Thermal neutron detection based on resistive gaseous devices

G. Bencivenni[1,*], I. Balossino[2], G. Cibinetto[2], R. De Oliveira[3], R. Farinelli[2], G. Felici[1], I. Garzia[2], M. Gatta[1], M. Giovannetti[1], S. Gramigna[2], L. Lavezzi[4], G. Mezzadri[2], G. Morello[1], G. Papalino[1], M. Poli Lener[1], M. Scodeggio[2]
[1] Laboratori Nazionali di Frascati – INFN, Italy
[2]INFN - Ferrara, Italy
[3]CERN, Switzerland
[4] INFN-Torino, Italy
(*) giovanni.bencivenni@lnf.infn.it

Abstract— **In the framework of the uRANIA (u-Rwell Advanced Neutron Imaging Apparatus) project, we are developing innovative thermal neutron detectors based on resistive gaseous devices such as micro-Resistive WELL (µ-RWELL) and surface Resistive Plate Counter (sRPC).**
The µ-RWELL is a single amplification stage resistive MPGD developed for HEP applications. The amplification stage, based on the same Apical® foil used for the manufacturing of the GEM, is embedded through a resistive layer in the readout board. The resistive layer is realized by sputtering the back side of the Apical® foil with Diamond-Like-Carbon (DLC). A cathode electrode, defining the gas conversion/drift gap, completes the detector mechanics. The deposition of a thin layer of ^{10}B4C on the cathode surface allows the thermal neutrons conversion into ^{7}Li and α ions, which can be easily detected in the active volume of the device. Results from tests performed with different detector layouts show that a thermal neutron (25 meV) detection efficiency up to 7% can be achieved with a single detector. A comparison between experimental data and the simulation of the detector behaviour has been performed.
In parallel, we are proposing the development of thermal neutron detectors based on a novel RPC concept. The sRPC is a revolutionary RPC based on surface resistive electrodes realized by exploiting the well-established DLC sputtering technology on thin (50µm) polyimide foils, the same used in the manufacturing of the µ-RWELL. The DLC foil is glued onto a 2 mm thick float-glass. The 2 mm gas gap between the electrodes is ensured by spacers made of Delrin®, inserted without gluing at the edges of the glass supports. By replacing DLC with ^{10}B4C sputtered electrodes, the device becomes sensitive to thermal neutrons. Different layouts of ^{10}B4C coated electrodes have been tested, allowing to achieve efficiency up to 6%. The robustness, ease of construction, and scalability of the sRPC technology should allow the construction of cost-effective large area detector units as required by applications in homeland security (such as Radiation Portal Monitor).

***Keywords* — Thermal neutrons, Boron coating, MPGD, RPC**

I. INTRODUCTION

Neutrons are subatomic particles with neutral electric charge and a mass slightly greater than that of a proton. Because of their high penetration power, they are used, by means of dedicated detectors, to probe the structure and the motion of the matter in a complementary way to X-ray imaging [1]. Neutrons play an important role in the illicit traffic of radioactive material, as any abnormal neutron flux, detected with proper devices, could suggest the presence of heavy radioactive material. This is the case of Radiation Portal Monitors (RPM), installed to detect illicit traffic of radioactive material through port or airport, that require for several square meters of sensitive area.
In literature, neutron detection is categorized according to the nuclear processes, mainly neutron capture and elastic scattering (not threatened in this paper). Nuclides such as ^{3}He, ^{10}B, ^{6}Li, have a high neutron capture cross section and large probability of absorbing a neutron, as reported in Table 1.

Reaction	Q-value [MeV]	Cross section for thermal neutrons [barns]
^{3}He + n + ^{3}H + p	0.764	5330
^{10}B + n → ^{7}Li + α	2.31	3840
^{6}Li + n → ^{3}H + α	4.78	940

Table 1. Reactions of interest involving neutron capture, the released energy (Q-value) and their cross-section for thermal neutrons are shown, where n represents a neutron, p a proton, α an alpha particle (He^{++}).

