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Development of a compact neutron collimator for imaging techniques within the ANET project

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Summary. — Neutron imaging techniques are of great interest to the scientific community, somehow complementary to radiography. Neutron imaging is usually performed on a reactor site involving large infrastructures. This article describes the development within the ANET project of a compact neutron collimator able to reach the same performances of a standard device, but on a factor ten reduced length, opening the possibility to perform neutron imaging on accelerator-based facilities. The results obtained at the INES facility in Rutherford Appleton Laboratory, that demonstrate the collimator working principle with both thermal and epithermal neutrons, will be shown.

1. – Introduction

Neutron imaging is a non-destructive method, which allows revealing the inner structure of the investigated objects. The high-penetration depth of the neutrons in heavy elements combined with the high sensitivity to light-elements like hydrogen, lithium and boron determines the complementarity of the method to the widespread X-rays. Moreover, neutron imaging allows to distinguish isotopes of the same element. This possibility is precluded using x-rays since the cross sections for the processes in which photons are involved do not depend on mass number A, but only on atomic number Z. In a typical neutron imaging setup, an object is exposed to a neutron beam, and a detector, placed downstream of the sample, reveals some higher-intensity regions and others with lower intensity, depending on the absorption of neutrons inside the sample. The image quality depends on the beam collimation. A beam with a wide angular dispersion makes analysis more difficult or even impossible. Generally, neutron sources are characterized by a wide angular divergence. Therefore a collimation system upstream the sample is required. For neutrons, most of the collimators work as a directional selector. They are, in fact, selectors that allow only neutrons with a specific direction to pass through; all the others are absorbed. The ratio between the collimator length L and its aperture D represents a very important parameter for neutron imaging technique. It quantifies some

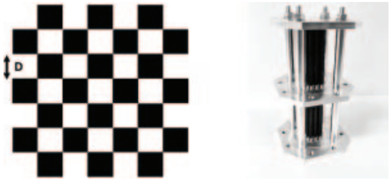

Fig. 1. – Left: cross section of the ANET collimator geometry. In white the “air” channels, in black the absorbent material channels. Right: a picture of the ANET collimator prototype assembled at the Frascati National Laboratories (LNF).

fundamental features,

(1) $r \propto (L/D)^{-1}$, (spatial resolution)

(2) $p \propto (L/D)^{-1}$, (penumbra phenomenon)

(3) $\phi_f/\phi_i \propto (L/D)^{-2}$. (beam attenuation)

To perform high-quality neutron imaging, a value of L/D greater than 100 is generally required. In common neutron imaging facilities [1] typical D are of the order of 10–20 cm and this fixes also the collimator field of view. This implies long collimator lines in which vacuum should be established to minimize multiple scattering. Given a certain L (forced by the facility dimensions), the aperture D of the collimator is determined to optimize spatial resolution and penumbra. As can be seen by (3), strong beam attenuation is expected and this obliges to have sources with very high input fluence (ϕ_i), traditionally based on nuclear reactors. A compact neutron collimator with high L/D would open up the possibility to perform neutron imaging on a wider range of neutron sources (*e.g.*, accelerator-based sources) or even portable sources.

2. – The ANET project

There are currently few centres in the world to perform neutron imaging because of the difficult-to-meet measurements condition. The aim of the ANET (Advanced NEutron Techniques) project is to break this paradigm and introduce a new concept of a neutron collimator, able to perform as well as the existing systems, but on a compact scale, with a typical length of 1 m or less. The idea [2] is to build a parallalepiped multi-channel geometry with an alternate structure of empty (air) and highly absorbing channels. In this new concept, the collimator field of view and the size D of the single channel are de-coupled. A cross section of the ANET collimator is shown in fig. 1. The ANET collimator will be characterized by $L = 40\,\text{cm}$, $D = 2.5$ mm resulting in $L/D = 160$ and a field of view of 5×5 cm^2. A first prototype (see fig. 1) with $L = 10\,\text{cm}$, $D = 2.5$ mm resulting in $L/D = 40$ and a field of view of 1.7×1.7 cm^2 was built and tested in 2019 at the INES facility as described in the following paragraph. This paper deals with the measurements performed using the ANET prototype.

3. – Experimental setup

In November 2019 an extensive measuring campaign has been carried out at the INES facility at the Rutherford Appleton Laboratory. The INES facility is located downstream to the ISIS neutron source and provides a pulsed neutron beam whose spectrum covers both thermal and epithermal energy range. In the thermal range it is peaked at about 30 meV, while in the epithermal range (500 meV $< E <$ 100 eV) it decreases as $E^{-0.9}$. The angular dispersion of the beam at the INES location is around 1/80 rad. All the data collected and analyzed have been extracted from the GEM detector recently installed at the INES facility. This detector is sensitive to thermal and, to a certain extent, to

Fig. 2. – The experimental setup used at the INES facility. The neutron beam, generated by the source, enters the room when the shutter is open (left), the ANET prototype is placed on a reference plane (centre), a GEM detector is placed downstream the plane. The data recorded were then stored (right).

epithermal neutrons thanks to a boron carbide-coated silicon sheet glued onto the cathode where the (n, α) conversion happens. Anode segmentation allows the GEM achieving a spatial resolution of 0.8 mm and a sensitive surface of about 102×102 mm^2 for a total of 128×128 pixels. The output of the GEM allows to determine the time of flight of the neutrons with a resolution of 10 μs. The distance between the collimator and the GEM could be varied: for this analysis a distance of 14.5 cm was chosen (close to the collimator length). The entire setup was also simulated using MCNP6 code [3]. In fig. 2 the experimental setup is shown.

