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Fast-ion orbit origin of neutron emission spectroscopy measurements in the JET DT campaign

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Abstract

In the JET DTE2 deuterium-tritium campaign, neutron diagnostics were employed to measure 14 MeV neutrons originating from D(T,n)⁴He reactions. In discharge 99965, a diamond matrix detector (KM14) and a magnetic proton recoil (MPRu) detector with a vertical and an oblique line-of-sight were used, respectively. At the timepoints of interest, a significant decrease in the expected diagnostic signals can be observed as electromagnetic wave heating in the ion cyclotron range of frequencies (ICRF) is switched off. Utilizing only TRANSP simulation data, the fast-ion distribution is found to have been likely composed mostly of trapped orbits. In contrast, analysis performed using orbit weight functions revealed that the majority of neutrons in the KM14 $E_d = 9.3$ MeV and MPRu $X_{cm} = 33$ cm measurement bins are to have originated from fast deuterium ions on co-passing orbits. This work explains the perhaps surprising results and shows that the relative signal decrease as ICRF heating is switched off is largest for counter-passing orbits. Finally, for the magnetic equilibria of interest, it is shown how stagnation orbits, corresponding to ~1% of the fast-ion distribution, were completely unobservable by the KM14 diagnostic.

^a See Mailloux *et al* 2022 (https://doi.org/10.1088/1741-4326/ac47b4) for JET Contributors.
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(Some figures may appear in colour only in the online journal)

1. Introduction

The recent deuterium-tritium (DT) campaign [1, 2] at the Joint European Torus (JET) [3] marked an important milestone on the path to viable fusion energy for the production of electricity for society. Compared with the previous JET DT campaign in 1997 (JET-DTE1), this campaign (JET-DTE2) planned a twenty-fold increase in the budget of reprocessed tritium gas (\sim 700 g vs \sim 35 g) and more than a five-fold increase in the budget of produced DT-neutrons (1.7×10^{21}) vs 3×10^{20}) [1, 4]. To measure the fusion-born DT-neutrons during such plasma operation is therefore seen as vital; both to ensure that the neutron budget is respected and to confirm fusion power output, but also to provide experimental data to reconstruct the distribution of fast ions [5-11]. The first generation of future fusion power plants, where fast ions will provide the bulk of the plasma heating, are envisioned to operate solely with DT fuel, due to the favorable cross-section of the $D(T,n)^4$ He fusion reaction [12]. Understanding the results from the JET-DTE2 campaign are therefore seen as crucial for the successful operation of such fusion power plants, as well as next-step magnetic confinement devices such as ITER [3, 13, 14] and SPARC [15, 16].

Compared to the 2.45 MeV neutrons produced in $D(D,n)^{3}$ He reactions, a different diagnostic setup if often required to measure the 14 MeV neutrons produced in $D(T,n)^4$ He reactions [17–19]. For JET-DTE2, two neutron diagnostics that were employed were the upgraded magnetic proton recoil diagnostic (MPRu) [18] and the diamond matrix diagnostic [20] (KM14). Given their frequent use, it can be argued to be of importance to investigate what type of fast ions can produce the DT-neutrons measured by the two diagnostics. Or, in other words, how sensitive these diagnostics are to fast ions with different energies, pitch ($p = v_{\parallel}/v$ where v is the speed and v_{\parallel} is the velocity component parallel to the magnetic field), major radius R and vertical positions z. Given the measurement of a certain number of neutrons with a certain energy, how many of these are likely to have originated from co-passing, counter-passing and trapped fast ions, and in what fractions? Are there fast-ion trajectories (also known as orbits) that are not observable at all by the MPRu and the KM14 diagnostics?

To answer these questions, it is convenient to employ socalled *weight functions* [6–8, 21–33]. Given the assumption of a linear relationship between a measurement signal *s* and the fast-ion distribution *f*, the weight functions provide the link between *s* and *f* as [34–36]

$$s = \int w(\mathbf{x}, \mathbf{v}) f(\mathbf{x}, \mathbf{v}) \, \mathrm{d}\mathbf{x} \mathrm{d}\mathbf{v}, \tag{1}$$

where \mathbf{x} is the position and \mathbf{v} the velocity, defining the phase space, and the integral is computed for the phase-space areas of

Table 1. Neutron flux in 10^5 per second for the KM14 diamondmatrix diagnostic for JET shot No 99965 at 8.4 s. The total flux isgiven by the sum of the neutrons contributions fromthermal-thermal and beam-thermal reactions. The fractions aresimilar for the MPRu diagnostic.