A well-known converter used for neutron detection is the ^{3}He due to its large cross-section (5330 at 25 meV). Helium-3 proportional counters use the ^{3}He(n,p)^{3}H reaction for the detection of thermal neutrons, where the energy of the reaction (Q=764 keV) is carried out as kinetic energy of the daughter products, which approximately move back-to-back. In the latest years a shortage of this element increased the ^{3}He cost with a large impact on neutron detector production and their application in the fields of interest. A call for alternative solutions triggered the URANIA and URANIA-V project [2,3], where two different gaseous detector technologies (µ-RWELL and sRPC) associated with a suitable ^{10}B4C based converters have been proposed. Thanks to the neutron capture process (tab. 1), neutron detection can be activated through a thin deposition of ^{10}B on suitable detector electrodes. The reaction products (1),

^7Li and α particles, generated nearly back-to-back on the converter, interact with the gas creating ionization electrons that are amplified by the amplification stage of the gaseous detector. The sputtered ^{10}B is chemically stable, mechanically robust and with very good adherence on several substrates. Moreover, the deposition of ^{10}B, based on standard industrial process, can be performed with high uniformity over surface in the order of ≈1 m^2.

$$n + {}^{10}B \rightarrow {}^{11}B* \rightarrow \alpha + {}^{7}Li\ (6\%)$$
$$n + {}^{10}B \rightarrow {}^{11}B* \rightarrow \alpha + {}^{7}Li + 477\ keV\ \gamma\ (94\%) \quad (1)$$

II. MICRO-RWELL FOR NEUTRON DETECTION

The μ-RWELL [4], Fig. 1, is a single-amplification stage resistive MPGD composed of two elements: the cathode, a simple FR4 PCB with a thin copper layer on one side, and the μ-RWELL_PCB, the core of the detector. The μ-RWELL_PCB, a multi-layer circuit realized by means of standard photo-lithography technology, is composed of a well patterned single copper-clad polyimide foil acting as amplification element of the detector; a resistive layer, realized with a Diamond-Like-Carbon (DLC) film sputtered on the bottom side of the polyimide foil, as discharge limitation stage; a standard PCB for readout purposes, segmented as strip, pixel or pad electrodes. The neutron conversion is no longer the gas inside the detector (as in the Helium-3 proportional counter), but a thin layer (few micrometers thick) of $^{10}B_4C$ deposited on the cathode, exploiting a well-known industrial sputtering process.

The thickness of the converter is a crucial parameter to be tuned to maximize the neutron conversion probability and at the same time to reduce the probability that the products are stopped by the same material, then not entering in the detector active volume.

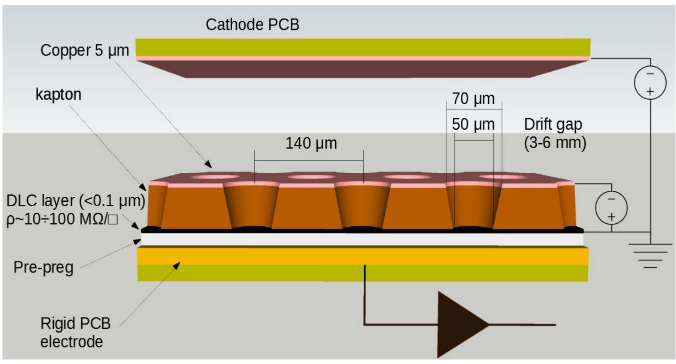

Fig.1. Sketch of μ-RWELL detector. The basic version of the neutron device is obtained with a suitable ^{10}B coating of the cathode surface. The detector is operated with Ar/CO2/CF4 (45/15/40) gas mixture.

The detector, operated with $Ar/CO_2/CF_4$ (45/15/40) gas mixture, is equipped with a single 10x10 cm^2 pad electrode readout with custom FEE developed by LNF electronic pool. The readout is based on the CREMAT CR-110 single channel charge sensitive amplifier (Gain = 14mV/fC - [5]), followed by the CR-200 shaping amplifier with a shaping time of 1 μs.

The simplicity and the modularity of the μ-RWELL can be exploited to adapt the technology to any desired application. Moreover, its compactness makes possible the realization of a stack of such detectors that, operating in OR-mode, sums up their efficiency.

III. NEUTRON CONVERTERS FOR μ-RWELL

The basic version of the neutron detector based on μ-RWELL technology is obtained with a suitable ^{10}B deposition on the planar cathode. The first prototypes were equipped with planar cathodes with different ^{10}B deposition thickness: 1.5, 2.5, 3.5, 4.5 μm.

