From Bonner Spheres to real-time single-moderator neutron spectrometers

Roberto Bedogni

INFN-LNF
Frascati Italy

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

LEMRAP
Laboratory for Environmental and Medical RAdiation Physics

SATIF-16

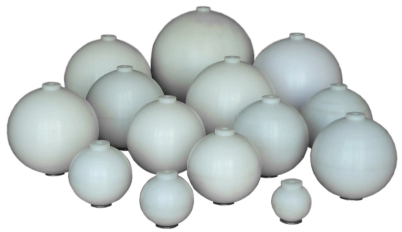
Talk breakdown

- Bonner Spheres fundamentals
- Single Moderator Neutron Spectrometers (SMNS)
- SMNS internal sensors and readout
- The Cylindrical Spectrometer CYSP (2012)
- NCT-WES (**N**eutron **C**apture **T**herapy **W**ide **E**nergy **S**pectrometer) (2021)
- The Spherical Spectrometer SP^2 (2013)
- Tetra-Ball (2024)

Bonner Spheres fundamentals

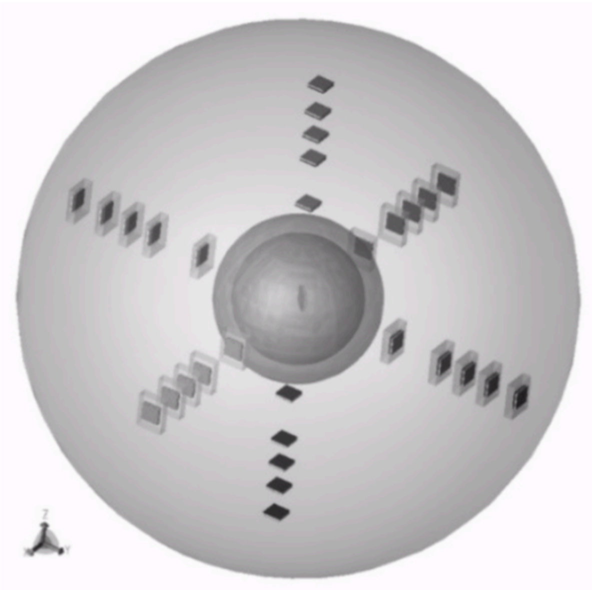
Physics Reports 875 (2020) 1–65

- BS (1960) still are the "state of art" for RP measurements over 10+ decades in energy
- Isotropic response
- Simple operation
- Very accurate: better than 5% for fluence in large bins
- Detector can be changed to match the field (intensity, photon component, pulsed)
- Resolving power is limited by the shape of the response functions
    - The unfolding problem is "under-determined"
    - Strategies needed to provide the "missing information" to the unfolding process
- Unfolding needs skills, but, after 60+ y, unfolding methods are now better established:
    - *established ways to provide pre-information according to the specific problem*
    - *uncertainty treatment*
    - *codes became "friendly" / training material online / unfolding courses / exercises*
    - *Modern codes are e.g. FRUIT (INFN-LNF), UMG package Maxed, Gravel*
- Sequential irradiations – time consuming – unsuited for real time monitor

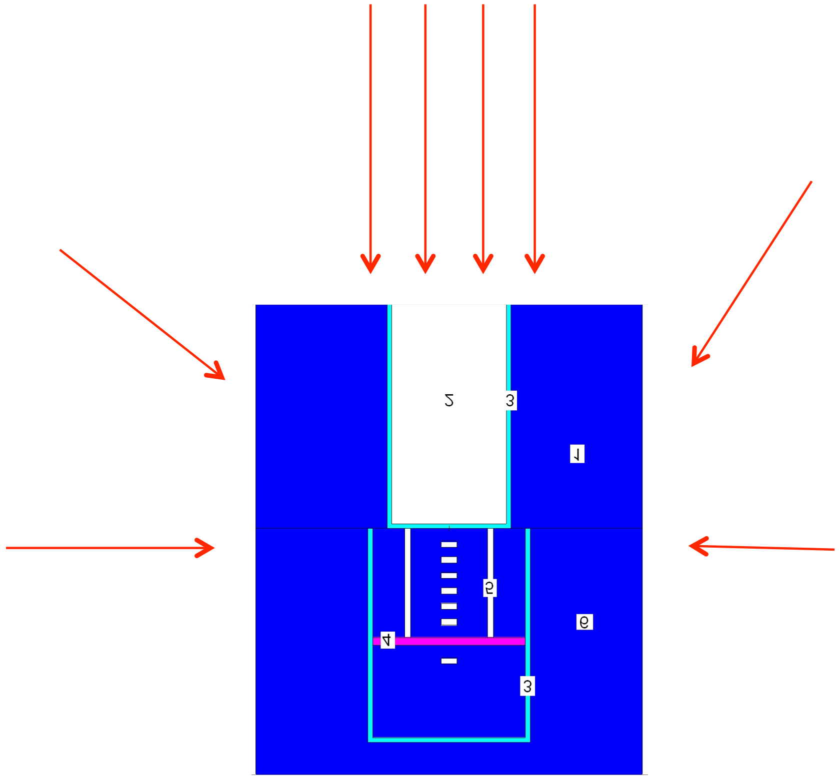


Single Moderator Neutron Spectrometers: the ideas

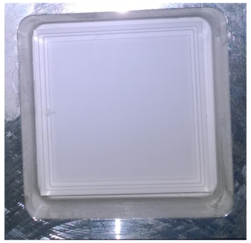
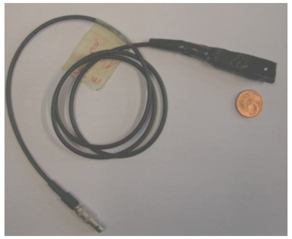
Spherical design



