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Neutron emission spectroscopy of D plasmas at JET with a compact liquid scintillating neutron spectrometer[a)]

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Neutron emission spectroscopy is a diagnostic technique that allows for energy measurements of neutrons born in nuclear reactions. The JET tokamak fusion experiment (Culham, UK) has a special role in this respect as advanced spectrometers for 2.5 MeV and 14 MeV neutrons have been here developed for the first time for measurements of the neutron emission spectrum from D and DT plasmas with unprecedented accuracy.

Twin liquid scintillating neutron spectrometers were built and calibrated at PTB (Braunschweig, Germany) and installed on JET in the recent years with tangential-equatorial (KM12) and vertical-radial (KM13) view lines, with the latter only recently operational.

This article reports on the performance of KM12 and on the development of the data analysis methods in order to extract physics information upon D ions kinematics in JET auxiliary-heated D plasmas from 2.5 MeV neutron measurements. The comparison of these results with the correspondents from other JET neutron spectrometers is also presented: their agreement allows for JET unique capability of multi-lines of sight neutron spectroscopy and for benchmarking other 14 MeV neutron spectrometers installed on the same lines of sight in preparation for the DT experimental campaign at JET.

I. INTRODUCTION

The VNS (Vertical compact Neutron Spectrometer) Project is part of the JET diagnostic enhancement included in the EFDA 2012 Work Programme, in view of JET DT Operations[1]. The VNS system was installed in JET Roof Lab in 2016 and it is composed by two kinds of neutron spectrometers: a BC501A (NE213 equivalent) liquid organic scintillator (KM13) and a diamond matrix (KM14), both with digital data acquisition systems for routine high count rate operations of JET with plasmas of Deuterium (D) or Deuterium-Tritium (DT) up to some limit of D/T fuel ratio[2,3,4,5]. KM13 and KM14 share the same vertical-radial line of sight as the TOFOR neutron spectrometer (KM11)[6]. KM13 is a twin spectrometer, with respect to detector material, geometry and components, of KM12, installed at JET in 2009, and of the CNS installed at AUG (Garching, Germany) in 2008[7,8]. KM12 features a horizontal-radial line of sight along the equatorial plane of the JET tokamak.

One of the goals of the VNS project consists in the assessment of the quality of KM12 and KM13 response functions, both measured at the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany)[9]. It is important to verify whether the response function is sufficiently detailed either to define the performance of the spectrometer itself in terms of energy resolution or to achieve a good interpretation of the measured data to support plasma physics studies. In this article it is reported the methods used to test KM12 response function and developed to interpret its data.

II. ASSESSMENT OF KM12 RESPONSE FUNCTION

D Ohmic plasma discharges produced at JET were selected to qualify KM12 response function. They refer to shots 90970 to 90981 relative to the experiment *"B15-11 Quantify N2 retention and confirm retention models based on lab data"* performed in July 2016. For each individual discharge KM12 measured data was analyzed considering the Light Emitting Diode (LED) information of the KM12 Control and Monitoring System and separating neutron events from gamma ray radiation signals[10]. The individual neutron pulse height spectra (phs, the distribution of the neutron pulse areas) were then summed up to define one D Ohmic plasma neutron phs to be analyzed using the response function delivered by PTB (FIG. 1).

For compact spectrometers like KM12, KM13 and KM14, the DD 2.5 MeV neutron phs is continuous, featuring a plateau extending up to an edge which corresponds to the interactions of the events which deposit their full energy in the detector material which corresponds

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to deposited energy $E_{dep} \cong 0.7$ MeVee. The edge and its shape of the phs contain the diagnostic information on the energies of the incoming neutrons.

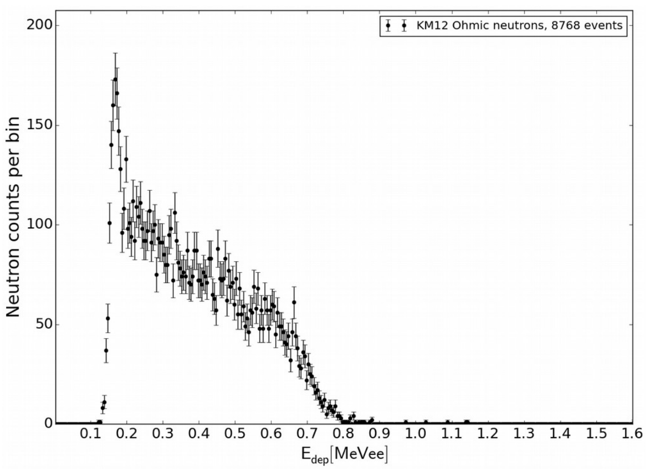

FIG. 1. (Color online). D Ohmic plasma neutron phs of 8768 total neutron events obtained adding up the KM12 phs of JET shots 90970-90981 and used for the assessment KM12 response function.

