-of-motion of the fast ions. It is presently being investigated to what extent it is possible to apply this formalism to the full set of fast ion diagnostics available on JET.

However, in many situations certain approximations about the weight functions can be justified, which reduces the complexity of the analysis. For instance, in many ICRH scenarios it is a good approximation to assume that the fast ions are well localized to a comparatively small region in the core of the plasma, which makes it possible to consider the weight functions in terms of only the velocity coordinates of the fast ions, e.g. $v_{\|}$ and $v_{\perp}$. This approach was followed in [39], where the neutron and gamma-ray diagnostics at JET were combined in order to estimate the fast ion velocity distribution during the 3rd harmonic experiment described in Section 4.1. The resulting distribution was seen to be in good agreement with the distribution simulated with the ASCOT-RFOF code (c.f. Figure 4), which is a further indication that ASCOT-RFOF reliably models the main features of the fast D distribution in this experiment.

In addition to the assumption of a well localized fast ion distribution, it is sometimes also possible to make simplifying assumptions about the pitch values of the fast ions. In particular, for many ICRH scenarios, theory strongly suggests that the pitch of the accelerated ions are driven towards zero, since the ICRH wave field mainly accelerates the component of the ion velocity that is perpendicular to the magnetic field. Thus, assuming that the pitch values of the fast ions are narrowly distributed around $v_{\|}/v = 0$ effectively makes the weight functions depend only on the fast ion energy, as described in [40] (note that in this paper the term "δ-spectra" is used instead of "weight functions").

As an example of such a one-dimensional weight function analysis we consider a JET discharge heated with ICRH tuned to the 2nd harmonic of the D cyclotron frequency in combination with NBI heating. During the discharge, the ICRH was switched on continuously for about 10s. During this period, the NBI was switched on for two shorter time intervals of about 2s each, with 3s in between. Through a weight function based TOFOR analysis it was possible to estimate the time evolution of the fast D distribution during this discharge, which allowed for a detailed comparison of the distribution during the combined ICRH+NBI and NBI-only heating phases. The TOFOR distributions were also compared with modeled distribution obtained with the PION code [41]. A brief overview of the main results is given in Figure 5. Panel (a) shows the measured TOFOR data together with the spectrum estimated from the weight function analysis. A selection of the weight functions used to build up the total spectrum is also shown, for illustration. Each of the weight function spectra corresponds to one deuteron energy and the deuteron distribution is obtained from the estimated intensity of each weight function. The resulting D energy distributions for periods with ICRH+NBI and NBI-only is shown in panel (b) together with the corresponding distributions obtained from PION modeling. It is clear from these results that there are fewer energetic deuterons when the NBI is switched off, the biggest difference being in the region around $E_{\mathrm{d}} = 100$ keV. This result is expected, since the NBI ions provide a seed of moderately energetic particles that the ICRH can couple to, which results in the observed energetic tail of deuterons up to about 2 MeV. When the NBI is switched off this seed disappears and the tail gradually decreases. These experimental observations are also seen to be in good agreement with the PION modeling. For a detailed account of this study the reader is referred to [42].

5 Outlook towards ITER

ITER will be equipped with a radial neutron camera (RNC) [43], allowing for measurements of the neutron emissivity profile (which is equivalent to the birth profile of the fusion alpha particles born in the DT reaction). A conceptual design of a high-resolution neutron spectrometer (HRNS) is also available [44]. The HRNS is currently in the "enabled" category of ITER diagnostics, which means that it has an allocated sightline in the ITER design, but a definitive decision whether or not this instrument will actually be built at ITER is yet to be taken. The main plasma parameter to be measured by the HRNS is the fuel ion ratio $n_{\mathrm{T}}/n_{\mathrm{D}}$ in the core plasma, which is a critical parameter for machine protection and control. The HRNS is considered the primary diagnostic for performing this measurement. As discussed in [45], the determination of $n_{\mathrm{T}}/n_{\mathrm{D}}$ requires that thermonuclear and beam-target neutron emission components can be separated from each other in the measured neutron spectrum. I.e., even though the $n_{\mathrm{T}}/n_{\mathrm{D}}$ determination is not a fast ion measurement per se, it still requires that the 1 MeV beam deuterons can be accurately measured.

