A Proposed Diagnostic for Time-Resolved 14 MeV Neutron Measurements on TFTR*

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Abstract

A novel method for time resolved measurements of the 14 MeV neutron flux in an intense 2.5 MeV neutron and γ -ray background has been developed. Discrimination against the background 2.5 MeV neutron and γ -ray flux is achieved by the use of polyethylene and lead shielding. A high detection efficiency of DT neutrons is obtained by the use of large volume plastic scintillators and photomultiplier tube designed for operating in high magnetic field environments. Design computations for such a detector system on TFTR show that an absolute detection efficiency of $\sim 10^{-8}$ counts per DT neutron may be obtained. A source strength of 10^{13} DT n/s may readily be detected by this method using both count mode and current mode operation with a resolution of ~ 10 ns within a statistical accuracy of $\sim 5\%$.

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I. Introduction

In present day large fusion facilities operating predominantly with deuterium plasmas, the 14 MeV neutron flux constitutes only a small fraction ($\sim 10^{-2}$) of the total radiation flux comprised mostly of neutrons and secondary γ -rays from DD fusion reactions. Although the 14 MeV neutron flux is weak in comparison with the total radiated flux, it furnishes direct information on the triton burn up rate in the plasma core, and hence is a valuable indicator of the quality of triton confinement in the energy range where the DT fusion cross section peaks.

Many techniques for measuring the 14 MeV neutron flux in an intense 2.5 MeV neutron field have been employed. Of the methods used, the foil activation technique provides no time resolution, whereas other techniques, such as the NE-213 spectrometry or the use of threshold detectors, lack sufficient sensitivity for statistically accurate measurements on short (≤ 10 ms) time scales.¹⁻³ For instance, on JET, the use of Si(Li) diode located near the vacuum vessel wall demonstrates a detection efficiency of $\sim 4 \cdot 10^{-10}$ counts per 14 MeV neutron and a time resolution of ~ 50 ms, and is reported to suffer serious problems related to γ -ray noise.⁴

In this report, we show that a detector of relatively simple design may be built for measuring the 14 MeV neutron flux in TFTR with very high detection efficiencies and excellent discrimination against the more intense lower energy neutrons and γ -ray radiation from the machine. Our approach is to take advantage of the large difference in neutron interaction cross sections in hydrogen between 14 MeV and 2.5 MeV neutrons to substantially reduce the flux from DD neutrons without severely reducing the DT neutron flux, and to use large volume high efficiency plastic scintillators to detect neutrons of all energies. The plastic scintillators have poor energy resolution, however, for the appropriate choice of shielding thickness of Pb and polyethylene (PE), both current mode and pulse mode operation may be used to resolve the 14 MeV neutron flux. Design computations show that a source strength of 10^{13} DT n/s

in TFTR may be detected with a temporal resolution of better than 10 msec.

II. Detection Principle and Method

A. Basic concept

Although hydrogen has long been used as an efficient moderator of fast neutrons, the large variation of the elastic scattering cross section to incident neutron energies above 2 MeV has yet to be exploited in the development of new detectors for measuring the weak 14 MeV neutron flux from DD plasmas.

Owing to the rapidly decreasing cross section of hydrogen above 1 MeV ($\sigma \propto E^{-2}$) and its very large, monotonic cross section in the keV and eV range, the local neutron flux level in a thick hydrogenous material is determined by the rate of attenuation of the neutrons possessing the highest energy in that material. For DD and DT neutrons the elastic scattering cross sections for 2.5 MeV and 14 MeV neutrons in hydrogen are 2.6 and 0.7 barns, respectively. Hence a substantial difference in flux may be realized for a sufficiently thick hydrogenous moderator. The challenge is to find an available material at an appropriate thickness that would allow for adequate discrimination against DD neutrons and provide sufficient signal intensity for time resolved measurements of the DT neutron flux.

