GP2M: A modular detector for the emergent field of energy resolved neutron imaging and 3D reconstruction

Daniel E. Pooley,[1*] Jaya J. John,[3] Winfried Kockelmann,[1] Jason W. L. Lee,[2,4] Ben Marsh,[1] Nigel J. Rhodes,[1] Erik M. Schooneveld,[1] Iain Sedgwick,[1] Claire Vallance[2]

[1] Rutherford Appleton Laboratory, Harwell Oxford, Didcot, OX11 0QX, UK;
[2] Department of Chemistry, Chemistry Research Laboratory, 12 Mansfield Rd, University of Oxford, Oxford, UK;
[3] Department of Physics, Denys Wilkinson Building, Keble Rd, University of Oxford, Oxford, UK;
[4] Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany;
*Corresponding author: daniel.pooley@stfc.ac.uk

ABSTRACT

GP2M is a modular system for large field-of-view, high spatial resolution, energy resolved neutron imaging. Our novel 'chip-on-board' PCB is minimally wider than the 'PImMS' sensor and protrudes sufficiently to place the sensor out in free space. A semi-tight tiling geometry provides full-beam coverage efficiently, whereas the freedom to position modules independently makes GP2M ideal for multi-axial tomography. No cooling or vacuum is required, permitting high spatial resolution 'contact' images. We discuss the merit of the production of a 'stitched' version of the sensor. We present the long-term vision (widespread industrial uptake alongside a compact neutron source) and the pragmatic route to market via the neutron facilities.

Keywords: GP2M; neutron; imaging, energy resolved, sensor, CMOS, gadolinium.

1. INTRODUCTION

New detector technology is critical to the application of energy resolved neutron imaging (ERNI) to industrial and scientific communities. ERNI is a powerful non-destructive technique that has already demonstrated scientific impact, particularly for materials development across energy storage, additive manufacturing and industrial applications. Neutron imaging can be thought of as the neutronic equivalent of the familiar 'broken-bone x-ray' imaging, and is a well-established non-destructive technique. The addition of energy analysis provides information on phase, texture and strain [1], making it ideal for the study and 3D visualisation of the failure-behaviour of components [2]. Neutron imaging is uniquely suited to the study of hydrogen and lithium, elements virtually invisible to x-rays. Neutron imaging of these light elements, particularly when encapsulated in metallic containers is important for clean energy science such as battery research [3].

This project has addressed a major challenge for ERNI detector technology: delivery of an efficient, high-resolution imaging system than can image a large field of view (FoV). To date, most of the scientific impact has come from samples suited to a FoV of just a few cm^2, limiting impact. To upscale ERNI to wider application, both as a technique at the international facilities and on an industrial scale, the FoV has to be substantially increased. Our development of the first detector system that can efficiently raster over the full FoV will demonstrate the scientific and socio-economic impact of this new capability and justify the wafer-scale sensor proposed for ATTRACT phase 2.

This project has delivered the world's first modular ERNI detector system. The key to our technology is the bespoke high aspect ratio PCB. The PCB is fractionally wider than the dedicated ERNI sensor that it accommodates, meaning that coverage can be built up by tiling modules together in a number of geometries. Our system demonstrates the benefits of a large FoV, while maintaining the flexibility of a modular system.

2. STATE OF THE ART

Comparison should be drawn to two technologies being developed to meet the requirements of ERNI, namely the 'MCP/Timepix' detector developed by Tremsin et al, based in Berkeley, USA [4] and the 'µNID' time-projection-chamber developed by Parker et al [5], based at JPARC, Japan.

The boron-doped micro-channel plate (MCP) technology is read out with a quad array of Timepix sensors. This technology has led to the development of many ERNI techniques, with numerous publications across a wide range of applications. Spatial resolution can be up to 15 µm [6] via centroiding, making the detector well suited

to samples (of size up to 28×28 mm^2) with very small features. Conversely, GP2M is being developed for scalability to large FoV.
The µNID is a gaseous time-projection-chamber with a large active area (10×10 cm^2). GP2M can be scaled to larger area and can improve on the spatial resolution and count rate capability, which needs to be in excess of $10^6 \cdot$counts$\cdot$s^{-1}cm^{-2}.

