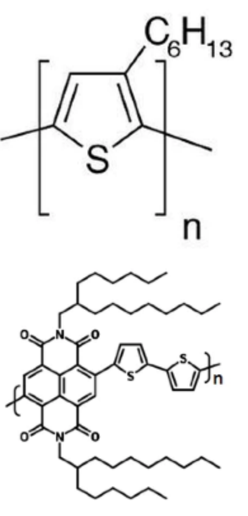
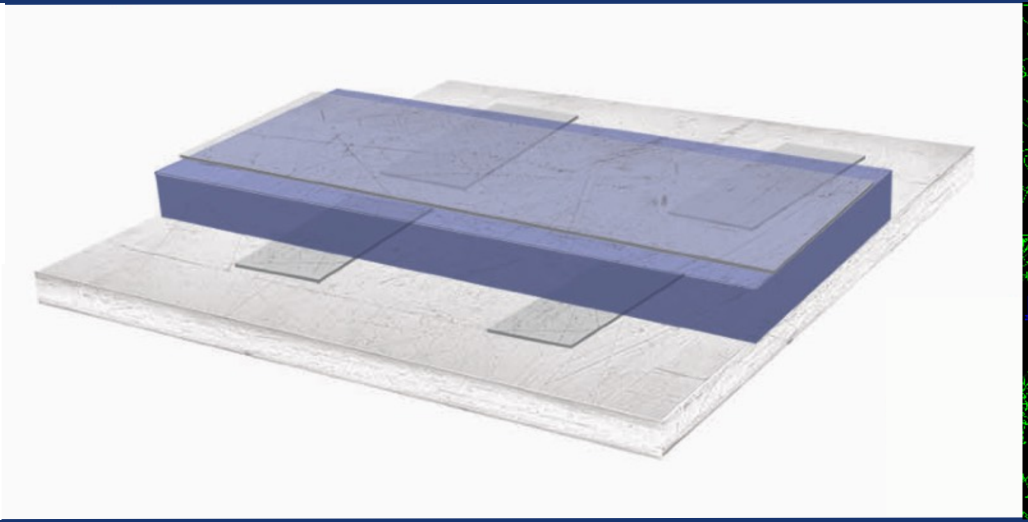
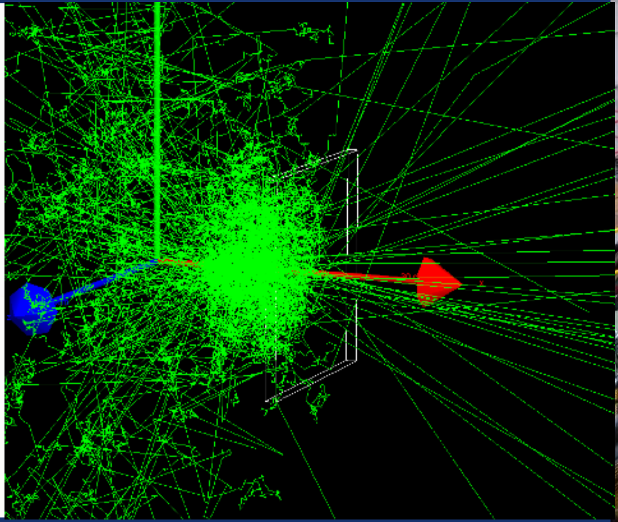
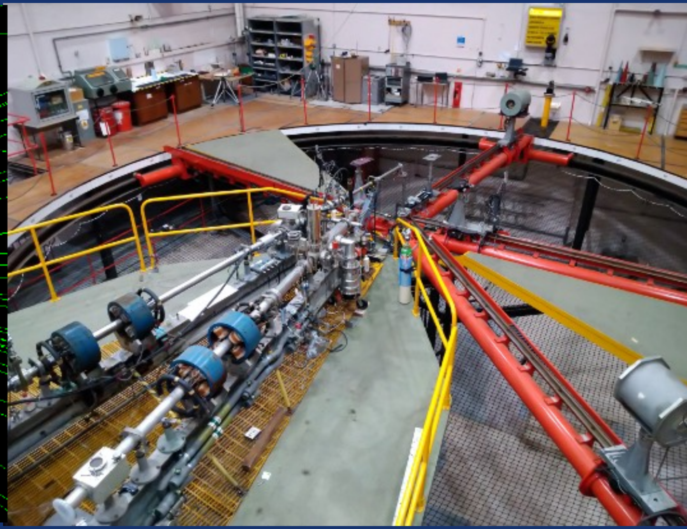
Organic and inorganic neutron detector developments @ QMUL









Position Sensitive Detectors 14, September 2026

Prof. Adrian Bevan a.j.bevan@qmul.ac.uk

QMUL Programme of work

- We are developing technologies over a range of specifications targeting fast and thermal neutron detectors for multiple sectors as discussed in the following

- Targeting solutions for:
  - Low and high flux scenarios
  - Ambient temperature
  - High temperature

- Started to work on system solutions for some technologies, including cost effective readout
  - Focus on what is good enough for current or transient mode detection to balance performance with cost.

Acknowledgements

- **Work presented was performed by the detector development team within QMUL's Detector Development Group**

C. Allwork[1,2], C. Z. Amjad[2], **AB**[2], I. Dawson[2], A. Gashi[2],
D. Gupta[2], P. R. Hobson[2], A. Horner[2], P. Miyagawa[2], F. E. Taifakou[2], S. Zenz[2]

F. Taifakou et al., ACS Appl. Mater. Interfaces 2021, 13, 5, 6470–6479

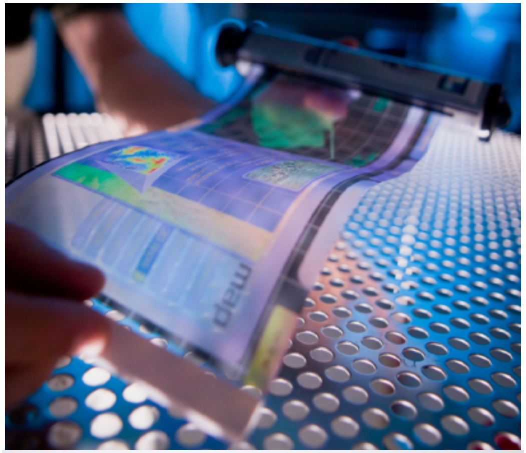
Borowiec et al., arXiv:2212.08438
Bevan et al., NIMA Volume 1069, December 2024, 169882
Horner et al., NIMA Volume 1082, Part 2, February 2026, 170981
Bevan and Dawson, arXiv:2605.03211

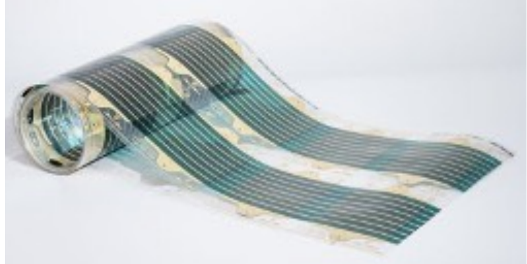
- **We thank our partners and sponsors for funding and other forms of support, and look forward to working with new parters coming onboard**

[1] AWE Nuclear Security Technologies, [2] QMUL

Motivation: ^{3}He alternative neutron detectors

- **Post 9/11: cost and resource constraints made ^{3}He scarce**
- **Illicit material traffic remains a concern for the international community**
- **Today the ^{3}He alternative drive comes from the expanding fission and fusion reactor market.**
- ***Particle physics shares the same neutron detection requirements as all of these market segments.***





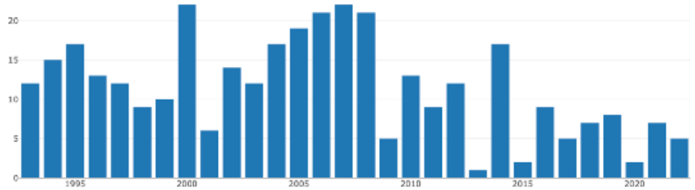
Authorities found two jars containing uranium in a car boot

BBC Article

Security

- Radioactive material exists in many forms
- Detecting Illicit material, out of regulatory control, is a key challenge for countries around the world
  - The whereabouts of 100 suitcase nuclear devices from the Soviet era are still unaccounted for
  - The Russian invasion of the Ukraine has resulted in significant amounts of radioactive material being out of regulatory control for several years
  - Industrial and medical sources are stolen and lost around the world
  - All of these possibilities raise the risk of a terrorist incident involving a viable radioactive device

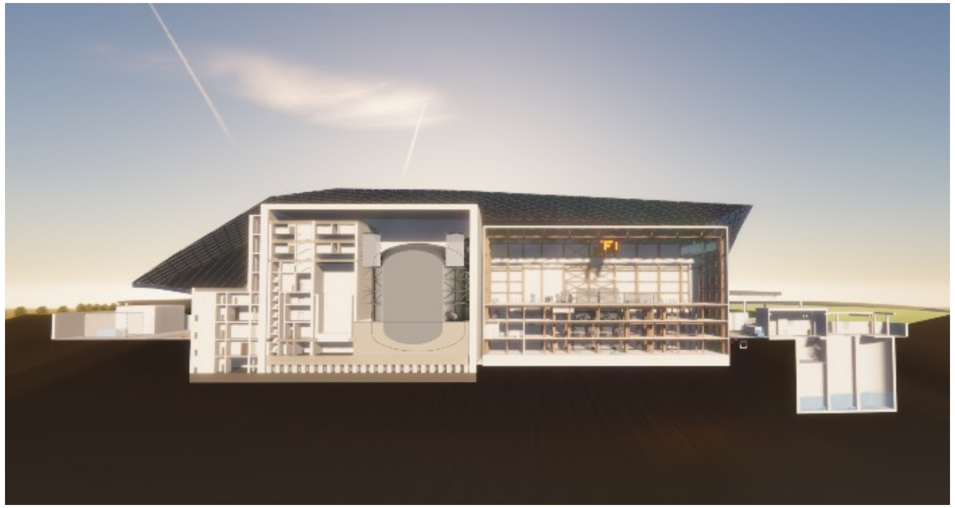
The dome at Chernobyl in the Ukraine



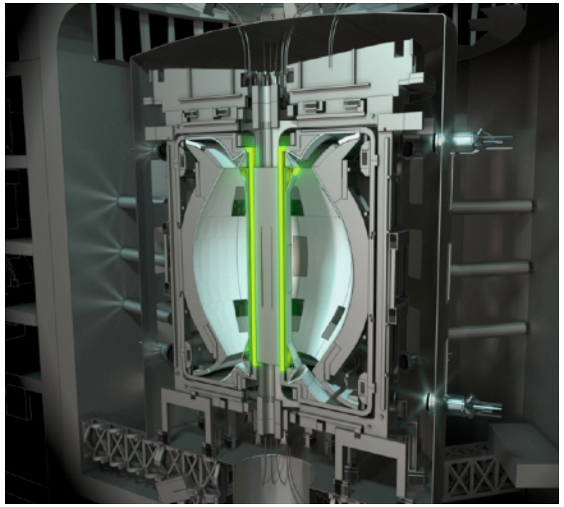
IAEA Incident Tracking Database reports of illicit radioactive material

Net Zero

- Climate change is impacting on global weather patterns and creating frequent severe weather events
- Governments around the world want to decarbonise while increasing energy production to embrace the latest technological advances
- Nuclear energy is a part of the solution: Government is investing £5 billion in SMR and fusion
- Need to detect radiation to properly manage the hazards associated with by products of the nuclear industry



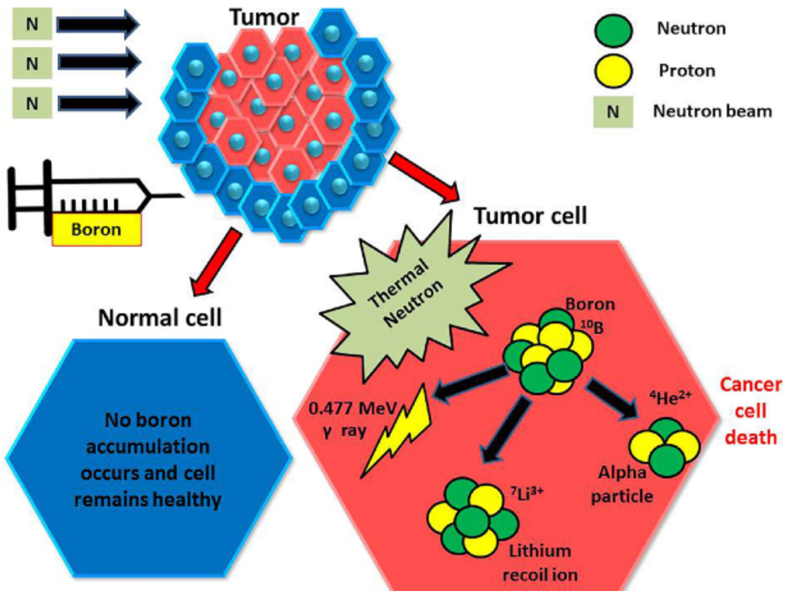
An artist impression of a Small Modular Reactor (c/o Rolls Royce)