Of all the readily available materials, paraffin and PE have the highest hydrogen density (hydrogen atomic density > 67%) and the lowest interaction cross sections at 14 MeV. Shown in Table 1 is the relative attenuation of 14 MeV and 2.5 MeV neutrons in PE of various thicknesses, assuming that the incident beam is perpendicular to the material, and that a single collision is sufficient to remove the neutron completely from the beam. The ratio of DT to DD neutron flux increases by a factor of ~ 5 for every 10 cm of additional PE. A difference of four orders of magnitude between DT and DD neutron flux may be achieved with ~ 60 cm PE shielding.

PE thickness	20 cm	30 cm	40 cm	50 cm	60 cm
ϕ_{DT}	1.22-1	4.28-1	1.50-2	5.25-3	1.84-3
ϕ_{DD}	5.41-3	3.98-4	2.92-5	2.15-6	1.58-7
ϕ_{DT}/ϕ_{DD}	2.26+1	1.08+2	5.13+2	2.44+3	1.16+4
Pb thickness	10 cm	15 cm	20 cm	25 cm	30 cm
ϕ_{γ}	6.74-3	5.53-4	4.54-5	3.73-6	3.06-7

Table 1: Attenuation of 14 MeV, 2.5 MeV neutrons, and 1-2 MeV γ -rays in polyethylene (PE) and lead for various material thicknesses. ϕ_{DT} , ϕ_{DD} , and ϕ_{γ} are the fluxes, normalized to a unit incident flux, for 14 MeV, 2.5 MeV neutrons and 1-2 MeV γ -rays, respectively.

In addition to the intense DD neutron background, there are also many secondary γ -rays resulting from interaction of neutrons with tokamak components. The interaction of the 2.5 MeV neutrons with the polyethylene also generates γ -rays which are not significantly attenuated due to the small atomic number of polyethylene. We require that the intense γ -ray field also be attenuated to negligible levels. Using the Compton cross section in the 1-2 MeV range, the attenuation of photon flux for Pb of various thicknesses is also shown in Table 1. Typically the γ -ray flux is reduced by a factor of 10 for every 5 cm of Pb.

B. Results of neutron transport analysis

In the previous section we did not consider the slowing down of fast neutrons and the diffusion of thermal neutrons in polyethylene and lead, nor did we consider the neutron energy dependence of the detector response. To help guide the design of the detector system, one-dimensional neutron transport calculations have been carried out using the ANISN radiation transport code.⁵ The detector system is modeled as infinite slabs of PE and Pb, as shown in Fig. 1. The calculations were carried out using the PRAX nuclear cross section data set.⁶ The results for neutrons and γ -rays normally incident on 60 cm PE and 20 cm Pb shielding are given in Table 2. The

Response	Incident Radiation		
	14 MeV	2.5 MeV	γ -Rays
Neutron flux (cm^{-2}), $E > 1 \text{ MeV}$	1.47-2	6.23-7	-
Neutron flux (cm^{-2}), $E > 100 \text{ keV}$	5.64-2	2.55-6	-
Neutron flux (cm^{-2}), $E > 0.4 \text{ eV}$	9.85-2	6.26-6	-
Neutron flux (cm^{-2}), total	1.22-1	1.40-5	-
γ -ray flux (cm^{-2}), total	1.72-3	2.51-6	1.56-5
Proton recoil energy (eV/proton)	1.13-19	5.04-24	-
Electron recoil energy (eV/electron)	2.49-22	3.35-25	2.40-24
H (n,p) reaction rate (reaction/gram H)	1.08+0	2.37-4	-
U-235 fission (fission/gram)	3.06-2	9.74-6	-
Boron-10 (n, α) (reaction/gram of ^{10}B)	5.20+0	1.67-3	-
He-3 (n,p) (reaction/gram of ^3He)	2.21+1	7.09-3	-

Table 2: Comparison of various responses for a detector located behind a 60 cm polyethylene and a 20 cm lead shield due to a unit current of 14 MeV neutrons, 2.5 MeV neutrons, and γ -rays normally incident on the shield. A back shield, of the same configuration as the front shield, has been also assumed.

total flux attenuation for DT and DD neutrons is shown in Figs. 2 and 3, and the neutron flux spectra at the detector location are shown in Figs. 4 and 5.

