Neutron spectroscopy for Boron Neutron Capture Therapy Beams Characterization

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on behalf of Enter_BNCT collaboration

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Boron Neutron Capture Therapy

BNCT is a radiation therapy based on the capture of thermal neutrons in B-10 atoms selectively accumulated in tumor cells.

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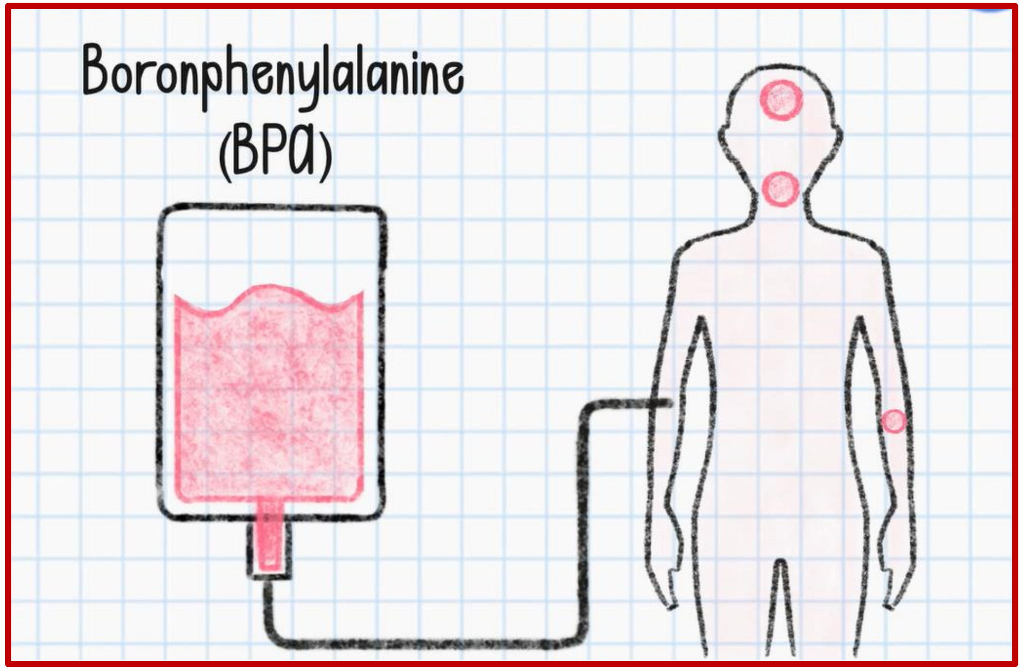

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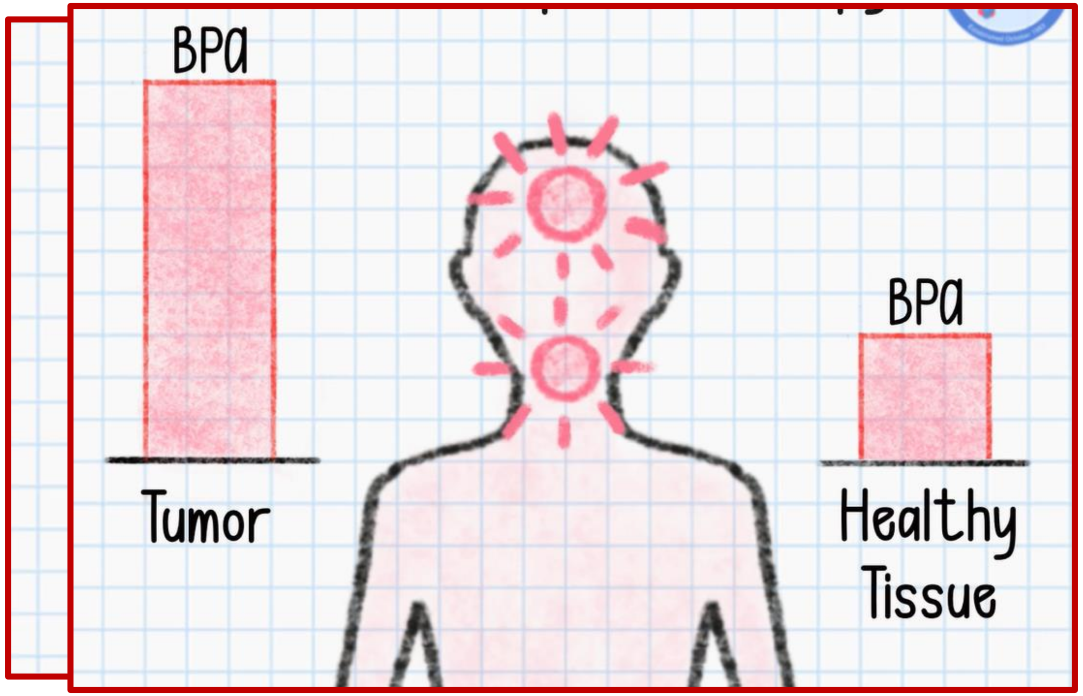