Both the MCP and the µNID detectors require high vacuum for operation, in contrast to GP2M which operates in open air and has a comparatively small footprint. GP2M sensors can be placed freely and flexibly in and around the sample, allowing it to specialise in ‘contact images’, where the sample to sensor distance is minimised to provide the best resolution possible.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

GP2M is unique amongst ERNI detectors due to the combination of features in one technology. For example it is operated in free space/air, with the sensor itself extending out independently as seen in **Fig 1** and **Fig 3**. No other services are taken to the sensor, such as vacuum or cooling. This provides complete flexibility for sensor placement, allowing contact-images of any part of a sample. Active area is easily increased by tiling the sensors together, leaving a gap less than one sensor width. A single sample-translation will efficiently fill the gaps, providing a full-width image. Combining this with the small form factor of the detector electronics and lightweight body makes the sensor portable and flexible, and opens up novel detector geometries. Importantly each detector can be operated independently, or multiple sensors can be triggered on the same start signal. The combination of these properties opens up new and efficient methods for data acquisition, such as multi-axial tomography, in which several samples are studied independently with one neutron source. No other ERNI detector is physically small enough to do this with high resolution and high count-rate capability.

4. PROJECT RESULTS

Our project develops the prototype ‘GP2’ detector [7], improving its area coverage and neutron detection efficiency to make it a leading ERNI technology. We report the design and development effort undertaken, emphasising the key innovations. Neutron beam results are expected in late 2020 once operations have recommenced in the wake of the COVID-19 pandemic.

Towards Large Area

‘Large area’ in the context of ERNI is approximately 20×20 cm^2, dictated by the capability of world-leading sources to produce well conditioned and intense neutron beams of this size. Our technology uses a monolithic CMOS sensor known as ‘PImMS’ [8] to record images at different times, resolving the neutron energy distribution within each pixel. The sensor measures 22.6×22.6 mm^2, the typical limit of any complex CMOS sensor due to diminishing fabrication yield with area.

Building up the total sensor area by tiling individual sensors on one large PCB is the traditional development pathway. Instead we developed a modular system. This enables us to achieve semi-tight tiling, in which the sensors are spaced apart less than the sensor dimension, but not close enough to be ‘gapless’, and provides unparalleled flexibility for detector positioning. The key to this flexibility is the high aspect ratio PCB, developed by aSpect Systems GmbH [9]. Further technical complexity arose as the sensor cannot have any material directly behind it without a reduced spatial resolution due to backscattering. The solution to this problem, removing a window of material, substantially reduced the available area to route tracks to the sensor, as seen in Fig 1. The final design uses a 16-layer PCB to provide 686 connections to the sensor bonding pads Fig 2.

Towards High Efficiency

The sensor is sensitive to neutrons due to a surface coating of gadolinium, which releases electrons upon neutron

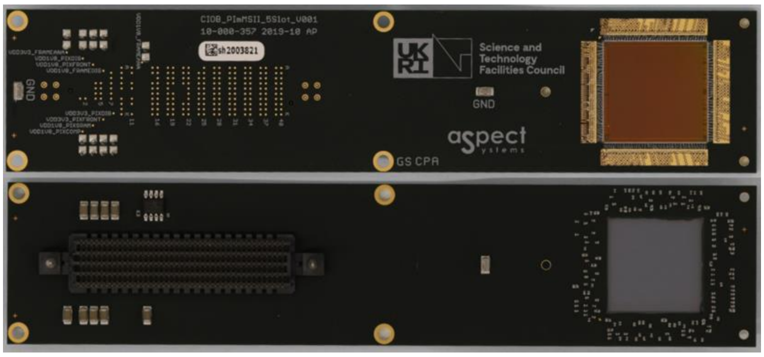

Fig 1. The high aspect ratio GP2M PCB. Front and back views of the same PCB. The sensor is mounted over the window seen bottom right. The board dimensions are 185 mm × 40 mm.