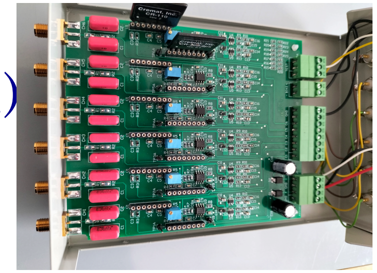
Cylindrical design



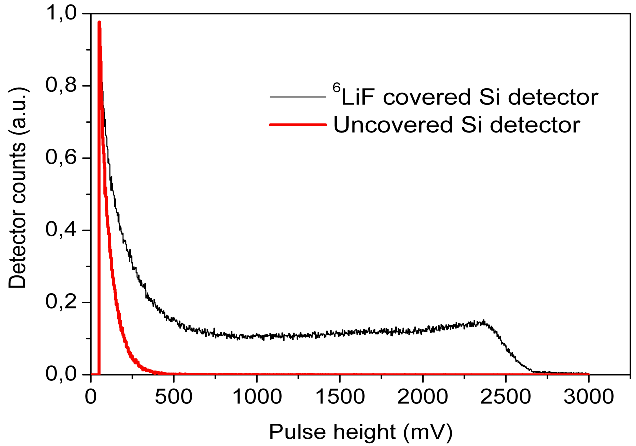
SMNS internal sensors and readout

- Thermal neutron sensors are semiconductors coated with 30 μm ^{6}LiF:
  - ❑ Si diode for calibration-grade fields
  - ❑ SiC diodes for intense neutron fields
- Custom multi-detector analog board (charge preamp. + shaper amp.)



- Individually calibrated in ENEA/INFN HOTNES reference thermal neutron field.
- Digital elaboration using commercial digitizer and laptop

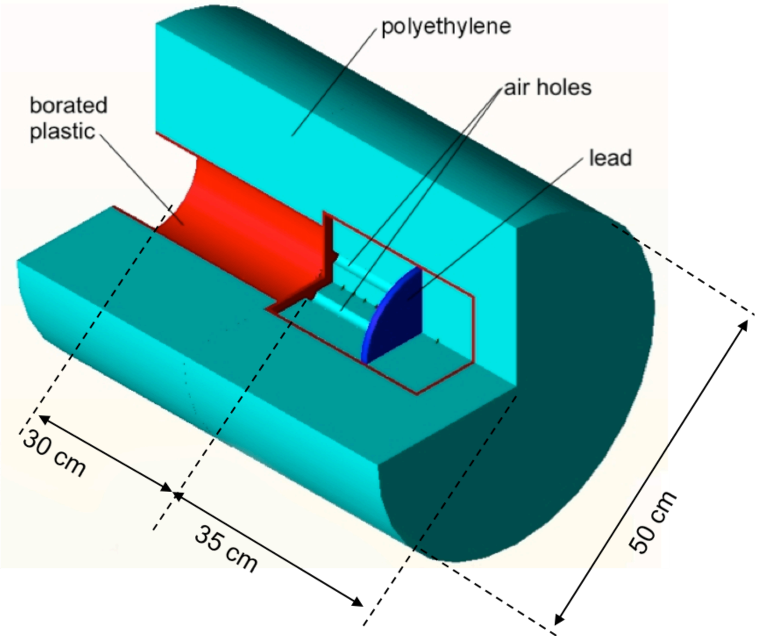


NIM A 1018 (2021) 16585
NIM A 780 (2015) 51-54
Radiat. Prot. Dosim. 161 1-4 (2014) 229-232
Eur. Phys. J. Plus 137 (2022) 1358