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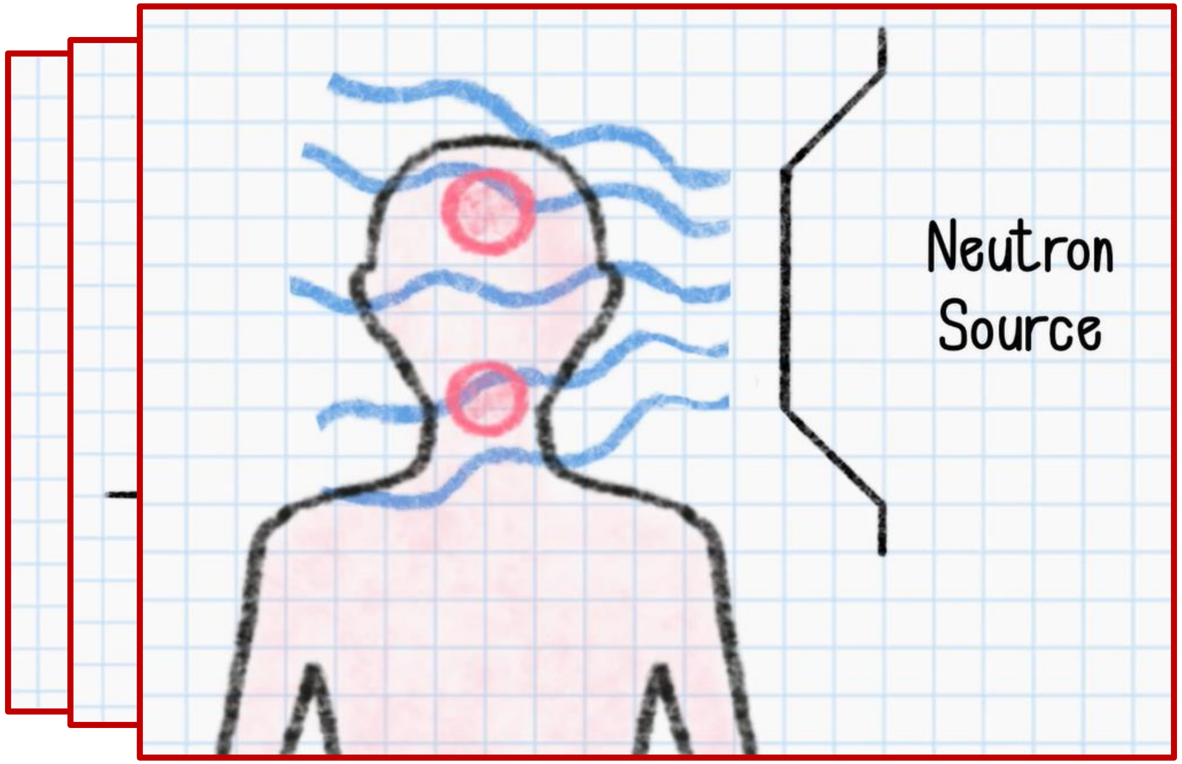

