Component wise DT fusion yield prediction with neutron spectrometry

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Abstract

This paper uses neutron emission spectroscopy to determine fusion plasma properties and reaction component intensities, and from those calculate the DT equivalent fusion power for deuterium-only shots at the JET tokamak. The developed method is applied to several hybrid and baseline pulses, and current record DD pulses reaches 6-7 MW of DT equivalent power. The results have been compared to DT predictions made with the codes JESTORR and TRANSP as well as previous DT pulses at JET.

Introduction

As a final step in JET's preparation for ITER a second Deuterium-Tritium (DT) campaign, DTE2[1], is scheduled. In preparation for this, the ability to quickly and robustly predict fusion yields in DT reactions is sought.

In this paper, the energy spectra of neutrons emitted from the fusion reactions in DD plasmas at the JET tokamak has been measured with the time-of-flight spectrometer TOFOR[2]. The measured neutron spectrum has been analyzed and is used to identify intensities of the different reaction components (thermonuclear, beam-target (BT) and RF-target) and how their reaction rate scales when going from a DD to a DT plasma. This upscaling is used with the total neutron rate found by the JET fission chambers[3] to estimate the DT reaction rate.

Several JET pulses have been analyzed with neutron emission spectroscopy (NES), and an estimation of the DT fusion yield of such shots has been made. Comparisons with other DT predictions done using the codes TRANSP[4] and JESTORR (a code for quickly estimating the reaction rate in JET pulses, with DT predicting abilities)[5] are also presented.

Calculations

The aim is to estimate the DT equivalent fusion power from a DD pulse in the JET tokamak. This paper investigates the use of neutron emission spectroscopy (NES) for DT prediction.

A DD to DT neutron rate scale-up factor is here defined as $S = \frac{R_{\rm DT}}{R_{\rm DD}}$, with $R_{\rm DD}$ and $R_{\rm DT}$ being the neutron rates in a DD and DT fusion plasma respectively. This scale-up factor will be different for each reaction component. The scale-up factors for the different components have been derived, for a plasma with a fuel ion ratio of $\frac{n_t}{n_d} = 1$, and are expressed as

$$S_{\rm th} = \frac{\langle \sigma v \rangle_{\rm th,DT}}{2\langle \sigma v \rangle_{\rm th,DD}}, \quad S_{\rm bt} = \frac{\langle \sigma v \rangle_{\rm bt,DT} + \langle \sigma v \rangle_{\rm bt,TD}}{4\langle \sigma v \rangle_{\rm bt,DD}} \quad \text{and} \quad S_{\rm rf} = \frac{\langle \sigma v \rangle_{\rm rf,DT}}{2\langle \sigma v \rangle_{\rm rf,DD}} \tag{1}$$

*See the author list of "X. Litaudon et al 2017 Nucl. Fusion 57 102001" for each reaction component respectively. These scale-up factors depend on both the plasma temperature, but also on the beam-ion distribution and RF-accelerated ion distribution. The scale-up factor for these neutron rate components are plotted in figure 1. The cross-section values used come from Bosch and Hale's formulas[6].

