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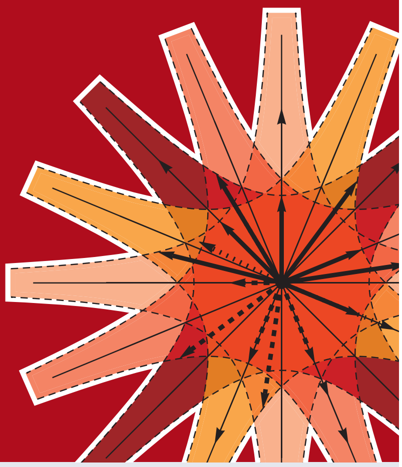

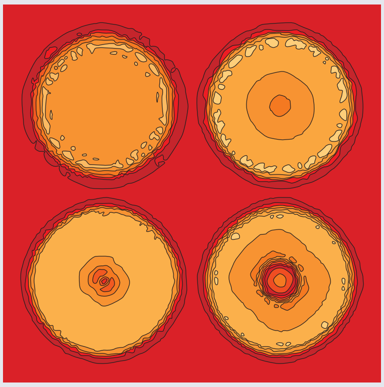

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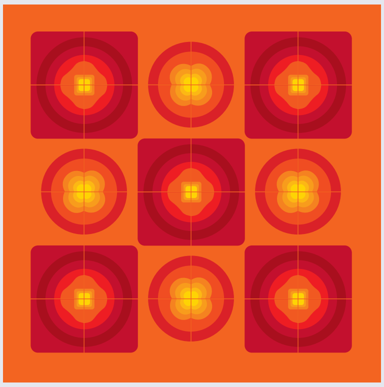

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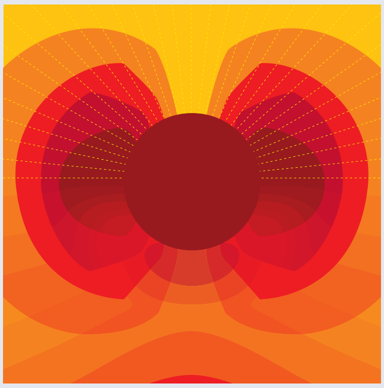

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Image: Ornamental multiplication of space-time figures of temperature transformation rules (adapted from T. S. Bíró and P. Ván 2010 *EPL* **89** 30001; artistic impression by Frédérique Swist).

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Diffraction measurements with a boron-based GEM neutron detector

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Abstract – The research of reliable substitutes of ^{3}He detectors is an important task for the affordability of new neutron scattering instrumentation for future spallation sources like the European Spallation Source. GEM (Gas Electron Multiplier)-based detectors represent a valid alternative since they can combine high-rate capability, coverage of up to 1 m^2 area and good intrinsic spatial resolution (for this detector class it can be better than 0.5 mm). The first neutron diffraction measurements performed using a borated GEM detector are reported. The detector has an active area of 10×5 cm^2 and is equipped with a borated cathode. The GEM detector was read out using the standard ISIS Data Acquisition System. The comparison with measurements performed with standard ^{3}He detectors shows that the broadening of the peaks measured on the diffractogram obtained with the GEM is 20–30% wider than the one obtained by ^{3}He tubes but the active area of the GEM is twice that of ^{3}He tubes. The GEM resolution is improved if half of its active area is considered. The signal-to-background ratio of the GEM is about 1.5 to 2 times lower than that of ^{3}He. This measurement proves that GEM detectors can be used for neutron diffraction measurements and paves the way for their use at future neutron spallation sources.

Introduction. – Due to the present ^{3}He worldwide shortage [1], an intense R&D phase [2] has been started in order to realize ^{3}He-free detectors that can represent valid candidates for detection systems for future spallation neutron sources such as the *European Spallation Source* (ESS [3]). In the case of ESS, besides the need for replacing ^{3}He, it is essential to develop high-rate neutron detectors that can fully exploit the increase of neutron flux of ESS relative to present neutron sources. Among the possible candidates, *Gas Electron Multiplier* (GEM [4]) based detectors offer good spatial resolution (from 80 μm up to few mm) and timing properties (few ns), excellent rate capability (MHz/mm^2), radiation hardness and the possibility to cover large areas [5,6]. GEM detectors properly modified to detect neutral particles [7–13] have been already used for neutron beam measurements. This paper describes the first neutron diffraction measurement recorded by the GEM-based detector described in ref. [12] and compares its performances with the standard ^{3}He-based detection system. This measurement took place on the INES instrument at the ISIS neutron spallation source.