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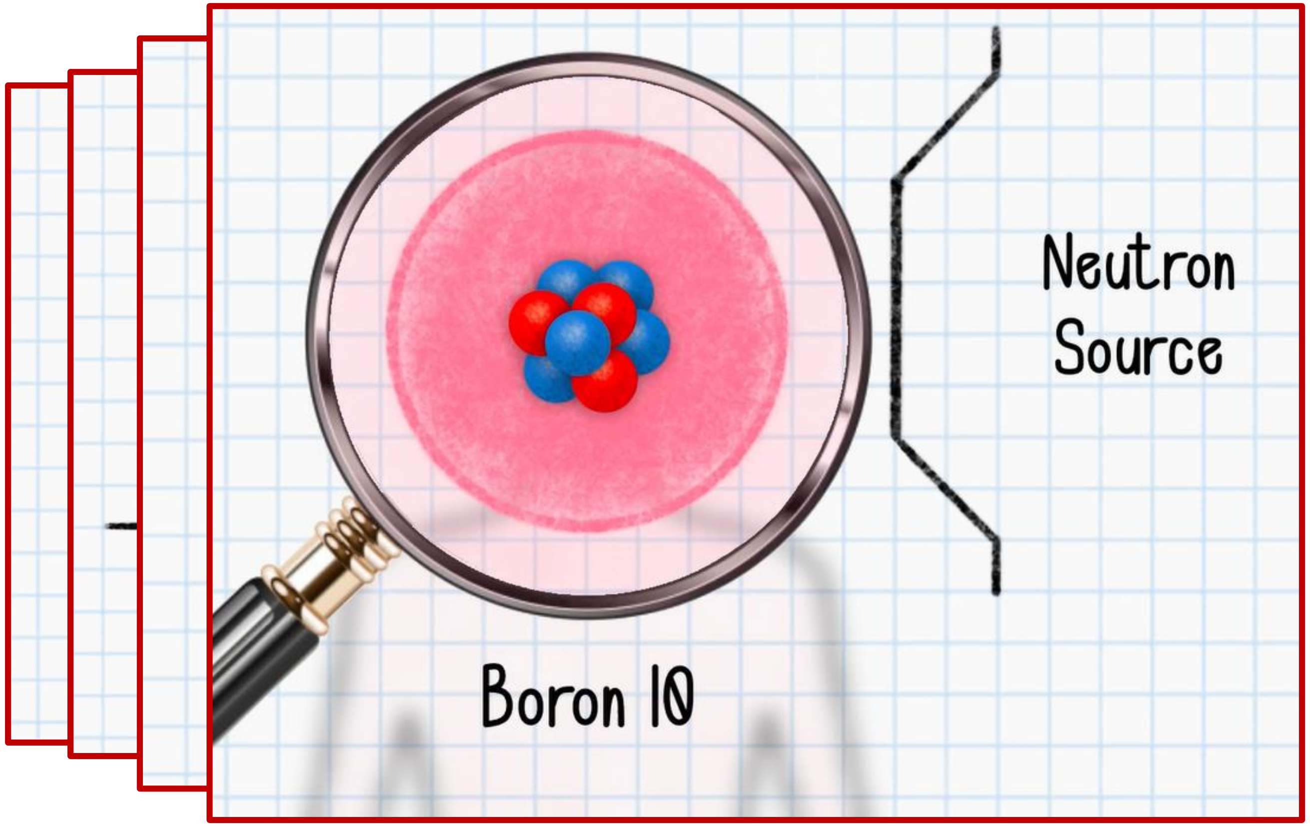