The characterization of these prototypes was performed at the ENEA HOTNES facility in Frascati [6], where a ^{241}Am-B neutron source is placed in a cylindrical cavity delimited by polyethylene walls. HOTNES exploits a polyethylene shadow bar that prevents fast neutrons from directly reaching the samples. The effect of the shadow bar and the cavity walls is combined in such a way that the thermal neutron fluency is nearly uniform. The resulting fluence rate at the HOTNES reference irradiation plane is 758±16 $cm^{-2}s^{-1}$. Experimental measurements and simulations evaluate the neutron fraction absorbed by the mechanical structure of the detector (mainly the cathode PCB made of FR4): a fraction of 17.7% is removed from the neutron fluence rate. A sketch of the HOTNES setup is shown in Fig. 2.

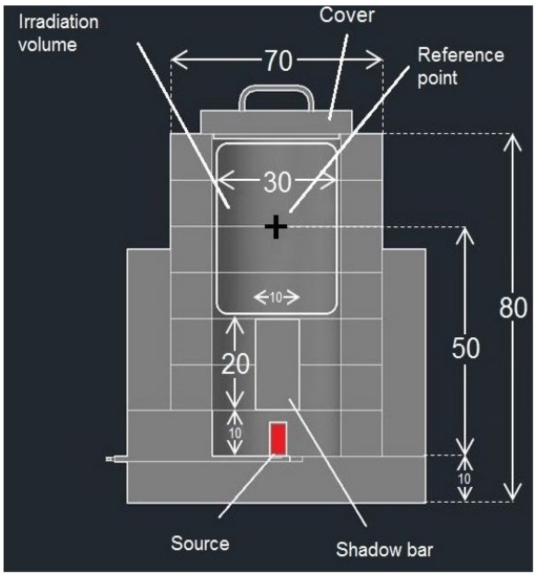

Fig. 2. Drawing of the HOTNES setup with the radioactive source and the shadow bar in the middle.

The energy spectrum of the HOTNES source is peaked at ~100 meV, with ~290 meV FWHM.

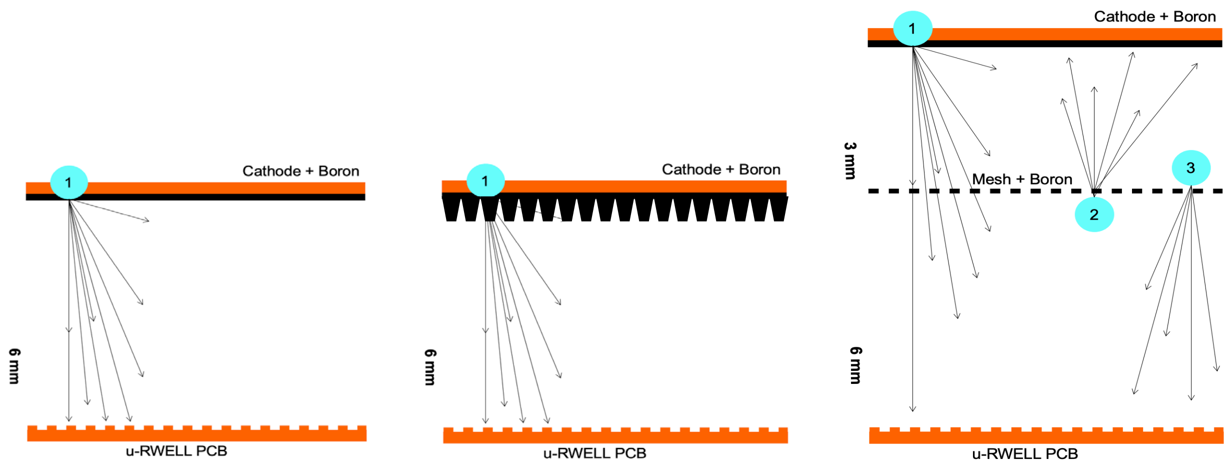

Fig.4. Sketch of the three converter layouts used for the μ-RWELL detector.

