Neutron spectrometry measurements of energetic deuterons in ICRF heated plasmas with the ITER-like wall at JET

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Abstract

At JET, experiments have been conducted in order to optimize the performance of ion cyclotron radio-frequency (ICRF) heating in the presence of the newly installed ITER-like wall. The ICRF was tuned to the cyclotron frequency of minority hydrogen (H), which is also the 2nd harmonic of the cyclotron frequency of deuterium (D). The relative H concentration was varied from a few percent up to about 25 percent in a series of plasma discharges and the neutron time-of-flight spectrometer TOFOR was used to measure the energy spectrum of neutrons from the D(D,n)^{3}He reaction during these discharges. It could be seen that the signal from ICRF accelerated deuterons depended strongly on H concentration. This observation indicates that the ICRF power absorbed by D at the 2nd harmonic cyclotron resonance increases with decreasing H concentration. This is in qualitative agreement with theoretical expectations obtained from the plasma wave equation solver TOMCAT.

Introduction

Ion cyclotron radio-frequency (ICRF) heating provides one way to heat a fusion plasma above the temperatures obtained by Ohmic heating. In deuterium (D) plasmas, one of the more common heating scenarios is to tune the RF frequency to the cyclotron frequency of a hydrogen (H) minority population in the plasma. Since the D cyclotron frequency is half of the H frequency, the fundamental H resonance coincides with the second harmonic D resonance. Second (or higher) harmonic cyclotron acceleration is a finite Larmor radius effect, which occur when the Larmor radius of the accelerated particle is non-negligible compared to the gradient in the electric field produced by the ICRF [1]. Therefore, 2nd harmonic heating works better when there is a seed of energetic ions for the ICRF to couple to. Such a seed population can be provided by neutral beam injection (NBI).

*See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US

In this work we use neutron emission spectrometry to study the neutron emission from the D(D,n)^{3}He (DD) fusion reaction. The energy of the neutron produced in this reaction is determined by the velocities of the reacting deuterons. For thermo-nuclear reactions energies around $E_n = 2.45$ MeV is expected, but for reactions involving fast (supra-thermal) deuterons – created e.g. by the ICRF heating – neutron energies both higher and lower than this value is obtained. Since the DD cross section increases rapidly when the reactant energies are increased above the thermal energy, fast deuterons leave strong signatures in the neutron emission, in particular in the form of a "tail" on the high energy side of the neutron energy spectrum.

From the kinematics of the fusion reaction it is possible to deduce the minimum deuteron energy required to produce neutrons above a given energy. For instance, a fast deuteron reacting with a stationary deuteron needs to have an energy of at least 0.5 MeV to produce a neutron of 3.5 MeV. If the deuteron energy is 1 MeV the corresponding neutron energy can be up to 4 MeV. Thus, the neutron energy spectrum can be used to probe the fast ion distribution in the plasma. This is exploited in the present paper, where we use the neutron spectrometer TOFOR at JET to probe the fast deuteron population for a set of ICRF heated plasma discharges with varying minority H concentration.

Experimental observations

Seven JET discharges have been studied for this paper. The discharges were part of an experiment conducted in order to optimize the performance of ICRF heating in the presence of the newly installed ITER-like wall, and were all heated with 15 MW of NBI together with ICRH that was varied in steps from 3 MW, to 5 MW and back to 3 MW. The ICRH frequency was 42 MHz, placing the H cyclotron resonance, as well as the second harmonic D resonance, close to the plasma center. The beam injection energy was 100 keV. The electron density was $7 \cdot 10^{19}$ m^{-3} and the electron temperature was 4 keV, as measured by Thompson scattering. The other discharges (85370, 85371, 85372, 85373, 85375 and 85379) were almost identical, apart from the hydrogen concentration $X[H]$, which was varied from about a few percent in discharge 85372 up to about 25 percent in discharge 85375. The H concentration was determined from Penning trap measurements of gas collected close to the divertor.

The time-of-flight spectrometer TOFOR [2] was used to measure the neutron emission during these discharges. TOFOR measures the time required for neutrons emitted from the plasma to travel between two sets of plastic scintillator detectors (t_{TOF}). The resulting time-of-flight spectrum is related to the energy spectrum of the neutrons. Neutrons can be detected in the plastic scintillators if they scatter elastically on one of the protons in the plastic. The scattering angle in the start detector (S1) needs to be about 30 degrees in order for the neutron to be

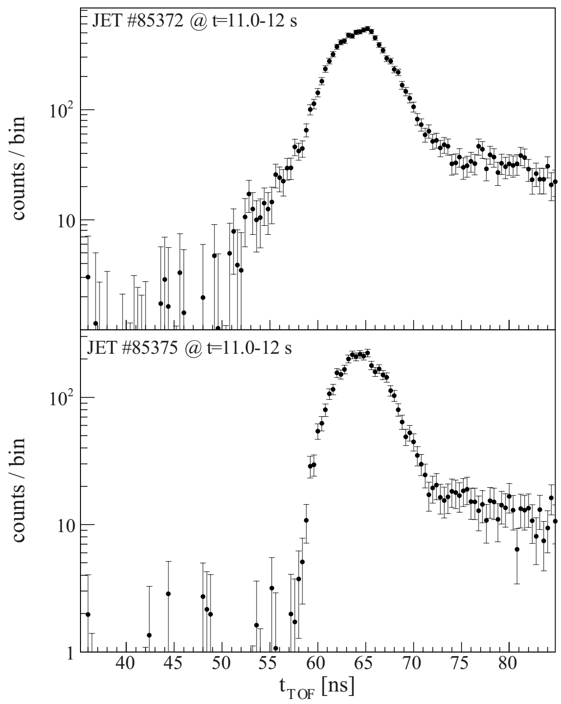

Figure 1: TOFOR data for JET discharges 85372 ($X[H] \approx 3\%$) and 85375 ($X[H] \approx 23\%$).

