Neutron energy measurements of trace tritium plasmas with NE213 compact spectrometer at JET

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INTRODUCTION

Neutrons in a tokamak plasma are mainly produced via thermal fusion reactions and reactions between accelerated ions and the thermal plasma, due to the application of auxiliary plasma heating systems like Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Frequency (ICRF). Properties of the energy distribution functions of thermal and high energy ions can be determined by measuring the spectral distribution of the neutron fluence [1-4]. During the 2003 JET Trace Tritium Experimental (TTE) campaign [5,6] a compact broadband neutron spectrometer was operated to acquire pulse height spectra of the neutron emission from different TTE plasma scenarios with NBI, ICRF and combined NBI+ICRF heating schemes. Experimental neutron spectra have been determined with newly developed data analysis techniques and unfolding codes finding satisfactory agreement with theoretical spectra calculated by means of the Monte Carlo neutron kinematics code FPS [7] which takes into account the various parameters of the investigated plasma scenarios.

INSTRUMENTATION and DATA ANALYSIS

The development and improvement of plasma measuring techniques are among the objectives of the EFDA JET programme. Within this frame, the diagnostic capabilities of a compact broadband neutron spectrometer have been successfully assessed in a real fusion experiment such as JET providing useful information for the determination of the various contributions to the neutron emission taking place with different heating schemes.

The compact neutron spectrometer is based on the NE213 liquid scintillator which has neutron/gamma discrimination properties and is well suited for high energy resolution spectrometry in mixed n/γ fields [8]. Particular features are: its compactness, detailed knowledge of the detector response function and photomultiplier gain control. The device was fully characterized for neutron detection (1.5 MeV $< E_n <$ 20 MeV) at the Physikalisch-Technische Bundesanstalt accelerator facility. The detector was installed in the JET roof-laboratory, viewing vertically at the plasma (major radius R = 2.95 m) through a collimator in the biological shield achieving energy resolutions of $\Delta E/E < 4$ % at E_n = 2.5 MeV and of $\Delta E/E < 2$ % at E_n =14 MeV [9].

By taking into account the various measured parameters of the investigated plasma scenarios and heating diagnostics, an evaluation of theoretical neutron spectra has been carried out with the FPS Monte Carlo code. This code provides spectra of the different neutron emission components, due respectively to thermal and to high energy ions-plasma bulk reactions. Neutral beam accelerated ions are slowed down in the plasma bulk whereas the ICRF heating accelerate ions perpendicularly to the magnetic field to energies up to the MeV range. The

ICRF heating can be approximated with a two maxwellian distribution with perpendicular and parallel temperatures representing the ion energy distribution in the plasma [1-4].

During the measurements pulse height spectra (PHS) of the light output in terms of equivalent electron energies (E_e) are acquired [8]. The discretized neutron spectrum φ_i is related to the measured number of counts N_k in channel k of the PHS by $N_k + e_k = \Sigma R_{ki}\varphi_i$, where R_{ki} is the response matrix of the detector, i.e. the relationship between neutron energy and light output, and e_k is a term that allows for experimental uncertainty. We first unfolded the measured PHS data using the code MAXED [10] with a constant default spectrum as input, for a first step exploratory data analysis. We then evaluated the neutron spectrum using Bayesian methods. To do this, we introduced a parametrized model of the neutron spectrum made up of different components estimated with the FPS code (i.e. thermal, NBI, ICRF) and defined parameters for the unknown fractions. We folded each of the components with the response functions and generated a set of model PHS to be compared with the measured PHS. We then determined the parameters using Bayesian parameter estimation [11].

NEUTRON ENERGY SPECTRA

We report the results (see table 1) of the analysis performed within time intervals where plasma conditions were stationary. Beam-beam as well as impurities-plasma reactions play a minor role and have been neglected.

2.5 MeV neutrons with NBI heating only. Plasma discharge 61039 is a low temperature plasma scenario with 3 MW total power injected of only deuterium NBI heating.

