Development of a large-area curved Trench-MWPC ^{3}He detector for the D16 neutron diffractometer at the ILL

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Abstract. The D16 instrument is a versatile cold-neutron diffractometer at the ILL. It has benefited from a number of upgrades over the years, such as the installation of a large-area ^{3}He Multi-Wire Proportional Chamber (MWPC) in 2011. This detector has provided a resolution of 1 mm x 1 mm over an area of 32 cm x 32 cm. After 12 years of operation, it was replaced by a new curved detector which covers a wider solid angle while maintaining a high angular resolution. Its 86° horizontal angular coverage makes it possible to perform time-resolved experiments with a large q-range. This new detector is based on the Trench-MWPC detector technology developed at the ILL. In the D16 Trench-MWPC, 6 modules are mounted side by side in an ^{3}He-filled curved vessel. Each module consists of 192 cathode blades positioned every 2 mm, and 192 anode wires spaced by 1.5 mm. The radius of curvature of the cathode blades is 1150 mm, providing a parallax-free resolution of 0.075°, horizontally along the 86° angular coverage of the 38 cm high detector. The various steps of the fabrication and mechanical inspection of the D16 Trench-MWPC detector modules and pressure vessel are presented, as well as experimental results obtained during the characterisation of the detector with neutrons.

1 Introduction

The D16 instrument is a versatile cold-neutron diffractometer which has evolved from the first biological membrane diffractometers from the early seventies, and has benefited from a number of upgrades over the years, such as the installation of MILAND (MIllimeter resolution Large Area Neutron Detector [1]), a large-area ^{3}He Multi-Wire Proportional Chamber (MWPC) in 2011. This detector provided a resolution of 1 x 1 mm^2 over an area of 32 x 32 cm^2. After 12 years of operation, the decision was made to replace it by a curved detector covering a wider solid angle while maintaining a high angular resolution.

Several neutron research facilities host one or more neutron diffraction instruments with a large high-resolution 2-dimensional curved ^{3}He-filled detector. These gaseous detectors are based on the well-known MWPC design [2]. A detector with 120° angular coverage was developed in 2002 at BNL by Fried et al. [3] and two examplars of this detector design were fabricated. The first BNL-120 detector was installed at the protein crystallography beam-line at the LANSCE spallation source of the Los Alamos National Laboratory [4] and was moved in 2018 to the Wide Angle Neutron Diffractometer (WAND^2) at the High Flux Isotope Reactor, Oak Ridge National Laboratory [5]. Another BNL-120 is operating in the Wombat High-Intensity Powder Diffractometer at ANSTO's Opal Reactor [6]. A large curved detector with 110° angular coverage was also fabricated by Moon et al. for single-crystal neutron diffraction studies at the research reactor HANARO [7]. During a collaboration between FRM II and PSI detector groups, the BNL detector design inspired the development of two detectors : one in operation on the DMC cold neutron diffractometer at PSI and another one under commissioning for the ERWIN new powder diffractometer at FRM II. The main difference between the FRM/PSI design and the BNL design concerns the read-out electronics. The BNL detector uses the charge-division technique whereas FRM/PSI have implemented individual channel read-out to enhance the counting rate of their detector. At the ILL, a large curved detector which covers 120° with a resolution of 0.19° horizontally has been in operation on the D19 diffractometer since 2006 [8]. More recently, a new large area-curved detector with 120° angular coverage and 0.15° resolution horizontally, similar to the D19 detector in dimensions, but with a higher count-rate capability, was developed at the ILL, and is now under commissioning on the XtremeD instrument [9]. The BNL and the FRM/PSI detectors are operated with a permanent gas cleaning system connected to the pressure vessel. At the ILL, both D19 and XtremeD detection modules have been fabricated with low-outgasing materials which allow the detectors to be operated without any permanent gas cleaning system. However, the detection modules in the XtremeD detector are based on a new type of MWPC design: the Trench-MWPC recently introduced by the ILL [10].

