Measuring RF-accelerated fast ions with DD and DT neutron spectroscopy: comparison of velocity-space sensitivity

J. Eriksson[1], E. Andersson-Sundén[1], S. Conroy[1], A. Dal Molin[2], G. Ericsson[1], B. Eriksson[1], J. Garcia[4], A. Hjalmarsson[1], L. Hägg[1], H. Järleblad[5], D. Keeling[6], D. King[6], K.K. Kirov[6], E. Lerche[6,7], C.F. Maggi[6], M. Maslov[6], M. Nocente[2,3], D. Rigamonti[2], M. Salewski[5], M. Tardocchi[2], and JET Contributors[†]

[1]*Uppsala University, Dept. of Physics and Astronomy, SE-75120 Uppsala, Sweden*

[2]*Institute for Plasma Science and Technology, National Research Council, 20125 Milan, Italy*

[3]*Dipartimento di Fisica, Università di Milano-Bicocca, 20126 Milan, Italy*

[4]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

[5]*Department of Physics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

[6]*Culham Centre for Fusion Energy (CCFE), Abingdon OX14 3DB, United Kingdom*

[7]*Laboratory for Plasma Physics, LPP-ERM/KMS, TEC Partner, 1000 Brussels, Belgium*

Two of the most important reactions in a fusion plasma are the D(d,n)^{3}He (DD) and T(d,n)^{4}He (DT) reactions. Both these reactions produce neutrons, and if a neutron spectrometer is used to resolve the emitted neutrons in energy it is possible to infer various features of the energy distributions of D and T in the plasma. A common application of neutron spectroscopy is the study of MeV-range fast ions produced by the application of radiofrequency (RF) heating, which typically result in distinct high-energy tails in the DD neutron spectrum [1][2][3].

The DD and DT reaction cross sections exhibit different dependences on the reactant energies [4]. For the case of a deuteron beam hitting a stationary D or T target, the DD cross section increases monotonically with the deuteron energy up to about 1 MeV, while the DT cross section peaks already for deuteron energies in the 100 keV range. In this contribution, we examine these different velocity-space sensitivities in detail, to quantify what parts of a given fast ion population that provide the largest contributions to the DD and DT neutron spectra, respectively. This information is important in order to correctly interpret neutron spectroscopy measurements, e.g. when validating a simulated fast ion distribution by comparing the corresponding calculated spectrum with measurements.

We first compute a selection of neutron energy spectra from a plasma heated with both neutral beam injection (NBI) and RF heating, using the Monte Carlo code DRESS [5]. We consider a plasma heated with 100 keV D NBI and compute the corresponding slowing-down distribution from a Fokker-Planck equation [6]. We then assume that a fraction of the deuterons in the plasma are accelerated to high energies through the application of RF heating. We do not consider a specific RF heating scenario here; instead we aim to capture the gross features of the

[†]See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

distribution arising from many different RF scenarios, by letting the energy distribution be given by a Maxwellian with different temperatures and by letting the pitch* distribution be centred closely around zero (thus mimicking the tendency of RF heating to accelerate mainly the perpendicular component of the ion velocity [6]). The calculated DD and DT neutron spectra corresponding to reactions between deuterons from the above distributions and ions from the thermal bulk plasma is shown in Figure 1, for neutron emission perpendicular to the plasma magnetic field (the absolute normalization of these spectra depends on the choices of densities of the different ion distributions, but the precise values are not important here). By comparing these neutron spectra for the different RF accelerated D populations, it is seen that the considered fast D distributions have a more pronounced impact on the DD spectrum than on the DT spectrum. Figure 1 also shows that the interesting regions of the neutron spectra (for measuring deuterons with energies above the NBI energy of 100 keV) are $E_n > 3$ MeV for DD neutrons and $E_n > 15$ MeV for DT neutrons, so in what follows we will only consider the signal in these parts of the spectra. We will refer to this region as the “neutron RF tail”.

The spectra were calculated using Monte Carlo methods, so it is straightforward to inspect the fast deuteron energies of each event and generate the spectrum of deuterons that actually take part in the fusion reactions giving rise to the neutrons in the neutron RF tail. Such spectra are shown in Figure 2, for each of the RF accelerated cases considered in Figure 1. We see that for the DD case, the spectrum of reacting deuterons extends to higher energies than in the corresponding DT case. Consequentially, we can deduce that energetic deuterons contribute to the signal in the RF neutron tail to a larger extent in the DD case than in the DT case. From such spectra of reacting deuterons, we can directly obtain quantitative information about how much deuterons in a given energy range contribute to the signal in the neutron RF tail. For instance, when T_{rf} is 75 keV, 90 percent of the DD neutron RF tail signal is generated by deuterons with energies below 475 keV. For the DT signal, the corresponding number is 325 keV. For $T_{rf} = 300$ keV, the same calculation gives 1425 keV for DD and 825 keV for DT.

