Neutron Emission Generated by Fast Deuterons Accelerated with Ion Cyclotron Heating at JET
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ABSTRACT
For the first time, the neutron emission from JET plasmas heated with combined deuterium neutral beam injection and 3rd harmonic ion cyclotron radio frequency heating have been studied with Neutron Emission Spectroscopy (NES). Very high DD neutron rates were observed with only modest external heating powers, which was attributed to acceleration of deuterium beam ions to energies of about 2-3MeV, where the DD reactivity is on a par of that of the DT reaction. Fast deuterium energy distributions were derived from analysis of NES data and confirm acceleration of deuterium beam ions up to energies around 3MeV, in agreement with theoretical predictions. The high neutron rates allowed for observations of changes in the fast-deuterium populations on a time scale of 50ms. Correlations were seen between fast deuterium ions at different energies and magneto hydrodynamic activities, such as monster sawtooth crashes and toroidal Alfven Eigen modes.

In an ignited fusion plasma, i.e. self sustained, the heating is produced solely by the slowing down of the fast alpha particles born in the fusion reaction $D + T \rightarrow n(14\text{MeV}) + \alpha(3.5\text{MeV})$ (DT). However, in present day fusion reactors, e.g. the Joint European Torus, JET [1], the main heating power comes from the slowing down of fast ions from auxiliary heating systems. This applies also to next step fusion experiments with the aim to approach ignition, such as ITER [2] as well as in driven reactor designs, like the component test facility [3], with high efficiency neutron production as the main goal. For high performance DT discharges at ITER, up to 50% of the heating power will be provided by fast ions from auxiliary heating systems and in a driven reactor, the heating will mainly come from external systems. In all cases, the fast ions from heating systems need to be well confined during their slowing down or the fusion performance will be reduced. There are several processes in a plasma that can degrade the confinement of fast ions. Among others, Magneto Hydro Dynamic (MHD) activities. Therefore, measuring the behavior of the fast ion distributions from auxiliary heating is a crucial task for optimizing the plasma performance [4], both for today’s and for future fusion experiments. In the intense neutron flux from a DT plasma, fast ions are normally difficult to probe, let alone determine quantitatively. On the other hand, high neutron fluxes can greatly benefit neutron measurements, increasing their statistics and hence the time resolution.

In this letter, we present the first Neutron Emission Spectroscopy (NES) measurements of Deuterium (D) plasmas heated with combined deuterium Neutral Beam Injection (NBI) and 3rd harmonic Ion Cyclotron Radio Frequency (ICRF) heating. The use of NES allowed studies of the energy distributions generated by 3rd harmonic ICRF. Also, for the first time, NES was used to correlate the time evolution of confined fast ions in different energy regions with MHD activity in the plasma, demonstrating its potential as a fast-ion diagnostic. The heating scheme was previously described in [5] for pure ICRF heating. In this experiment, a seed of fast D ions from NBI heating was used to achieve better absorption of the RF wave on the plasma ions, which was previously demonstrated for 4He acceleration in [6]. The heating scheme produced large populations of fast deuterium, which resulted in very high neutron rates using only moderate heating powers, without
any seeded tritium in the plasma. For example, JET Pulse No: 74952 was heated with a combination of 3MW NBI and 3MW ICRF. During the first second of the heating phase ($t = 11-12s$), only NBI heating was applied, resulting in a total neutron emission rate of about $5 \times 10^{14} s^{-1}$. During the phase of combined NBI and ICRF heating, the neutron rate peaked at $7 \times 10^{15} s^{-1}$ ($t = 14-15s$), which is an enhancement of the fusion performance by a factor 14 due to an increase in the heating power by a factor 2. The high neutron rates obtained in the experiment gave high quality NES data with a diagnostic performance comparable to what could be achieved in DT plasmas.