Thermal-thermal	Beam-thermal	Total
0.45	4.05	4.5

interest. However, the validity of the linear relationship relies on the assumption that the fraction of neutrons originating from beam-thermal reactions is much larger than the fraction of neutrons originating from thermal-thermal and/or beambeam reactions [7]. With 'beam', we mean (fast) ions heated to energies well above that of the thermal ions via neutral beam injection (NBI) and/or electromagnetic wave heating in the ion cyclotron range of frequencies (ICRF) [37]. With 'thermal', we mean the bulk plasma below the fast-ion energy range. For JET discharge 99965 examined in this paper, the beamthermal reactions dominate, as can be seen in table 1 making orbit weight functions suitable to use for analysis.

In this study, we use fast-ion data from TRANSP [38] via the NUBEAM [39] module (in future studies, fast-ion data from tomographic reconstruction from experimental measurements can be used as well). TRANSP with NUBEAM were used in simulations of fast-ion dynamics during JET DD and DT campaigns and have been proven able to produce reliable data consistent with various neutron and fast-ion diagnostics [40–42].

Orbit weight functions can be used to decompose a computed diagnostic signal in terms of orbit-type constituents [34]. If the computed signal matches the experimental data adequately well, and equation (1) still holds after a discretization of phase space, the most likely fast-ion orbit origin of a diagnostic (e.g. neutron) measurement can be calculated. Given the simulation, we can, for example, say in what fractions the fast-ion orbit types (co-passing, counter-passing, trapped, potato, stagnation and counter-stagnation) contribute to measurements of neutrons with a specific detected energy (which is up- or downshifted with respect to the nominal birth energy). With the orbit weight functions alone, we can also identify fast-ion orbits that are not observable by a certain diagnostic.

In this work, orbit weight functions have been used to perform a *fast-ion orbit analysis* of the MPRu and KM14 diagnostics in JET DT-shot No 99965 at 7.9 and 8.4 s using synthetic measurements. The difference between the signals at the two timepoints, corresponding to a decrease in measured neutrons, is also investigated, and causes in terms of fast-ion orbits are identified. The method of using orbit weight function to perform a fast-ion orbit analysis is novel. It is generally faster and has results that are easy to interpret, compared to traditional methods such as velocity-space tomography, orbit tomography and parameter scans (to fit experimental data). The method can be applied to any fusion experiment and toroidally symmetric magnetic confinement device. This paper is organized as follows. In section 2, JET pulse No 99965 is discussed, along with the diagnostic setup and method of analysis. In section 3, the effects of switching ICRF heating from on to off in JET pulse No 99965 are discussed in terms of weight functions and signals. In section 4, the decrease in diagnostic signal as ICRF heating is switched off is analyzed in terms of orbit types. Finally, a conclusion follows in section 5.

2. Experimental and diagnostics setup

JET discharge No 99965 was a DT shot with a hydrogen minority $\mathcal{X}[H] \sim 1\%$ [43]. Heating schemes included NBI and ICRF. Deuterium beams were shot into a tritium-rich plasma where the mixture was $n_D/n_T \sim 0.15/0.85$. Together with solely D-NBI having been employed in shot No 99965, we can further strengthen our confidence in using weight functions for analysis, since the few fast T ions that appear will have little thermal D to react with. Therefore, the fast ions were mostly deuterium ions, and the thermal ions were mostly tritium ions, and most DT reactions will thus be between fast deuterium and slow tritium. Pulse 99965 was run to experimentally try to quantify the effect of fundamental D heating on the fusion productivity. Time traces of the heating power, electron and ion temperature on axis, and the deuterium and tritium density onaxis can be seen in figure 1. For the ICRF, heating deuterium at the fundamental frequency of 29 MHz was used. The magnetic field strength on-axis was $B_0 = 3.85$ T, and the plasma current was $I_p = 2.45$ MA. In figure 1(b), we can observe the electron and ion temperatures on-axis as functions of time. The deuterium and tritium temperatures are assumed equal. We can observe how the plasma is without sawtooth activity in the time windows of interest (stable T_e). T_i is only stable in the second time window. However, since we are interested in averages over the whole time windows and since T_i only causes a broadening of the high sensitivity regions of weight functions [21], the data is suitable for use in this study. As we can see in figures 1(a) and (d), when the ICRF heating was active at 7.9 s, the fast-ion distribution (figure 1(d)) has a 'tail' that stretches up into the megaelectronvolt (MeV) range. When ICRF heating was off at 8.4 s, the fast-ion high-energy tail has almost completely disappeared.