The results indicate that:

(1) The thicknesses of PE and Pb required for a given DD and DT neutron attenuation remain about the same as those given in Table 1. A more precise determination of the required shielding thickness would require modeling the detailed characteristics of the detector response and sensitivity.

(2) Pb is very effective in removing photons, but does not significantly reduce the

neutron flux in the keV range.

(3) The γ -rays produced by the DD neutrons in the polyethylene [primarily due to the (n,γ) reaction with hydrogen] are of about the same intensity as the γ -rays produced by the DD neutrons in the tokamak.

(4) The Pb shielding may be used to reduce the γ -ray flux to the point where it may no longer be a consideration in the choice of an appropriate detector.

(5) A significant fraction of the DT neutrons in the detector cavity remains above 100 keV, indicating that fast neutron detection techniques may be used.

C. Considerations of detection method

Since time resolved measurements in the millisecond range are of interest, it is important to estimate the loss of time resolution due to the slowing down of fast neutrons and the diffusion of thermal neutrons. An upper limit can be estimated by considering an infinite, homogeneous shielding material. The slowing down time, the average time required for a fast neutron with initial energy >1 MeV to slow down to ~ 1 eV, is $\sim 400 \mu\text{s}$ and $\sim 1 \mu\text{s}$ in Pb and PE, respectively. The average time that a 1 eV neutron spends in thermalization and diffusion before it is captured is ~ 1 msec and ~ 0.2 msec in Pb and PE, respectively. These thermalization and diffusion times are well within the desired resolution of 10 msec.

Of the commonly used fast neutron detectors, plastic scintillators are known to have very high detection efficiencies for neutrons >100 keV.⁷ Neutrons with energies greater than 100 keV constitute $\sim 30\%$ of the total DT neutron flux in the detector cavity for 60 cm of PE shielding (c.f. Fig. 5). The high transparency of plastic scintillators also makes it possible to use large volumes to increase the overall detection efficiency, whilst the high sensitivity of plastic scintillators to γ -rays is not of concern because of the very low γ -ray flux in the detector cavity. Also γ -rays from

thermal neutron capture may be removed by introducing a thin layer of neutron absorbing cadmium or boron at the interface of PE and Pb and on the inner wall of the detector cavity if necessary.

The size of the plastic scintillator and the thickness of PE and Pb may be determined for current mode operation by the criterion

$$(Q_{DD} + Q_{dark})/Q_{DT} < \alpha, \quad (1)$$

where Q_{DD} , Q_{DT} , and Q_{dark} are the charges produced at the anode of the photomultiplier tube by DD and DT neutron induced scintillations and by the anode dark current, respectively, and α is the maximum acceptable DD and dark current contribution to the collected charge. In pulse mode operation we may set the minimum discriminator level at a point where any contribution from the dark current may be neglected. The scintillator size and shielding thickness are then determined by the criterion

$$C_{DD}(E_d, t)/C_{DT}(E_d, t) < \alpha, \quad (2)$$

where, for a given discriminator setting, C_{DD} and C_{DT} are the counts produced by DD and DT neutrons respectively and are defined as

$$C_{DD}(E_d, t) = \int_{\tau} \int_V \int_{E_d}^{\infty} N_H(\vec{r}) \sigma_H(E) \phi_{DD}(E, t, \vec{r}) \epsilon(E, E_d) dE d\vec{r} d\tau \\ + \int_{\tau} \int_V \int_0^{E_d} N_H(\vec{r}) \sigma_H(E) \phi_{DD}(E, t, \vec{r}) p(E, E_d) dE d\vec{r} d\tau, \quad (3)$$

$$C_{DT}(E_d, t) = \int_{\tau} \int_V \int_{E_d}^{\infty} N_H(\vec{r}) \sigma_H(E) \phi_{DT}(E, t, \vec{r}) \epsilon(E, E_d) dE d\vec{r} d\tau. \quad (4)$$