capture. To improve the detection efficiency we are developing a novel 'sandwich structure'. The sensor has to be thinned (~30µm) and coated on both sides with gadolinium metal. Previous attempts at a similar process have failed due to the deposition process causing thermal stress and fracture of the thinned sensors. To overcome this problem a new process has been developed. Gadolinium is first deposited on a full thickness sensor, and encapsulated in SiN (Fig 2) for protection during the thinning process. The sensor is subsequently affixed to a rigid substrate, also coated in gadolinium. Construction of the sandwich structure in this way ensures minimal manipulation of the thinned sensors, increasing yield.

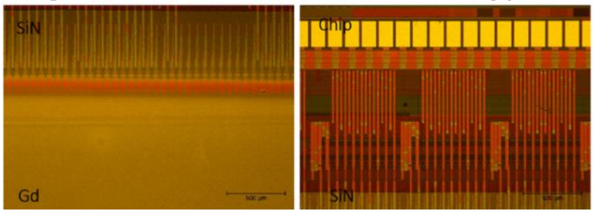

Fig 2. Close up of the SiN encapsulation. LEFT: Gadolinium covering the PImMS sensor pixels, with a larger area of SiN encapsulation also coving the metallic tracks. RIGHT: showing that the SiN encapsulation does not cover the bond pads, used to connect to the PCB. Scale bars measure 500 µm.

A Modular Approach

GP2M is designed to be flexible, providing detector coverage for any required geometry. One example, shown in Fig 3 provides semi-tight tiling geometry in one dimension. The chassis is also used for multi-axial tomography, where each sensor is used in conjunction with an individual and independent rotation axis.

Fig 3. Three GP2M units populating a 5-slot chassis. Each camera is operated independently and can be placed in any slot or outside of the chassis entirely.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Scaling the GP2M system from TRL-4 to TRL-7 requires the development of a robust user interface and a standardised detector commissioning process. Currently the technology is only operable by expert users with in-depth knowledge of detector technology and debugging competency. We require a dedicated test & commissioning programme, working alongside software and firmware engineers to create a seamless user interface. Sensor quality-assurance measures such as pixel-probing techniques are required, along with new laboratory infrastructure. However, the size and focus of our scaling operation is contingent on the project vision, which is considered and defined at this stage.

Vision strategy

Our long-term vision of ERNI finding widespread 'in-house' industrial application is contingent on compact neutron source (CNS) development. The realisation of an appropriate CNS **[10]** is likely on a 10+ year time scale, outside of ATTRACT-2, during which time detector technology will have progressed. The prudent development strategy for GP2M is to provide ERNI to the industrial and academic communities at international facilities, while simultaneously developing the next-generation of detector. The single biggest limitation is the lack of continuous active area. GP2M will demonstrate the benefits of increased active area, and will build up continuous coverage via detector translation and images post-processing. However, increasing the size of the PImMS sensor itself will provide unprecedented detection capability and is the key to developing a market-leading product on the timescale of CNS deployment. We propose to increase the sensor area using 'stitching' techniques [11], which has been successful for simpler CMOS sensors [12]. To ensure economical yield we would restrict stitching to one dimension, creating rectangular sensors (25×97 mm^2) compatible with the PCB developed here Fig 1. A sketch of our design proposal is shown in Fig 4. The estimated fabrication cost is £800k, with the supporting development programme over 3 years being similar.

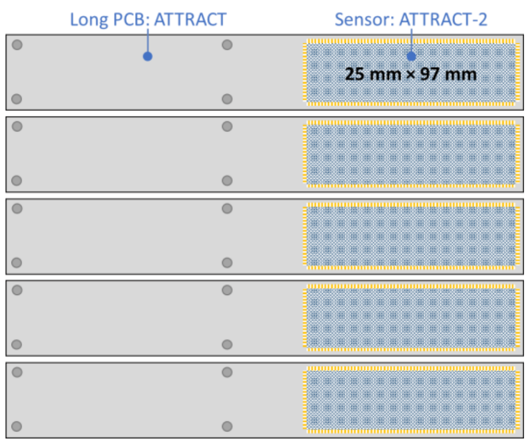

Fig 4. Camera system build using stitched sensors and the long-thin PCB developed within ATTRACT.

