BrightnESS

Building a Research Infrastructure and Synergies for Highest Scientific Impact on ESS

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Grant Agreement Number: 676548

Deliverable Report: D4.13 “Module for NMX Detector”

1 Project Deliverable Information Sheet

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	Approved by	BrightnESS Steering Board

3 List of Abbreviations

ESS	European Spallation Source
NMX	Neutron Macromolecular Crystallography Instrument
GEM	Gas-Electron-Multiplier
Gd	Gadolinium
GDD	Gas Detectors Development
VMM	Virtual Machine Manager
ASIC	Application Specific Integrated Circuit
SRS	Scalable Readout System
PCB	Printed Circuit Boards
FEC	Front-End Concentrator
UDP	User Datagram Protocol
DMSC	Data Management and Software Centre
DAQ	Data Acquisition
FPGA	Field-Programmable Gate Array

4 Content

5 Executive Summary

This deliverable represents the culmination of the majority of task 4.1 ”The resolution challenge”, which is part of work package 4 of BrightnESS. As final deliverable of the task, a Gd-GEM detector module has been constructed. This demonstrator module was designed to meet the requirements for the detector of the NMX (Neutron Macromolecular Crystallography) instrument. The position resolution requirements, along with a high rate capability, were a particular challenge. The detector module has been engineered and designed to match the environmental and operational requirements for ESS instruments. To read out the detector, the complete data acquisition chain, consisting of frontend electronics, readout electronics and DAQ software, has been implemented.

The design of the Gadolinium GEM detector for NMX has previously been optimised throughout task 4.1 of BrightnESS. The primary aim of task 4.1 was the provision of time-resolved detectors with reasonable efficiency and a position resolution of a few hundred microns. Gadolinium was chosen as the convertor material to meet these requirements. The design of the Gadolinium convertor and the subsequent performance was investigated, as reported in deliverable 4.3, “Natural and enriched Gadolinium convertors design". A prototype design of the electronics data acquisition chain was reported in deliverable 4.9, “Detector electronics chain”.

The detector design meets the requirements of the NMX instrument: namely the high position resolution (a few hundred microns); time-resolved measurements; lack of parallax error in the detector design; and a 60x60cm modular design with>50x50cm active area; along with excellent rate performance. The design must be light enough, with flexible services (gas, cooling, power and data cables, etc) to be fitted onto a robotic arm, which is a key aspect of the NMX instrumental design. The detailed CAD and integration engineering of the module design has been done. As part of this process, the detailed engineering design has been demonstrated to be feasible. The module occupies the right footprint, and the services are compatible with the ESS environment. A scalable and affordable electronics data acquisition chain exists to read out this detector. All components of the detector module have been manufactured and assembled, documenting and overcoming issues and challenges that occurred during this process.

The constructed module is shown in the cleanroom at CERN in Figure 1 and Figure 2 below.

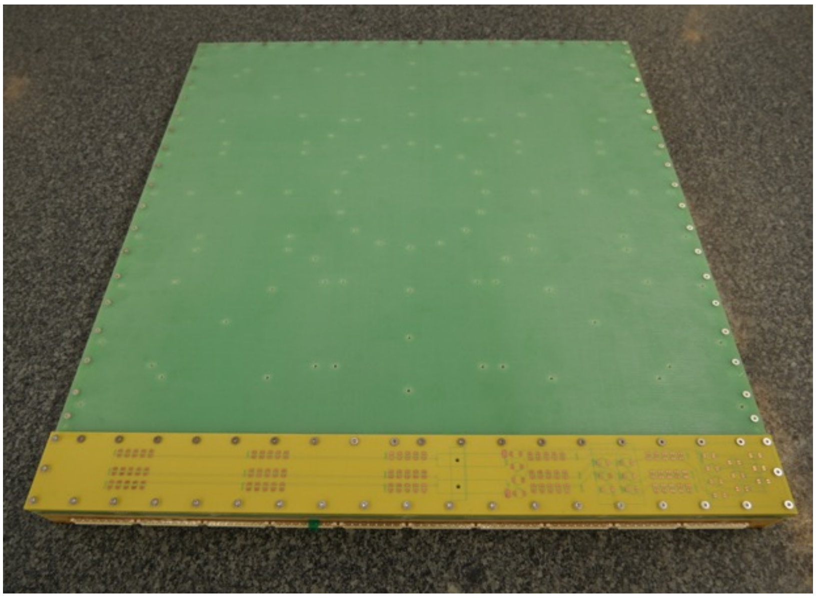


Figure 1. The constructed demonstrator module of the Gd-GEM detector design for the NMX instrument in the clean room of the GDD Workshop at CERN. This module is approximately 60x60 cm, length of the yellow part 37.5 mm.

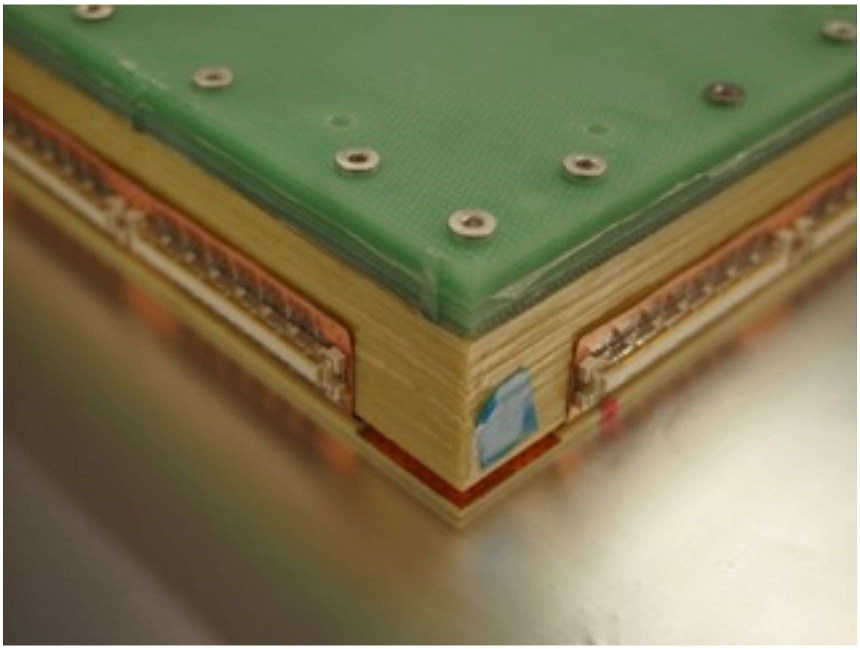


Figure 2. Detailed view of detector housing with connectors for the frontend electronics (VMM3 hybrids). Height for the side shown 32.5 mm.

6 Implementation of Results

This deliverable report documents the design and construction of the Gd-GEM demonstrator module for the NMX instrument. The design parameters were investigated in previous deliverables 4.3, "Natural and enriched Gadolinium convertors design" and 4.9, "Detector electronics chain". During the detailed engineering and integration work special care was given to ensure that the module matches the detector requirements for the NMX instrument.

The content is presented in the technical content section. Here, firstly, the description of the detector requirements for the NMX instrument is given, followed by a summary of the chosen design. An overview on the electronics chain is given. Then a detailed step-by-step guide explains the construction of the NMX detector module. Lastly, a short summary of key results from a smaller version of the module recently tested at the BNC neutron source is presented.

7 Technical Content

7.1 Description of Requirements for NMX

The NMX (Neutron Macromolecular Crystallography) Instrument is one of the first 15 instruments at ESS selected for construction. It is designed to be a large step forward in Neutron Macromolecular Crystallography, where, at present, state of the art instruments need weeks of data taking to characterise a sample. Compared to X-ray Macromolecular Crystallography, Neutron Macromolecular Crystallography has the advantage of being able to detect and resolve the location of hydrogen atoms, which makes it a highly interesting complementary technique. This allows for an easy transition so that expert Macromolecular Crystallography users can quickly start to use Neutron Macromolecular Crystallography techniques. A key aspect of the design is the flexibility obtained by placing the detector arrays on robotic arms, so that they can be repositioned for the measurements. Figure 3 below shows the sample and the detector panels that are mounted on the robotic arms.