The assessment of the quality of KM12 response function has been carried out making use of different methods of data analysis: the unfolding data analysis based on MAXED code, as performed at PTB[11,12], is compared to the forward fitting method on KM12 Ohmic neutron phs as it is used for other neutron spectrometers at JET[13-23].

The problem to be solved can be expressed as: $phs = RF^{KM12} * S$ where *phs* is the Ohmic neutron phs (displayed in FIG. 1), RF^{KM12} is KM12 response function to incoming neutrons convolved with the incoming neutron energy spectrum *S*. In this case, *S* is the D Ohmic plasma neutron energy spectrum. In Ohmic plasmas, the ion populations are in thermal equilibrium characterized by Maxwellian velocity distributions. The nuclear fusion reactions of these ion species give rise to a neutron energy spectrum which is Gaussian shaped[24].

In MAXED unfolding method the inverse problem is considered, namely the deconvolution of *phs* with RF^{KM12} resulting in the neutron energy spectrum which depends on the MAXED input parameters[25] such that a good solution *S'* approximates the exact one *S*: $S' \cong S = (RF^{KM12})^{-1} * phs$.

The forward fitting method implies instead the assumption of a model neutron energy spectrum *S'* to be convolved with RF^{KM12} to produce a tentative *phs'* which best fit to *phs* provides confidence of the good interpretation of the data: namely, if $phs \cong phs'$ it follows $S \cong S'$. In this analysis, the forward fitting method is used to benchmark also MAXED unfolding results, meaning that the same part of KM12 phs is used for the comparison.

A. MAXED unfolding

KM12 phs shown in FIG. 1 has been analyzed using MAXED unfolding code[11]. As assumptions of the analysis, only a portion of the measured KM12 phs is considered, namely the *phs* for $E_{dep} \geq 0.35$ MeVee (see FIG. 2, top panel, blue crosses) of 4475 neutron events. MAXED unfolding code requires setting an input energy spectrum which was chosen Gaussian[24] and a reasonable Chi-squared χ^2 value. This is required for the comparison of *phs* and $phs' = RF^{KM12} * S'$ such that, once MAXED converges to χ^2, the unfolding process stops and the solution $S' \cong S$ found. Theoretically, for $\chi^2 = 1.00$ it would follow that $S = S'$ but unfortunately the risk of overfitting and/or artifacts is often present. For this reason a value χ^2 slightly larger than 1.00 is usually a good choice[25]. FIG. 2 bottom panel displays the Ohmic neutron energy spectrum *S'* obtained for $\chi^2 = 1.15$. *S'* gives rise to a *phs'* (FIG. 2, top panel, red line) which is very similar to *phs* (blue crosses).

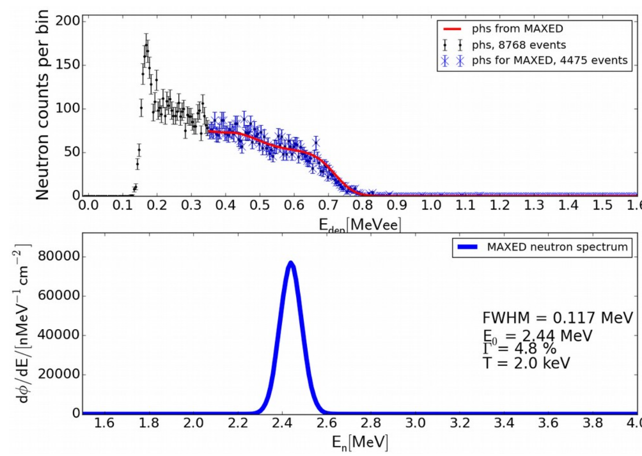

FIG. 2. (Color online). D Ohmic plasma neutron phs measured by KM12 and unfolded with MAXED code. The top panel shows the data (as FIG. 1, black dots) of 8768 total neutron events, the *phs* selected for MAXED unfolding analysis (blue crosses) of 4475 neutron events for $E_{dep} \geq 0.35$ MeVee. The bottom panel displays the Ohmic neutron energy spectrum *S'* resulting from the analysis. The corresponding *phs'* obtained from *S'* is shown in the top panel (red line) for comparison with *phs*.

