Velocity-space interrogation regions of neutron spectrometers

A.S. Jacobsen[1], M. Salewski[1], J. Eriksson[2], G. Ericsson[2], S.B. Korsholm[1], F. Leipold[1], S.K. Nielsen[1], J. Rasmussen[1], M. Stejner[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, Abingdon, OX14 3 DB UK

[1] *Association Euratom - DTU, Technical University of Denmark, Department of Physics, Kgs. Lyngby, Denmark*

[2] *Association Euratom - VR, Uppsala University, Department of Physics and Astronomy, Uppsala, Sweden*

Introduction

Neutrons created in fusion reactions carry information about the ions taking part in the reactions. By measuring the energy spectra of neutrons from a fusion plasma, it is thus possible to gain information on the velocity-distribution of the ions. Here, we describe the velocity-space sensitivity of energy spectra of neutrons produced in the fusion process between a thermal ion and a fast ion [1]. The velocity-space sensitivities of fast-ion diagnostics are described by so-called weight functions. Weight functions have previously been calculated for neutron yield detectors [2], neutral particle analyzers [2], fast-ion D_α spectroscopy (FIDA) [2, 3, 4] and collective Thomson scattering (CTS) [5]. Here we present weight functions for neutron emission spectrometry (NES) and show examples of their applications using data from the time-of-flight neutron spectrometer TOFOR at JET [6, 7].

NES weight functions

NES weight functions, w, relate the measurement, s, of a neutron energy spectrum in the neutron energy range $E_{n,1} < E_n < E_{n,2}$, to the fast-ion velocity-space distribution function f:

$$s\left(E_{n,1}, E_{n,2}, \phi\right) = \iiint w\left(E_{n,1}, E_{n,2}, \phi, E, p, \mathbf{r}\right) f\left(E, p, \mathbf{r}\right) \,\mathrm{d}E\,\mathrm{d}p\,\mathrm{d}\mathbf{r}\,. \tag{1}$$

E and p are the energy and pitch of the fast ions, respectively. ϕ is the angle between the magnetic field and the line-of-sight of the neutron spectrometer. Neutron weight functions can be written as a product of the neutron rate and the probability that a produced neutron will have an energy in the given energy range, given the energy and the pitch of the ions and the angle towards the spectrometer [1]. The part of velocity space accessible by a given part of a neutron energy spectrum is determined by the probability part. The shape of NES weight

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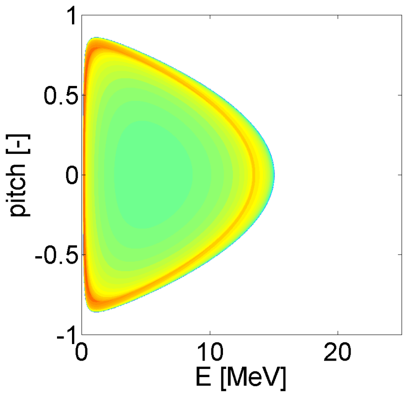
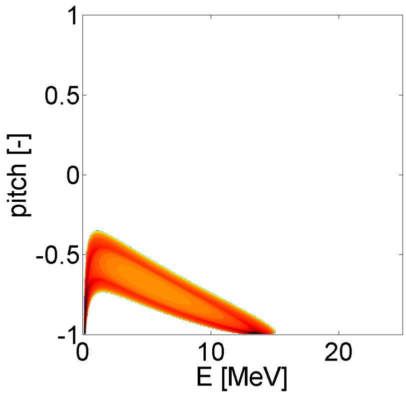


(a) $\phi = 90°$.



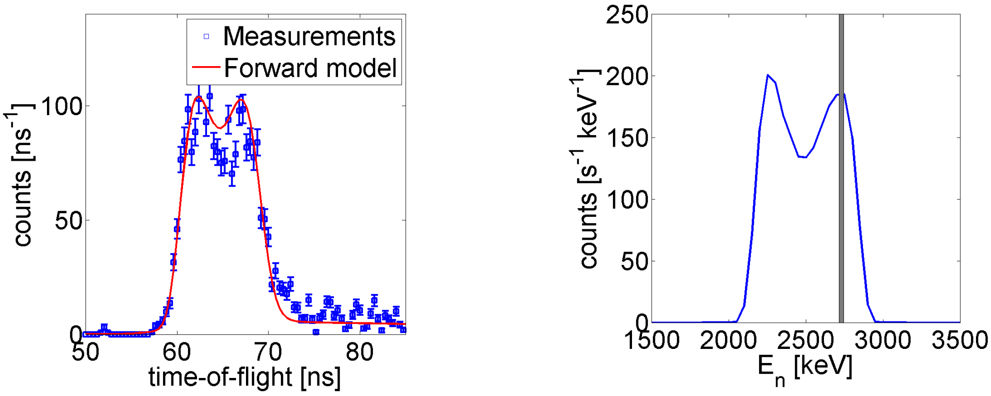
(b) $\phi = 10°$.

