PLASMA DIAGNOSTICS USING COMPOSITE NEUTRON EMISSION SPECTRA

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1 INTRODUCTION

Recent operations at JET with deuterium-tritium (DT) discharges have produced record power levels and accompanying record neutron yield rates (Y_n) from d+t→α+n fusion reactions. Together with the use of a new type of neutron spectrometer, based on the magnetic proton recoil (MPR) technique, this has dramatically increased the opportunities for neutron emission observations of the plasma [1,2,3]. The MPR, counting at rates approaching MHz for the record pulses, combines the capabilities to observe the main neutron emission at high time resolution with the ability to detect weak spectral components in the high-energy tail. The weak components arise when one of the reacting fuel ions is supra thermal (ST), where the ST velocity distribution is caused by a preceding fusion reaction.

Triton burn-up neutron emission (TBN) comes from d+d→t_{dd}+n reactions, where the triton (of birth energy E_t = 1.0 MeV) has a certain probability (typically 1%) for a subsequent t_{dd}+d→α+n reaction before thermalization. Measurements of the TBN spectrum permits detailed studies of the fast particle behavior, such as that of the α:s produced at 3.5 MeV (due to the similarity in Larmor radii) without the need for tritium fuel. The TBN is the dominant 14-MeV neutron component in pure D plasmas and gives similar yields as the bulk d+t→α+n reaction in DT plasmas with small tritium concentrations (about 10^{-4}). In this latter case the TBN emission can be used to deduce the residual tritium concentration.

Another weak component is the neutron emission due to the so-called α knock-on effect. α-particles from the d+t→α+n reaction, born with an energy of E_α = 3.5 MeV, slow down by interactions with the plasma electrons and ions, involving, occasionally, a large energy transfer to one of the fuel ions, thus creating ST d_α and t_α populations. The knock-on neutrons are generated in subsequent d_α+t→α+n and t_α+d→α+n reactions. Theory predicts the effect to be just at the level of detectability for the MPR spectrometer [4] observing DT plasmas at JET.

This paper reports on a study of the residual tritium concentration in JET, relating it to the TBN signal, and the search for the predicted α knock-on effect in the neutron spectrum.

2 THE MPR NEUTRON SPECTROMETER

In the MPR, the neutron emission from the plasma is viewed through a collimator at the end of which is situated a thin plastic conversion foil. A fraction (order 10^{-6}) of the incoming neutrons are converted to nearly the same energy recoil protons. These protons are collimated, momentum analyzed and focused in the magnetic spectrometer and finally detected in a focal plane detector, consisting of an array of scintillation counters (Fig. 1). The detector is a 36-channel hodoscope, covering an energy bite of ±20%. The principal experimental data are thus a proton position distribution. Knowing the spectrometer's response function, this position distribution can be translated into a neutron energy distribution. Besides the count rate (scaler) information, signal pulse height information (ADC spectra) is routinely recorded for each scintillator channel.

To benefit from the spectrometer's high count-rate capability (several MHz), the MPR has been placed close to the torus, about 10 m from the plasma center. Together with the high detection efficiency, about $5 \cdot 10^{-5}$ cm^2 at dE/E = 4 % (FWHM), this enables measurements with good counting statistics **and** good time resolution; the instrument has routinely been operated with 10 ms time resolution, with the possibility for 1 ms bins. During the record fusion power DT discharge (16.1 MW) at JET, the MPR count rate peaked at 630 kHz.

