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ABSTRACT

Neutron emission spectroscopy has been demonstrated to be a powerful plasma diagnostic at tokamaks. This was shown with the magnetic proton recoil spectrometer developed for measurement of the 14-MeV neutron emission from DT plasmas at JET. For diagnosis of D plasmas, a 2.5-MeV spectrometer is needed with a factor of 100 higher effciency to maintain the count rate because of the lower neutron emission rate. The Time-Of-Flight (TOF) technique has the right attributes for these measurements. However, previous instruments have not achieved the full potential of the technique, especially, with respect to count rate capability. A TOF spectrometer for Optimized Rate (TOFOR) has been conceptually defined and is now under design and development for construction and use at JET. The TOFOR design goal is a count rate capability of about 300 kHz which should be attainable in high power D discharges at JET. The TOFOR project is now in a R&D stage where the instrument is being characterized through neutron transport calculations and test experiments. The tests aim to determine the response of the plastic scintillator elements from which TOFOR will be constructed. This contribution will present the TOFOR design principles, the results of the simulations and test measurements and the steps taken to reach the optimized design.

1. INTRODUCTION

Neutron Emission Spectroscopy (NES) diagnostic can give valuable information of both thermal and auxiliary heated tokamak plasmas. High quality information can be obtained given that the neutron yield rate (Y_n) is high and that the NES diagnostic can operate at high count rates. That this is possible has been demonstrated with the Magnetic Proton Recoil (MPR) neutron spectrometer[1;2] at the Joint European Torus (JET) for 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. This can be achieved with the time-of-flight technique, which, however, has a problem in the count rate capability, C_n, the design must be optimized to approach its intrinsic upper limit. This paper describes the time-of-flight optimized for rate (TOFOR) instrument, which is a NES diagnostic designed to operate at high count rates and give high quality data for D-plasmas.

2. GENERAL DESCRIPTION OF TOFOR

The TOFOR spectrometer consists of plastic scintillators, used to detect proton-recoils from the reaction $n + p_H \rightarrow n' + p$ in the detector material. A start scintillator (S1) is placed in the collimated neutron flux (beam), acting as a combined scattering target and recoil proton detector. Neutrons that scatter in S1, with scattering angle $\theta \pm \Delta\theta / 2$, are detected in a second, ring-shaped array of stop scintillators (S2), placed on the constant time-of-flight sphere (Fig.1). With this detector arrangement the flight time, t, of the scattered neutrons can be measured, by requiring a coincidence between S1 and S2. With knowledge of t and the neutron flight path, given by $L^2 = 4R^2\cos^2(\theta \pm \Delta\theta / 2)$, where R is the radius of the time-of-flight sphere, the scattered neutron energy

$E_n' = 2mR^2\cos^2(\theta \pm \Delta\theta / 2) / t^2$ is obtained. The incoming neutron energy (E_n) is in turn determined by (non-relativistic) kinematics, $E_n = E_n' = \cos^2(\theta \pm \Delta\theta / 2)$, which gives a final expression $E_n = 2mR^2 / t^2$ independent of scattering angle. Due to the finite dimensions of the detectors and the resolution of the time measurement, a broadening of the neutron energy spectrum will occur, defining the energy resolution, ΔE/E, of the spectrometer.

In coincidence measurements the events can be of two types, true and accidental, where the accidental fraction increases with C_n to a level where the system suffers paralysis. Thus, the performance of the spectrometer must be optimized in order to minimize the fraction of accidental events. The accidental rate B_a is proportional to the count rates, C_1 and C_2, in the S1 and S2 detectors, and the time resolution of the spectrometer, τ, $B_a \propto C_1 C_2 \tau$. C_2 in turn is proportional to the true signal rate, S, and C_1 is proportional to S and inversely proportional to the detection effciency, χ, for neutrons scattered into the angular interval $\theta \pm \Delta\theta / 2$. Thus, $B_a / S \propto S\tau / \chi$ which shows that τ should be as narrow as possible and that be as high as possible to provide a good (i.e, small) B_a / S ratio. Furthermore, to attain high C_n the S1 must be thick enough to produce a large number of scattered neutrons, but thin enough to minimize multiple scattering. Since, at the same time, S1 is a proton recoil detector its thickness is also of importance when considering saturation effects in the readout system. To increase the neutron interaction rate in the S1 detector without running into saturation, it is divided into layers with separated readout systems. With this solution, the total neutron interaction rate can be increased, in proportion to the number of detector layers, before saturation occurs. However, with thin detectors problems with light collection effciency will arise. This, together with small energy transfer to the recoil protons, implies that the photo-electron production in the PM tubes will be modest. Therefore, to collect as much light as possible from the S1 scintillators, each detector will be equipped with three PM-tubes.

