Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA 9 Physics		
Title of case study: From astronaut protection to microscopy, medical and civil nuclear areas: The safety and economic impacts of UofG's advanced particle-detector chips		
Period when the underpinning research was undertaken: 2009–present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Valentine O'Shea	Professor	1992−present
Damien McGrouther	Senior Lecturer	2006−present
Stephen McVitie	Professor	2010−present
Dzmitry (Dima) Maneuski	Research Fellow	2009−present
Michael Perreur-Lloyd	Research Fellow	2002−present
Period when the claimed impact occurred: 2013−present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

MediPix and TimePix are particle detector chips characterised by UofG researchers, which have generated [text removed for publication] licensing royalties and created [text removed for publication] skilled jobs in licensee companies. The chips have been used by NASA to better understand crew protection needs and also underpin a USD1.05 million project with radiation detection company, Kromek, to deliver next-generation nuclear radiation detectors to the US Defense Threat Reduction Agency. UofG research also developed technology to integrate MediPix3 into high-value electron microscopes, licensed to Quantum Detectors Ltd (QD). The technology enabled development of 4 new products for QD, (earning the company GBP2.6 million in revenue) and inspired other companies to enter the TEM (transmission electron microscopes) market with MediPix-based products.

2. Underpinning research

Background

The MediPix family of integrated circuits are directly bonded to pixelated semiconductor detectors for high-speed counting of single-photon events. Initially developed for quantitative imaging of fundamental particles at the Large Hadron Collider, CERN, a key strength is their high pixel density and capability to tile multiple detectors for large-area x-ray imaging with very high contrast. UofG co-founded the MediPix1 collaboration in the 1990s (with CERN and Universities of Freiburg & Napoli/Pisa) with the aim of transferring technologies to applications outside of high-energy physics. The collaboration's success led to the MediPix2, MediPix3 collaborations (in which UofG was the only UK partner) and, in 2016, to the MediPix4 collaboration, reliant upon critical through-silicon-via (TSV) technology developed by UofG. Two main chip types have been developed:
(1) MediPix chips target spectroscopic X-ray imaging at rates compatible with medical CT (computed tomography) imaging
(2) TimePix chips provide spatial and timing resolution, enabling identification of different particle types in radiation dosimetry.

UofG research using MediPix/Timepix chips

UofG has played a leading role in the developments of MediPix/Timepix chips, driving technology development, assessment and application across the MediPix1-4 collaborations.

Outstanding UofG contributions include:

(1) **Development of TSV technique for MediPix4/Timepix4:** fabrication protocols developed by UofG through a STFC-sponsored programme at CERN enables readout of signals from the back of the MediPix4 and TimePix4 chips, rather than from one edge, to facilitate optimal distribution of power and timing signals across larger die sizes [3.1]. This technology is a defining difference for the new MediPix4 chips which can be tiled on all four sides enabling large-area arrays to be assembled.

(2) **MediPix3/Timepix in electron microscopy:** funded across a range of EPSRC programmes, UofG's O'Shea and McGrouther pioneered integration of MediPix3 detectors into transmission electron microscopes (TEMs). Their research developed novel imaging capabilities including, 4-dimensional data acquisition for >10x increased magnetic/electric field image sensitivity [3.2], "ideal" detector performance suited to low atomic number materials [3.3], and high-speed movies of structure dynamics [3.4]. This integration technology has been licensed to Quantum Detectors Ltd. Funded by STFC, efforts continue to further improve performance through use of semiconductor detector materials and Timepix3. Maneuski and colleagues also demonstrated the use of TimePix chips to directly detect electrons in scanning electron microscopy (SEM), a step-change improvement in SEM functionality compared to indirect scintillation-based detectors [3.5].

(3) **Assessment of MediPix3 for enhanced positron emission tomography (PET):** UofG has demonstrated the superior signal-to-noise ratio provided in combining MediPix3 chips with microfluidics to detect clinical radiotracers for positron-emission tomography (PET) during their manufacture [3.6]. This research demonstrated the ability to produce dose-on-demand radiotracer synthesis for stratified patient treatment.

3. References to the research

3.1. Maneuski, D., Bates, R., Blue, A., Buttar, C., Doonan, K., Eklund, L., Gimenez, E.N., Hynds, D., Kachkanov, S., Kalliopuska, J. and McMullen, T., 2015. *Edge pixel response studies of edgeless silicon sensor technology for pixellated imaging detectors.* Journal of Instrumentation, 10(03), p.03018. DOI: 10.1088/1748-0221/10/03/P03018

3.2. Krajnak, M., McGrouther, D., Maneuski, D., O'Shea, V. and McVitie, S., 2016. *Pixelated detectors and improved efficiency for magnetic imaging in STEM differential phase contrast.* Ultramicroscopy, 165, pp.42–50. DOI: 10.1016/j.ultramic.2016.03.006

3.3. Mir, J.A., Clough, R., MacInnes, R., Gough, C., Plackett, R., Shipsey, I., Sawada, H., MacLaren, I., Ballabriga, R., Maneuski, D. and O'Shea, V., 2017. *Characterisation of the MediPix3 detector for 60 and 80 keV electrons.* Ultramicroscopy, 182, pp.44–53. DOI: 10.1016/j.ultramic.2017.06.010

3.4. Rendell-Bhatti, F., Lamb, R.J., van der Jagt, J.W., Paterson, G.W., Swagten, H.J. and McGrouther, D., 2020. *Spontaneous creation and annihilation dynamics and strain-limited stability of magnetic skyrmions*, Nature Communications, 11 (1), pp.1–9 (2020). DOI: 10.1038/s41467-020-17338-7 *