E_d is the equivalent neutron energy corresponding to the discriminator setting; t is the total thickness of shielding material; N_H is the atomic density of hydrogen in the plastic scintillator, σ_H is the neutron elastic scattering cross section, $\phi_{DD}(E, t, \vec{r})$ and $\phi_{DT}(E, t, \vec{r})$ are neutron fluxes at energy E and at location $\vec{r}$ in the scintillator for DD and DT neutrons, respectively; $\epsilon(E, E_d)$ is the conversion efficiency of collisions to scintillator counts which takes into account dead-time corrections. $p(E, E_d)$ appearing in the second term for C_{DD} is the probability for multiple neutrons of

individual energy less than E_d producing a scintillation event of equivalent energy greater than E_d within the pulse integration time τ_p . The second integral for C_{DD} effectively estimates the contribution due to DD neutron pileup. The DT neutron pileup contribution due to neutron energies less than E_d is negligible and so is omitted from the expression for C_{DT} . The integrations are carried out over all neutron energies, scintillator volume (V), and sampling time τ_b for flux estimation, where $\tau_b \gg \tau_p$.

Both ϵ and p are complicated functions of the scintillation pulse height distribution. To illustrate how the discriminator settings relate to the polyethylene shielding thickness for a given α , we use the following assumptions: (1) $\epsilon(E, E_d) = 0.1$ for $E > E_d$. (2) The minimum E_d required to eliminate counts from the photomultiplier dark current noise is ~ 100 keV. (3) Only 2.5 MeV neutrons producing proton recoil energies greater than 2 MeV are considered likely to contribute to pileup counts. The probability of a 2.5 MeV neutron collision with the scintillator leading to a pulse height greater than 2 MeV neutron equivalent is taken to be 0.1. Hence, the probability of pileup pulses with $E_d \sim 5$ MeV is equal to the probability of having at least three scintillation events within time τ_p . Similarly, a minimum of four scintillation events within τ_p are required to produce a pulse height greater than 8 MeV equivalent. Using the mean collision rate calculated by the ANISN code, p , C_{DD} , and C_{DT} can be evaluated for a given shielding thickness, incident neutron flux, and maximum allowable α . Figure 6 illustrates the equivalent discriminator settings versus polyethylene thickness for $\alpha = 0.02$ and $\tau_p = 10$ ns. The thickness of Pb used in the calculation is 25 cm, and the scintillator volume is assumed 100 cc (a 5 cm thick slab). The incident neutron fluxes on the front surface of the PE shielding are 10^6 and 10^8 n/cm²/s for 2.5 MeV and 14 MeV neutrons, respectively. Also shown in Fig. 6 is the relative DT neutron counting efficiency defined as the number of counts per 14 MeV neutron incident on the front surface of the shielding. To understand the rapid variation of both the detection efficiency and threshold level for ~ 50 cm PE,

we note that below 40 cm of PE,

$$|C_{DD}(E_d, t)/C_{DT}(E_d, t)| \gg 0.02 \quad \text{for } E_d \leq 2.5 \text{ MeV.} \quad (5)$$

Hence, for thickness less than 40 cm of PE, the threshold level is fixed at $E_d \geq 2.5$ MeV. For thickness less than ~ 10 cm PE, pileup becomes statistically significant, hence the threshold must rise to maintain constant α . Beyond ~ 40 cm PE, we have

$$|C_{DD}(E_d, t)/C_{DT}(E_d, t)| < 0.02 \quad \text{for } E_d \leq 2.5 \text{ MeV,} \quad (6)$$

in which case the threshold level drops rapidly with the exponential decrease of the 2.5 MeV neutron flux with the thickness of PE. Beyond ~ 50 cm of PE, the threshold level is basically determined by the dark current contribution and settles to around 100 keV. The efficiency of detection of DT neutrons must naturally drop (almost exponentially) with PE thickness for a given threshold setting. However, with the drop in the threshold level down to ~ 100 keV, the detection efficiency of DT neutrons rapidly increases.

