RPC for thermal neutron detection

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Abstract. The possibility to detect thermal neutrons with single gap Resistive Plate Chambers has been investigated. To detect neutrons a $^9$B,C thin coating on the inner surface of one RPC electrode is used as thermal neutron converter. The RPC detects the charged particles generated by neutrons via the (n,α) reaction on Boron. Tests on converter samples have been performed with a thermalized $^{252}$Cf source in order to evaluate the conversion efficiency: a good agreement between experimental results and simulation has been achieved. A detector prototype has been developed and tested on a low energy neutron beam at the European laboratories JRC in Belgium. A detailed description of the detector and the experimental test results are presented.

1. Introduction

Resistive Plate Chambers are gaseous detectors widely used for trigger purpose in large particles physics experiments, with cosmic rays and at accelerators. They achieve high efficiency for charged particles (~97%), they offer a fast response with a time resolution of about 1÷2 ns and a space resolution of few mm.

Single gap RPC [1] are made up of two resistive plane electrodes with a gap between them filled by an appropriate gas mixture; on their external surface there is a coating of graphite paint on which high voltage is applied. Usually electrodes are made of bakelite or glass whose resistivity is $10^9$÷$10^{12}$ Ω·cm. Two planes of orthogonal strips pick-up by induction the signals generated by charged particles crossing the detector. The strip width determines the spatial resolution which can achieve ~3 mm for 1 cm wide strips [2].

RPCs are usually operated in streamer or in avalanche mode [3]. The former provides large signals (few hundreds of mV) that can be discriminated without amplification but it imposes constraints on the rate capability of the detector. The latter uses low amplification gas mixture in order to reduce the current dissipated in a single discharge, thus improving the rate capability of the detector and reducing the deterioration due to the aging effects. Obviously, the lower gain of the gas mixture has to be compensated by an amplification of the avalanche signals (few mV). A new gas mixture with higher quenching properties than the one for streamer mode has been developed in order to operate the detector in a highly saturated mode providing stable signals with amplitude of a few tens of mV.
2. RPC as thermal neutron detector

The thermal neutron detection by RPC requires the conversion of neutrons into charged particles inside the detector gas gap. For this reason a thin coating of converter material on the inner surface of one electrode is foreseen. In figure 1 the structure of a single gap RPC for thermal neutron detection is shown.

![Figure 1. Structure of a single gap RPC for neutron detection.](image)

Among the three materials characterized by the highest neutron absorption cross section, $^6$Gd, $^{10}$B and $^7$Li, Boron has been chosen because of its better chemical properties with respect to Lithium and because the energy loss in the RPC gas gap of $\alpha$ and $^7$Li produced in the neutron absorption is much higher with respect to the electrons produced via $\gamma$ internal conversion on Gadolinium. The cross section for the reaction $^{10}$B($n$, $\alpha$)$^7$Li for thermal neutrons is quite high ($\sim$4 kbarn), and the energy of produced charged particles are: $T_\alpha \sim$1.5 MeV and $T_{^7\text{Li}} \sim$0.8 MeV in 94% of events and $T_\alpha \sim$1.8 MeV and $T_{^7\text{Li}} \sim$1.0 MeV for the remaining 6% of events. To optimize the thermal neutron conversion efficiency into $\alpha$ particles, it is necessary to use Boron enriched with $^{10}$B isotope as pure material or in chemical compounds with high content of Boron. For technical reason the converter coating on the RPC electrodes has been produced with B$_4$C enriched with $^{10}$B isotope by more than 97%.

2.1. The thermal neutron converter.

Monte Carlo simulation has been performed to define the Boron Carbide coating thickness which optimizes the conversion efficiency, defined as the probability for a neutron to produce a charged particle ($\alpha$ or $^7$Li) coming out of the converter layer.

The transport and thermalization of neutrons from a source towards the neutron detector have been performed in the frame of the GEANT code using MICAP package for low energy neutron simulation. To estimate the conversion efficiency, the simulation takes as input the energy distribution of neutrons impinging the converter and generates charged particles according to the cross section for the nuclear reaction $^{10}$B($n$, $\alpha$)$^7$Li; it also takes into account $\alpha$ and $^7$Li absorption inside the converter.
The simulated conversion efficiency of a $^{10}$B$_4$C coating for thermalized neutrons from a $^{252}$Cf source is shown in figure 2 as a function of the converter thickness for three different neutron incident angles. The curves present a broad maximum ($\varepsilon \sim 3.5\% \div 4\%$) for ~3 $\mu$m thick converter, this means that a $\sim 0.5$ mm accuracy on the converter thickness is sufficient.