In Fig.3 the thermal neutron efficiency (as measured at HOTNES) as a function of the thickness of the ^{10}B layer deposited on the planar cathode structure is compared with the results obtained with the simulation. The detector response simulation is based on GEANT4, SRIM[7] and GARFIELD++[8] software codes used in cascade: the first one considers the physics of thermal neutron interaction with the ^{10}B layer, while the other two SW codes simulate the ionization of the heavy particles in the gas mixture and the drift of the free electrons towards the amplification channel of the detector.

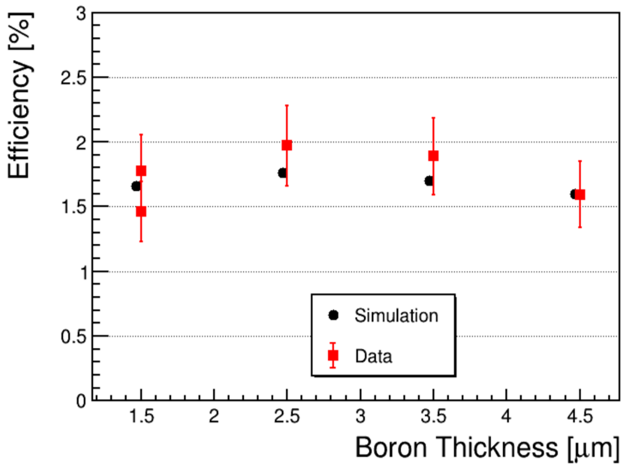

Fig. 3. Neutron detection efficiency of a μ-RWELL detector with planar boron-coated cathode as a function of the ^{10}B thickness. The measurements have been performed at the HOTNES calibrated neutron source facility.

The efficiency measured with the neutrons provided by HOTNES, about 2% for a 2.5 μm thick ^{10}B deposition, corresponds to about 4% for thermal neutrons (E_n ~25 meV).
These results clearly show that to increase the conversion efficiency it is not convenient to have a thicker boron layer, but rather increase as much as possible the converter surface. For this purpose, two different converter layouts have been considered:

- a grooved cathode
- a metallic mesh coupled with a standard planar cathode

All converter components were sputtered with a 2.5 μm thick ^{10}B layer. Fig.4 sketches the three converter layouts studied.
The summary of the results obtained with the three μ-RWELL layouts is reported in Fig.5, where the efficiency has been normalized for thermal neutron. It is worth to remind that, due to the higher neutron cross section, the efficiency for 25 meV neutron is twice the one obtained with the neutrons emitted by the HOTNES source (~100 meV). The study demonstrates that it is possible to achieve efficiency up to 8% with a single detector layer.

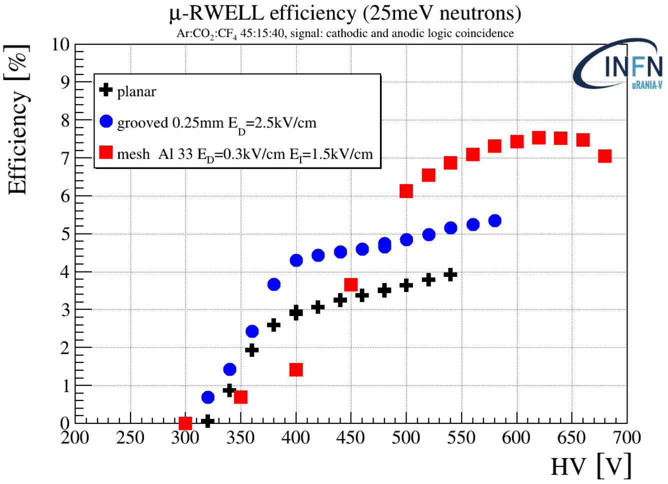

Fig.5. Efficiency obtained with the three different μ-RWELL layouts, tested at the HOTNES neutron source facility. The efficiency has been normalized to 25 meV neutrons.

IV. THE SURFACE RESISTIVE PLATE COUNTER FOR NEUTRON DETECTION

The Surface Resistive Plate Counter (sRPC- [9]) is a novel RPC based on surface resistivity electrodes, a concept completely different from traditional RPCs [10,11,12] that use electrodes characterized by volume resistivity. The electrodes of the sRPC exploit the well-established industrial DLC sputtering technology on thin (50μm) polyimide foils, which have already been introduced in the manufacturing of the μ-RWELL.