To investigate the measurement of DT-neutrons (originating from the interaction between the *fast-ion deuterium* distribution and the *thermal tritium* plasma), models of the MPRu and diamond matrix sightlines were used. They have been visualized in figure 2. The MPRu has an oblique line-ofsight(LOS) which views the plasma in the counter-clockwise direction. The KM14 has an almost completely vertical LOS and views the plasma from above. In brief, the MPRu works as follows [18]. Neutrons from the plasma pass through a



Figure 1. (*a*) Time traces for the NBI and ICRF heating of JET shot No 99965. (*b*) The electron and ion temperatures on-axis, as functions of time. (*c*) The deuterium and tritium densities on-axis, as functions of time. (*d*) The energy dependence of deuterium fast-ion distribution (integrated over the entire plasma). The solid and dotted profiles correspond to the fast-ion distribution averaged over the time windows denoted by the solid and dotted vertical lines, respectively. Electron and ion temperatures and densities are predicted by TRANSP, and are consistent with Thomson scattering and charge exchange measurements, respectively. TRANSP ID is 99965K73.

collimator into the diagnostic, where they may hit a thin polythene (CH₂) foil. Some neutrons scatter elastically, and result in protons escaping the foil. In the internal magnetic field (|B| < 1 T) of the MPRu, the protons travel in curved trajectories and impact a plane detector. The energy of the protons, and thus the neutrons, can be deduced via the proton impact positions. For measuring DT-neutrons, the MPRu is more suitable to employ compared to e.g. time-of-flight diagnostics such as TOFOR [17], due to its more favorable energy resolution and signal-to-background (S/B) noise ratio [17, 18].

Continuing, the KM14 diagnostic consists of a matrix of 12 Single crystal Diamond Detectors (SDDs) [20]. The incoming neutrons are detected via the collection of electron/hole



Figure 2. Sightlines for the MPRu and KM14 diagnostics, projected onto the JET poloidal cross-section in (a) and viewed from above in (b). Examples of all six standard fast-ion drift orbit types have also been plotted in (a), including their maximum major radius coordinate (R_m) (colored points). Trajectories are computed for deuterons. The red and purple arrows in (b) show directions of the plasma current and toroidal magnetic field, respectively. Magnetic flux surfaces for JET pulse 99965 at 7.9 s have been included in (a) as dotted lines.

pairs generated by the charged particles produced in nuclear reactions between the neutrons and carbon nuclei of the SDDs Specifically, for 14 MeV DT-neutrons, the α particle of the ${}^{12}C(n,\alpha)^9$ Be reaction releases its energy in the detector, producing a peak in the recorded spectrum. The position and width of the peak depends on the incoming neutron energy. The total energy of the α and ⁹Be is $E_{\alpha} + E_{Be} = E_n - 5.7$ MeV. Even though the KM14 shares LOS with TOFOR [17, 20] at JET, to measure DT-neutrons the KM14 is preferred due to its H Järleblad et a



Figure 3. Instrumental response function for the KM14 diamond matrix [20] and MPRu diagnostics [18] at JET, for detecting neutrons in the range of 14 MeV.

more favorable resolution and S/B ratio, similar to the MPRu. However, the KM14 has a perpendicular LOS while the MPRu has an oblique LOS w.r.t the B-field. This will make the KM14 sensitive to neutrons originating from fast ions in different parts of phase-space compared to the MPRu [7, 8, 34, 44].

To model the instrumental response (diagnostic resolution) of the diagnostics, the following response functions were used. For the KM14, a Gaussian response function centered around 5.7 MeV and with a full-width at half-maximum of 100 keV was used. It has been visualized in figure 3(a). For the MPRu, a transfer matrix between incoming neutron energies and measured proton impact positions was used, and has been visualized in figure 3(b). It was computed via Monte Carlo methods [18].