Figure 1: Weight functions for $E_n = 2.2$ MeV ± 0.015 MeV and a stationary target distribution.

functions depends strongly on the angle ϕ between the magnetic field and the line-of-sight of the instrument. This is illustrated in figure 1 where the probability part is calculated for a perpendicular view with $\phi = 90°$, and a tangential view with $\phi = 10°$. The white regions in figure 1 correspond to regions in velocity space that cannot contribute to the signal in the given neutron energy range. In figure 1, the probability part is plotted for very high ion energies to show the complete behaviour of the probability part even though ions usually do not have these high energies in a fusion device. Relativistic effects are not considered here. The probability part of the NES weight function is completely symmetric in pitch for a perpendicular view. In contrast, it is highly asymmetric for the tangential view in the neutron energy range between 2.185 MeV and 2.215 MeV where only ions with negative pitch contribute to the signal. Thus, the same neutron energy range of two identical instruments oriented differently with respect to the magnetic field can probe two completely different regions in velocity-space.

Applications

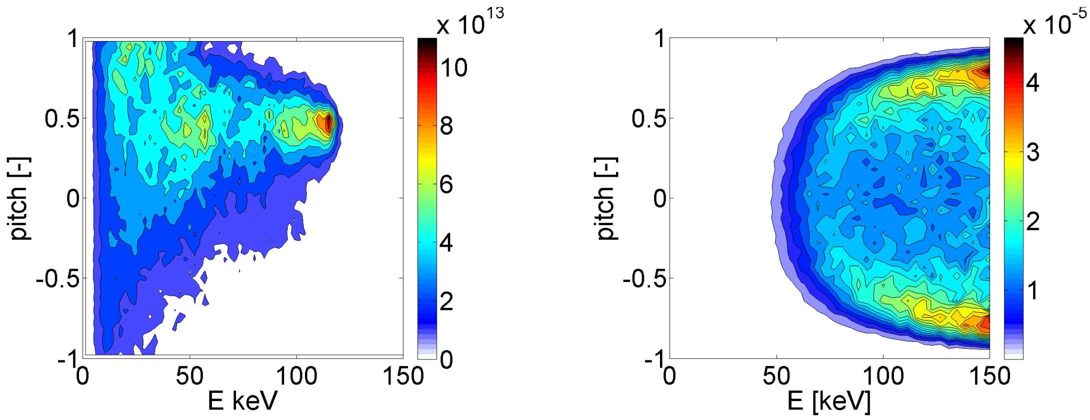
The simplest application of NES weight functions is as an illustration of the so-called interrogation regions. The velocity-space interrogation regions are the part of velocity-space that a given part of a neutron energy spectrum can measure as illustrated in figure 1. Secondly, given a fast-ion distribution function, the product of the distribution function and a weight function shows the origin of the detected signal in a given energy range resolved in velocity space. Figure 2(a) shows a measured time-of-flight spectrum from the neutron time-of-flight spectrometer TOFOR for JET discharge #68138. The spectrum is well described by the synthetic measurement calculated using a forward model. The corresponding neutron energy spectrum is shown in



(a) Time-of-flight spectrum.

(b) Energy spectrum.

Figure 2: Neutron time-of-flight spectrum from JET discharge #68138 and the corresponding neutron energy spectrum calculated using a forward model.



(a) Central fast-ion distribution function in units of ions per keV.

(b) Weight function calculated for $E_n = 2.73$ MeV ± 0.15 MeV in units of neutrons per second per fast ion. A thermal ion temperature of 2.3 keV is used in the calculations.

Figure 3: A central fast-ion distribution function calculated using TRANSP/NUBEAM for JET discharge #68138 and an NES weight function.

figure 2(b) calculated with the forward model. Figure 3(a) shows a central fast-ion distribution function calculated with TRANSP/NUBEAM [8] for the same discharge. Figure 3(b) shows the weight function calculated for the neutron energy range shown as a grey stripe in figure 2(b). A bulk ion temperature of 2.3 keV has been used to calculate the weight function. Figure 4 shows the product of the central fast-ion distribution function and the weight function shown in figure 3. The weight function approach shows that the main part of the measured neutrons in the given neutron energy range are created in fusion reactions involving full-beam-energy ions.

Finally, on the horizon, NES weight functions enable us to combine neutron energy spectra with FIDA and CTS measurements to measure 2D fast-ion velocity distribution functions by tomographic inversion [9, 10].

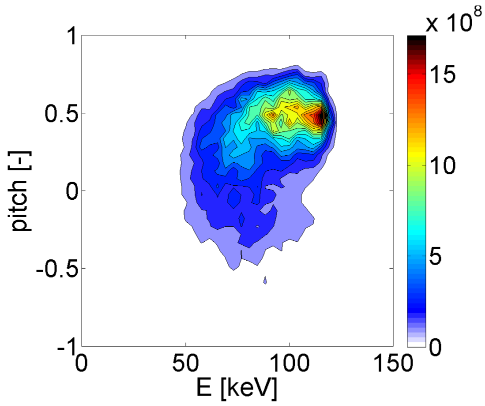


Figure 4: The product of the fast-ion distribution function and NES weight function in units if neutrons per second per keV illustrates which fast ions contribute to the measured signal.

Conclusions

We have developed NES weight functions. This allows us to calculate the interrogation region for any given part of a neutron energy spectrum. Furthermore, the product of a weight function and a given fast-ion distribution function shows the velocity-space origin of the signal in a given neutron energy range. These results are general and can be applied to any neutron energy spectrometer.

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