Experimental set-up. –

The GEM detector. Figure 1(a) shows the detector installed inside the INES blockhouse.

The detector used in this measurement is a triple GEM equipped with an aluminium cathode coated by 1 μm of natural boron carbide (B_4C). The detector gaps (Drift, Transfer 1, Transfer 2 and Induction) —*i.e.* the spaces between the three GEM foils, the cathode and the

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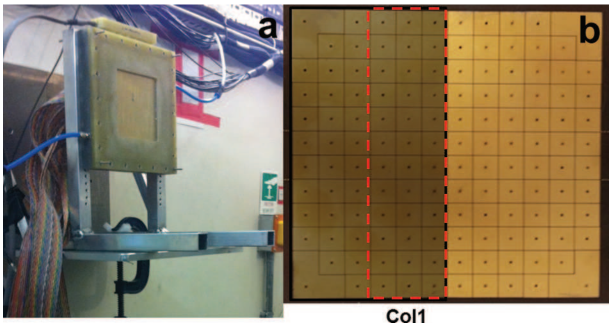

Fig. 1: (Colour on-line) (a) The GEM detector installed in the INES blockhouse; (b) picture of the padded read-out anode; the active area used in the measurement (shaded) as well as only three columns of pads (Col1 —dashed rectangle) are shown (see text for details).

anode— were, respectively, 13 mm, 2 mm, 3 mm and 1 mm wide. The following electrical configuration was applied to the GEM: E_{d} (drift field) $= 0.69\,\mathrm{kV/cm}$, ET_1 (Transfer 1 field) $= 1.5\,\mathrm{kV/cm}$, ET_2 (Transfer 2 field) $= 2\,\mathrm{kV/cm}$, E_{Ind} (induction field) $= 5\,\mathrm{kV/cm}$ and V_{GEM} (sum of the voltages on the three GEMs) $= 870\,\mathrm{V}$. This configuration corresponds to an effective gas gain of 100. This device is equipped with a padded anode (whose substrate is made of fiberglass which is few mm thick) composed by 132 $8 \times 8\,\mathrm{mm}^2$ pads (made of gold-plated few microns thick copper) plus 4 L-shaped angular pads with an area of $192\,\mathrm{mm}^2$. The signal of each L-shaped pad is shortened with the signal coming from 2 adjacent pads in such a way that the resulting total number of channels is 128. Only half of the anode (64 channels corresponding to 68 pads —shaded area in fig. 1(b)) was read out and measurements were performed either considering the 64 channels all together or only 36 pads (dashed rectangle in fig. 1(b) - Col1). The GEM was positioned at 90° with respect to the beam and it was flushed with an Ar/CO_2 70%/30% gas mixture.

The electronic set-up. The front-end chips used to read out the pads are of the CARIOCA [14] type. The CARIOCAs were positioned on the back of the anode and are digital, self-triggered chips. The LVDS signals generated by four CARIOCAs were routed to a user-designed FPGA board that formed the interface between the front-end electronics and the standard ISIS Data Acquisition Electronics (DAE), known as DAE2. Data from the CARIOCAs were first buffered inside the FPGA, using an individual buffer per GEM pad, so that the interface electronics did not introduce any additional dead time. When the FPGA found data in one of the buffers, the position of the corresponding GEM pad that generated the signal was sent to the DAE for histogramming. The DAE performed the time stamping of these events and incremented the corresponding bin in the ToF histogram associated with this GEM pad, thereby creating the diffractograms that were recorded.

