NEUTRON EMISSION SPECTROSCOPY FOR MAGNETIC CONFINEMENT EXPERIMENTS

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INTRODUCTION

The purpose of neutron diagnostics (ND) for magnetically confined plasmas of extended volumes, such as those of tokamaks, is to measure the flux and the energy distribution (spectrum) of the neutron emission for a representative selection[1)] of volume elements. ND should determine the total and local neutron yield rates of the plasma, $Y_n(t)$ and $y_n(x,y)$, as well as provide information for the deduction of the velocity distribution of the ions responsible for $y_n(x,y)$. Unfortunately, local ND measurements are impossible so three surrogates are used, namely, (i) calibrated flux measurements for information on Y_n; (ii) collimated flux measurements for $y_n(x,y)$ and $Y_n(t)$; (iii) spectral measurements[2)] of collimated fluxes for information on the fuel ionic state of the plasma as well as on fast ions of other species besides collective ion motion (rotation).

Calibrated flux measurements are successfully performed with fission chambers over a large dynamic range of Y_n. However, the calibration reference, for the flux-yield conversion, is problematic as is its constancy over time. The reference is based on neutron transport calculations and modeling with empirical support from *in situ* neutron source measurements [1] besides complementary information from neutron activation of samples close to the plasma; the sample response is time invariant and serves as verifier of the time constancy of the fission detectors. A second calibration route is afforded by neutron cameras (see below).

A collimated flux measurement selects the neutron emission from a plasma volume (V) along the sight-line λ representing the neutron brightness $B_\lambda=\int y_n(x,y)\cdot dv$ for V_λ. A linear array of collimators forms a camera whose sight-lines should intersect a large segment of the poloidal plane so as to provide a neutron brightness picture of the plasma,

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1) Because of toroidal symmetry, the area coordinates (x,y) of the poloidal plane can be used.

2) The direction of observation is an important measurement parameter because of possible anisotropicities in the energy distribution of the neutron emission arising from ion velocity distributions that are anisotropic relative to the magnetic field.

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$B_{\lambda k}$, $k=1-k^{max}$ [3]. Two orthogonal neutron pictures can, in principle, be used to determine the emissivity distribution $y_n(x,y)$ through tomographic reconstruction while the total yield, Y_n, can be obtained by summation of the B_λ-data. The diagnostic performance depends on the front and back ends of cameras in different ways. The front end defines the neutron optics and the related machine interface space; the latter is a cost to be paid for increased diagnostic benefit. The back end houses the detectors that record the flux of signal neutrons, with suitable and stable detection efficiency, while they also have to handle predictably the background of γ-rays and other radiation besides the admixture of scattered neutrons[4]. The latter is an intrinsic problem of B_λ-measurements and need to be further assessed by theoretical neutron-transport studies and verified empirically with spectrometer, which should ideally be installed in some camera channels. The development of neutron cameras should aim at increased accuracy, resolution, sensitivity and radial extension of brightness measurements.

Neutron spectrometers use a collimated sight-line which is often chosen to pass through the plasma core to give maximum neutron flux. Radial sight-lines can be accommodated in the horizontal plane, or vertically, while those at different angles to the reference direction of the tangent to the toroidal magnetic field ($\underline{B}_T$) are usually in the horizontal plane. Tangential, perpendicular and intermediate viewing directions can be selected in order to change the sensitivity of neutron emission observations to anisotropicities in the fuel ion motion relative to the direction $\underline{B} \approx \underline{B}_T$[5]. This neutron emission spectroscopy (NES) diagnostic is the one least developed relative to its information potential and, yet, is the one that has seen the most instrumental and functional development since its first exploitation at the very beginning of fusion research in the 50's. The deuterium-tritium experiment (DTE1) of 1997 at JET [2] meant a dramatic leap forward through the combination of high neutron flux from the plasma and a new instrument with high count rate (C_n) capability with matching high accuracy and stability of calibration. There is a want of yet higher fluxes (to boost C_n into the several MHz-range) and enhanced instrumental sensitivity. This would make still finer and weaker details in the neutron spectrum accessible for diagnostic exploitation. A new 2.5-MeV spectrometer could facilitate needed NES-diagnosis of D-plasmas as it is now available for DT.

This paper discusses NES diagnostics as seen from its lines of development marked by the mile stones already passed to the present achievements, as illustrated by the JET results, from which the forward role of NES is projected to the planned next-step fusion experiments such as ITER

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[3] Here, k is an index that increases with plasma radius.