Comparison of the measured PHS with the PHS that results from folding the evaluated neutron spectrum with the response function is shown in fig. 1, finding good agreement. The neutron spectrum is reported in fig. 2 with a thermal contribution less than 1 % and the beam-plasma one > 99 %.
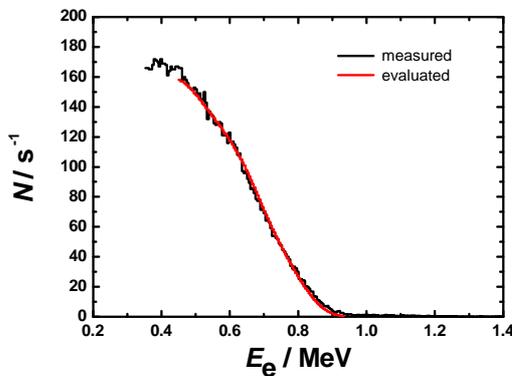

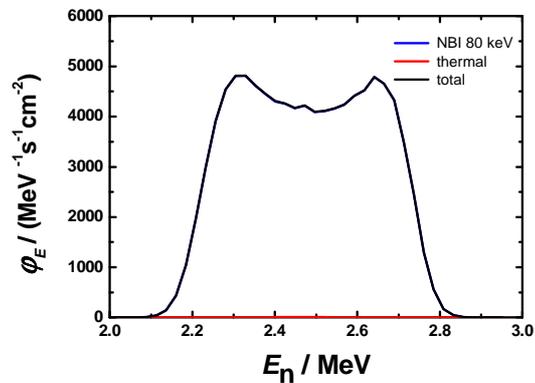Fig.1 Shot 61039 Measured and evaluated PHS   Fig. 2 Shot 61039 neutron spectrum

Shot 61206 is a discharge with higher level of NBI power and the contributions to the neutron emission for the thermal and beam plasma components are 26 % and 74 %, respectively.

2.5 MeV neutrons with combined NBI+ICRF heating. The discharge 61112 is a typical "low temperature ELMy H-mode" plasma scenario [12] with combined heating schemes, i.e. deuteron neutral beams plus ICRF heating tuned on the proton minority, ICRF-(H)D. The plasma has been heated with 3.5 MW of NBI (as in 61039) and with 6 MW RF polychromatic mode which has a large resonant region between 2.8 m and 3.05 m of the major radius *R*.

A recent study [13] has been carried out to investigate if the ICRF-(H)D scenario can affect the deuteron distribution function. Analysis based on the PION code indicates that such ICRF scenarios can produce an accelerated deuteron component which contributes to the total

neutron emission besides the other beam-plasma and plasma-plasma (i.e. thermal) reactions. There is good agreement between the measured PHS and the PHS that results from folding the evaluated neutron spectrum with the response functions (fig. 3). The small disagreement for $E_e > 0.9$ MeV is caused by the presence of 14 MeV neutrons which have not been taken into account in the analysis. The ICRF fraction is ~ 9 % (as determined by the median of its probability density) and the thermal and beam plasma fractions are ~ 17 % and ~ 73 % (fig. 4), whereas for the ICRF low power shot 61118 the thermal (~ 40 %) and NBI (~ 59 %) components are dominant. The probability density of the ICRF fraction parameter of shot 61112 has a long tail, and a fraction ~ 15 % is not excluded by the data. Due to the limited statistics of the PHS, the analysis is somewhat insensitive to the precise ICRF temperature, and here we have assumed a ICRF deuteron suprathermal population with a perpendicular tail temperature of 20 keV based on the initial exploratory data analysis done with the MAXED unfolding code.
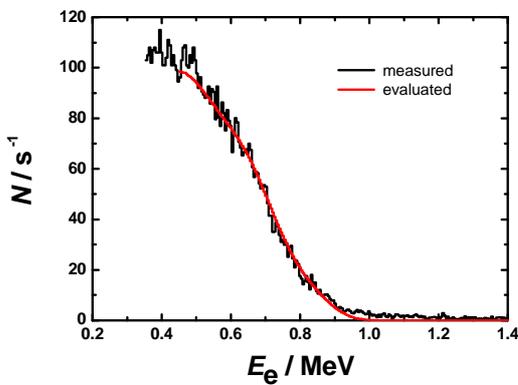
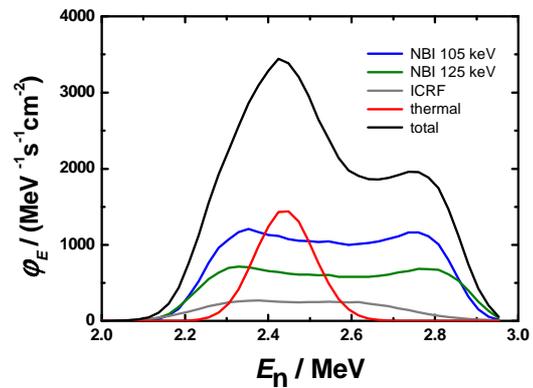Fig. 3 Shot 61112 Measured and evaluated PHS   Fig. 4 Shot 61112 neutron spectrum