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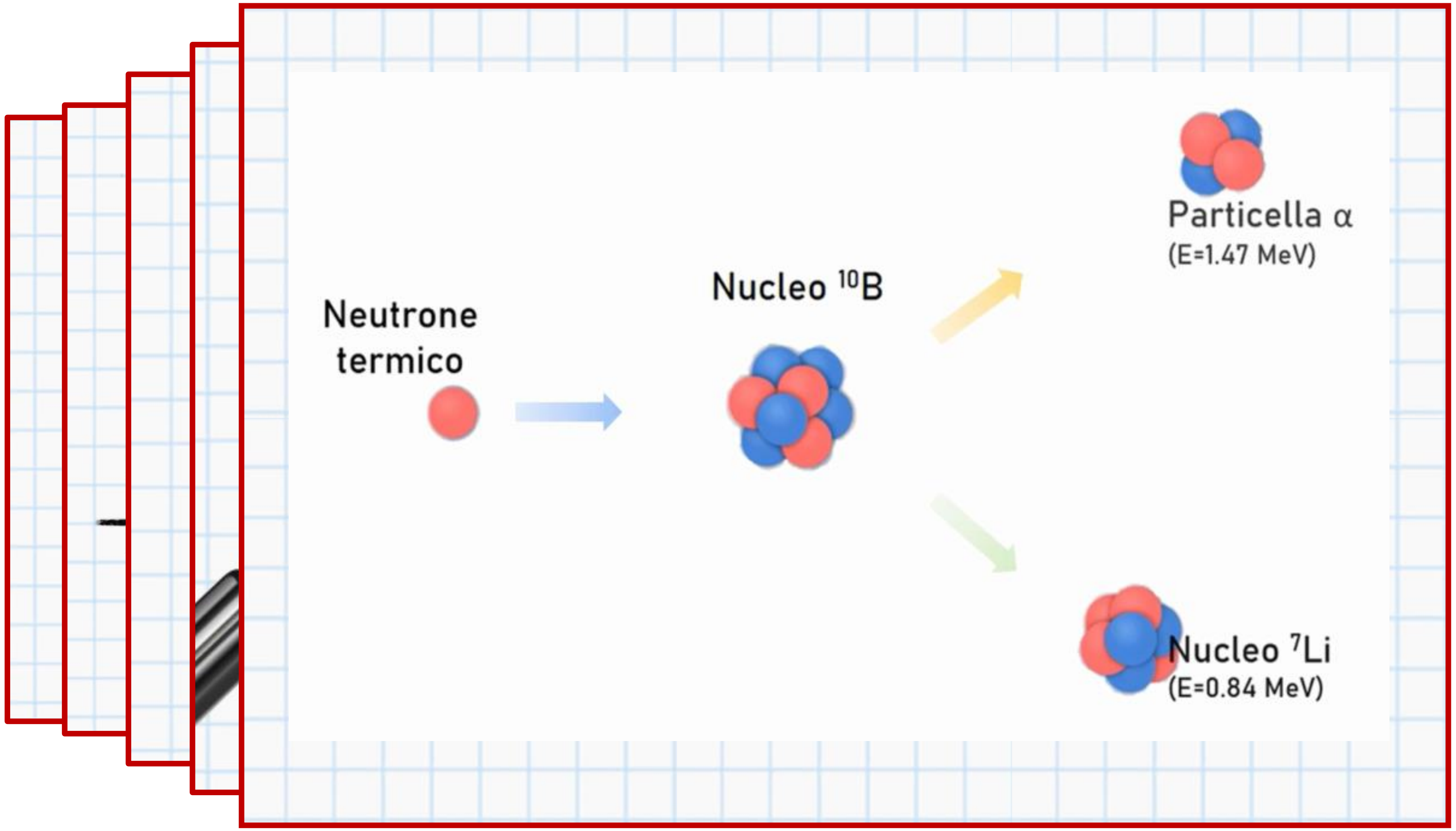