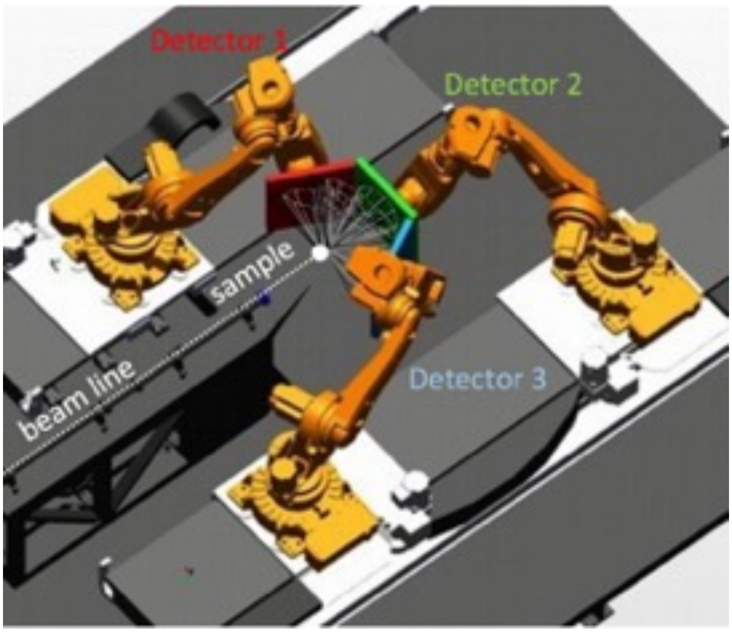


Figure 3. Neutron beam line, sample and robotic detector positioning system

To illustrate the science case and detector challenge for NMX, Figure 4 shows the simulated reflections from a protein crystal, the bovine heart cytochrome c oxidase. In addition to cases like this, the NMX instrument aspires to measure even much more complicated patterns. It can be seen that the data is highly complex and there are many overlaps in space and time. A detector with excellent spatial resolution and good timing resolution is essential in resolving the spatial and time overlaps in the pattern.

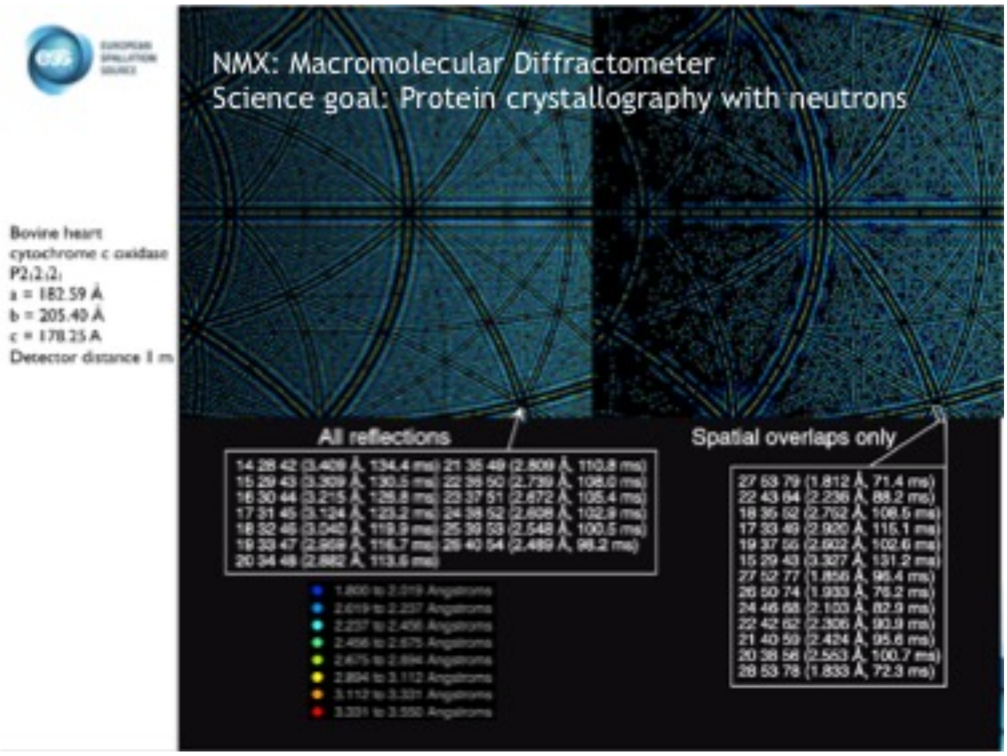


Figure 4. Protein crystallography with neutrons: Simulation of the reflections from a protein crystal (bovine heart cytochrome c oxidase).

The complete assembly of the three detector panels and the robotic arms is called scattering characterization system (SCS). Each of the three detector panels has a envelope of 60 cm by 60 cm and an active area of 51.2 cm by 51.2 cm. The mounting of the detector units on robotic arms allows the movement of the detectors to various positions around the sample. Figure 5 illustrates the flexibility of the SCS. Six common configurations to position the detectors around the sample are shown. The neutrons that are scattered from the sample always impinge with close to normal incidence on the detectors.

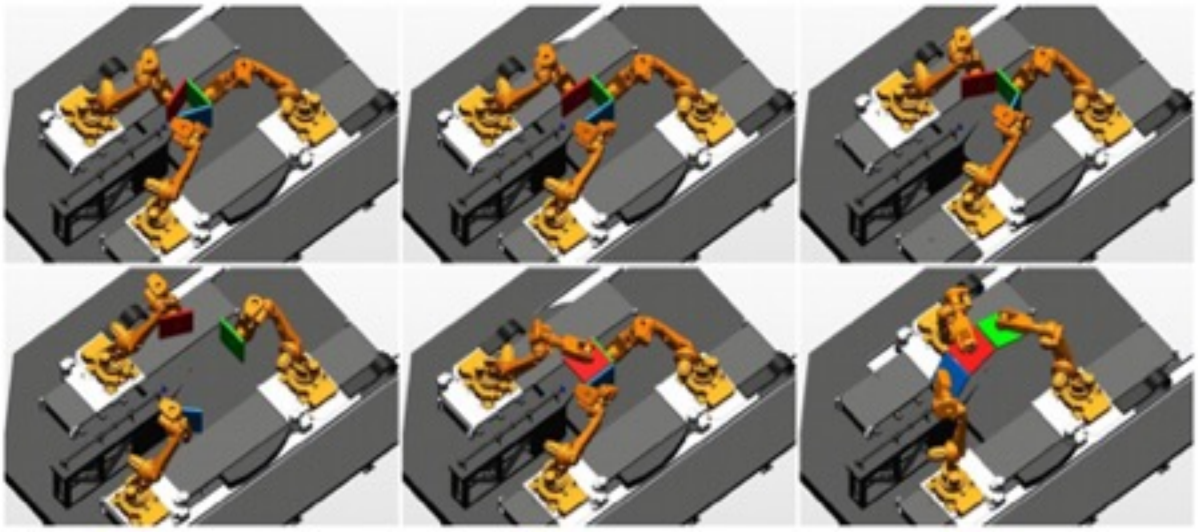


Figure 5. Six common configurations to position the NMX detectors.

7.2 Summary of Design

The systematic investigation of the Gd-GEM detector design and its implications on the detector performance was the subject of deliverable D4.3. The chosen design is summarised briefly below.

The GEM detectors with Gadolinium cathode are used in a backwards configuration, i.e. the neutron beam, impinging orthogonally to the detector, crosses the readout board and the GEMs before reaching the cathode, as shown in the schematic Figure 6 below. In this way the conversion electrons do not need to traverse the entire gadolinium thickness in order to reach the active volume (the so-called drift space), which leads to a higher neutron detection efficiency.

In forwards configuration the neutron impinges directly on the cathode, and the majority of the conversion electrons have to transverse the converter. Since most of the neutrons interact in the first few hundred nanometres of the converter, a smaller percentage of the conversion electrons manages to reach the drift space of the detector. The detection efficiency in forwards configuration is thus always lower than in backwards configuration. If a very thin Gd converter is used, a second mirrored detector that uses the same Gd cathode as the first detector can be added.

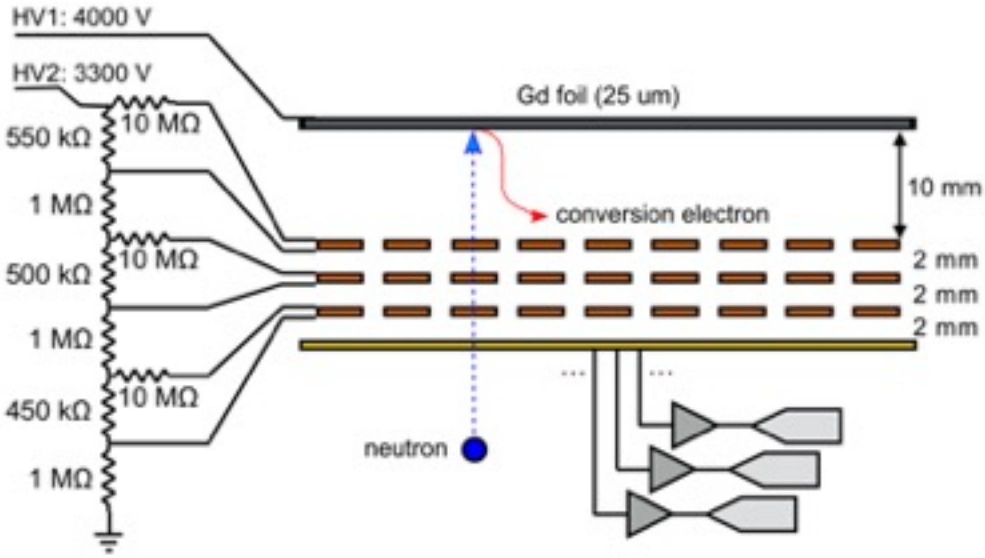


Figure 6. Schematic representation of the detector used in backwards configuration

The Gadolinium layer used is a 25 microns thick foil. It is welded to a thin Aluminium frame, supporting the foil, using an ultrasonic welding technique. An example of a welded Gd cathode is shown in the photo below in Figure 7.