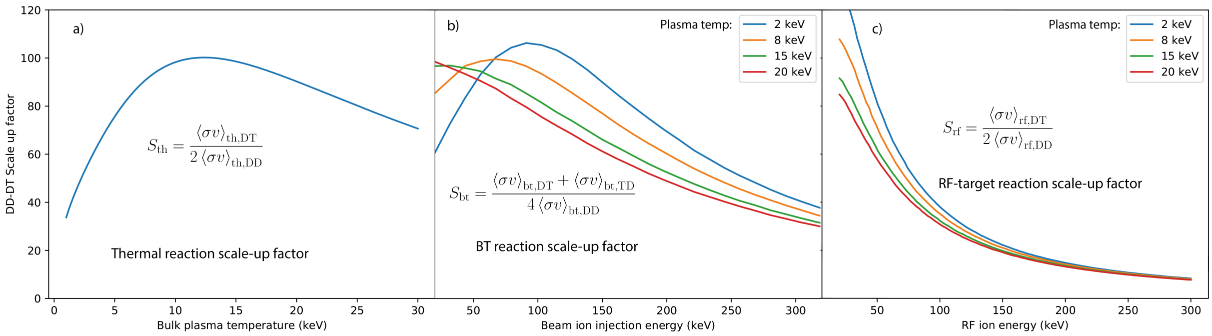

Figure 1: The DD to DT scale-up factors for the thermal, beam-target and RF-target reaction rates. A 50/50 deuterium-tritium plasma is assumed. The BT and RF scale-up factors are shown for different temperatures.

Once the component scale-up factors are determined, a weighted sum of those becomes the total neutron rate scale-up factor

$$S_{tot} = \frac{S_{th}I_{th} + S_{bt}I_{bt} + S_{rf}I_{rf}}{I_{th} + I_{bt} + I_{rf}}, \tag{2}$$

where I_{th}, I_{bt} and I_{rf} are the relative intensities of the neutron rate components. These relative intensities, along with the plasma temperature and RF ion temperature can be determined by NES by fitting these parameters to the neutron energy spectrum measured by the time-of-flight neutron detector TOFOR using modelled neutron spectral components. To calculate S for the beam-target component, the beam-ion energy distribution is needed, which here is calculated by either TRANSP or the method described by Stix[7].

Results and discussion

Several JET pulses have been extrapolated to DT with NES, and their resulting fusion power is shown in figure 2a. For comparison, three prolonged pulses from the previous 1997 DT campaign are plotted. Note that this does not include the record-breaking shots since these do not have a sustained reaction and are not comparable to the rest of the studied pulses.

The pulses from the previous DT campaign fall in line with extrapolated DD pulses of similar heating power. The currently best pulses reach 6-7 MW of DT equivalent fusion power.

If we look at the thermal component of the neutron rate only, which is the component most interesting for future fusion reactors, its estimated DT fusion power is shown in figure 2b.

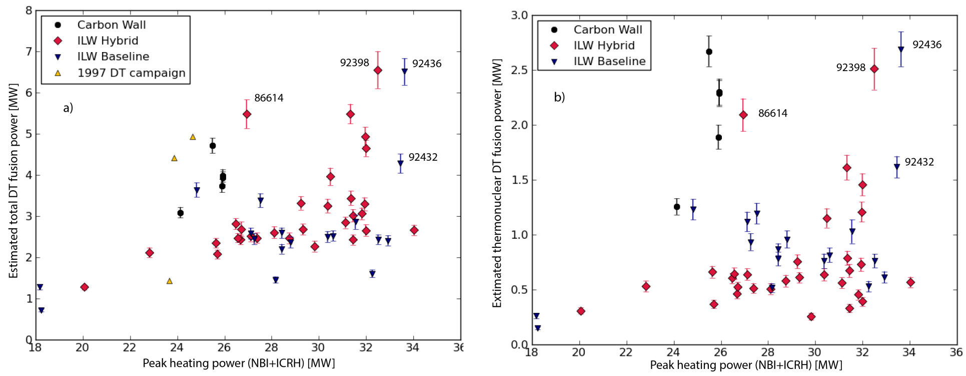

Figure 2: The DT equivalent fusion power found by NES is shown in a). The thermonuclear component of this is shown in b).

The DT prediction comparison with TRANSP for three pulses are shown in figure 3. The plot shows the time trace of the total neutron rate, as well as the beam-target and thermonuclear neutron rate components, for the DT TRANSP simulation.

For the time-interval where the NES based DT extrapolation was conducted, the resulting scale-up factor has been multiplied with the DD TRANSP neutron rates and is shown in the figure as a comparison.