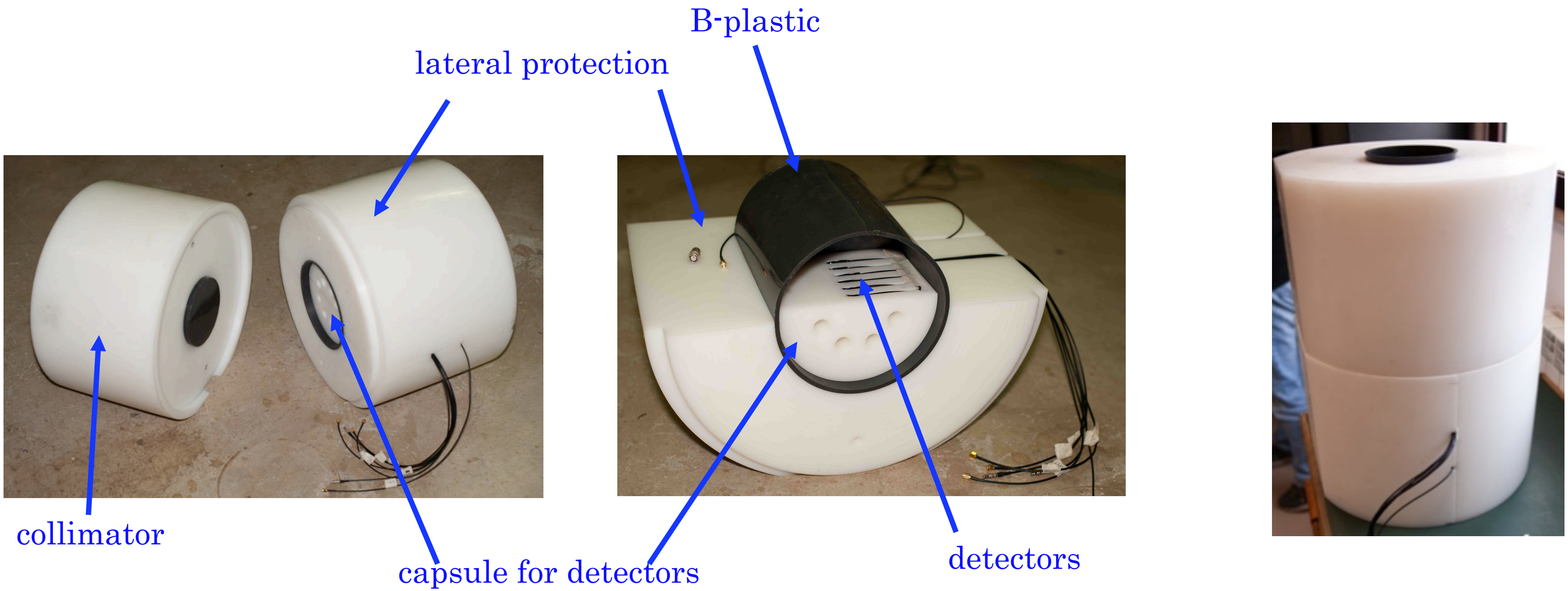
The Cylindrical Spectrometer CYSP

- Designed to provide a sharply directional response
  - collimating aperture
  - sensitive capsule laterally protected by PE + Borated rubber
- Seven TND at different depths + 1 cm lead
- Air holes enhance response of deeper detectors
- Mimic a 7-sphere BSS
- Refs:

Radiat. Meas. 82 (2015) 47-51
NIM A 782 (2015) 35-39
Eur. Phys. J. Plus (2015) 130: 24
Radiat. Prot.Dosim.161(2014) 37-40.

