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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

The ratio of the tritium and deuterium concentrations (n_t/n_d) in the core plasma is a key parameter in future burning plasma experiments, such as ITER. However, performing measurements of this parameter in the plasma core is difficult. In this paper we present a method to derive n_t/n_d using the ratio of the thermonuclear neutron emission to the beam-target neutron emission. The method we use is thus not limited to low tritium concentrations, and we apply it to neutron spectroscopy data from the Magnetic Proton Recoil spectrometer taken during the deuterium tritium experiment at JET. n_t/n_d-values obtained using neutron spectroscopy are in qualitative agreement with those from other diagnostics measuring the isotopic composition of the exhaust in the divertor.

1. INTRODUCTION

In a deuterium (D) tritium (T) plasma the fusion power is proportional to the product of the deuterium and tritium densities, ndnt. The optimum fuel ion mix is therefore a 50/50 plasma, or a fuel ion ratio $n_t/n_d = 1.0$. Consequently, for efficient burn control it is important to measure this ratio. Of equal importance is to measure the ratio of the summed fuel ion density to the electron density (n_{d+t}/n_e), or the fuel ion dilution. E.g. 5% helium in the plasma core would lower n_{d+t}/n_e to 90%. This would in turn decrease the fusion power by 19%.

There are several suggested techniques to perform these measurements at the International Experimental Fusion Reactor (ITER) [1], but few have been tested and proven experimentally. This is especially true for the fuel ion ratio, and finding good candidates for this measurement is a crucial task in preparation for ITER. While it is possible to measure nt/nd from the ratio of the thermonuclear DD to DT emission [2], this measurement will typically be restricted to $n_t/n_d < 0.2$. For higher fuel ion ratios the DD emission at E_n= 2.5MeV is drowned by scattered, energy degraded, DT neutrons. Instead, in this paper we propose to use the ratio of the thermonuclear (TH) emission to the beam-target emission from Neutral Beam (NB) heating, as this measurement is not hampered by scattered neutrons.

The TH emissivity is given by $R_{TH} = n_d n_t <\sigma v>_{TH}$, and the NB emissivity is, assuming a T beam, given by $R_{NB} = n_d n_{nb} <\sigma v>_{NB}$. Here $<\sigma v>_{TH}$ is the thermo-nuclear reactivity, nnb is the beam-ion density and $<\sigma v>_{NB}$ is the beamtarget reactivity. These three quantities can be calculated, and by separating R_{TH} from R_{NB}, using a neutron spectrometer, one can derive n_t/n_d as well as $n_d + n_t$. Neutron spectroscopy measurements capable of separating TH from NB emission therefore provide a promising possibility for diagnosing near burning beam-heated plasmas with fuel-ion ratios around 1, i.e., of ITER relevance. For this reason we revisit data taken by the Magnetic Proton Recoil (MPR) neutron spectrometer [3] during the DT experiment at the Joint European Torus (JET) in 1997.

2. EXPERIMENTAL

In this paper we study the neutron emission from JET Pulse No: 42780. In this discharge the plasma was fueled exclusively with tritium by means of T gas puffing and T NB heating at 10MW; the deuterium present in the plasma is therefore entirely from recycling with the carbon wall.

Neutron spectroscopy data were taken with the MPR, which is installed at JET with a tangential sight-line. In the MPR a collimated neutron beam from the plasma impinges a thin plastic foil. A fraction of the neutrons scatter on hydrogen in the foil, producing recoil protons. The recoil protons are further momentum analyzed by a magnetic spectrometer and their energy is measured on a 38-channel detector hodoscope. For the settings used during Pulse No: 42780 there is a near Gaussian mapping of the original neutron energy to the location of the recoil protons on the hodoscope. The energy resolution is 2.5% (FWHM).

To analyze the neutron energy spectrum we fit model components of the TH and NB neutron emission to the data, after folding the model components with the Spectrometer Response Function (SRF). The TH component is modeled as a Gaussian with FWHM given by 177 $\sqrt{T_i}$ (in keV), while the NB component is modeled with the Monte Carlo code Control Room, which is employed e.g. in [4]. An early version of the code is also described in [5].