The above calculations were done for a specific example, with simple analytical expressions for the RF accelerated deuteron populations, but the same procedure can be directly applied to any kind of fast ion distribution. As a more realistic example, we consider a TRANSP [7] simulation of discharge 99965 from the recent DT experimental campaign at the JET tokamak. The plasma had a T/D mixture of about 90/10 and was heated with about 29 MW of NBI and 4 MW of RF, tuned to the fundamental cyclotron frequency of deuterium. The details of this discharge will be described in other publications; here we focus only on the fast deuterium distribution obtained from the TRANSP simulation, shown in Figure 3. From this distribution

*Here, the pitch of a plasma ion is defined as $v_{\parallel}/v$, where v is the particle speed and $v_{\parallel}$ is its velocity component parallel to the plasma magnetic field.

we can, just like in the previous example, calculate the DT neutron spectrum and the corresponding spectrum of reacting deuterons. From these results we then deduce that, for this particular deuterium distribution, the average energy of the reacting deuterons is 135 keV and 90 percent of the signal in the DT neutron RF tail is generated by deuterons in the range [90, 245] keV (again for the case of neutron emission perpendicular to the magnetic field).

Quantifying what part of the fast ion distribution that contributes to the signal in a given neutron spectroscopy measurement is valuable when validating simulated distributions against measured neutron spectroscopy data. The results presented here suggest that a DT spectrometer will typically be sensitive mainly to fast deuterons up to a few hundred keV, whereas a DD spectrometer is sensitive to significantly higher energies (similar results will apply for fast tritons). It can still be possible to measure deuterons (or tritons) with MeV-range energies using a DT spectrometer, but it places higher demands on statistics, and/or require a larger number of fast ions, than if the same fast ion population were measured with a DD spectrometer.

To conclude, in this contribution we have developed and demonstrated a method for assessing how much different parts of a given fast ion distribution contribute to the signals measured with a neutron spectrometer. The method is particularly well suited to use when the neutron spectrum is calculated with Monte Carlo methods, which is the typical case when validating fast ion distributions from plasma modelling codes such as TRANSP, ETS and ASCOT. The method can be used to better understand what parts of a modelled fast ion distribution that can, and cannot, be validated with neutron spectroscopy.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] C. Hellesen *et al* 2013 *Nucl. Fusion* **53** 113009
[2] M. Salewski *et al* 2017 *Nucl. Fusion* **57** 056001
[3] A. Sahlberg *et al* 2021 *Nucl. Fusion* **61** 036025
[4] H.-S. Bosch and G.M. Hale 1992 *Nucl. Fusion* **32** 611
[5] J. Eriksson *et al* 2016 Comp. Phys. Commun. **199** 40
[6] T.H. Stix 1975 *Nucl. Fusion* **15** 737
[7] J. Ongena *et al* 2012 Fusion Science and Technology **61** 180

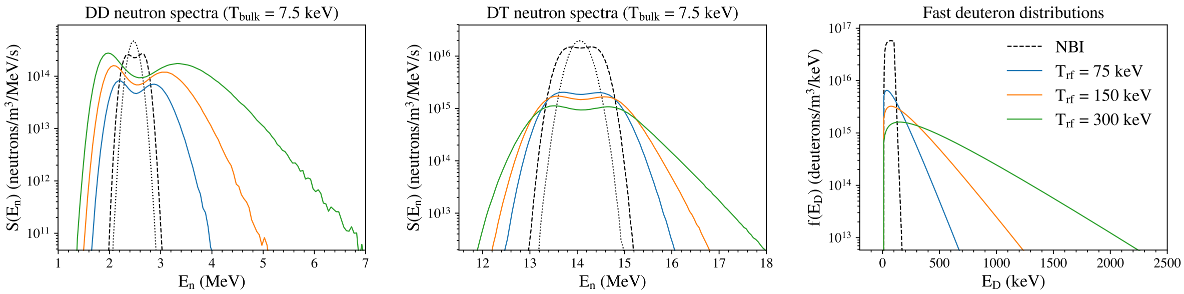

Figure 1. Calculated DD (*left*) and DT (*middle*) neutron energy spectra for several different distributions of fast deuterons (*right*). Each neutron spectrum is the result of reactions between the corresponding deuteron distribution and a thermal bulk plasma with 7.5 keV temperature. The neutron spectrum from purely thermonuclear reactions is also shown for comparison (dotted lines in left and middle panels). The fast deuteron distributions are (i) one NBI slowing down distribution and (ii) several distributions of RF-accelerated deuterons, modelled as Maxwellian energy distributions with different temperatures. When calculating the neutron spectra from these distributions, the pitch (i.e. $v_{\parallel}/v$) of the fast deuterons is assumed to be isotropically distributed in the range [0.5,0.7] for the NBI (roughly reflecting the effect of NBI alignment at JET) and [-0.1,0.1] for the RF (mimicking the tendency of RF heating to accelerate mainly the perpendicular component of the ion velocity).

