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Single moderator neutron spectrometers for monitoring neutron facilities

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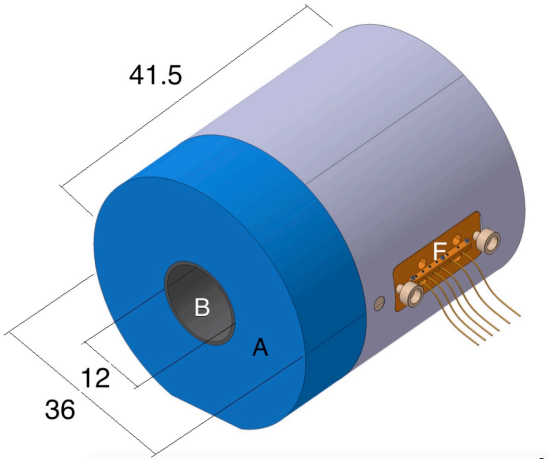
Introduction

- Single Moderator Neutron Spectrometers (SMNS) were developed to provide an alternative to Bonner Spheres in operational scenarios
- BSS are bulky, time consuming, unsuited for real time monitor, and require sequential irradiations.

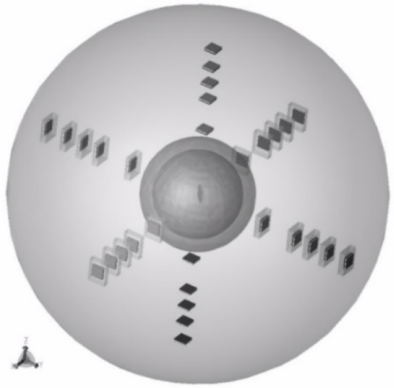


Collimated cylinder geometry – directional response

- 2012 Cylindrical Spectrometer CYSP
- 2021 NCT-WES
  Neutron Capture Therapy Wide Energy Spectrometer

Spherical geometry – isotropic response

- 2013 The Spherical Spectrometer SP^2
- 2024 Tetra-Ball

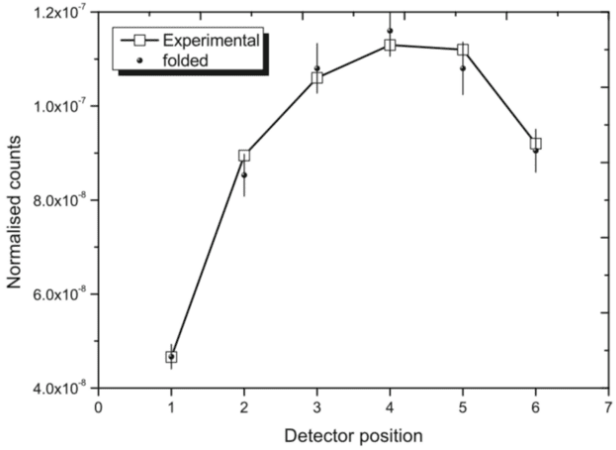


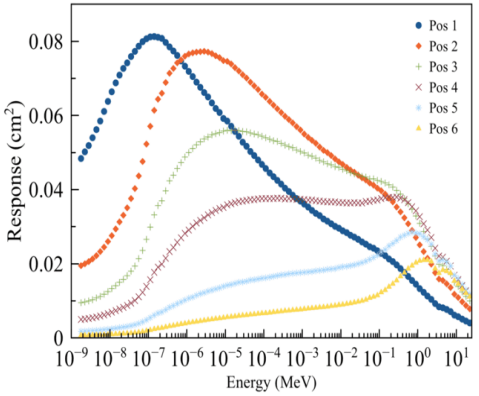
Unfolding

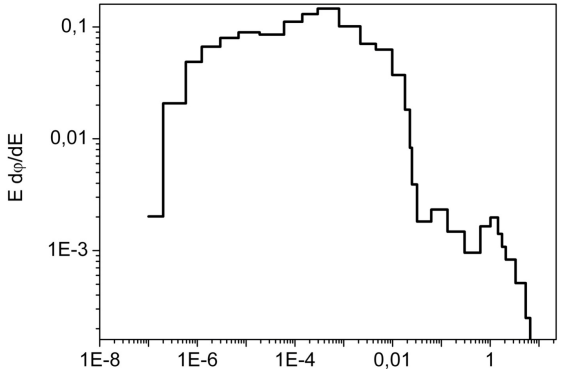
Counts profile & uncertainties

Unfold using Response matrix

spectrum

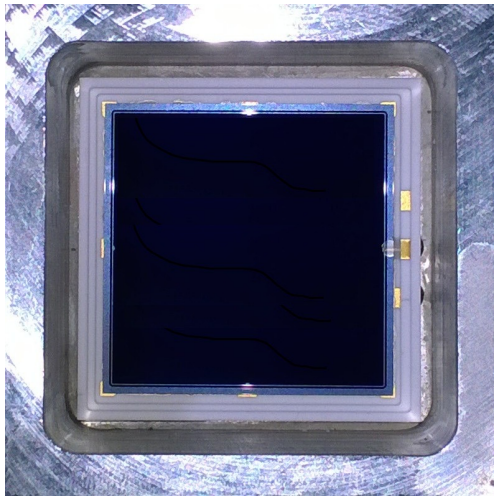




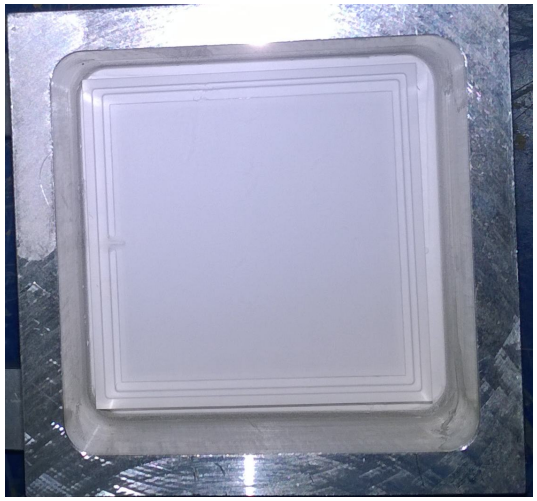


Solid state thermal neutron detectors

- Windowless diodes coated with ^{6}LiF (30 μm)
  - ❖ Si 1 cm^2 (-5% per 10^{12} n cm^{-2})
  - ❖ SiC 1 mm^2 (no fading up to 10^{14} n cm^{-2})



