uRANIA: a µ-RWELL Advanced Neutron Imaging Apparatus

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ABSTRACT

We are developing an innovative neutron imaging detector based on micro-Resistive WELL technology to be an efficient and convenient alternative to the ^{3}He shortage. The µ-RWELL, based on the resistive detector concept, is a highly reliable, cost effective, easily scalable device for charged particles. A thin layer of B_4C on the cathode surface allows the thermal neutrons detection through the release of ^{7}Li and α ions in the active volume. First results from test beam data with different prototypes show good agreement with the simulation and the possibility to use this technology for fundamental physics and social applications. In this paper the main achievements of the project will be reviewed together with an envision of future developments.

Keywords: Neutron Imaging; Micro Pattern Gaseous Detectors; µ-RWELL; Homeland Security.

1. INTRODUCTION

Smart materials play an important role in modern industry and technology. The behavior of such materials is often governed by their structural properties. Knowledge on their specific grain formation and orientation is crucial for their development and use in prospective applications. Neutron diffraction plays a central role in the structural characterization of such materials, in particular when assessing the representative volumes in bulk specimens the superior penetration of neutrons, as compared to other transmitting radiation, is required for many materials [1].

By 2023, the European Spallation Source [2] will provide the world's most powerful pulsed neutron source for world class experiments, playing a fundamental role in the science of everyday life (e.g. the development of better computer chips, cosmetics, detergents, textiles, paints, fuels, drugs, batteries and plastics). Nowadays, the use of 3He as a neutron converter is severely restricted by the shortage of commercial 3He worldwide and a general effort is currently carried out for a replacement.

We are developing an innovative detector, for diffractive neutron imaging and radiation monitoring applications, based on micro-Resistive WELL (µ-RWELL) technology [3]: a compact, spark-protected, single-amplification stage Micro Pattern Gaseous Detector. Key points are the scalability and production of large area detectors, as well as the mechanical flexibility that allows to adapt the design to different geometries and applications: cylindrical µ-RWELL detectors are under study for HEP but could also be exploited for large acceptance neutron diffraction for crystallography studies, constituting a breakthrough for neutron instrumentation.

The µ-RWELL, based on standard photolithography processes, leads also to a straightforward technological transfer to industry. Taking into account the involvement of private industries in the R&D, our technology can positively affect all those fields of applications where large area tracking systems with excellent space and good time resolution, together with rad-hard characteristics, are required, such as HEP, industrial, medical and homeland security applications. In particular, Radiation Portal Monitors (RPM) and Radiation Waste Management (RWM) could take great advantage from the μ-RWELL features; in this regard, a feasibility study, with the involvement of an industrial partner, is in progress.

In this paper, after reviewing the state of the art of the neutron detection, we will discuss the first experimental results of a neutron beam test we performed at the ENEA-HOTNES facility in Frascati [4]. Test beam data have been used to validate the simulation in order to proceed to an optimized design of the detector. Finally, an outlook of the technology potential will be given to outline the vision of the future of the project.

2. STATE OF THE ART

Being the neutrons electrically neutral, their identification must rely on a conversion process. Traditional techniques to identify thermal neutrons are based on ^{3}He conversion. ^{3}He is a rare, inert stable isotope of the helium. It is produced as a tritium decay product and has been stored until 2000. It has a very large cross section with neutrons, owing to the process $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV. This has allowed it to become the best source for neutron identification with gas detectors. However, due the shortage of ^{3}He, for the increasing demand for security applications, nuclear fusion, and cryogenics, the production cost of such devices is becoming unbearable for large area detectors.

The challenge is then to identify cost-effective techniques that will allow an industrial-oriented production of thermal neutron detectors. Typical materials are ^{10}B and ^{6}Li, that have large capture cross sections (~ 1 kbarn). Gadolinium would have a much higher reaction cross section, but it produces photons and electrons that make the detection more complicated.

Thanks to the possibility to deposit a few micrometers of B_4C, boron-based techniques are the cheapest solution to produce large area detectors. The DC magnetron deposition technique at ESS Linköping [5] can produce uniform layers, with low impurities, on areas as large as ~50 X 200 cm^{2}. In the boron-neutron interaction both ^{7}Li nuclei and α particles are produced. These are emitted back-to-back, so only one charged particle is detected per each conversion, thus guaranteeing mutually exclusive events. The projectiles have enough energy to travel a few millimeters and ionize the gas volume, with a signal that can be easily separated from the background (typically photons).