Interestingly, for PE thickness below ~ 45 cm, all scattered DT neutrons are lost to the detection system due to the high-threshold setting needed for rejecting the unscattered DD neutrons. However, beyond a thickness of ~ 45 cm PE, the threshold level for DD neutron rejection comes down sufficiently rapidly that we gain the advantage of being able to detect scattered DT neutrons in the 100 keV range or above. This contribution of scattered DT neutrons to the count rate results in a dramatic increase in the efficiency of DT neutron detection as shown in Fig. 6 as the average energy of a DT scintillation event is around 500 keV, still sufficiently high to allow for pulse mode detection of the scintillation light. For a high DT neutron flux (as would be the case in 'supershot' plasmas) current mode operation is equally applicable for PE thickness > 50 cm.

III. Proposed Detector System for TFTR

A. Detector configuration

A schematic diagram of the detector configuration is illustrated in Fig. 7. In this section, a system design for both current mode and count mode operation is considered. The detector system is located at a major radius of ~ 6 m at the machine midplane and faces an open bay. The important elements are: 65 cm thick polyethylene attenuator for removing the 2.5 MeV neutron flux; 25 cm thick Pb shielding for attenuating the γ -radiation (for the side facing the tokamak, c.f. Fig. 7); 7.5 cm diameter, 10 cm long cylindrical plastic scintillator (e.g., Bicron-400⁸) with a conic transition piece tapered to 5 cm in diameter; a 5 cm diameter photomultiplier tube (PMT) butted to the conical light pipe. The PMT is expected to be of a variety insensitive to high magnetic fields (e.g., R2490-01 by Hamamatsu Inc.⁹). A green LED source is provided to calibrate out field effects on the PMT (0 – 20% gain variation is expected from 0 – 3 kG fields). The 65 cm PE and 25 cm Pb shielding are determined by keeping the DD neutron and DD neutron-induced γ -ray contribution down to less than 2% of the total signal in current mode operation for a DD to DT neutron source strength ratio of 100:1.

In the following, we detail calculations and computational results used to derive a final design specification for time resolved 14 MeV neutron detection on TFTR.

B. Scintillator sensitivity

The light production in a plastic scintillator resulting from the interaction of neutrons and γ -rays is primarily due to the energy dissipation of recoil protons and Compton electrons. The scintillation photon production due to electrons is almost linear with respect to electron energy throughout most of the range of interest. Hence,

the equivalent electron energy due to other nuclear processes is a useful quantity for comparing the conversion efficiency of particle energy to photon production. The equivalent electron energy for photon production due to proton recoil energy E_p can be approximated by¹⁰

$$E_{eq} = 0.95E_p - 0.8(1.0 - e^{-0.1E_p^{0.8}}) \quad \text{if } E_p > 0.3 \text{ MeV}, \quad (7)$$

$$= 0.07E_p \quad \text{otherwise.} \quad (8)$$

When E_{eq} is combined with the neutron and photon interaction cross sections, the expected photon production can be estimated. Figure 8 shows the expected scintillation photon production as a function of neutron and γ -ray energy. The scintillation photons due to carbon and α particles are negligible and are ignored in this analysis. E_{eq} is used to calculate the expected charge production at the photomultiplier anode in current mode operation.

For pulse mode operation, the details of the pulse-height distribution have to be evaluated. Lacking detailed information and experimental data, we assume that a minimum discriminator threshold of ~ 100 keV equivalent is required for rejecting the dark current contribution, and that the collision to count conversion efficiency is ~ 0.1 [see $\epsilon(E, E_d)$ in Eq. (3)].

C. PMT

The dominant wavelength for scintillation light from a plastic scintillator is ~ 420 nm. For most photocathodes, the corresponding radiant sensitivity (photoelectric current from the photocathode per unit incident scintillation light power) is typically ~ 50 mA/watt (equivalent quantum efficiency $\sim 20\%$). When weighted by the spectral distribution of photons from the plastic scintillator, the efficiency is $\sim 10\%$ lower, or ~ 45 mA/watt. A spectrally weighted radiant sensitivity is used to calculate the efficiency for converting the scintillation photon energy to photoelectrons collected at the first dynode (See $\eta_{p,e}$ in subsection D.2).