Original device



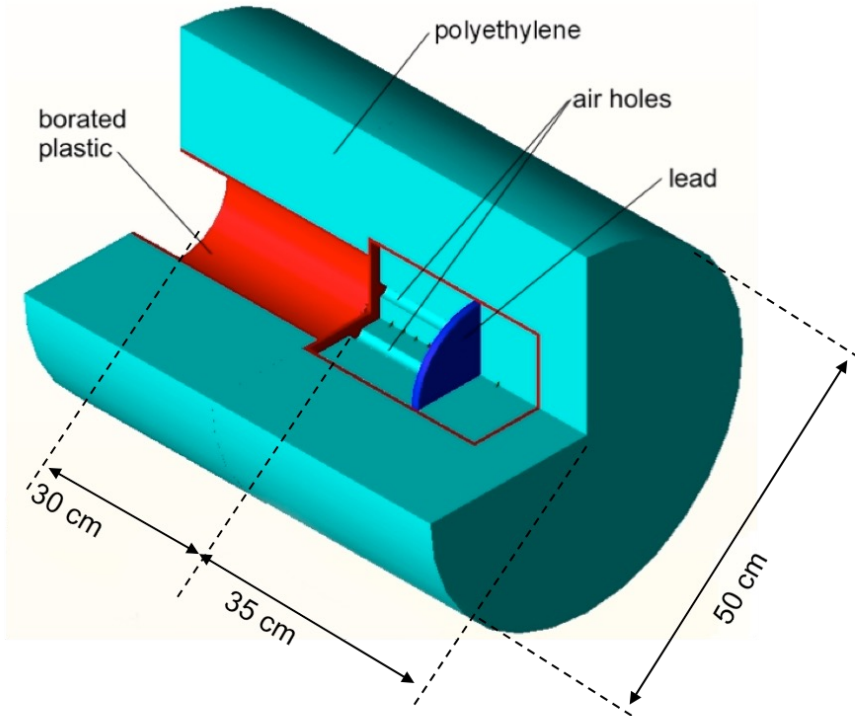
After deposition

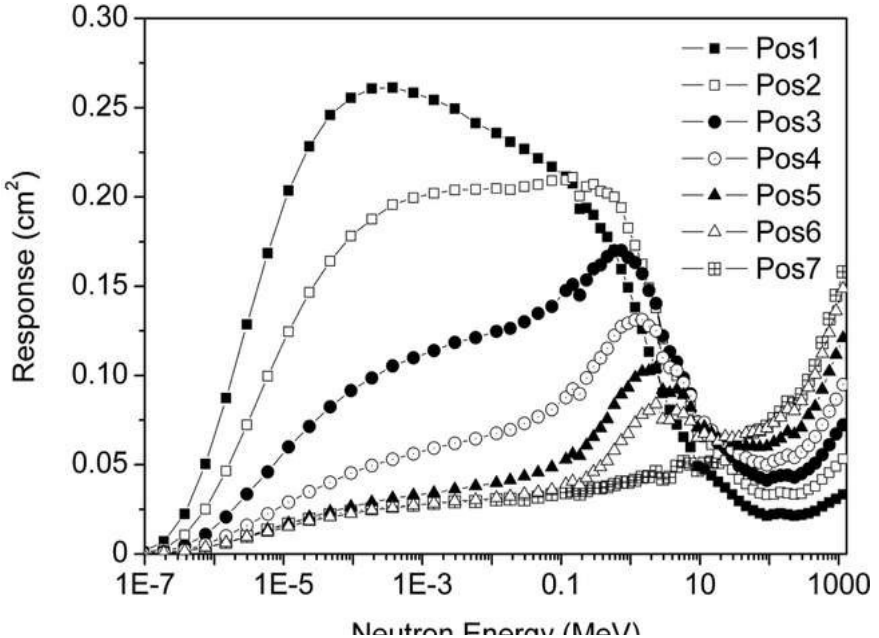
- Individually calibrated in HOTNES facility
- Custom multi-detector analog board
- Rad hardness studied in reactors

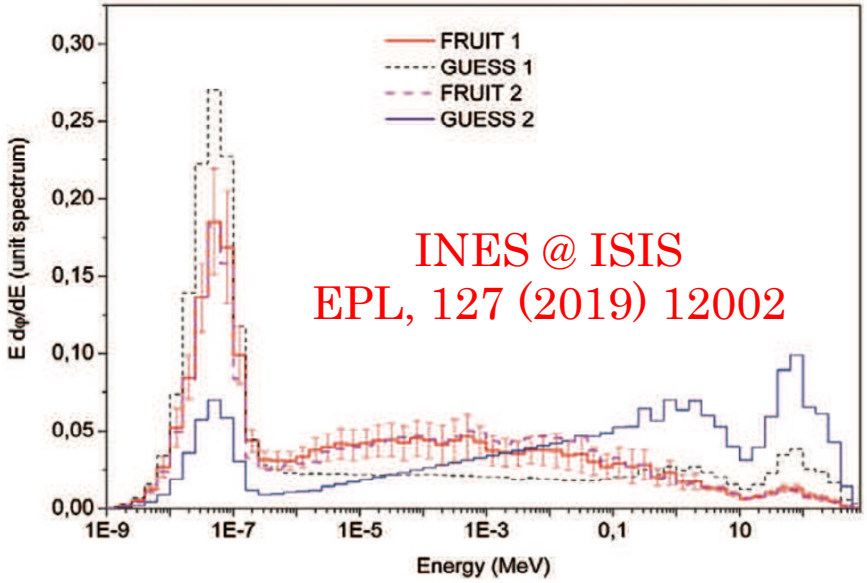
NIM A 1018 (2021) 16585
NIM A 780 (2015) 51-54
RPD. 161 1-4 (2014) 229-232
Eur. Phys. J. Plus 137 (2022) 1358

