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ABSTRACT.
The measurement of fast ion populations is one of the diagnostic capabilities provided by Neutron Emission Spectroscopy (NES). NES measurements were carried out during JET Trace Tritium campaign with the Magnetic Proton Recoil neutron spectrometer. A favorable plasma scenario is (T)D where the resulting 14MeV neutron yield is dominated by supra-thermal emission from energetic tritons accelerated by Radio Frequency (RF) at their fundamental cyclotron frequency. Information on the triton distribution function has been derived from NES data with a simple model based on two components referred to as Bulk (B) and High-Energy (HE). The HE component is based on strongly anisotropic tritium distribution that can be used for routine best-fit analysis to provide tail temperature values (THE). This paper addresses to what extent the THE values are model dependent by comparing the model above with a twotemperature (bi-) Maxwellian model featuring parallel and perpendicular temperatures. This model is strongly anisotropic and frequently used for RF theory.

1. INTRODUCTION

The fusion Neutron Emission Spectroscopy (NES) is directly sensitive to the velocity distribution of the interacting fuel ions [1], namely d and t ions in deuterium-tritium plasmas, the main reaction being $d + t \rightarrow \alpha + t$. For a thermal plasma the neutron energy spectrum is nearly Gaussian in shape, with a Doppler broadening which is a function of the ion temperature [2]. Often plasmas have varying amounts of non-Maxwellian ion populations due to the use of auxiliary power heating in the form of neutral beam injection or radio frequency wave power. Despite being often in a minority, these suprathermal populations give rise due to their enhanced reactivity [3] to significant larger contributions to the neutron emission than the thermal populations. The shape of the neutron spectrum of these suprathermal populations is no longer Gaussian and varies depending on the underlying ion velocity distribution function. Suitable modeling is needed to describe the measured neutron energy spectrum [1].

The 2003 JET Trace Tritium campaign provided a rare opportunity for Ion Cyclotron Resonance Heating (ICRH) of tritium at low concentrations in deuterium plasmas. A favourable heating scheme in these conditions is (T)D where tritons are accelerated at their fundamental cyclotron frequency. Up to 1.5 MW ICRH was coupled to the plasma, mostly by direct deposition on the puffed tritium by cyclotron damping. The resulting neutron yield is dominated by supra-thermal emission from energetic tritons, which provides good conditions for testing of models used in the analysis of Neutron Emission Spectroscopy (NES) from ICRH plasmas.

NES measurements were carried out with the Magnetic Proton Recoil (MPR) neutron spectrometer viewing the plasma horizontally at an angle of about 47^{o} relative to the magnetic field on-axis [4]. The viewing volume is representative of the core plasma where fast triton reactions with deuterons take place. For the NES analysis it is assumed that plasma conditions are uniform within this volume and the neutron emission has two contributions referred to as “bulk” (B) and “high energy”

(HE) [1]. The bulk contribution is described by reactions between thermal deuterons of temperature T_d and tritons with an effective temperature T_B. The HE component, which shows directly the effect of the ICRH on the plasma, is a strongly anisotropic "cut Maxwellian" distribution that can be used for routine best-fit analysis of ICRH neutron spectra to provide "tail temperature" values.

This work studies to which extent the extracted temperature values are model dependent. This is addressed by comparing the "cut Maxwellian" results with a two-temperature (bi-) Maxwellian model featuring parallel ($T_{||}$) and perpendicular ($T_{\perp}$) temperatures with $T_{\perp}>T_{||}$. The bi-Maxwellian can be strongly anisotropic and frequently used for ICRH theory.