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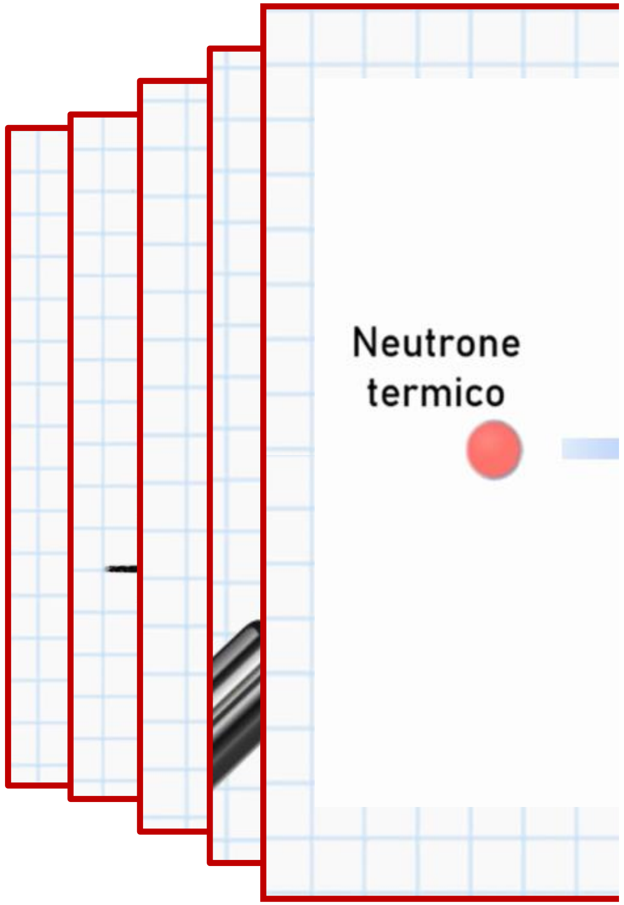
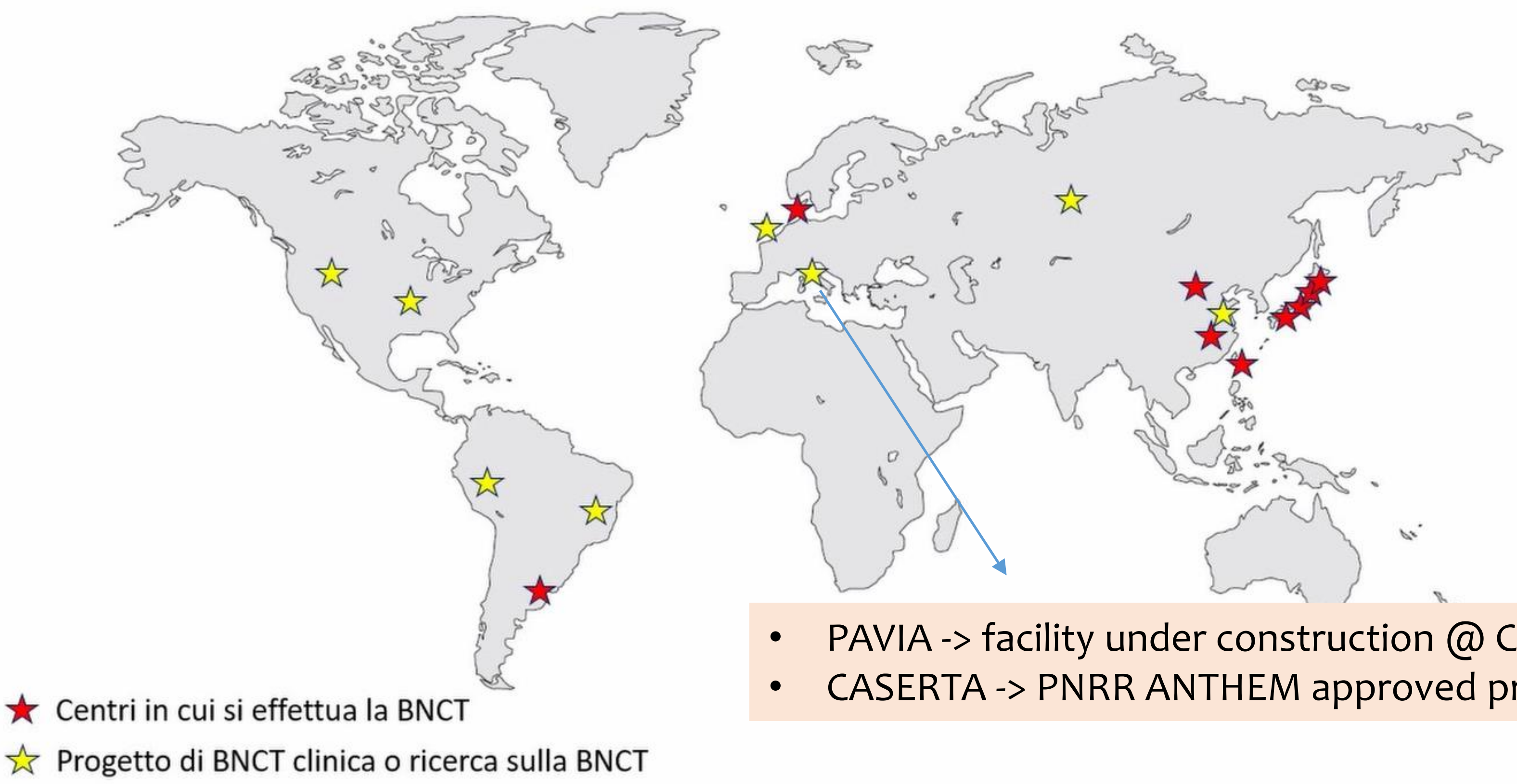