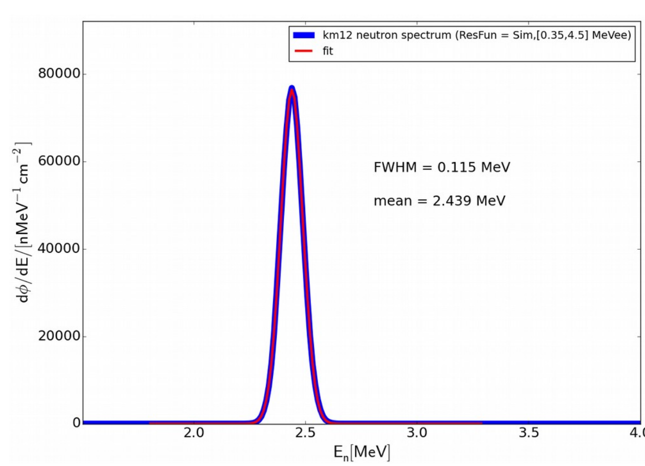

FIG. 3. (Color online). Gaussian fit of *S'* obtained with MAXED unfolding analysis (FIG. 2, bottom panel).

FIG. 2 bottom panel also reports a direct analysis of *S'* in terms of its peak energy emission E_{n0} = 2.44 MeV with full width at half maximum *FWHM* = 0.117 MeV. Considering the relation Lehner and Pohl[24] obtained for D Ohmic plasmas in thermal equilibrium $FWHM = 82.5 * T^{0.5}$, with the plasma temperature *T* expressed in keV, it results *T* = 2.0 keV. Now, a Gaussian function can be chosen for the direct fit of the MAXED Ohmic plasma neutron energy spectrum *S'* shown in FIG. 2 bottom panel: it results E_{n0} = 2.439 MeV and *FWHM* = 0.115 MeV as reported in FIG. 3. The temperatures obtained are consistent with the temperatures of JET Ohmic plasmas and are confirmed by the electron temperature measured on the magnetic axis for the shots of interest 90970-90981 as displayed in FIG. 4.

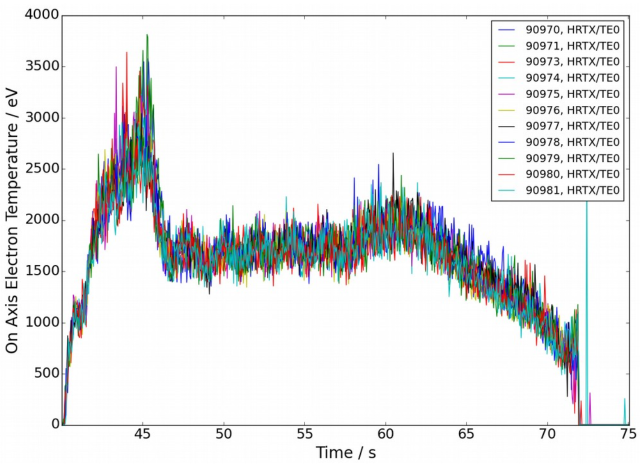

FIG. 4. (Color online). Traces of the electron temperature measured on the magnetic axis for JET shots 90970-90981. The average electron temperature is about 2 keV in the main part of the plasma discharges within 45-60 s.

From these results the performance of KM12 neutron spectrometer can also be quantified. The energy resolution of KM12 neutron spectrometer can be calculated as $\Gamma = FWHM / E_{n0} = 4.8$ %. This is much better than 6.7 % originally fixed as design goal for measuring minimum plasma temperatures of *T* = 4.0 keV.

This analysis demonstrates that the KM12 response function RF^{KM12} is well defined and very accurate such that plasma temperatures as low as *T* = 2.0 keV can be measured which is a much lower limit then the one originally fixed as project goal.

