NEUTRON EMISSION FROM JET DT PLASMAS WITH RF HEATING ON MINORITY HYDROGEN
H. Henriksson¹, S. Conroy¹, G. Ericsson¹, G. Gorini², A. Hjalmarsson¹, J. Källne¹ and M. Tardocchi²

¹Dept. of Neutron Research, EURATOM-VR, Uppsala University, Uppsala, Sweden
²INFM, Physics Department, Milano - Bicocca University, and Plasma Physics Institute, Association EURATOM-ENEA-CNR, Milano, Italy

Introduction

The auxiliary power injection has often the effect of perturbing the thermal equilibrium of the ion populations. Neutron emission spectroscopy (NES) is a sensitive probe of such changes in the velocity distributions of fuel ions. Supra-thermal components are created such as those caused by radio frequency power (P_{RF}) at a certain ion cyclotron resonance. A special case is the tritium (T) discharges produced at JET using RF tuned to hydrogen (H) as a minority species together with deuterium (D) heated through second harmonic resonance. These RF discharges are special since fast protons can cause significant neutron yield rates (Y_n) through the reaction p + t \rightarrow ^3\text{He} + n if E_p is high enough. The pt-reaction is endothermic with a neutron emission spectrum that peaks at E_n = 0 MeV; this gives a high total Y_n for a given fusion power (P_F). Moreover, the presence of the pt neutrons can only be detected as an extra-ordinary enhancement of the neutron yield above that of the dd- and dt-reactions. The latter neutrons, on the other hand, can be made the subject of detailed NES measurements giving information about the fuel ions and, hence, the plasma response to P_{RF} injection. Here we present results from measuring the dt neutron spectrum with the magnetic proton recoil (MPR) spectrometer on the (HD)T discharge #41759 at JET with the minority concentrations c_p = n_p/(n_p+n_d+n_t) = 4 % and c_d = 4 - 6 %.

Experimental

The MPR has been used since the beginning of the DT campaign at JET in 1997. High quality data have thus been obtained for several important DT and D plasmas as already reported [1,2]. The spectrometer works on the principle of converting dt fusion neutrons to nearly the same energy recoil protons. The protons are magnetically momentum analysed over the energy range of E_n \approx 11-17 MeV and focused onto an array of plastic scintillators, which records a proton position histogram, H_p(x). The histogram reflects the spectrum of the incident neutron flux, S(E_n), where the relationship between H_p(x) and S(E_n) is specified by the well-known MPR response function [2]. The MPR count rate, C_n, is proportional to the dt neutron yield rate Y_n(dt) \equiv Y_{dt} [3]. This can be compared (Fig. 1) with Y_n measured with the fission chambers [4] sensitive to the neutron emission from E_n = 0 MeV and upwards. As the MPR sight line is quasi-tangential to the central plasma, the neutron spectrum is Doppler
shifted ($\Delta E_3$) for toroidally rotating plasmas [1]. The thermal Doppler broadening of the neutron spectrum scales with the square root of the ion temperature, $T_i$, of the plasma.

The RF was tuned to the fundamental resonance frequency of hydrogen, which takes up most of the $P_{RF}$ through the creation of a supra-thermal component in the $p$-population ($p'$). Although hydrogen dominates the $P_{RF}$ absorption, a weak supra-thermal $d'$ component is also created whose corresponding reactivity, $\rho_{d't}$, can be almost an order of magnitude higher than $\rho_{d't}$ at $T_{d'} = 10$ keV. For this discharge $\rho_{d't}$ always dominates $\rho_{d't}$, as does $\rho_{d't}$ compared to $\rho_{dd}$. Therefore, the total neutron yield rate is made up of the sum $Y_n = Y_{p't} + Y_{d't} + Y_{d't}$ [5].

**Analysis and interpretation models**

The spectrum of the neutron emission from $dt$-reactions in the plasma was determined based on the $H_p(x)$ data of the MPR. The amplitude ($A$) and the width of the spectral components were varied to obtain the best fit to the data. Data for the Ohmic and RF periods of the discharge are shown in Fig. 2 together with the computed fits. Here, the first histogram is fitted with a Gaussian distribution representing the neutron emission from a thermal plasma. The second histogram is fitted with a two-component spectrum representing reactions between I) thermal ions in the bulk ($T_b = T_i$), and II) fast RF-accelerated deuterons ($T_{HE} = T_{d'}$) that interact with thermal tritons ($T_b = T_t$). The fits were based on the neutron spectra shown in Fig. 3. From these results, information was inferred on the fuel ion populations such as the ion temperature ($T_i$) for the Ohmic periods, and the bulk and high-energy temperatures for the deuteron population ($T_b$ and $T_{d'}$) for the RF periods. In the latter case, $T_b$ was taken as the common ion temperature for $p$, $d$ and $t$. For more details about the analysis model and interpretation, the reader is referred to Refs. 1 and 5.

