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## ABSTRACT

Neutron Emission Spectroscopy (NES) diagnostic can give valuable information of both thermal and auxiliary heated tokamak plasmas. The information can be achieved given that the neutron yield rate ($Y_n$) is high and that the NES diagnostic can operate at high count rates. This has been demonstrated with the Magnetic Proton Recoil (MPR) neutron spectrometer [1] at the Joint European Torus (JET). The MPR has reached count rates of 0.6MHz measuring the neutron emission from $d + t \rightarrow \alpha + n$ reactions in Deuterium-Tritium (DT) plasmas. To achieve the same NES performance in pure D-plasmas, the efficiency of the instrument must be a factor of 100 higher due to the lower $Y_n$ value of the $d + d \rightarrow {}^3He + n$ reaction so correspondingly higher efficiency is needed. This can be achieved with the time-of-flight technique but it has a problem in the count rate $C_n$ capability so the design must be optimized to approach its intrinsic upper limit. This project is about the time-of-flight optimized for rate (TOFOR), which is a NES diagnostic designed for high count rates to give high quality data for D-plasmas comparable with those obtained with the MPR for DT-plasmas.

The $C_n$ limitation is due to the fact that it is a coincidence measurement based on neutron events in two different detectors. The coincidence can be of two types, true and accidental, and the accidental fraction increases with $C_n$ so the system suffers paralysis. So it is essential to control and minimize the fraction of accidental.

The principle design and fundamental specifications of the TOFOR concept has been presented earlier [2] with an estimated count rate of up to 0.5 MHz. The results obtained with the MPR spectrometer [3] can be used as a basis to predict what NES diagnostics can provide for D-plasmas based on measurements of the 2.5-MeV neutron emitted form $d + d \rightarrow {}^3He + n$ reactions.

## 2. PRINCIPLE OF TOFOR

The TOFOR spectrometer makes use of a CH based plastic scattering scintillator (S1) placed in a collimated neutron flux (beam) and a ring shaped array of scintillators (S2) in a special configuration (Fig.1). Recoil protons in S1 from $n + p_H \rightarrow n' + p$ reactions are detected while the scattered neutrons (at angle $\theta \pm \Delta\theta/2$) are detected in S2. The recoil proton events in S1 and S2 give the flight time, $t$, of the scattered neutron energy. The radius of the time-of-flight sphere $R$, gives the flight path $L^2 = 4R^2 cos^2 (\theta \pm \Delta\theta/2)$. This gives, together with the measured $t$, the scattered neutron energy $E_{n'} = 2mR^2 cos^2/t^2 (\theta \pm \Delta\theta/2)/t^2$,where $m$ is the neutron mass. The incoming neutron energy ($E_n$) is determined by (non-relativistic) kinematics, $E_n /E_{n'} /cos^2 (\theta \pm \Delta\theta/2)$, so that $E_{n'} = 2mR^2/t^2$ is independent of scattering angle.

Due to the finite length of the S2 scintillators, the interaction of neutrons will not always be on the constant time-of-flight sphere. This gives a spread in the time spectrum, which, in turn, implies a broadening in the neutron energy spectrum, i.e, incident energy resolution, $\Delta E/E$.

## 3. NEUTRON TRANSPORT CALCULATIONS

The neutron transport calculations have been done with the Geant4 code as a means to simulate and predict the performance of TOFOR. The first objective for the calculations was to predict the TOFOR response to mono-energetic 2.5MeV neutrons. The geometry and dimensions for the TOFOR scattering scintillator, S1, is a 12.5mm cylinder with a diameter of 36mm. The second scintillator, S2, has a trapezoidal shape with sides 100mm and 65mm, length 350mm and thickness 12.5mm (Fig.1). In the calculations, the neutrons fluxis assumed to be perpendicular to the S1 surface and randomly distributed. The flight time for the scattered neutrons was calculated to determine the incoming neutron energy using the expression above. Moreover, the energy resolution $\Delta E/E$ was predicted compared with the requirement of $\Delta E/E \leq 5\%$ (FWHM); this value was chosen as a reference as it corresponds to the Doppler broadening of neutrons emitted from low temperature plasmas ($T_i = 2.3$keV).