An artist impression of a STEP style fusion reactor

Healthcare

- Cancer will affect every 1 in 2 people, according to the NHS
- Radiotherapy is a key component in the treatment portfolio of medical professionals
- Ranges from the use of X-rays and radioisotopes to proton and neutron beams
- Being able to detect these types of radiation is critical to ensure an appropriate delivery of radiation dose to the tumour region in a patient, minimising the dose to healthy tissue
- e.g. Inertial Electric Confinement Fusion can be used to make radioisotopes from neutrons using DD and DT reactors like the ones being developed by Astral Systems

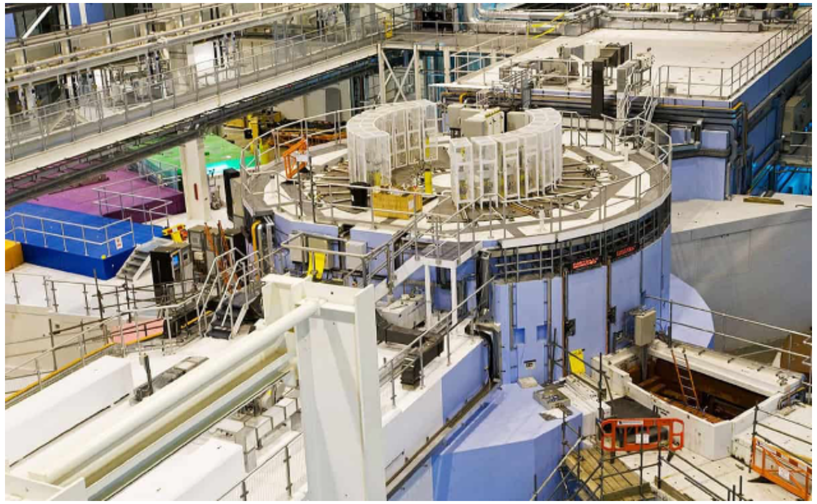


IEC fusion reactor electrode

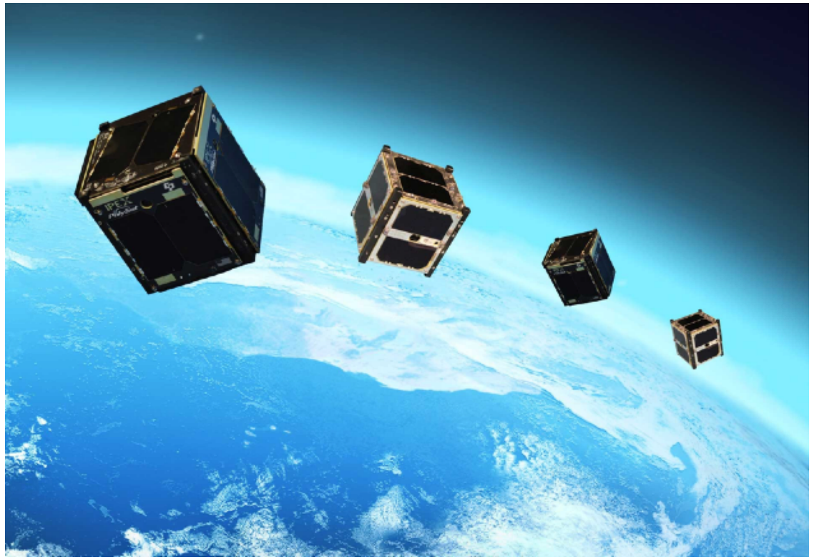
M. Bakr et al., Fusion Engineering and Design 167 (2021) 112346

Industrial Application

- Neutrons are used, or produced in a broad range of industrial applications including:
  - Imaging
  - Minesweeping
  - Oil well logging
- These areas are potential customer bases for neutron detector technologies
- Neutrons are also a measure of space weather and radiation levels in orbit:
  - Lots of space weather can affect communications
  - Astronauts and instrumentation can also be affected
  - Metrology is key



The ISIS neutron facility at the Harwell Campus



Cube sats are a cost effective way to monitor radiation environments in low earth orbit

Fundamental Science

- Neutrons are a key background problem for many aspects of particle physics
- e.g. Beam background sources for SuperKEKB
- e.g. Dark Matter experiment background
- High sensitivity devices with real-time readout would enable a detailed understanding of backgrounds for neutrino and dark matter experiments
  - e.g. real-time mapping of laboratories, to understand cosmic activation of rock near the laboratory in the mine
  - e.g. neutron veto systems to surround active regions of the detector/calibration source monitor

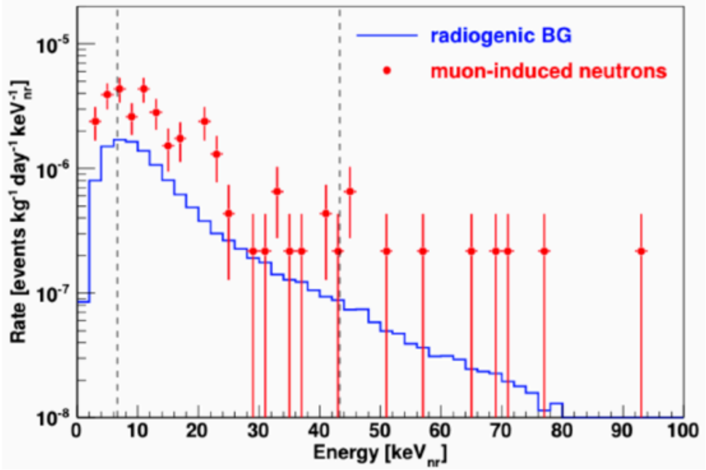
Thermal neutrons in Belle II

Background type	Accelerator tunnel	Flux [$\times 10^2$ n/(cm^{2}s)]
Single-beam	BWD/FWD	1/30
Luminosity	BWD/FWD	20/4

Fast neutrons in Belle II

Background type	Accelerator tunnel	Fluence per smy [$\times 10^9$ n_{eq}/cm^2]
Single-beam	BWD/FWD	6/90
Luminosity	BWD/FWD	40/4

Xenon 1T at LGNS

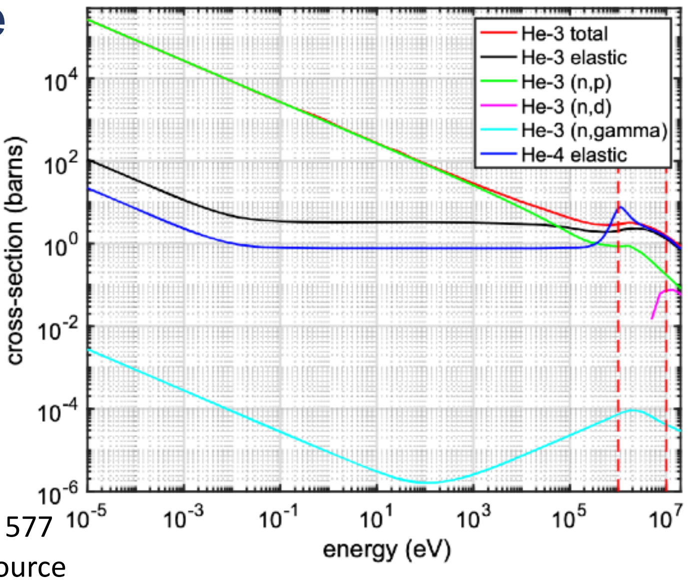


Gas detectors

- ^{3}He proportional detectors are the gold standard for neutron detection via $^3He + n \rightarrow T + p + 0.764\, MeV$.
- High cross section for low energy neutrons

$$\sigma_{thermal}\ (n, p) = 5330\ (\text{barn})$$

- Typically highly efficient detectors, >80% efficiency for devices with some reaching 99%
- Low density, so high γ rejection rate
- Limited supply of ^{3}He, pushes the cost up, and limits the ability to adopt the technology
- BF_3 alternatives exist, but that gas is toxic, so not ideal for wide spread use



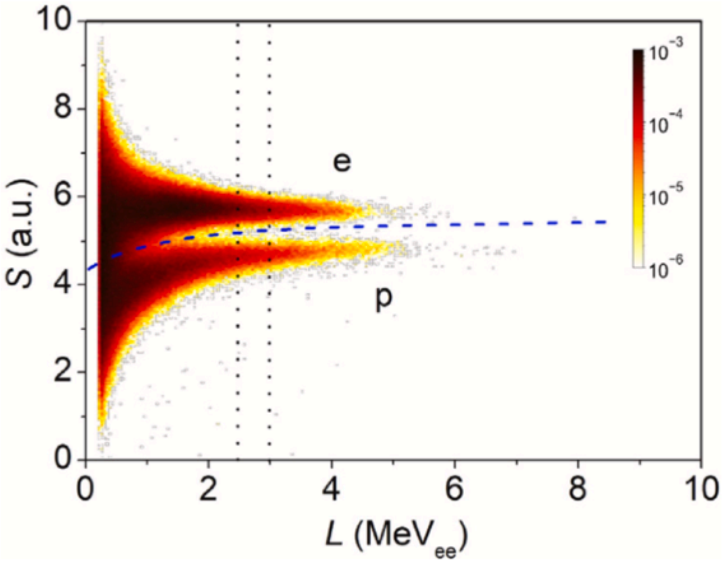
e.g. see Piscitelli et al., The European Physical Journal Plus **135**, Article number: 577 (2020) for a recent study of ^{3}He and ^{4}He detectors at the European Spallation Source

R.T. Kouzes et al., NIM A 623 (2010) 1035–1045

Scintillator systems

A. Buffler et al., Radiation Physics and Chemistry 220 (2024) 111698

- Plastic scintillators are inherently fast neutron detectors, adding high $\sigma_{n(th)}$ material like ^{10}B, ^{7}Li can enhance the thermal neutron sensitivity
- e.g. EJ-276, read out using SiPMs (liquid scintillators are commonly used)



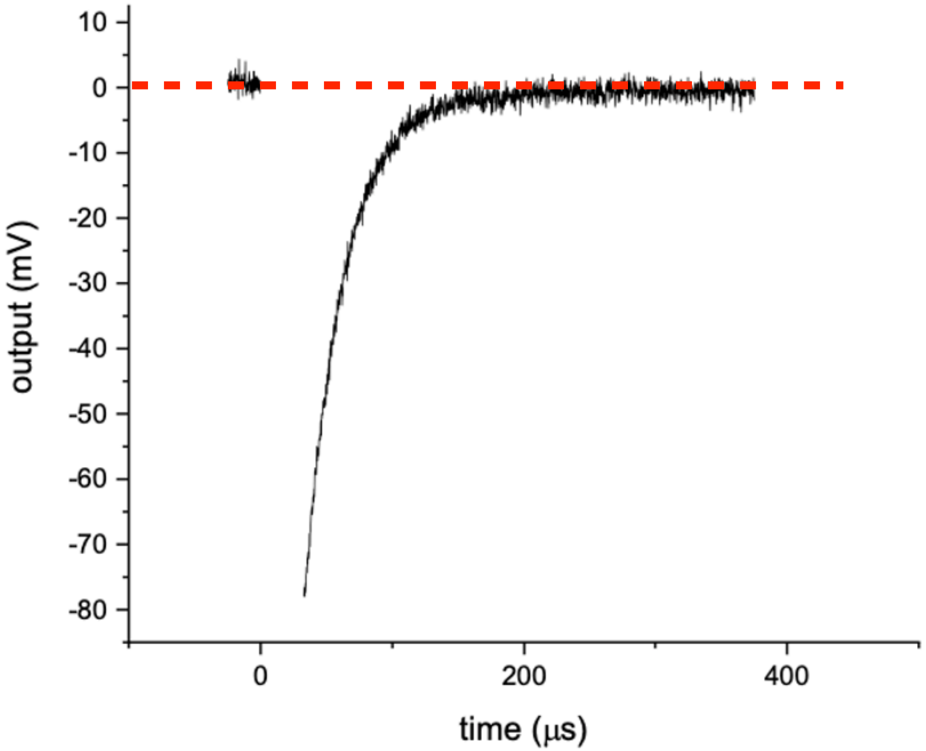
AmBe source exposure shows photon (recoiling e) and neutron (recoiling p) responses.