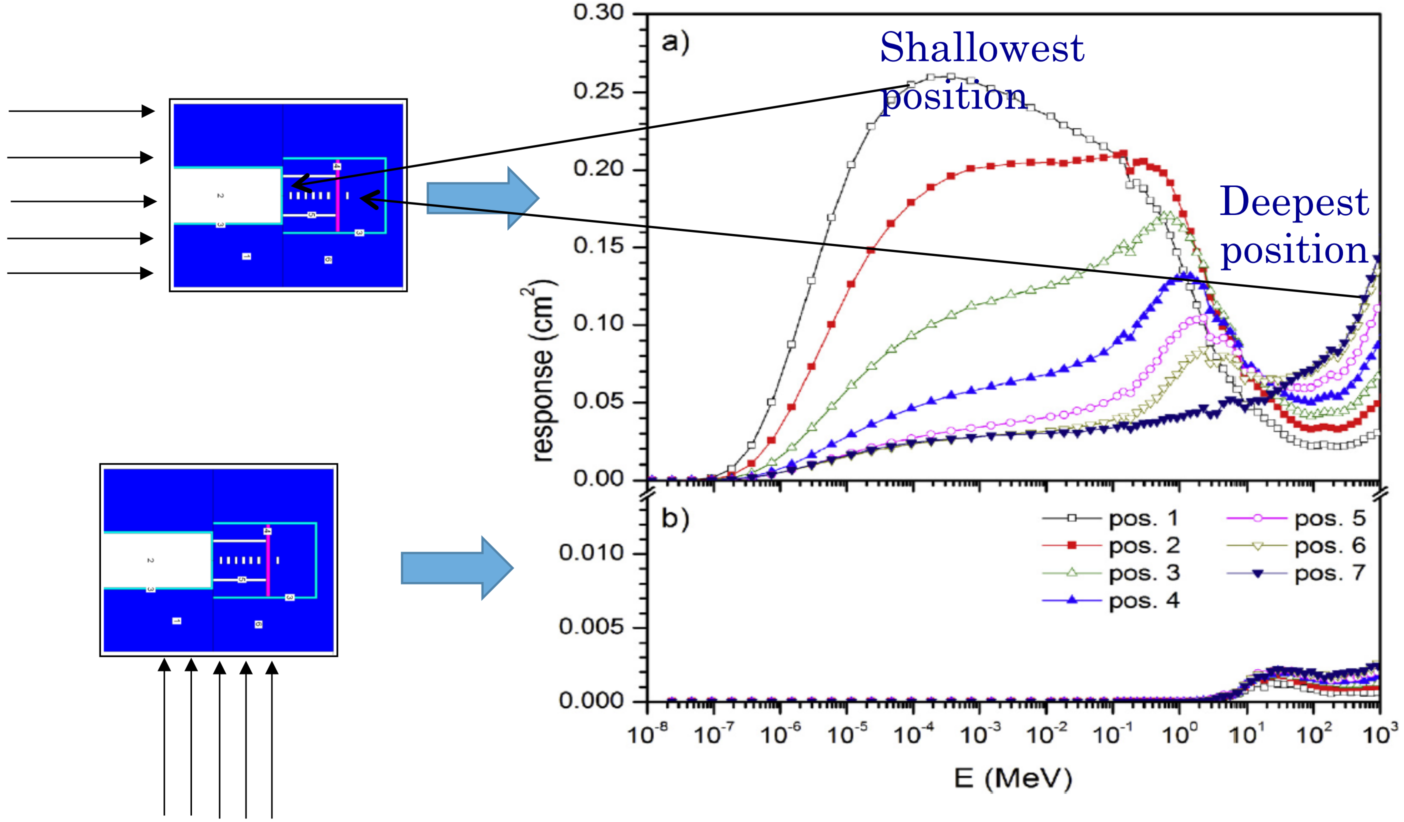


The Cylindrical Spectrometer CYSP

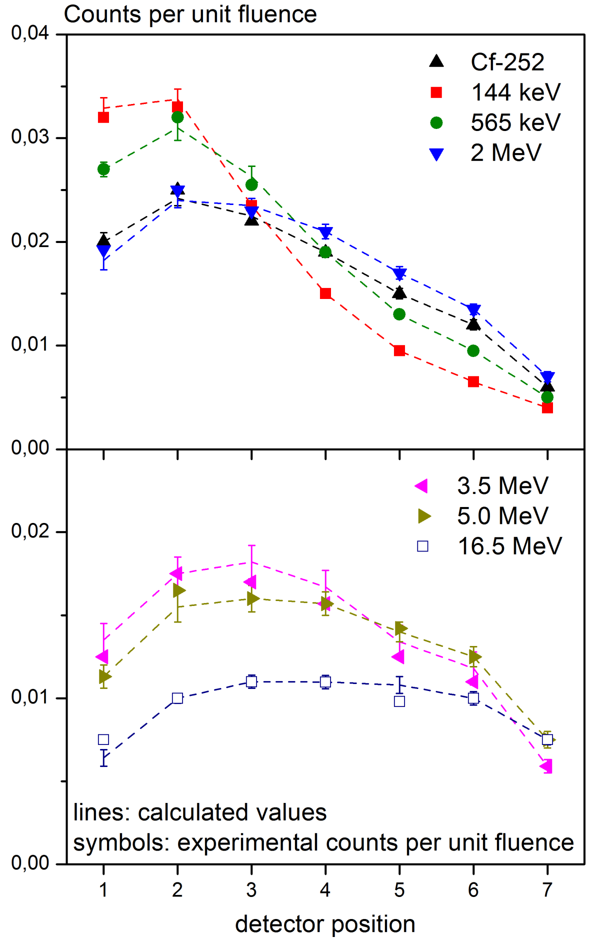


The Cylindrical Spectrometer CYSP

Response directionality

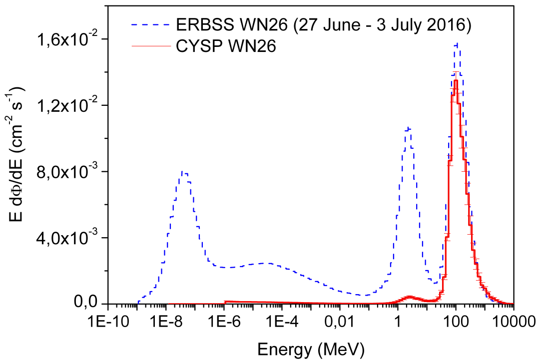


Response validation @ NPL

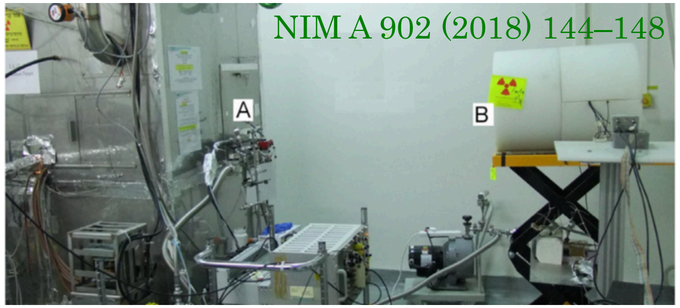


Some applications of CYSP

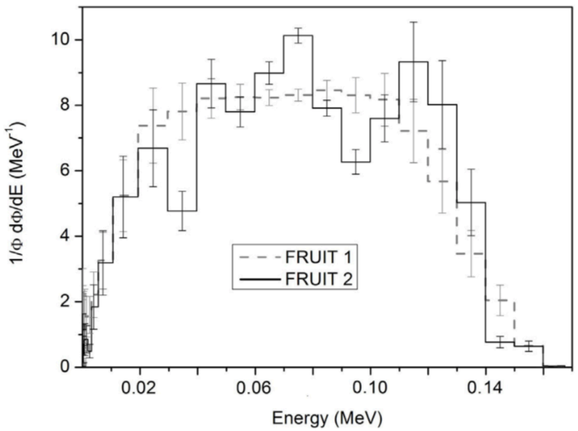
Measuring the vertical component of cosmic neutrons



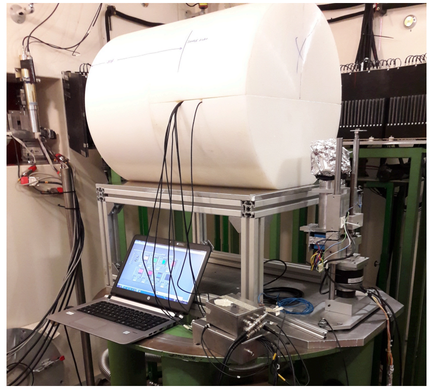
Neutron spectrum from the Liquid Li p,n target @ SOREQ

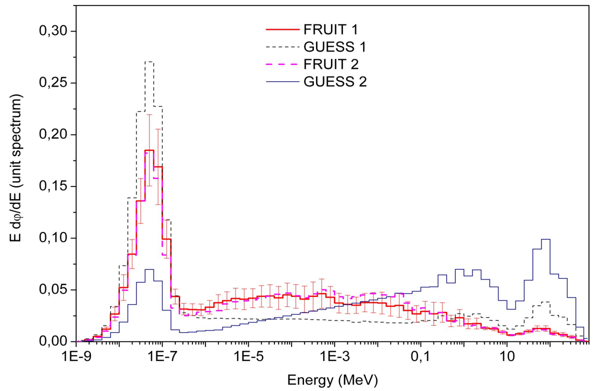


Ep=1.92 MeV, 0.5 mA x 0.1 ms @ 500 Hz



INES neutron beam-line @ ISIS (RAL, UK)