Fast ion diagnostics using NES is performed by analyzing the kinematic energy shift of the emitted neutrons from fusion reactions. This can be done using the neutron emission from both the DT reaction as well as the DD reaction, i.e. $D + D \rightarrow n (2.5\text{MeV}) + ^3\text{He}(0.8\text{MeV})$; in this paper we focus on the DD reaction. The quoted energies of the reaction products are valid for reactant energies of a few keV, which is the typical case for the thermal ion distribution in a fusion plasma. The thermonuclear DD neutron emission is well approximated with a Gaussian energy spectrum centered at 2.5MeV. On the other hand, fast deuterons, with $E_d \gg T$, interacting with a thermal bulk plasma are characterized by very broad energy spectra. Examples of neutron energy spectra, viewed at 90° angle to the magnetic field, from simulations of mono-energetic deuterium distributions reacting with a 5keV bulk plasma are shown in Figure 1 for $E_d = 0.5, 1.5$ and $3.0\text{MeV}$. This results in neutron energies reaching up to about $3.6, 4.7$ and $6.3\text{MeV}$, respectively. In this letter, neutron emission spectra measured with the time-of-flight spectrometer TOFOR are presented. TOFOR is described in detail in [7] and here it suffices to note that the flight time, $t_{\text{TOF}}$, of neutrons is proportional to $1/\sqrt{E_d}$. For TOFOR, neutrons with $E_n = 2.5\text{MeV}$ will result in a $t_{\text{TOF}}$ around 65ns while neutrons with $E_n = 3.5\text{MeV}$ correspond roughly to a $t_{\text{TOF}}$ of 55ns.

The high neutron rates achieved can be understood from the neutron emission spectroscopy data measured by TOFOR. In Figure 2, the TOFOR $t_{\text{TOF}}$ data from the NBI and NBI+ICRF heating phases of JET Pulse No: 74952 are shown in red circles and blue crosses respectively. The $t_{\text{TOF}}$ spectrum from the NBI phase is mainly characterized by events between 60 and 70ns, corresponding to $2-3\text{MeV}$ neutron energies. This is the typical spectrum from a beam around 120keV that is interacting with a cold background plasma. For the NBI+ICRF phase, on the other hand, the TOFOR spectrum reaches down to $t_{\text{TOF}} = 42\text{ns}$. This corresponds to neutron energies of roughly 6MeV. To generate such high neutron energies, deuterons with an energy of 3MeV are required, as shown in Figure 1. The high neutron rates observed in this experiment are a consequence of the capability of the 3rd harmonic heating scheme to accelerate beam ions to energies of several MeV. At these energies, the DD reactivity is almost 2 orders of magnitude higher than around the neutral beam injection energy ($E_d = 120\text{keV}$) and exceeds the DT reactivity. Due to the high neutron rates, it was possible to analyze the neutron emission from fast ions with an unprecedented timeresolution of 50ms in a D plasma.

Simulated neutron emission spectra from mono-energetic ion distributions, such as those shown in Figure 1, can be used to build up a neutron spectrum from an arbitrary fast deuterium distribution,
This is done by summing several such spectra and adjusting their weights proportionally to the level of \( f_d \) at the corresponding deuterium energy, \( E_d \). In the same way, by iteratively fitting the weights so that the summed spectrum matches the measured TOFOR data, the distribution \( f_d \) can be derived. An example of a fitted \( f_d \) from JET Pulse No: 74937 is shown in Figure 3a (points with error bars). The raw TOFOR data are shown in Figure 3b with examples of fitted mono-energetic spectra from deuterium distributions at 0.1, 0.5, 1.0, 1.5 and 2.0MeV. Also shown in Figure 3a is an integration of the Fokker Planck equation describing 3\textsuperscript{rd} harmonic acceleration of a 110 keV NBI slowing down distribution [8]. 3\textsuperscript{rd} harmonic ICRF heating is a Finite Larmor Radius (FLR) effect and preferentially heats high-energy deuterons. Because of this, the heating scheme is expected to result in a rather flat \( f_d \). Above a certain energy, \( E^* \), the efficiency of the heating goes to zero and \( f_d \) is thus expected to drop above this energy [9]. \( E^* \) depends on the electron density and the magnetic field, among other parameters. For the time slice studied in Figure 3, \( E^* \) is expected to be around 2MeV. It is striking to see how the main features of the theoretical prediction of \( f_d \) are well in agreement with the \( f_d \) derived from TOFOR data. Especially the location of \( E^* \), which is correctly modeled within 200keV, as seen in Figure 3. Depending on the plasma parameters, all discharges in the 3\textsuperscript{rd} harmonic heating experiment showed similar shapes of \( f_d \), i.e., a flat shape with a drop in the range between 2 to 3MeV.