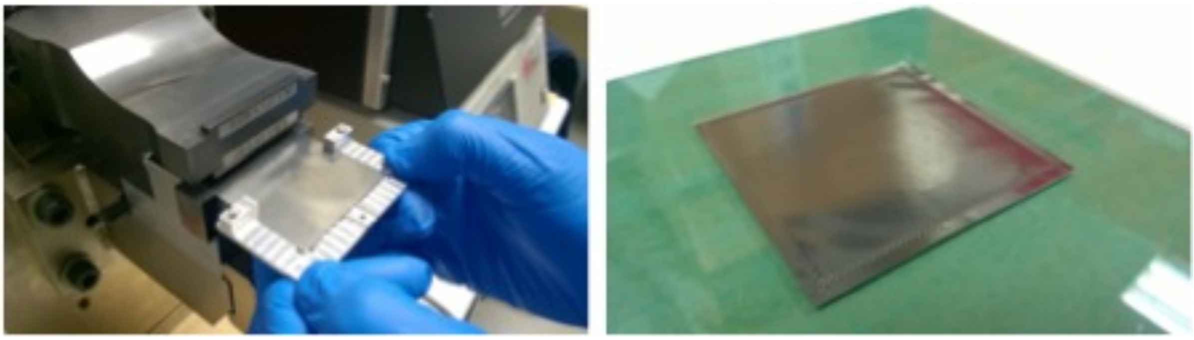


Figure 7. Ultrasonic welding of Gd foil to Aluminium support frame.

The Gd-GEM detector uses the GEM foils in the standard CERN triple GEM configuration. This allows the essential detection units to be treated as a standard and well understood item, which performs the charge transport, amplification and collection. This means that the development can be focused on understanding the particular aspects of the Gadolinium conversion layer. The functional principle of a standard GEM detectors is as follows: In the drift space the conversion electrons ionize the gas by creating electron-hole pairs or secondary conduction electrons. These electrons drift then to the first GEM foil. In the holes of all the GEM foils, the electrical field is high enough to create an electron avalanche, i.e. that the number of the electrons is multiplied. After passing three amplification stages, the electrons reach the induction region above the readout. Here, the movement of the conduction electrons induces a signal in the x/y strip readout of the detector.

7.3 Electronics Chain

An electronics chain is needed to read out the detector. The analog signals in the strip readout are read out by the VMM ASIC developed by Brookhaven National Laboratory for the New Small Wheel Phase 1 upgrade ref. [9]. As part of BrightnESS task 4.1, the VMM ref [10] has been implemented into the SRS at CERN. A schematic drawing of the readout chain is shown in Figure 8. The so-called front-end hybrids are directly mounted onto the detector. This PCB holds two VMM3a ASICs, each with 64 input channels connected to the anode strips with a spark protection circuit. For each hit strip where the signal surpasses a configurable threshold, the VMM outputs a 38 bit binary word. A Spartan-6 FPGA on the hybrid controls the ASICs and bundles the data, that are transmitted via HDMI cables to the core of SRS, the Front-End Concentrator (FEC) card. Up to eight hybrids can currently be connected to one FEC. The data are encapsulated into UDP packages of a 1 Gb/s Ethernet connection to the readout computer. The readout of the Gd-GEM detector is partitioned into 4 sectors. Each of these 4 sectors has 640 strips read out by 5 hybrids in x and y direction, resulting in a total of 5120 strips and 40 hybrids. If a signal is recorded on a detector strip, the VMM on the hybrid generates the 38 bit of hit data for the corresponding channel. Before sending out the data via UDP, the FEC adds the VMM ID and the FEC ID to the hit data. With the information tuple (channel, VMM ID, FEC ID), the geometrical position of each hit can be reconstructed and displayed. On the computer, the DAQ system developed by the DMSC within BrightnESS Task 5.2 is used ref [6]. VMM, VMM3 and VMM3a are different versions of the same basic chip. This is not quite the final readout system as it does not yet interface with the ESS timing system.

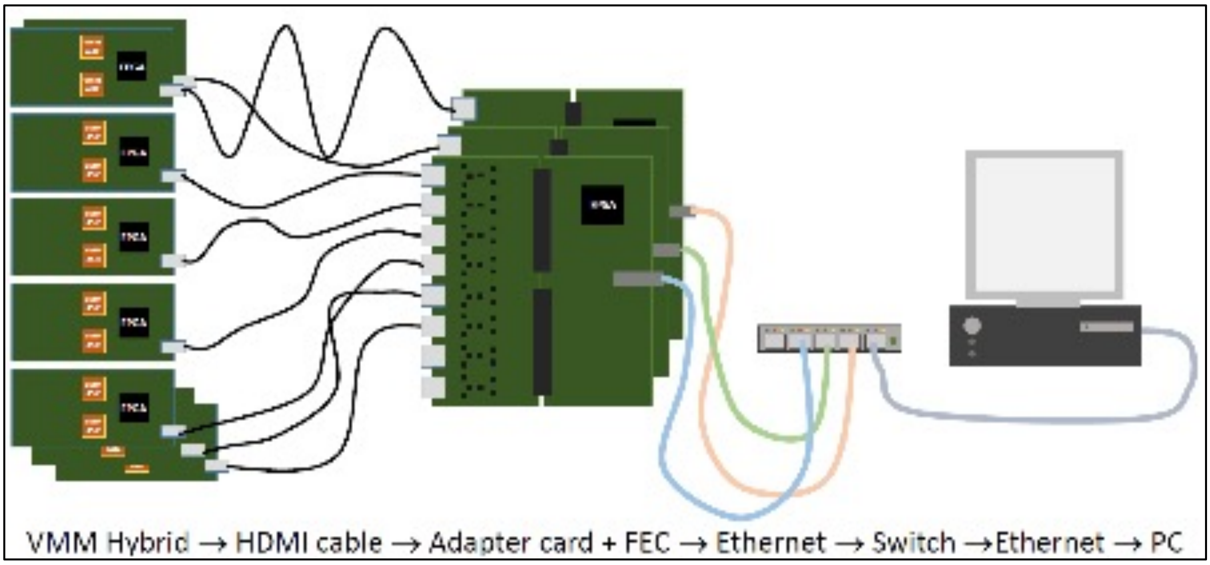
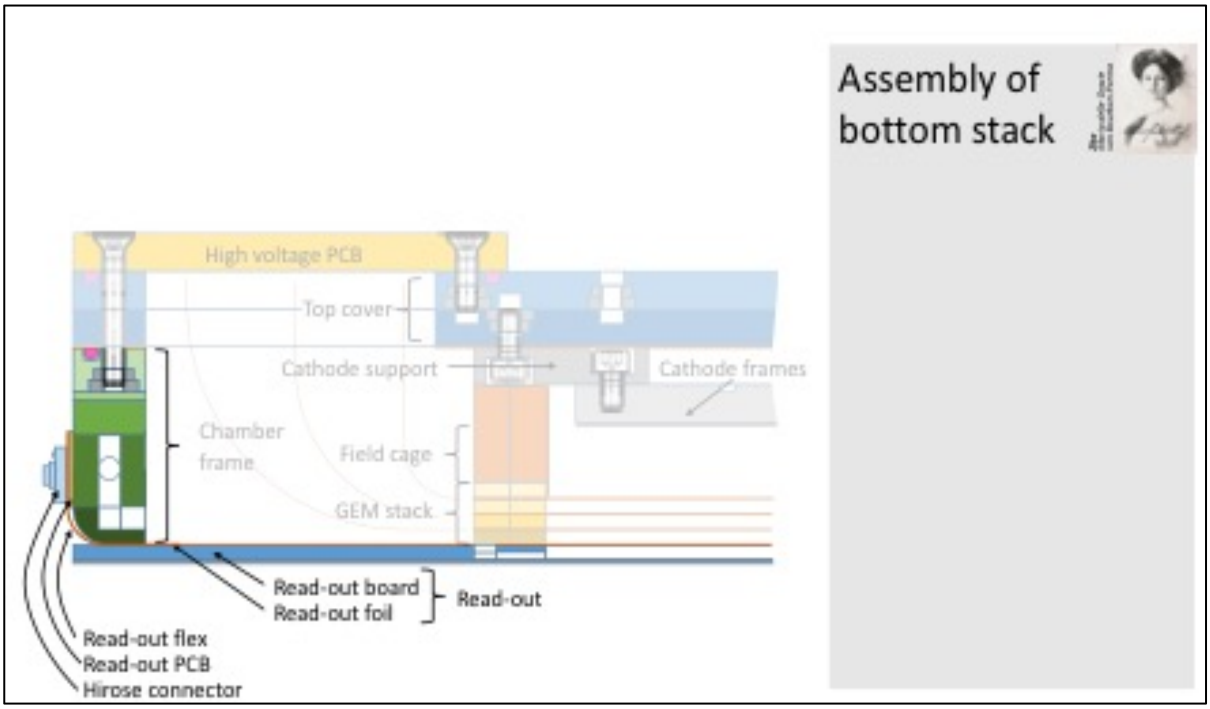
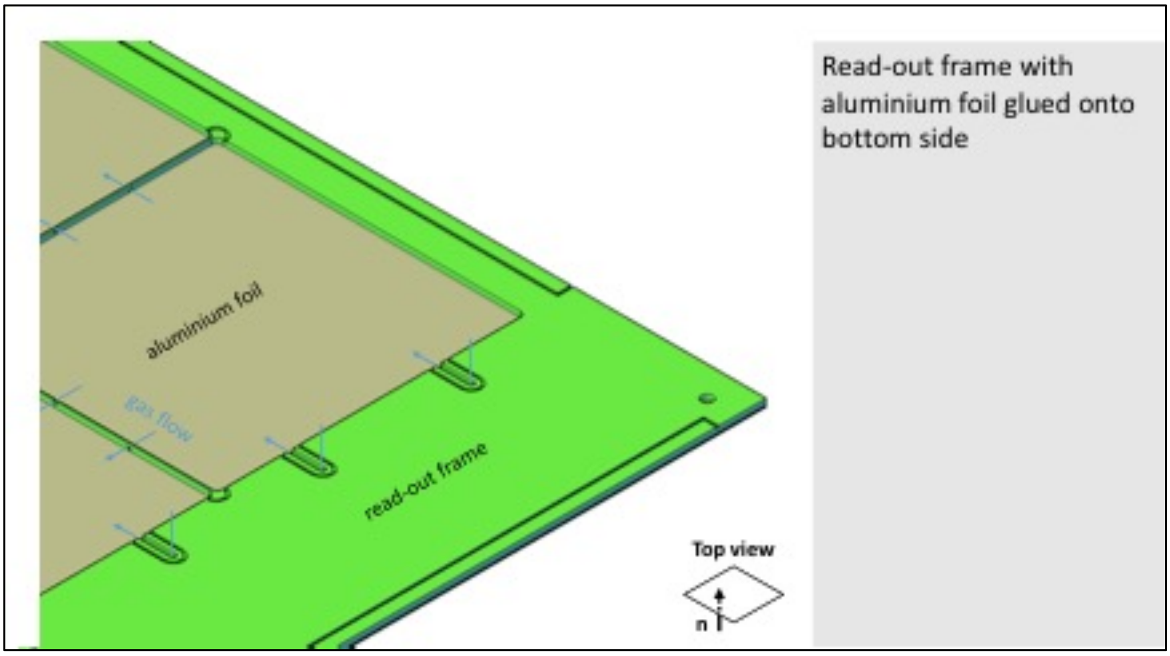


