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Development and Characterization of the Proton Recoil Detector for the MPRu Neutron Spectrometer

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ABSTRACT

The Magnetic Proton Recoil neutron spectrometer has been upgraded (MPRu) with a new focal plane hodoscope detector as a major part to improve the immunity to background and to extend the measuring range from 18 down to 1.5 MeV. The MPRu detector project has entailed the development of the phoswich technique for this new application. This was done through tests of prototype scintillators to reach the final design. The paper reports on the tests conducted, the projected specification and demonstrated performance through the first MPRu results obtained at JET.

INTRODUCTION

The Magnetic Proton Recoil spectrometer (MPR) at JET works on the principle of converting the incoming neutron flux from the plasma into an energy distribution of spatially dispersed proton flux [1] impinging on the focal plane detector, an array of plastic scintillators. The proton count rate depends on the plasma conditions and reached 0.7MHz during the JET DT experiment (DTE1) in 1997, well below the MPR maximum capability, with single detector rates up to 50kHz. In principle, the MPR spectrometer can be set to record fusion neutrons from 1.5 to 18MeV (over a range of ±20%). In practice, there is a limitation in the capability of the focal plane detector to record (count) protons at a reasonable ratio of signal to background (S/B). The previous array (hodoscope) of plastic scintillation detectors had sufficient S/B value to measure details of the 14MeV neutron d + t $\rightarrow \alpha$ + n emission from DT plasmas down to the 10-5 level of the neutron spectrum. However, the immunity to background, especially to electrons, has been found insufficient to measure the 2.5MeV d + d \rightarrow ³He + n emission from D plasmas [2]. A detector with enhanced background immunity has therefore been developed and built as the principal part of the MPR upgrade project (MPRu) [3 and 4, contribution to this conference]. The main difference is that the monolithic scintillators of the MPR have been replaced with laminated ones using the so-called phoswich technique. It affords selection of the desired fraction of recorded events based on pulse height and also the range in matter of ionizing radiation.

In the present phoswich application, the thickness of the first layer was chosen to correspond to the range of proton recoils of dd neutrons (i.e., 0.3mm for $E_p < 5$ MeV) and the total thickness covers the range of dt neutron recoils (<3.5 mm). Scintillators 1 and 2 have different (fast and slow) response times to radiation and their contribution to the pulse height sum P = P1 + P2 is determined through the waveform, P(t). The waveform was recorded with an oscilloscope in the tests and with fast Data Acquisition electronics with Analysis/storage Capability (DAAC), custom built for MPRu [5]. This paper describes the development of the phoswich technique for the hodoscope through the test of prototypes to reach the final design for MPRu. The performance specifications based on the test results are presented and are compared with the first results on the waveforms recorded for signal proton recoils from dd fusion neutrons at JET as well as with those of background radiation.

PRINCIPLE OF THE PHOSWICH SCINTILLATORS IN A HODOSCOPE.

The phoswich method is rather common in various applications for low energy radiation detection.

The present application requires the use of bars of scintillators where the total thickness as well as that of the thin layer are both used as a means to discriminate against background. Moreover, to fit into a hodoscope, the light is collected with PM tubes attached to the scintillator ends. This means that special care must be paid to the bonding of the two active layers plus the backing where that is used. Finally, the MPRu hodoscope must be able to handle recoil protons in the range 1.5 to 18MeV. The material chosen for the thin layer was the same as for MPR monolithic scintillators, i.e., Bicron BC-404 with a fast decay time of 1.8ns and Bicron BC-444 for the second layer with a slow (180ns) decay time; different thicknesses of the latter were used depending on hodoscope position to correspond to the varying range (2.5 to 3.5mm) of protons about $\pm 20\%$ in energy with the MPR set to $E_n = 16$ MeV in the middle to record the extreme high energy tail of dt neutrons.

The signals from the PM tubes have the waveform characteristics of the superposition of light emitted from the fast and slow layers. The waveforms were recorded with an oscilloscope for low data rates offering very high precision with sampling rates of 1GHz. In the MPRu, the PM tubes are read out up to high (100kHz) event rates at a 5-ns sampling time; the covered ranges are t = -200 to 800 ns and t = -110 to 390ns, respectively, with triggering at t = 0ns.

THE SCINTILLATION DETECTORS AND RADIATION TESTS

The MPRu phoswich detectors were designed based on tests of prototypes [6] of similar geometries. The tests used sources of 5.5MeV alpha particles and variable energy protons (both stopping in the scintillator), penetrating (minimum ionizing, $E_e \le 3.5$ MeV) electrons and pulsed light sources of controllable amplitude, width and rate (not reported here). These different sources were chosen because they simulate the radiations that are anticipated to be detected with the hodoscope when it is deployed at JET. The MPRu hodoscope is made of 32 plastic scintillators. The scintillator ends have cross section areas of between 38 and 76mm² which coupled to PM tubes with photo cathodes of 12mm diameter and can receive light distributed over an area of up to 110mm². To utilize this limit, a backing layer of acrylic plastic (Bicron BC-800) was used in some cases. The tests were performed on phoswich prototypes 10-mm wide with and without backing.

The backing has a considerable effect on the fraction of light collected by the PM tubes as demonstrated in the measurement with a collimated alpha source used to irradiate the fast side of the prototypes (Fig.1a). The backing improves the fraction of the produced light received at the PM tube by more than a factor of 2. These data represent the average waveform for an ensemble of events. For individual events it is convenient to use two amplitudes, A1 and A2. These are defined as the integrals of the waveform over periods t = 0-60ns and t = 60-460ns with the trigger set at t = 0 (Fig.1a); the amplitude in the region t = -20 to -2ns is used to determine the offset level that is subtracted to obtain A1 and A2.