2. MODEL CALCULATIONS OF THE NEUTRON EMISSION SPECTRUM

The most successful approach to describe NES data of ICRH plasmas has been so far to identify the main features of the neutron emission spectrum in terms of reactions between ions of distinct velocity distributions [1]. The neutron spectrum is described in terms of up to three main components, as illustrated in Fig.1: i) reactions of ions within the thermal (TH) population of the plasma; ii) reactions between tritons of the Epi-Thermal (ET) population and bulk deuterons iii) reactions between tritons of the High-Energy (HE) population and bulk deuterons. The ET component represents the contribution of the tritons which by slowing down below the critical energy loose energy and change their pitch angle relative to the magnetic field direction elastic collisions with the thermal deuterons and tritons. Both the TH and ET populations are isotropic giving neutron spectra of nearly Gaussian shape of Doppler widths of temperature T_{TH} and quasi temperature T_{ET}, respectively If the TH and ET components can not be separated (bulk component B = TH + ET), the derived quasi temperature is denoted as T_B. The resulting neutron energy spectrum shape is nearly Gaussian and would exactly be exactly so if $T_B = T_d$. The HE population is a "cut Maxwellian" triton distribution in velocity space consisting of Maxwellian tritons of temperature THE, with velocities in the angular range $90^o \pm 10^o$ relative to the magnetic field. This is a simple model prescription providing a strongly anisotropic distribution that can be used for routine best-fit analysis of ICRH neutron spectra to provide "tail temperature" values T_{HE} (see Fig.1).

With the above prescribed model, NES measurements on DT plasmas have shown to be a useful fast fuel ion diagnostic, with ability to distinguish velocity components of the ions (tail temperatures and relative intensities) as well as their collective motion (rotation) [5]. We observe here that why the derived tail temperatures values are somewhat model dependent, the opposite is true for the plasma rotation velocity which can be directly derived from the energy shift of the neutron spectrum [5].

An alternative anisotropic model often used in ICRH theory is to describe the triton velocity distribution with a two-temperature bi-Maxwellian with parallel ($T_{||}$) and perpendicular ($T_{\perp}$) temperatures [6] and $T_{\perp}>T_{||}$. Here $T_{\perp}$ represent the high energy tail of the triton distribution and can thus be directly compared with THE. Figures 2-3 show Monte Carlo simulations of neutron energy spectra resulting from reactions between thermal deuterons of $T_d = 2.5$keV and tritons belonging to bi-Maxwellians with different values of $T_{\perp}$ and $T_{||}$. The simulations show that the slope (in log scale) of the high energy tail of the neutron spectrum is directly related to $T_\perp$ as clearly visible in Fig.2b where $T_\perp$ is varied in the range 80 to 140keV for the same $T_\parallel = 10$keV; on the other hand the same slope is only weakly dependent on the $T_\parallel$ value (Fig. 3b).

A comparison of the two models for the case $T_d = 2.5$keV and tail temperature = 100keV indicates that $T_\perp \approx T_{HE} = 100$keV with $T_\parallel = 20$keV, suggesting that the bi-Maxwellian model features for the same high-energy tail higher values of $T_\parallel$. The central part of the spectrum is more sensitive to the details of the models, as can be seen from Fig.2a-3a. We note in particular that in the central part the HE component is more hollow reflecting a stronger anisotropy compared to the bi-Maxwellian. The above mentioned spectral differences between the two models are well understood in terms of the difference in the space phase ($v_\perp$, $v_\parallel$) of the underlying triton distributions .

3. RESULTS AND DISCUSSION

The two models have been used to analyze the JET Pulse No: 61281 taken during the Trace Tritium Campaign. The discharge had a toroidal B-field of 3.9T and plasma current of 2.9MA. The Ion Cyclotron Frequency was set at the lowest available value (23MHz) which allowed to locate the first harmonic triton resonance at about 0.6m off-axis on the high field side. The ICRH power was about 2MW and provided an integrated 14MeV neutron yield of $3.5 \cdot 10^{16}$ neutrons.