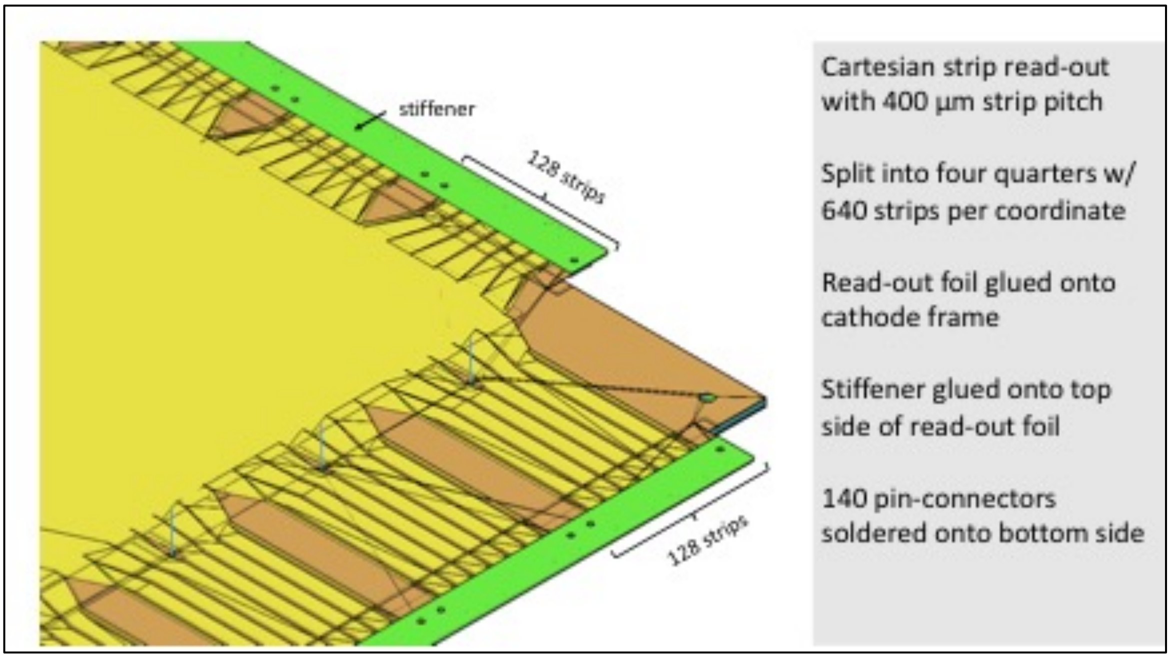
Figure 8. Schematic drawing of the readout chain.

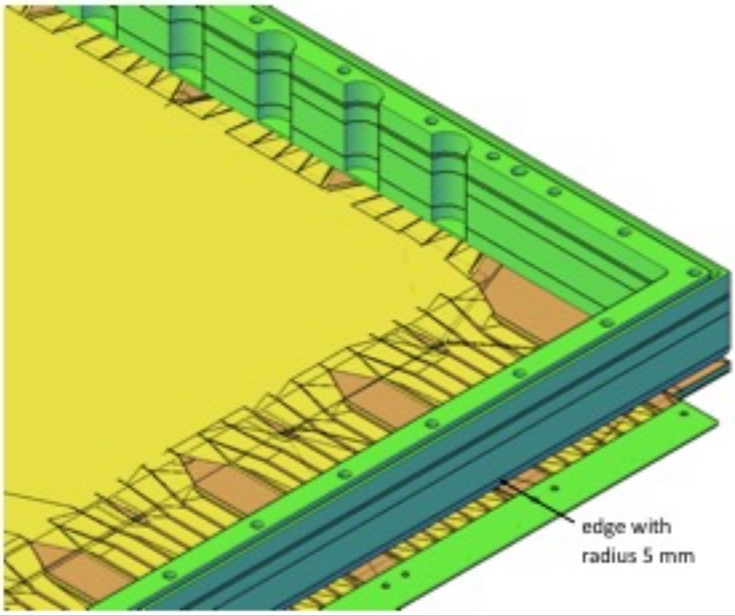
7.4 Design and Construction of NMX Module

In the following section, a walkthrough guide of the assembly illustrates all necessary steps of the detector assembly.

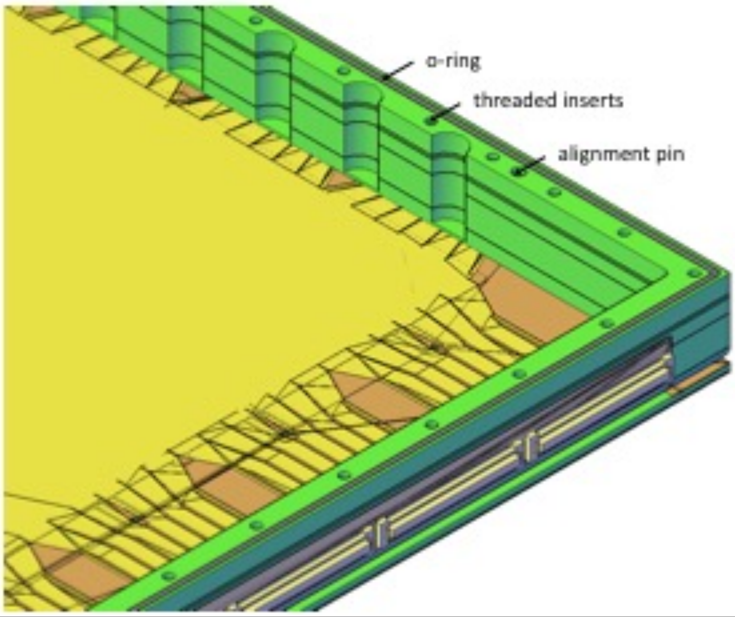



aluminium foil
gas flow
read-out frame
Top view
n
Read-out frame with aluminium foil glued onto bottom side


stiffener
128 strips
128 strips
Cartesian strip read-out with 400 µm strip pitch
Split into four quarters w/ 640 strips per coordinate
Read-out foil glued onto cathode frame
Stiffener glued onto top side of read-out foil
140 pin-connectors soldered onto bottom side