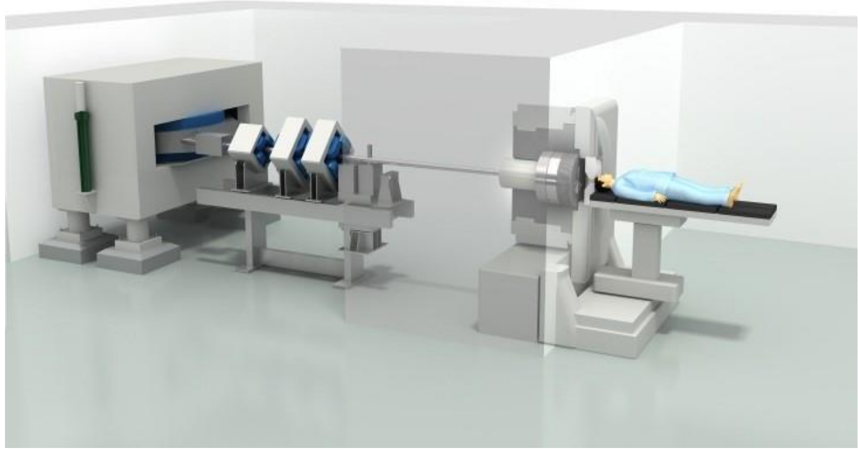
- PAVIA -> facility under construction @ CNAO
- CASERTA -> PNRR ANTHEM approved project

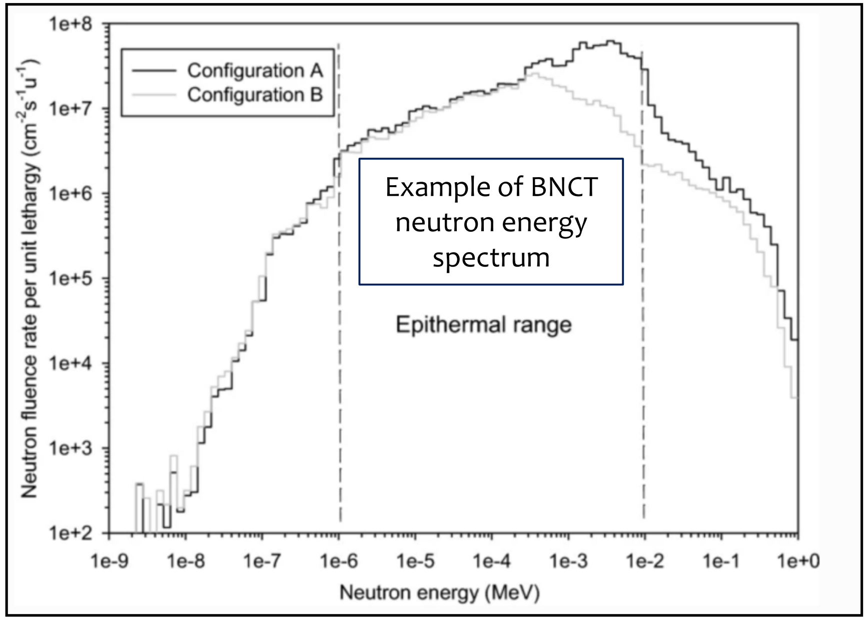
Neutron Beams for BNCT

- Epithermal neutron beams generated by accelerator based neutron sources or by nuclear reactors through customized beam shaping assemblies.