3.5. Vespucci, S., Maneuski, D., Edwards, P.R., Day, A.P., O'Shea, V. and Trager-Cowan, C., 2015. *Digital direct electron imaging of energy-filtered electron backscatter diffraction patterns.* Physical Review B, 92(20), p.205301. DOI: 10.1103/PhysRevB.92.205301 *

3.6. Tarn, M.D., Maneuski, D., Alexander, R., Brown, N.J., O'Shea, V., Pimlott, S.L., Pamme, N. and Archibald, S.J., 2016. *Positron detection in silica monoliths for miniaturised quality control of PET radiotracers*. Chemical Communications, 52(45), pp.7221–7224. DOI: 10.1039/c6cc00660d

* = best indicators of quality

4. Details of the impact

The impact of the MediPix and TimePix technologies has been the result of fundamental circuit research carried out by UofG, and also on UofG's leadership in the application of the technology within the transmission electron microscopy (TEM) field. These include:

[Text removed for publication.]

Electron microscopy − Economic impacts for Quantum Detectors Ltd. and inspiring a shift to using MediPix chips in leading TEM manufacturers

TEMs are widely used by research institutions and multinational companies in life sciences, electrical engineering and material sciences. In most TEMs, digital images were recorded using an indirect camera, where the electron signal was first converted to light before being recorded. This approach limited imaging performance, in terms of noise levels and image recording rate. The MediPix3 integration work performed by UofG, which showed performance gains from the ability to count each individual electron, was of crucial importance to Quantum Detectors Ltd (QD) in enabling them to develop 4 new products [5.3] and to gain new access to the global TEM market (expected to grow by USD222.1 million by 2022). Leveraging EPSRC Impact Acceleration Funds, UofG and QD collaborated to develop the MerlinEM range of static and retractable detectors. The technology was licensed by UofG to QD in February 2017, and a consultancy agreement in 2018 facilitated technology transfer supporting the production of the detector system by QD [5.3, 5.4]. Sales of >20 detector systems by QD to date have generated GBP2.6 million of revenue for the company and has directly led to an increase in staff from 4 to 18 [5.3].

The vision at UofG and the accelerated speed of the development programme enabled Quantum Detectors to be the first to enter the TEM market with MediPix3. Influenced by the success of Quantum Detectors, during the recent period 2019/20, rival firms Amsterdam Scientific Instruments B. V. [5.5] and X-Spectrum GmbH [5.6] have entered the TEM market, with MediPix3-based detectors. Due to their market penetration, QD have been able to gain recognition from the main TEM manufacturers Hitachi High Technologies and ThermoFisher Scientific, through having products assessed for "approved" status. The success of the detector has also led to the largest TEM detector manufacturer, AmeTek Gatan Inc. (valued at USD925 million) entering the marketplace with a detector that provides similar capabilities to the QD MerlinEM [5.7].

Safety impacts for NASA using TimePix

[5.8] Since 2009, NASA has been assessing the use of TimePix-based radiation detectors to monitor the levels of high-speed ionising radiation on the International Space Station (ISS). TimePix radiation detectors are key to monitor and protect both astronauts and vital equipment during solar storms. TimePix detectors have enabled NASA to develop lighter radiation detectors, including the TimePix USB Lite Interface devices (in collaboration with the Czech Republic's Institute of Experimental and Applied Physics). These were deployed on the ISS in 2012 and continually send data to the Mission Control Center, providing information on the location, dose, and speed of radiation. Following the success of initial deployments, a battery-powered version of the detector was used in 2014 on the Orion test flight EFT-1, providing first measurements in the Van Allen radiation belts since the 1960s from within a human-rated space vehicle. Results of trials using TimePix underpinned the development of a new Hybrid Electronic Radiation Assessor (HERA) system for use in NASA exploration missions. A HERA system is scheduled to travel on the first spaceflight of the Space Launch System and Orion crew module, Artemis I, which aims to put the first woman and next man on the moon by 2024.

TimePix3 detectors underpin US Defense Threat Reduction Agency contracts

TimePix3 provides time-resolved measurement of electron energies, widening the application of MediPix3 to medical and civil nuclear areas. UofG collaborated with Kromek (a radiation detection technology company) to develop new algorithms to examine imaging performance of TimePix3 in detecting gamma ray radiation [5.9]. These algorithms have allowed Kromek to enter contracts with the US Department of Defense; UofG is a key collaborator with Kromek in a 3-year, USD1.05 million project to deliver next-generation handheld nuclear radiation detectors to the US Defense Threat Reduction Agency [5.9].

5. Sources to corroborate the impact

5.1. Testimonial, Head of Knowledge Transfer, CERN
5.2. PIXcel3D MalvernPanalytical Specification Sheet https://www.malvernpanalytical.com/en/products/category/x-ray-components/detectors/pixcel3d
5.3. Testimonial, Founder and CEO of Quantum Detectors
5.4. Licence agreement between UofG and Quantum Detectors Limited
5.5. ASI Cheetah MediPix3: https://www.amscins.com/products/em-cheetah/cheetah/
5.6. X-spectrum Amber MediPix3: https://x-spectrum.de/products/amber/
5.7. Gatan/Dectris STELA : https://www.gatan.com/products/tem-imaging-spectroscopy/stela-hybrid-pixel-camera
5.8. NASA article “NASA, CERN TimePix Technology Advances Miniaturized Radiation Detection” https://www.nasa.gov/feature/nasa-cern-TimePix-technology-advances-miniaturized-radiation-detection
5.9. Kromek secures two contracts from US government https://markets.ft.com/data/announce/full?dockey=1323-13726704-476JOCHMD9FDVNJ8HUSR1OBR9E