3. SCINTILLATOR TEST

Tests have been performed on both the S1 and S2 detectors, to determine their pulse-height and time response properties. The S2 test scintillator has a trapezoidal shape with a thickness of 5 mm, a length of 350 mm, and sides of 65 and 100 mm, where the PM tube couples to the 100-mm end. As a consequence, the light propagation time to the PM-tube will depend on the interaction points within the S2 scintillator. To be able to compensate or this propagation time, experiments have been performed to quantify the effect.

In these experiments a β-source, with an end point energy of 3.5 MeV, was used. Electrons which penetrate the S2 scintillator are essentially minimum ionizing, depositing a fairly well-defined amount of energy in the detector; this is used for discrimination purposes. A coincidence occurs when the electrons interact with a small scintillator placed above the S2 detector, and aligned with the β-source. With this set-up, the time between events in S2 and the coincidence scintillator can be measured and the relative light propagation time determined. To map the entire S2 scintillator surface, the source and the coincidence scintillator were mounted on a computer controlled xy-table. In Fig.2 a schematic picture of the experimental set-up is shown. Test results in the form of a time vs position plot are displayed in Fig.3. The propagation time from one end of the S2 scintillator to the other is approximately 2.4 ns. This empirical result is used as input to simulation calculations (Sec.4) to determine the TOFOR design for optimum performance.

4. SIMULATIONS

To simulate and predict the performance of TOFOR, neutron transport calculations have been performed using the Geant4 code. The first objective of the calculations was to predict the TOFOR response to mono-energetic 2.5-MeV neutrons. In these simulations, the S1 scattering scintillator was a single cylinder with a diameter of 36 mm and variable thickness from 15 mm to 35 mm in steps of 2.5 mm. The S2 scintillator had a trapezoidal shape with sides 125 mm and 85 mm, length 350 mm and thickness varying between 10 mm and 20 mm in steps of 2.5 mm. The neutron flux is assumed to be randomly distributed and perpendicular to the S1 surface. In the simulations, the flight time of the scattered neutron was determined and the energy of the incoming neutron was calculated, using the expression for E_n given in Sec. II; the width and shape of the resulting energy distribution determines the resolution and response of the spectrometer (in this case for 2.5-MeV mono-energetic neutrons). Moreover, the empirical results on the light-propagation were implemented in the code. From the calculations, the energy resolution , $\Delta E / E$ (FWHM), and the effciency, $\in$, were determined. In general, the resolution of the spectrometer should be chosen to match the Doppler broadening of neutrons emitted from plasmas of low temperature (about 2.3 keV).

In order to maximize $\in$, for a given $\Delta E / E$ value, a set of simulations were performed where the geometry of S1 and S2 were varied. Fig.4(a) shows the results for a S2 detector placed tangentially to the constant time-of-flight sphere. The reason for the rather poor resolution in Fig. 4(a) is the large spread in S2 signal times, where one factor is the light propagation time. To compensate for this, the S2 scintillator was tilted away from the constant time-of-flight sphere. From the experimental results (Fig.3), the optimal angle of S2 was determined to 5:7 (with respect to the tangential). As a consequence of this tilting, the dimension of one side of the S2 scintillator were changed to 131 mm. The simulation results for the tilted scintillator are shown in Fig.4(b). Comparing the results for the untilted and tilted cases, one observes almost no change in $\in$, while a considerable improvement in $\Delta E / E$ is obtained for the same thickness of S1 and S2. Further improvements of the simulation code include non-perpendicular beam, segmented S1, pulse-height considerations, etc.

5. CONCLUSIONS

The time-of-flight neutron spectrometer for Optimized Rate (TOFOR) has been described in terms of its performance based on neutron transport calculations. The obtained results on efficiency and energy resolution shows that TOFOR will be able to provide information on D plasmas approaching the quality of MPR data for DT plasmas. The next step in this work project is to include more detailed effects in the simulation code to obtain a detailed response function of the final design of TOFOR.