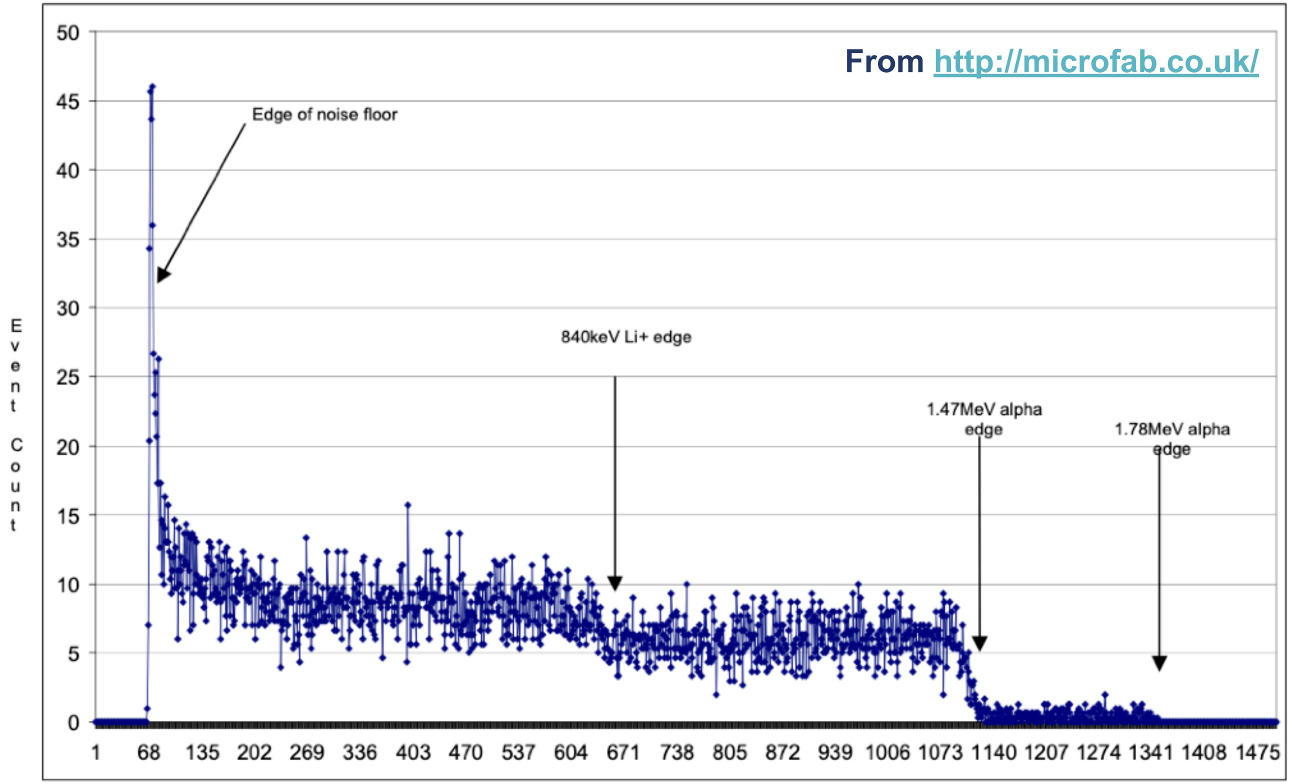
- Similar systems are used for muon tomography, neutrino detectors, muon hodoscopes for high energy physics and border security systems.

SiC with a boron converter

Also see Proc. of SPIE Vol. 7119 71190H-9

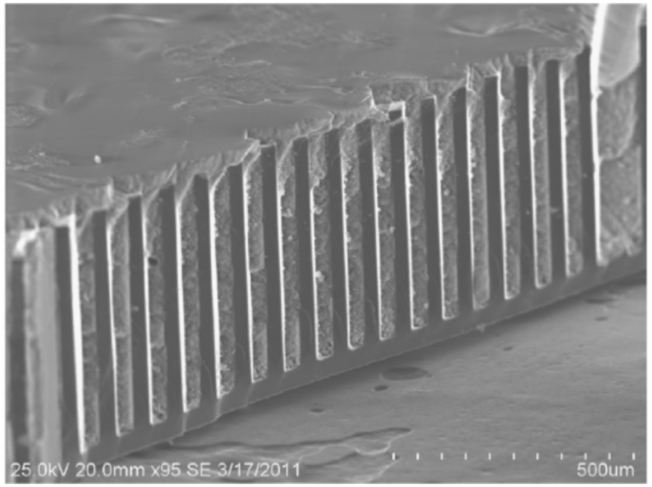
- 50 mm^2 active area based on a SiC detector with ^{10}B enriched converter foil mechanically attached
- Able to resolve α and Li recoils from the resulting spectra
- Efficiency is 5-8%





Micro Structured Neutron Detectors (MSND)

- MSNDs are small area silicon detectors with pits or trenches, filled with ^{10}B or ^{6}Li material.
- Efficiencies range up to a theoretical maximum of 40%



SEM image of an MSND device with ^{6}LiF as the neutron sensitive converter material.

Able to construct devices with similar overall count rate performance to ^{3}He detectors as an suitable alternative to this detection medium.

HeRep vs. ^{3}He-proportional counter with and without moderator

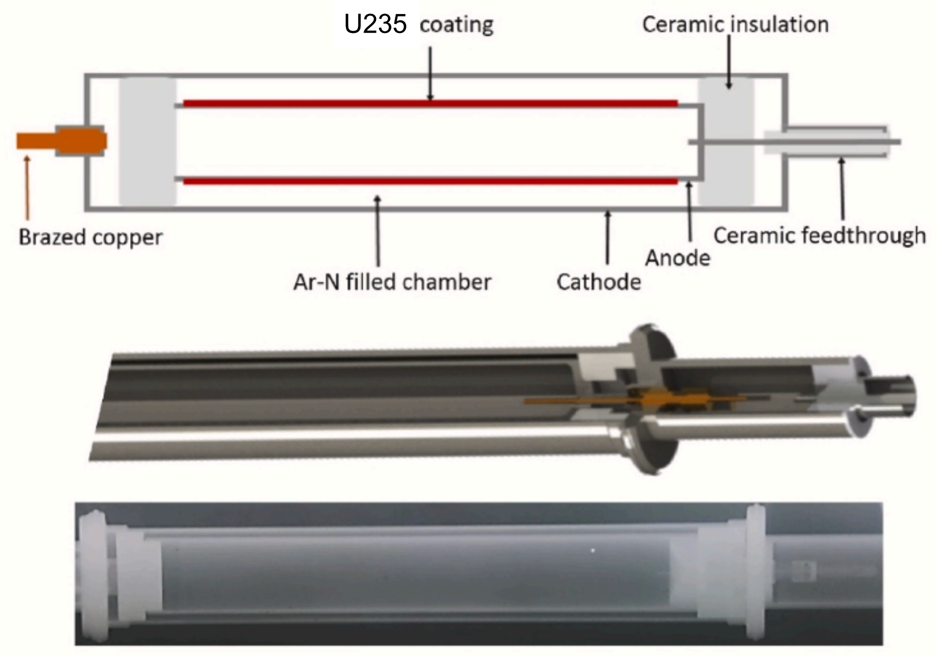
Detector	Measurement	Ct. Rate (cps)	% of He-3
HeRep	Moderated	17.60 ± 0.10	102.71 ± 2.65
HeRep	Bare	3.19 ± 0.05	95.15 ± 9.04
^{3}He Prop. Ctr.	Moderated	17.13 ± 0.10	–
^{3}He Prop. Ctr.	Bare	3.35 ± 0.05	–

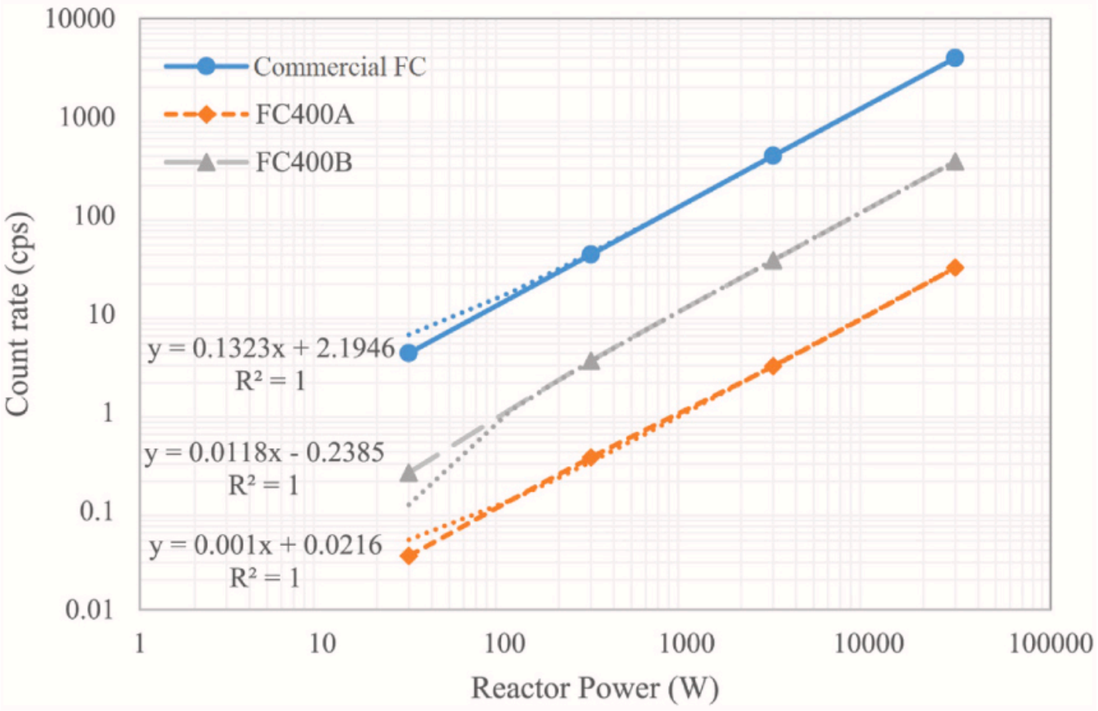
R.G. Fronk et al. / Nuclear Instruments and Methods in Physics Research A 779 (2015) 25–32

Fission chambers

E. Teimoory et al., Radiation Physics and Chemistry 215 (2024) 111360

- Fissile material is used to enhance fast neutron response in fission chambers
- Relies in incident neutrons inducing fission in the detector, and detecting the products





- Uses include monitoring the power output from nuclear reactors

Organic Semiconductor Detectors

- Inherently fast neutron detectors (hydrocarbons)

- Add isotopically enriched B, Li etc. to turn into a thermal neutron device

Technology Roadmap

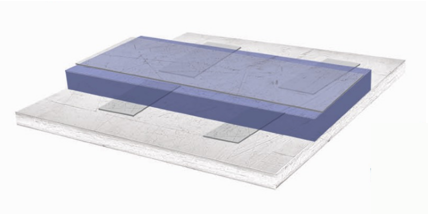
2015

10's fA signal from ^{241}Am α particles

P3HT devices made using a hot press

Measurements in a vacuum

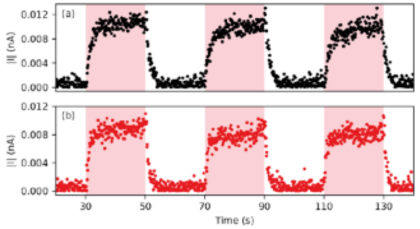
Thick devices under high voltage and thin devices for low voltage



2020

First n tests with enriched B_4C contaminants

The data raised more questions than it answered…



2021

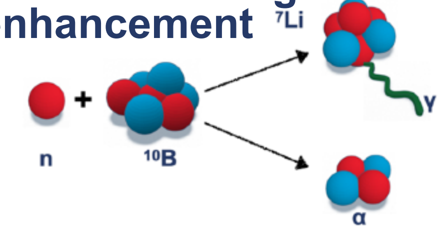
10's - 100's pA signal from ^{241}Am α particles and n's.

Move to modern air stable n and p-type OSC materials:

DPP-DTT, PNDI(HD)

Detect thermal neutrons and disambiguate thermal and fast neutron responses.

Start working in air to benefit from signal enhancement



2022

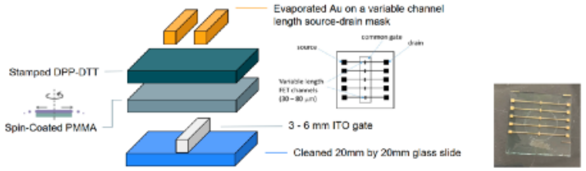
10's - 100's pA signal from ^{241}Am α particles and n's.

Study PNDI(OD) and carborane devices

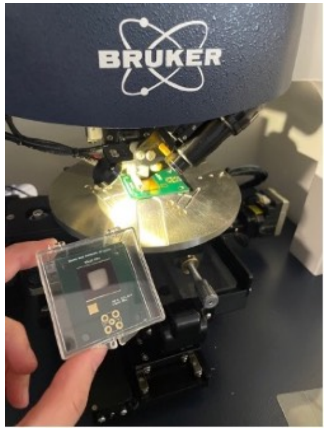
Start work with OFETs

Explore capacitor polarisation-based sensors

Study longevity, air and N_2 environment responses.