CYSP – Cylindrical Spectrometer (2012)

Size/weight	50 Φ x 65 h, 120 kg
Energy range	Thermal - GeV
Detector spacing	≥ 2 cm
Applications	Cosmic rays, neutron beam-lines

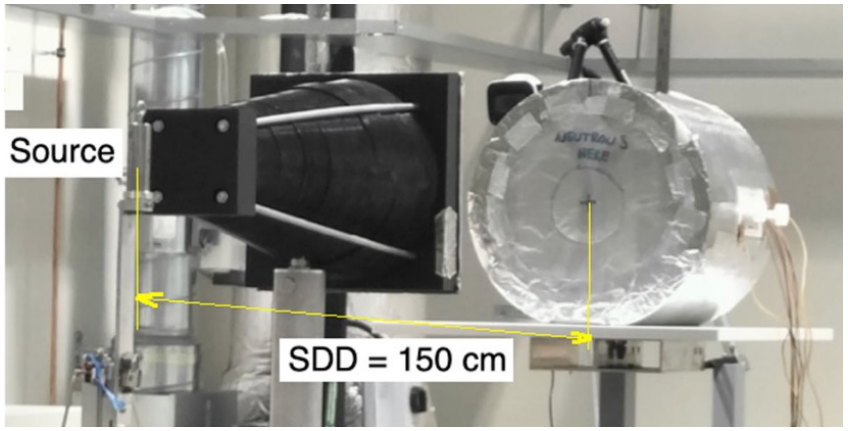


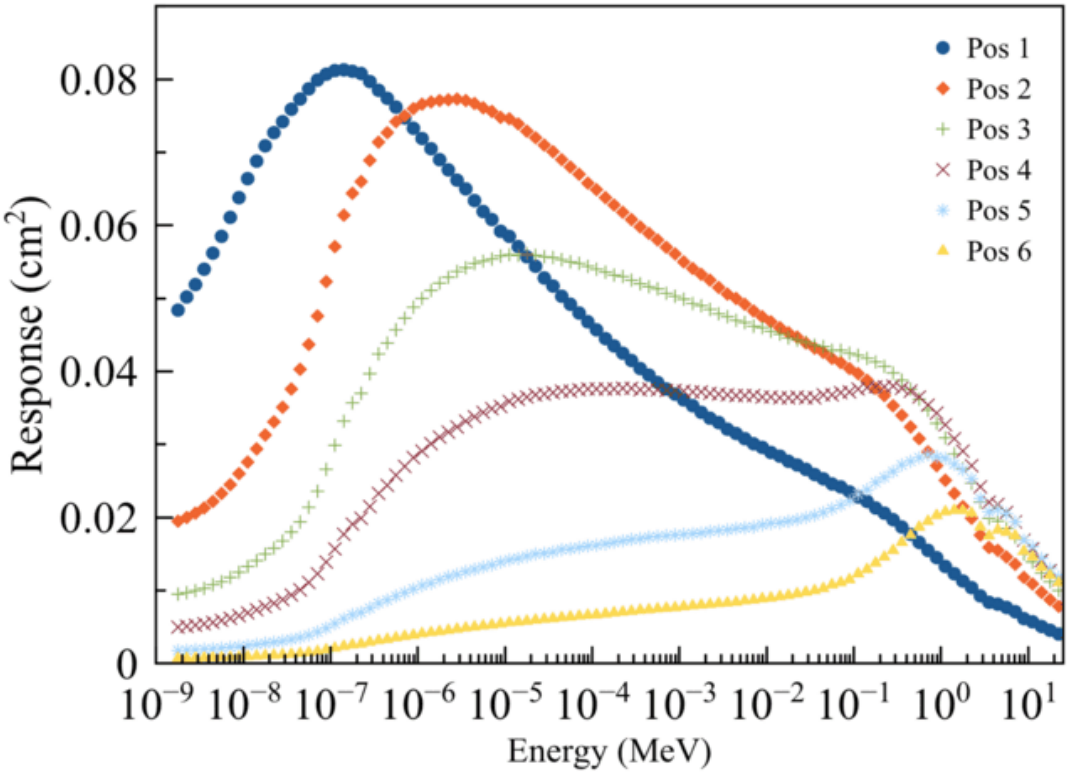


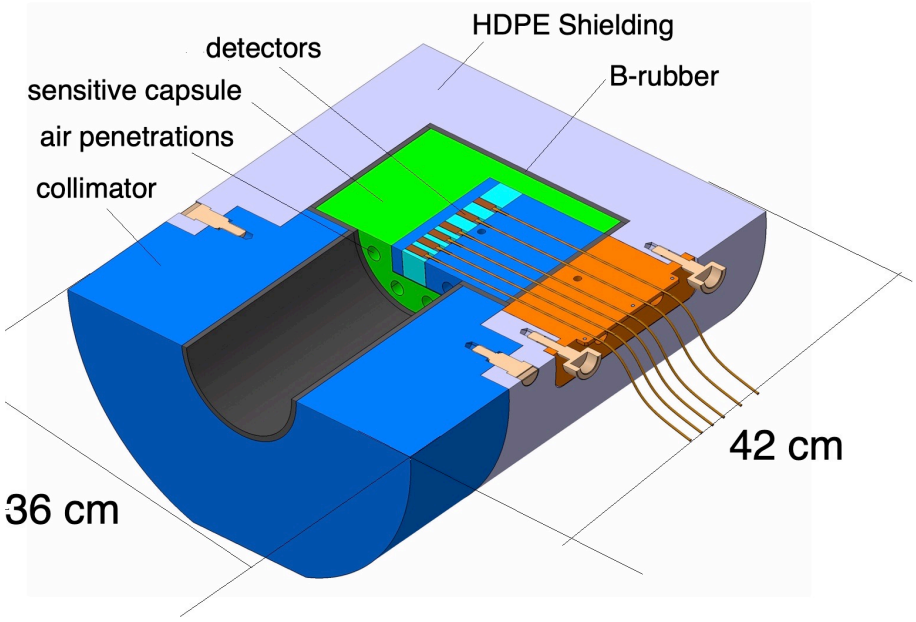


Neutron Capture Therapy-Wide Energy Spectrometer
NCT-WES (2020)