It has been shown [10] that fast ions in the MeV range are prone to excite and be affected by MHD activity. From two experiment sessions, 18 discharges with 3\textsuperscript{rd} harmonic ICRF heating were studied and in all of them different types of MHD effects were observed. These include, fast-particle stabilized “monster” sawteeth, Toroidal Alfvén Eigen modes (TAE) and tornado modes, which are core localized TAEs inside the \( q = 1 \) radius. As shown above, it was possible to derive detailed information on \( f_d \) with a 0.5s time resolution. However, this is too coarse to follow the evolution of MHD activity. Instead, by integrating the high-energy part of the neutron spectrum it is possible to probe the fast ion content above a certain energy threshold. For a DD reaction to produce a neutron with \( E_n > 3.5 \text{MeV} \), or equivalently with \( t_{\text{TOF}} = 55 \text{ns} \), a deuterium ion with \( E_d \geq 0.5 \text{MeV} \) is required (see Figure 1). Thus, a probe for deuterons with energies above 0.5MeV can be obtained by integrating the TOFOR spectrum below 55ns. This is referred to as \( I_{\text{HE 55}} \). Similarly, setting lower \( t_{\text{TOF}} \) limits in the integration will allow for probing ions of higher energies; e.g., \( t_{\text{TOF}} < 48 \text{ns} \) corresponds to \( E_d = > 1.3 \text{MeV} \) and is referred to as \( I_{\text{HE 48}} \).

As an example, we discuss the time evolution of JET Pulse No: 74951. In Figure 4a, the spectrogram from a magnetic pick-up coil is shown together with the mode numbers of the strongest MHD modes. In Figure 4b, TOFOR high-energy signals, \( I_{\text{HE 55}} \) and \( I_{\text{HE 48}} \) are shown in solid red and dashed blue, respectively. Finally, in Figure 4c, the central electron temperature measured from electron cyclotron emission is shown (solid black) together with NBI and ICRF heating powers (dash blue and solid red, respectively). The discharge started with 1.5MW of NBI heating and at \( t = 12s \), 3MW of ICRF power was applied. The ICRF acceleration of D ions can be seen in \( I_{\text{HE 55}} \), which increased for about 1 second and leveled out at 160 counts / 50ms. The effect of the fast ions is also seen in the sawtooth period (\( T_e \) in Figure 4c), which increased as expected due to the
stabilization by high-energy ions. At $t = 14s$, the NBI power was doubled, correlating with a second rise of $I_{\text{HE 55}}$, despite no additional ICRF heating. This shows how the ICRF acceleration saturates for a beam ion seed of only 1.5MW; with a seed of 3MW, there are more ions to accelerate and the fast ion population can build up further and $I_{\text{HE 55}}$ reached a maximum of 350 counts / 50ms. This period also coincided with a fast ion stabilized sawtooth free period of 1.5s, followed by a monster sawtooth crash at $t = 15.5s$. In a sawtooth crash, energy is expelled from the core of the plasma to its surroundings [11] and the crash correlates with a conspicuous drop in $I_{\text{HE 55}}$ showing that the monster sawtooth crash was responsible for a significant loss or redistribution of fast deuterons with energies above 0.5MeV.

From $t = 14.4$ s and during the remainder of the sawtooth-free period, strong MHD activities in the form of TAEs and tornado modes were observed. TAEs and tornado modes are fast-particle driven MHD instabilities and as such, they require the presence of a fast ion population that can resonate with the modes [12]. In JET Pulse No: 74951, the TAEs were triggered when $I_{55}$ reached about 260 counts and for similar discharges in the experiment, it was seen that strong TAE activity was systematically observed when $I_{55}$ reached above 230–270 counts. The results thus indicate a rather well defined threshold in the number of fast ions needed to drive the TAE modes. TAE modes are excited by trapped ion precession resonance and the deuterium energy required for resonance can be obtained from the resonance condition, $\omega_{\text{TAE}} = n \cdot \omega_\phi \propto n \cdot E_d$, where $\omega_{\text{TAE}}$ is the frequency of the mode; $\omega_\phi$ is the toroidal precession frequency and $n$ is the toroidal mode number.

For the plasma conditions of JET Pulse No: 74951, TAEs with $n = 3$ and 4 resonate with deuterons at $E_d \approx 1.4$ and 1.1MeV, respectively. This is well in range of the fast deuterium distributions that were observed during the experiment where 3rd harmonic ICRF heating was seen to effectively accelerate deuterium beam ions to energies between 1 and 2MeV (see Figure 3). Consequently, strong TAE and tornado activities with $n \geq 3$ were seen for a large number of pulses during the experiment. On the other hand, for $E_d > 2$MeV, $f_d$ starts falling off due to the FLR effect of the ICRF heating and in JET Pulse No: 74951, the $n = 2$ TAE mode, which requires $E_d \approx$ MeV, was considerably weaker, as seen in Figure 4.