Now



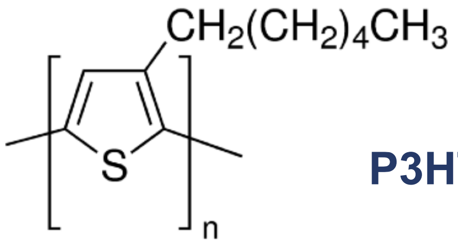
Developing system solutions for neutron detector measurement

Organic systems studied

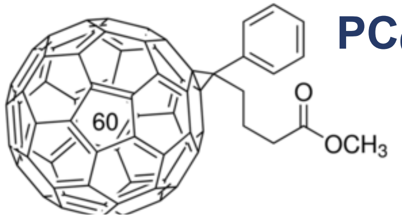
- Started with P3HT:
  - Well-known system
  - Cheap (£280/g + VAT)
  - But …. not air-stable

- Moved to heterojunction devices with $PC_{60}BM$ (donor-acceptor systems)

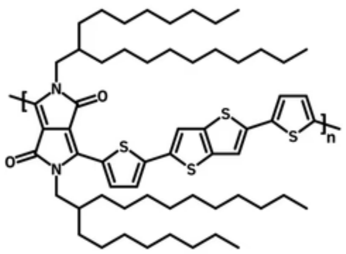
- Breakthrough moving to emerging air-stable OPV materials:
  - x1000 increase in signal
  - Simplified manufacturing
  - PNDI ~£2500/g



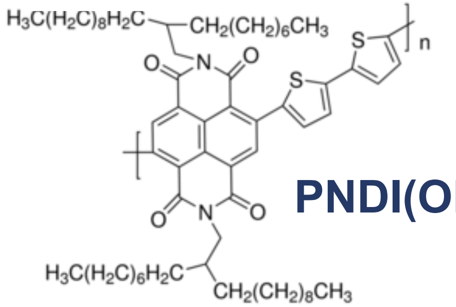
P3HT



$PC_{60}BM$



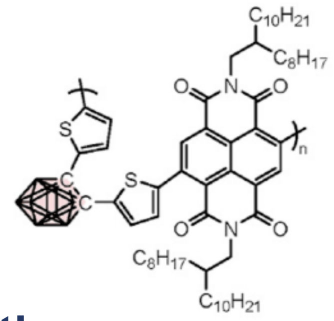
DPP-DDT



PNDI(OD/HD)

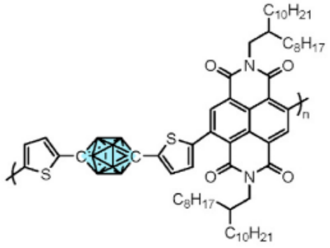
Ossila used for commercial supply of polymers.
Tafaikou fabricated very pure P3HT in-house

"carboranes"



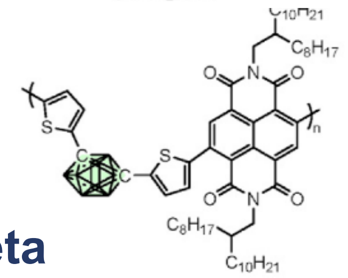
ortho

$oCbT_2$-NDI



para

$pCbT_2$-NDI



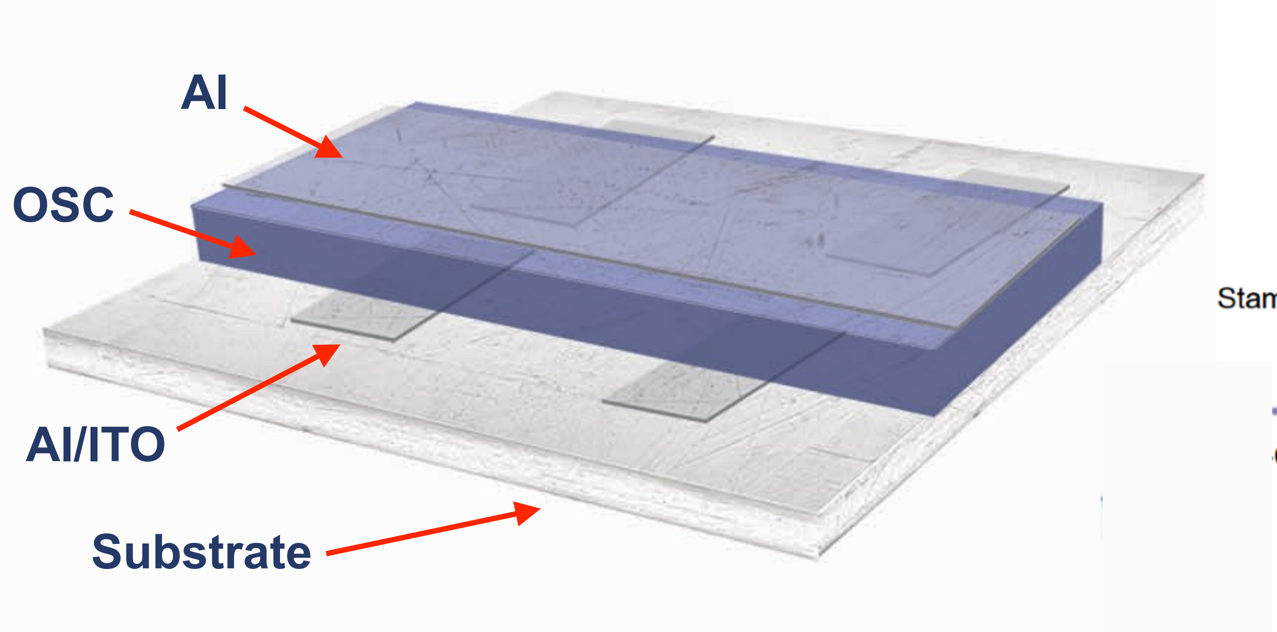
meta

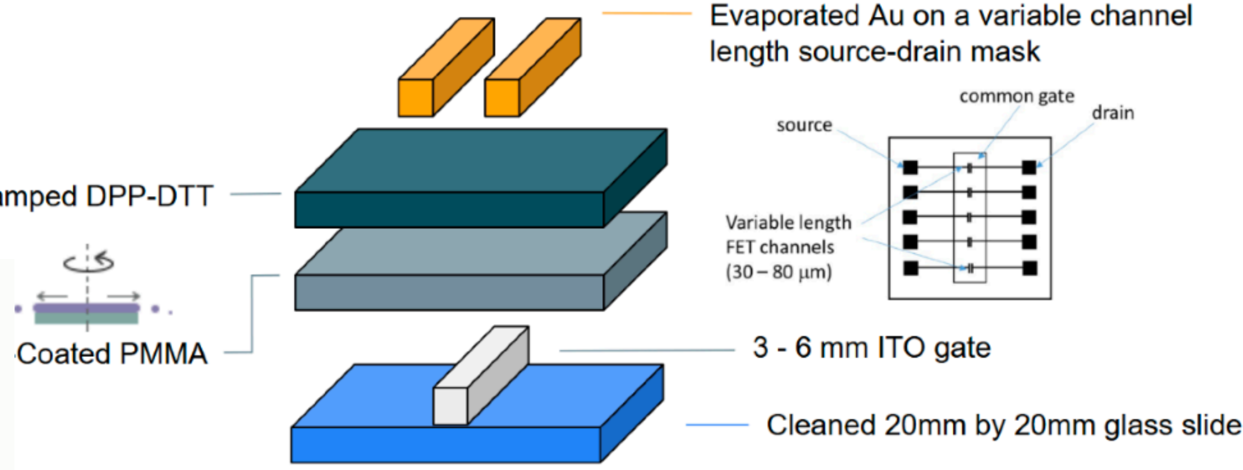
$mCbT_2$-NDI

Aniés et al., Polymer, 240, 124481 (2022), https://doi.org/10.1016/j.polymer.2021.124481

Diodes and Field Effect Transistors (FETs)

- **Started with diode structures, and have expanded to explore FETs**





- **Organic semiconductors are natural fast neutron detectors**
- **Add $^{10}B_4C$ "dirt" to sensitise for thermal neutron detection**
- **Have explored more complicated circuits with diodes feeding into organic and silicon FETs**

Illustration of the detector manufacture process for R&D samples (now making detectors directly on PCBs)