The D16 detector is also based on the Trench-MWPC detector technology. This technology is described in more detail in the next section. The design and the fabrication of the D16 Trench-MWPC detector are also presented, as

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well as detector characterisation results obtained with an AmBe neutron source. Finally, some information regarding the installation of the detector on the D16 instrument, and data obtained with a neutron beam are provided.

2 Trench-MWPC concept

The Trench-MWPC electrode structure used in the new large-area curved D16 detector is illustrated in figure 1. This concept was initially proposed for XtremeD detector at the ILL [9] and the advantages of this approach were demonstrated on a prototype detector which is described in reference [10].

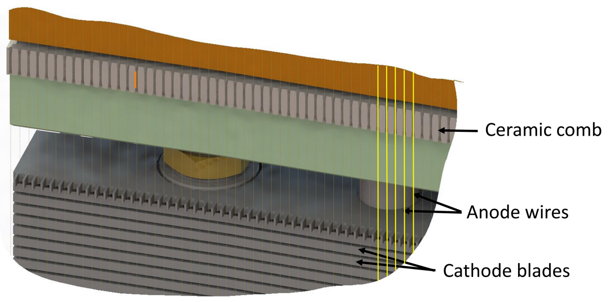

Figure 1. Schematics of the Trench-MWPC electrode design used in D16 detector. In this 3D view, the row of teeth along cathode electrode blades are shown only on the first blade. Anode wires are stretched along the trenches formed by the cathode blades.

In the Trench-MWPC design, cathode electrodes (providing the Y coordinate of neutron interactions in the detector) take the shape of a stack of curved aluminium blades. A row of teeth is present along the edge of each blade so that this stack of electrically isolated toothed blades forms trenches along which anode wires (providing the X coordinate of neutron interactions) are stretched. This Trench-MWPC configuration is used as the electron avalanche multiplication electrode structure inside the ^{3}He-filled pressure vessel. In the Trench-MWPC there is no need for a cathode electrode wire plane on top of the anode wires (used in standard MWPCs to counterbalance the electrostatic attraction of the anode wires by the bottom cathode electrode plane). In the Trench-MWPC, the electrostatic stability of the wires is provided by the cathode blade teeth surrounding the anode wires and produces a uniform gain multiplication factor even along 40 cm long wires. The absence of a cathode electrode wire on top of the anode wires leads to simple maintenance and simple assembly procedures. Moreover, neutron detection events produce electric charges which are confined within the trenches and induce pulses on a limited number of electrodes (only 1 or 2 anode wires and 1 or 2 cathode blades) increasing the signal-to-noise ratio per channel, which allows for an operation with low electron multiplication gain. In addition to the low-gain, the presence of cathode trench side-walls surrounding anode wires improves the collection of slow ions, produced during the gas avalanche process, and also contributes to a reduction of space-charge effects which usually limit the maximum local count rate of MWPCs. Another advantage is the low high-voltage difference required between anodes and cathodes (< 1000 V).

3 Detector design

The mechanical design of the D16 detector is adapted from the XtremeD detector design. The main difference between the two detectors lies in their geometrical characteristics. The height of the active area of the D16 detector is 38 cm whereas it is 32 cm for XtremeD. The horizontal angular resolution is twice as high for the D16 detector (0.075° instead of 0.15°), however the angular coverage is higher for XtremeD detector (120°) than for the D16 detector (86°).

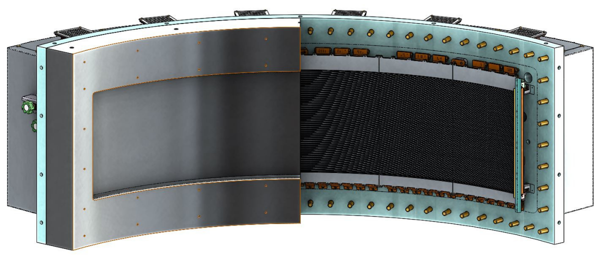

Figure 2. 3D view of XtremeD detector design showing the pressure vessel and 3 of the 6 Trench-MWPC detection modules.

