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ABSTRACT.

A new time-of-flight neutron spectrometer (TOFOR) has been developed to measure the 2.45MeV $d + d \rightarrow {}^3He + n$ neutron emission from D plasmas. The TOFOR design features the capability to operate at high rates in the 100kHz range, data collection with fast time digitizing and storing, and monitoring of the signals from the scintillation detectors used. The paper describes the principles of the instrument and its installation at JET, and presents preliminary data to illustrate the TOFOR performance as a neutron emission spectroscopy diagnostic.

INTRODUCTION

TOFOR is a Time-Of-Flight (TOF) neutron spectrometer Optimized (O) for high count Rate (R) measurements of 2.45MeV $d + d \rightarrow {}^3He + n$ neutrons [1, 2, 3]. It will be used for Neutron Emission Spectroscopy (NES) diagnosis [4] of D plasmas at JET. NES is a powerful diagnostic tool that yields results on, e.g., fractional contributions to the neutron emission from reactions between fuel ions in different velocity states,produced by different plasma heating schemes. This was demonstrated with the MPR spectrometer [5] for measurements of 14MeV $d + d \rightarrow {}^3He + n$ neutrons from DT plasmas in the MW range produced in the DTE1 campaign at JET in 1997. TOFOR is dedicated to D plasma NES diagnosis of high statistical accuracy and time resolution,comparable to the achievements of the MPR during DTE1. This means that the detection efficiency must be high to compensate for the factor of 100 lower rate of dd compared to dt, and that ability to handle rates approaching 0.5MHz is needed, i.e., ahundred-fold rate increase compared to its predecessor [6]. The paper describes how these requirements were implemented in the TOFOR design. This is done in the framework of the anticipated diagnostic contributions of TOFOR. These entail the understanding of the fusion aspects of the plasmas produced at JET based on the first results. Moreover, since the bulk of fusion research is devoted to D plasma studies, TOFOR has an important mission to fill for the further development of the NES line of diagnostics.

THE INSTRUMENT

TOFOR measures the flight time of scattered neutrons with the help of twosets of plastic scintillator detectors, namely, S1, placed in the collimated flux of neutrons from the plasma, and S2 (Fig.1). A fraction of the neutrons scatter on hydrogen in S1, some of which are detected in S2 at the distance $L(\alpha)$ given by $L(\alpha) = 2R \cos \alpha$, where α is the scattering angle and R the radius of the so called sphere of constant TOF. The energy of the incoming neutron is uniquely determined by the TOF related to the measured S2-S1 time difference $t_{TOF} = t_2 - t_1$, i.e., $E_n = 2mR^2/t^2_{TOF} =$. This holds under the assumption of a collimated incoming neutron flux, S1 of small area and an extended S2 on the constant TOF subtending a large solid angle as seen from S1. The practical design requires compromises in the geometrical implementation steered by the TOFOR design objectives of maximum efficiency (ε), high count rate (C_n) at given flux (requiring S1 of large volume), and count rate capability (C_n^{CAP}, related to the S2 solid angle). The target energy resolution $\Delta E_n/E_n \leq 6.0\%$ (FWHM) was set by the requirement of diagnosing plasmas of ion temperatures ≥4 keV with an energy coverage of $E_n = 1.5$-4MeV.

The TOFOR geometry was selected after extensive GEANT4 neutron transport simulations [7]. In short, it was determined that the optimal balance was reached with $\varepsilon = 0.12\text{cm}^2$ and $\Delta E_n/E_n = 5.8\%$ due to geometrical effects, with a projected count rate of $C_n = 300\text{kHz}$ for a maximum neutron flux at JET of 3×10^6 n/(cm^{2}s) on S1.