Chamber frame glued onto read-out

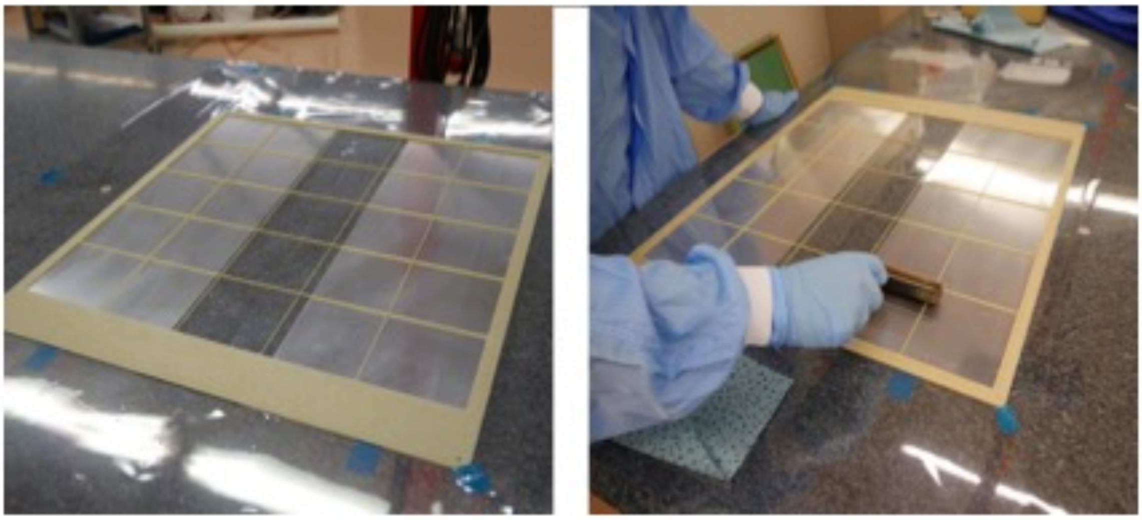


140-pin connectors folded onto side of chamber frame

O-ring inserted into groove on top of chamber

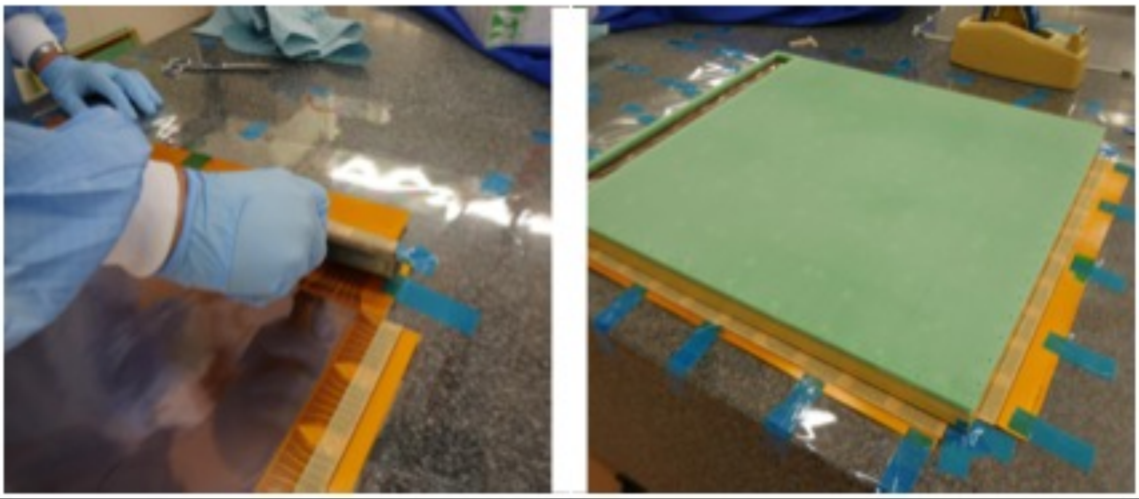
Read-out frame

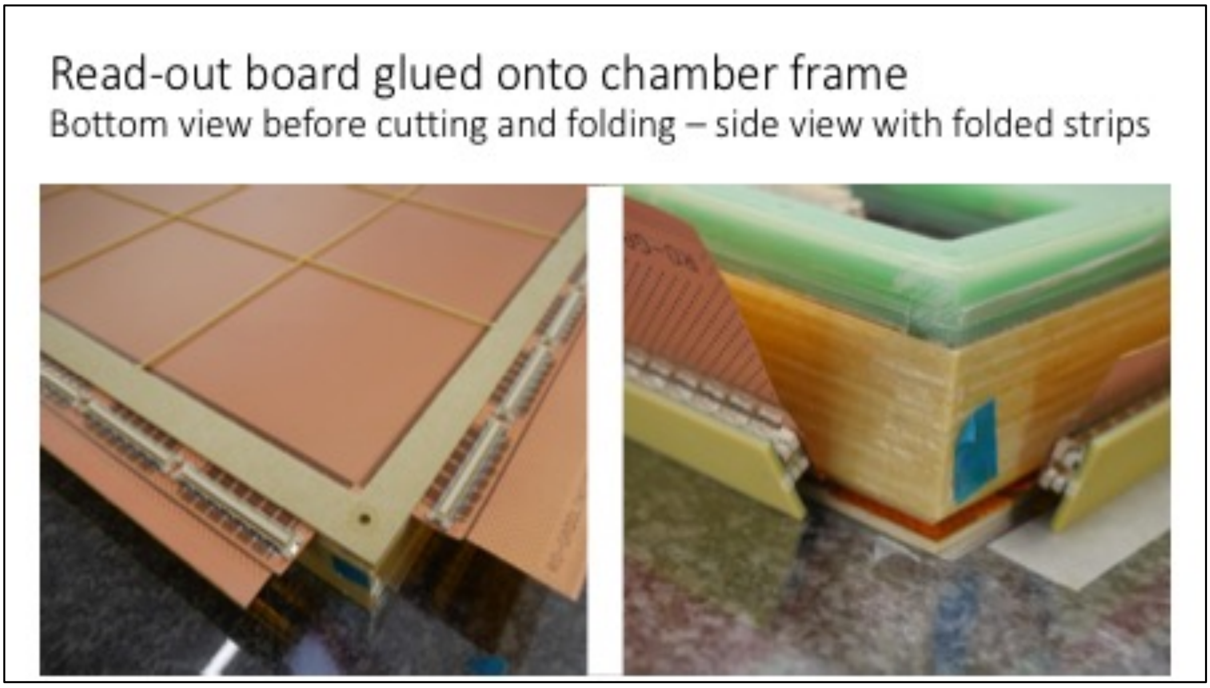
Inner grid fully covered with PU, top side covered with glue

