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A New Approach to the D-T Neutron Monitor using Water Flow

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A new approach was proposed to significantly improve the D-T neutron monitoring system, which is based on the activation of flowing water via $^{16}O(n,p)^{16}N$ reaction. The basic idea of this approach is to utilize the Cherenkov light, produced by energetic β-particles from ^{16}N in water near the neutron source, and then transmit the light by the optical fiber to the remote light detector. To support this idea, several experimental phases were scheduled. In the present paper, the first phase, measurements of Cherenkov light using a remotely located detector are described. According to the study, the water Cherenkov detector is very efficient for measurements of the ^{16}N activity, due to: high counting efficiency; absence of the scintillation detector; and simplicity of the method.

KEYWORDS: D-T neutrons, Water activation, Nitrogen-16, Cherenkov light, Fusion, Monitor, ITER, FNS

I. Introduction

The neutron activation of the ^{16}O via $^{16}O(n,p)^{16}N$ reaction and subsequent γ-ray detection of the ^{16}N activity in a flowing fluid was applied for a variety of purposes. Since the threshold energy for the $^{16}O(n,p)^{16}N$ reaction is 10.24 MeV, ^{16}N nuclei is produced only by the 14 MeV neutrons, with water flowing in the vicinity of the D-T neutron source. Thus, a fusion power monitor, based on activation of flowing water, was proposed for ITER, and experimental studies were completed[1,2].

The activation product, ^{16}N, decays by β-emission (100%) with a half-life of 7.13 seconds[3], **Table 1**.

Table 1 Radioactive decay properties* of ^{16}N

Ray	$E_\beta$endpoint (keV) / E_γ (keV)	I_β (%) / I_γ (%)	Decay mode
β	1548.1	1.06	β^-
	3303.2	4.8	
	4290.1	66.2	
	10420	28.0	
γ	6128.63	67	
	7115.15	4.9	

* Only branches with intensities of more than 1 % are listed in the table

Presently, activity of the ^{16}N is measured using a γ-ray scintillation detector[1,2]. Such method leads to insufficient time resolution and the delaying of the neutron monitor response, since water has to transfer the ^{16}N from the point of production to the position of a remote γ-detector. In order to overcome these disadvantages a new approach was proposed. The basic idea of this approach is to utilize the Cherenkov light, produced by β-particles from ^{16}N in water near the neutron source, and then transmit the light by the optical fiber to the remote light detector.

The proof of the principle experiment is divided into two phases. The main idea of the first experimental phase is to examine the Cherenkov light measurements using a remotely located water radiator and a light detector. During the second phase the temporal resolution of the proposed technique will be studied comprehensively. In the present paper, theoretical considerations and experimental investigations of the first experimental phase are presented.

II. Theoretical Aspects of a Water Cherenkov Detector

Cherenkov emission is a physical process.[4] Electrons emit light under a characteristic angle when passing through the medium of the refraction index n, if their velocity exceeds the speed of light in the medium, c/n. For water (n=1.33) the threshold energy for electrons is 0.264 MeV and the emission angle is under 42°. According to the classical description of the Cherenkov effect by Frank and Tamm[5] the number of photons dN emitted per unit path length dx with wavelengths between λ_1 and λ_2 is given by:

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right)\frac{d\lambda}{\lambda^2}, \qquad (1)$$

for $n(\lambda) > 1$, where z is the electric charge of the particle producing Cherenkov radiation, $\beta = v/c$, and $\alpha = 1/137$ is a fine structure constant. Assuming that a photomultiplier tube (PMT) with a bialkali photocathode will be utilized for registration of the Cherenkov light, the spectral range of the maximum response was estimated to be as follows. **Figure 1** (curve A) shows the calculated Cherenkov spectrum expressed in terms of the number of generated photons that are proportional to $1/\lambda^2$. Curve B shows the spectral response for the PMT. The product of curves A and B (curve C) shows the number of photoelectrons, liberated at the photo-cathode when Cherenkov light irradiates the cathode.