Size/weight	36 Φ x 42 h, 36 kg
Energy range	Thermal – 20 MeV
Detector depth Inside capsule	1 – 2 cm Optimised for epithermal – few MeV
Applications	BCNT, neutron metrology

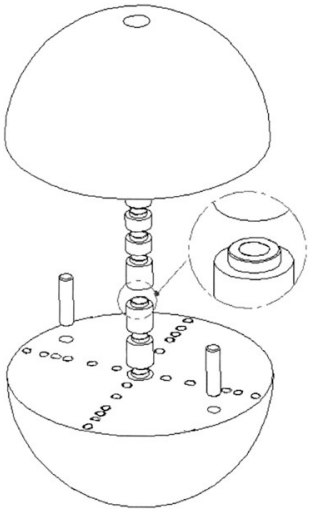






The history of the Spherical Spectrometer

Spherical geometry – passive detectors



TL, foils,..
arrangement

2008

30 cm PE sphere w 37 TLD pairs

Averaging the detectors at the same radius gives nearly isotropic response

NIMA 584 (2008) 196-203; NIMA 613 (2010) 127-133

2011

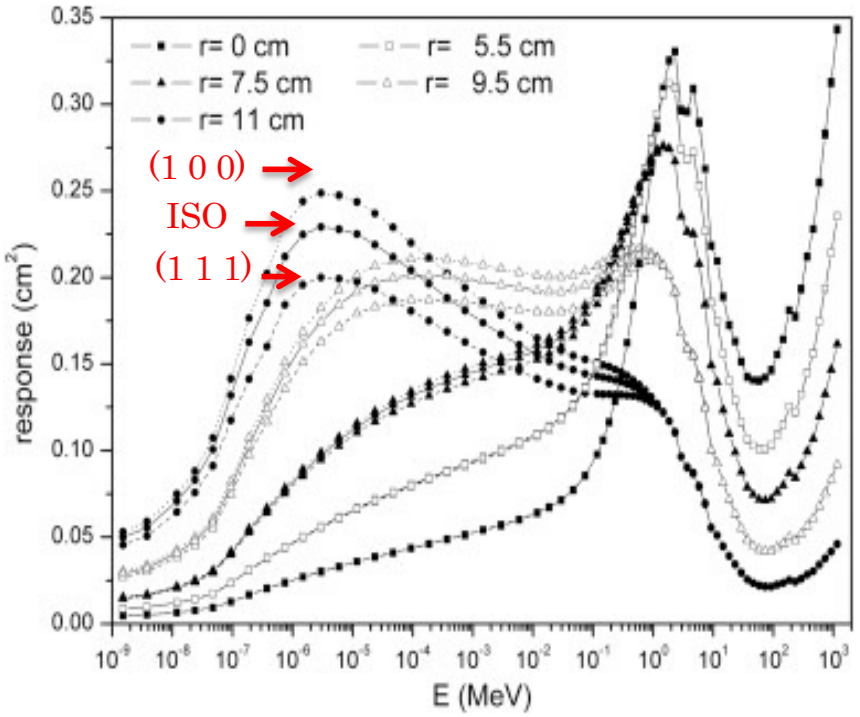
30 cm PE sphere w 31 activation foils

Radiat. Meas. 46 (2011) 1712-1715

2012

Added 1 cm thick internal lead shell for high-E

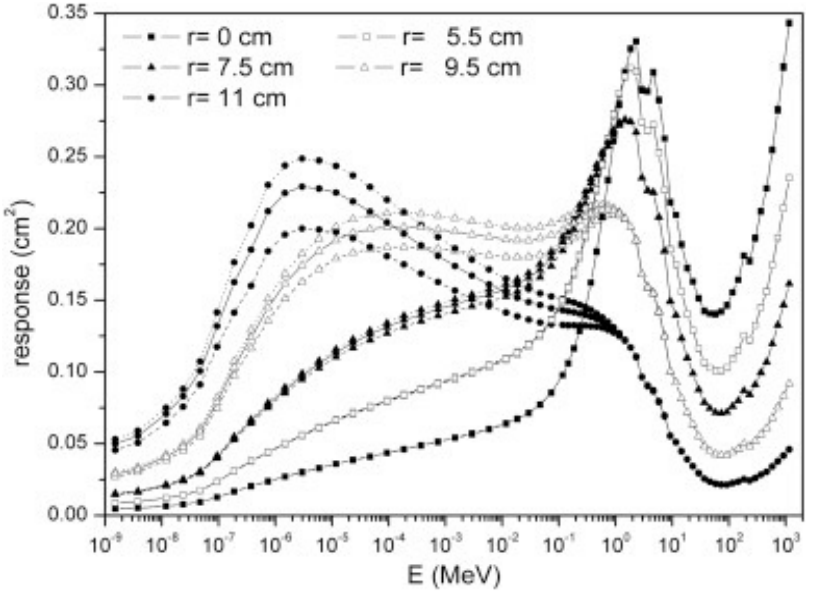
NIMA 677 (2012) 4-9

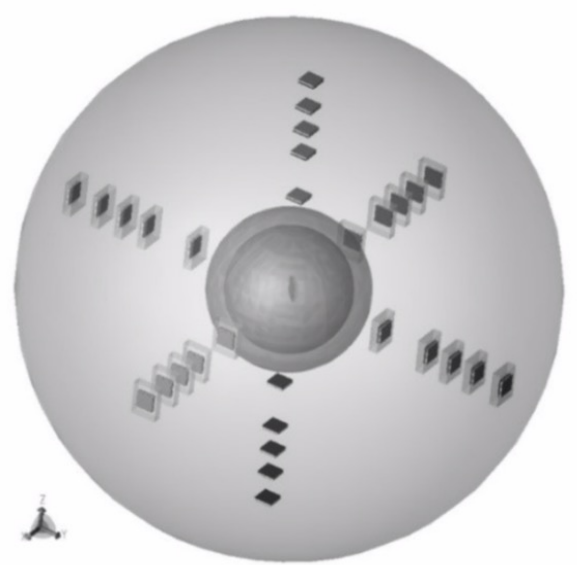


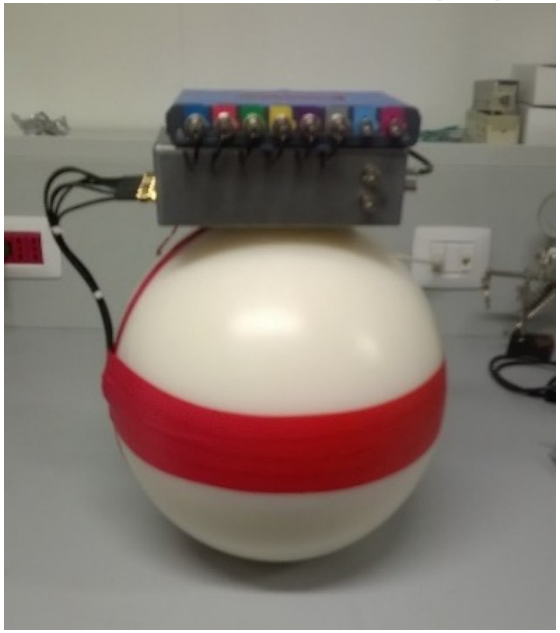
2014: The Spherical Spectrometer SP^2 From eV to GeV