TOFOR was designed as described in ref. [1, 2, 3]. In short, it consists of a stack of five S1 scintillators, each with 3 PM tubes, and 32 S2 detectors forming a ring around the instrumental axis along the collimator. The S1 detector was segmented to allow operation at higher rates than a single scintillator would permit. The S2 geometry was dictated by the requirement of a large solid angle with a ring of flat scintillators approximating the constant TOF sphere with a radius of R = 705mm. TOFOR was constructed in modules consisting of a bottom support plate with the S1 detector set, support legs, the S2 ring and the 32 S2 detectors (see Fig.2) to allow for easy mounting and disassembly for the purpose of transportation.

DATA ACQUISITION AND ANALYSIS

The data acquisition system includes new fast, free-running time digitizing electronics (PCI) boards [8]. TOFOR uses 5 synchronized boards, each with 8 input channels, i.e., altogether 40 channels. Out of these, 5+32 are used for the signals from the individual S1 and S2 detectors and two for 1 Hz and 1kHz clock pulses from the JET computer system to provide reference timing. Each detected event is stored in the form of a time stamp on the board. The 37 detector time trains recorded give 160 S1-S2 combinations of t_{TOF} spectra. The boards have a time bin resolution of 0.4ns and can collect events at a peak rate of 1.25GHz or a sustained pulse rate of 5MHz.

The TOFOR response function R is based on neutron transport simulations, complemented with empirical scintillator characterization tests [9]. In short, it is a matrix of E_n versus t_{TOF} for 81 neutron energies in the interval 1-5MeV. The response depends on the settings of gates for selection of the desired events that are adjustable to suit the experimental conditions. R determines the relationship between the measured t_{TOF} spectrum, $M(t_{TOF})$, and the spectrum of the neutron emission from the plasma volume defined by the collimator, the flux $F_n(E_n)$. In other words, the t_{TOF} spectrum equals the integral product of R and F_n, $M(t_{TOF}) = \int R(t_{TOF}, E_n)\, F_n(E_n)\, dE_n$. The neutron spectrum consists of trial spectral components, which are used to calculate a trial t_{TOF} function. This is fitted to the measured $M(t_{TOF})$ to determine $F_n(E_n)$ through best fit routines.

TOFOR AT JET

TOFOR was built and subjected to extensive testing in Uppsala before it was shipped to JET for installation in February 2005. From its location in the roof laboratory (Fig.3) it has a vertical sight line through the plasma core. The neutrons leave the JET torus through a vertical port, which partly limits the neutron flux that reaches S1 through a 1.90m long collimator of 4cm diameter in the roof laboratory floor. The sight line includes a pre-collimator that can be used to restrict the viewed plasma volume and the flux level for a given neutron yield rate. TOFOR was accurately aligned above the collimator as determined in a photogrammetry survey [10]. An extensive control and monitoring (C&M) system is in place [11], and methods for automatic setting and drift control will be implemented. TOFOR will operate automatically and the data will be transferred to the JET analysis cluster for detailed post discharge processing.

FIRST NEUTRONS THROUGH TOFOR

TOFOR recorded its first JET neutrons in November 2005 and the first high yield rate ($>10^{16}$ n/s) plasmas were observed in March 2006. This will be followed by further fine tuning of the instrument and building of an experience base for selecting optimum operating points for realistic neutron measurement scenarios. A TOF spectrum for Pulse No: 65814 (March 2006) has been produced (Fig. 4a) by summing the contributions from the 160 individual S1-S2 spectra. No physical plasma neutron events will occur for $t_{TOF} < 0$ ns so those present are accidentals whose level can thus be determined. They were used to subtract the accidental contribution, which yields the reduced t_{TOF} spectrum shown in Fig 4b. The reduced spectrum has practically no events in the region $t_{TOF} < 50$ns which is consistent with no expected neutrons of $E_n > 5$ MeV.