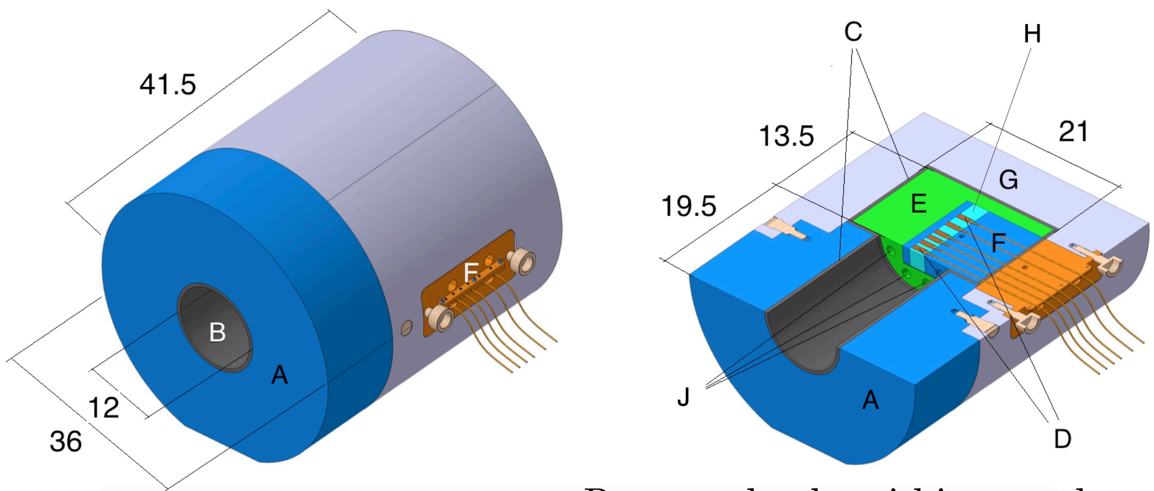




EPL, 127 (2019) 12002
NIMA 927 (2019) 151

The advent of AB-BCNT is requiring fast spectrometry techniques for beam monitoring

- Directional response would be desirable to reject room scatter
- INFN project ENTER_BCNT designed a modified CYSP with the objectives:
  - ❑ Emphasise resolution in epithermal domain
  - ❑ Reduce the weight and improve portability
  - ❑ Limit the energy limit to 20 MeV
  - ❑ Implement rad-hard sensors

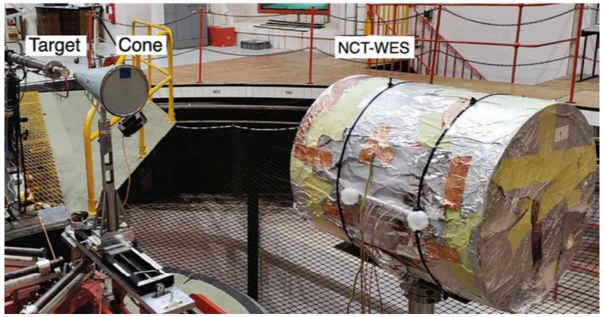


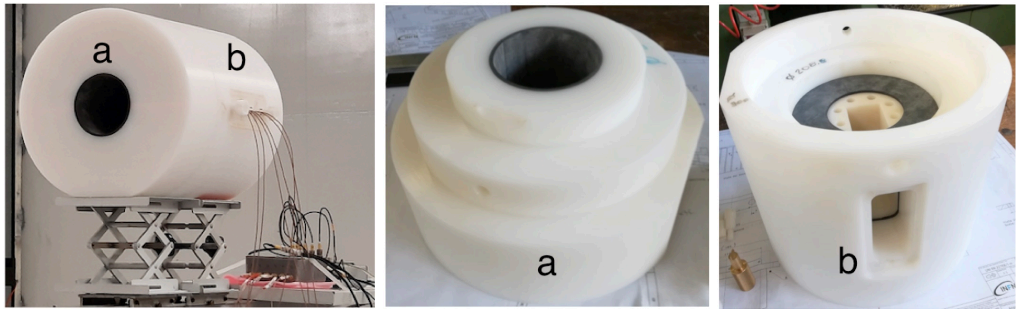
Detector depths within capsule
7.5, 20.5, 33.5, 46.5, 66.5, 86.5 mm

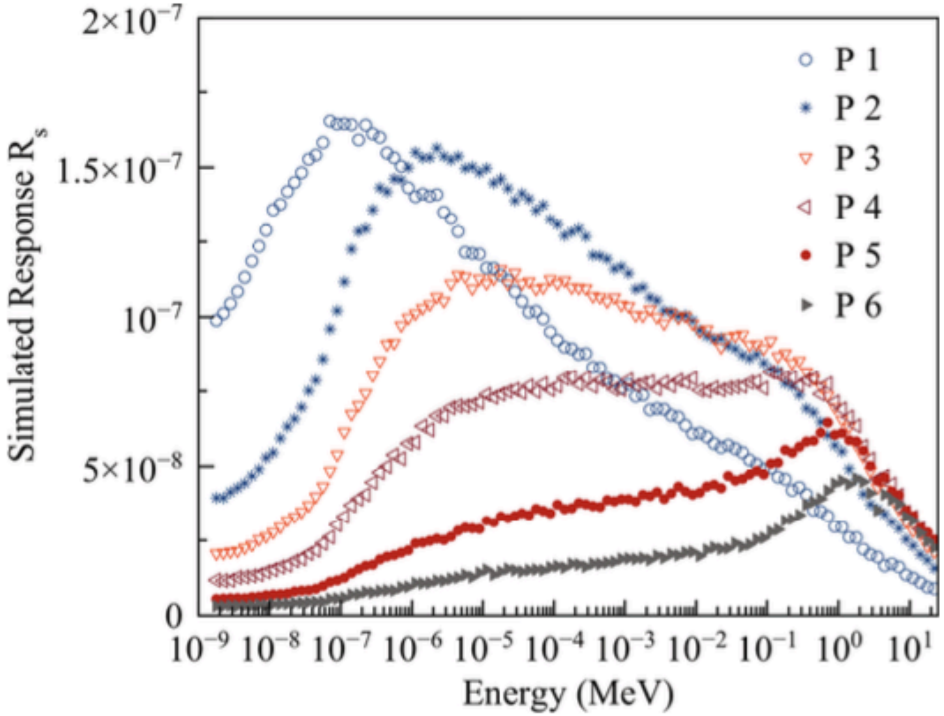
- Advances in BCNT, 2023 (IAEA book)
- Modern Neutron Detection IAEA-TECDOC-1935 (2020)
- Europhys. Lett. 134, 42001 (2021).