With the model of the diagnostic sightlines in figure 2 and the instrumental response functions, we can use the DRESS code [45] to compute the expected measurement signals, given the deuterium fast-ion distributions f(E, p, R, z) (their energy dependencies f(E) are given in figure 1(d)) and the thermal tritium plasma profiles shown in figures 4(a) and (b). E is energy, p is the pitch, R is the major radius coordinate and



Figure 4. The (*a*) density and (*b*) temperature profiles for the bulk plasma of JET discharge 99965 at 7.9 and 8.4 s. The temperature profiles were assumed to be the same for deuterium and tritium at both timepoints. The profiles were predicted by TRANSP, and are consistent with Thomson scattering and charge exchange measurements. TRANSP ID is 99965K73.

z is the vertical coordinate, respectively. The resulting synthetic signals for the MPRu and the KM14 diagnostics can be viewed in figure 5. The $E_{dep} = 9.3 \text{ MeV}$ and X = 33 cmmeasurement bins have been chosen as measurement bins of interest for this study, since the upper end of a diagnostic spectrum is where information about the fast-ion distribution is located. We can observe how there is a decrease in the expected signals for both diagnostics when the ICRF heating has been switched off. This decrease is significant and noticeable across both diagnostic spectra. Most of the decrease is likely to originate from the loss of the fast-ion high-energy tail (figure 1(d)) as ICRF heating is switched off. With the Orbit Weight Computational Framework (OWCF) [46], we can investigate the origin of this signal decrease in more detail. By splitting the synthetic signals into their orbit-type constituents, a detailed analysis can be performed in terms of fast-ion orbit types (co-passing, counter-passing, trapped etc). Examples of all fast-ion orbit types are shown in figure 2(a). Using the OWCF, we can also split the fast-ion distribution



Figure 5. The synthetic diagnostic signals for the (*a*) KM14 and (*b*) MPRu diagnostics, computed using the DRESS [45] code with models of the sightlines, instrumental response functions and TRANSP [38] data for JET shot 99965 at 7.9 and 8.4 s. In (*c*) and (*d*), the same signals have been plotted with logarithmic scaling for the *y*-axis. The black lines mark the diagnostic measurement bins of interest, $E_{dep} = 9.3$ MeV and $X_{cm} = 33$ cm, for analysis in sections 3 and 4.

itself into its orbit-type constituents, thereby enabling further analysis. This is done in the following section.

3. ICRF heating on/off effects

When ICRF heating is switched off, the density and temperature profiles for the thermal plasma change (figure 4). Since the phase-space sensitivity [6, 8, 23, 27, 28, 30, 31, 47] of a fast-ion diagnostic depends on the thermal plasma profiles, one might expect the *fast-ion orbit sensitivity* [34, 35, 47–49] to change as well. The fast-ion orbit sensitivity quantifies how sensitive a diagnostic is to fast ions on different drift orbits. This quantity can be parameterized in different orbit coordinates. In this study, due to its simplicity, we have chosen to work with the so-called *orbit-space coordinates* [34, 49–52]. These are the energy *E* of the fastion, the maximum major radius position R_m along the orbit and the pitch p_m at R_m . An (E, p_m, R_m) triplet uniquely labels any possible fast-ion guiding-center trajectory in a tokamak



Figure 6. A 2D slice of constant fast-ion energy E = 250 keV of the full 3D orbit weight function for the $E_{dep} = 9.3 \text{ MeV}$ measurement bin of the KM14 neutron diamond matrix diagnostic at (a) 7.9 and (b) 8.4 s of JET DT shot 99965, respectively. The marginal change between timepoints is representative for other 2D slices of constant fast-ion energy and the MPRu diagnostic as well.

plasma (assuming toroidal symmetry, collisionless regime for the fast ions and $r_L/\delta_B \ll 1$ where r_L is the fast-ion Larmor radius and δ_B is the lengthscale over which the magnetic field changes). In orbit-space coordinates, equation (1) takes the form

$$s = \iiint w(E, p_{\rm m}, R_{\rm m}) f(E, p_{\rm m}, R_{\rm m}) \,\mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m}. \tag{2}$$

As we can observe in figure 6, the change in shape of the non-zero regions of the fast-ion orbit sensitivity is only marginal between the two timepoints of interest for this study. However, the sensitivity increases overall. We can therefore conclude that most of the decrease in the diagnostic signals as ICRF heating is switched off (figure 5) is likely due to the retraction of the high-energy tail of the fast-ion deuterium distribution (figure 1(*d*)). But as the high-energy tail disappeares when ICRF heating is switched off, how do the individual populations of orbit types change?