[4] The two main sources are the plasma wall within the collimator view and the collimator wall; whose admixed flux is suppressed by pulse height discrimination and the rest calculationed.

[5] Ion motion anisotropy is a feature that mostly manifests itself in the energy distribution of the neutron emission and to a lesser extent in the brightness distribution observed with the camera.

FUSION NEUTRON SPECTROMETRY SINCE THE 50'S

A cloud chamber was used in 1958 to measure the spectrum of the neutron emission from D-plasmas of ZETA [3]. The spectrum was observed to be Doppler shifted depending on the plasma current direction, in consistence with an ordered center-of-mass velocity of the deuteron pairs producing the neutrons (d+d->τ+n of E_n=2.5 MeV). It was concluded that the fusion reactions were not due to thermal but driven ions thus disproving that thermonuclear reactions had be attained.

The first proof of thermonuclear reactions was obtained with a ^{3}He ionization chamber (see Table 1) at the PLT tokamak in 1979 [4]. Neutron spectra were recorded for D-plasmas injected with neutral beams (NB) of H or D atoms which allowed separation of neutrons from thermal and driven ion reactions. A few years later, the thermal Doppler broadening (Γ_D) of the neutron emission was measured for Omically (Ω) heated D-plasmas produced in the Alcator C tokamak [5]; ion temperature (T_i) was derived from $\Gamma_D=k\cdot\sqrt{T_i}$ with k≈83 for dd-reactions (units in keV) compared to k=177 for14-MeV neutrons from d+t->α+n. This proof-of-principle experiment required summing many discharges which, a decade later at JET, would take only a fraction of a discharge thanks to higher flux. Besides T_i the spectral amplitude (A) could also be measured for a well collimated sight-line which allowed n_d to be determined [6]; since A is proportional to the density-reactivity product $n_d^2\cdot\rho(T_i)$, and, hence, the fuel dilution factor, $(n_e-n_d)/n_e$. This proved unambiguously that the dilution was much higher than had been surmised.

To improve NES data, a neutron time-of-flight (TOF) spectrometer was developed in the 80's which could operate at a significantly higher count rate (C_n of several kHz) and thus acquire better statistics [7]. This made it possible to detect contributions to the fusion power due to reactions between thermal ions and those involving supra-thermal ions caused by injected power (P_{in}) through neutral beams (NB) or radio-frequency waves (RF). This was the beginning of NES as a probe of the fuel ion population while the data quality was short of the limit for quantitative plasma information. This changed with the development of the magnetic proton recoil (MPR) technique

The MPR was designed specifically to attain maximum performance for ignited plasmas [8] and was put to the test for the sub-ignited conditions reached in JET's DTE1 of 1997. This fourth generation NES diagnostic meant drastically improved data quality (up 10^3 by C_n) which, e.g., permitted plasma information to be extracted from the shape of the neutron emission and not only the width.[9]. This resulted in unique information on the fuel-ionic state of plasmas subjected to NB and RF injection relative to the thermal equilibrium plasmas of Ohmic heating. Similarly, the effects of fast fusion ions, viz. tritons from d+d->t+p in D-plasmas and α's from d+t->α+n in DT, were detected for the first time as the spectral components of triton burnup and α-particle knock-on neutron emission (TBN[6)] and AKN[7)]) [10]. Plasma rotation was also measured with the MPR.

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6) Fast (1-MeV) tritons are created in d+d->t+p reactions which, during their slowing-down with a certain probability (about 1 % , typically), suffer nuclear burn-up through t+d->α+n; the triton burnup neutron (TBN) emission is used to study the fast ion behavior in D-plasmas that partly mimics that of α-particles in DT

7) Fast α's create a high velocity component in the deuteron and triton populations through knock-on scattering; these fast d's and t's give rise alpha-particle knock-on neutron (AKN) emission. NES records the

These achievements indicate the development of the next step NES diagnostics towards (i) further increase in sensitivity through proton detectors with better background handling capability and use of orthogonal sight-lines and (ii) development of a high-performance 2.5-MeV spectrometer (TOFOR, see below) for NES diagnosis of D plasmas.