The high angular resolution of the D16 detector is provided by the longer radius of curvature of the cathode blades (115 cm for D16 compared to 76 cm for XtremeD) and a smaller space between anode wires (1.5 mm for D16 compared to 2 mm for XtremeD). The smaller spacing and higher length of D16 anode wires make mechanical precision requirements in cathode blades and anode wires positioning more stringent than they are for the XtremeD detector; the specifications of D16 detector are listed in Table 1.

Angular coverage	Horizontally : 86° Vertically : 19° (38 cm high)
Angular resolution	Horizontally : 0.075° Vertically : 0.1°
Radius of curvature	115 cm
Number of pixels	221 184
Conversion depth	26 mm
Detection efficiency	67% at 4.5 Å
Local count rate	50 kHz per read-out channel
Global count rate	1 MHz

Table 1. D16 Trench-MWPC detector specifications.

The detector consists of a curved pressure vessel machined from aluminium inside of which 6 detection modules are mounted side by side, as illustrated in figure 2. Each detection module is composed of 192 cathode blades, separated by ceramic spacers. The 29 cm long cathode blades, shown in figure 6, are curved and a series of 192 teeth have been cut-out along them, spaced out by 1.5 mm. In each module, 192 gold-plated tungsten-rhenium anode wires are stretched perpendicularly to the cathode blades along the trenches formed by the teeth of the cathode blades. From a mechanical point of view, the overall detector is therefore composed of 1152 anode wires and 1152 cathode blades. Cathode blades located at the same height in two adjacent modules are electrically connected together in order to reduce the number of signals to read-out via the high-voltage feedthroughs at the back of the detector vessel. Therefore, from a signal read-out point of view, the detector is composed of 3 double-modules, each with 192 cathode blades and 384 anode wires, resulting in a total of 1728 channels to read-out.

The read-out of anode and cathode electrode signals is performed by the front-end electronics, located in an enclosure mounted to the back of the detector vessel. High-voltage signals are AC-coupled to pre-amplifier boards via 54 decoupling boards, each with 32 channels. The pre-amplifier boards are developed by the ILL and are common to all detectors requiring an individual electrode signal read-out. The boards are based on a FET pre-amplifier with low-noise and low-power consumption characteristics, followed by two filtering stages, a gain stage and a pulse amplitude discrimination circuit. Analogue pulses with amplitude above a selectable global threshold produce logic pulses, which are sent to 8 NIM-format FPGA-based pulse processing electronics modules. These FPGA-boards are the main parts of the back-end read-out electronics set-up, together with a VME-based acquisition module receiving processed data via an optical fibre link.

The signal processing performed by FPGA boards is identical to the one described for XtremeD in reference [9]: a one-dimensional hit cluster analysis performed separately on x-coordinate anode wires and y-coordinate cathode blades followed by xy coincidence detection. The xy coincidence window implemented in D16 detector signal processing is 250 ns long and applies to each double-module independently. The specific processing to avoid count loss in regions located at the junction between modules, described in the XtremeD detector paper [9], is also implemented in the D16 detector. However, in the D16 detector, this processing concerns only the junction between double-modules since adjacent cathode blades are connected together and read-out as a single electrode in double-modules (as explained in the previous section).

4 Detector fabrication

The D16 detector required precision machining and alignment techniques for the fabrication of the Trench-MWPC detection modules as well as heavy-duty machining of 2.5 m diameter forged aluminium rings, used to fabricate the pressure vessel parts. The D16 detector is shown in figure 3 before the closing of the two parts of the pressure vessel: the vessel flange with its 6 detection modules mounted side-by-side and the vessel itself with a large metallised polyimide film drift-electrode stretched across the internal surface of the vessel window. This large electrode is biased negatively in order to generate an electrical field sufficient to drive the electrons created after neutron interactions in the gas towards the amplification region of the Trench-MWPC. This amplification region consists of the positively biased anode wires stretched across the electrically grounded cathode blades.