- The neutron energy spectrum is continuous and its shape determines the depth of maximum efficacy in the tissue

- **Instruments to measure the neutron dose and the neutron fluence with high precision are demanded (full spectrum coverage over about 8 order of magnitude)**





NEW

- INFN developed NCT-WES and NCT-ACS for the **beam characterization and QA**

NCT-WES

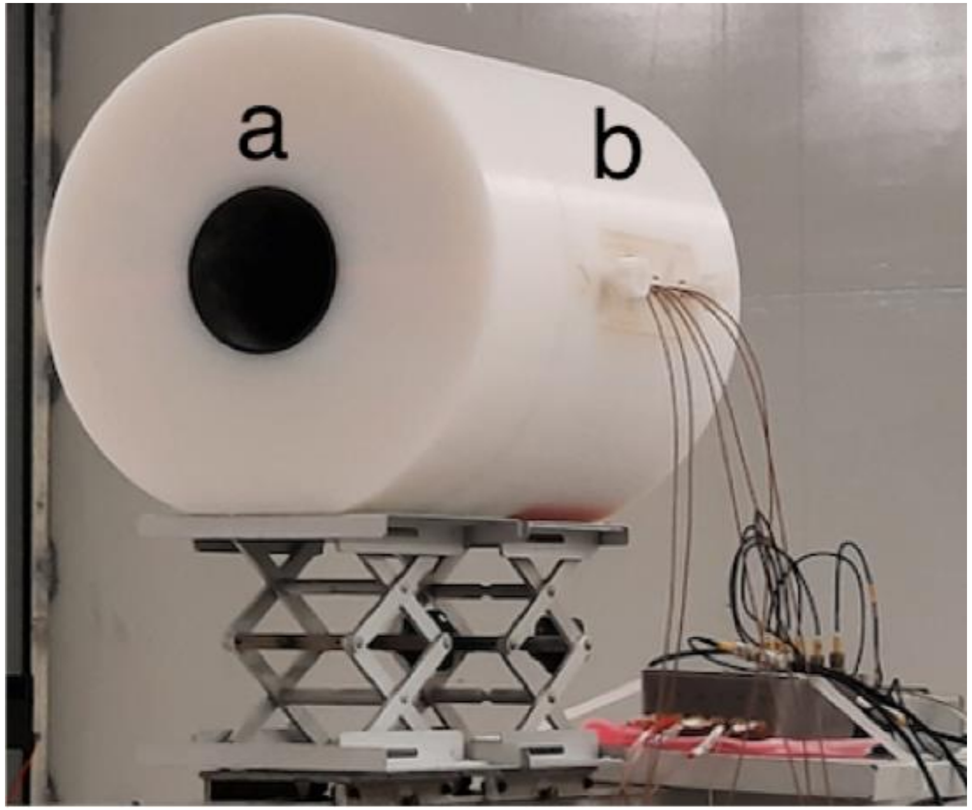
Neutron **C**apture **T**herapy **W**ide **E**nergy **S**pectrometer

NCT Wide Energy Spectrometer

Single moderator, directional, real time, neutron spectrometer for beam characterization and periodical QA

MAIN CHARACTERISTICS:

- **Bonner Spheres concept** but single exposure



NCT-WES

Standard Bonner Sphere Spectrometer

Bonner Spheres Spectrometer: main aspects
Physics Reports 875 (2020) 1–65

- Covers thermal to GeV energy range
- Isotropic response
- Simple operation
- Very accurate → *the fluence in large energy intervals can be determined with <5% unc.*
- Detector can be changed to match the field in terms of intensity and photon component
- Resolving power is limited by the shape of the response functions