Boron carbide coatings have been realized with the technique of the magnetron sputtering on glass samples ($5 \times 5$ cm$^2$) at the Engineering Support and Technologies Division at CERN. To improve the adhesion of $^{10}$B$_4$C on the glass surface a thin film of Ti ($2 \mu$m thick) has been sputtered before the converter coating. The converter samples were tested at the INFN Laboratori Nazionali di Legnaro where a test site was equipped with a $^{252}$Cf neutron source ($10^7$ n/s); the neutrons were thermalized by a polyethylene block. The $\alpha$ particles, produced by the interaction of thermal neutrons with the $^{10}$B atoms and coming out of the converter layer, were detected by a Si detector $5 \times 5$ cm$^2$ wide. The air gap between the converter and the detector could vary from 1 mm to 1.5 mm in the different measurements.

Figure 3 resumes the results obtained for three samples ($0.5, 0.75, 1.0 \mu$m thick $^{10}$B$_4$C coating) positioned at a 1 mm and 1.5 mm distance from the silicon detector: the measured $\alpha$ counting rate as a function of converter thickness is shown, a cut at 600 keV on the $\alpha$ energy is applied in order to eliminate the fluctuation of the background. The data were compared to simulation results taking into account the experimental conditions: neutron energy spectrum from the moderator surrounding the $^{252}$Cf source and the presence of air between converter and Si detector (1+1.5mm). The trend of $\alpha$ rate as a function of converter thickness is well reproduced by simulation. A good agreement between the experimental $\alpha$ energy spectra and the simulated ones was obtained as it can be seen in figure 4 where the comparison has been performed for a $^{10}$B$_4$C converter 0.75 $\mu$m thick.

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3. RPC prototype

A prototype of RPC was built according to the design described in section 2. The size of the detector is $10 \times 10 \text{cm}^2$ and the electrodes are glass plates 2mm thick ($\rho \sim 10^{12} \Omega \cdot \text{cm}$). The neutron converter consists of a $^{10}\text{B}_4\text{C}$ coating 3μm thick of circular shape with a 25mm radius, directly sputtered on the positive electrode. The surface of the glass under the converter coating was slightly rough due to a light sandblasting process in order to increase the adhesion of the coating on the glass surface without using any substrate such as Ti.

The detector was operated with a “saturated avalanche” gas mixture (89.5% $\text{C}_2\text{H}_2\text{F}_4 + 10\% \text{C}_4\text{H}_{10} + 0.5\% \text{SF}_6$), the signals were amplified by a factor 10 and discriminated with a threshold set at 50mV. The prototype has been equipped with 2cm wide strips and tested with cosmic rays in order to measure the efficiency for charged particles as a function of the high voltage and to evaluate the single counting rates, which are related to the detector noise. Figure 5 shows the RPC efficiency as a function of high voltage: a 98% efficiency was measured with an average counting rate always less than 0.1 Hz/cm$^2$.

The same prototype was tested with a low energy neutron beam at the European research centre JRC (Geel, Belgium) in July 2005. The detector was equipped with two circular read-out pads with a 3mm radius: one centred on the Boron Carbide coating to count the $\alpha$ particles generated by neutrons, the other positioned outside the Boron Carbide coating to measure the background mainly due to $\gamma$ rays associated to the neutron beam.

4. Test with neutron beam

The test was performed at the GELINA (Geel Electron LINear Accelerator) facility which provides a pulsed neutron source in combination with a time of flight (TOF) facility which allows to determine the neutron energy [4].
GELINA is a linear electron accelerator producing pulsed electron beams of an average energy of 100 MeV with a repetition rate which can be tuned at 40, 100, 800 Hz. The neutrons are produced by the electron bursts impinging on a rotating U target. In order to have a significant number of neutrons in the thermal energy range, a hydrogen rich moderator is added. The partially moderated neutrons have an approximate $1/E$ energy dependence plus a Maxwellian peak at thermal energy. During the test the moderator was used and GELINA was operated at 40Hz in order to avoid overlapping of slow neutrons of a burst with the fast ones of the following burst. In these conditions the neutron flux at $L = 12$ m from the source was about $10^3$ n/s cm$^2$ with a $1/L^2$ decrease as neutrons are isotropically emitted. Moreover an intense $\gamma$ flux came from the U target at each neutrons bunch and a $\gamma$ field associated to the neutron beam was present.