In the fitting routine there are 4 free parameters: intensities of the TH and NB components (I_{TH} and I_{NB}, respectively), ion temperature (T_i) and Doppler shift from plasma rotation (ΔE_{rot}). Uncertainties in the parameters are found with a Monte Carlo sampling of the 4D likelihood surface and are fully unconstrained, i.e., all parameters are allowed to vary freely at all times. At the MPR settings used for this discharge about 15 000 proton counts are typically required to accurately fit all 4 parameters. This puts a neutron rate dependent limit on the time resolution of the analysis. To increase the time resolution it is possible to set T_i as a Bayesian prior. The prior value can be taken either from another diagnostic, or as in this paper from an interpolation of the fitted Ti from the MPR analysis.

The slowing down distribution of the NB heating (f_{NB}) was calculated with the code NUBEAM [6], which provides f_{NB} in 4 dimensions (energy, pitch-angle and poloidal position). The result was used to calculate the shape of the NB component as well as the beam-ion density and the beam-target reactivity. The TH reactivity can be found with a table lookup once the ion temperature is known.

3. RESULTS

The central electron density is shown in Figure 2. At the beginning of the heating phase (t = 15s) the plasma density was low at $n_e = 3\times10^{19}$ m^{-3}, but starting at t = 15.5s the density gradually increased and reached a plateau around $n_e = 8\times10^{19}$ m^{-3} (t > 18s).

In Figure 3 (a) we show an example MPR proton position histogram from Pulse No: 42780 (points with error-bars). The fitted TH and NB components are also shown (solid red and dashed blue, respectively) as well as a low energy component describing scattered neutrons (dash-dot). In Figure 3 (b) the fitted components are shown on the neutron energy scale, i.e., prior to folding with the SRF. In the example shown here the width of the thermal component was fitted to 460keV, which corresponds to T_i = 6.5keV. There are some discrepancies between this temperature and measurements by charge exchange recombination spectroscopy, but this will be the topic of a forthcoming paper.

The time evolution of the fitted components are shown in Figure 4. I_{TH} and I_{NB} are shown (a) and T_i in (b). Note that the time resolution in (a) is higher since the requirements on the statistics in the data is lower when only the intensities of the two components are fitted. In (a) T_i is instead set as a Bayesian prior from interpolations of the results in (b).

In Figure 5 (a) we show the results on the fuel-ion ratio (nt/nd) derived from the MPR data (points with error-bars). The error-bars were obtained with a sensitivity analysis. This includes uncertainties in the fitted components I_{TH}, I_{NB} and T_i (see Figure 4) as well as uncertainties in Te and n_e (10% assumed for both). For comparison the fuel-ion ratio obtained with a penning trap measuring neutral gas below the divertor is also shown (solid line).

Finally, in Figure 5 (b) the fuel ion dilution (nd+t/ne) is shown. Points with error-bars refer to estimates from the MPR data. Also shown are estimates of n_{d+t}/n_e from Bremsstrahlung Z_{eff} measurements assuming an impurity charge of 6. Measurements with horizontal and vertical sight-lines are shown in solid red and dashed blue, respectively.

4. DISCUSSION

There are three phases in the heating period of the discharge analyzed here. First a transient phase when the beams are turned on (t = 15s). Here the plasma density is low and the plasma is still at the ohmic temperature. The neutron emission is therefore dominated by the NB component, which levels out at the time scale of the beam slowing down time, i.e., a few 100ms.

Second, the bulk plasma is heated and the ion temperature increases and peaks at T_i = 11keV. The density has increased slightly to 4.5×10^{19} m^{-3}. ITH therefore increases and reaches a maximum at t = 16s.

Third, the density increases further and levels out at 8×10^{19} m^{-3}. At the same time Ti decreases and levels out just above 6 keV (t = 17–20s). Since the TH reaction rate scales with both temperature and density squared, the combined effect is a rather constant level of TH emission from t = 16s and onwards. The temperature and density variations, by almost a factor 2, cancel out.

In the time evolution of the fuel-ion ratio (Figure 5a) two features are standing out. First, during the entire heating phase the T-fraction estimated by the MPR is significantly higher than that measured by the penning trap. This is a reasonable result since the MPR measurement is weighted to the core plasma, which dominates the neutron emission. On the other hand, the penning trap measures below the divertor and sees a higher Dfraction since the measurement is closer to the D-source, i.e., the carbon tiles.

Second, the T-fraction is highest in the beginning of the heating phase (n_t/n_d = 30) and then decreases to an equilibrium around n_t/n_d = 10. Since no deuterium is fueled to the plasma, but comes from wall recycling, it is reasonable to assume that there would be a delay in the core deuterium content. The NB heating fuels T directly to the core plasma while the wall recycling adds D from the plasma edge. The MPR suggests that the delay is around 1.5s.