B. Forward fitting mimicking MAXED unfolding

The forward fitting method was developed to prove both the quality of KM12 response function and the reliability of MAXED unfolding as data analysis method. For this, a sensible model neutron energy spectrum *S'* was assumed and folded with RF^{KM12} to produce a tentative $phs' = RF^{KM12} * S'$ to be compared with the measured *phs*. The best fit of *phs'* to *phs* gives confidence on the goodness of the model *S'* and thus on the interpretation of the measurement such that $S \cong S'$. As previously mentioned, for Ohmic plasmas *S* is Gaussian shaped[24] which calls for this assumption for *S'*. The same *phs* for $E_{dep} \geq 0.35$ MeVee was selected for the forward fitting analysis as for MAXED unfolding. The comparison of *phs'* to *phs* is performed in terms of Cash statistics[26] without setting any convergence limit. FIG. 5 displays the results of the good fit (Cast statistics *Cstat* = 1.015) of *phs* and a solution *S'* which corresponds to a D Ohmic plasma temperature of *T* = 2.46 keV. This is similar to what measured with the Gaussian fit of *S'* from MAXED unfolding analysis (FIG. 4) with 10 % variation in *FWHM*. This result confirms the quality of KM12 response function and also the reliability of MAXED unfolding as analysis method of measured KM12 neutron phs provided its input parameters are carefully chosen[25].

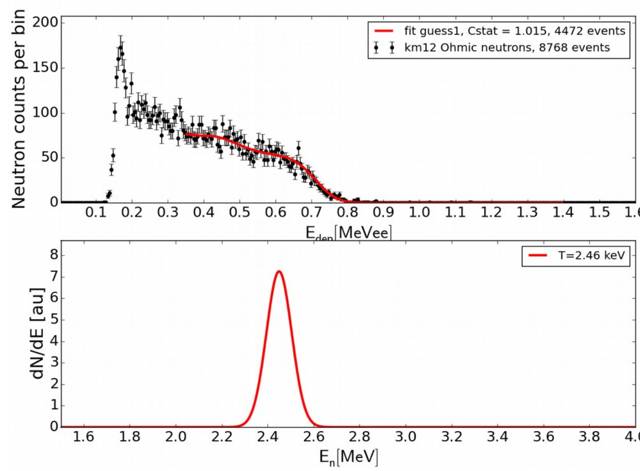

FIG. 5. (Color online). Results of the forward fitting analysis of KM12 Ohmic *phs* of 4472 neutron events performed with the same selection as for MAXED unfolding analysis shown in FIG. 2 top panel. The neutron energy spectrum *S'* is displayed in the bottom panel and it provides a D Ohmic plasma temperature of *T* = 2.46 keV (E_{n0} = 2.411 MeV, *FWHM* = 0.129 MeV).

III. KM12 AND MULTI-LINES NEUTRON SPECTROSCOPY AT JET

Various neutron spectrometers based on different diagnostic techniques have been installed at JET over the years[5,6,7,13,18,20]. They have been designed aiming at optimal performance for DT 14 MeV or DD 2.5 MeV neutron measurements. Lately, the new instruments KM12[7], KM13, KM14[1] and the Afterburner (another liquid organic scintillator[18,19]) are capable of simultaneous measurements of both 2.5 MeV and 14 MeV neutrons up to a certain T concentration limit and represent the enhanced neutron diagnostic capability in view of the planned JET DT experiments. They have been located around JET tokamak with different lines of sight.

The TOFOR neutron spectrometer KM11 constitutes the reference for DD 2.5 MeV neutron measurements[6,16,17,23]. It is a Time-Of-Flight spectrometer Optimized for the Rate which features a n energy resolution $\Gamma = 4$ % and can be used to benchmark the performance of the other new neutron spectrometers for the same D plasma measurements. If consistent, these results confirm the JET capability of multi-line of sight DD neutron spectrometry and provide confidence for the same agreement in case of the diagnosis of 14 MeV neutron emissions in DT plasmas.