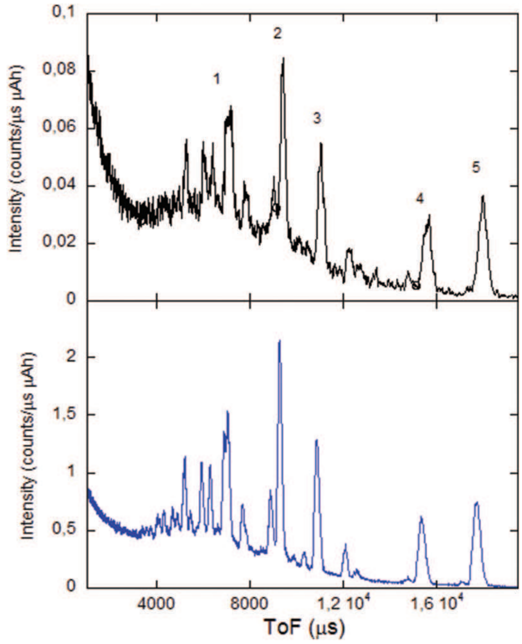

Fig. 2: (Colour on-line) Top: ToF diffractogram recorded by the GEM from a bronze sample; the total measurement time is 18 h; representative peaks are labelled for reference to table 1. Bottom: the same measurement but taken by two ^{3}He detectors from the INES beamline. Broadening of peak 1 is not due to detectors feature but it is intrinsic to the sample.

The INES beamline. INES [15] is a neutron *Time-of-Flight* (ToF) diffractometer at the ISIS neutron source. The pulsed nature of the ISIS source makes it ideal to exploit the possibility offered by the ToF technique. INES exploits thermal neutrons with wavelength between 0.17 Å and 3.24 Å with a $\Delta d/d$ up to 0.002. INES is equipped with 144 high-pressure (20 bar), squashed ^{3}He tubes (frontal width of 12.5 mm) as neutron detectors, each spanning an angle of about 1° in the horizontal plane. Such detectors are credited with an efficiency of about 60% to 70% for neutrons in the thermal energy range. Two of such ^{3}He detectors (positioned at 90° with respect to the neutron beam, symmetrically to the GEM) were taken as a reference for the present tests. As a scattering sample we used a 5 mm deep, $20\,\mathrm{mm} \times 50\,\mathrm{mm}$ surface bronze slab.

Results and discussion. – In fig. 2, top panel, a diffractogram obtained by the GEM detector is shown. The lower panel shows the result of the same measurement recorded with two standard INES ^{3}He detectors (the signals coming from the two detectors are summed). A number of Bragg peaks from the bronze (copper) phase are visible. In table 1 a comparison of the performances of the two detector systems relatively to the current measurement is presented. All features of the data are correctly reproduced by the GEM detector.

For sake of simplicity, we summarize the following three facts:

a) The total count rate of the 68 GEM pads used in the measurement is about 7% the count rate of the two ^{3}He

Table 1: Comparison between GEM and ^{3}He tubes in terms of FWHM and S/B for the peaks labelled in fig. 2 (top panel). The errors associated to the fitting procedure are reported.

Peak number	1	2	3
ToF - GEM (μs)	7076 ± 6	9404 ± 3	11039 ± 4
FWHM - GEM (μs)	459 ± 114	240 ± 12	322 ± 18
S/B - GEM	1.1 ± 0.1	1.6 ± 0.2	2.3 ± 0.4
ToF - ^{3}He (μs)	6690 ± 20	9277 ± 1	10877 ± 1
FWHM - ^{3}He (μs)	325 ± 20	195 ± 4	231 ± 5
S/B - ^{3}He	1.2 ± 0.1	2.3 ± 0.1	2.8 ± 0.1
Peak number	4	5	
ToF - GEM (μs)	15603 ± 7	17994 ± 5	
FWHM - GEM (μs)	446 ± 48	435 ± 16	
S/B - GEM	4.9 ± 1.5	9 ± 3	
ToF - ^{3}He (μs)	15381 ± 2	17746 ± 3	
FWHM - ^{3}He (μs)	336 ± 6	378 ± 8	
S/B - ^{3}He	5.3 ± 0.4	12 ± 1	

detectors (9% in the case of the vanadium run), but with a different Signal-to-Background (S/B) ratio. These values are compatible with what was estimated from a simple calculation.

b) The FWHM of the diffraction peaks recorded with GEM is larger than that of the two ^{3}He detectors. Here we neglect the intrinsic broadening of the peaks since we are only interested in the effect of the detectors: in the present set-up, in order to optimise the count rate, all the 68 pads connected to the ISIS DAE were summed. This means that the full sensible area used in the measurement shown in fig. 2 spanned about 2.6° (compared to about 1° for the two adjacent ^{3}He tubes), thus causing a loss of angular resolution compared to the two INES detectors.