INSTRUMENTS TESTED AT JET

JET has had an extensive NES-program [11] since its start in 1983 in which instruments of different types have been tested and a few were put to diagnostic use (see Table1). Some were commercially (or otherwise) available (nos. 1,2,3,4), while others were specifically developed for the NES application (nos. 3, 5, 6, 10, 11, and 12) of which no. 12 is a NES prototype for ITER. Two (nos. 7 and 13) are the TOFOR and MPRu development projects (12, 13) intended for the forward enhanced program at JET (JET-EP). The latter represent the leading techniques for fusion neutrons of 2.5- or 14-MeV. TOFOR will increase the C_n-capability by two orders of magnitude relative to that of the present generation TOF spectrometers (no. 6) and raise the quality of NES

Table 1. Summary of instruments tested as neutron spectrometers at JET for 2.5- and/or 14-MeV neutrons; also listed are their NES diagnostic status (used, proposed or tested), size, and the 7 type of nuclear reaction/scattering processes underlying the neutron detection. Reference spectrometers are checked in shaded boxes.

Instrument		E_n[MeV]		NES	Size	Type
No	Description	2.5	14	usage		
1	Nuclear emulsion track recorder	√	√	tested	S	S1
2	NE213 liquid scintillator	√	√	tested	S	S1
3	Spherical hydrogen ionization chamber	√		tested	M	S1
4	^{3}He ionization chamber.	√		used	M	R1
5	Forward proton-recoil pulse-height spect.	√		tested	M	S2
6	Neutron time-of-flight (TOF) spect.	√		used	L	S3
7	Optimized rate TOF spectrometer (TOFOR)	√		prop.	L	S3
8	Silicon neutron reaction detector		√	tested	S	R2
9	Diamond neutron reaction detector		√	tested	S	R3
10	Associated-particle neutron TOF spect.		√	(used)	L	S3
11	Annular proton-recoil pulse-height spect.		√	tested	M	S2
12	Magnetic proton recoil (MPR) spect.		√	used	L	S2
13	MPR upgrade spectrometer (MPRu)	√	√	prop.	L	S2

S1 $n+\underline{p}\rightarrow\underline{p}+n$. **S2** $n+p\rightarrow\underline{p}(\underline{\theta}^{np})+n$. **S3** $n+p\rightarrow p+\underline{n}(\underline{\theta})$. **S4** $n+p\rightarrow\underline{p}+\underline{n}$. **R1** $n+{}^3He\rightarrow\underline{p}+\underline{t}$.
R2 $n+{}^{28}Si\rightarrow\underline{\alpha}+{}^{25}Mg$. **R3** $n+{}^{12}C\rightarrow\underline{\alpha}+{}^{9}Be$. Underlined particles/angles are measured.

presence of confined α's, monitors their confinement/slowing-down behavior (as well as that of fast d's and t's) as function of time, and provides a measure of the α pressure in the plasma.

diagnosis of D-plasmas to the level of that attained with MPR for DT-plasmas. The MPRu would be the only spectrometer capable of measuring both 2.5- and 14-MeV neutrons in either DT or D; for D-plasmas, the MPRu will provide high accuracy for prolonged data accumulation, thus complementing TOFOR.

The MPR- and TOF-spectrometers are the reference instruments for DT and D plasmas with regard to both performance and size. Concerning size, there are small instruments which laterally do no extend beyond the dimensions of a typical collimator bore and some larger, medium sized ones of equally limited NES diagnostic capability. Diagnostic performance does not increase gradually with size but is coupled to certain minimum dimensions as set by the nature of neutron detection. Small size is not a benefit in this connection as lack of performance cannot be compensated for (cf. ref. [11]).

GROSS FEATURES OF THE NEUTRON FLUX SPECTRUM

The collimated flux of direct neutrons of d+d->τ+n and d+t->α+n is restricted to energies around 2.5 MeV and 14 MeV (Fig. 1). Scattered neutrons of these sources form continuous spectra which can embarrass certain NES measurements. Camera detectors with modest capability for pulse height discrimination cannot separate scattered (energy degraded) and direct neutrons. Another example concerns measurement of the peak of 2.5-MeV dd-neutrons from DT plasmas which is superimposed on the continuum of scattered dt-neutrons [14]. The scattered spectrum is presently only known from neutron transport predictions which need data or verification of the results and their improvement. Generic tokamak data on the scattered spectrum is non-existent which would be remedied with MPRu measurements at JET-EP.