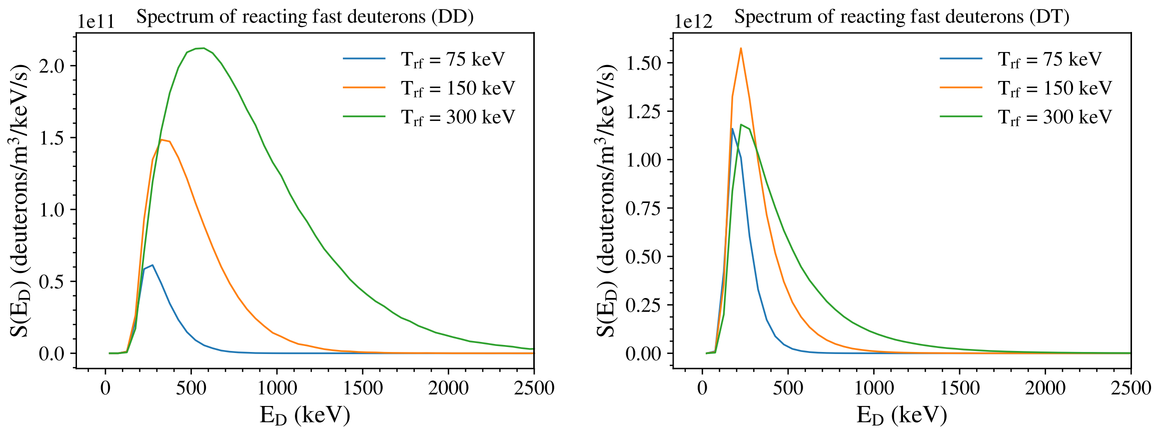

Figure 2. Calculated spectra of deuterons that take part in DD reactions (*left*) and DT reaction (*right*), for the neutron spectra in Figure 1. Only reactions that give rise to neutrons in the neutron RF tail (see main text for details) are considered.

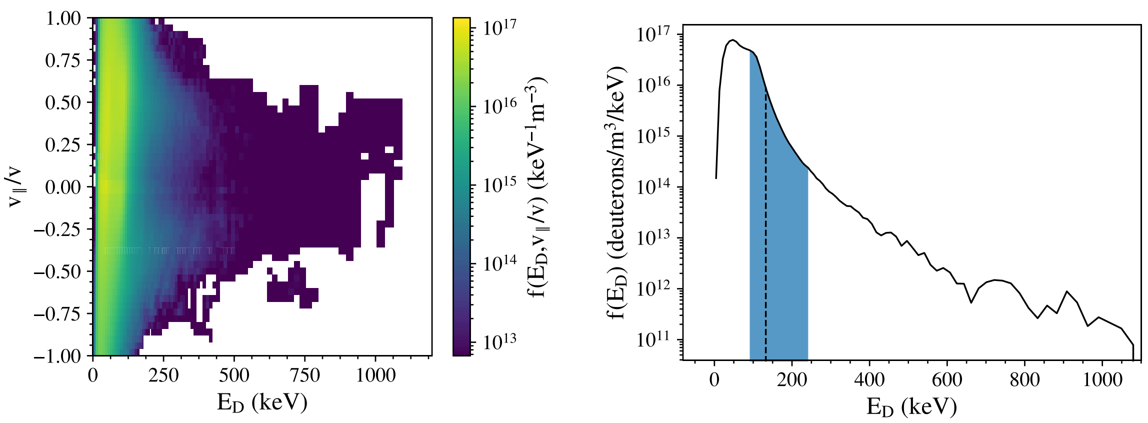

Figure 3. *Left:* Fast deuterium distribution obtained from a TRANSP simulation of JET discharge 99965, resolved in both energy and pitch. *Right:* The same distribution integrated over all pitch values (black line). The dashed line shows the average energy of the reacting deuterons (for neutron emission perpendicular to the plasma magnetic field) and 90 percent of the signal in the neutron RF tail originates from the shaded region.