5.2. Project Synergies and Outreach

Production of a new CMOS sensor requires a multi-disciplinary approach. STFC Technology will lead on the sensor design and fabrication. The sensor will be optimised for the requirements of ERNI, tuning its sensitivity, timing properties and count rate capability. Development of a new sensor is an opportunity to ensure that its operational range is suitable for other similar techniques, providing there is no compromise with regard to its primary use. Generally speaking, a pixelated imaging sensor with high temporal resolution is suited to numerous ‘time of flight’ techniques. One such example is time-of-flight mass spectrometry, for which the PImMS sensor was designed [13]. This technique has wide reaching application across multiple fields [14]. Potential commercial applications requiring highly sensitive chemical identification would further the impact of this development. This class of sensor would also be suited to proton beam imaging as a tool in proton beam therapy, improving dose control and accuracy.

5.3. Technology application and demonstration cases

The deployment of ERNI detector technology to the European neutron facilities will enable the study of a range of scientific and engineering challenges such as:

- Energy materials: Solid Oxide Fuel cells [15]
- Battery Materials: Lithium concentration mapping [16]
- Environment: Heavy toxic metal uptake in plant systems [17]

Many of these systems are uniquely suited to neutron imaging, which can resolve light elements in the presence of heavy elements in many cases. They are also highly penetrating, allowing investigation into systems that are not accessible by X-rays. For example, neutrons are uniquely sensitive to hydrogen and lithium isotopes, critical materials for the renewable energy sector. The technique that our ATTRACT-1 detector specialises in, ‘energy-resolved’ imaging, provides advanced information such as the material distribution, and spatial maps of the residual strain and texture of a material inside a sample. These are critical parameters in failure-mechanism investigations and quality assurance, such as the manufacture of components for aerospace, submersibles, and high-performance machines. Energy-resolved imaging can provide this information in both 2D and 3D.

The recent drive to produce laser-driven and ‘table top’ accelerator-based neutron sources makes wider application of ERNI across both industry and smaller research institutes an exciting opportunity. Many of these compact sources are ideally suited to ERNI due to their pulse structure; a synergy readily exploited provided that suitable detector technology is developed. Techniques ranging from diagnostic tools to conveyor-belt quality control can be envisaged in an industrial setting, while adoption of ERNI across academic subjects at research institutes is already developing. While the development of laser sources has only recently passed the proof-of-principle stage [14], it is realistic to envisage such sources becoming available over a 10-year time scale. Clearly, at this point the demand for ERNI detectors will increase dramatically. The potential “European network” of accelerator-driven facilities is articulated by Rücker et al [18], who propose source availability to rival that in Japan [19].

5.4. Technology commercialization

Deployment of GP2M would likely be through the commercialisation arm of either STFC or the University of Oxford. The technology scaling described in section 5.1 is considered a pre-requisite to producing a minimal viable product, with the second product coming from the new CMOS sensor described. Our initial market (early adopters) will be neutron beam source facilities, which are generally more flexible. Interested parties include the Chinese Spallation Source and the ESS, both of whom have expressed interest in our technology.

Widespread application and maximum return goes hand-in-hand with the commercialisation of compact neutron sources (CNS). CNS are under development worldwide, attracting high levels of funding and effort. There are several companies now commercialising accelerator based sources, while the multi-modal laser source technique has only recently been demonstrated [20]. Next generation CNS are truly disruptive technologies, as neutron techniques that are only possible at the few facilities that exist worldwide will become widespread. The appropriate parallel would be the advent and application of an X-ray tube, which is now widely used across industry and academia.