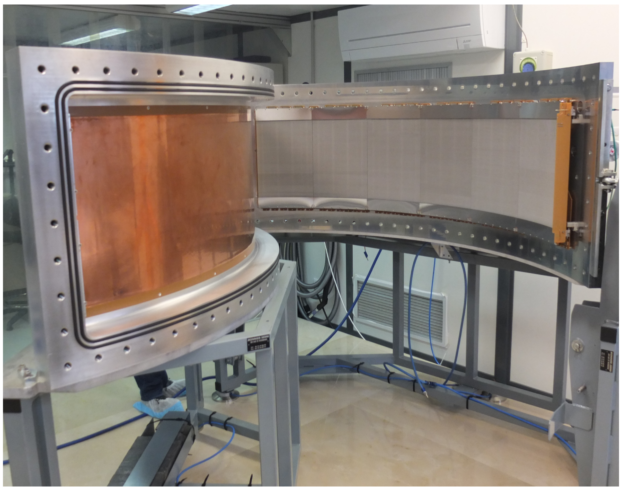

Figure 3. Photograph of the D16 detector before the closing of the pressure vessel, showing the detector modules mounted side by side on the vessel flange.

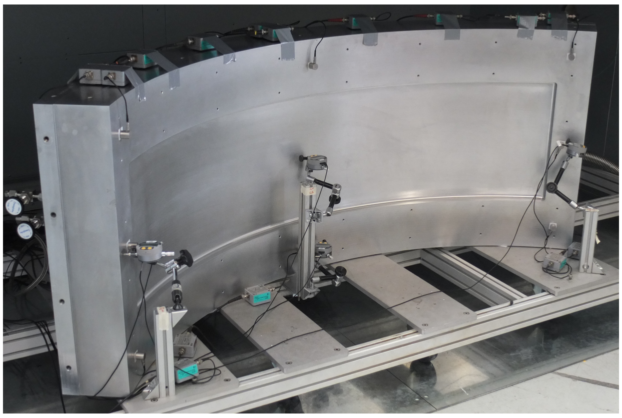

Figure 4. D16 detector vessel during pressure testing. Position sensors are used to control the elastic deformation of the vessel front window.

Guard electrodes are mounted on each side of the detector. These electrodes consist in polyimide circuits with copper tracks connected by resistors and are used to shape the electrical field between the negative voltage of the drift electrode and the 0V potential of the cathode blades. In addition, aluminium plates, polarised at a specific high-voltage, are mounted on the top and bottom of each detection module, to serve the same purpose of avoiding image distortion caused by a non-uniform drift field.

The detector vessel is filled with 2.4 bar of ^{3}He to provide a detection efficiency of 67% at 4.5Å and 4.6 bar of

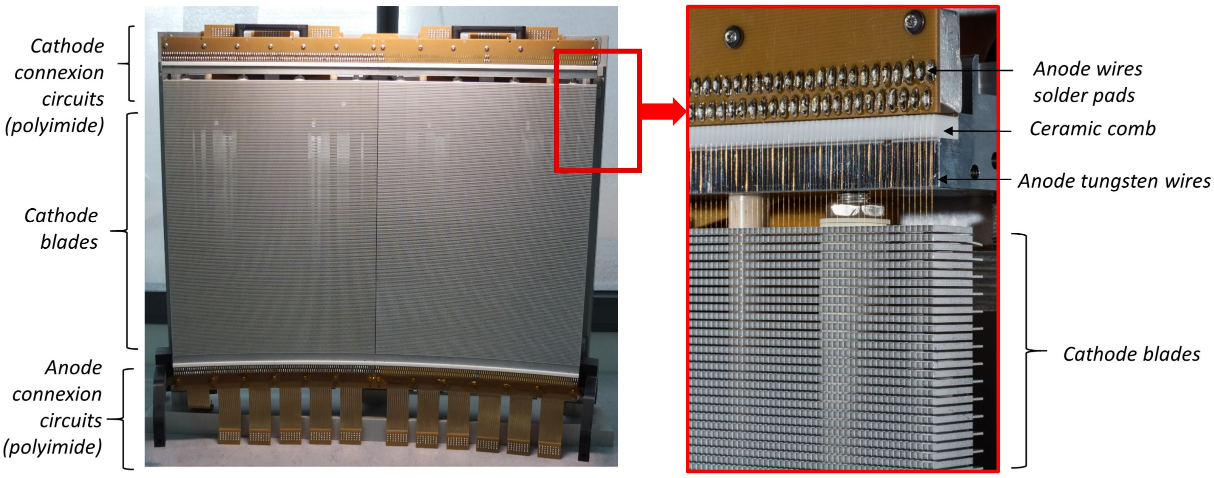

Figure 5. Photograph of a double-module of D16 Trench-MWPC detector (left) with a close-up view of the anode wires stretched along the cathode toothed blades (right).