In addition to the radiant sensitivity, two major concerns in connection with the PMT design are the effect of magnetic fields on the tube performance as well as the dark current level for current mode operation. At the location in TFTR where the detectors may be located, the typical magnetic flux density (with plasma) is ~ 1 kG vertical field. Magnetic shielding of conventional PMTs is impractical in such environments. PMTs designed to operate in kG fields are available however. For example, R2490-01 tubes manufactured by Hamamatsu Inc.⁹ have a gain of $3 \cdot 10^6$ for up to 5 kG fields (parallel to tube axis) and with a 20% response variation over that range.

The dark current constitutes the major source of noise in current mode operation for DT neutron source strengths $\leq 10^{13}$ n/s. Dark currents vary with many factors, such as temperature, surface condition, etc., and are difficult to estimate accurately. We use 100 nA as the reference value for the noise estimate (R2490-01 has a calibrated dark current level of 50 nA at zero field, and interestingly, the gain to D.C. ratio improves substantially in the presence of ~ 1 kG vertical field.)

D. Estimate of detection efficiency

1. Procedure of calculation

To provide a realistic estimate of the expected detector response, the energy and angular distributions of the neutron and γ -ray flux calculated for TFTR are used as the input to the one-dimensional detector model shown in Fig. 7. The computed flux spectrum in the detector cavity was folded into the scintillator response to obtain the count rate and PMT current output in terms of unit scintillator volume per DD and DT neutrons from TFTR. The time resolution and statistical accuracy of measurement may then be estimated.

2. Calculation of detector response

The assumed neutron and γ -ray distributions in TFTR are based on a three-dimensional Monte Carlo simulation, assuming that the bay regions between TF coils are not occupied by neutron attenuating structures, and that the detector is placed at a major radius of 6 m at the machine midplane. Previous use of similar data to estimate neutron induced noise in the X-ray imaging system compared well with measurements.¹¹ A detailed description of the simulation model can be found in Ref. 12.

Typical plastic scintillators contain $3.5 \cdot 10^{23}$ electrons/cm³ and $5.3 \cdot 10^{22}$ hydrogen atoms/cm³. Using the response function given in Fig. 8 we obtain an expected energy deposition, in terms of the equivalent electron energy, of $5.3 \cdot 10^{-11}$ MeV/cm³ and $9.5 \cdot 10^{-15}$ MeV/cm³ per DT and DD neutrons from TFTR, respectively. The expected PMT anode current is calculated using the expressions

$$I_a = 1.6 \cdot 10^{-19} \cdot \eta \cdot E_{eq} \cdot M \cdot g, \quad (9)$$

$$\eta = \eta_{n,p} \cdot \eta_p \cdot \eta_{p,e}, \quad (10)$$

where I_a is the anode current in amperes per unit scintillator volume (cm³) per source neutron, E_{eq} is the equivalent electron energy deposition inside the scintillator, η is the conversion efficiency from the equivalent electron energy to photoelectron production, M is the PMT current gain, and g is a correction factor to account for additional flux attenuation due to materials in the TFTR bay region and other possible uncertainties. $\eta_{n,p}$ is the conversion efficiency from the equivalent electron energy to scintillation light energy (which takes into account the loss of recoil particles due to the finite scintillator size); η_p is the efficiency of light collection at the photocathode; and $\eta_{p,e}$ is the conversion efficiency from scintillation light to photoelectrons which takes into account the variation of PMT sensitivity over the bandwidth of scintillation light and also the loss of electrons in the transit from the photocathode to the first dynode. Using $\eta_{n,p} = 2.7\%$, $\eta_p = 30\%$, $\eta_{p,e} = 0.036$ electrons/eV, $M = 10^6$, and

$g = 0.2$ we obtain $I_a = 5.0 \cdot 10^{-22}$ and $8.9 \cdot 10^{-26}$ amp/cm³ per DT and DD source neutron, respectively.