In a gas detector, the thin B_4C layer is deposited onto the cathode and the internal structure provides the multiplication needed to detect the signals. Several realizations of neutron detectors based on similar schemes are available [6] but have still limited possibility of mass production of large area detectors, due to construction techniques that rely on manual operations.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The uRANIA project aims to build scalable, light, cost-effective devices for the identification of thermal neutrons. This will be guaranteed by unique features of μ-RWELL devices.

The μ-RWELL is an innovative Micro Pattern Gaseous Detector that profits from the best features of its predecessors (e.g. from GEMs the amplification stage; from MicroMegas the construction scheme) and combines them into a resistive, spark-protected, reliable scheme.

A μ-RWELL, described in detail at [3], is composed of just two main elements, as shown in Fig. 1: a cathode and the readout PCB. The cathode is usually based on a Cu layer of a glass epoxy plate. Here, few μm of B_4C are deposited to convert the thermal neutrons into detectable charged α particles or ^{6}Li ions that then ionize the gas. The readout-PCB combines the anode and the amplification stage, a WELL patterned Apical foil with a thin copper layer. The pattern is realized by a photolithographic technique on a 50 μm thick polyimide substrate by the TECHTRA agency, Poland. This amplification stage is then embedded into a readout board prepared by ELTOS S.p.A., Italy. The electrical contact is provided through a resistive layer realized by means of the Diamond-Like Carbon (DLC) process. The resistivity can be tuned to maximize the performance in terms of rate capability, spark-protection, and available gain.

Compared to its predecessors and to the state-of-the-art neutron detection techniques, the construction process is relatively easy, since it does not foresee any gluing, stretching or doping. This allows μ-RWELL to be intrinsically fully scalable: prototypes for high energy physics experiments have been realized up to one meter length. Since the B_4C deposition technique at the ESS Linköping workshop can now cover up to 1 m^{2}, μ-RWELL based detectors can efficiently cover larger areas. Moreover, it has already been proven that it is possible to mold the PCB and the cathode also in different shapes, to increase the detector acceptance by matching the angular distribution of the neutron from the source. This can be useful for RPM and RWM applications.

Finally, the construction techniques allow to use more effective converting structures or to place additional converting layers between the cathode and the multiplication stage, like mesh or blades, to increase the boron-coated material and thus the efficiency of the single detector.

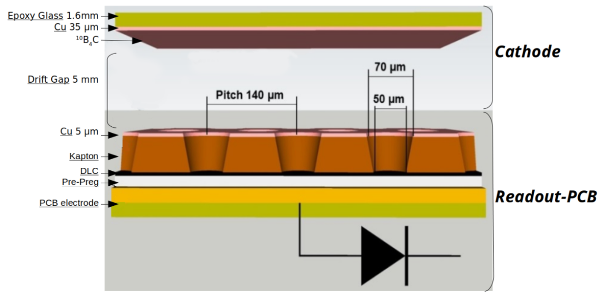

Fig. 1. A typical μ-RWELL design.

There is also an additional advantage: the construction process of the components of a μ-RWELL is already performed by industrial partners (ELTOS, TECHTRA) and within the scope of the project there is also the full technological transfer for industrial-level production of these devices to further reduce the production cost for society-oriented application.

4. PROJECT RESULTS

The aim of the project is to build and validate prototypes for thermal neutron detection based on μ-RWELL technology, to show that such instruments are able to match the present state-of-the-art, but with a reduction of cost and intrinsic scalability.

Thanks to the collaboration with industrial partners inside the consortium, within the uRANIA project we have been able to build more than 20 different prototypes. The assembly has been performed in INFN Frascati National Laboratory, after receiving all the materials from the partners. After their assembly, each prototype is calibrated by means of an X-ray gun. This process is crucial for the calibration curve of the detector response as a function of the amplification voltage. This calibration is also used to determine the efficiency when the μ-RWELL detection efficiency is studied just by measuring the current drained by the electrodes (current-mode readout).

A crucial part of the success of the project relies on the validation of the simulations, which are a fast tool to understand the behavior of the detectors in conditions that will be tested in the future. A set of simulations was performed in GEANT4. In the simulations, the expected conversion efficiency, with different boron coating thicknesses, has been evaluated. The simulation also estimates the reduction of the impinging neutron flux caused by the other materials that constitute the μ-RWELL, like the FR-4 glass epoxy. For a boron thickness ranging from 2 to 3 μm, the best trade-off between neutron conversion and charged particle absorption is found. An efficiency around 4% is expected for neutrons at 25 meV (1.8 Å). Simulations show also that efficiency decreases at higher energy.