$ArCO_2$ as stopping gas to provide a spatial resolution of 1.5 mm corresponding to the wire anode pitch.

4.1 Detector vessel

The pressure vessel assembly of the D16 detector, shown in figure 4, was machined in aluminium alloy EN AW-5083 forged rings. The vessel was designed to operate at a maximum internal pressure of 8 bar (absolute pressure). The entrance window of the vessel has a thickness of 10.2 mm and the deformation at the centre of the window is 1.4 mm under a differential pressure of 7 bar. The gas tightness between the curved flange and the curved vessel itself is provided by a double O-ring gasket in FPM Fluoroelastomer material, and 54 custom-designed multipin HV feedthroughs with a knife edge on a stainless steel body are directly bolted onto the vessel flange.

Various inspections of the raw material and a pressure test of the final vessel were performed to ensure that the vessel complies with the A2 module of the European directive on pressure equipment, and it has received CE marking. The main mechanical characteristics of the pressure vessel are listed in Table 2

Angular opening	98.5°
Height	735 mm
Internal radius	1086 mm
External radius	1259 mm
Weight	420 kg
Window thickness	10.2 mm
Internal volume	90 litres

Table 2. D16 Trench-MWPC detector specifications.

4.2 Detection modules

The detection modules are assembled by pairs as shown in figure 5(a) because the cathodes located at the same height of the two adjacent modules have to be connected together electrically at the back of the modules in order to reduce the number of read-out channels. With this configuration, the dead-time introduced by the xy coincidence detection window of 250 ns applies in parallel to 3 double-modules rather than 6 individual modules.

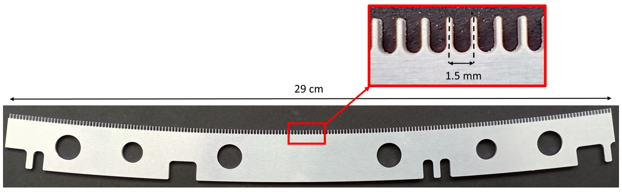

Figure 6. Photograph of an aluminium cathode blade used for D16 detector with a close-up view on the teeth machined along the blade.

A photograph of one of the 1152 aluminium cathode blades of the detector is shown in figure 6. Each blade is 29 cm long with an opening angle of 14.4°. The close-up view in figure 6 shows the row of 0.4 mm wide teeth machined by spark erosion along the blade. The mechanical frame holding the stack of 192 blades in each module was manufactured at the ILL workshop since the mechanical precision of these parts is crucial so as to avoid any deformation of the overall assembly which would otherwise lead to an error in anode centring along the trenches. The precision in the vertical positioning of each blade is obtained by using corrective spacers with a thickness of 0.05 mm or 0.02 mm above and below the nominal thickness of the 1 mm-thick ceramic spacers used to isolate the cathode blades electrically from each other. The maximum error in the vertical positioning of the cathode blades is of 0.4 mm across the 6 modules of the detector.

The exact positioning of anode wires inside the cathode trenches is of great importance in the Trench-MWPC design. Error in anode wire centring leads to a non uniform electron multiplication gain since the deformation of the wire due to an unbalanced electrical field produces variations in the anode wire/cathode tooth distance across the detector. Precision in anode centring is achieved by MACOR combs used to position each wire along a module as shown in figure 5. The spark-erosion technique used to produce the cathode blades also contributes to the overall uniformity of anode wire/cathode tooth distances. The maximum error in wire centring inside the 1.1 mm-wide trench is 50 microns across the whole module. However, on two modules, a manufacturing error on the MACOR combs resulted in a lateral shift of the wires by 70 microns between the two halves of each module. This systematic error produces a difference in amplification gain of only 10% between the two half-modules and is not visible on 2D neutron images.