To answer this question, we can split the fast-ion orbitspace distribution $f(E, p_m, R_m)$ into its orbit-type constituents. Mathematically, this can be expressed as

$$N_f = \iiint f(E, p_m, R_m) \, \mathrm{d}E \mathrm{d}p_m \mathrm{d}R_m \tag{3}$$

$$=\sum_{h}\iiint_{h}f(E,p_{\rm m},R_{\rm m})\,\mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m}\tag{4}$$

$$=\sum_{h}N_{f,h}$$
(5)

where N_f is the total number of fast ions, $N_{f,h}$ is the number of fast ions with a drift orbit trajectory of type h and h includes all valid standard orbit types, i.e. h =co-passing, trapped, counter-passing, potato, stagnation, counter-stagnation. By not effecting the energy integral in (4), we can obtain the energy dependence of the orbit-type constituents of the fast-ion distribution. That is,

$$N_{f,h} = \iiint_{h} f(E, p_{\rm m}, R_{\rm m}) \,\mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m} \tag{6}$$

$$= \int f_h(E) \,\mathrm{d}E \tag{7}$$

where $f_h(E)$ is the energy dependence of orbit-type constituent *h*. Also note that



Figure 7. A plot showing the split of the energy dependence of the fast-ion distribution into its orbit-type constituents. The sum of the colored lines equals the black line in figure 1 (minus the more 'exotic' potato, stagnation and counter-stagnation orbit types; omitted for clarity). The solid and dotted profiles correspond to the time windows at 7.9 and 8.4 s, respectively. Zoomed-in linear scale included as an inset, showing trapped dominance. The fast-ion distribution TRANSP ID is 99965K73.

$$f(E) = \sum_{h} f_{h}(E) = \iint f(E, p_{\rm m}, R_{\rm m}) \,\mathrm{d}p_{\rm m} \mathrm{d}R_{\rm m} \tag{8}$$

where f(E) is the energy dependence of the fast-ion distribution, plotted in figure 1(*d*). The energy dependencies of the orbit-type constituents of the fast-ion distribution, $f_h(E)$, have been plotted in figure 7. As shown in figure 7, as ICRF heating is switched off, regardless of orbit type, all orbit-type distributions retract downwards in fast-ion energy. For some higher energies that are still populated (e.g. $E \approx 250 \text{ keV}$), the populations are approximately two orders of magnitude smaller. For the counter-passing distribution at $E \approx 250 \text{ keV}$, the population is almost six orders of magnitude smaller.

In figure 7, we can also observe how the peak of the trapped orbit population is the highest of all orbit types. One might therefore expect a fast-ion diagnostic signal s to be a result of DT-neutrons originating from mostly trapped orbits. However, as discussed earlier, a diagnostic signal s can be written as the result of a multiplication between the fast-ion distribution fand the weight function *w* of the diagnostic, i.e. $s = \int w f d\mathbf{x} d\mathbf{v}$. Similarly to f(E), we can examine the energy dependence of the weight function w and split it into its orbit-type constituents. By doing this, we can examine how sensitive the diagnostics are to different orbit types as functions of fast-ion energy. However, a weight function has dimensions of signal per ion. To investigate e.g. energy dependence, we therefore need to take averages instead of integrating, to take the orbit-space metric into account. Mathematically, this can be expressed as

$$\bar{w}_h(E) = \left(\iint_h \mathrm{d}p_\mathrm{m}\mathrm{d}R_\mathrm{m}\right)^{-1} \iint_h w(E, p_\mathrm{m}, R_\mathrm{m}) \,\mathrm{d}p_\mathrm{m}\mathrm{d}R_\mathrm{m}.$$
 (9)

The dependence on upper and lower diagnostic energy bin $(E_{d,1}, E_{d,2})$ has been omitted for brevity. Even though the average orbit sensitivity does not account for specific fast-ion

distributions, as we shall see it is sufficient for the discussion in this study.

The energy dependence of the average orbit sensitivity for each orbit type has been computed and shown for the KM14 and MPRu diagnostics in figures 8 and 9, respectively. As we can observe, for the $E_{dep} = 9.3 \text{ MeV}$ measurement bin of the KM14 diagnostic, the average orbit sensitivity is highest for counter-passing orbits, followed by co-passing orbits, followed finally by trapped orbits. The peaks of the average orbit sensitivity of trapped orbits are about half the height of the co-passing peaks, and about a third of the height of the counter-passing peaks. We would therefore expect a corresponding reduction and increase in the signal contribution from trapped and passing orbits, respectively. For the MPRu and the X = 33 cm measurement bin, the peak of the average orbit sensitivity for co-passing ions is almost 6 times higher than the peak of the average orbit sensitivity of trapped ions. Therefore, even if we had a fast-ion distribution consisting of six times as many trapped as co-passing orbits, we could expect the measurement of a proton at X = 33 cm to be (roughly) just as likely to have originated from a trapped orbit as from a co-passing orbit.