To validate the simulations and the prototypes, a test beam was performed at ENEA-HOTNES, that was chosen among the different test areas for the availability of a calibrated source of neutrons, with an expected nominal flux of 758 ± 16 Hz/cm2, with very low gamma background. Since the neutron energy spectrum peaks at 100 meV, data have been simulated accordingly, showing an expected efficiency in the range 1.5-2%.

We have prepared 4 prototypes with boron thickness ranging from 1.5 to 4.5 μm. All the prototypes were read in current-mode so that efficiency is the only parameter to be extracted and possibly in-homogeneities in the detector response are not taken into account. In current mode, the efficiency can be extracted by the following formula:

$$\varepsilon = \frac{i}{e \cdot \Phi \cdot G \cdot < N > \cdot \Sigma}$$

where i is the current measured at the electrode, e is the electron charge, Φ is the effective rate impinging on the boron coating, G is the gain of the amplification stage, $<N>$ is the mean number of ionizations extracted from GARFIELD++ simulations, and Σ is the chamber surface ($10{\times}10 cm^2$).

The first study was used to validate the simulation of the effect of the cathode materials (mainly FR-4 glass epoxy), a crucial parameter to extract the proper flux. Cathodes with no coating have been sacked in front of a test prototype, a reduction of the observed current of (17.7 ± 0.7)% for each cathode has been observed, in nice agreement with the simulation that predicted a reduction around 19%. The effective flux is then (624 ± 28) Hz/cm^2.

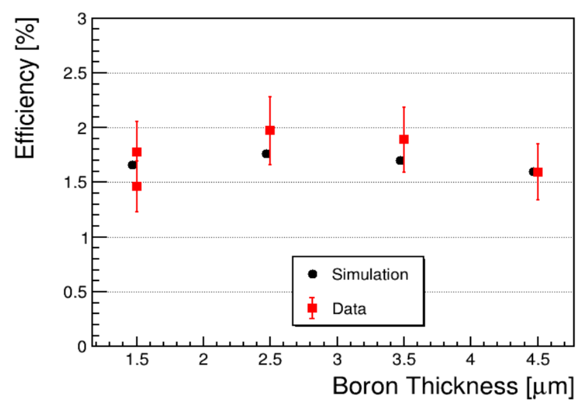

Fig. 2. Efficiency of thermal neutron detection as a function of the boron thickness. Red squares with error bars represent the experimental measurements, while the black dots are the simulated results. The energy spectrum of the neutrons detected is quite spread (peak 100 meV, FWHM = 208 meV).

It is then possible to extract the efficiency: the results for the different coating thicknesses are shown in Fig. 2. The efficiency is found to be between 1.5 and 2%, with a slight maximum at boron thickness 2.5 μm, as expected by the simulations. The experimental measurements and the simulations are in remarkable agreement. On the one hand, these results verify the working principle of boron-coated μ-RWELL for the detection of the thermal neutron in a wide energy distribution as provided by the HOTNES source; on the other hand, they validate the simulations code and procedure. It is therefore possible to fully extend our measurements to different geometries (e.g. grooved cathode [6]), that will maximize the efficiency of neutron detection above 10% for 1.8 Å neutron energy.

5. FUTURE PROJECT VISION

The experimental results reported in the previous section show the proof of concept of the detection technology. Moreover, the validation of the Monte Carlo simulation allows to make an additional step by the end of the ATTRACT project: a cathode, designed and optimized by means of simulations is expected to reach about 10% thermal neutron detection efficiency. A prototype has been produced and will be tested soon with neutrons, therefore completing the technology validation and the achievement of TRL4.

Given the versatility of the technology, if selected, the second phase will be focused on two final applications. 1. The design of detection systems for neutron imaging requires fine optimization depending on the neutron beam and instrument characteristics, for this application a general, high granularity detector will be developed. 2. In addition, a system based on μ-RWELL technology can be very competitive for detecting radioactive material in Radiation Portal Monitors (RPM) or for Radiation Waste Management (RWM). In this regard, one of the main goals of phase 2 will be to build a complete demonstration to bring the TRL to a level between 6 and 7 for this specific application, building and testing a prototype in an industrial facility. Between phase 1 and phase 2 proposal, an investigation will be done to understand the feasibility of a demonstration of the technology in an operational environment within the project.