5 Detector test with an AmBe neutron

The detector was tested in the lab with an AmBe neutron source in order to determine the optimum operation voltages. At a drift voltage $V_d = -750\ V$, the anode voltage was increased while recording the neutron count-rate over the detector to produce the counting curves shown in figure 7.

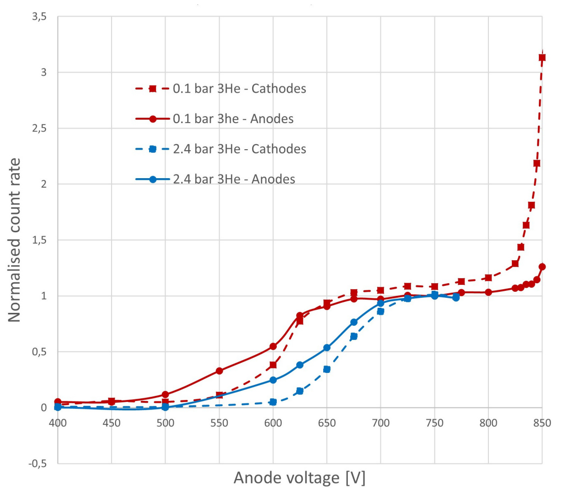

Figure 7. Counting plateau recorded over the whole detector at V_d=-750 V for two different pressures of ^{3}He (100 mbar and 2.4 bar) and a pressure of $ArCO_2$ of 4.6 bar.

These counting plateaux were obtained by recording the number of pulses above the discriminator thresholds as a function of anode wire high-voltage. The discriminator thresholds were adjusted above the electronics noise : at -350 mV for the anode channels and at a slightly higher value of 400 mV for the cathode channels due to the higher capacitance of the cathodes blades compared to the anode wires.

These curves can be used to identify the anode voltage corresponding to the centre of the neutron counting plateau which is 775 V for an ^{3}He pressure of 2.4 bar and an $ArCO_2$ pressure of 4.6 bar corresponding to the standard operating conditions of the D16 detector. This rather low operating voltage for a MWPC is due to the close proximity between anode wires and cathode blades teeth in the Trench-MWPC design: anode wires are located at 1.5 mm from the bottom of the 2.2 mm-deep, 1.1 mm wide cathode trenches.

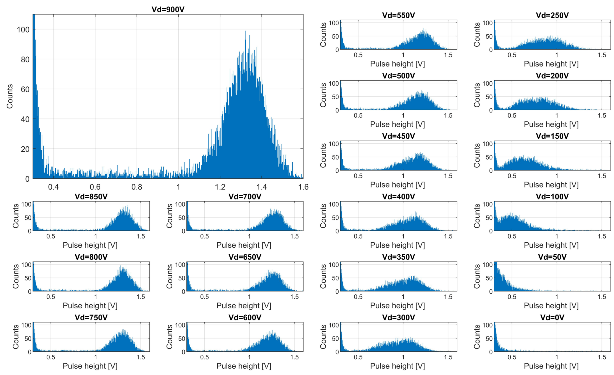

Figure 8. Anode-wire-summed-signal pulse height spectra as a function of HV applied to the drift electrode.

The optimum drift voltage was determined by varying the drift voltage at a constant anode voltage $V_a = 750\ V$. The pulse-Height-Spectra (PHS) recorded on the sum of the analogue output signals from one of the 32-channels pre-amplifier boards are shown in figure 8. These data show that amplification gain remains constant and that charge collection is complete for drift voltages V_D<-500V. For V_D>-500V, the shapes of the PHS indicate that the signal duration is longer than the shaping time of the preamplifiers (pulse FWHM of 600 ns).