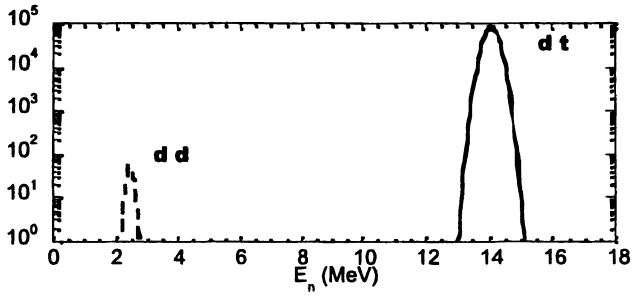

Figure 1. The spectrum of the direct neutron emission from a 10-keV thermo-nuclear DT plasma.

THERMAL AND DRIVEN REACTION CONTRIBUTIONS TO P_F.

The yield rate, $Y_n(t)$, and hence the fusion power, P_f, is routinely measured providing a gauge and compass for the progress in fusion research. Presently studied plasmas are subjected to strong auxiliary heating ($P_{aux} \approx P_{in}$) in the form of NB and RF injection and

the ratio $Q=P_f/P_{in}$ is the quantitative progress parameter. The equivalent quality parameter can be defined as $\eta_{TN}=P_{TN}/(P_{TN}+P_{ST})$ where P_{TN} is the thermonuclear reaction contribution to P_f and P_{ST} is the remaining one due to reactions involving driven (supra-thermal) ions. Both Q and η can be predicted based on models describing the underlying plasma conditions which can be well assessed and understood only if empirical η-results are available for comparison. It has been demonstrated that NES can provide this information for DT plasmas and it could also be provided for D-plasmas with the new TOFOR spectrometer. Studies of sub-ignited plasmas will include transitions regions of η-values affected by different P_α/P_{aux}-ratios as schematically shown in Fig. 2. This transition region would be approached with JET-EP and would indeed be the operating regime of ITER-FEAT [13]. NES is the prime source of information on η in these fusion plasma studies and can provide the empirical basis to test our understanding of sub-ignited and similar plasmas while it can also guide in the work to optimize the fusion quality of the plasma, i.e., conditions for maximum P_{TN}.

ANALYSIS OF NES DATA AND INTERPRETATION

A phenomenological model, based on heuristic ion physics assumptions, has been successfully used to describe the salient features of measured neutron spectra [9]. The model uses a limited number of components and is parameterized so that the predicted spectrum can be fitted to the data to give quantitative results in terms of spectral amplitudes and shape parameters (e.g., T_i). The model contains a T-component of Gaussian shape from reactions between thermal ions and an epithermal (E) component from super-thermal ions interacting with the thermal ones (normally being the bulk of the population). There is a third high-energy (H) component involving ions of energies above the critical limit (typically above ≈100 keV) where the slowing down is due to electrons

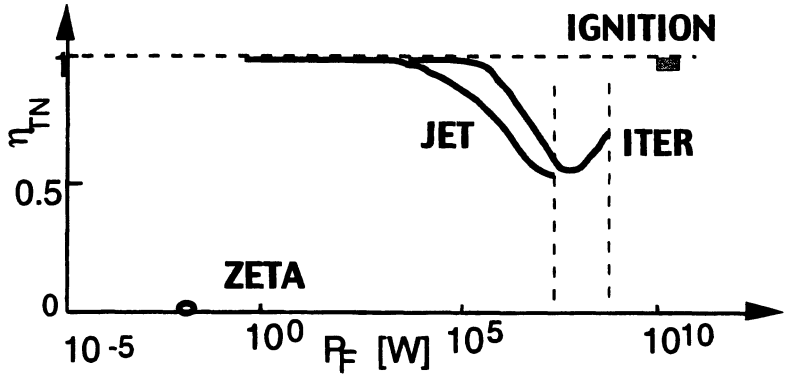

Figure 2. Schematic depiction of the variation of the thermo-nuclear quality factor as function of fusion power for JET and ITER operating with pre-ignition DT plasmas as compared to the first attempt to see thermo-nuclear fusion in the ZETA machine.

with little pitch angle scattering. The high-energy ions can be anisotropic leaving a specific imprint in the H-component which is not present in the E-component. The spectrum is fitted by varying the amplitude of the spectral component and the temperature of the underlying ion velocity distributions whenever a Maxwellian approximation is motivated; the neutron energy is also allowed to vary with a Doppler shift common for all components. The AKN and TBN features are calculated based on the use of computedvelocity distributions to describe the source and slowing-down of the fast ions responsible. It is noteworthy that the neutron energy is calculated to an absolute accuracy of better than 10^{-5} compared to an experimental accuracy, presently in the range 10^{-3} to 10^{-4}. The energy difference between calculated and measured spectra constitute a Doppler shift which is the basis for NES determination of plasma rotation; the present sensitivity level is about ±5 km/s with a potential of improvement to ±1 km/s with the next generation of spectrometers. Generally, the results obtained have been used for systematic studies of the neutron emission response to specific changes made to the plasma as well as for establishing the types of plasma phenomena that show up in NES diagnostic data.