- 25 cm diameter sphere + 1 cm lead insert
- 31 thermal neutron detectors (1-cm^2 Si-diode + ^{6}LiF)
- Response validated in mono-energetic fields
- Studies to evaluate the degree of isotropy
- Mimics a 6-sphere BSS + high-E capability

- 400+ citations
- inspired 10+ published research projects
- 2 companies selling versions of SP^2



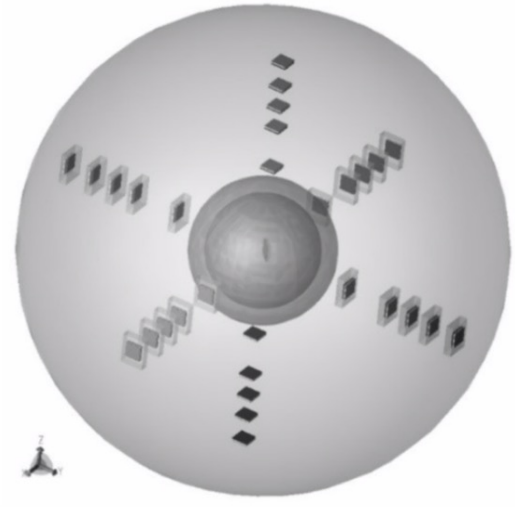




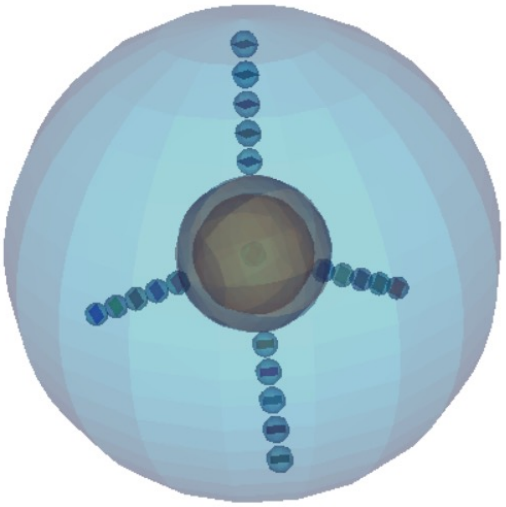
NIMA 767 (2014) 159-162
EPJP 130 (2015) 24

The Tetra-Ball

- Benchmarking the FLUKA CMS background in LHC High-lumi Ph.
- Accumulated fluence up to 10^{13} cm^{-2} / rate up to 10^{5}-10^{6} cm^{-2} s^{-1}
- Manufacturing 3-4 portable spectrometers for CMS
- Rad-hard sensors: pairs of SiC (7.6 mm^2): bare / ^{6}LiF coated
- Trying to minimise the number of internal positions



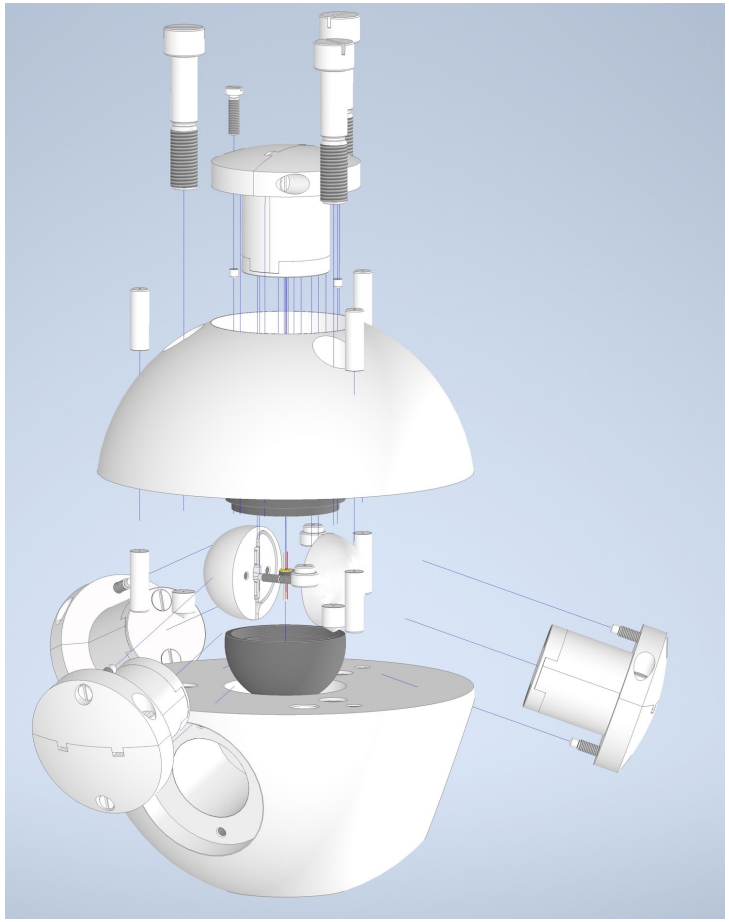
SP^2 (2014)