If it is assumed that the DT neutron source strength is $\sim 1\%$ of the DD neutron source strength, then the 2.5 MeV neutrons and their associated γ -rays contribute to $\sim 2\%$ of the total PMT current. If we require to limit the contribution of the dark current ($0.1 \mu\text{A}$) to less than 5% of the total anode current, then the product of scintillator volume and DT source strength must be $\geq 5 \cdot 10^{15}$ cm³-n/s. Clearly, a DT neutron source strength of 10^{13} n/s in TFTR is readily detectable by a scintillator with an effective volume of 500 cm³, producing an anode current of $2.5 \mu\text{A}$.

The equations used to calculate the count rate in pulse mode operation have been discussed in Sec. II. The calculated collision rates for neutrons with energies greater than 150 keV are $4 \cdot 10^{-10}$ and $2 \cdot 10^{-14}$ per cc of scintillator per DT and DD neutrons, respectively. For a 500 cc scintillator we obtain $2 \cdot 10^{-8}$ counts per 14 MeV neutron from TFTR. For a DT source strength of 10^{13} n/s, we obtain a count rate of $2 \cdot 10^5$ cps.

3. Time resolution

Due to the rapid decay of the scintillation pulse in plastic scintillators (~ 5 ns) and given a PMT response time of ~ 10 ns, the optimal time resolution can be shown to depend primarily on the limit set by the counting statistics. From the above discussion, a ~ 10 ns time resolution may be obtained with $\leq 2\%$ statistical error due to the count rate statistics alone for a DT neutron source strength of 10^{13} n/s. This noise level may be added in quadrature with the DD induced noise to obtain the statistical error of measurement. Similarly, in current mode operation the time resolution, τ , realizable for $\leq 1\%$ statistical error in the measured signal can be

estimated from the expression

$$\tau \geq 10^4 \frac{q}{dQ/dt} \cdot S_{DT}, \quad (11)$$

where q is the average charge produced per scintillation event, Q is the total charge produced in the detector per unit DT source neutron, and S_{DT} is the total number of DT neutrons from TFTR per second. Again, ≤ 10 ms time resolution may be achieved for 10^{13} DT n/s.

E. Additional design considerations

The neutron flux is not isotropically distributed at any point in the test cell of TFTR. The thicknesses of PE and Pb used in this study were determined using the calculated radiation flux incident on the front surface of the shielding. We have also estimated the required thickness of PE and Pb for the sides, top, bottom, and back of the detector, using the energy and angular distributions of neutrons and γ -rays from the same Monte Carlo simulation for TFTR. The thickness of Pb needed remains approximately the same, namely 25 cm. The thickness of polyethylene for the back, bottom, and top are about 40 cm, and those needed for the sides are about 45 cm.

The calculations so far have assumed that the bay regions are devoid of other materials. Since this situation does not exist on TFTR, some degradation in the estimated performance will occur. The correction factor g in Eq. (9) takes some of this into account. The precise effect cannot be easily estimated unless the details of the material and its distribution are known.

The above estimates do not include the additional contribution from the high energy photons due to runaway electrons. Since in our model we assume $\sim 20\%$ of the secondary γ -rays incident on the PE and Pb shielding will have energies above 2 MeV, runaway induced photons (except during disruptions) are not expected to make a significant contribution to the overall noise.

IV. Detector Calibration

The neutron attenuation properties of polyethylene and lead may be tested using a DD or DT neutron generator in the neutron laboratory. The source strength of a DD neutron generator ($\sim 10^8$ n/s) will not be sufficient to give a detectable signal if the detector assembly is configured according to design specifications. Since the above results are predicated on the assumption that the shielding materials may be considered as a uniform, homogeneous medium exhibiting attenuation properties which vary exponentially with penetration length, any effect or irregularity which instead introduces a linear or quadratic dependence on the attenuated flux, such as small streaming channels in tile gaps or in penetrations for cabling, may destroy the high quality of 2.5 MeV neutron rejection required for proper operation. Thus, a calibration using a DD source in the laboratory is an essential step to reveal any possible defect in the detector construction.