Response verification at NPL

- 71.5, 144.2, 565.1, 841.9, 1200.4 keV
- $R_{calculated}$ agrees with vs. $R_{measured}$ within 2%



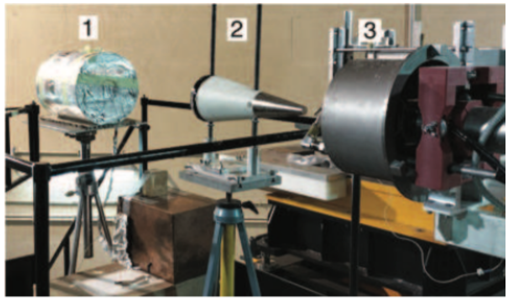


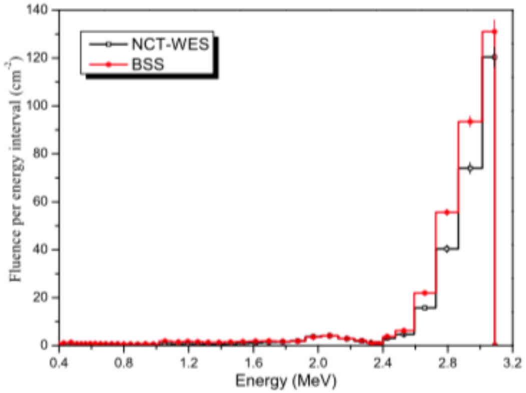


EPJP 137 (2022) 773

Some applications of NCT-WES

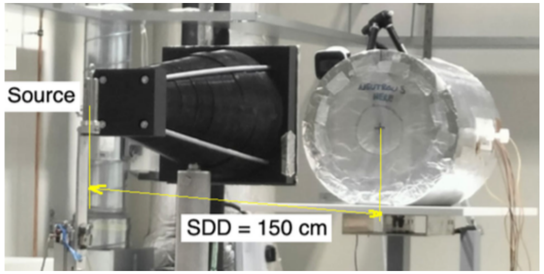
ENEA Fast Neutron Generator in D-D



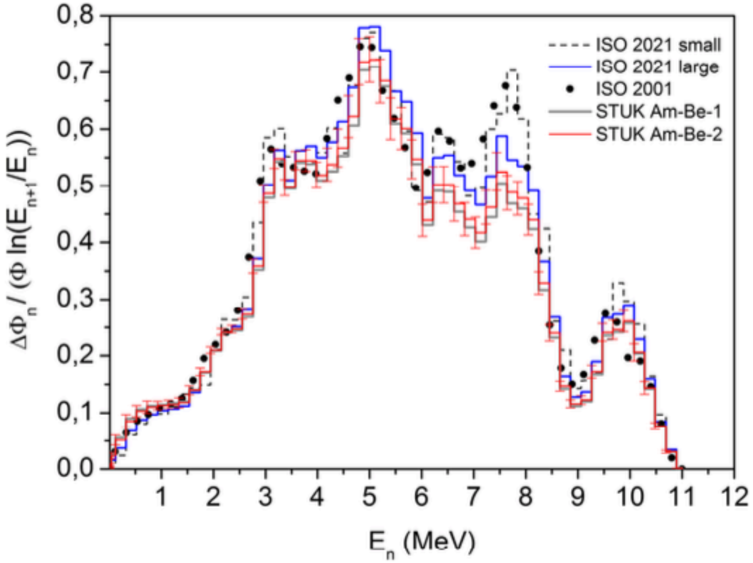


EPJP 137 (2022) 773

Characterizing n sources at Finnish neutron metrology center (STUK)



EPJP 139 (2024) 384

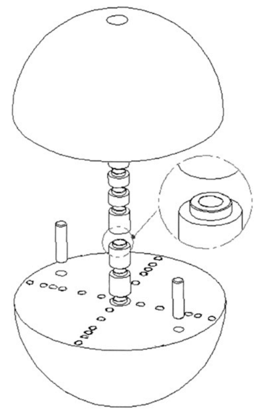


Source	$B_{nominal}$ (s^{-1}) 12/7/2023	$B_{measured}$ (s^{-1}) 12/7/2023
Cf-1	9.12×10^6	$(1.08 \pm 0.03) \times 10^7$
Cf-2	2.82×10^7	$(2.98 \pm 0.08) \times 10^7$
Am-Bc-1	2.09×10^6	$(1.98 \pm 0.05) \times 10^6$
Am-Be-2	1.99×10^7	$(1.92 \pm 0.05) \times 10^7$

Spherical Spectrometer: the history

1997 B-loaded plastic scintillator sphere + light sensors (V. Vylet et al.)
IRPA Regional Symposium, Prague 1999

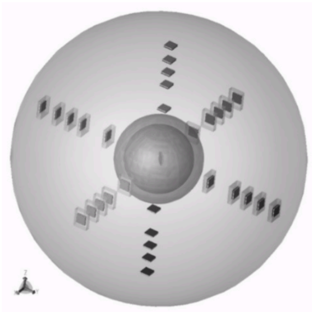
1999 S Yamaguchi, et al. *Spherical neutron detector for space neutron measurements*
NIM A 422 (1999) 600.