The uniformity of the detector response was investigated by using the B_4C mask shown in figure 9(a) mounted on the detector front window. Two-dimensional images obtained by xy coincidence detection as described in the previous section were acquired over several hours in order to obtain sufficient counting statistics with the AmBe source. The raw image of the B_4C mask, the flat-field image (without mask) and the flat-field-corrected mask image are shown in figure 9(b). The presence of regions with 5% sensitivity reduction are visible in the raw data. These regions with lower sensitivity are due to the drift electrode not being perfectly stretched across the internal surface of the detector front window. Some ripples appearing across the large curved drift electrode when a high-voltage is applied to the copper surface create some gaps between the electrode and the entrance window of the vessel. These gaps, filled with the $^3He/ArCO_2$ gas mixture, stop a small fraction of the neutrons without generating the corresponding charge in the drift region, therefore causing sensitivity variation across the detector active area. These sensitivity variations are suppressed by a flat-field correction, as illustrated in figure 9(b) with the AmBe source. On the D16 instrument various samples such as Vanadium can be used to produce the sensitivity map required for flat-field correction.

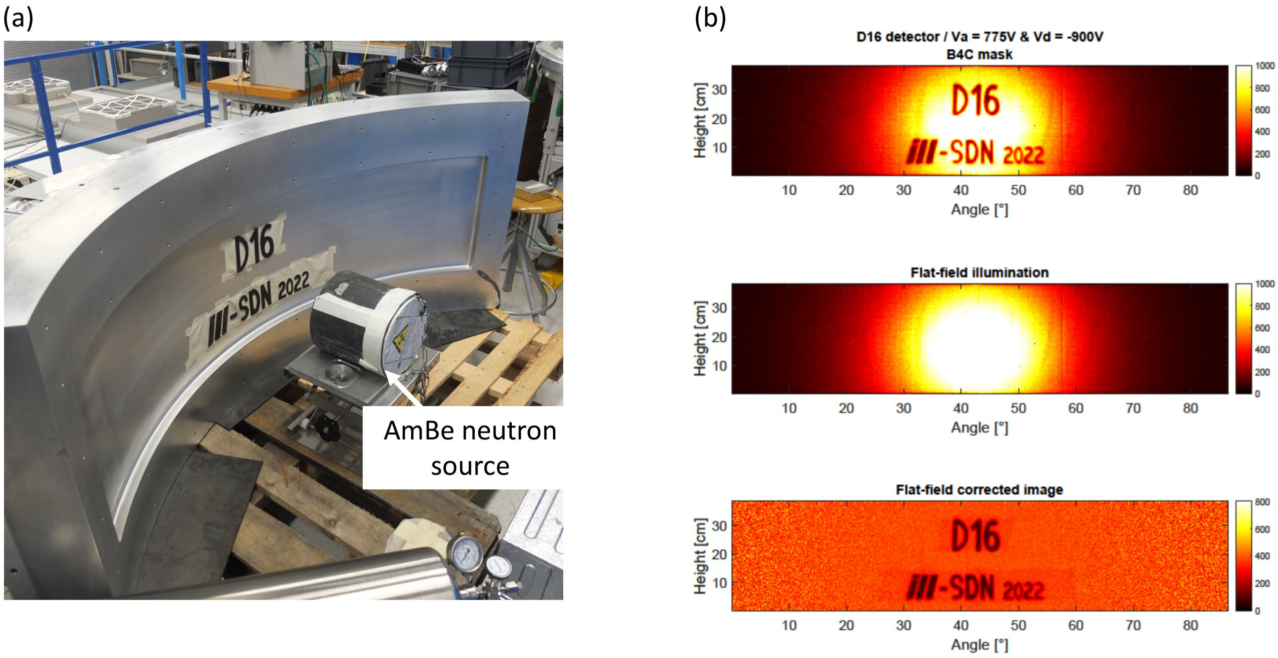

Figure 9. (a) B4C mask (neutron attenuator) mounted on the detector entrance window; (b) Mask image, flood-field image and flood-field corrected image of the mask obtained with an AmBe neutron source.