**Results and discussion**

The result of the measurement is $T_i = 1.1 \pm 1.6$ keV for the Ohmic conditions. The RF plasma have a bulk component of $T_b = 8.4 \pm 0.5$ keV and a high energy tail component with $T_{d'} = T_{HE} = 300 \pm 50$ keV. The average count rate at $P_{RF}^{MAX}$ is $C_n = 1.8$ kHz (compared to 0.03 kHz during the Ohmic periods); $C_n$ is split according to the measured relative spectral intensities, i.e., $A_b = 91 \pm 2$ % and $A_{HE} = 9 \pm 1$ %. The plasma toroidal rotation was found to
be 70 ± 16 km/s (relative to the Ohmic heating conditions [1]) based on a measured energy shift of ΔEₜ = 59 ± 5 keV.

The velocity distribution of the p-population was measured with the neutral particle analyser (NPA) diagnostic from which Tₚ = 380 keV was determined [6]. Yₐ was found to increase by k ≈ 50 % during the RF phase of the discharge as compared to Yₐ measured by the MPR (see Fig. 1).

The relative densities of fast and thermal ions were determined [5] resulting in the ratios nₚ / nₐ = 1.4 % and nₚ / nₜ = 22 %. This means that the RF power is about 16 times more efficient for protons than deuterons indicating the difference in fundamental and second harmonic RF actions on minority ions (p and d in this case). The relative densities nₚ, nₐ and nₜ were taken as the isotopic hydrogen concentrations cₚ = 4, cₐ = 5 and cₜ = 91 % [7]. The particle kinetic energy density for ions (w) was determined relative to wₑ for electrons; w is found to be a factor of 1.25 higher than wₑ with the division on species being wₚ = 34, wₐ = 5 and wₜ = 61 %. In total, the energy density of fast ions (w') is estimated to 63 % of the total wtot = wₑ + w compared with the calculation in Ref. [7] which determined the ratio w'/wtot to be 59 % in disagreement with the experimental estimate of 45 % [7].

The temperature dependencies of the neutron yield rates of different ion reactions can be compared by approximating the reactivity values with exponential functions T². The results are Yₚt ∝ T⁻².₇, Yₐt ∝ T⁻⁴ and Yₜt ∝ T⁻⁰.⁵₄ for the temperatures used here [5]. It is then found that the fast ion yield ratio Yₚt / Yₜt has a strong temperature dependence (∝ T⁻².⁷) while the ratio k = Yₚt / Yₜt is essentially temperature independent. This means that the two ratios

![Fig. 2. Data, as a function of position, obtained with the MPR representing the dt neutron emission during the Ohmic (a) and RF heated periods (b) of the JET discharge #41759; the curves are fits to data. Increasing proton energy on the x-axis.](image)

![Fig. 3. Results on the thermal (TH) bulk and high energy (HE) tail components of the neutron emission from the JET plasma discharge #41759 during periods of Ohmic heating only (a) and during RF heating (b).](image)
reflect, respectively, the fast ion amplitude and temperature effects of the RF power assuming that the temperature changes are concurrent.

**Conclusion**

Neutron emission spectra have been measured from tritium plasmas heated with RF power coupled to the hydrogen and deuterium minorities through their fundamental and second harmonic resonances. From MPR data on the dt-reaction for a JET discharge, results were obtained on the temperature and amplitude of the bulk and fast component of the deuteron population besides plasma toroidal rotation. The results were used in conjunction with other data to gain insight on the plasma response to the applied RF heating compared to during Ohmic heating only. It is found that RF excites the proton population a factor of 16 more strongly than that of deuterons while their temperatures are both in the 300-keV range (compared to 8.4 keV for the bulk). This study demonstrates neutron emission spectroscopy measurements in RF plasmas and their ability to provide unique information. The discharge studied here is of special interest as it illustrates a heating scenario with the adverse effect of having a neutron yield contribution from the endothermic \( p + t \rightarrow \text{^3He} + n \) with an anomalously low fusion power contribution.

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**References**