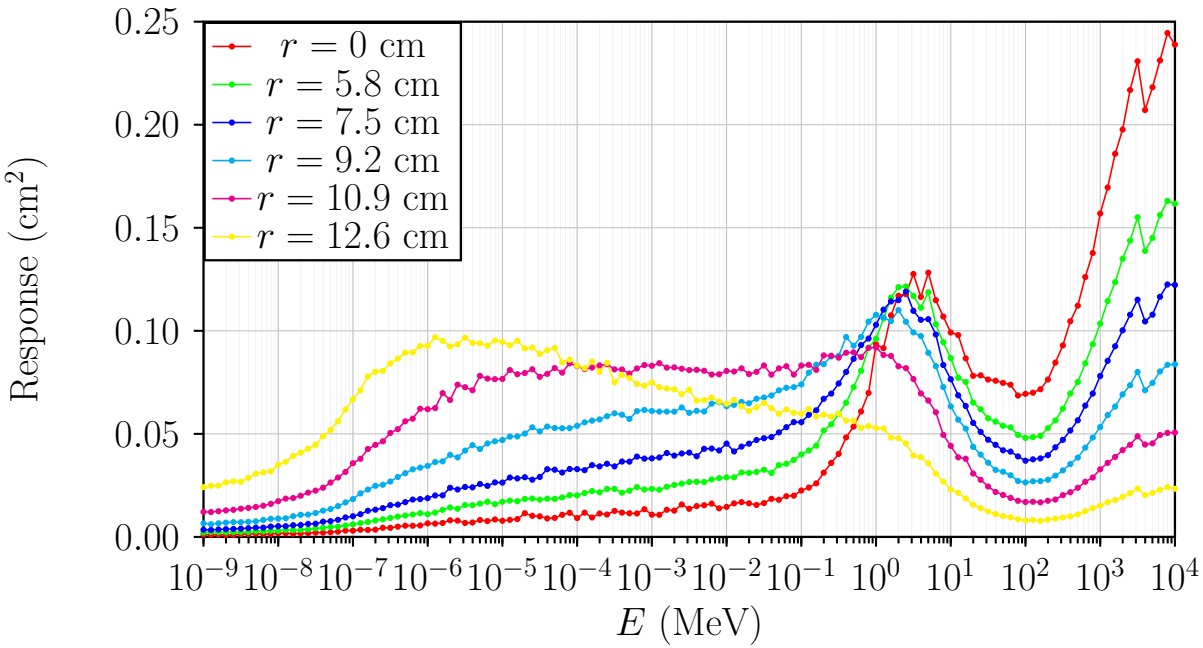


Tetra-ball (2024)

The Tetra-Ball

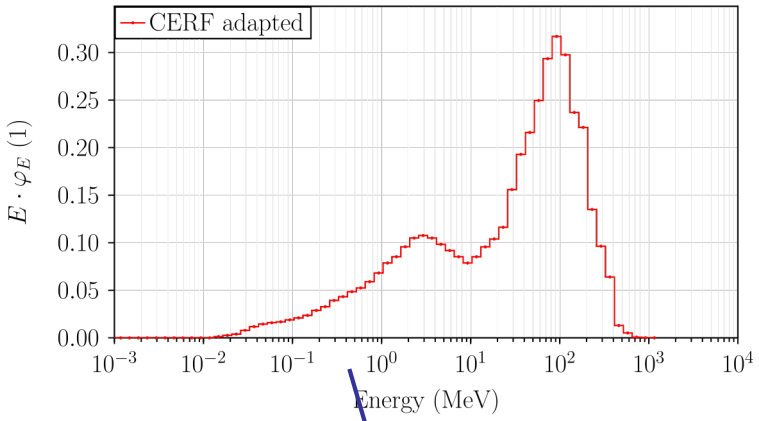
Response matrix under isotropic irradiation