To test the performance of the Afterburner and KM12, JET shot 84792 was selected. It happened in August 2013 to study D plasma confinement in hybrid scenario. The plasma current was 1.4 MA and the toroidal magnetic field 1.7 T. Auxiliary power in the form of Neutral Beam Injection (NBI) of 13.1 MW was applied to heat the plasma. Of particular interest is the time interval 5.10-5.60 s of the discharge with plasma conditions and NBI power stable and neutron emission at its maximum. TRANSP code[27] has been used to simulate this plasma to attain information on D ion kinematics and on the corresponding neutron emission of nuclear fusion reactions involving thermal ions and especially the fast ion species, namely, thermal-NBI accelerated (Beam) ions and Beam-Beam ions. These TRANSP calculated neutron spectral components have then been used as model *S'* of the analysis of KM11 data measured in that time interval. For this, the projection of these components along the vertical-radial line of sight of KM11 was carried out for the analysis taking into account the scatter component which includes the energy downgraded neutrons due to collisions happening in the divertor and in the tokamak structures during their travel to KM11 through the collimated line of sight. Each of these individual component is used to build the model *S'* used for the analysis.

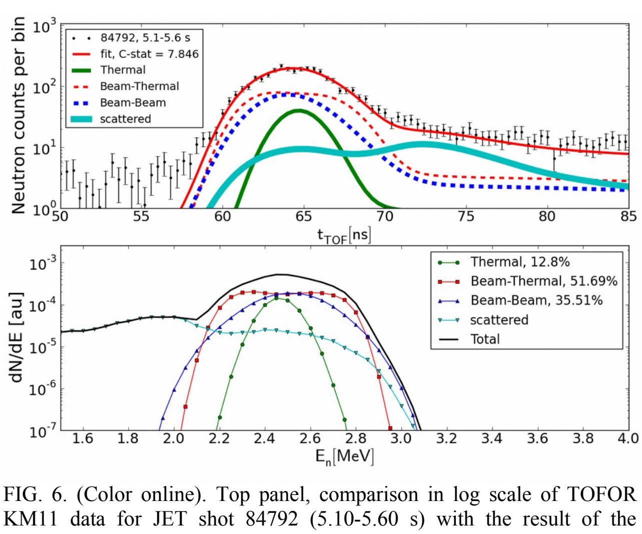

FIG. 6. (Color online). Top panel, comparison in log scale of TOFOR KM11 data for JET shot 84792 (5.10-5.60 s) with the result of the forward fitting analysis. Bottom panel, the neutron energy spectrum *S'* emitted by the plasma according to KM11 data in log scale.

FIG. 6 top panel displays the measured KM11 time of flight neutron data peaked about 65 ns which, for the spectrometer geometry, corresponds to incoming DD 2.5 MeV neutrons. The spectrum is broadened because of the contribution of energetic neutrons born in reactions involving Beam D ions. The contribution to the data of the different D ions reactions thermal, Beam-thermal and Beam-Beam is shown together with the scattering one. The total, sum of all these contributions, obtained with the forward fitting method $RF^{KM11} * S'$ match well the data providing confidence in the model *S'* which is shown in FIG. 6 bottom panel.
The thermal component is peaked about E_{n0} = 2.5 MeV corresponds to a thermal plasma temperature of 3.3 keV. Diagnostic information on the plasma composition, i.e., the reacting D ion species can be obtained by looking at the intensities of the various components and at their comparison. The thermal neutron emission measures 12.8 $\pm$ 3.3 % compared to 51.7 $\pm$ 8.0 % of the Beam-thermal and 35.5 $\pm$ 8.0 % of the Beam-Beam which are important to qualify the efficiency and effects of the auxiliary-heating[17,28,29,30]. Here the auxiliary NBI power highly contributes to the acceleration of the D ions which becomes then responsible of the majority of the neutron emission in view of the favorable cross section values[15].

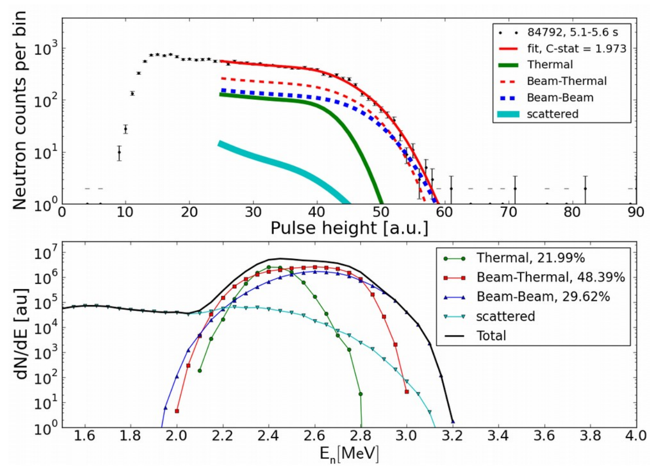

FIG. 7. (Color online). As FIG. 6 but for the Afterburner.