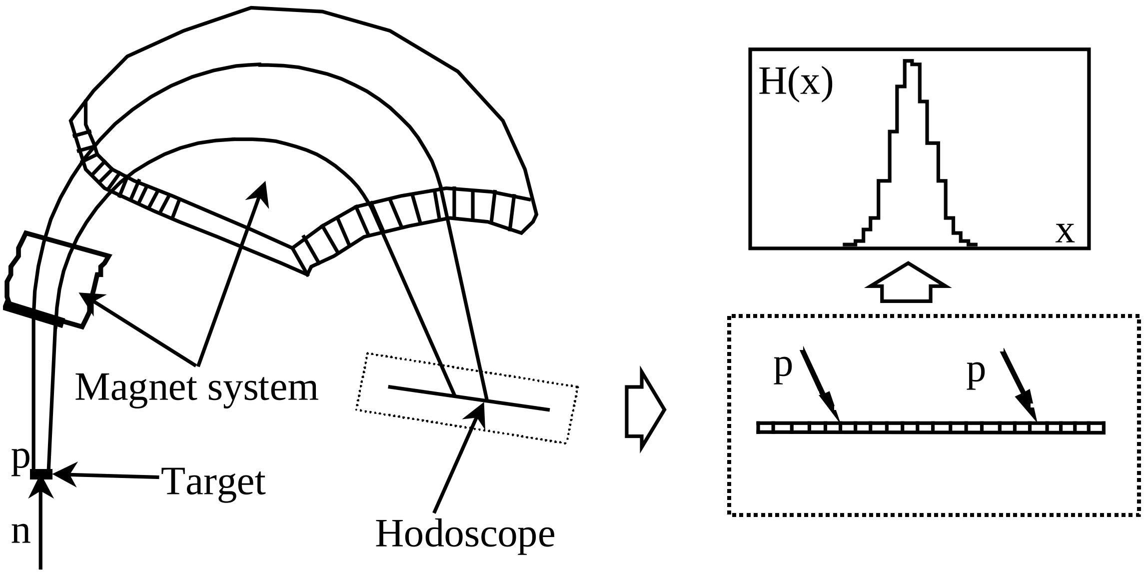

Fig. 1: Schematic drawing of the main components of the MPR spectrometer.

The ability to detect weak components in the neutron emission requires good background control. The background suppression is performed in three steps. First, the spectrometer is enclosed in 65 tons of concrete and lead radiation shields. Second, pulse height discrimination is imposed on the detector signals prior to digitization and registration. Finally, the remaining background admixture can be determined, by studying the pulse height distribution of each scintillator channel, and corrections applied to the recorded scaler data. The last step in the background reduction chain is illustrated in Fig. 2, where we compare the pulse height spectrum obtained in one of the high-energy hodoscope channels (filled circles) with that of a scintillator dedicated for background monitoring (open squares). The shape of the background in the hodoscope channel is well represented by the monitor spectrum, giving confidence that the monitor can also represent the part of the background hidden under the proton signal peak. By weighting the monitor data to reproduce the discriminator cut in the hodoscope channel (full-drawn line), one can estimate the total number of background counts in the signal spectrum. The extracted background correction numbers have been collected in a database that is available as part of the MPR data reduction and analysis software. The errors in the background corrections are of the order 10%, mainly originating from systematic uncertainties, and they limit the sensitivity to weak components with magnitudes $>2 \cdot 10^{-5}$ of the peak amplitude. The best prospect for observing these weak components is as a high-energy tail in the neutron spectrum. At low energies, collimator in-scattering and vessel back-scattering contribute appreciably, thus concealing the weaker components.

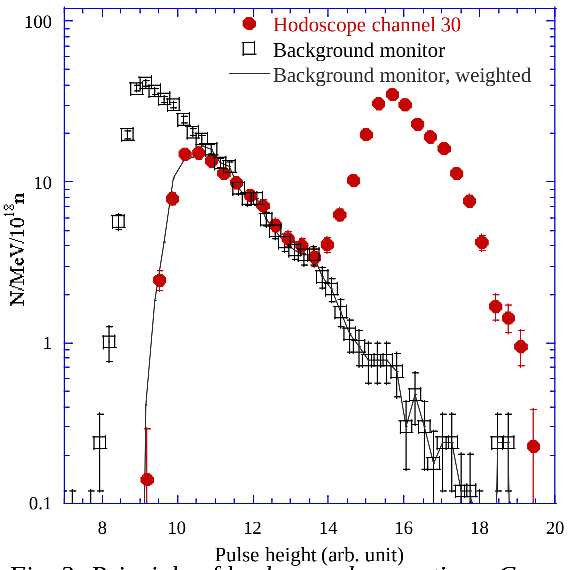

Fig. 2: Principle of background corrections. Comparison of pulse height spectra from hodoscope channel 30 and the background monitor. Integration over the weighted monitor spectrum (full line) gives the expected number of background counts in the hodoscope data.

3 EXPERMIMENTAL RESULTS

3.1 The α knock-on effect

Calculations of the α knock-on effect show that, for E_n>15.5 MeV, the effect should be observed at the $5 \cdot 10^{-4}$ level of the integrated neutron yield [4]. With the background reduction described above, this is within the MPR capabilities. While the theory assumes an ideal, thermal bulk plasma, the experiments at JET employed strong neutral beam (NB) heating. Thus, disentangling the α knock-on effect requires a detailed understanding of the NB-generated neutron spectrum.

Data from the most favorable discharges (42847 and 42856) of the JET DTE1 campaign have been interpreted as showing clear evidence of α heating of the bulk plasma, mainly through the observation of an increase in the electron temperature [5]. The best prospect of finding the α knock-on effect is in the neutron emission of high power pulses, heated by NB only, with high electron temperatures. We are in the process of analyzing such discharges, and an example of the preliminary results is shown in Fig. 3. Here, the data are described with three spectral components: 1) a Gaussian part, representing both the isotropic part of the interactions between the neutral beams and the bulk plasma and any bulk-bulk interactions; 2) a beam-thermal component, representing interactions between beam particles streaming counter to the MPR line-of-sight and the bulk ions; 3) a knock-on component, where the shape is given by the calculations in Ref. 4. These preliminary results support the hypothesis that knock-on events dominate the spectrum from 400 mm and above, i.e., for E_n>15.5 MeV. This is still an on-going analysis and confirming evidence is being sought. For instance, we have selected a set of reference pulses with NB heating only, but lower electron temperature (4 – 6 keV); no high-energy tails are found in these discharges.