The MPR neutron spectrometer records proton position histograms which represents the convolution of the instrumental response function and the incoming source neutron spectrum. The measured proton recoil spectrum of Pulse No: 61281 is shown in Fig.4 with the best fit to the data with the HE plus B model. The spectrum, which was collected with an instrumental resolution set at 4.0%, has 2650 counts collected during the ICRH phase (6.4-8.0s). In order to enhance the sensitivity in the tail of the spectrum data have been background corrected with a standard procedure [4]. Also shown in Fig.4 are the contributions to the fit from the HE and B spectral components, besides an additional “inscatter” component which is below the 2% level and affects mostly the low energy part of the spectrum. The fit describes well the data ($\chi^2 = 1.05$) and provides temperature values of $T_{HE} = 108 \pm 7$keV, $T_B = 9 \pm 3$keV with about 80% of the emission in the HE component. The energy shift of the spectrum is consistent with no plasma rotation ($E_S = 8 \pm 12$keV). We observe that the errors on the derived parameters are somewhat large and reflect the limited statistics of the data.

The data of Fig.4 have also been fitted with the bi-Maxwellian model plus a B component. It is found that $T_\perp = T_{HE} = 108$keV provides good fit ($\chi^2 = 1.02$) to the NES spectrum for reasonable value of $T_\parallel = 20$keV. The derived parameters are $T_B = 11 \pm 5$keV with about 90% of the emission in the bi-Maxwellian component. The energy shift of the spectrum is again consistent with no plasma rotation ($E_S = 11 \pm 12$keV).

From the fitted proton recoil spectrum one derives the best incoming neutron spectrum for both models (Fig.5). One can see that the two neutron spectra are very similar and slightly differ only near the peak. This has some effect on the intensity value of the B component being generally higher with bi-Maxwellian model. It is thus found that the high energy tail of the spectrum can be used to determine T_{HE} and the energy shift in a model independent way, while extraction of the B component intensity and T_B are more sensitive to model assumptions.

A more quantitative approach for the analysis model, suggested in Ref. [1], would require to integrate NES observations with the state of the art ICRH simulation codes, thus providing a fully quantitative interpretation of NES results. This analysis method is at the moment in progress and its main steps are summarized below. The first step is to calculate the distribution function of the heated ion species using the code package SELFO [7]. SELFO calculates the ICRH power deposition and the triton distribution function self-consistently by coupling the Monte Carlo code FIDO for Fokker-Plank simulation [8] and the global wave solver LION [9]. The distribution functions are calculated at steady state condition using input from experimental measurements averaged over a period of about 200ms. The calculated distribution function in velocity and space is f(v, χ, r, θ); here v is the ion velocity, χ is related to the ion pitch angle (θ) via the relation $\chi=\cos^2(\theta)$, r and θ are respectively the radial and poloidal space coordinates in the JET tokamak. f(v, χ, r, θ) is thus used as input to a second Monte Carlo code which simulates the neutron emission spectrum incoming in the line of sight of the MPR spectrometer.

CONCLUSIONS

Neutron Emission Spectroscopy (NES) is used to probe the non-thermal features of the fuel ion velocity distributions in tokamak plasmas, especially, those arising from auxiliary heating in the form of Ion Cyclotron Resonance Heating (ICRH). In this work we have addressed to which extent the extracted temperature values are model dependent. The model which is routinely used to fit MPR spectra have been compared with the bi-Maxwellian featuring parallel and perpendicular temperatures. The results show that the two models are compatible; in particular, the high energy tail of the spectrum can be used to determine the tail temperature THE and the energy shift in a model independent way. A more general approach for the analysis model which requires integration of NES observations with ICRH simulation codes is in progress.

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REFERENCES

[1]. M. Tardocchi et al., Nuclear Fusion **42** (2002) 1273.

[2]. L. Ballabio et al., Nuclear Fusion **38** (1998) 1723

[3]. M. Tardocchi et al., Review of Scientific Instruments **70** (1999) 1171; M. Tardocchi et al., Review of Scientific Instruments **72** (2001) 836.

[4]. Ericsson et al., Review of Scientific Instruments **72** (2001) 759.

[5]. M. Tardocchi et al., Review of Scientific Instruments **75** (2004) 661.

[6]. G.Gorini et al., Review of Scientific Instruments **70** (1999) 1209

[7]. T. Hellsten et al, Nuclear Fusion **44**, 8 (2004) 892.

[8]. J. Carlsson et al, Proc. Joint Varenna-Lausanne Workshop 'Theory of Fusion Plasmas' (1994) 351.