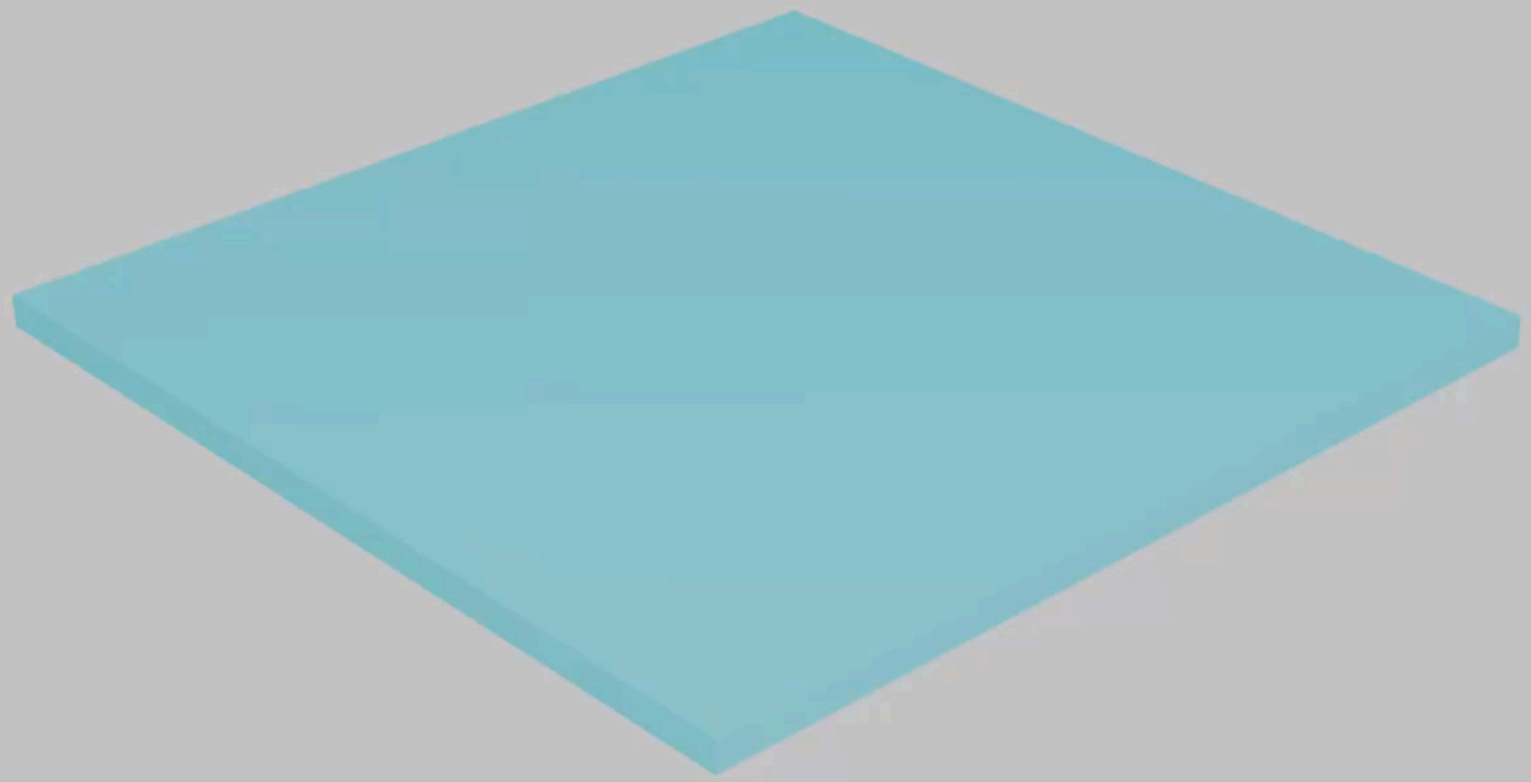
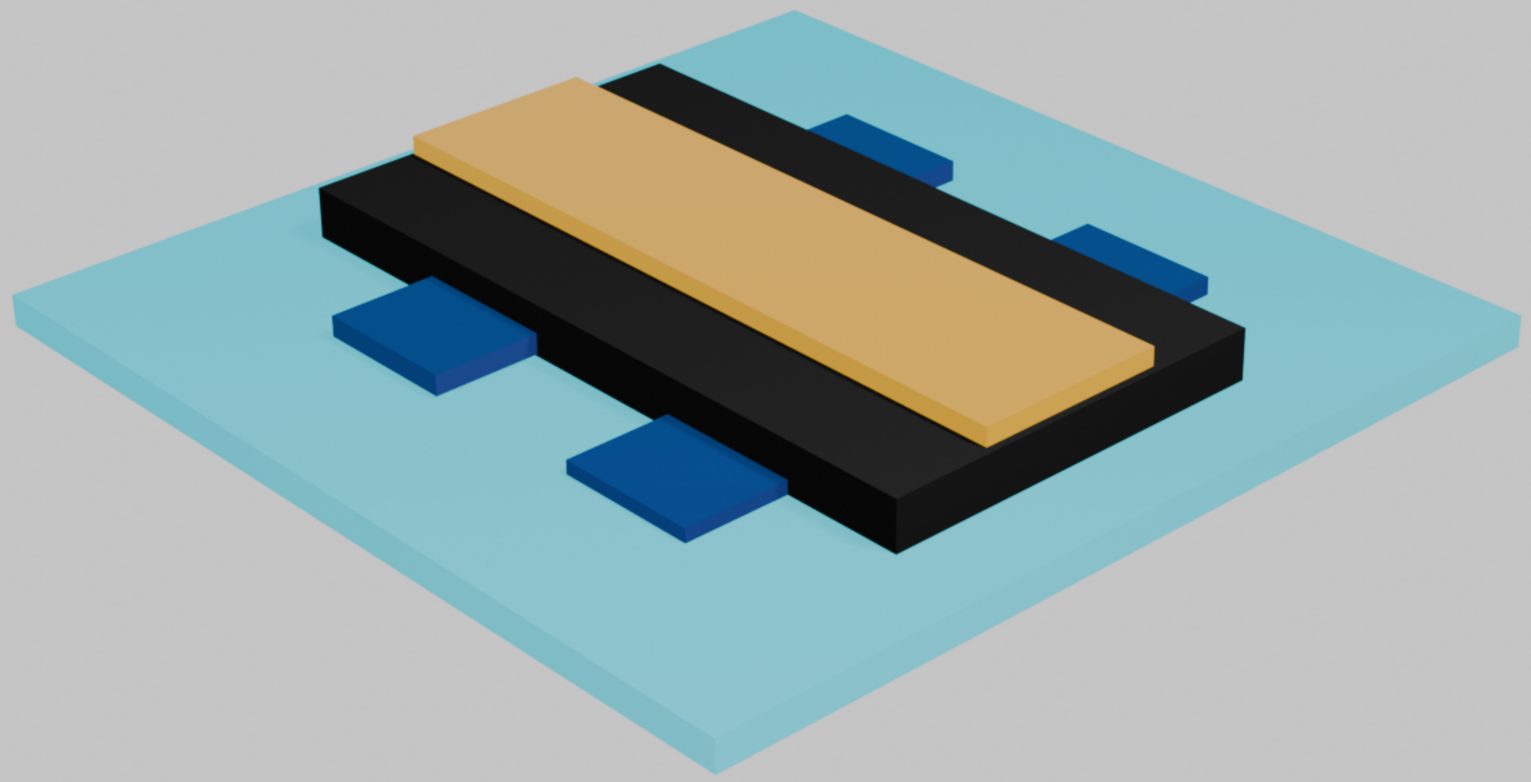
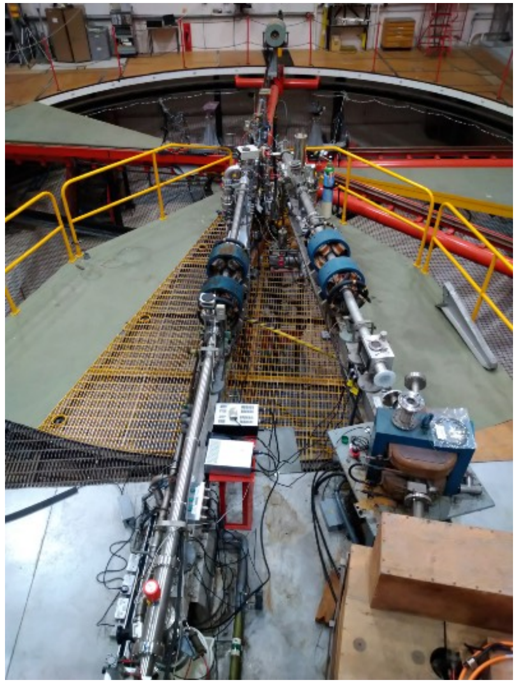


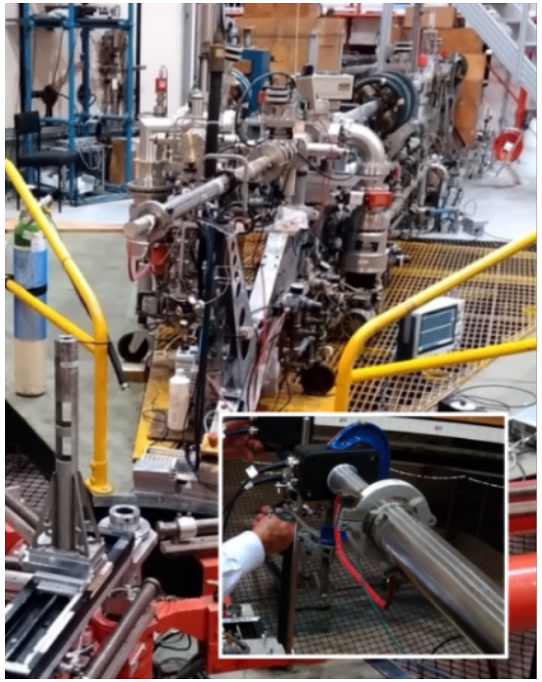
Illustration of the detector manufacture process for R&D samples (now making detectors directly on PCBs)

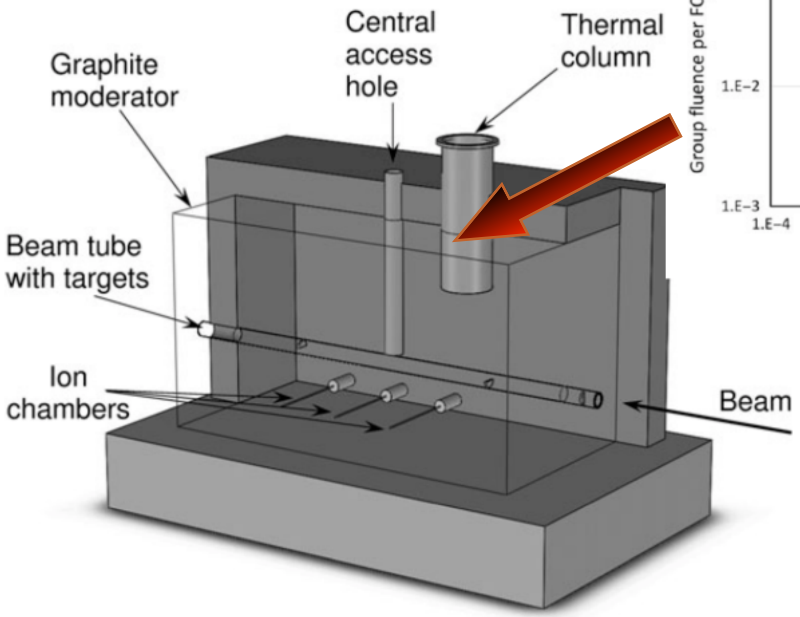


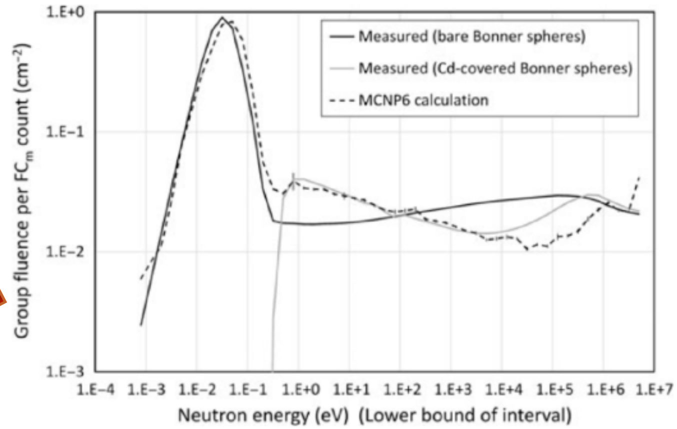
Test Facilities

- **Use AmBe sources and the NPL accelerators for fast neutrons:**
  - **0.565 and 16.5 MeV (monoenergetic beams from ^{7}Li on Be and D on T)**
  - **Mixed field of thermal and fast neutrons in the NPL thermal pile**









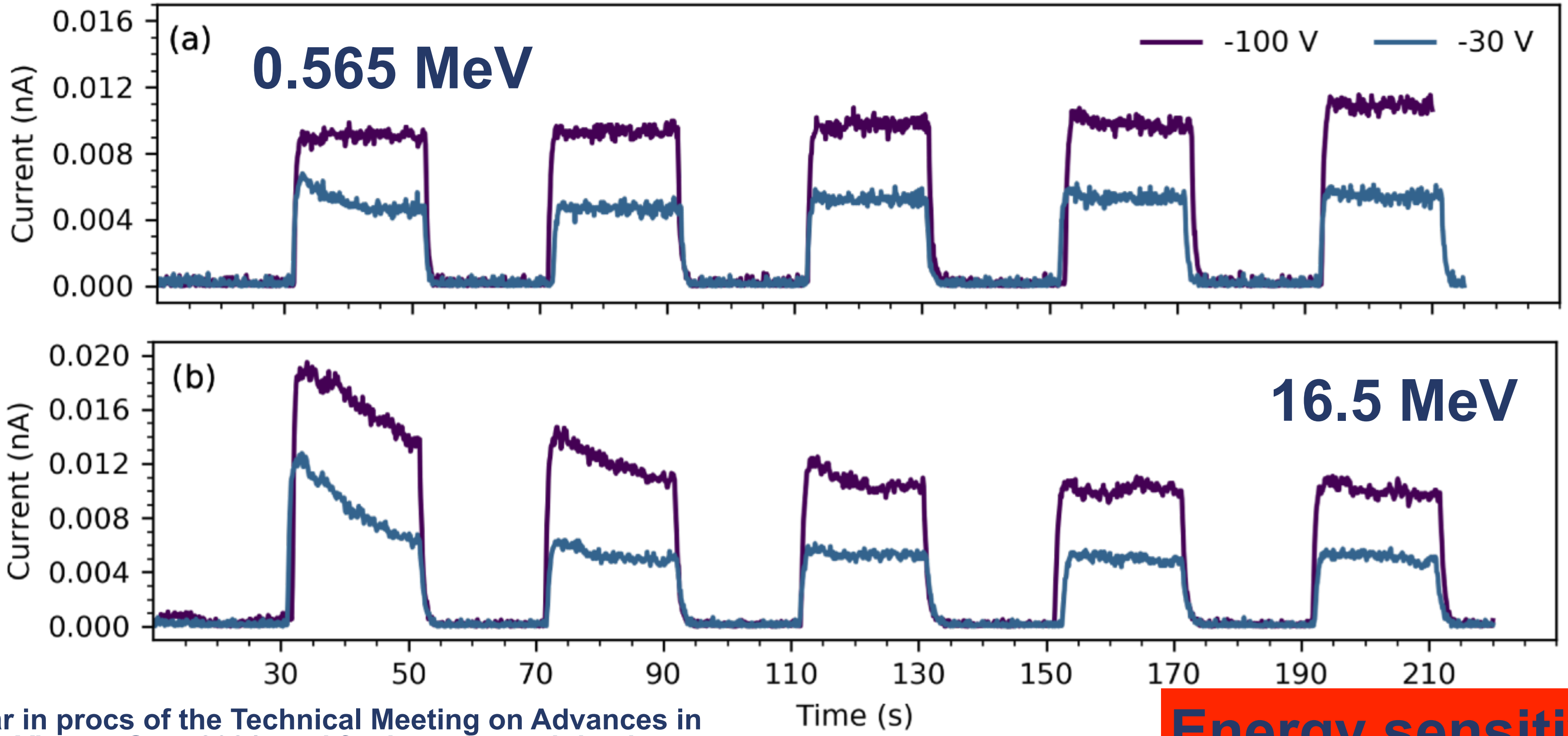
Energy spectrum for the thermal column

Access hole "assumed" to have a similar energy spectrum

Results using PNDI

PNDI(HD)2HT

- Clear signal responses to the beam (~5-10pA)
- Devices settle down in a few tens of seconds
- Beam flux ~1.8×10^6 for 0.565 and ~2.1×10^5 for 16.5MeV n/cm^2/s