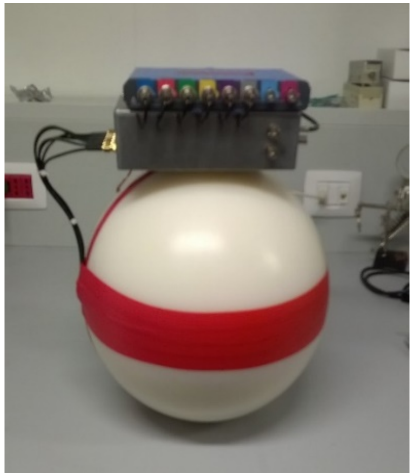


2008 30 cm PE sphere with 37 TLD pairs along the 3 axes. Averaging the detectors at the same radius gives nearly isotropic response
NIMA 584 (2008) 196-203; NIMA 613 (2010) 127-133

2011 Prototypal PE sphere with 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

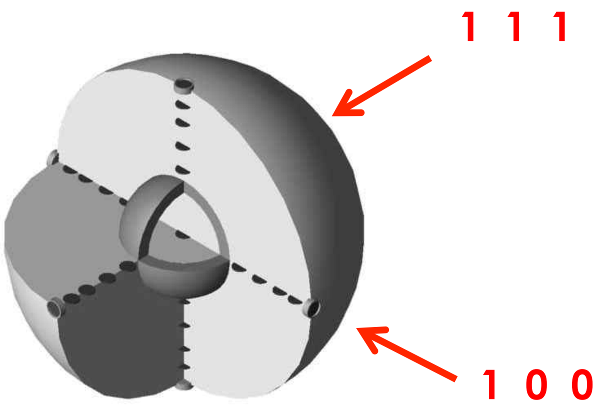


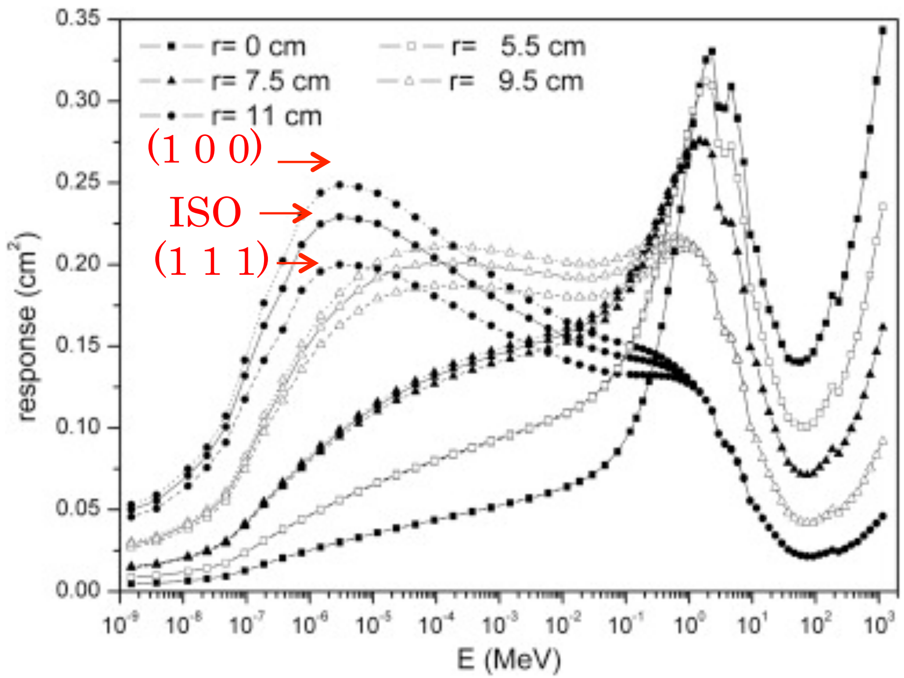


2014 SP² Spherical Spectrometer, meV-GeV, real-time
NESCOFI, NEURAPID INFN projects

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

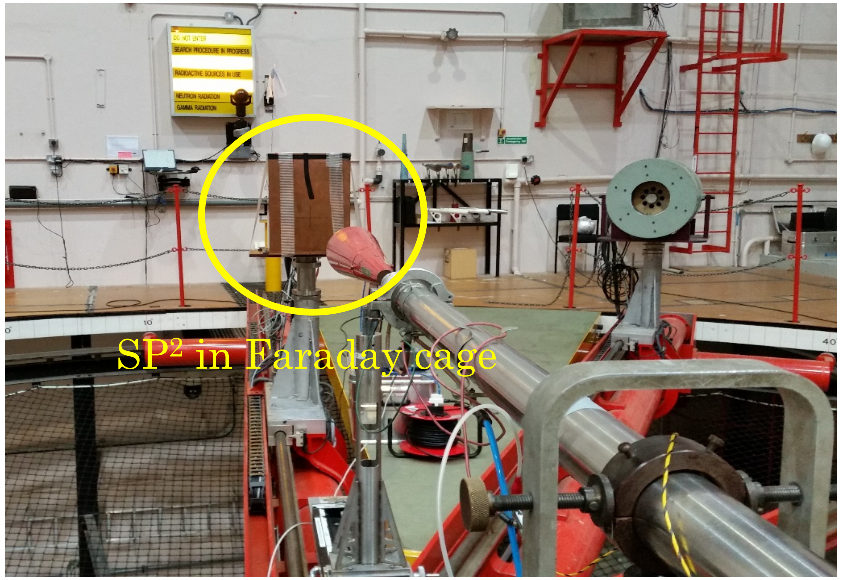
- 25 cm diameter sphere including a one cm lead insert
- 31 thermal neutron detectors (customised: usually 1-cm² Si-diode + ^{6}LiF)
- Response matrix is in principle direction-dependent
- Studies to evaluate the impact of this "imperfect" isotropy
- Single exposure
- Mimics a 6-sphere BSS