The reduced spectrum shows two peaks at tTOF=4 and 65 ns, which are the times it takes for γ's and 2.45MeV d+d neutrons scattered through a 30^o angle to travel the distance of 1221mm (from S1 to S2, center-to-center).The neutron peak has a tail on the long t_{TOF} side due to multiple neutron scattering in the S1 and S2 scintillators besides external materials. The main peak is Doppler broadened by the energy distribution of the neutron emission from the deuterons in the plasma subjected to Neutral Beam (NB) injection at $E_D = 80$keV and 130keV, with a total power of 17MW for 8s. Analysis with a preliminary response function gives a neutron energy distribution (of assumed Gaussian shape) centered at $E_n = 2.45$MeV with $\Delta E_n/E_n = 15\%$ (FWHM), which is consistent with a neutron emission under NB heating. Multiple component spectral analysis is underway.

The reduced spectrum contains 105 events of which 90% are in the main peak. This translates into a count rate of $C_n \approx 12$kHz for a plasma yield rate of $Y_n = 6 \bullet 10^{15}$ n/s, from which one can project 200kHz at JETs expected limit of $Y_n = 10^{17}$ n/s.

CONCLUSIONS AND OUTLOOK

An innovative design of a TOF spectrometer for measurement of 2.45-MeV fusion neutrons (TOFOR) has been presented and its installation as a Neutron Emission Spectroscopy (NES) diagnostic at JET described. TOFOR is the first TOF spectrometer able to operate at rates above 10 kHz with a capability limit of several 100 kHz according to simulations. The first measurements imply that this capability will be exploited for maximum power JET D discharges. The results also show that the problem of accidental coincidence rate effects in TOF spectrometers is reduced in TOFOR thanks to the use of fast time digitizing electronics. Based on the presented results from simulations and first measurements, it is concluded that TOFOR represents a significant step in the development of NES diagnostics for magnetic fusion plasmas.

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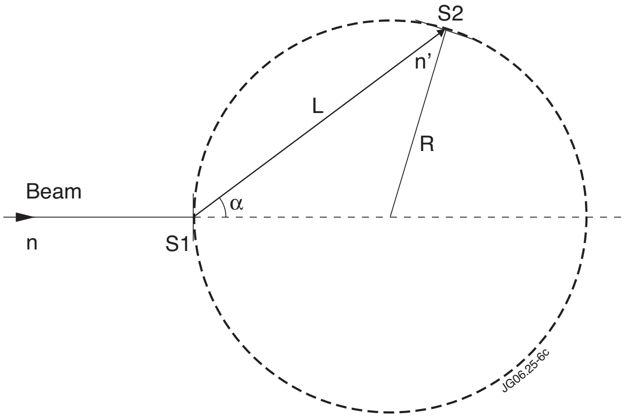

Figure 1: Principle of the TOFOR spectrometer showing the S1 scintillators placed in the incoming neutron flux (n) and the S2 detectors on the constant time-of-flight sphere of radius R and at a distance L(α) from S1 receiving scattered neutrons (n').

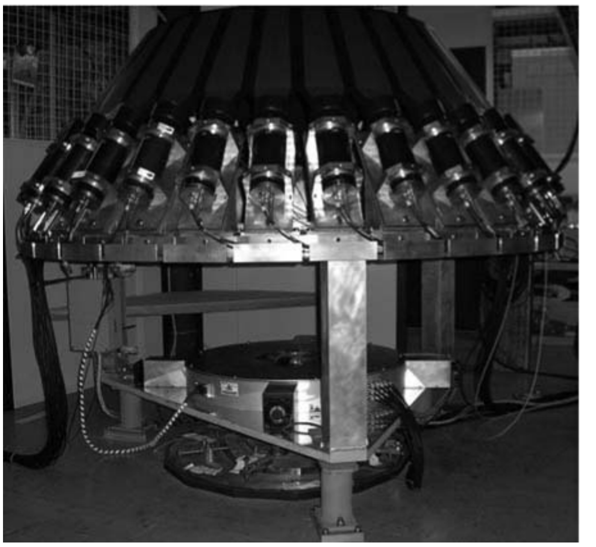

Figure 2: Photograph of the TOFOR instrument in the JET roof laboratory with the S1placed in the circular box on the base plate and the ring of S2 detectors above.