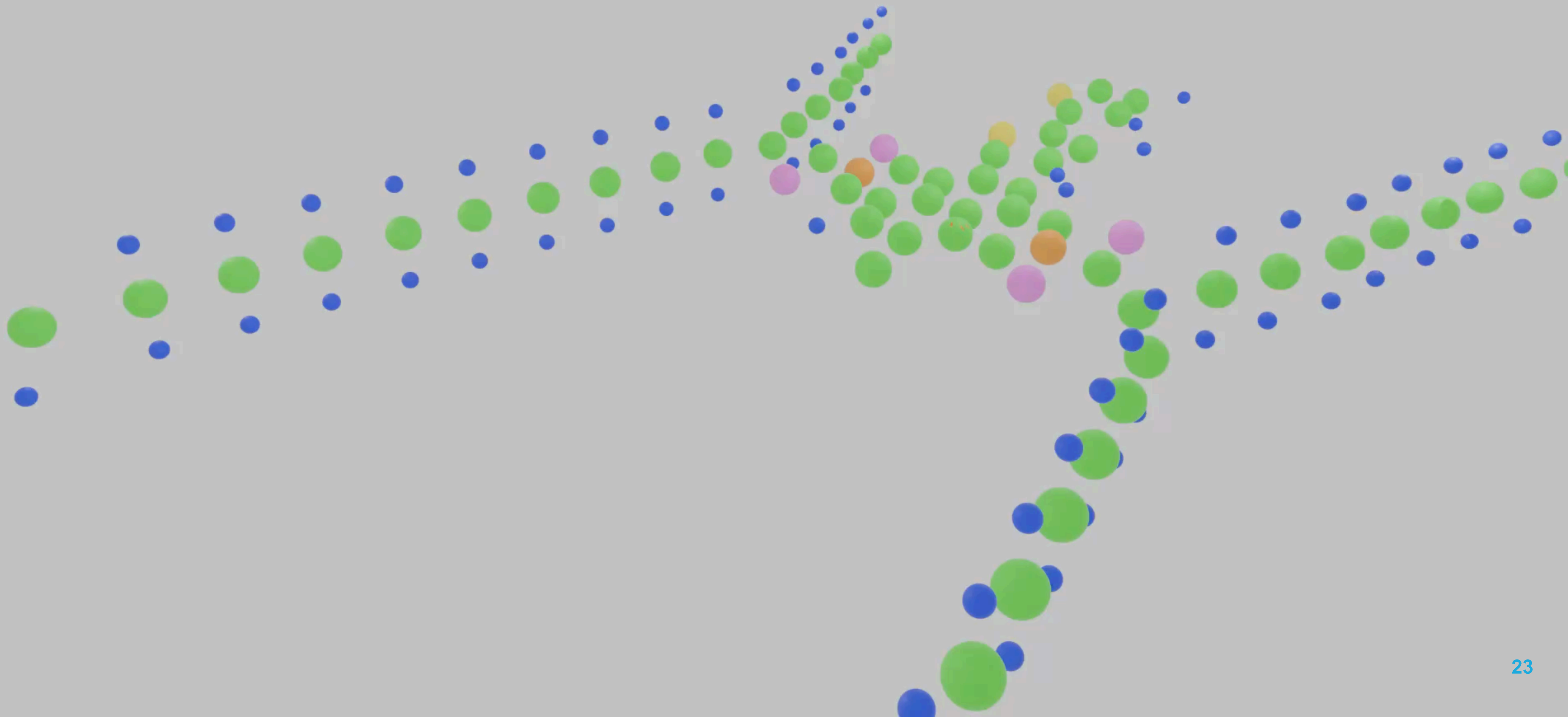


Borowiec et al., to appear in procs of the Technical Meeting on Advances in Neutron Detection, IAEA, Vienna, Sept 2021, and forthcoming publication

Energy sensitivity apparent

Borowiec et al., arXiv:2212.08438

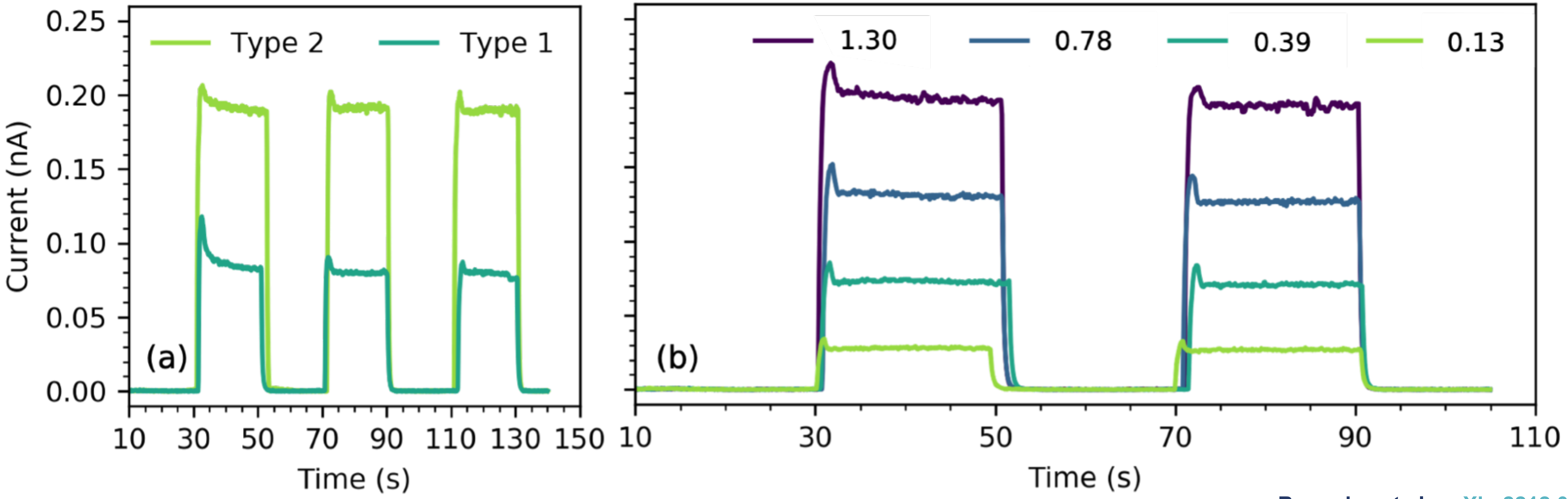
Illustration of elastic scatter processes in PNDI



Results using PNDI

PNDI(HD)2HT

- ~ nA currents achievable
- Approx 50% of the signal from thermal neutrons, significant fast neutron background evident for devices with ^{10}B
- Linear response with flux to ~10^7 n/cm^2/s

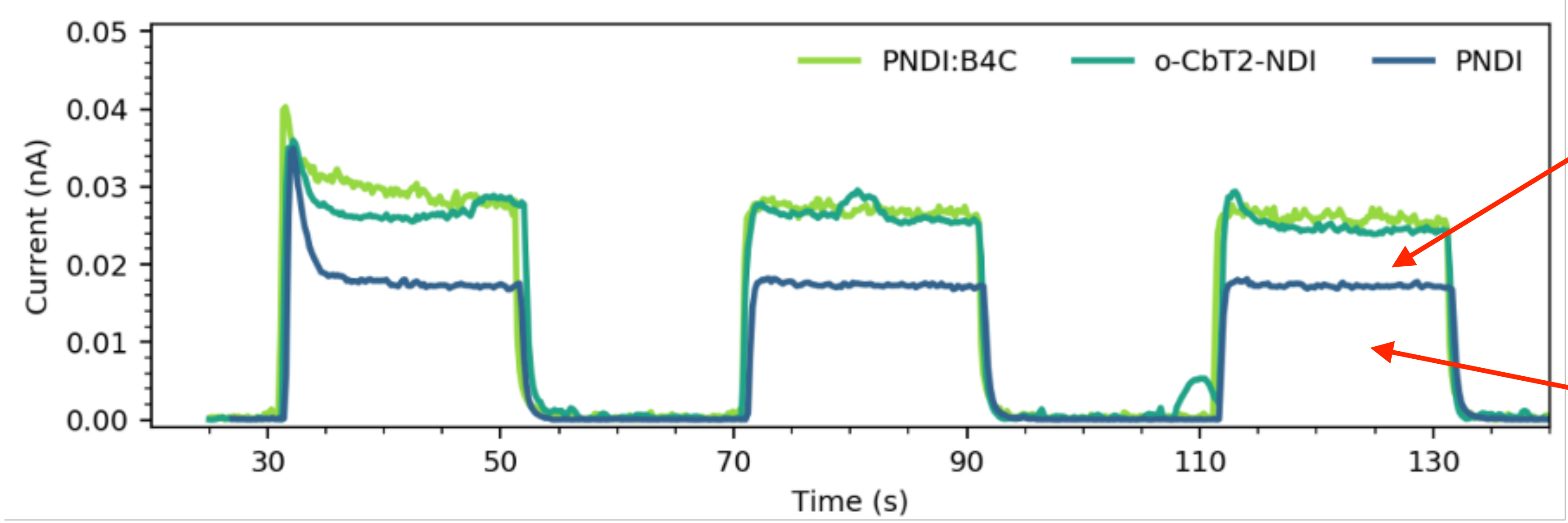


Borowiec et al., arXiv:2212.08438

Results using PNDI and oCbTNDI

PNDI(OD)2HT
oCbTNDI

- B_4C addition increases signal noise in the PNDI detector
- Carborane-containing system in the polymer chain yields comparable performance, lower noise
- Lower ^{10}B content than our 2022 paper to ensure moiety matches the carborane polymer ^{10}B level.



Thermal Neutrons (BNC)

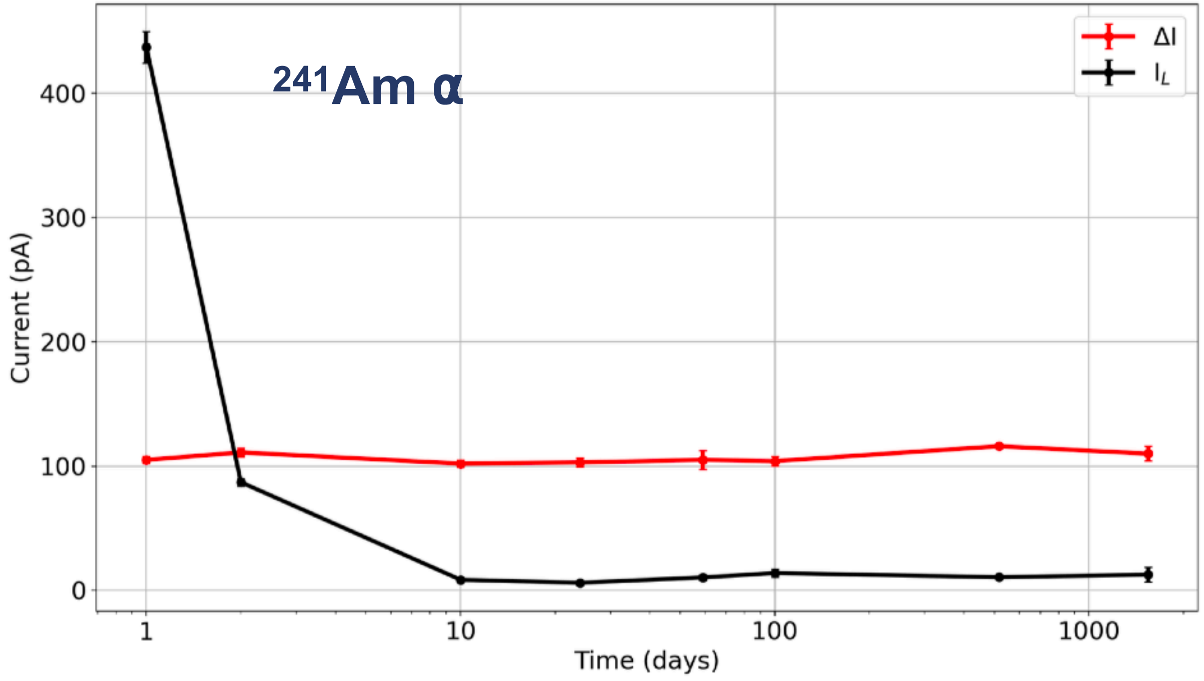
Fast neutrons elastic and inelastic scattering