## 4. RESULTS AND DISCUSSION

As shown in Fig. 2, the predicted TOFOR neutron response consists of several different reaction components. The total spectrum is shown in Fig. 2a and its contributions in Fig.2b-d. For instance single elastic neutron scattering on protons in both S1 and S2, give rise to a Gaussian shaped response in Fig.2b and single scattering in S1 and multiple scattering in S2 gives Fig.2c. The low energy tail arises from cross-talk between scintillators. The cross-talk is a consequence of neutron scattering on carbon in one scintillator and then entering a neighboring scintillator where it scatters on a proton. Due to the low energy transfer, when neutrons scatter on carbon, carbon events will not be registered. Neutrons that multiple scatter in both S1 and S2 give rise to the spectrum shown in Fig.2d.

A Gaussian fit to the histogram in Fig.2 can be used to estimate the energy resolution. This gives the result $\Delta E/E \leq 4.6\%$ (FWHM) corresponding to $T_i = 1.9$keV and $\Delta E/E = 4.9$ ($T_i = 2.1$keV) for Figs.2b and a respectively. These FWHM-values are only rough estimates of the TOFOR performance as it is the detailed spectrum that will be used as response function to extract plasma information from the measurements; the high energy tail enhancement is too small to impede spectral shape analysis. Finally, the neutron flux detection efficiency was determined to $\in = 00.05\text{cm}^2$. This means that it would require a neutron flux of about $10^7$ $n/cm^2$ s to exploit the estimated count rate capability of 0.5MHz. Such plasma conditions would be offered at JET.

## CONCLUSIONS

The time-of-flight neutron spectrometer for optimized rate (TOFOR) has been described in terms of its predicted performance based on neutron transport simulation. The results confirm that the efficiency, energy resolution and count rate are as conceptually anticipated. We therefore conclude that TOFOR should make neutron emission spectroscopy (NES) diagnostic available to D-plasma studies at JET and provide information with a quality approaching that of the MPR neutrons spectrometer already demonstrated for DT-plasmas. The next step in the TOFOR project is experimental studies of the scintillation detectors making up the system to provide input to refined computations of the detailed response function of the final optimized design.

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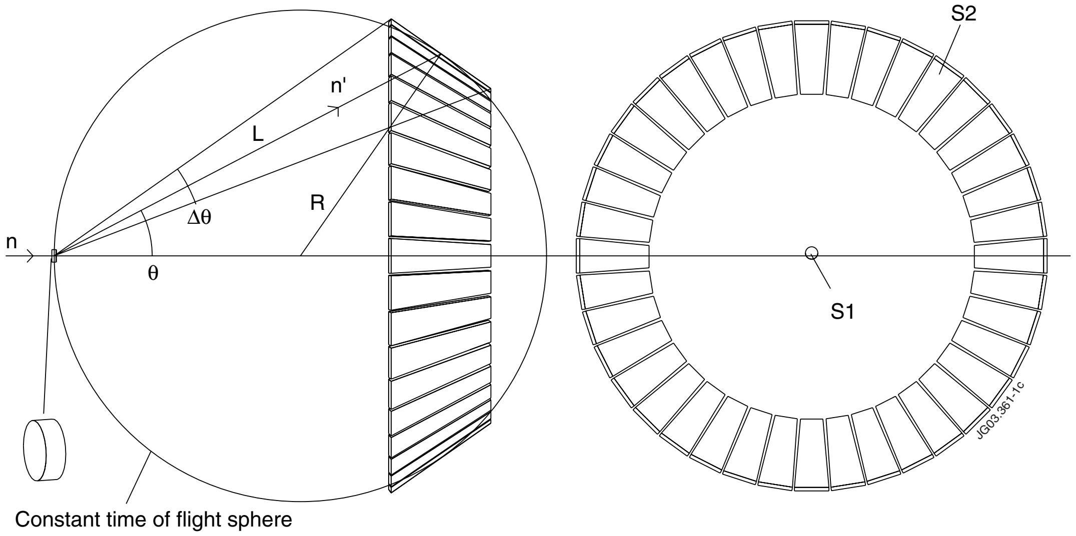