5.5. Envisioned risks

The investment risk is difficult to quantify. Part of our strategy is to develop technology for use at international facilities, where it will be used to tackle global challenges such as energy storage and industrial innovation. These facilities generally serve the academic community without fee, or offer their services to industrial partners at cost. Neither scenario reflects the true value derived from the experiment, but both directly address the core aims of ATTRACT-2. Mitigation against mismatched expectations requires understanding of the socio-economic impact this technology has, with effective communication to our stakeholders, inclusive of the public.

The largest technology risk within ATTRACT-2 is sensor fabrication. This will be minimised by working with a trusted sensor architecture, in a volume large enough to ensure a minimal number of viable devices.

5.6. Liaison with Student Teams and Socio-Economic Study

Supporting young scientists at MSc level is already well established at our facility. For example, during ATTRACT we recruited a sandwich student (one-year degree placement) to commission GP2M. Expanding our engagement to MSc teams is a natural extension, with the corresponding author being the correspondent.

ATTRACT's expert-driven socio-economic study will be extremely valuable to our project, and links back to the value-assessment risk discussed in 5.5. The nature of our project does not fit neatly into a commercialisation model, as it is highly dependent on the large-scale facilities. Therefore we highly prize understanding of the socio-economic impact of our work and would engage via all appropriate channels. We would provide comprehensive usage information, particularly for scientific studies as these seed technology innovation on a much longer timescale and are often undervalued.

6. ACKNOWLEDGEMENT

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

The authors are additionally thankful for support from the following funding bodies: the UK EPSRC (C.V. - EP/L005913/1), STFC (PNPAS award and mini-IPS Grant No. ST/J002895/1) and STFC Centre for Instrumentation.

7. REFERENCES

[1] R. S. Ramadhana, A. K. Syed, A. S. Tremsin, W. Kockelmann, R. Dalgliesh, B. Chen, D. Parfitt & M. E. Fitzpatrick, 2018. Mapping residual strain induced by cold working and by laser shock peening using neutron transmission spectroscopy, Materials & Design, (143): pp. 56.

[2] R. Woracek, D. Penumadu, N. Kardjilov, A. Hilger, M. Boin, J. Banhart & I. Manke, 2014. 3D Mapping of Crystallographic Phase Distribution using Energy-Selective Neutron Tomograph, Advanced Materials, (26): pp. 4096.

[3] R. F. Ziesche, T. Arlt, D. P. Finegan, T. M. Heenan, A. Tengattini, D. Baum, N. Kardjilov, H. Markötter, I. Manke, W. Kockelmann, D. J. Brett & P. R. Shearing, 2020. 4D imaging of lithium-batteries using correlative neutron and X-ray tomography with a virtual unrolling technique, Nature Communications, (111): pp. 777.

[4] J. Vallerga, R. Raffanti, A. Tremsin, J. McPhate & O. Siegmund, 2011. MCP detector read out with a bare quad Timepix at kilohertz frame rates, JINST, 1(6): pp. C01049.

[5] J. D. Parker, M. Harada, H. Hayashida, K. Hiroi, T. Kai, Y. Matsumoto, K. Oikawa, M. Segawa, T. Shinohara, Y. Su, A. Takada, S. Zhang, T. Tanimori & Y. Kiyanagi, 2016. Development of the next-generation micro pixel chamber-based neutron imaging detector (μNID) for energy-resolved neutron imaging at the J-PARC/MLF, IEEE NSS pp. 1.

[6] A. S. Tremsin, J. V. Vallerga, J. B. McPhate, O. H. Siegmund, W. B. Feller, L. Crow & R. G. Cooper, 2008. On the possibility to image thermal and cold neutron with sub-15 μm spatial resolution, Nuclear Instruments and Methods A, (592): pp. 374.

[7] D. E. Pooley, J. W. L. Lee, M. Brouard, J. J. John, W. Kockelmann, N. J. Rhodes, E. M. Schooneveld, I. Sedgwick, R. Turchetta & C. Vallance, 2017. Development of the "GP2" Detector: Modification of the PImMS CMOS Sensor for Energy-Resolved Neutron Radiography, IEEE TNS, 12(64): pp. 2979.