In figures 8 and 9, it is also interesting to note that the average orbit sensitivity increases in general when ICRF heating is switched off, as discussed already for figure 6. This is likely due to the general increase of the thermal tritium density profile (figure 4(*a*)) as ICRF heating is switched off, which would affect the orbit sensitivity more directly than the thermal tritium temperature profile (figure 4(*b*)) ($w \propto n_{\text{thermal}}$ while T_{thermal} just creates a blurring effect on *w* via the sampling of the thermal Maxwellian temperature distribution). In addition, the relative increase of the thermal tritium density profile ($\approx 20\%$) is similar to the relative increase of the sensitivity peaks ($\approx 20\%$), further supporting the hypothesis. However, this only holds for the KM14 diagnostic (figure 8), for which the increase in sensitivity is more pronounced. This is likely resolved by the fact that KM14 has a LOS observing a larger



Figure 8. A plot showing the split of the energy dependence of the KM14 orbit weight function (average) for the $E_{dep} = 9.3 \text{ MeV}$ measurement bin into its orbit-type constituents. The solid and dashed profiles correspond to the time windows at 7.9 and 8.4 s, respectively. For both timepoints, the orbit sensitivity was mapped only for the energy range of interest, i.e. where f(E) > 0. The profiles correspond to averages for each orbit type and energy.



Figure 9. A plot showing the split of the energy dependence of the MPRu orbit weight function (average) for the X = 33 cm measurement bin into its orbit-type constituents. The solid and dashed profiles correspond to the time windows at 7.9 and 8.4 s, respectively. For both timepoints, the orbit sensitivity was mapped only for the energy range of interest, i.e. where f(E) > 0. The profiles correspond to averages for each orbit type and energy.

portion of the plasma center compared to the outer plasma. A change in the plasma center (figures 4(a) and (b)) would thus be likely to result in a larger change in the orbit sensitivity, compared to e.g. the MPRu with a less poloidally localized LOS.

$$=\sum_{h}\iiint_{h} w(E,p_{\rm m},R_{\rm m})f(E,p_{\rm m},R_{\rm m})\,\mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m} \qquad (11)$$

$$=\sum_{h}s_{h},$$
(12)

4. Orbit origin of signal loss

Having discussed the change of the fast-ion distribution f and the orbit sensitivity w as ICRF heating is switched off in section 3, we are now ready to investigate the diagnostic signal s in terms of orbit types. This can be done similar to (4) and (9) by splitting (2) into its orbit-type constituents. Mathematically, this can be expressed as

$$s = \iiint w(E, p_{\rm m}, R_{\rm m}) f(E, p_{\rm m}, R_{\rm m}) \, \mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m} \tag{10}$$

where
$$s_h$$
 is the signal contribution from orbit type *h*. It can
be helpful to note that $\bar{w}(E)$ (discussed above and plotted
in figures 8 and 9) is not used when splitting the signal *s*
into its orbit-type constituents, but the full weight function
 $w(E, p_m, R_m)$ is used.

As we can observe in figure 10, for the measurement bins of interest $E_{dep} = 9.3 \text{ MeV}$ and X = 33 cm, the signals from all orbit types decreases as ICRF heating is switched off (even though the overall sensitivity increases, as discussed above). We can also observe how the KM14 and MPRu signals at $E_{dep} = 9.3 \text{ MeV}$ and X = 33 cm are dominated by contributions from co-passing orbits, even though the trapped fast-ion



Figure 10. The (synthetic) diagnostic measurements at $E_{dep} = 9.3$ MeV and X = 33 cm for the (*a*) KM14 and (*b*) MPRu diagnostics, respectively, split into their most likely orbit-type constituents. The sum of the solid bars in (*a*) and (*b*) equals the value of the solid lines in figures 5(a)/(c) and (b)/(d) at $E_{dep} = 9.3$ MeV and X = 33 cm, respectively. The sum of the striped bars in (*a*) and (*b*) equals the value of the dotted lines in figures 5(a)/(c) and (b)/(d) at $E_{dep} = 9.3$ MeV and X = 33 cm, respectively.

orbit population is the largest (figure 7). As previously discussed, this is because of the relatively high orbit sensitivity to co-passing ions of the KM14 and MPRu diagnostics at $E_{dep} = 9.3$ MeV and X = 33 cm (figures 8 and 9). A detailed discussion on the mechanisms behind a high orbit sensitivity can be found in [34, 44].