*Figure 1: Front and side view of the TOFOR. TOFOR consists of one scattering scintillator (S1) in the neutron beam and 40 scintillators (S2) for detection of scattered neutrons. The S2 scintillators are placed on the sphere of constant time-of-flight as shown to the left; S1 is also shown in magnification.*

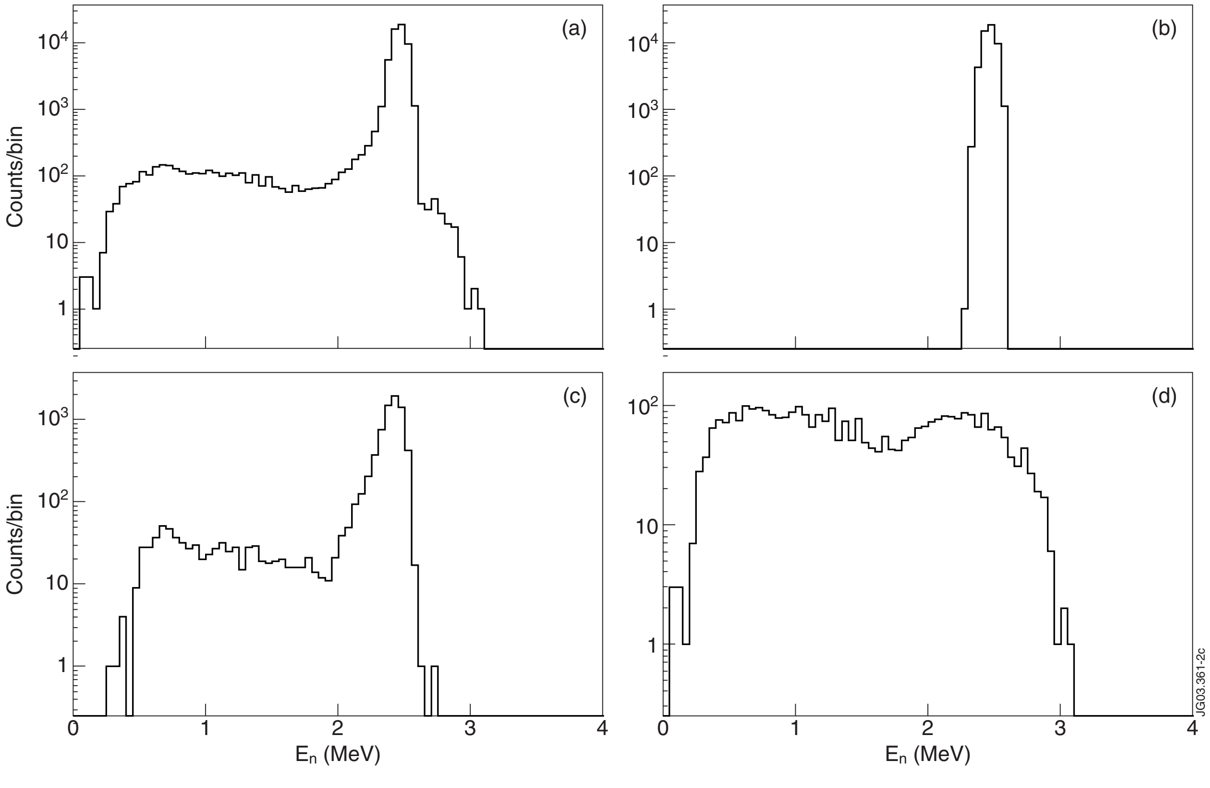

*Figure 2: The predicted response of the TOFOR neutron spectrometer to 2.5-MeV mono-energetic neutrons. The total response (a) is made up of several scattering/reaction components such as, single scattering in S1 and S2 (b), single scattering in S1 and multiple scattering in S2 (c) and multiple scattering in both S1 and S2 (d).*