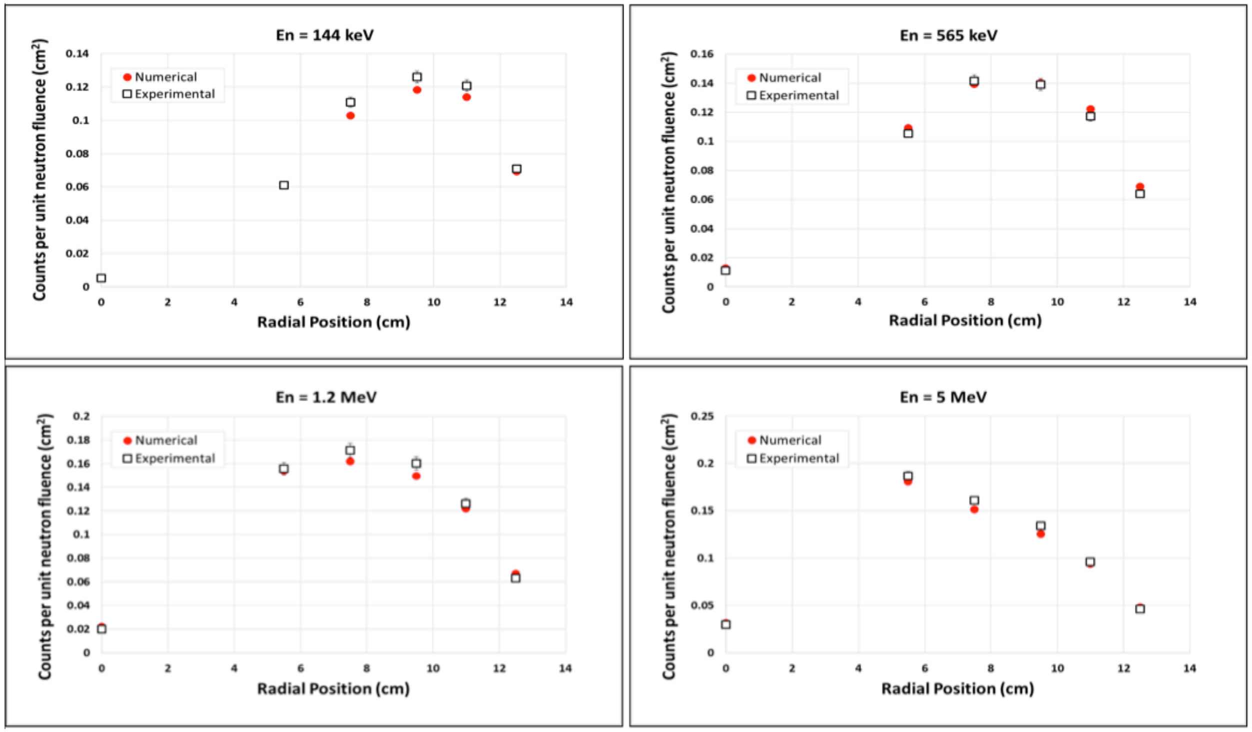




The Spherical Spectrometer SP^2

- NPL – UK mono-energetic beams 144 keV, 565 keV, 1.2 MeV and 5 MeV
- Shadow cone technique to measure scattering
- Calibration distance ≈ 2 m
- Fluence per irradiation ≈ 10^5 cm-2





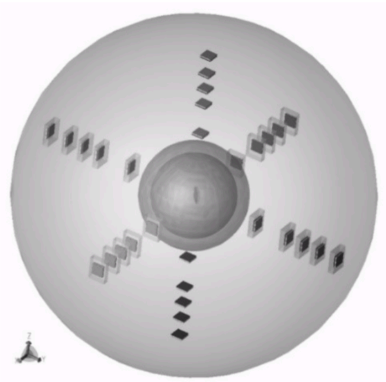
"Fallout" of the Spherical Spectrometer SP^2

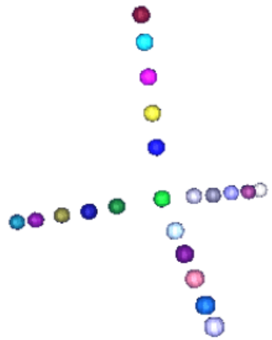
- INFN-LNF papers on SMNS: 398 citations (Google Scholar)
- Prototypes openly inspired by INFN SMNS:
    - Y. Zou, Construction and test of a single sphere neutron spectrometer based on pairs of 6Li-and 7Li-glass scintillators, Radiation Measurements, 127 (2019) 106148.
    - W. Zhang et al., Development of a portable Single Sphere Neutron Spectrometer, Radiation Measurements, 140 (2021) 106509.
    - X. Li et al Design and verification of a multi-layer single-sphere neutron spectrometer with water as the moderator. JINST 16 (2021) T12010
    - S. Paulet al. Neutron spectrometry and dosimetry using a multi-shell Single Sphere Neutron Spectrometer with thermo-luminescent and optically stimulated luminescent detectors. NIM A 1053 (2023) 168395.
- Two private companies replicated SP^2 for commercial purposes

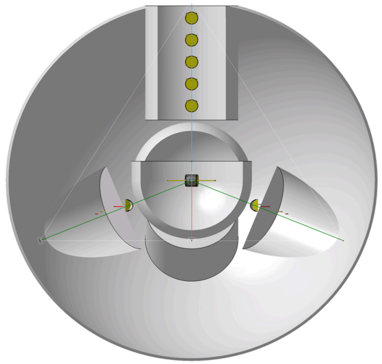
CMS BRIL collaboration

- Measuring the n background in CMS during LHC Phase 2 High-Luminosity
- 4000 fb^{-1} @ 7 TeV per beam (BRIL TDR)
- Accumulated n fluence **up to** 10^{13} cm^{-2}
- Instantaneous fluence rate **up to** 10^{5}-10^{6} cm^{-2} s^{-1}
- Less than ten portable spectrometers

- Rad-hard sensors: pairs of SiC (7.6 mm^2): one bare, one coated with 30 μm ^{6}LiF
- Developing an isotropic, spherical SMNS, with less detectors than SP^2







See next talk on Tetra-Ball by M.A. Caballero

Conclusions & perspectives

- ✔ Bonner Spheres evolved in single moderator spectrometers, suited for real-time monitoring, with BS-like performance

- ✔ A cylindrical, directional design: CYSP, NCT-WES
  Relevant perspective: monitoring AB-BNCT therapeutic beams

- ✔ A spherical design suited for RP applications:
  Successful design
  Replicated in various formats by third parties for research and market
  Relevant perspective (T-Ball): High-flux applications at particle accelerators

Conclusions & perspectives

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