The results on the event distributions A1 vs A2 for the two scintillators (Fig.1b) are individually well clustered with their centers lying on a line of fixed A1/A2 ratio as expected for the same kind

of radiation. The spreading area of the event groups depends on the fraction of the generated light in the scintillator that is collected. In other words, this spread represents the pulse height resolution which varies in proportion to the square root of the collected light in terms of the Poisson statistics of the number of photo-electrons generated in the PM tube cathode. This expresses the underlying quality of the pulse information contained in A1 and A2. The pulse height resolution results for the cases described above showed that it improves from 36 to 25 % (FWHM) with backing for A1+A2. This is about the factor 1.5 expected from the pulse height difference taking the square root of the summed A1+A2 ratio for the two cases. For the amplitude A1 one obtains 33 to 22 % which gives approximately the same ratio. The A1 values are slightly better which can be ascribed to the fact that the alphas stop in the thin layer. Adding A2 deteriorates resolution from the increase in the error coming from base line subtraction; in fact, the latter aspect makes the results on A2 unsuitable to extract a meaningful pulse height resolution.

The above result for the alphas can be compared with that for electrons depositing energy in both layers in proportion to their thickness. Here we determine the pulse height resolution for the scintillator with backing to be 54% and 45% (FWHM) for A1 and A1+A2, respectively, and 54% for A2 only; the interpretation of these results are complicated by the presence of straggling. It can be mentioned in this context that the monolithic MPR scintillators performed better than the phoswich type which is the price to pay for the added range information. Another source of imprecision in pulse height is the variation that comes from longitudinally different interaction positions (x), i.e., the light transport distances to a PM tube. Such pulse response studies were performed with a collimated electron flux from a beta sources penetrating the prototype scintillator and detected with a small coincidence detector on the opposite side. The results obtained for a scintillator with backing (Fig.2) show that the pulse height from the individual PM tubes changes more than a factor of 2 end to end with an x dependence of a double exponential. The summed pulse from the two PM tubes has a total variation span of about 20% from either scintillator end to the minimum in the middle and is a factor of almost 2 higher than the pulse of a single PM tube. As the summed pulse height is always used from the MPRu detector, the longitudinal variation is negligible compared the pulse height resolution connected to the fraction of light that is emitted in the direction of the cone of total reflection transportation to the PM tubes. The MPRu scintillators have backing to approach the area limit set by the PM tubes.

A Tandem accelerator was used to expose a phoswich detector to a collimated beam of protons of fixed but changeable energy in the range $E_p = 1$ to 7MeV. With the protons impinging into the thin layer one finds a response in terms of the A1 vs A2 event distribution as presented in Fig.3a. For each energy, the events are well clustered with centers following a curve close to that of a fixed A1/A2 ratio up to $E_p = 5$ MeV. Beyond this point, there is no further increase in A1 but only A2. The abrupt change in the A1/A2 ratio indicates that the range of the impinging protons exceeds the 0.3mm thick plastic scintillator, just below 5MeV, the nominal value being 4.7MeV.

The above range information was derived from the change in the measured waveforms produced

by protons as exemplified by the data presented in Fig.3b. Here one can see that the waveforms stay steady from $E_p = 1$ to 4.7MeV while that of $E_p = 7$ MeV shows the same leading edge shape but a broad tail setting in at t≈30 ns. At JET, the scintillators of the MPRu spectrometer will be irradiated with practically mono-energetic recoil protons, so they will show A1 vs A2 event distributions of the type shown of Fig.3a.

SCINTILLATOR RESPONSE TO FUSION NEUTRONS AND BACKGROUND AT JET

The phoswich hodoscope has been put to the first test under realistic measuring conditions at JET operating with deuterium plasmas and the MPRu set to measure the 2.5MeV dd neutron emission. An example of the results on the A1 vs A2 event distribution (Fig.4a) shows a close clustering of the proton recoil events well separated from the ones due to the detector exposure to background radiation. Underlying these results are the measured waveforms. Those for protons are presented in Fig.4b which are found to be similar to those projected from the prototype results (Fig.3b).

CONCLUSIONS

In this paper we have described the application of the phoswich scintillator technique to the focal plane detector hodoscope of the MPR spectrometer in its upgraded version (MPRu). The MPRu hodoscope was developed on the basis of the prototype tests described in the paper to assess the required performance with regard to the ability to identify recoil protons against background. The MPRu hodoscope is performing as expected based on the first results of the MPRu under realistic measuring conditions at JET.

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Figure 1: The response of the fast layer of the phoswich scintillator with and without backing to 5.5MeV alpha particles with results on the average waveforms (a) and presentation of the individual event distributions A1 versus A2 (b).



Figure 2: The response of the phoswich scintillator with backing in response to the flux of minimum ionizing electrons localized to different longitudinal positions x. The mean value m of the event distributions A1+A2 from individual PM tubes compared to fitted double exponential curves, and the sum (normalized to 1 for x=0mm).

Figure 3: The response of the phoswich detector with backing presented as function of the event distributions A1 vs A2 for a protons of fixed energies (a) and average waveforms for $E_n = 2$, 4.7 and 7MeV (b).

GOB

800

MA.

1 MeV Noise

3

E_p 2Mev 4.7Mev

7Mev



Figure 4: Data from the MPRu phoswich detector taken at JET for D plasmas with example of A1 vs A2 event distribution showing groups of recoil protons and background radiation (a) and waveforms for protons recorded with DAAC system (b). The MPRu was set at 2.5MeV to record $d+d \rightarrow^{3}He+n$ neutron emission.