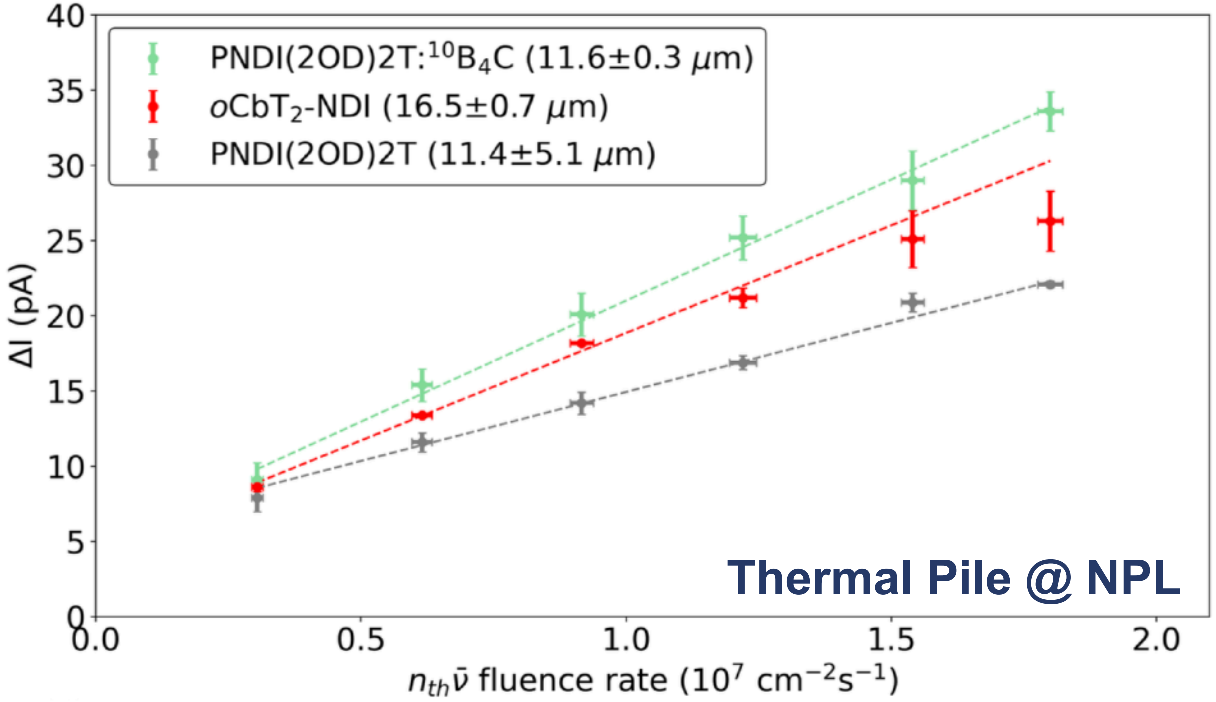
Horner et al., to appear in forthcoming publication

Aniés et al., Polymer, 240, 124481 (2022), https://doi.org/10.1016/j.polymer.2021.124481

Is this technology useful for the real world?

- **Longevity and linearity with flux**



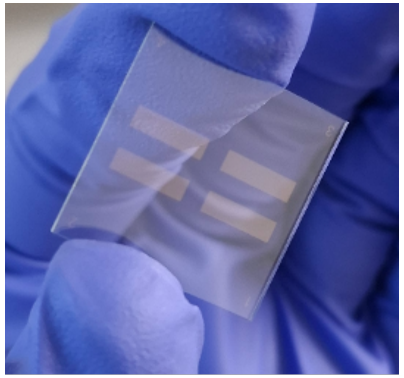


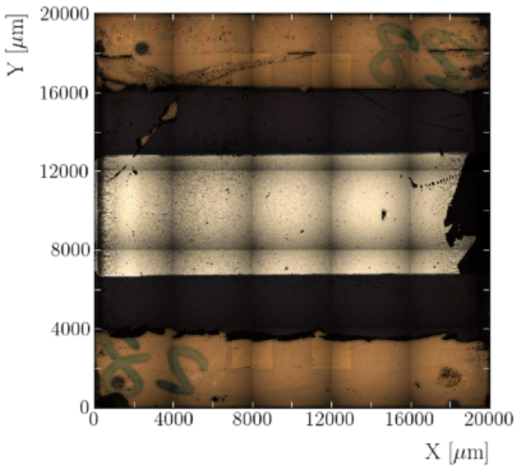
Devices last for over 1500 of days

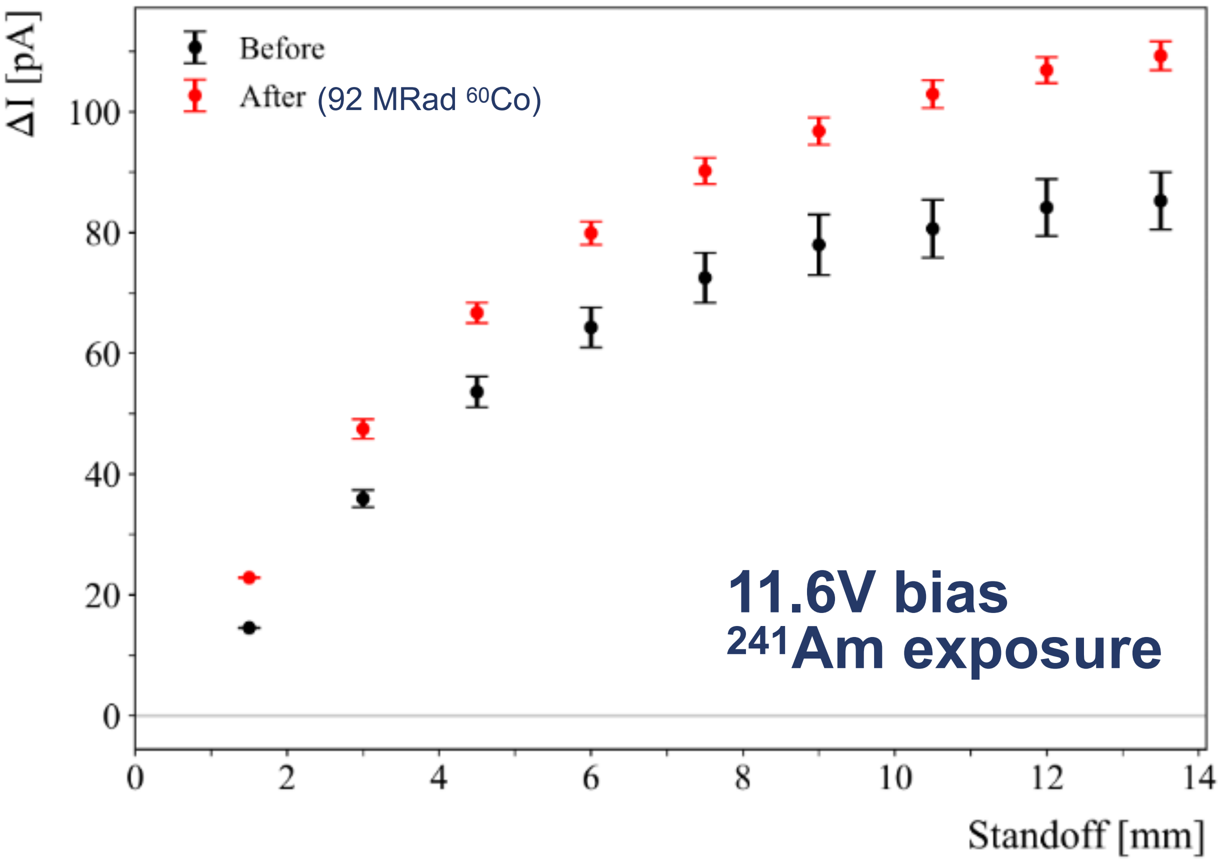
Reproducible results with B_4C added (enriched in ^{10}B), and with carborane devices (natural abundance of B).

Is this technology useful for the real world?

- Tested with ^{60}Co up to 92 MRad @ BRIGETTE, SCK-CEN (with help from the MBI Belle II group in Vienna)





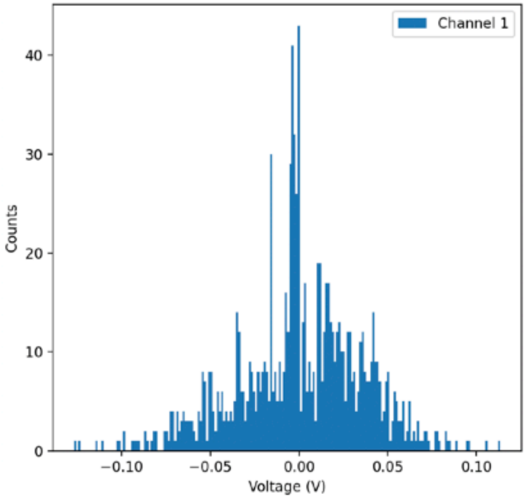


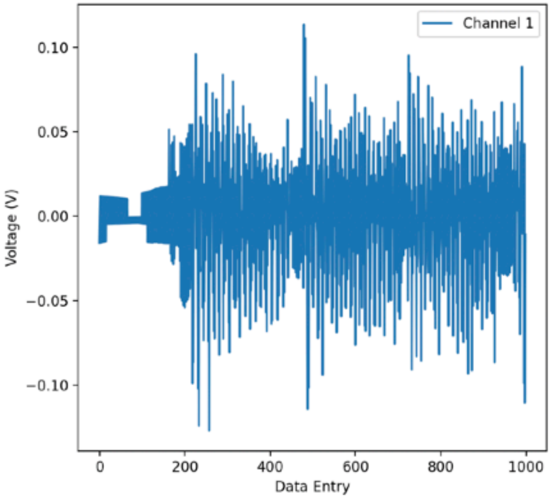
Is this technology useful for the real world?

- The limitation is cost per channel
  - Testing prototype of a custom 16 bit digitiser system designed to replacement for our bench top parameter analyser/source measure unit readout setup
  - 2 channel systems are being tested in our labs on Linux and Mac operating systems
  - Also testing a 2 channel solution integrated with a data logging UI, environment sensors and touchscreen.
  - Aiming to use in its first field test in a relevant industrial environment this autumn with one of our commercial partners

Detector data logger with environment sensors

2 channel 16 bit digitiser





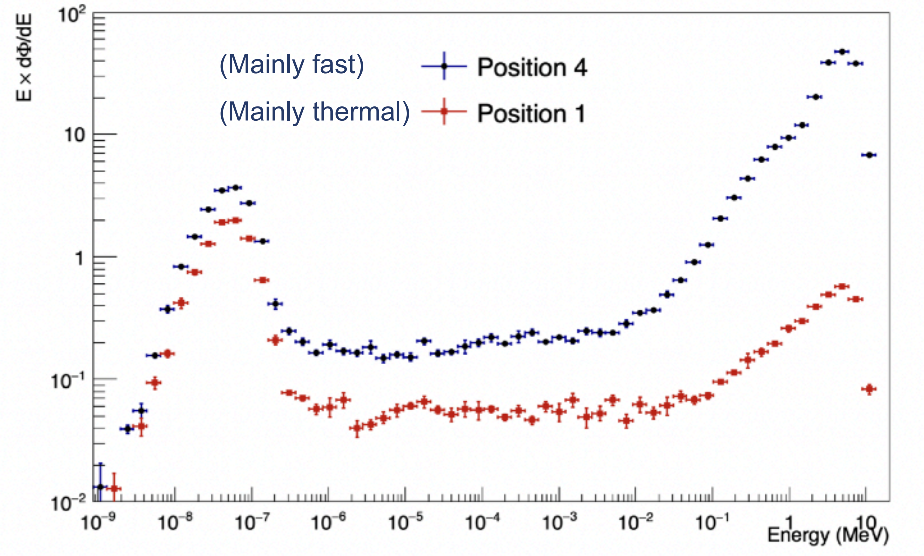
Input signal used to demonstrate response: Guitar

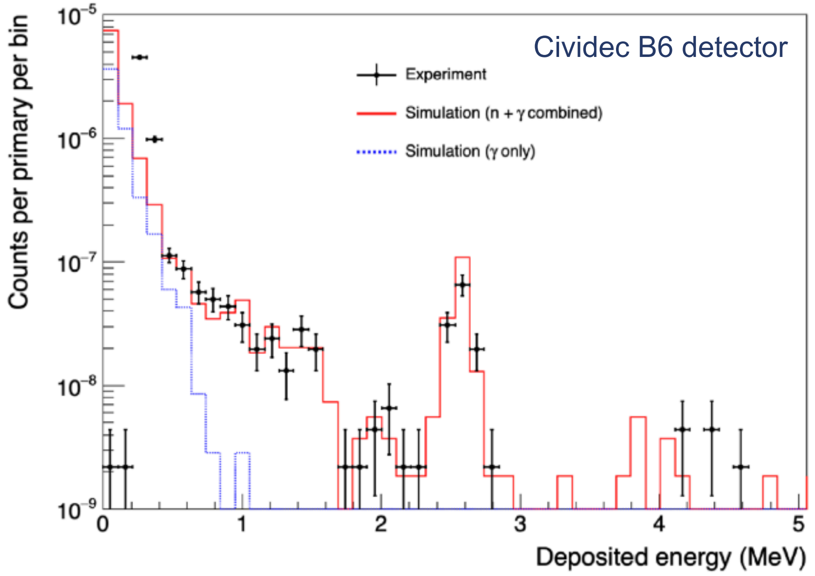
Test facility

- 300 MBq AmBe source

QMUL Neutron Facility

- AmBe neutron irradiation facility established @ QM this year





- Validated using simulation and a CVD diamond detector
- Setup designed for detector development and characterisation/calibration
- Developing a black box simulator to test source inference for different shielding environments

Energy spectrum follows ISO 8529-1:2001

QMUL Neutron Facility

- **300 MBq (18500 ± 320 n/s) AmBe source**

Position	γ_{total}	n_{total}	$n_{thermal}$ ($E < 0.5\,eV$)	n_{fast} ($E \geq 100\,keV$)	
1	66	107	70	25	"Thermal Neutron Field"
4		1683	134	1485	"Fast Neutron Field"

Table 1: Simulated particle fluxes ($cm^{-2}\,s^{-1}$).