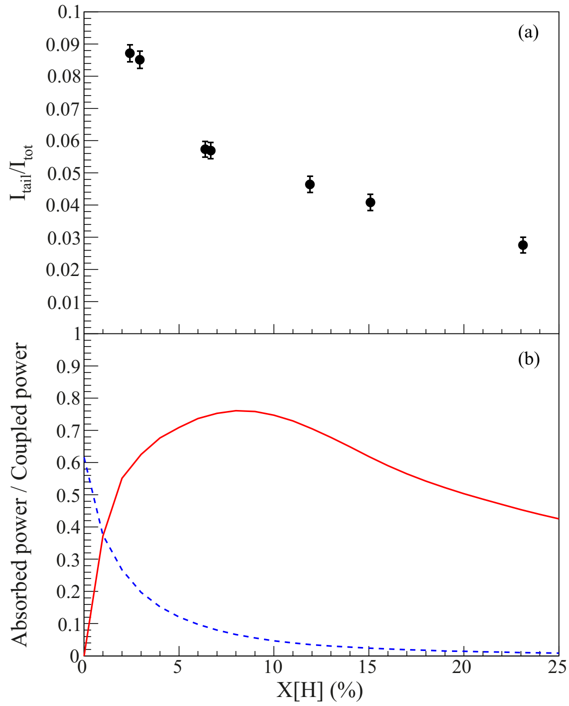

Figure 2: (a) TOFOR neutrons below 57 ns, normalized to the total number of neutrons, for all discharges of the X[H] scan. (b) TOMCAT calculations of the absorbed ICRF power for D (blue dashed line) and H (red line).

detected in the stop detector (S2). The distance between S1 and S2 is about 1.2 m, which means that a 2.5 MeV neutron has t_{TOF} around 65 ns. TOFOR is situated in the roof laboratory, 19 meters above the JET tokamak. The viewing cone is about 28 centimeters wide at the plasma mid-plane and covers a significant part of the neutron producing region of the plasma, including the plasma center.

TOFOR data for discharges 85372 and 85375 is shown in figure 1, for a 1 second time interval with 5 MW of ICRF power. These two discharges represent the lowest and highest H concentrations, respectively. A tail of neutrons with t_{TOF} shorter than about 57 ns can be seen for 85372 ($X[H] \approx 3\%$) but not for 85375 ($X[H] \approx 23\%$). These short t_{TOF} neutrons have energies above 3.5-4 MeV which, as described in Section , corresponds to reactions involving fast deuterons with energies higher than about 0.5 MeV. In order to quantify how prominent the tail is for given TOFOR data, we sum all the neuron counts below $t_{\mathrm{TOF}} = 57$ ns and divide by the total number of neutrons in the spectrum. This has been done for all discharges of the $X[H]$ scan and the result is shown in figure 2a. A clear dependence of $X[H]$ can be seen; the tail in the neutron spectrum gets more prominent as $X[H]$ decreases.

Discussion and conclusion

The TOFOR results show signs of fast deuterons with energies above 500 keV in these plasmas, if $X[H]$ is less than about 10%. 500 keV is significantly higher than the beam injection energy

(100 keV), which means that the D ions must have been accelerated further after being injected to the plasma. ICRF acceleration at the second cyclotron harminic if D is deemed to be the most probable candidate for this acceleration. For higher values of $X[H]$, the data shows no signs of fast deuterons above the beam energy. The analysis presented here is very straightforward and does not depend on any modeling or auxiliary diagnostics in addition to the TOFOR data. This means that there are very few sources of errors apart from counting statistics, which is represented by the error bars in figure 2a.

It is interesting to compare the above results with calculations of the absorbed ICRF power, made with the 1D plasma wave equation solver TOMCAT [3]. The calculated absorbed power for D and H, as a function of $X[H]$, is shown in figure 2b. Note in particular that the absorption on D increases strongly when $X[H]$ decreases, which is qualitatively the same behavior as seen in the TOFOR data. It should be stressed, however, that the TOFOR and TOMCAT results are not strictly a measure of the same quantity. The TOMCAT calculations give the power absorbed by all the deuterons, but it does not give any information about their energy distribution. The TOFOR results presented above, on the other hand, give a qualitative measure of the number of fast deuterons accelerated above 500 keV. However, it is reasonable to assume that the significant increase in D absorption seen from the TOMCAT calculations at low $X[H]$ would also result in an increase of the number of fast deuterons. We therefore conclude that the TOFOR and TOMCAT results are in qualitative agreement. The results are also consistent with previous JET results, reported e.g. in [4]

In future work a more quantitative analysis could be performed, by estimating the fast deuterium distribution function from the TOFOR data, using the method presented in [5]. These distributions could then be compared with theoretical expectations, using e.g. the ICRF code SELFO [6] or a similar code.

Acknowledgments

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