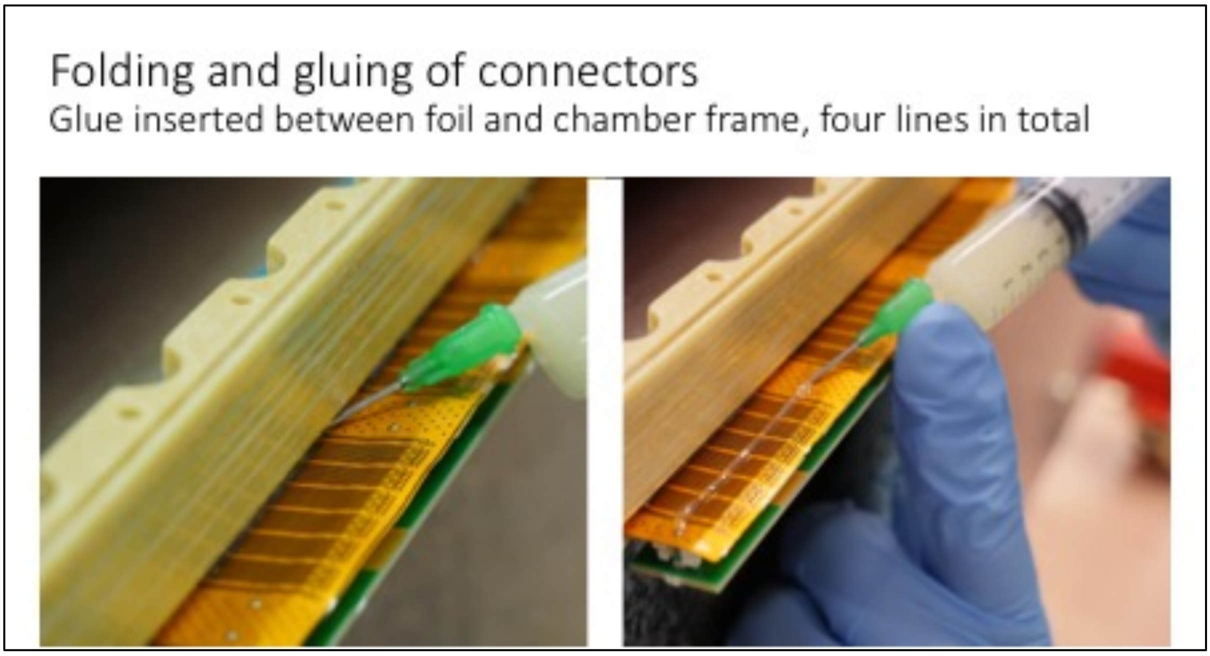


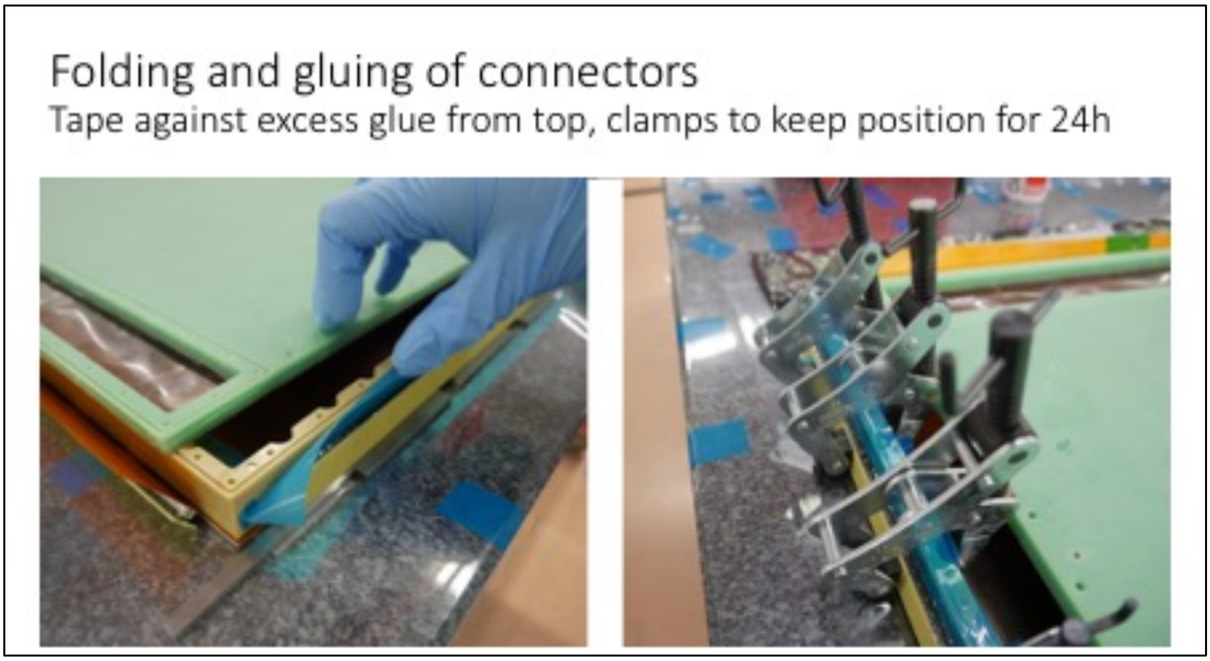
Read-out board glued to frame

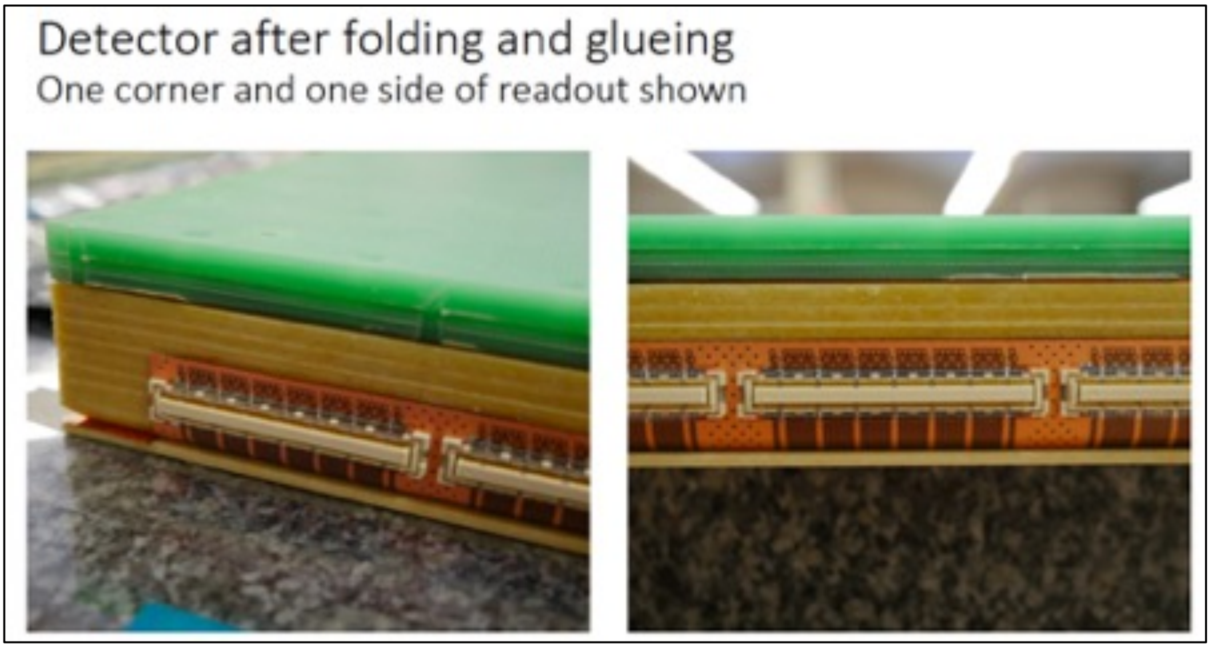
Stretched with tape and pressed down with cathode + metal rods

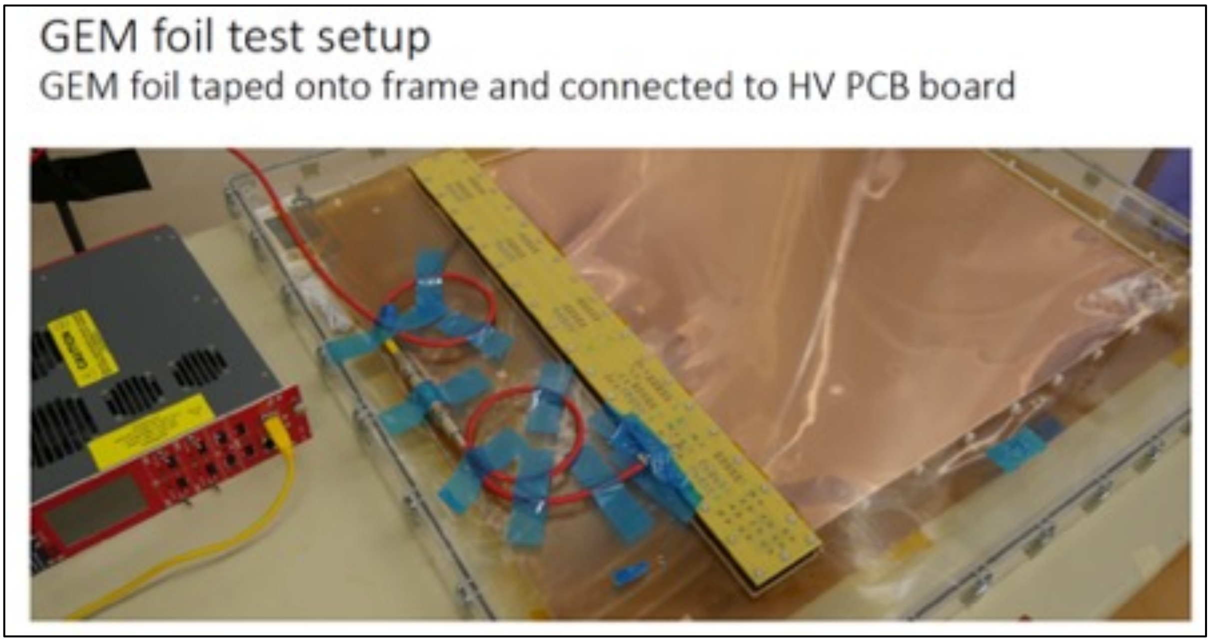



Read-out board glued onto chamber frame
Bottom view before cutting and folding – side view with folded strips


Folding and gluing of connectors
Glue inserted between foil and chamber frame, four lines in total


Folding and gluing of connectors
Tape against excess glue from top, clamps to keep position for 24h


Detector after folding and glueing
One corner and one side of readout shown


GEM foil test setup
GEM foil taped onto frame and connected to HV PCB board

7.5 Results

A smaller version of the NMX detector module has been tested at the BNC neutron reactor in Budapest/Hungary in the week from July 2nd – July 6th. With the exception of the orientation of the connectors for the VMM3 hybrids, the tested detector was identical with respect to the used materials and the assembly to the full-size detector module. Figure 9 to Figure 11 show the frontend electronics, the beamline at BNC and the detector under test.

Figure 9. VMM3a hybrids under test.