The MPR results on the fuel-ion dilution suggests that the plasma is cleanest during the beginning of the heating phase and that impurities dilute the core plasma at the same time scale as D is added. The first time point stands out with $n_{d+t} > n_e$, which is an unphysical results, but we note that within the error-bars all results are physical. The MPR results are further corroborated by Z_{eff} measurements, which also suggest decreasing values of n_{d+t}/n_e. Within error-bars the MPR estimates of the fuel ion dilution is in agreement with the estimates from the vertical Z_{eff} measurement. However, the horizontal Z_{eff} measurement suggests a cleaner plasma with $n_{d+t} > n_e = 0.9$; this is significantly higher than the MPR estimates

CONCLUSIONS

In this paper we have demonstrated that a high-resolution neutron spectrometer, capable of separating the thermo-nuclear emission from the beam-target emission, can be successfully used to derive the fuel-ion ratio (n_t/n_d) as well as the fuel-ion dilution (n_{d+t}/n_e). The results are of high relevance to ITER since the main plasma scenario at ITER is a NB heated plasma, suitable for this type of analysis.

While we only present results from one discharge in this paper, there are high-quality data from the MPR for a number of discharges during the JET DT-campaign, and a more systematical analysis of these results will be presented in a follow-up paper.

Finding a reliable method for measuring the core fuel-ion ratio is a high-priority task for ITER, and we conclude by noting that a high-resolution neutron spectrometer, such as the MPR, would provide valuable information. Focus should be put on a neutron spectrometer system with demonstrated capabilities to accurately resolve the thermonuclear and beam-target emissions.

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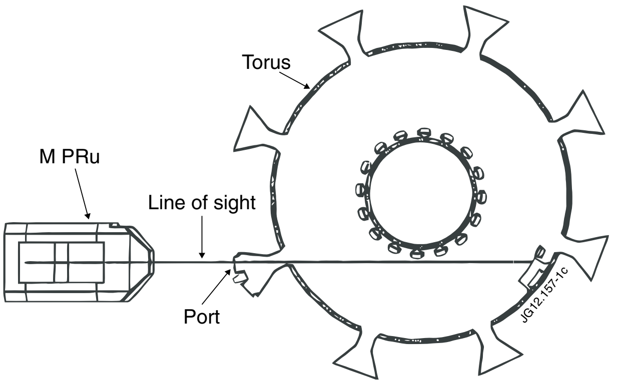

Figure 1: Top view of the tangential sight-line of the MPR making a double pass through the plasma center.

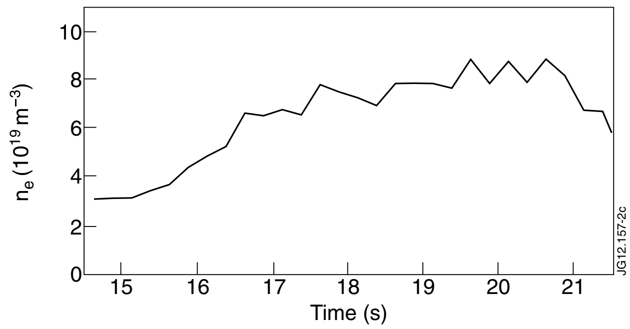

Figure 2: Central electron density of JET Pulse No: 42780 measured byLIDAR.