In principle, all methods for measuring fast ions described in the previous section will be applicable also to ITER experiments. In addition to measuring D and T ions, it is also possible to measure alpha particles, which

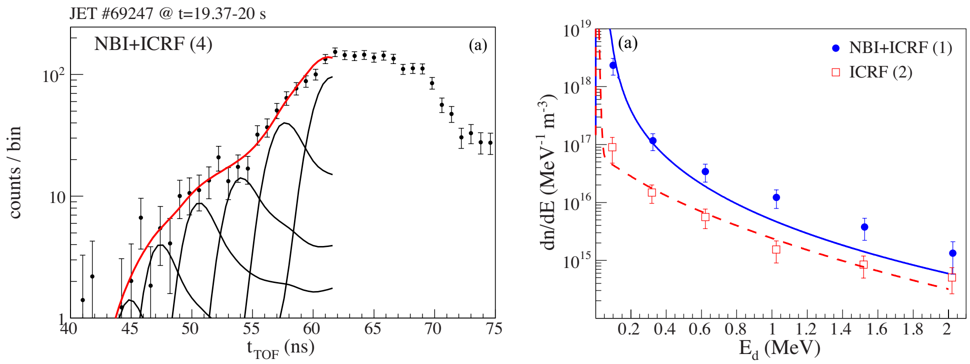

Figure 5: (a) TOFOR data (points with error bars) from a period of combined NBI and 2nd harmonic ICRH, together with the spectrum estimated by iteratively adjusting the intensities of a set of fast deuterium weight functions to the data. The weight function spectra are shown as black lines and the total spectrum is shown in red. (b) D distributions for time windows with ICRH alone as well as in combination with NBI. The solid lines are the distributions obtained from PION simulations and the points represent the corresponding TOFOR results.

are manifested in the neutron spectrum due to elastic scattering on the fuel ions [46]. However, at ITER the plasma density and temperature is expected to be higher than in contemporary fusion experiments, which places higher demands on the dynamic range of an ITER neutron spectrometer compared to those of today. In a full power DT plasma at ITER it is likely that the intensity of the fast ion signatures in the neutron emission will be about 1000 times smaller than the thermonuclear intensity [45], which means that the dynamic range of the spectrometer needs to be at least three orders of magnitude. The scintillator detectors in the RNC sightlines will not meet this requirement unless the time integration is longer than ~ 1 s, due to limitations in count rate capability. However, with a dedicated spectrometer system, such as the HRNS, this dynamic range is attainable down to a time integration window of 100 ms [44], which conforms with the ITER requirements on the time resolution for $n_{\mathrm{T}}/n_{\mathrm{D}}$ measurements.

6 Summary and conclusions

Several of the most important fast ions in fusion plasmas (notably deuterons, tritons and, to some extent, alpha particles) give rise to neutrons emitted from the plasma. Neutron measurements can be used to study several different aspects of the physics of these fast ions. In particular, if a measurement resolves the energy spectrum of the emitted neutrons, it is possible to obtain detailed information about the distributions of the fast ions. Dedicated neutron spectrometers are installed on several major tokamaks, including JET, EAST and ASDEX-U. Furthermore, the scintillator detectors used in the neutron profile monitors e.g. at JET also has spectroscopic capabilities, which has recently started to be exploited.

A measured neutron spectrum can be analyzed in several different ways, depending on the physics scenario under consideration. It is possible to set thresholds in the measured spectrum, in order to selectively probe fast ions in different energy regions. This approach has proved useful for studying transient phenomena that require high time resolution, such as the redistribution of fast ions during magnetohydrodynamic instabilities. Another option is to perform direct comparisons between neutron measurements and plasma modeling, by calculating the neutron emission expected from a given modeled fast ion distribution. If the model contains free parameters, such as relative densities of different ion populations, it is possible to estimate these parameters by fitting them to the experimental data. By utilizing the concept of kinematic weight functions, which map the fast ion phase space to the possible neutron energies that the fast ions can give rise to, it is possible to make a model independent estimate of the fast ion distribution. This method allows for combining different fast ion diagnostics in a consistent way, by including the relevant weight functions for the respective diagnostics.

Fast ion measurements of the type described in this paper will be possible to perform with neutron spectroscopy also at ITER, provided that the spectrometers have a dynamic range of at least 3 orders of magnitude (in order to resolve the fast ion spectral features in the presence of the dominating thermonuclear neutron emission).

Acknowledgments

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