- **Choose between an 88% fast neutron field through to a 65% thermal neutron field**

- **For complete understanding of the detector response, simulation is required of the environment, sensor and packaging.**

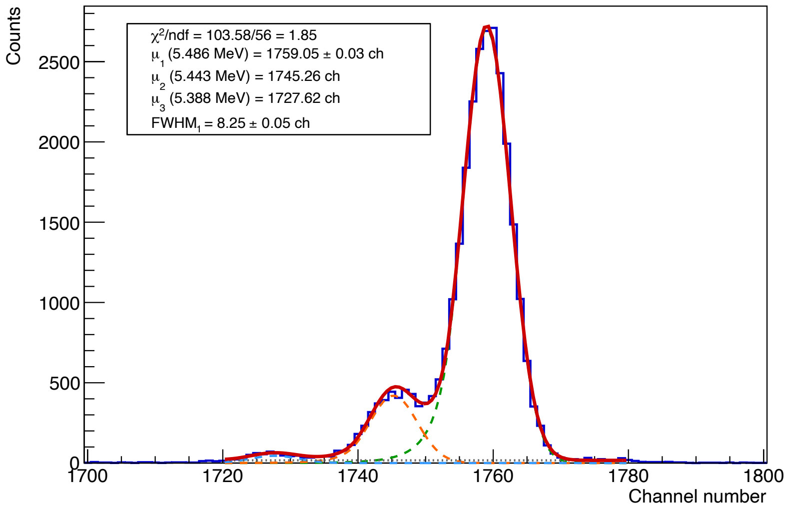
Inorganic neutron detectors

- CVD diamond
- Silicon

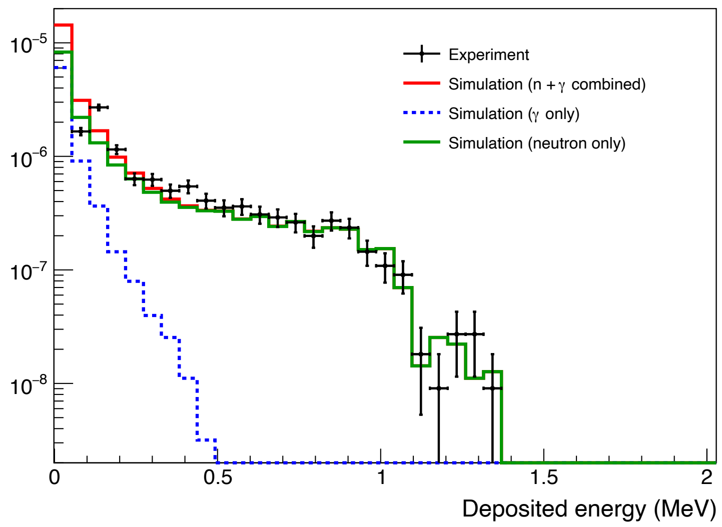
CVD Diamond Neutron Detector

- Using converter layer containing ^{10}B enriched material and a CVD diamond to create a thermal neutron detector
- Able to resolve the 3 α peaks from ^{241}Am

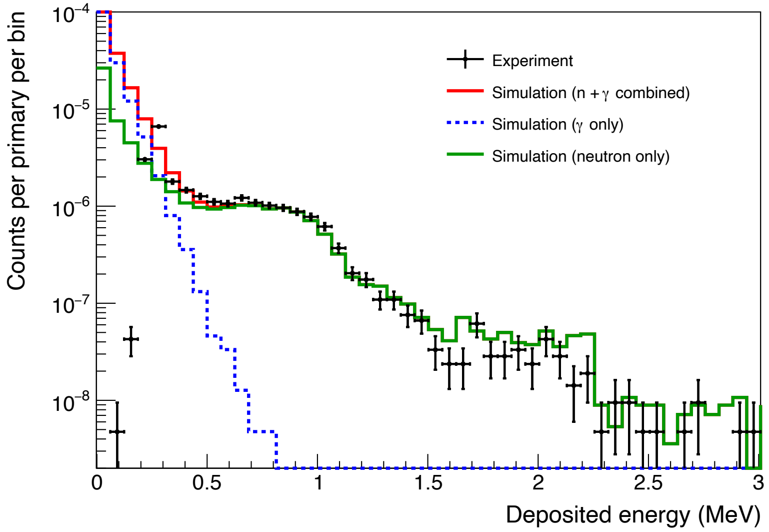
α calibration test



Thermal neutron dominated field



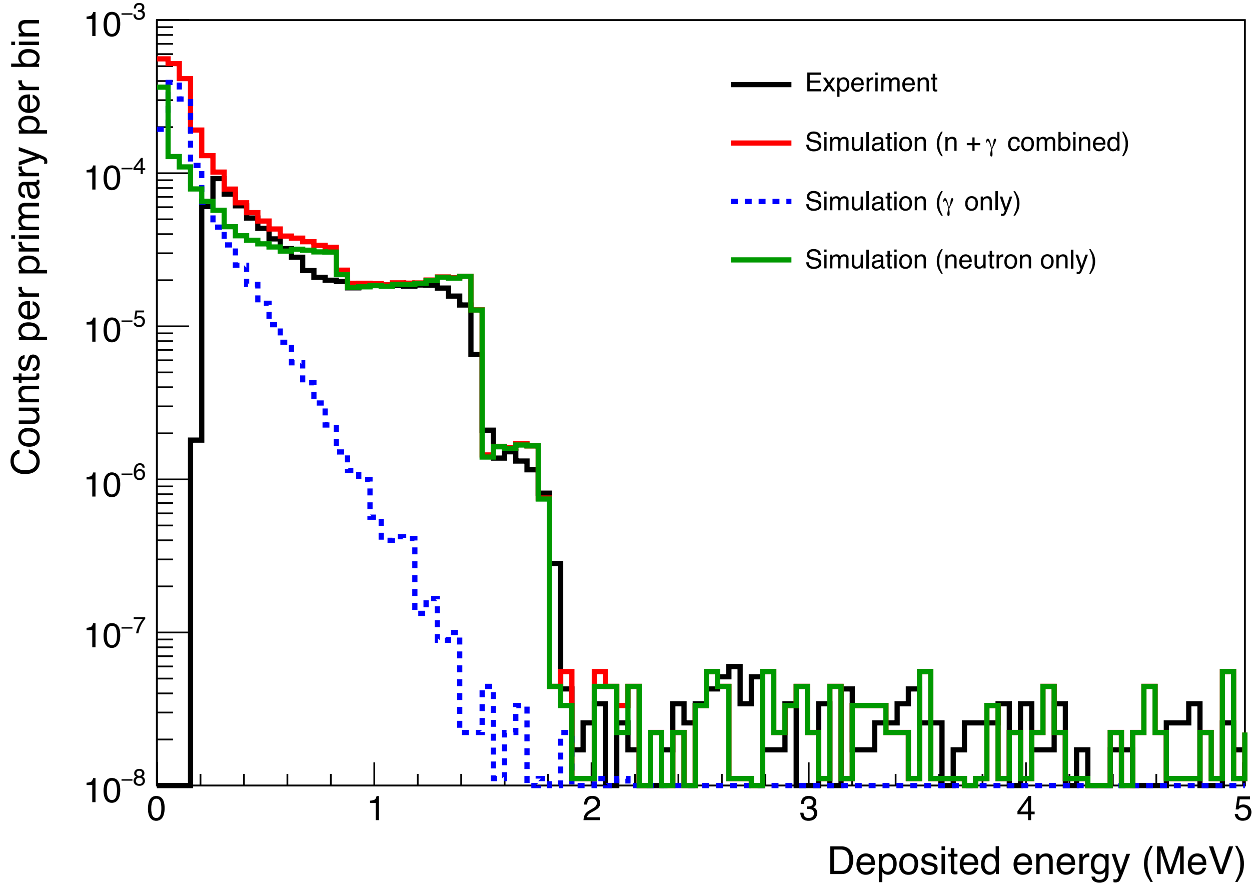
Fast neutron dominated field



- Good Data Monte Carlo agreement above a few hundred keV
- Intrinsic efficiency of this detector ~4%, theoretical maximum 8%

Silicon Neutron Detector

- Same approach is taken to create a 5×5 cm thermal neutron detector based on a silicon sensor
  - Targeting high sensitivity for precision measurements and fast evaluation of environments
- Reasonable data/Monte Carlo agreement
- Contributions from photons, fast, and thermal neutrons evident in the data
- Intrinsic efficiency of this detector ~4%, theoretical maximum 8%



Summary

- Over the past decade, we have developed several types of neutron detector

- Organic Semiconductors: Roadmap showing progress over the last decade and upcoming direction for our research activities
  - Longevity of devices verified to be years
  - Good understanding of fabrication reproducibility and yield
  - Now targeting real-world applications

- Have established a detector characterisation neutron source test facility at QMUL

- Excellent progress in developing CVD diamond and silicon thermal neutron detectors

Thank you for listening!

QMUL's Detector Development Group

We are a multidisciplinary team of experts working on

- Novel radiation sensing technologies
- System design, construction and operation
- Radiation damage simulation
- Radiation response testing

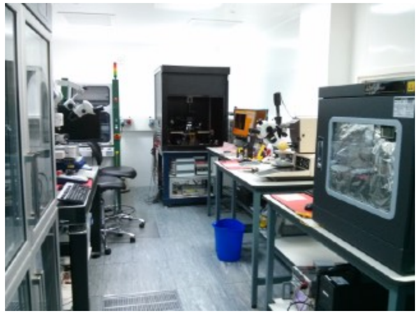
for industrial applications and for nuclear and particle physics scientific work.

Technologies

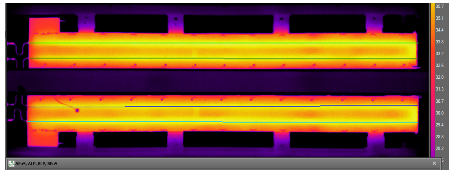
- Diamond
- Silicon
- Organics
- Perovskite
- Scintillator
- Quantum

Simulation

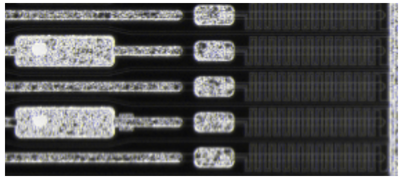
- ABAQUS
- ANSYS
- FLUKA
- GEANT4



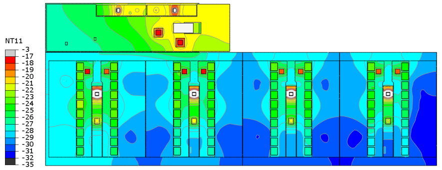
Fully equipped ISO 7 certified clean rooms



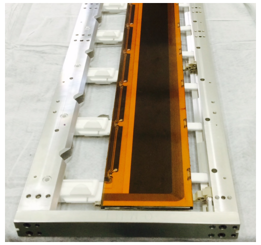
Infra-red thermal imaging system



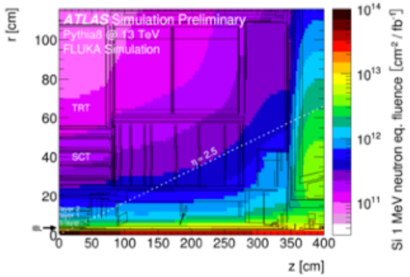
Silicon strip sensors for LHC



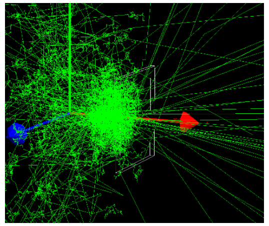
Heat transfer simulation for detector system cooling design



Module assembly engineering



FLUKA radiation environment simulations



Geant4 sensor interaction simulations

Labs with state of the art equipment