PLASMA RESPONSE TO P_Ω, P_{RF} AND P_{NB}

A tritium discharge (JET#41759) with minority H- and D-admixtures (10 %), (HD)T, can be taken as example reults from the NES heating response studies. [16] The base plasma was formed with P_Ω of the order MW to which was applied a 2-s pulse of 8 MW ICRF-power tuned to the principal cyclotron resonance of hydrogen with 2ω–coupling also to deuterons. There were three 0.2-s NB-blips as well , namely, one during the period of P_ω only and two during the RF-pulse, thus, forming the periods of the heating combinations P_ω [1], $P_\omega+P_{NB}$ [2], $P_\Omega+P_{RF}$ [3] and $P_\Omega+P_{RF}+P_{NB}$ [4]. The plasma of these periods changed markedly as reflected in the NES data which were analyzed to give plasma results of the type described above such as on temperature. Thus, the measured T_i was increased from 1.1±1.6 to 12.9±1.4 keV when P_{NB} was added to P_ω [1→2], and to 8.4±0.5 keV for $P_\omega+P_{RF}$ [1→3]. P_{RF} created also a H-component of deuterons with T_H=300±50 keV; the spectrum recorded for period [3] is shown in Fig. 3. The combined

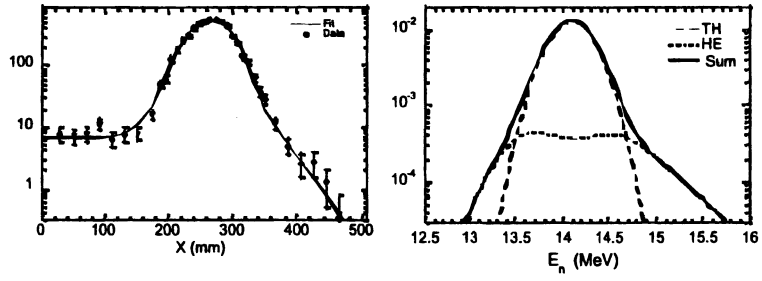

Figure 3: The spectrum recorded for the neutron emission from the period with RF-heating (left panel) and the extracted T and H components of the neutron spectrum in the right panel

injection of P_{NB} and P_{RF} [3→4] was found to raise T from 8 to 18±0.9 keV for the bulk deuterons but without affect on the tail within (T_H=300±120 keV). The results show the prompt and effective temperature impact of P_{NB}-injection and its boost to the effectiveness of P_{RF} in raising the bulk ion temperature.

As an example of derived information we consider the particle number (n) and energy ($w \propto n \cdot T$) densities where, during the RF-pulse, the deuteron density is the sum of the partial densities, $n=n_T+n_H$. The n_T and n_H values can be determined from the measured spectral amplitudes, A_T and A_H, and the reactivities, ρ_T and ρ_H, from the measured temperatures T_T and T_H, i.e., $n_T=n/[A_T/\rho_T+A_T/\rho_T]\cdot(A_{TH}/\rho_T)$ and $n_H=n-n_T$. The result is $n_T=0.98\cdot n$ and $n_H=0.02\cdot n$ for the measured ratio $A_T/A_H=10.1$ and the derived ratio $\rho_T/\rho_H\approx0.17$. The partial deuteron kinetic energies are estimated to $w_T=0.57\cdot w_{RF}$ and $w_H=0.42\cdot w_{RF}$ of the total for the RF-heated plasma [3]. For the combination RF+NB [4], it is found that $A_T/A_H=24.0$ and $\rho_T/\rho_H\approx1$. The partial kinetic energies are $w_T=0.59\cdot w^*$ and $w_H=0.61\cdot w^*$ where $w^*=w_{NB}+w_{RF/NB}$, and $w_{RF/NB}$ is due to the RF+NB synergy. The realtive population energies during the different auxiliary heating scenarios are thus estimated to $w_{RF/NB}:w_{RF}:w_{NB}$=130:110:100 while $w_\Omega:w_{NB}$=10:100 for the P_Ω and P_{NB} periods. The synergetic effect of NB during the RF pulse is estimated to be about 20 %.