3.2 Residual tritium concentration

Despite efforts to clean up the JET vessel after the DTE1 tritium campaign, low levels of tritium are still present in the torus. During operations with D plasmas this residual tritium concentration will show up as an additional weak spectral component in the 14-MeV range. We have measured the 14-MeV neutron emission from D plasmas during three periods since the end of the DTE1; in October 1998, February 1999 and March 1999. These measurements can be compared with TBN spectra from pure D plasmas taken prior to the DTE1, in the spring of 1997. Using the experimentally known shape of the TBN spectrum, and assuming a Gaussian shape to represent the interactions of the residual, thermal t population, we can decompose the neutron emission spectrum as shown in Fig. 4.

The results from the three periods show a clear shift in proportion between the residual and the TBN components: the intensity ratio $I_{thermal}/I_{TBN}$ is 1.9 in Oct. –98, 1.0 in Feb. –99 and 0.92 in March –99. These are average results for many discharges. A rough calculation relates the intensity ratio to the number density ratio as:

$$\frac{n_t}{{n_d}^2} \propto \frac{I_{thermal}}{I_{TBN}}$$

Assuming constant deuteron density for the data of the different periods, we can conclude that the residual tritium concentration in the plasma would have dropped by a factor of 2 between October 1998 and February/March 1999. On the other hand, if the deuteron density has changed significantly, a more detailed analysis is necessary. In general, these measurements could be used to test different models regarding the tritium emission from the vessel walls. This will be the subject of future work.

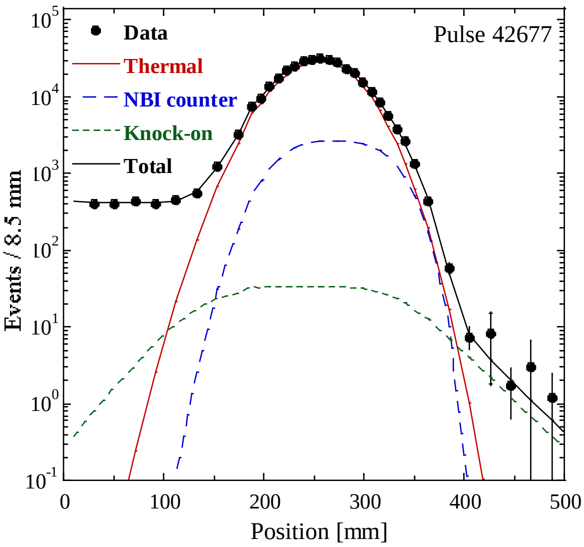

Fig. 3: Decomposition of n spectrum from a NBI heated plasma for JET pulse 42677 into three components. The α knock-on component dominates for positions > 400mm.

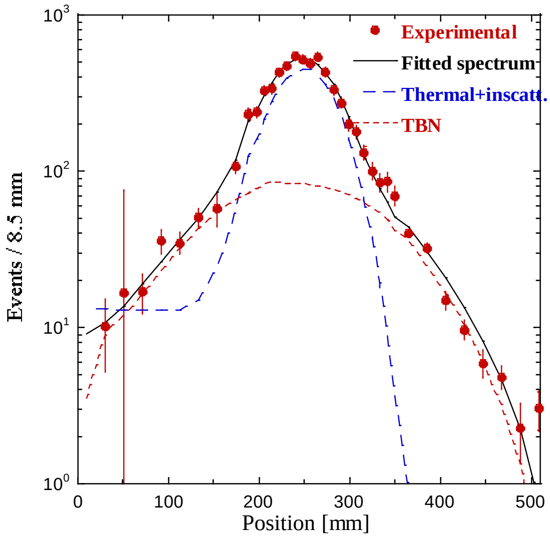

Fig. 4: Residual tritium and TBN components of the n emission spectrum recorded in a D plasma. The fit to the experimental spectrum uses two spectral components as described in the text.

4 CONCLUSIONS

It has been shown that the MPR neutron spectrometer is capable of simultaneously measuring the main d+t→α+n neutron emission spectral component as well as weaker components down to the 10^{-5} level. This ability has been exploited in a search for the α knock-on signature in NB heated plasmas. A high-energy tail, consistent with the knock-on effect, is seen in neutron emission spectra of pulses with the highest electron temperatures (10-12 keV). We have also observed the weak triton burn-up component in D plasmas, mixed with a principal dt→α+n reaction component due to residual tritium left in the vessel walls after the DTE1 campaign. An observed change in the neutron intensity ratio over time would be consistent with a drop in the residual tritium density.

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