5.1 Technology Scaling and Project Synergies

To scale the TRL to a demonstration level particular effort will be committed to the tasks described in the following.

optimization of the detector design: the implementation of an RPM requires large coverage area, detailed background studies and redundancy. INFN and Lund University groups developed the experience in simulation and optimization; a direct involvement of the European Spallation Source in the boron coating task would be a great benefit for the project, this will be discussed. A mechanical engineer and a physicist (PostDoc) for two years will be needed to complete the tasks.

reduction of the production cost of the detector. This will be accomplished by the industrial partners in collaboration with INFN and with the design activities described previously.

the development of custom electronics will be also needed to reduce the costs for RPM and RWM applications. Low-noise, operational amplification and discrimination boards will be developed to readout the detectors in counting mode, i.e. with no information of the particle position. Preliminary lab tests show the feasibility task that will be performed by INFN (two years of an engineer and two years of a physicist will be needed). For the engineering of the electronics an additional industrial partner is needed to reinforce our group. Discussion is ongoing with a possible candidate that has also experience in the development of RPM and could help in the final design and optimization.

Additional synergies will be explored with other ATTRACT phase 1 funded projects with similar goals (e.g. other projects for neutron imaging, radiation monitoring or based on similar MPGD technologies).

5.2 Technology application and demonstration cases

This section highlights the concrete benefits of the applications, that will be developed in an eventual phase 2, to the areas of Scientific Research, Industry and Societal Challenges.

The first application will be a high granularity detection module for neutron imaging with excellent spatial resolution that can be the building block of neutron diffraction instruments that can be used to investigate the bulk structure of the material playing a fundamental role in the science of everyday life: the development of better computer chips, cosmetics, detergents, textiles, paints, fuels, drugs, batteries and plastics are only few of the possible studies that will benefit from our development. ESS, currently under construction, will be the largest European Research Infrastructure for neutron science; most of its beamlines are designed to boost science for society. Our project will have an impact on the design of future instruments. ESS already participated in phase 1 of the project with the Linköping boron coating facility, through Lund University; for phase 2 a direct involvement will be investigated.

The second application will be a module demonstrator for radioactive material detection. The cost-effective application in an RPM is a key element for Homeland Security; it can be used in airports and seaports both for people and goods. The unique geometrical flexibility makes the technology suitable for the RWM where cylindrical shape of the detector is preferable for radioactive barrel monitoring with a direct impact on industry and society.

5.3 Technology commercialization

The commercialization of the final products must be addressed in advance and will move together with the technological development. We are in contact with a new industrial partner that has a worldwide, long lasting experience in development and commercialization of radiation monitoring devices. The discussion will be finalized before submitting the proposal for ATTRACT phase 2.

5.4 Envisioned risks

The main risk for a potential phase 2 is the ability to control the cost production, specifically for the large area applications like RPMs.

DLC, with proper characteristics, is currently provided only by the Be-Sputter Co., Ltd. (Japan) but R&D projects and contacts with other companies are ongoing to explore other options. In this regard, CERN could play an important role in the future and could be involved in the project.

The boron sputtering is currently performed by the ESS Linköping workshop. The layer thickness homogeneity largely depends on the prototype size: the larger is the area, the lower is the quality. Optimization of the production process together with the detector design will be needed; the direct involvement of ESS in a potential phase 2 would help addressing this point.

Commercial electronics is reliable, ready to use but expensive. A study about the possibility to develop custom electronics to amplify and discriminate the signal for large area, low spatial resolution applications has been started by the INFN group. In a potential phase 2, two FTE for two years would be dedicated to this task.

5.5 Outreach

The dissemination program of the project has been reduced by the Covid-19 global emergency which forced to cancel most of the public events in 2020. Despite that, our results have been presented at the INSTR'20 conference [7], the proceeding has been submitted for publication, and an ArXiv paper is available at [8]. We have been active on the web and social media to broaden the reach of our research outside the Academia [9]. We understand that, in order to be able to compete with Future and Emerging Technologies, the interest in our project has to grow with it: web sites, social and press communications must be handled and coordinated in a professional way; a fraction of the budget will be allocated for that.

5.6 Liaison with Student Teams and Socio-Economic Study

In January 2020, the activity of the uRANIA project was presented to BSc and MSc students in Physics of the University of Ferrara offering internship possibilities. In addition, a Hackathon had to be run this year but, due to the Covid-19 emergency, could not be arranged. In a potential phase 2 the dissemination and outreach group will also help engaging students inside the Academia organizing dedicated seminars and events. Special attention will be paid to categories usually underrepresented for gender or social condition.

We would contribute to the socio-economic study of the ATTRACT initiative and ecosystem with dedicated interviews and other acts throughout the duration of the project, in coordination with the ATTRACT experts.

6. ACKNOWLEDGEMENT

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