4. – Measurement results

Data have been collected in order to provide a total charge on the ISIS target of 250 mC (around 1 h 30 min beam time). All the data have been analyzed using the Mantid Software [4]. Figure 2 shows the heat map collected by the GEM. The data have been appropriately normalized [5]. The "neutron" structure of the collimator can be seen very clearly. The high count regions (Hot) correspond to the air channels; while the low-count regions (Cold) correspond to the regions of absorber material. The nominal mechanical channel width is $d_m = (2.50 \pm 0.08)$ mm. In order to reconstruct the measured width, the horizontal and vertical GEM profiles were studied. The results are the convolution between the collimator geometry with the GEM granularity. Moreover, thanks to the time of flight selection, the analysis could be repeated in different energy range.

Figure 3 shows the field profiles (Counts-Pixel) for the central pixel row in the two different energy ranges. Hot-Cold regions alternation can be also seen (peaks-valleys). The ideal square wave shape is modified by the GEM spatial resolution that causes a Gaussian smearing over all the points. The evaluated mean widths of the air channels were $d_{th} = (2.34 \pm 0.04)$ mm for the thermal range and $d_{epi} = (2.34 \pm 0.10)$ mm for the epithermal range. The values are in a good agreement with the nominal mechanical value. The obtained results give an indication that the ANET collimator can work in both energy ranges.

In order to evaluate the prototype "selection performance", the count ratio R between the hot and the cold regions has been evaluated both in data and in MC simulation. To take into account the GEM pixel granularity, clusters of 4×4 pixels have been considered. The analysis consisted of the following steps: 1) a sub-selection of a fiducial region inside the clusters, based on a statistical cut, was performed; 2) the mean of the counts inside the fiducial region was evaluated; 3) the ratio between the mean values of the Hot regions

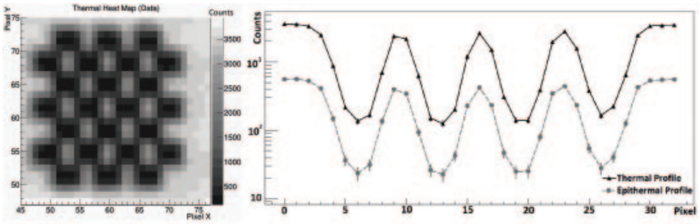

Fig. 3. – Left: the ANET collimator structure is visible on the neutron heat map extracted by the GEM. Right: GEM field profiles (expressed as counts *vs.* pixel position) for thermal and epithermal energy range. Black triangle: thermal, grey circle: epithermal.

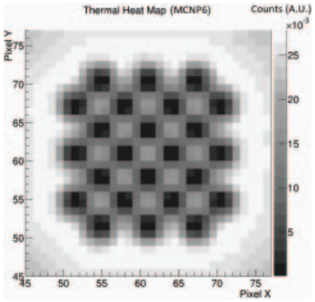

Fig. 4. – Simulated heat map using MCNP6 code.

and the Cold regions was obtained. An exhaustive treatment of the analysis method can be found in [5]. The experimental value of the ratio is $R_{sim} = 15.9 \pm 0.8$. The same procedure has been also repeated using MCNP6 simulation (fig. 4). The simulation includes the GEM pixel geometry, the energy and angular distributions of the beam. The ratio value is $R_{sim} = 18.1 \pm 1.1$. The measured value R_{meas} and the simulated one R_{sim} are compatible within the errors. The compatibility proves that the selection performance of the ANET prototype is well understood.

5. – Conclusions

The collimator prototype developed within the ANET project was studied via MC simulations and via the analysis of the data collected by the GEM installed at the INES facility (R.A.L.). The analysis allowed to reconstruct the width of the air channels measured by the GEM (d_{th},d_{epi}) and compared it with the nominal mechanic value (d_m): $d_m = (2.50 \pm 0.08)$ mm, $d_{th} = (2.34 \pm 0.04)$ mm, $d_{epi} = (2.34 \pm 0.10)$ mm. The values are in a good agreement with the nominal mechanical value.

In order to estimate the selection performance of the prototype, the ratio between counting with in the air channel with respect to absorber channels was used. The ratio was evaluated both in the simulation (R_{sim}) and in the data analysis (R_{meas}): $R_{sim} = (18.1 \pm 1.1)$, $R_{meas} = (15.9 \pm 0.7)$. The expected performance of the ANET prototype evaluated through MCNP6 simulations is in agreement with the measured results and proves that the selection performance is well understood. These results were a major milestone in the ANET project and open up the next phase of the project, dedicated to the costrunction of the full-size collimator.

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