6 Detector commissioning on the D16 instrument

The previous MILAND detector (32 x 32 cm^2 MWPC detector with a 1x1 mm^2 resolution) was dismounted from the D16 instrument at ILL in Oct 2021 and a new instrument platform was installed on D16 during the ILL long reactor shutdown period in 2022. This platform comprises the following elements:

- A granite table on air-pads: to move the whole platform between two positions which correspond to two different take-off angles of the monochromator (83° for 4.5 Å or 115° for 5.6 Å neutron beam wavelength with a vertically bending HOPG monochromator).
- An helium-filled chamber: to reduce neutron attenuation and scattering between the sample and the detector. Helium circulates constantly in the chamber, maintaining an overpressure of 20 mbar above ambient pressure.
- The large-area curved MWPC-trench detector described in the previous sections.
- A motorised support frame: used to scan both the detector and the helium chamber to cover a wide Q-range of diffracted data corresponding to an angular range between -43° and 133°.
- A motorised beamstop: located in a 1 cm-thin air-gap between the helium chamber aluminium window and the detector front window.

The new platform is still compatible with previous sample environments including controlled temperature and humidity chambers, cryostats, furnaces, magnets, cryomagnets, high pressure cryostats, high pressure cells and an automatically positioned, temperature controlled, horizontal sample changer.

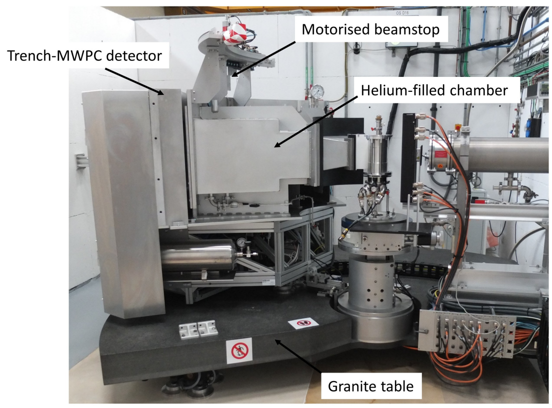

Figure 10. Photograph of the Trench-MWPC detector installed on the new platform of the D16 instrument.

After the restart of the ILL reactor in March 2023, flat-field data and diffraction data from various samples were acquired at a neutron wavelength of 4.5 Å. These results, obtained with the neutron beam, were used to optimise the detector data processing (1D pulse clusters processing and xy coincidence analysis) at a high count rate. Figure 11 shows the diffracted data recorded from a YIG (Yttrium Iron Garnet) crystal powder sample with the new Trench-MWPC detector at 4.5 Å. The Q-range covered by the new detector in one position is 4.5 times higher than the one achievable with MILAND, the previous detector installed on D16, demonstrating the new capabilities of the

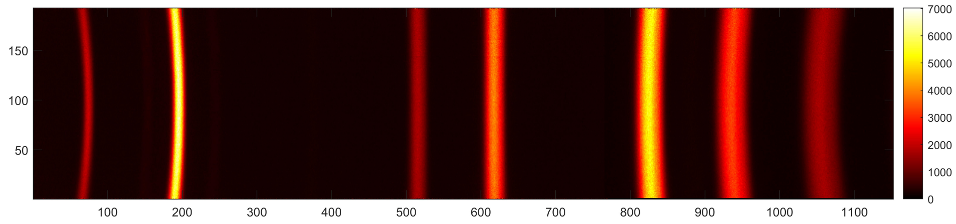

Figure 11. Neutron diffraction image produced by a YIG (Yttrium Iron Garnet) powder sample with the new Trench-MWPC detector during its commissioning on D16.

instrument for dynamic diffraction experiments over wide Q-ranges.

7 Conclusion

A new large-area curved detector is now operational on the D16 cold-neutron diffractometer instrument at ILL. This ^{3}He detector is based on the Trench-MWPC detector technology developed at the ILL. The Trench-MWPC design requires simple maintenance procedures, low operating voltages, low-electron multiplication gain operation and reduces space-charge effects due to the slow drift of ions produced during electron multiplication in the detector. The new curved D16 detector, a 38 cm high detector, offers a continuous horizontal angular coverage of 86° with an angular resolution of 0.075°. The 221 184 pixels of this high-granularity detector produce high-quality neutron diffraction images. The D16 instrument platform was upgraded to take full advantage of this new detector and to allow dynamic neutron diffraction experiments over a wide Q-range.

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