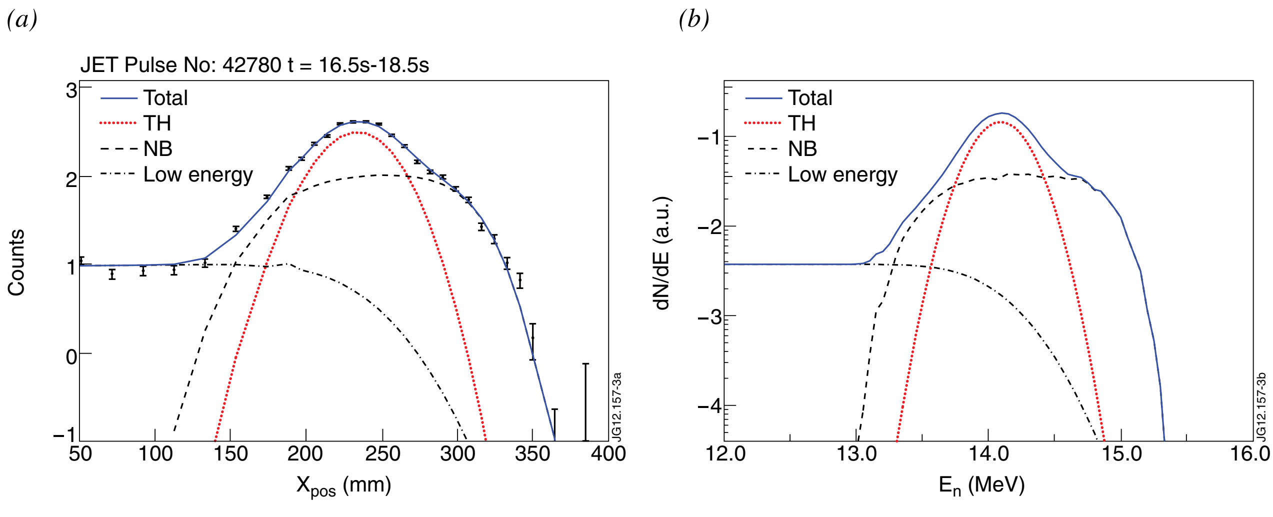

Figure 3: (a): Example of fit to proton recoil histogram measured by MPR during JET Pulse No: 42780, TH, NB and Low energy components are shown in solid red, dashed and dashdot, respectively. (b): Fitted components are shown on a neutron energy scale.

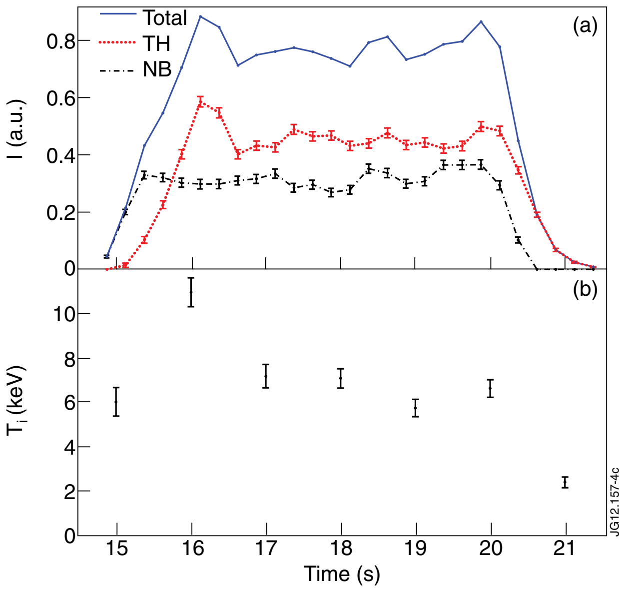

Figure 4: (a): Time evolution of thermo-nuclear (red) and beam-target (blue) neutron emission measured by MPR. (b): Time evolution of ion temperature measured by MPR.

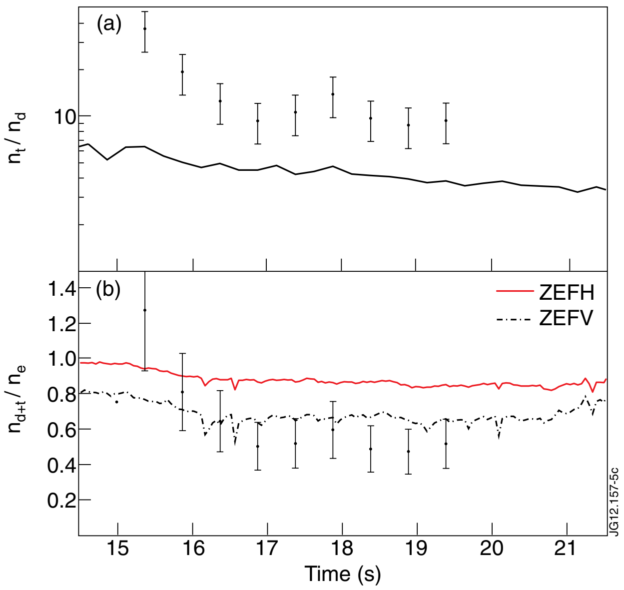

Figure 5 (a): Fuel ion ratio (nt/nd) derived from MPR data (points with error bars) and from the penning trap (solid line). (b): Ratio of summed fuel ion density to electron density (n_{d+t}/n_e) derived from MPR data (points with error bars) and Z_{eff} measurements (horizontal channel solid red and vertical dashed blue).