Conclusions and hints for future developments. – The results obtained in this paper show the possibility for GEM detectors equipped with borated cathodes to obtain good neutron diffraction data with the ToF technique. The detector proved to be fully compatible with the standard ToF DAE in use at ISIS. These results have a comparable quality with standard ^{3}He detectors, but GEMs need further optimisation to be really competitive with other detection systmes in such an application. The present authors envisage three areas of optimisation:

a) *Efficiency.* The overall efficiency to thermal neutrons of the present GEM is of the order of 1% for thermal neutrons, *i.e.* 60 to 70 times lower than common high-pressure ^{3}He tubes in the same energy range. The proposed way to improve the efficiency are the *3-D cathodes*, *i.e.* borated cathodes characterised by a three-dimensional configuration made to optimise the mean free path of both neutrons and reaction products into the converter material. Examples of 3-D cathodes are, for instance, presented in refs. [16,17]. Integration of 3-D cathodes with the present GEM set-up will be the subject of a future publication.

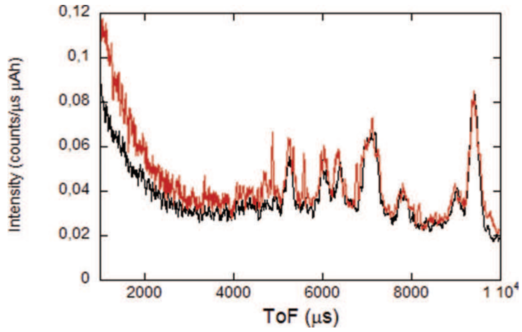

Fig. 3: (Colour on-line) zoom (in the region up to 10000 μs) of ToF diffractograms taken by the GEM detector from the mentioned sample with (black line) and without (red line) a boron-enriched plastic mask positioned on the detector structure. A sensible reduction of the background is especially visible in the shorter-times region.

b) *S/B ratio.* In the present experiment, the S/B ratio for the GEM was lower than for the ^{3}He tubes by approximately a factor 2. A likely source of background is the (H-atoms–rich) plastic structure of the GEM itself. A quick measurement performed with the same detector covered with a rough mask cut in boron-enriched plastic showed a sensible reduction of the background, especially at lower ToF, following a typical trend of neutron-induced background (fig. 3). We expect that proper design of boron carbide or cadmium masks will greatly improve the S/B ratio.

c) *Resolution.* As mentioned in the previous section, in order to optimise the count rate in fig. 2 all the 68 pads connected to the ISIS DAE were summed together, with consequent loss of angular resolution compared to the INES detectors. This effect can be reduced envisaging the possibility of summing single columns of pads, thus lowering the angular extension of the sensible area associated to a ToF channel. Padding makes the GEMs to be intrinsically position-sensitive detectors: this allows a better *focusing* of ToF data for larger-area detectors. As an example, when summing the signals from 36 pads only, arranged in three columns (thus reducing the angular span of the sensitive area —see fig. 1 - Col1), the FWHM of peak No. 4 and 5 is reduced by about 10%. For other, less intense peaks, due to the relatively low count rate, the resolution of single peaks is limited by the effect of counting statistics, as it occurs while summing a single column of pads with the present setup. A study in depth of the dependence of resolution on the shape and span of the detector requires further tests with a suitable collimation (for instance obtained with gadolinium-coated slits), and will be the subject of future work. An increased detector efficiency will also give the possibility of summing single-pad columns, thus improving the spatial resolution.

This test proves that GEM detectors can be used for neutron diffraction measurement and paves the way for their use at future neutron spallation sources.

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