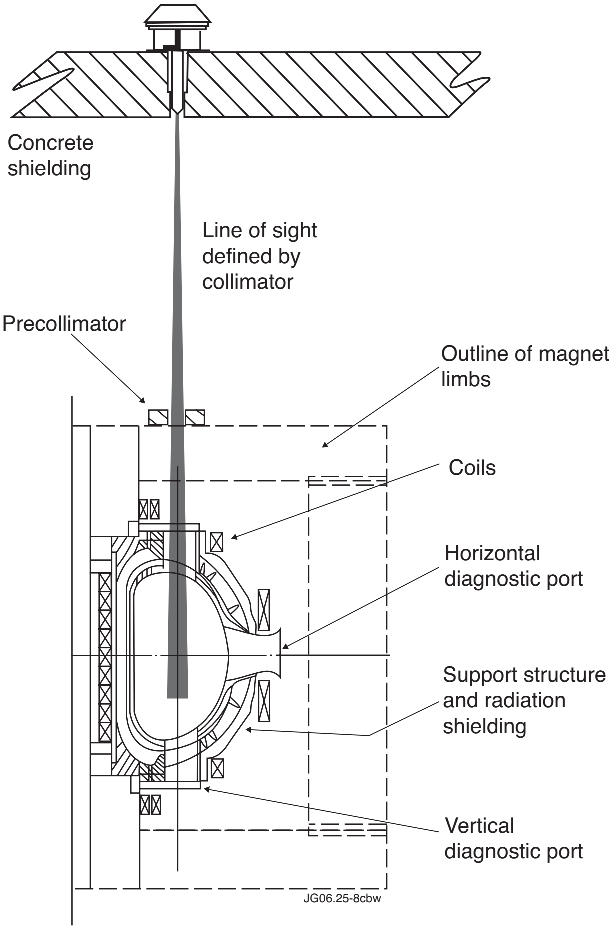

Figure 3: Schematic showing TOFOR in position relative to the JET torus and the sight line to the plasma defined by the collimator through the concrete shield.

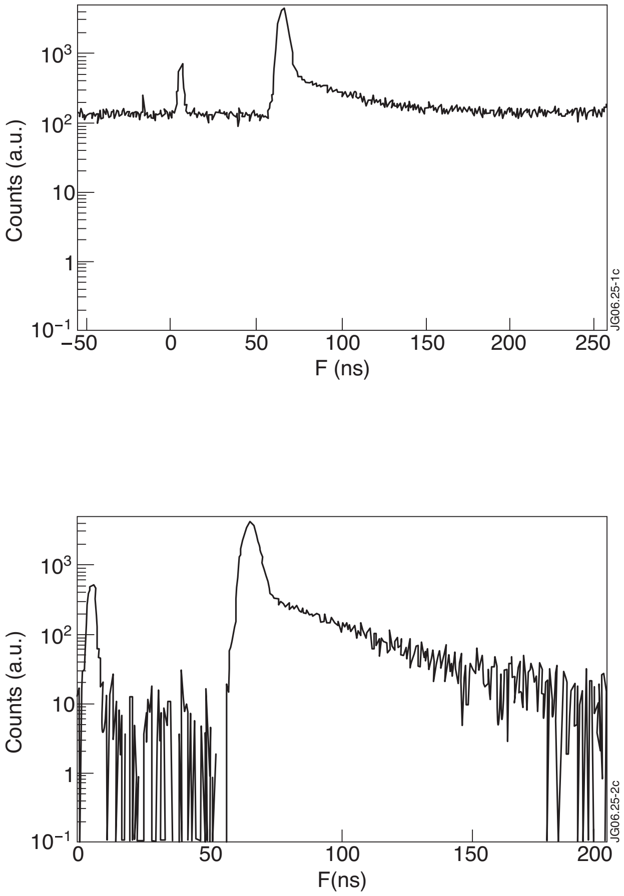

Figure 4: TOF spectra for JET D plasma Pulse No: 65814 subjected to NB heating at 17MW for 8s. (a) Raw spectral data and (b) after subtraction of accidentals.