[8] I. Sedgwick, A. Clark, J. Crooks, R. Turchetta, L. Hill, J. J. John, A. Nomerotski, R. Pisarczyk, M. Brouard, S. H. Gardiner, E. Halford, J. W. Lee, M. L. Lipciuc, C. Slater, C. Vallance, E. S. Wilman, B. Winter & W. H. Yuen, 2012. PImMS: A self-triggered, 25ns resolution monolithic CMOS sensor for Time-of-Flight and Imaging Mass Spectrometry, IEEE NEWCAS.

[9] Available: http://aspect-sys.com.

[10] J. M. Carpenter, 2019, The development of compact neutron sources, Nature Reviews Physics, 3(1): pp. 177.

[11] R. Turchetta, N. Guerrini & I. Sedgwick, 2011. Large area CMOS image sensors, JINST, (6): pp. C01099.

[12] I. Sedgwick, D. Das, N. Guerrini, B. Marsh & R. Turchetta, 2013. LASSENA: A 6.7 Megapixel, 3-sides Buttable Wafer-Scale CMOS Sensor using a Novel Grid-Addressing architecture, Proc. International Image Sensor Workshop pp. 297.

[13] M. Brouard, E. Halford, A. Lauer, C. Slater, B. Winter, W. Yuen, J. John, L. Hill, A. Nomerotski, A. Clark, J. Crooks, I. Sedgwick, R. Turchetta, J. Lee, C. Vallance & E. Wilman, 2012. The application of the fast, multi-hit, pixel imaging mass spectrometry sensor to spatial imaging mass spectrometry, The Review of Scientific Instruments pp. 83.

[14] C. Vallance, M. Brouard, A. Lauer, C. S. Slater, E. Halford, B. Winter, S. J. King, J. W. Lee, D. E. Pooley, I. Sedgwick, R. Turchetta, A. Nomerotski, J. J. John & L. Hill, 2014. Fast sensors for time-of-flight imaging applications, Phys. Chem. Chem. Phys., (16): pp. 383.

[15] M. G. Makowska, M. Strobl, E. M. Lauridsen, H. L. Frandsen, A. S. Tremsin, N. Kardjilov, I. Manke, J. F. Kelleher & L. T. Kuhn, 2017. Effect of stress on NiO reduction in solid oxide fuel cells: A new application of energy-resolved neutron imaging, Journal of Applied Crystallography, (48): pp. 401.

[16] K. Kino, M. Yonemura, Y. Ishikawa & T. Kamiyama, 2016. Two-dimensional imaging of charge/discharge by Bragg edge analysis of electrode materials for pulsed neutron-beam transmission spectra of a Li-ion battery, Solid State Ionics, (288): pp. 257.

[17] G. Burca, S. Nagella, T. Clark, D. Tasev, I. A. Rahman, R. J. Garwood, A. R. Spencer, M. J. Turner & J. F. Kelleher, 2018. Exploring the potential of neutron imaging for life sciences on IMAT, Journal of Microscopy.

[18] U. Rücker, T. Cronert, J. Voigt, J. P. Dabruck, P. E. Doege, J. Ulrich, R. Nabbi, Y. Beßler, M. Butzek, M. Büscher, C. Lange, M. Klaus, T. Gutberlet & T. Brückel, 2016. The Jülich high-brilliance neutron source project, The European Physical Journal Plus, (19): pp. 131.

[19] Japan Collaboration on Accelerator-driven Neutron Sources, Available: http://phi.phys.nagoya-u.ac.jp/JCANS/jcans.html.

[20] S. R. Mirfayzi, A. Alejo, H. Ahmed, D. Raspino, S. Ansell, L. A. Wilson, C. Armstrong, N. M. H. Butler, R. J. Clarke, A. Higginson, J. Kelleher, C. D. Murphy, M. Notley, D. R. Rusby, E. Schooneveld, M. Borghesi, P. McKenna, N. J. Rhodes, D. Neely, C. M. Brenner & S. Kar, 2017. Experimental demonstration of a compact epithermal neutron source based on a high power laser, Appl. Phys. Lett., 4(111): pp. 044101.