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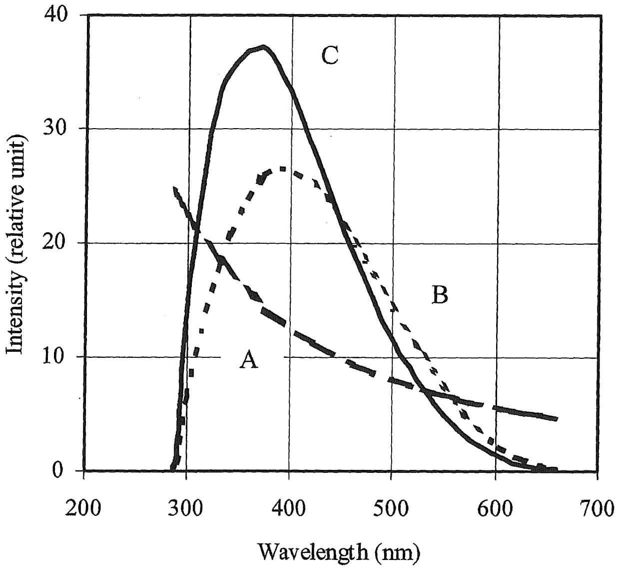

Fig. 1 A – Cherenkov spectrum, displaying the $1/\lambda^2$ dependence; B – Quantum efficiency of the PMT; C – Response of the PMT to Cherenkov radiation.

Considering the curve C, it is possible to conclude that the region of the maximum response is estimated to be in the range of 300 – 600 nm. The area under curve C represents the total number of photoelectrons liberated and depends upon initial energy of the particle that generated the Cherenkov light. The intensity of Cherenkov light produced in water by an electron, moderating from E_{max} to the Cherenkov threshold, was estimated by the integration of the equation (1) converted to dN/dE form[6], over the spectral region and energy range. It was integrated numerically and the obtained data is shown in **Fig. 2**. The photon output increases rapidly with beta-energy to about 2 MeV, and further increases in energy result in smaller proportionate increases of light output. However, the number of β-particles of sufficient energy to cause Cherenkov radiation in water increases markedly with the increase of maximum emission energy, due to the energy-spectrum characteristics of β-emitters. The ratio of this number and the total number of electrons in the β-spectrum is the Cherenkov yield. The yield calculated for ^{16}N equals 98.6%[6]. Performed analysis have shown[6] that in addition to ^{16}N radionuclide, other radioactive nuclei, which can generate the Cherenkov light, can be produced in the irradiated water. There are radionuclides (^{15}C, ^{17}N, ^{18}N) whose energies are very close to the energy of ^{16}N, but their appearances limit the abundance of the origin nuclide and the nuclear cross section. As a result, contribution of all nuclides to the Cherenkov signal from ^{16}N is less than 0.2%. Since the emitted Cherenkov light is roughly proportional to the beta particle energy, the ^{16}N can be instantly identified. Thus, the Cherenkov counter offers an advantage for counting ^{16}N in water. Explained briefly, it consists of selective detection of large light pulses originating from the passage of high-energy electrons in a volume of water. Utilizing electronic components and altering the desired "window setting" can discriminate against contributions from Compton electrons, produced in the water from γ-ray interactions.

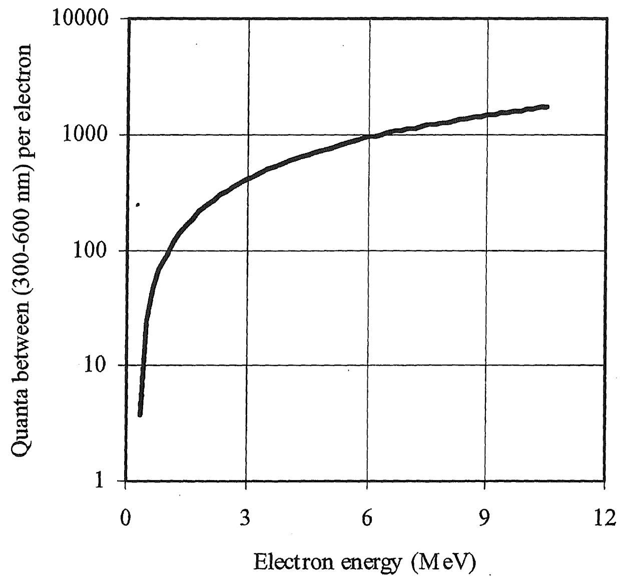

Fig. 2 The number of Cherenkov photons emitted per electron as a function of energy, calculated for the spectral region 300-600 nm.

