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Simulation and prototyping of 2 m long resistive plate chambers for detection of fast neutrons and multi-neutron event identification

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ABSTRACT

Resistive plate chamber (RPC) prototypes of 2 m length were simulated and built. The experimental tests using a 31 MeV electron beam, discussed in details, showed an efficiency higher than 90% and an excellent time resolution of around $\sigma = 100$ ps. Furthermore, comprehensive simulations were performed by Geant4 toolkit in order to study the possible use of these RPCs for fast neutron (200 MeV–1 GeV) detection and multi-neutron event identification. The validation of simulation parameters was carried out via a comparison to experimental data. A possible setup for invariant mass spectroscopy of multi-neutron emission is presented and the characteristics are discussed. The results show that the setup has a high detection efficiency. Its capability of determining the momentum of the outgoing neutrons and reconstructing the relative energy between the fragments from nuclear reactions is demonstrated for different scenarios.

1. Introduction

Neutron detection is one of the most difficult tasks in studying nuclear reactions, because only the secondary reaction products can be observed. Detectors for fast neutrons are operated worldwide at the radioactive ion beam facilities, e.g., the Radioactive Ion Beam Factory (RIBF) (see e.g., Ref. [1]) at the Institute of Physical and Chemical Research (RIKEN), Japan and the National Superconducting Cyclotron Laboratory (NSCL) [2] at Michigan State University (MSU), USA. The R^{3}B (Reactions with Relativistic Radioactive Beams) collaboration [3] uses the Large Area Neutron Detector (LAND) [4] at Helmholtz Centre for Heavy Ion Research (GSI).

Commonly, neutron detectors based on plastic scintillators detect the light induced mainly by the recoiled protons. However, photomultipliers with good timing characteristics, which convert the light and multiply the electrons to a measurable signal, can be quite expensive. This is especially relevant when working with radioactive ion beams of low intensities where a high detection efficiency of the nuclear reaction products is essential, so numerous modules have to be employed. Recently, the R^{3}B collaboration has investigated the possibility of constructing a fast neutron (200 MeV–1 GeV) detector setup called New Large Area Neutron Detector (NeuLAND) [5]. The most important design goals are a high efficiency of at least 90% at 400 MeV neutron energy, large angular coverage of 80 mrad in a distance of 12 m to the target, excellent time resolution of 150 ps and a fine granularity to achieve good invariant mass resolution, e.g., $\sigma = 20$ keV at 100 keV excitation energy above the threshold. Furthermore, the setup should be able to identify multi-neutron events, reconstruct the momentum of the incoming neutrons correctly and deliver the excitation energy spectrum with good resolution.

One possible approach to address these challenges is based on RPCs, known for their outstanding time resolution for minimum ionizing particles [6] and low price. RPC prototypes of different

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configurations (number of gaps, glass thickness, etc.) and with dimensions of 40×20 cm^2 (in the first phase) and of 200×50 cm^2 were built at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The results of electron beam tests carried out on the small 40×20 cm^2 prototypes to optimize the structure for the large 200×50 cm^2 detectors, was published earlier [7]. Some of these RPCs were tested by quasi-monoenergetic neutrons, the preliminary results of which were published in Ref. [8]. The present paper concentrates on the final adopted structure for the large 200×50 cm^2 detector, showing extensive Monte Carlo simulations, electron beam data, and in details the simulated response of a hypothetical full array.

Parallel to this effort, a study of a setup built from plastic scintillators was carried out, as well. The latter approach was adopted for the final NeuLAND array [5]. Here, we report on the former approach for future reference instead.

We note that the idea of operating RPCs as neutron detectors is not new and was investigated experimentally for thermal [9,10] and higher (14 MeV) [11] energies. Simulations focussing on the neutron sensitivity of different kind of RPCs were performed previously for various energies [12,13] as well as detailed simulations of the RPC physics and signal production [14,15]. Here, we outline the capability of a neutron detector setup based on RPCs for multi-neutron event identification and reconstruction.

2. Simulation framework and parameter optimization

The 9.4.p01 version of GEANT4 and that of the low energy neutron datafile (`G4NDL3.14`) were used. For the electron primary particles, the standard electromagnetic physics builder `G4EmStandardPhysics` was applied while `HadronPhysicsQGSP_BIC_HP` physics list was switched on for the neutron primaries.