The DLC foil is then glued to a 2mm thick float-glass, which is characterized by excellent planarity. The DLC surface resistivity interesting for this detector ranges between 0.1÷1 GΩ/square. The 2 mm gas gap between the electrodes is ensured by E-shaped spacers made of Delrin®, inserted without gluing at the edges of the glass supports. The electrodes sandwich is inserted in a fiber-glass box that acts as gas volume container, Fig. 6. With this layout, operated with the usual RPC gas mixture ($C_2H_2F_4$/Iso-C_4H_{10}/SF_6 = 93.5/5/1.5), an efficiency for m.i.p. of 95-97% and a time resolution of ~1 ns have been measured.

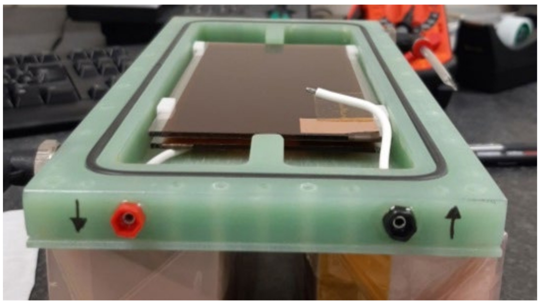

Fig. 6. sRPC prototype: the electrodes, realized with the DLC coated Apical® foil glued on float-glass supports, are coupled by E-spacers made of Delrin® (the internal tooth of the spacer is 2 mm thick). The sRPC prototypes were readout with the same electronics developed for the μ-RWELL.

The sRPC technology, initially developed for HEP applications, can be exploited for thermal neutron detection, by replacing DLC with ^{10}B4C sputtered electrodes. Three different combinations of ^{10}B4C coated electrodes, according to the orientation of the chamber inside HOTNES, have been tested:

- Boron cathode - DLC anode
- DLC cathode - Boron anode
- Boron cathode - Boron anode

As shown in Fig. 7 with these layouts, a thermal neutron detection efficiency of 4%, 2%, and 6% has been respectively achieved.

The construction simplicity and the scalability are the main advantages of the sRPC technology, that should allow an easy implementation of high efficiency multi-stack structure exploitable for large area Radiation Portal Monitors.

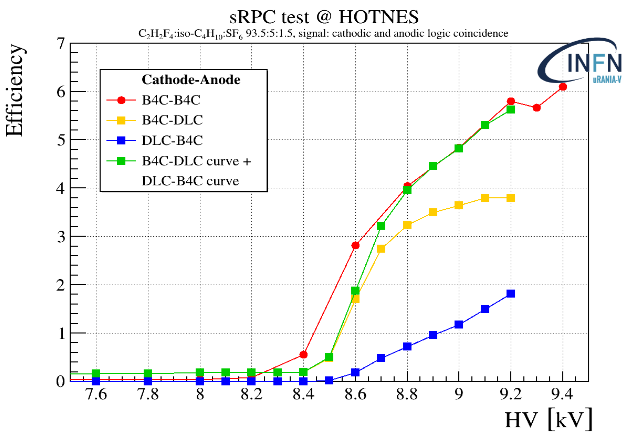

Fig.7. Efficiency obtained with the three different sRPC layouts, tested at the HOTNES neutron source facility. The efficiency has been normalized to 25 meV neutrons.

V. Conclusions

In the framework of the uRANIA project, we developed innovative thermal neutron detectors based on resistive gaseous devices such as μ-RWELL and sRPC. In such devices neutrons are converted on a ~2.5 um thick ^{10}B-coated cathode/electrode, releasing charged particles (α/7Li), which passage can be identified by the gaseous detector.

The μ-RWELL, a mature technology, with suitable converters allows to achieve a neutron detection efficiency per single layer ranging between 4÷8%.

Very promising results with ^{10}B coated sRPC have been achieved (4÷6% /single detection layer), opening the way for a cost effective, scalable thermal neutron detection technology for homeland security applications.

Neutron detection efficiency of 40÷50% seems to be achievable with both technologies by stacking order of 10 detector layers.

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