III. Experimental Studies and Results

1. Equipment and experimental setup

The experiment was carried out using the FNS facility at JAERI. The ^{16}N radionuclide produced in water near the D-T neutron source, was transported to the chamber of the Cherenkov detector using flowing water in the closed loop, with flow velocity of 2 m/s. The chamber consists of an aluminum cylinder with dimensions of 5 cm in length, a 15 cm diameter, and a glass window. The inside walls were covered with 1mm thick Teflon sheets for light reflection. This chamber was far from the optimum, since the thickness of the reflecting Teflon layer must be about 6 mm for good reflection characteristics, and the material of the window has to be quartz. The PMT, Hamamatsu R1250, was optically coupled to the window chamber. The chamber and the detector were shielded with 10 cm thick Pb blocks. The associated electronic package consists of a high voltage supply, signal amplifiers, and a multichannel analyzer, used for accumulating acquired counts within a selected window.

2. Test measurements of Cherenkov light by β-particles from ^{32}P in water

Prior to measurements of the Cherenkov light by β-rays from ^{16}N, test and calibration measurements were completed for β-rays from ^{32}P. This radionuclide was chosen for calibration of a water Cherenkov detector and estimation of the PMT response function for a number of reasons. The main reason being the fact that the radionuclide is a pure β-emitter with a relatively high energy endpoint, 1.7 MeV. The β-ray spectra of ^{32}P and ^{16}N are shown on **Fig. 3**.

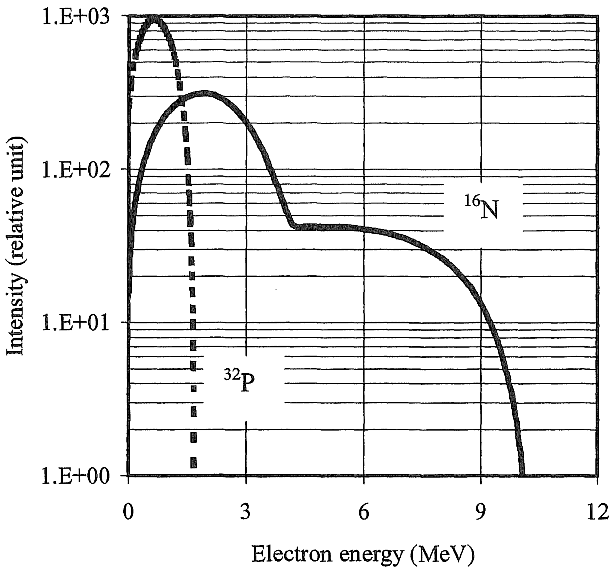

Fig. 3 Beta spectrum of ^{16}N and ^{32}P radionuclides

Measurements were performed with the radionuclide ^{32}P, whose activity is known, in the same conditions as measurements for the Cherenkov light by β-rays from ^{16}N. The water Cherenkov detector was investigated with respect to its response to ^{32}P, at several phototube voltages and amplifier gains. The typical pulse height spectrum is shown in **Fig. 4**. For the high energy part of the spectrum, the curve happens to have a near-exponential shape, and is therefore nearly linear on the semilogarithmic plot.