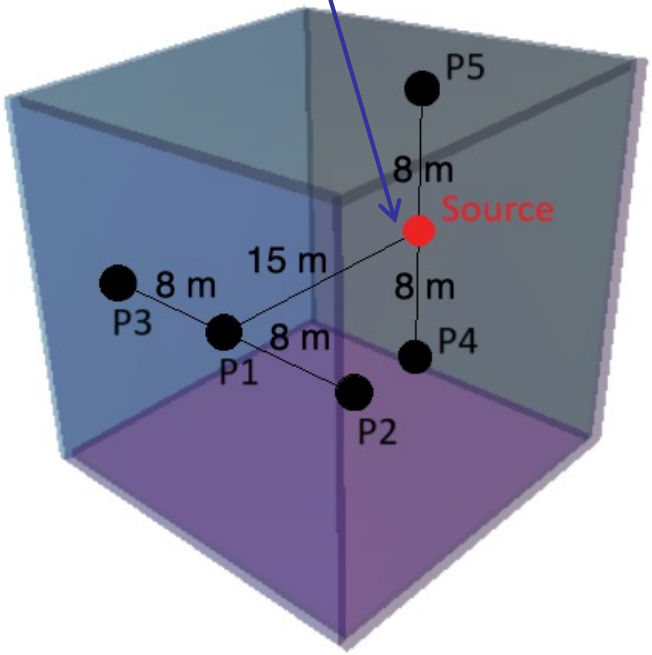




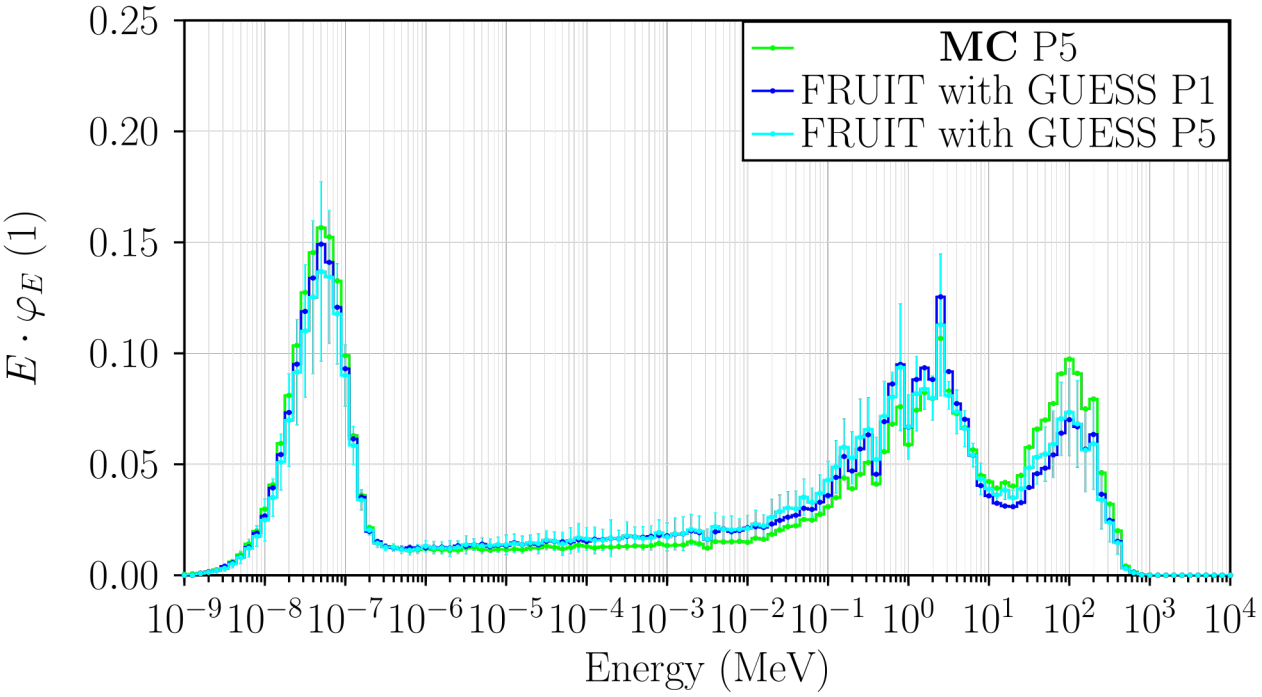
NIM A 1069 (2024) 169952
Eur. Phys. J. Plus (2025) 140:180

The Tetra-Ball





- Simulated irradiation
- Unfolding tests with unspecific guess



Conclusions

- BS have evolved into single moderator spectrometers, suited for real-time monitoring, with BS-like performance

- Cylindrical, directional design, low- / high-Energy, mostly suited for:
  - ❖ direction-dependent neutron fields (beam-lines)
  - ❖ transfer instrument in neutron metrology

- A spherical design suited for RP application (SP^2)
  - ❖ Successful idea for getting nearly isotropic response
  - ❖ Studied and replicated by third parties
  - ❖ Commercial models available
  - ❖ Tetra-Ball

Thank you

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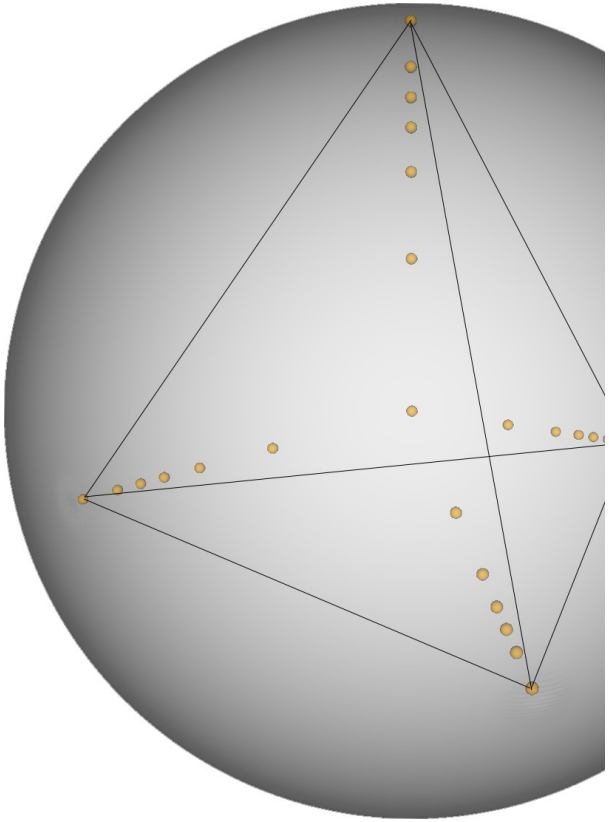
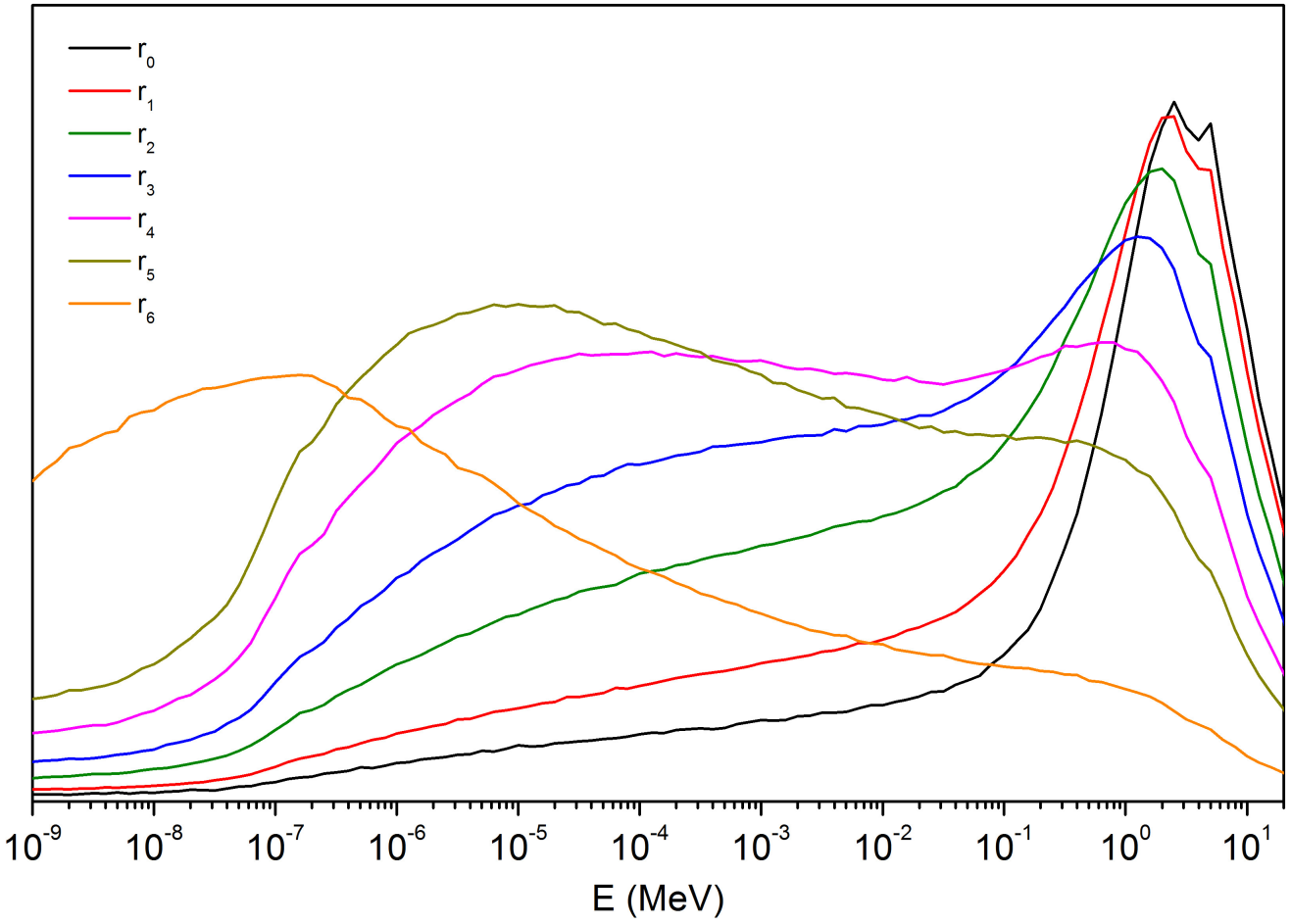
Spares