[9]. L. Villard et al, Computer Physics Reports **4**, (1986) 95.

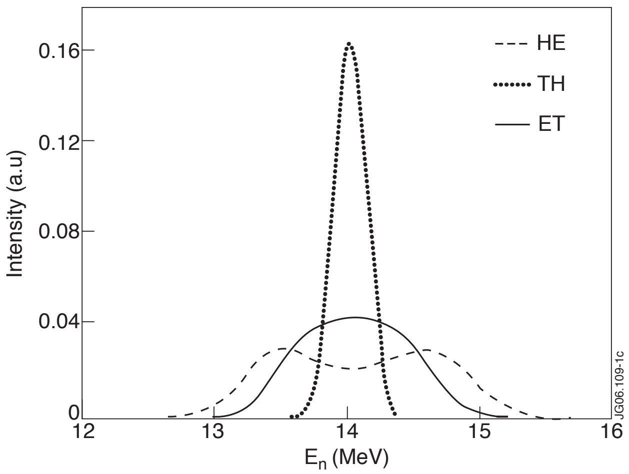


Figure 1: Examples of simulated neutron spectra (normalized to the same area) for the HE, ET and TH neutron spectral components. Here T_{HE} = 100keV, T_{ET} = 20keV and T_{TH} = 2.5 keV.

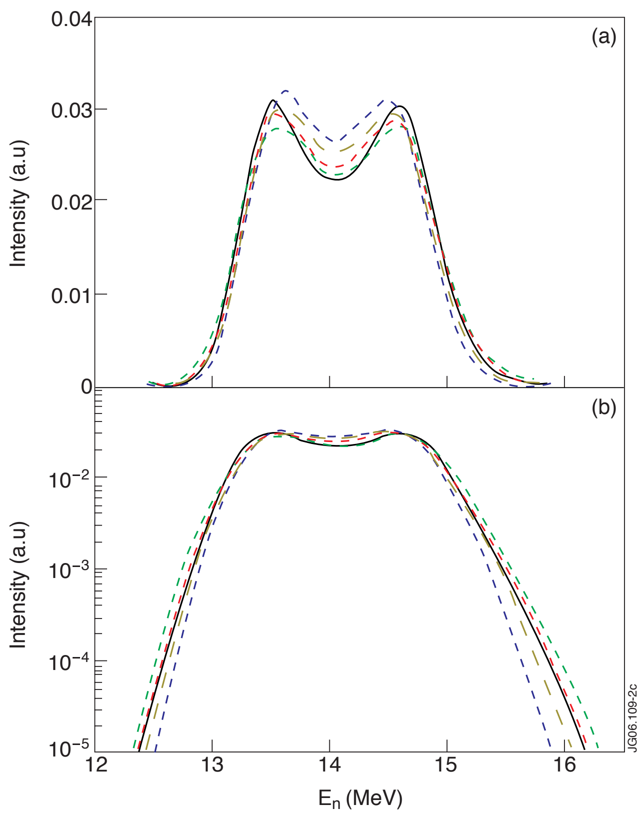
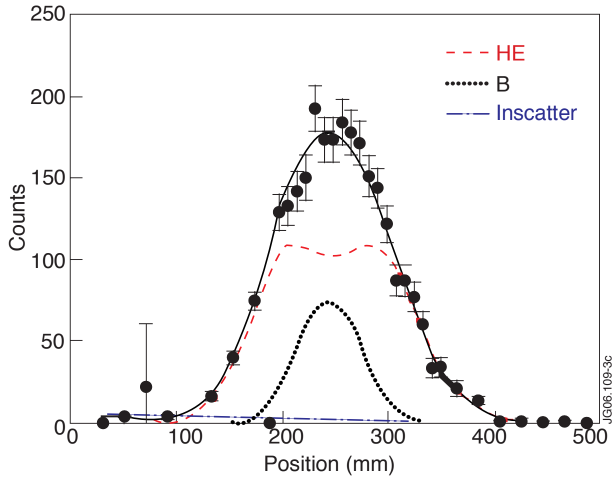


Figure 2: Simulated neutron energy spectra in linear (a) and logarithmic (b) scale from fusion reactions of thermal deuterons (T_d = 2.5keV) with fast tritons. Dashed lines are due to reactions with tritons of $T_\perp$ = 80, 100, 120, 140keV and $T_\parallel$ = 10keV; $T_\perp$ increases going from the narrower to the broader spectrum. The HE component (T_{HE} = 100keV) is shown for comparison in continuous line.