The simulations were done in two stages. In the first stage, the Monte Carlo engine generated the primary and secondary particles, transported and tracked through the setup providing the deposited energy, hit position and time information. The first phase of the second stage was the electron avalanche in the RPC gas gaps and the signal production, which followed the physics fundamentals of an RPC and was a simplified form of the method described in Ref. [15]. The deposited energy (ΔE) by the charged particles entered the gas gaps of the RPC was converted to primary electron clusters. The number of primary electrons were determined by dividing ΔE by the average energy required to form an electron–ion pair in the RPC gas (ionization yield, W). Since W was not precisely known for our specific gas mixture, its value was adjusted until the distribution of the number of electrons were similar to the distribution coming from HEED [16] calculations in Ref. [15]. This resulted in $W{=}40$ eV, a realistic value comparable to W of other gases [17]. The electron clusters were grown into avalanches, governed by the Townsend and attachment coefficients, and propagated in steps toward the anodes. It is worth noting that the Townsend and attachment coefficients are responsible for the multiplication and recombination effects, respectively. The space-charge effect was taken into account by an adjustable parameter (P_{CutOff}), which allowed the avalanches to grow up to only a certain limit [18,19]. An additional distance parameter (P_{Dist}) (not in Ref. [15], but used in other simulations, e.g., in Ref. [14]) was also introduced to consider the interplay between the avalanches, i.e., if they are close to each other they are merged into a single avalanche, and the P_{CutOff} parameter was applied on the new avalanche. As the avalanches move, they induce current on the readout strips, which were calculated in each step. In the next phase, independent of Ref. [15], the induced currents were combined into signals and transported to both end of the readout strips where the arrival times – the experimental observables – were recorded if the charge exceeded a certain threshold set by a parameter (T). This means that T was applied at the input of the front-end electronics (FEE), which was of FOPI type [20] same as in our earlier publication [7]. Since the FEE was not coded in the simulation, T was kept as a variable. This was necessary because the FEE modified the input signal. The FOPI card included a three-stage broadband amplifier and a leading-edge type comparator. The threshold for discrimination was set on the amplified signal. A monitor value for the threshold given in mV, proportional to the real threshold, was available at a test point.

The three simulation parameters (P_{CutOff}, P_{Dist}, T) were adjusted to match the experimental data. For this purpose, numerous efficiency measurements using 31 MeV electron beam were performed with different configurations of the small chambers. The FEE's were used with three different monitor threshold values (110 mV, 220 mV, 440 mV) while the detectors were operated in a wide range of high voltage [7].

This parameter adjustment yielded $P_{CutOff}{=}1.6\text{E}7$, $P_{Dist}{=}0.3$ mm, $T{=}31$ fc (e.g., for the 440 mV FEE threshold). The P_{CutOff} value is close to 1.2E7 reported earlier in Ref. [18]. As an example, Fig. 1 shows a comparison between experimental and simulated efficiency values of a 2×3 gap RPC at different high voltages for 220 mV threshold value of the front-end electronics. Similarly, quite good agreement was achieved for the other configurations as well.

3. Experimental tests for the 2 m long prototypes

The main design parameters were developed in Ref. [7]. Briefly, in order to achieve high neutron detection efficiency, the setup is imagined to include steel layers to convert neutrons into charged particles. The prototypes were constructed in a way that the converters are part of the chamber as structural elements.

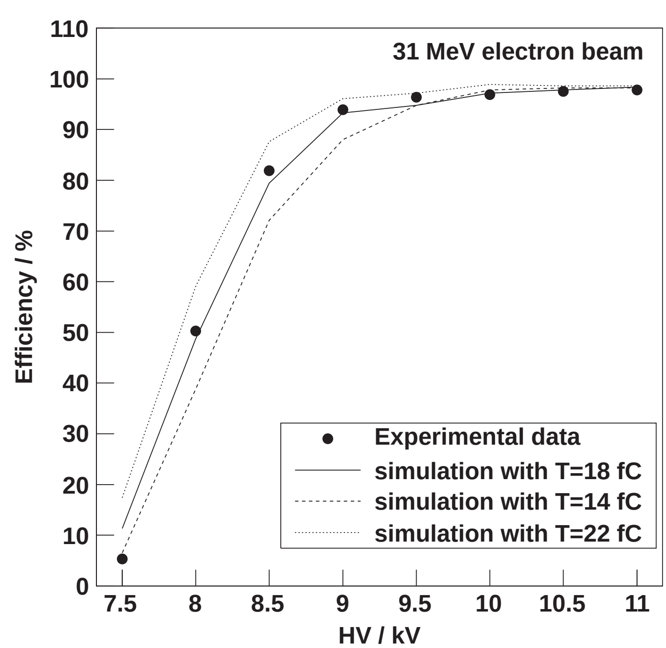

Fig. 1. Dependence of the detection efficiency of a 2×3 gap RPC on the high voltage applied at 220 mV threshold for the front-end electronics. A gas mixture of 85% Freon R134a, 10% SF6, 5% iso-butane was used. Experimental data are shown with dots, while the solid line represents the simulation result using $T{=}18$ fC. For comparison, simulated curves with $T{=}14$ fC (dashed line) and $T{=}22$ fC (dotted line) are also plotted.