14 MeV neutrons with RF heating only. New heating schemes have been performed during TTE, such as the ICRF minority tritium heating (T)D experiments [14] where the whole neutron emission is only due to the 14 MeV neutrons induced by reactions of high energy ICRF accelerated tritons with thermal deuterons.
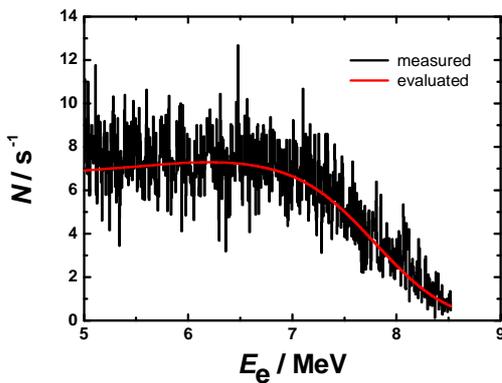
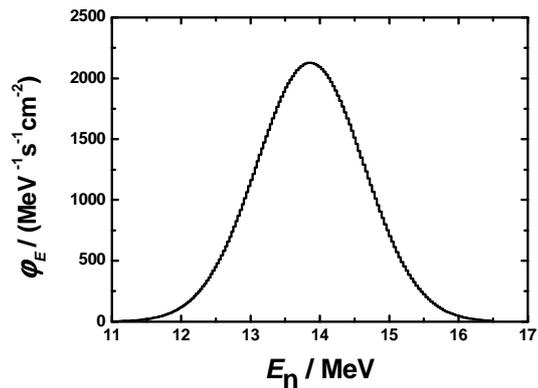Fig. 5 Shot 61280 Measured and theoretical PHS   Fig. 6 Shot 61280 neutron spectrum

Due to the limited statistics in the pulse height spectrum (fig. 5), details of the spectral shape can not be unambiguously resolved. By assuming a Gaussian shape the evaluation corresponding to shot no. 61280 indicates a full width half maximum of 1850 keV corresponding to a high energy equivalent perpendicular temperature of 120 keV. The 61280

neutron spectrum is shown in fig. 6 and the comparison of the measured and evaluated pulse height spectra in fig. 5, finding again good agreement. The results of the present neutron spectra analysis are summarized in table 1.

Table 1. Shots investigated and observed contributions to the neutron emission

Shot number	Acquisition time start/end (s)	NBI/ICRF power (MW)	RF tail temperature (keV)	Fraction of neutron fluence (%)		
				Thermal	NBI	ICRF
61039 DD	55 /65	3 /--	--	<1	99	--
61206 DD	60/63	8 /--	--	26	74	--
61112 DD	59/62	2 / 6	20	17	73	9
61118 DD	57/60	10 / 2	5	40	59	<1
61280 DT	46.5/49	-- / 1.5	120	--	--	100

CONCLUSIONS

The diagnostic capabilities of a compact NE213 broadband neutron spectrometer in a real fusion experiment have been assessed by performing neutron energy measurements at JET. A method has been developed which allows to quantitatively determine the contribution of the various neutron production mechanisms taking place in different plasma scenarios with various heating schemes. Further analysis will be carried out on more plasma discharges for a more detailed investigation of the fast particle interactions with the plasma and on the analysis of uncertainties.

R&D activity is in progress on compact neutron spectrometers aiming at high counting rates operation with new developed digital acquisition systems [15] and at a complete assessment of the diagnostic capabilities for burning plasma diagnostic at JET-EP and ITER [16, 17].

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