The same TRANSP calculated neutron spectral components have been used for the analysis of Afterburner and KM12 data for the same plasma, JET shot 84792 time 5.10-5.60 s. Since their detector material is sensitive also to gamma radiation, it is necessary to remove this contribution beforehand[10]. The obtained neutron phs can then be analyzed with the projected TRANSP neutron spectral components along the spectrometers equatorial-tangential lines of sight, at 47° for the Afterburner in

Octant 4 and at 22° for KM12 in Octant 7, to determine their tentative *S'*.

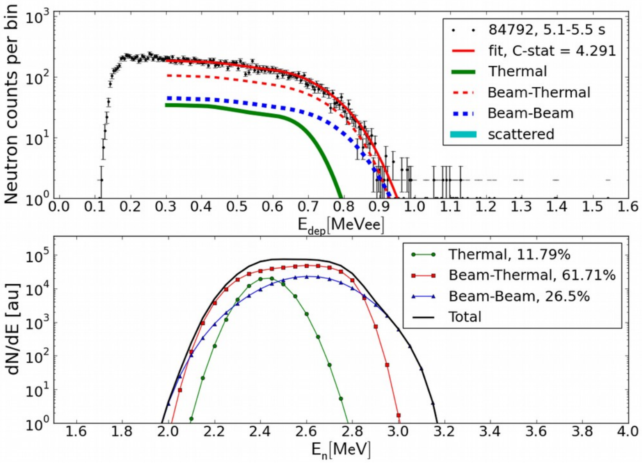

FIG. 8. (Color online). As FIG. 6 but for KM12 in linear scale the top panel and in log scale the bottom panel.

FIG. 7 shows the results for the Afterburner while FIG. 8 for KM12. For the Afterburner the thermal neutron emission measures 22.0 ± 4.4 %, the Beam-thermal 48.4 ± 13.0 % and the Beam-Beam 29.6 ± 10.0 %. For KM12, it results 11.8 % thermal, 61.7 % Beam-thermal and 26.5 % Beam-Beam with a negligible contribution of the scattering neutrons in view of the distance of the spectrometer and of its reduced viewing angle which allows for double-crossing of JET plasma core. For both Afterburner and KM12, the thermal plasma temperature results 3.3 keV in perfect agreement with KM11 TOFOR.

IV. CONCLUSIONS AND OUTLOOK

This article reports on the assessments of the quality of the response function of the compact liquid scintillator neutron spectrometer KM12 installed at JET, on the reliability of MAXED unfolding data analysis method and on the KM12 neutron spectroscopy capability to diagnose neutrons born in nuclear fusion reactions of D ions characterized by different velocity distributions.

A forward fitting method of data analysis has been developed to allow for an independent evaluation of the KM12 response function and of MAXED unfolding technique. This study has demonstrated the following results: the accuracy and reliability of KM12 response function; the reliability of MAXED unfolding data analysis technique for KM12 neutron data as it provides a consistent Ohmic plasma temperature with the electron temperature; the performance of KM12 neutron spectrometer in terms of energy resolution as it results $\Gamma <$ 5 %, well below its original project design goal; the sensitivity of KM12 neutron spectrometer to contributions as low as few percent in intensity to the neutron energy spectrum obtained from fusion reactions of different D plasma ions populations; the agreement of KM12 data analysis results with the ones of the Afterburner and of the KM11 (TOFOR), reference for D 2.5 MeV neutron spectroscopy at JET.

The multi-line of sight neutron spectroscopy capability of JET, formed by independent instruments and measurement techniques, allows for the determination of the Ohmic plasma ion temperature and the intensities of the various plasma ion species with good accuracy.

The multi-component analysis method needs to be further developed for KM12 considering the ion cyclotron resonance heating and proper modelling of the ion velocity distributions. As soon as JET experiments will resume, the same analysis and comparisons are going to be performed on KM13 and KM14 such that the enhanced JET capability of multi-lines of sight neutron spectroscopy can be brought to routine during experiments. The agreement of neutron results for D plasmas obtained with independent instrument based on different detection and spectroscopy techniques give confidence and expectations for their use in JET DT operations.

V. ACKNOWLEDGMENTS

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