Furthermore, it is also interesting to note that the KM14 diagnostic signal at $E_{dep} = 9.3$ MeV has no contribution from stagnation orbits for this fast-ion distribution. This is simply because, for JET discharge 99965 at 7.9 and 8.4 s, the LOS of the KM14 diagnostic (figure 2) misses the region of the poloidal cross-section where the stagnation orbits have their trajectories (i.e. the low-field side area close to the magnetic axis). For JET discharge 99965 at 7.9 and 8.4 s, about 0.3% of the fast-ion population consists of stagnation orbits. Therefore, unless the orbit sensitivity is very concentrated to the stagnation region in orbit phase-space, such a small fraction would have made a negligible contribution to the diagnostic signal anyway (e.g. figure 10(*b*)). However, as has been discussed in [34], the relative population of stagnation orbits is likely to be

larger in future burning plasmas. It should be mentioned that stagnation orbits can be observed in other fusion experiments, as long as the LOS of the diagnostic crosses the low-field side area close to the magnetic axis.

Continuing, we can perform a more detailed analysis by investigating the fast-ion energy spectrum of the signal contributions in figure 10. Mathematically, this is equivalent to not effecting the energy integral in equation (11). Let

$$\zeta(E, p_{\mathrm{m}}, R_{\mathrm{m}}) = w(E, p_{\mathrm{m}}, R_{\mathrm{m}})f(E, p_{\mathrm{m}}, R_{\mathrm{m}})$$
(13)

denote the *signal phase-space density*. Such signal phase-space densities for given distribution functions have proven useful in 2D velocity-space tomography [32, 53]. We can split ζ into its orbit-type constituents and isolate its energy dependence as

$$s = \iiint \zeta \left(E, p_{\rm m}, R_{\rm m} \right) dE dp_{\rm m} dR_{\rm m} \tag{14}$$



Figure 11. A plot showing the split of the energy dependence of the KM14 signal phase-space density for the $E_{dep} = 9.3$ MeV measurement bin into its orbit-type constituents. The solid and dashed profiles correspond to the time windows at 7.9 and 8.4 s, respectively. The integral of a solid (or dashed) profile with a specific color equals the height of the solid (or striped) bar with the same color in figure 10(*a*).



Figure 12. A plot showing the split of the energy dependence of the MPRu signal phase-space density for the X = 33 cm measurement bin into its orbit-type constituents. The solid and dashed profiles correspond to the time windows at 7.9 and 8.4 s, respectively. The integral of a solid (or dashed) profile with a specific color equals the height of the solid (or striped) bar with the same color in figure 10(b).

$$=\sum_{h}\iiint_{h}\zeta(E,p_{\rm m},R_{\rm m})\,\mathrm{d}E\mathrm{d}p_{\rm m}\mathrm{d}R_{\rm m} \tag{15}$$

$$=\sum_{h}\int \zeta_{h}\left(E\right)\mathrm{d}E,\tag{16}$$

where h again denotes orbit type and

$$\zeta_h(E) = \iint_h \zeta(E, p_{\rm m}, R_{\rm m}) \,\mathrm{d}p_{\rm m} \mathrm{d}R_{\rm m}. \tag{17}$$

The energy dependence of the signal phase-space density split into orbit types ($\zeta_h(E)$) has been plotted in figures 11 and 12 for the KM14 and MPRu diagnostics, respectively. We can observe how most of the measurements at $E_{dep} = 9.3$ MeV and X = 33 cm are likely to have originated from fast ions with an energy of around E = 100 keV. This energy is approximately in the middle of the peak of the fast-ion distribution (figure 7)

and the orbit weight functions (figures 8 and 9) where the *wf* product is maximized. We can also observe how, when ICRF heating is switched off, even though the signal densities for all orbit types decrease, the peaks of the signal densities remain roughly at the same fast-ion energy $E \approx 100$ keV.

Furthermore, we can examine the difference between the solid and striped bars in figure 10, color by color, to deduce the most likely orbit-type origin of the decrease of the diagnostic signals in figure 5 at $E_{dep} = 9.3 \text{ MeV}$ (difference between the solid and dotted lines in figure 5(a)/(c)) and X = 33 cm (difference between the solid and dotted lines in figure 13. We can observe how most of the decrease in both the KM14 and MPRu signals is likely due to a loss in co-passing orbit contribution to the signals. This is because the orbit sensitivity is relatively high for co-passing orbits for both diagnostics (figures 8 and 9) for the measurement bins of interest ($E_{dep} = 9.3 \text{ MeV}$ and X = 33 cm, respectively). Combined with a substantial



Figure 13. The signal decrease of the (*a*) KM14 and (*b*) MPRu diagnostics at $E_{dep} = 9.3$ MeV and X = 33 cm, respectively, as ICRF heating is switched off, split into its most likely orbit-type constituents. For every color, it is the difference between the striped and solid bars in figure 10.

decrease in the co-passing distribution in the fast-ion energy range where the peak of the orbit sensitivities are located $(E \approx 250 \text{ keV})$ (figure 7), this results in a substantial decrease in the signal originating from co-passing fast-ion orbits.