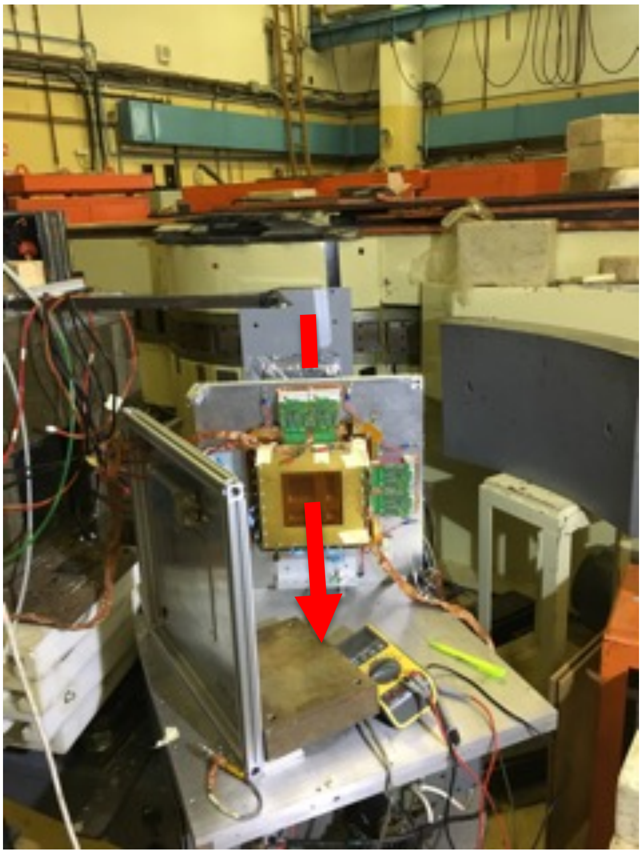


Figure 10. Beamline at BNC with smaller Gd-GEM detector module under test.

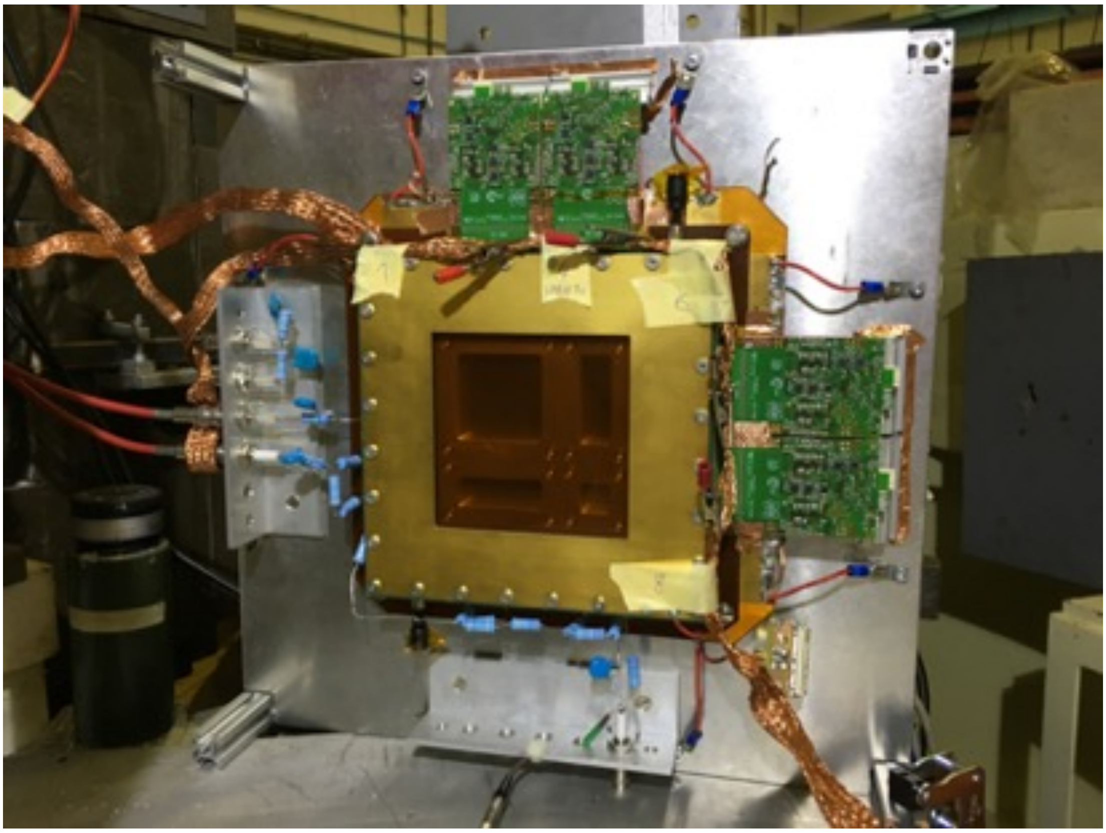


Figure 11. Internal structure of Gd-GEM detector: The Aluminium support frame and the Gd-foils welded to the inside of the frame are clearly visible.

The complete electronics readout chain, that will be the core used for the NMX instrument, has been successfully tested. As in the final instrument, the data has been analysed and displayed by the DMSC DAQ and monitoring software that was developed within BrightnESS WP 5. Figure 12 shows the monitoring tool DAQUIRI. Per VMM3a ASIC, neutron rates of up to 10 Mbit/s (these rates are comparable to the rates at NMX) were read out without any data loss. To study the position resolution, a Cd mask (Figure 13) with holes of 1.0 mm diameter was put in front of the detector the holes of the mask had a minimum separation (centre to centre) of about 2 mm horizontally, 1.5 mm vertically, and 1.2 mm diagonally. The neutron beam (wavelength 3.5 Å) was focused in such a way that the lowest three rows of the mask were illuminated. Figure 14 shows the neutron image of the mask. In the lowest three rows, all holes are clearly resolved. Even the diagonal separation of only 1.3 mm, which is equivalent to 300 um of material between holes, did not pose a problem for the detector. The required position resolution of a few hundred micrometers has thus been proven. The two dark blue vertical and horizontal lines are defective channels of the VMM3a chip. In the final version of the detector readout, only quality class A chips will be used, so that such artefacts will not pose a problem.

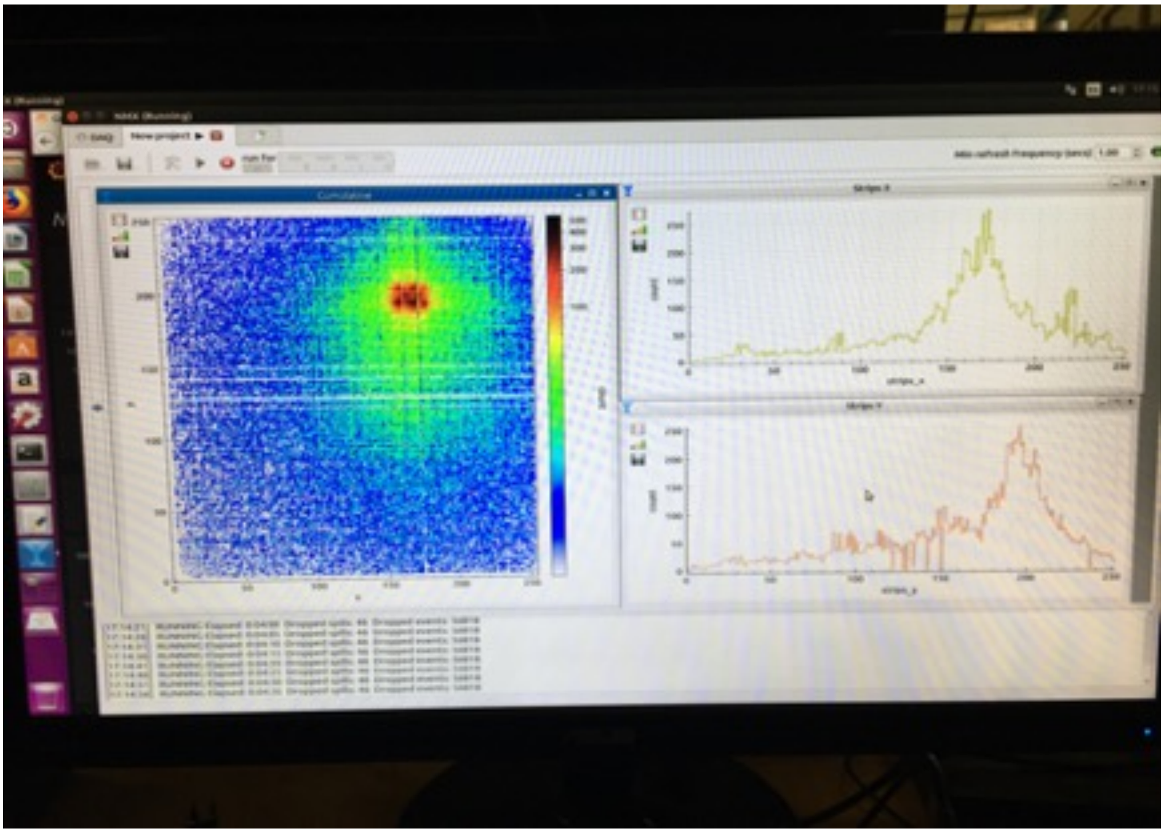


Figure 12. DAQ PC running the DMSC DAQ and the online monitoring tool DAQUIRI. Picture taken during the BMC test beam.