MHD activities in the form of TAEs and tornado modes are known to be responsible for losses and redistributions of fast ions interacting with the modes [10, 13]. Prior to the TAE modes in JET Pulse No: 74951, $I_{55}$ and $I_{48}$ evolved in the same way but at the onset of the TAEs, there was a discontinuity in the two time traces. $I_{55}$ continued to grow during the MHD activity, showing that the fast deuterium population was still building up for energies above 0.5MeV, albeit at a lower rate. On the other hand, $I_{48}$ started to decrease during the time of the MHD activity, showing how the number of fast deuterons above 1.3MeV were limited by the modes; either they were redistributed in the plasma or lost. The TAE modes in JET Pulse No: 74951 with the highest amplitudes were the $n = 3$ and 4 modes. Since ICRF heating is a diffusion process, accelerating ions from lower to higher energies, a loss of ions around 1.1 and 1.4MeV would result in a lowering of $f_d$ for all higher energies. This is in line with the measured data where $I_{55}$, which probes ions both below and above
the resonant energies continued to rise while $I_{48}$, which probes ions exclusively above the resonant energies decreased during the activity. The same trends during strong TAE activities were also observed in other discharges during the experiment. The NES results are in agreement with gamma spectroscopy data on the 3.1MeV line from $^{12}$C(d,p$\gamma$)$^{13}$C reactions [14] and scintillator probe [15] measurements of lost deuterons in the energy range 0.8–1.5MeV.

It is also worth noting that while $I_{55}$ was strongly affected by the monster sawtooth crash, $I_{48}$ was not noticeably affected, showing that a majority of the fast deuterons in this energy range were outside the plasma core. This is a further indication that the decrease of fast deuterons with $E_d > 1.3$MeV, described above, is connected to the $n = 3$ and 4 TAE activities, since such modes are located outside the sawtooth inversion radius.

The Monster sawtooth crash in JET Pulse No: 74951 also triggered an $m/n = 3/2$ tearing mode from $t = 17.5s$ and for the remainder of the discharge. Such modes are known to degrade plasma performance and during this time the entire fast ion population was limited, which can be seen from both the $E_d > 0.5$MeV as well as the $E_d > 1.3$MeV signals. For other discharges in the session, e.g. JET Pulse No: 74952, similar tearing modes were also triggered but decayed after about 1s; in that case, the fast ion distribution was quickly restored and a second monster saw-tooth was triggered.

CONCLUSIONS
To summarize, the neutron energy spectra from JET plasmas heated with deuterium NBI and 3rd harmonic ICRF were measured using the TOFOR spectrometer. Very high neutron rates were observed, which is attributed to the heating scheme’s exceptional ability to accelerate deuterons to MeV range energies, where the DD fusion reactivity is on a par with that for DT reactions. This was confirmed by detailed analysis of NES data where fast deuterium distributions reaching up to 3MeV were seen. The high neutron rates allowed for the time evolution of the fast deuterium distribution to be followed with a time resolution of 50ms in D plasmas, comparable to what could be achieved for a DT plasma. This made comparisons of fast deuterium distributions with the MHD activity in the plasma possible. Separate energy ranges were studied by analyzing different parts of the neutron spectra and different types of MHD modes were seen to affect and be affected by different ion energies. The NES results are consistent with data obtained with gamma rays and fast-ion loss measurements. We have shown how neutron emission spectroscopy can be used as a tool for studies of high-energy fuel ions and their interactions with MHD activity. This has great potential for future fusion experiments, such as ITER, where both fast deuterium and tritium will be present from ICRF and NBI heating systems. Finally, it is also worth mentioning that the properties of the 3$^{rd}$ harmonic ICRF heating scheme, with the high efficiency production of neutrons in the energy range up to 6MeV, makes it a viable candidate for a driven neutron source without the need to use tritium.

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REFERENCES

Figure 1: Simulated neutron spectra for three different mono-energetic deuteron distributions, illustrating how the deuteron energy affects the width of the neutron spectrum.

Figure 2: TOFOR time-of-flight spectrum from NBI (t = 11–12s) and combined NBI+ICRF (t = 14–15s) heating phases of JET Pulse No: 74952. Red circles and blue crosses respectively.
Figure 3: (a) Fast deuterium distribution function derived from TOFOR data for JET Pulse No: 74937 at $t = 15 - 15.5s$ (points with error-bars). Also shown in the solid line is an analytical solution. (b) TOFOR data with fitted high-energy distribution together with examples of monoenergetic spectra after folding with the TOFOR response function.

Figure 4: (a) Magnetic spectrogram of JET Pulse No: 74951 with mode numbers of TAEs indicated. (b) TOFOR IHE signals and (c) central electron temperature together with auxiliary heating power.