Finally, we can also examine the *relative* decrease of the signal per orbit type. This has been done in figure 14. We can observe how the relative decrease in signal contribution is greatest for counter-passing orbits. As we can observe in figures 8 and 9, the sensitivity to counter-passing orbits is quite different for the KM14 and MPRu diagnostics for the measurement bins of interest. One can thus conclude that the great relative decrease in counter-passing signal contribution is due to the great decrease in the counter-passing distribution (figure 8) as ICRF heating is switched off. However, as can be observed in figure 10, the absolute contribution of counter-passing orbits to the diagnostic signal is small ($\sim 1\%$).





Figure 14. The relative signal decrease of the (*a*) KM14 and (*b*) MPRu diagnostics at $E_{dep} = 9.3$ MeV and X = 33, respectively, as ICRF heating is switched off, for each orbit type. For every color, it is the difference between the striped and solid bars in figure 10, divided by the value of the solid bar.

5. Conclusion

In this work, we have investigated the decrease in signal for the KM14 and MPRu fast-ion neutron diagnostics at JET as ICRF heating was switched off in DT-discharge 99965. It was found that, for the measurement bins of interest and given the simulation, the signal decrease was mostly due to a decrease in contribution from co-passing deuterium orbits. This was due to the relatively high sensitivity for co-passing orbits for both diagnostics for the measurement bins of interest. It was also due to the decrease in the high-energy co-passing population by several orders of magnitude as ICRF heating was switched off.

Continuing, given the simulation data of JET DT-discharge 99965, the KM14 diamond matrix diagnostic is completely unable to observe any signal originating from stagnation orbits. This is because its sightline does not observe the volume just to the low-field side of the magnetic axis, where the stagnation orbits are localized. However, for the 7.9 s and 8.4 s timepoints, the stagnation orbits are unlikely to make up more than about 0.3% of the fast-ion population, making their contribution negligible anyway.

Furthermore, even though the fast-ion distribution is comprised of mostly trapped orbits for JET DT-discharge 99965 at 7.9 s and 8.4 s, the signals in the measurement bins of interest for the KM14 and MPRu diagnostics have originated mostly from co-passing orbits. This is due to the orbit sensitivity being greater for co-passing orbits than trapped orbits for the KM14 and MPRu diagnostics, for the timepoints and measurement bins of interest.

In future work, this method of splitting the fast-ion distribution and diagnostic signals into their orbit-type constituents will have several areas of application. This includes confirming the presence of high-energy co-passing orbits as a result of heating schemes such as the three-ion heating scheme [37, 54, 55], or clarifying the interaction of fast ions and Alfvénic modes [56-58]. This could for example be done by trying different experimental approaches aimed to achieve a particular amount of MeV-range co-passing ions via the three-ion heating scheme, and then use the methods developed in this study to confirm such a population, given a fast-ion distribution obtained via orbit-space tomography [35] or phase-space tomography [59]. Alfvénic modes can cause resonances in phase space and thus changes to the ratios between the different orbit populations of the fast-ion distribution. Fast-ion orbit analysis could be used to analyze and compare these ratios before and after the presence of an Alfvénic mode, possibly providing greater insight into the physics of the interaction between Alfvén modes and fast ions.

Furthermore, it should be mentioned that, even though the focus of this study is on neutron measurement signals, in future work the method of using orbit weight functions for fast-ion orbit analysis can be applied to many other types of fast-ion diagnostics. Suitable types of diagnostics for an investigation that could build upon this study include gamma-ray detectors [60, 61] and fast-ion D-alpha spectroscopy detectors [62, 63].

Finally, the methods developed in this work can also be used to optimize the design of fast-ion diagnostics [44], to ensure that their sightlines are able to observe the full fastion distribution function. This is seen as vital for understanding how the behavior of the fast-ion distribution function will affect the fusion plasma as a whole, in both presentday and future fusion experimental reactors such as JET and ITER.

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