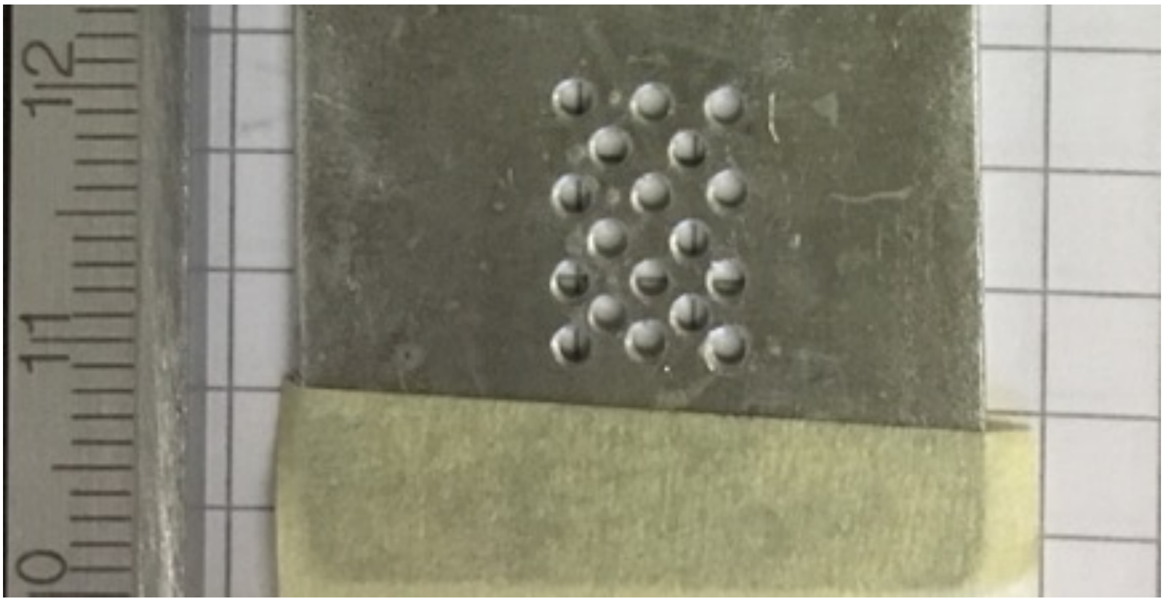


Figure 13. Cd mask with holes of 1.0 mm diameter. The holes have a minimum separation (centre to centre) of about 2 mm horizontally, 1.6 mm vertically, and 1.3 mm diagonally.

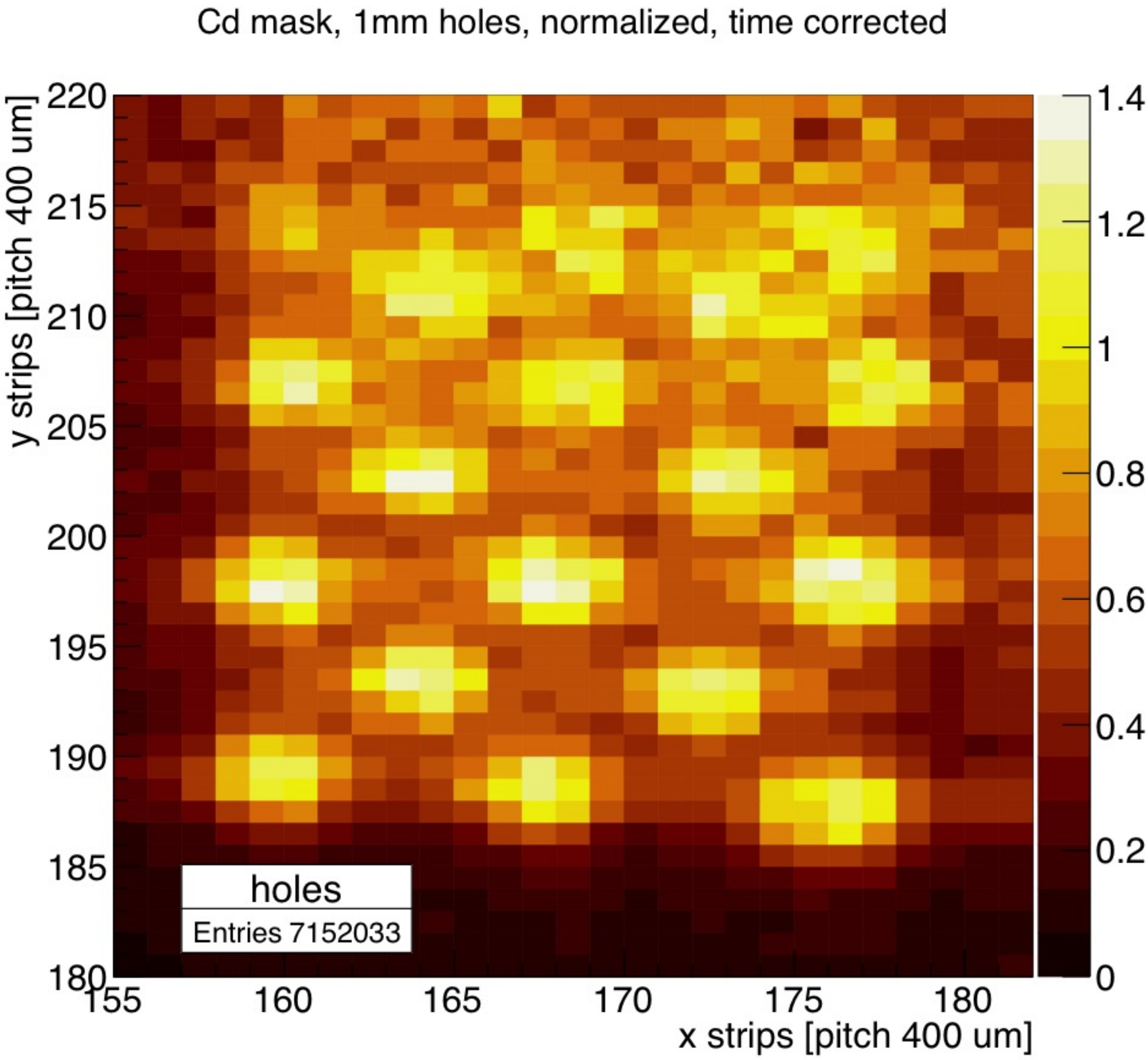


Figure 14. Image of the Cd mask with 1.0 mm holes size. The beam was focused on the lowest three rows of the mask. The holes there can be clearly resolved.

Figure 15. Patrik Thuiner, responsible for the detector design and construction, during the tests at BNC.

8 Conclusions

This deliverable documents the design and construction of a demonstrator module for the NMX instrument at ESS, as the culmination of task 4.1. The technology chosen for this is the Gd-GEM detector design. As part of this deliverable, the design summary, a description of the electronics chain, a step-by-step guide of the detector assembly as well as recent results from a reduced scale demonstrator have been shown. This deliverable in particular shows the engineering design assembly. The demonstrator module meets the requirements set as part of this task.

As well as delivering the demonstrator, this task has pushed the boundary of understanding on several fronts, which will have a lasting impact in the coming years. First of all, the systematic investigation of Gadolinium convertors has concentrated the current state of knowledge of these convertors in one place, namely the ESS detector group. Since the literature states diverging data with regard to the neutron detection efficiency, the review of the Gd convertor properties carried out under BrightnESS will act as a resource for the future. This allows a greater understanding on how and for which specific application Gd-based detectors can be realized. There has also been much practical progress on the current availability of enriched Gadolinium, enabled by this task. The engineering knowledge of how to roll Gd foils of appropriate properties is also a great advance, as well as the method developed for welding Gd to Al. As Gd is a material of potentially wide application, this allows steps to be made in realising this. Task 4.1 has also an impact on the realm of MPGD detectors, because this task set out to explicitly to use GEMs as amplification stage of the detector. The low material budget readout has been designed to be as neutron transparent as possible. The design optimisations made here, will be helpful for other future detector designs in different fields of application.

In terms of more generic impact, advances have been made in simulations and in terms of electronics and data acquisition. In terms of simulations, to be able to simulate the complete NMX detector, it was necessary to link Garfield++ and GEANT4, which is the subject of a paper currently under review. This was a gap in simulating gaseous detectors that has existed since many years.

The electronic readout of detectors is a fundamental aspect of their design. Since the beginning a special effort was made on having a complete readout chain available at the end of BrightnESS. By taking a leading role here on the implementation of the VMM chip into the RD51 Scalable Readout System (SRS), a complete working readout chain has been obtained. Such a capable and performant chain is of great interest to the RD51 community as a whole, not just ESS, and allows the possibility for its spread and popularisation.

This task took a very proactive and open approach to the data acquisition since the beginning. One of the particular aspects that has benefited hugely is the cross links with WP5 on data. The electronics and DAQ system was used to drive the implementation and commissioning of the computing parts of the ESS data acquisition system, and cemented the strong cross cutting tasks within BrightnESS WP4/5. The complex data analysis required from the Gd-GEM design as part of task 4.1 was used to stress-test the algorithm and capability of the event formation tasks within WP5. In turn this development has led to wider interest in the ESS data acquisition system from outside parties.

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