The discussion above provides an illustration of the ion kinetic information that NES can provide for different heating scenarios including synergy effects. Results are still inclusive of the line integration effects that need to be considered.

FROM LINE INTEGRATED DATA TO LOCAL INFORMATION

NES measurements receive neutron emission along a sight line over which the plasma conditions can vary depending on popoidal locus. The neutron brightness profile is measured with cameras which provide the weight factors for calculating the relative contributions along the sight-line through the plasma. This can now be done qualitatively with a new computer code (YAPAN [17]) which will make it possible to assess profile effects in NES-data and ascribe a radial parameter value to measured quantities. Moreover, the profile calculations will be important for predicting NES signals of anisotropic plasma effects and their dependence of the sight-line angle relative to the $\underline{B}$-direction. Preliminary attempts to consider profile effects have been done in comparison with CXRS data on T_i-profile [18]. There has also been an early study on $T_i(r)$-effects in measured spectra which showed that the data for thermal plasmas contain extractable information on the temperature density distribution, $n(T_i)$. With the YAPAN-code and the high quality MPR-data it would be possible, for the first time, to include profile effects in the analysis of NES data and make interpolations with radial parameter assignment to the extracted plasma information.

FUEL DENSITY MEASUREMENTS.

From simultaneous measurement of the spectra of d+d->τ+n and d+t->α+n one can potentially determine the densities[5)] n_d and n_t of the mixed fuel DT plasmas This is

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5) The ratio n_d/n_t would be available with higher accuracy.

done from measurements of the amplitudes A_2 and A_{14} besides T using $A_2 \propto n_d^2 \cdot \rho(T)$ and $A_{14} \propto n_d \cdot n_t \cdot \rho(T)$ where the reactivity function $\rho(T)$ is known. [19]. The A_2-signal (S) is superimposed on a background (B) of scattered neutron with a predicted S/B-ratio of about 1. This S/B-level does not in itself prevent this density diagnosis but it lowers the quality compared to the case S/B>>1 which, however, can be compensated for by increasing the statistics. On the other hand, the tolerance for ambient radiation background is very low because of the weak A_2-signal so that only a neutron spectrometers of the MPR-type are feasible and then only in its new MPRu version. An n_d/n_t-diagnostic is essential on ITER thus motivating the proposal to develop MPRu for JET-EP, where it would be used specifically to test the background handling capability besides providing the first generic data base on the scattered neutron spectrum for tokamaks.

The above derivation assumes that the plasma conditions are thermal but ITER-FEAT will operate in the sub-ignited plasma regime ($Q \leq 10$) where 2/3 or less of P_f is from thermal ion reactions ($\eta \leq 0.7$). The remaining driven contributions will increase the Doppler broadening of the neutron emission thus increasing apparent temperatures to $T_2 = T + \Delta T_2$ and $T_{14} = T + \Delta T_{14}$ so that $A_2 \propto n_d^2 . \rho(T+\Delta T)$ and $A_{14} \propto n_d \cdot n_t \cdot \rho(T+\Delta T)$ if $\Delta T = \Delta T_2 = \Delta T_{14}$. The boost in A from ΔT can be estimated from the $\rho(T)$-function so the non-thermal plasma conditions of ITER-FEAT should not preclude the use of NES as a density diagnostic. It is interesting to note here that NES provides direct information on the separate fusion reactivity components related to the Q and η parameters which one ultimately wishes to maximize for given $T_i \approx T_{eff}$ where n_d/n_t is an inclusive factor.

CONCLUSIONS

It was noted that neutron emission spectroscopy (NES) has been used for over four decades of magnetic fusion research to answer questions pertaining to the fusion quality of plasmas and to gauge progress towards the ignition condition. The JET deuterium-tritium (DT) experiments of 1997 meant record high fusion power and a breakthrough for NES where both projeceted and new diagnostic functions were demonstrated. The present JET and its planned enhanced program (JET-EP) will offer and require extended use of NES diagnostics in the further exploration of pre-ignition plasmas of yet higher Q and η. This will be exploited with new instrumentation incuding the strategically important development of a high performance spectrometer for D-plasmas. The NES program at JET is the main (presently only) base of developing NES diagnostics for the next step experiments, viz. ITER, operating in the pre-ignition regime where fusion quality issues should be central. Why is then ITER presently without a NES program?

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