The method evaluating the Cherenkov counting efficiency of ^{16}N is based on the modified idea originally proposed by Grau Carles and Grau Malonda[7]. This idea separates the counting efficiency into two terms: the yield and the intrinsic Cherenkov counting efficiency. Thus, the counting efficiency can be expressed as follows:

$$\varepsilon_{Ch} = \eta \cdot \varepsilon_{Int} \qquad (2)$$

The yield, η, is the ratio between particles emitted over the set energy threshold, and the total number of emitted particles. The intrinsic Cherenkov counting efficiency, ε_{Int}, is defined as the ratio between counted particles and emitted particles over the set energy threshold. It is assumed that the response of the spectrometer to monoenergetic radiation is unique for electrons with kinetic energies over the Cherenkov threshold. If measurement conditions and the equipment will not vary, the detection probability function is assumed to be identical for every electron emitter. The detection of high-energy electrons by Cherenkov light depends only on the established measurement conditions. According to the solution[7], the detection probability is unity for β-rays with sufficient energy for total detection; that is, the detection probability nearly 1 for electrons of E > 1MeV in water. This energy value was used in all measurements performed in this study, as the lower energy threshold. For this condition, the intrinsic Cherenkov counting efficiency was evaluated with the ^{32}P radionuclide and later used for estimation of counting efficiency of the ^{16}N.

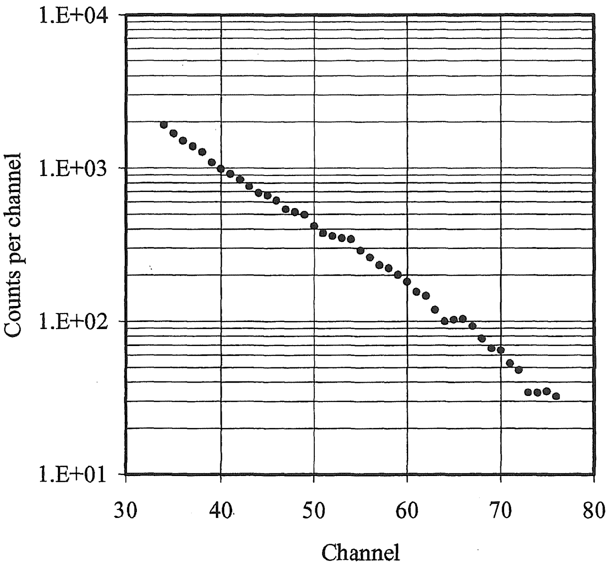

Fig. 4 Pulse height spectrum of ^{32}P measured by the water Cherenkov detector

The dependence of the yield, η, on the energy threshold was calculated for ^{32}P and ^{16}N. For the set threshold energy of 1 Mev, the calculation of the yield gives the value of 20.6% for ^{32}P and 85.9% for ^{16}N. Considering the experimental value of the Cherenkov counting efficiency obtained for ^{32}P, 5.2%, from equation (2), the intrinsic Cherenkov counting efficiency for the used detector was evaluated to be 25.2%. The application of the obtained value to other nuclides requires maintenance of the measurement conditions applied to the measurement of ^{32}P radionuclide. Thus, the Cherenkov counting efficiency for ^{16}N is 22.2%. As was expected, measurements of the ^{32}P and ^{16}N showed that the utilized camera is not optimized for measurements of the Cherenkov light and requires modification.

3. Measurements and identification of the Cherenkov light by β-particles from ^{16}N in water

The ^{16}N radionuclide was generated by D-T neutron irradiation of water flowing next to the source in the position of a neutron flux of about $1 \cdot 10^8$ n/cm^2/s. The transit time to the Cherenkov radiation detector was ~ 6 sec. The identification of the registered Cherenkov signal from ^{16}N was performed using the time decay and pulse height distribution spectrum. During the experimental run, the water flow in the chamber was stopped to estimate the time decay. It fully corresponds to the decay time of ^{16}N. The obtained experimental result is shown in **Fig. 5**.

A pulse-height spectrum (points) of ^{16}N is shown in **Fig. 6**.