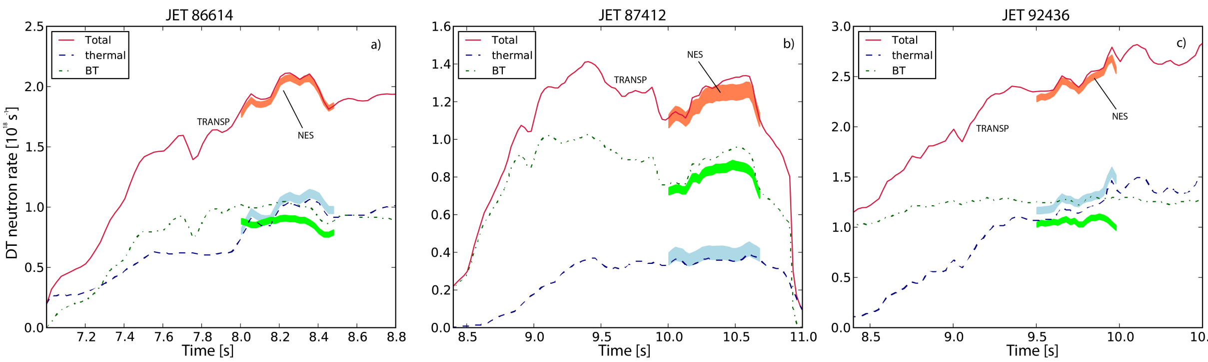

Figure 3: The TRANSP DT extrapolation for the JET pulses 86614 (a) and 87412 (b), along with the scaled-up neutron rate from the NES based DT extrapolation.

There is a good agreement between the upscaled neutron rate found by NES and TRANSP, although there is a discrepancy between the scale-up factors for the BT and thermonuclear components. Consistently TRANSP estimates a higher BT and a lower thermonuclear scale-up factor than the one gained by NES, but these cancel since the total neutron rate matches.

Comparisons between DT equivalent fusions power gained from TRANSP, JESTORR, and NES are shown in figure 4. Here the DT neutron rate is found by multiplying the measured neutron rate with the scale-up factors found from the ratio between the simulated DT and DD neutron rates. This up-scaled neutron rate is multiplied by 17.6 MeV which gives the predicted

DT fusion power. As seen above, the NES estimation shows a good agreement with TRANSP and a fair agreement with JESTORR.

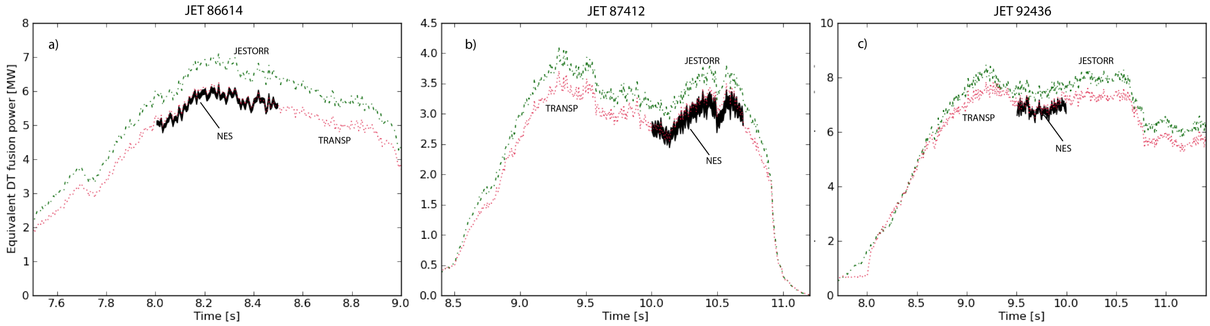

Figure 4: DT equivalent fusion power estimated by the codes JESTORR and TRANSP, compared to the DT extrapolation done with NES. Shown for pulse 86614 (a), 87412 and 92436 (c).

Conclusions

NES provides the means to identify reaction components, plasma properties and use these to calculate the DT equivalent fusion power of a deuterium-only plasma. The results fall in line with results from TRANSP and JESTORR, as well as pulses from the previous DT campaign. Current record shots at JET reach a DT equivalent fusion power of 6-7 MW. Hence to reach the desired 15 MW of DT fusion power, more heating power, which will be available in the upcoming campaign, is needed.

Acknowledgements

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