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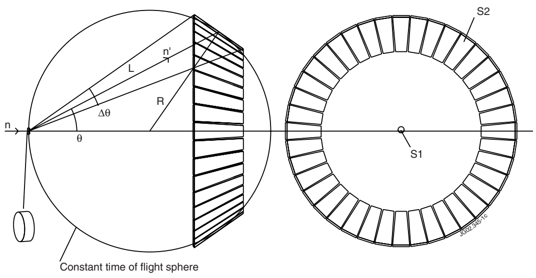

Figure 1: Front and side view of the TOFOR neutron spectrometer. TOFOR consists of one scattering scintillator (S1) in the neutron beam and 32 scintillators (S2) for detection of scattered neutrons. The S2 scintillators are placed on the sphere of constant time-of-flight as shown to the left; S1 is also shown in magnification.

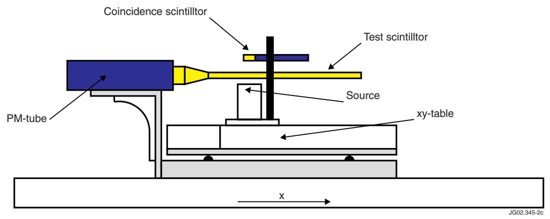

Figure 2: The TOFOR test set-up for the S2 scintillator containing source, test scintillator and coincidence scintillator.

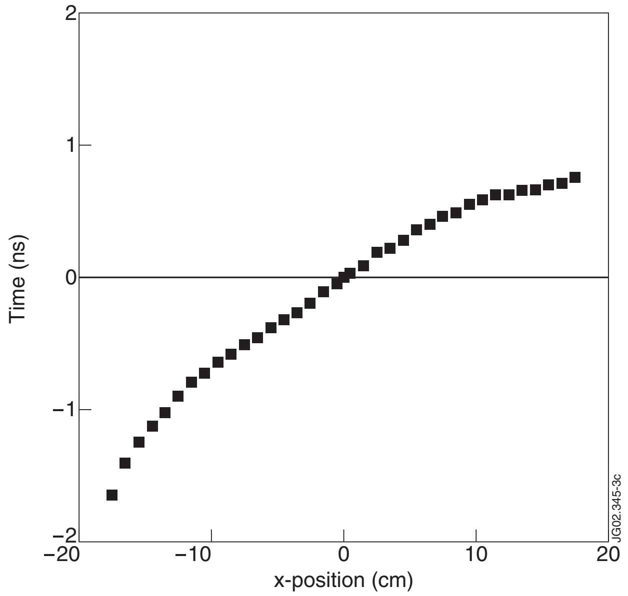

Figure.3: Experimental result of light-propagation time in the S2 scintillator. Zero x-position correspond to the center of the S2 scintillator.

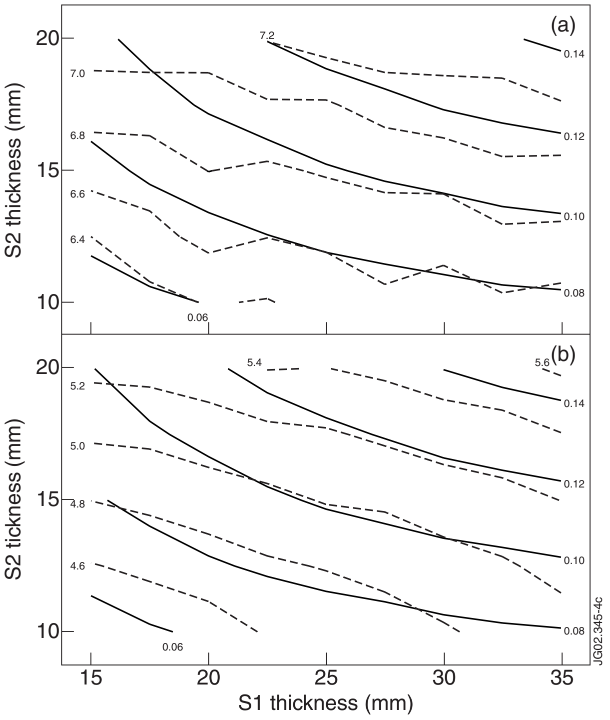

Figure.4: Simulation results to obtain the optimum combination of S1 and S2 thickness. (a) is for a S2 tangential to the constant TOF sphere, (b) is for a S2 tilted by 5.7^o (see text). The solid lines representing efficiency, ∈, in cm^2 and dotted lines resolution in %.