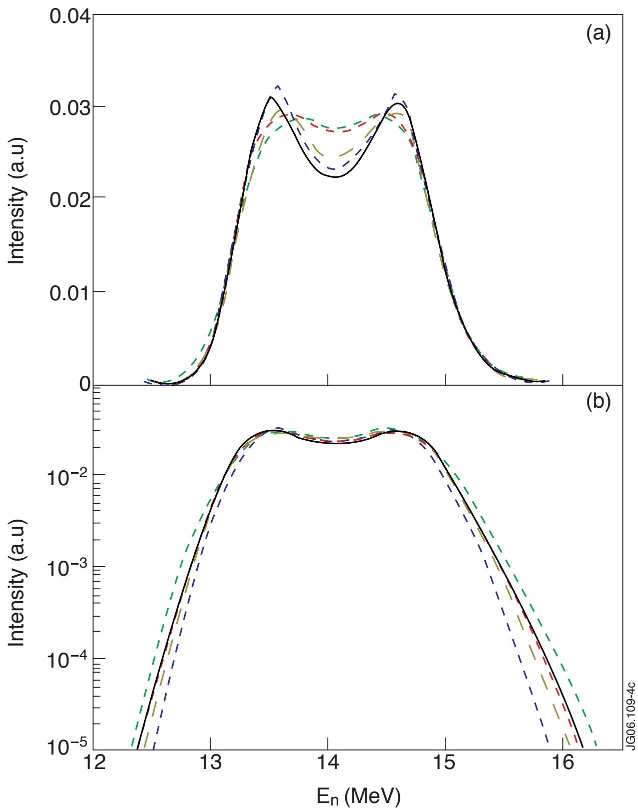


Figure 3: Simulated neutron energy spectra in linear (a) and logarithmic (b) scale from fusion reactions of thermal deuterons ($T_d = 2.5$keV) with fast tritons. Dashed lines are due to reactions with tritons of $T_{\|} = 2$, 10, 20, 40keV and $T_{\perp} = 100$keV; $T_{\|}$ increases going from the narrower to the broader spectrum. The HE component ($T_{HE} = 100$keV) is shown for comparison in continuous line.

Figure 4: Best fit with the HE-B model of the proton recoil spectrum of Pulse No: 61281; in dashed lines are shown the contribution to the fit from each spectral component.

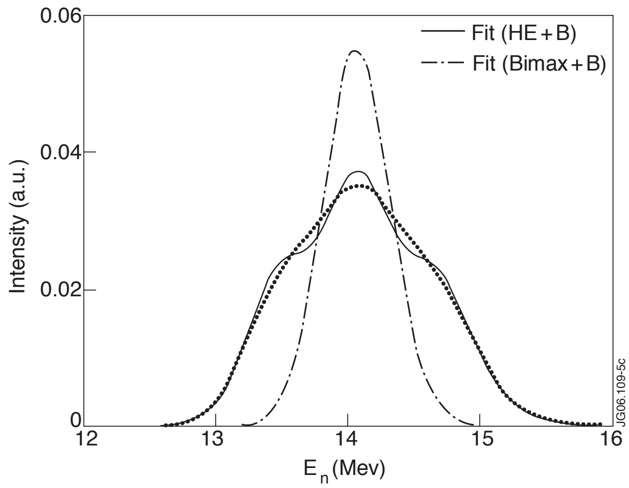


Figure 5: Comparison of the best incoming neutron spectrum for Pulse No: 61281 as derived from the HE-B (continuous line) and from the bi-Maxwellian (dashed line) models; in dotted dashed line the detector response function is shown for comparison.