The RPC was positioned on the beam line behind an ionization chamber used as a reference counter; the distance from the neutron source was 13.76 m and 12.16 m respectively for the RPC and the reference detector. The ionization chamber detects neutrons via the same nuclear reaction $^{10}$B($n,\alpha$)$^7$Li by means of two converter layers of $^{10}$B 0.17$\mu$m thick. Along the neutron beam line, filters of different materials were placed: Pb in order to reduce the $\gamma$ yield generated in the U target, W and Ag which fully absorb neutrons of definite energies providing black resonances useful for the background evaluation.

### 4.1. Results and comments.

The signals from the ionization chamber and from both the RPC pads were used to measure the time of flight of neutrons on the path from the U target to the detectors. Measurements were performed at two different high voltages: 9700 V and 10100 V. The second voltage optimizes the signal/background ratio even if the detector is not fully efficient ($\varepsilon \sim 80\%$) for m.i.p. as shown in figure 5. This is due to the high energy loss of $\alpha$ with respect to minimum ionizing particles. At higher voltages the background produced by the intense $\gamma$ field becomes more and more important.

The time of flight spectrum of neutrons detected by the RPC at 9700 V is shown in figure 6: the Maxwellian distribution of thermal neutrons is evident together with the contribution of epithermal neutrons in the low time of flight region. The holes present in this region are due to the black resonances of W (18 eV) and Ag (5 eV and 4 eV).

![Figure 6](image-url)
Figure 7. Energy spectra of neutrons detected by the RPC at 10100 V (red) and by the ionization chamber (black). Data are not normalized to the same incident neutron flux.

The shape of background, mainly due to γ rays, was evaluated by means of a fit to the TOF spectrum measured by the pad positioned outside the converter coating and normalized to the bottom of the W and Ag black resonances up to 20 eV.

The energy spectra of neutrons detected by the RPC and by the ionization chamber were obtained from the time of flight spectra after the background subtraction. The two spectra, respectively from the RPC at 10100V and from the ionization chamber are presented in figure 7.

Counts from the RPC and from the ionization chamber were normalized to the same estimated neutron flux taking into account the different detector size and position along the beam line. Data were compared for 6 energy bins in the thermal region up to 2 eV as shown in table 1. Errors are due to the uncertainty in the background estimation.

| Energy bin         | RPC counts / IC counts RPC HV=9700 | RPC counts / IC counts RPC HV=10100 |
|--------------------|------------------------------------|------------------------------------|
| 0.02 eV + 0.05 eV | 0.118 ± 0.007                      | 0.81 ± 0.07                        |
| 0.05 eV + 0.10 eV | 0.118 ± 0.007                      | 0.81 ± 0.07                        |
| 0.10 eV + 0.20 eV | 0.118 ± 0.007                      | 0.81 ± 0.07                        |
| 0.20 eV + 0.50 eV | 0.125 ± 0.007                      | 0.88 ± 0.14                        |
| 0.50 eV + 1.00 eV | 0.125 ± 0.007                      | 0.88 ± 0.14                        |
| 1.00 eV + 2.00 eV | 0.125 ± 0.007                      | 0.96 ± 0.14                        |

Results are resumed in figure 8 and 9 where the ratio of counts from the RPC and the ionization chamber is plotted for each energy bin and for the two operation high voltage. The ratio shows no evident energy dependence up to 2 eV.
Figure 8. Ratio of counts from the RPC at 9700V and from the ionization chamber. Data are normalized to the same estimated neutron flux.

Figure 9. Ratio of counts from the RPC at 10100V and from the ionization chamber. Data are normalized to the same estimated neutron flux.

5. Conclusions
RPCs for thermal neutron detection were developed and a prototype was built and tested. Preliminary studies about the neutron converter were performed and good agreement between simulation and experimental results was obtained. The performances of the RPC prototype were investigated with a low energy neutron beam: the measured RPC efficiency for thermal neutron is ~86% of the ionization chamber efficiency used as a reference counter, but an important background due to the γ field associated to neutrons is present.

Data analysis is still in course and will provide an estimation of the absolute efficiency of the RPC for thermal neutron detection. Nevertheless the study performed so far shows that RPCs can be used to detect thermal neutrons, in particular for measurements in coincidence with other counters and where neutron localization is required, as RPC are position sensitive detectors.

References
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