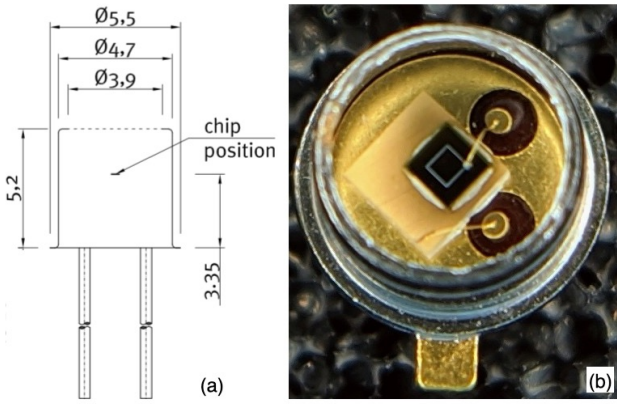

r0
r1
r2
r3
r4
r5
r6
10-9
10-8
10-7
10-6
10-5
10-4
10-3
10-2
10-1
100
101
E (MeV)

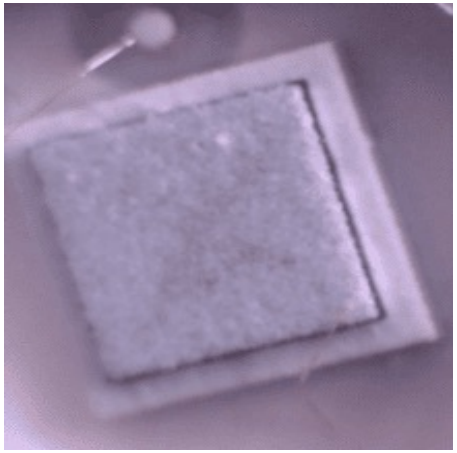
Rad-hard active thermal neutron sensors

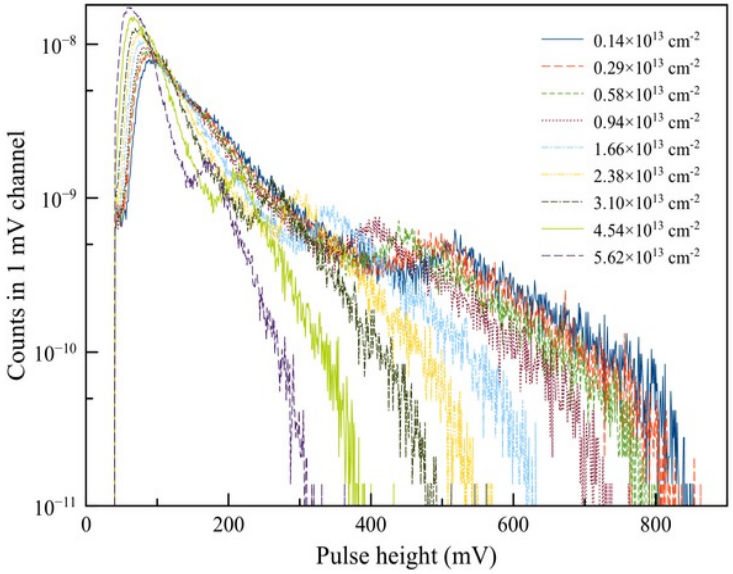
- Previous studies of the response of SiC based thermal neutron sensors up to severe irradiation Eur. Phys. J. Plus (2022) 137:1358

  - ❖ SiC 1 mm^2 + 30 mm ^6LiF

inversely biased to 12 V (depletion 1.8 μm) and connected to a spectrometry chain formed by charge sensitive amplifier and shaper amplifier







- The semiconductor is "bombarded" with high-LET particles (2.05 MeV α and 2.73 MeV ^3H), thus a spectrum left-shift is observed with accumulated fluence
- However: the integrated signal (total number of pulses above a threshold) remains constant up to 5.6×10^{13} cm^{-2} (thermal).

Collimated cylinder directional spectrometers