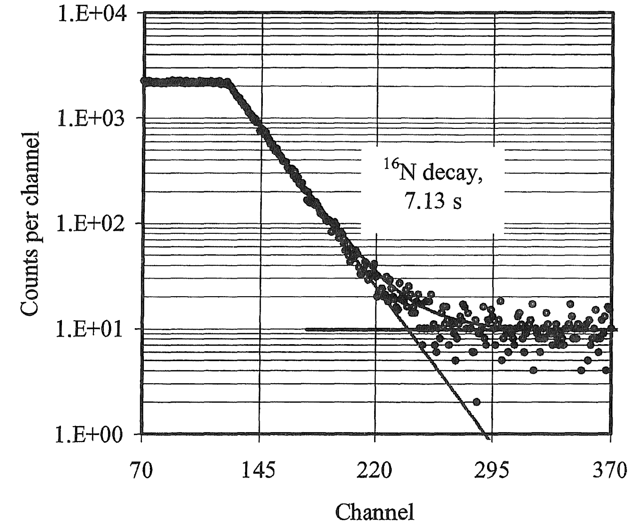

Fig. 5 Intensity of the Cherenkov signal from ^{16}N as a function of cooling time

The slope of the most energetic half of the pulse-height spectrum is a function of the $E_{\beta max}$ for each β-emitter. ^{32}P has only one β-decay branch ($E_{\beta max}$=1710 keV), thus the highly energetic part of the experimental spectrum corresponds to one slope. The result of the deconvolution of ^{16}N spectrum is also shown in **Fig. 6**. Two obtained slopes correspond to major β-decay branches of the ^{16}N, with endpoint energies of 4290 keV and 10420 keV (**Fig. 3**).

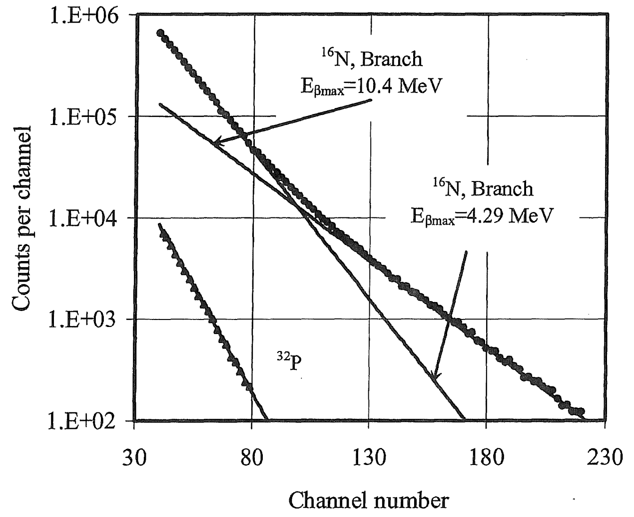

Fig. 6 The deconvoluted pulse height spectrum of ^{16}N measured by the water Cherenkov detector. ^{32}P is shown for the comparison.

IV. Future Work

In order to complete the feasibility study of the Cherenkov detector as a DT fusion power monitor for ITER, two more, the second and the third experimental phases are scheduled. The main idea of the second experimental phase consists of studying the temporal resolution of the proposed technique. For purposes of this study, a special Cherenkov detector is to be created, consisting of a water radiator, an optical fiber, and a remotely located light detector. It is proposed, that the water radiator is to be placed next to the DT neutron source, and the Cherenkov light generated in the water radiator from the β-rays of the ^{16}N, will be then transmitted by an optical fiber to the remotely located light detector. The third phase consists of finding the optimal solution of transmitting the Cherenkov light in conditions of heavy neutron radiation.

V. Conclusions

For the purpose of monitoring the D-T neutrons in the system using neutron activation of flowing water, a new approach was proposed. It enables to solve problems associated with the response delay and temporal resolution, which are the most important drawbacks of the previous approach. In support of this idea, the first experimental phase was completed. The response of the detector to the Cherenkov light from the ^{16}N was studied comprehensively. It was concluded, that the water Cherenkov detector is very efficient in measuring the ^{16}N activity, due to: high counting efficiency; absence of the scintillation detector; and simplicity of the method. The present study elaborates upon the feasibility and effectiveness of utilizing the Cherenkov radiation detector in the D-T neutron monitoring system.

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