The absolute detection efficiency may be determined by both numerical simulations and in-situ calibration using a DT neutron generator. With $\sim 10^{10}$ n/s source strength, it is estimated that ~ 30 cps may be obtained with the DT generator inside the TFTR vacuum vessel at the nearest bay location and with the detector located at $R \sim 6$ m.

Gain variations of the PMT due to the magnetic field variations and power supply voltage fluctuation may be calibrated out by use of standard green LEDs located in the detector cavity with an oscillating (~ 10 kHz) light output. As the useful bandwidth of the detector will not exceed 1 kHz, at 10 kHz the anode current spectrum should essentially be white noise, and the LED signal operated continuously through every discharge may be filtered out of the data after detector normalization.

V. Summary and Conclusion

In this paper we have investigated a method for measuring the tritium burnup in fusion plasmas with good temporal resolution. The detector system consists of polyethylene and lead shielding, a large volume plastic scintillator, and a photomultiplier tube designed for high magnetic field operation. By utilizing the differential attenuation properties of hydrogen to different neutron energies, excellent DD neutron discrimination is achieved. When coupled with plastic scintillator detectors, good detection efficiency to 14 MeV DT neutrons is also obtained. Such a system can be designed to operate in either pulse mode or current mode. Design computations carried out on TFTR show that an absolute counting efficiency of $\sim 10^{-6}$ counts per DT neutron may be achieved in pulse mode operation. Thus, a DT source strength of 10^{13} n/s may be detected with a time resolution of ~ 10 ms and with a statistical accuracy of $\sim 2\%$, given a DD to DT neutron source strength ratio of 100:1. In current mode operation, for 10^{13} n/s, $\sim 5\%$ noise level is expected for the same time resolution.

These figures are based on the assumption that the PE and Pb shielding are perfectly homogeneous with no in-leakage DD neutrons through streaming paths. Detector calibration with a DD neutron generator or ^{252}Cf source is essential for identifying possible streaming paths. Estimates made for TFTR show that in-situ determination of the absolute efficiency to the 14 MeV neutron flux is feasible using a DT generator producing $\sim 10^{10}$ n/s.

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Figure Captions

- Fig. 1** One-dimensional model of detector/moderator assembly used for the neutron transport calculation.
- Fig. 2** Calculated attenuation of total neutron and γ -ray fluxes in 60 cm polyethylene and 20 cm Pb. Incident radiation is 2.5 MeV neutron normalized to 1 n/cm².
- Fig. 3** Calculated attenuation of total neutron and γ -ray fluxes in 60 cm polyethylene and 20 cm Pb. Incident radiation is 14 MeV neutron normalized to 1 n/cm².
- Fig. 4** Calculated neutron flux spectrum due to 2.5 MeV neutrons attenuated by 60 cm polyethylene and 20 cm Pb.
- Fig. 5** Calculated neutron flux spectrum due to 14 MeV neutrons attenuated by 60 cm polyethylene and 20 cm Pb.
- Fig. 6** Neutron discrimination energy and DT neutron counting efficiency as function of polyethylene thickness. Pb thickness is 25 cm; Pulse intergration time is 10 ns; Acceptance level for DD to DT count ratio is 0.02; Scintillator volume is 100 cc. The incident neutron fluxes are 10^4 n/cm²/s and 10^6 n/cm²/s for 2.5 MeV and 14 MeV neutrons, respectively.
- Fig. 7** Diagram showing the proposed configuration of polyethylene, Pb, and scintillation detector on TFTR.
- Fig. 8** Scintillation photon production in terms of equivalent electron energy as function of neutron and γ -ray energy for plastic scintillators.

FIG. 1

FIG. 2

FIG. 3

4. FIG.

FIG. 5

#90X0156

FIG. 7

#90X0188