- Sequential irradiations – time consuming – unsuited for real time monitor

Bonner Sphere System

NCT-WES

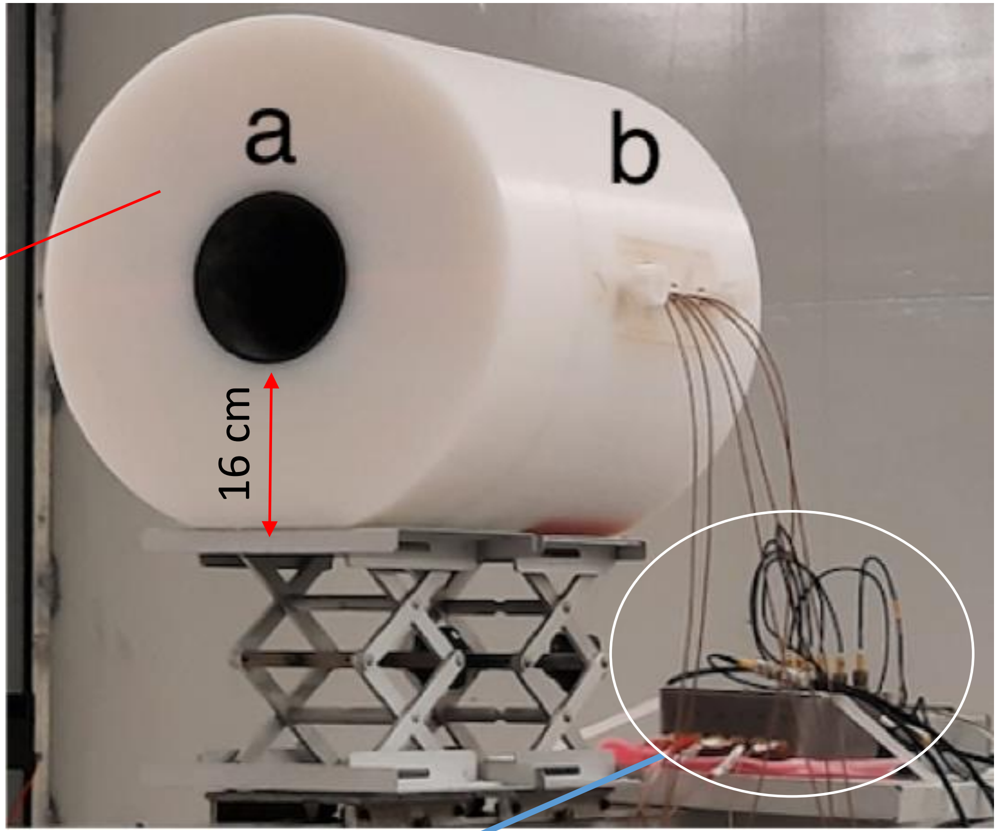
Solved by single moderator spectrometer
All the detectors work simultaneously

The response function depends on the position inside the moderator

NCT Wide Energy Spectrometer

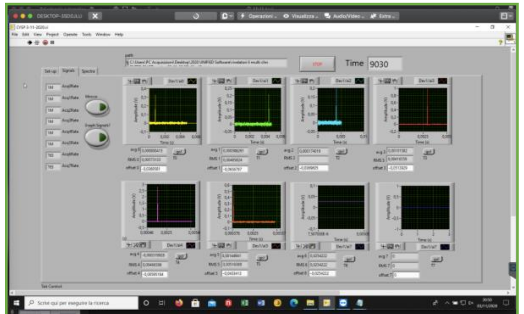
Single moderator, directional, real time, neutron spectrometer for beam characterization and periodical QA

HDPE moderator (b) and collimator (a)



MAIN CHARACTERISTICS:

- 0.01 eV-10MeV energy sensitivity range
- Cylindrical collimator for minimizing the room scattered component
- 6 neutron sensitive silicon detectors simultaneously read by a 6 channel DAQ system
- Weight 40 kg, length 41.5 cm, external diameter 36 cm.



NCT Wide Energy Spectrometer

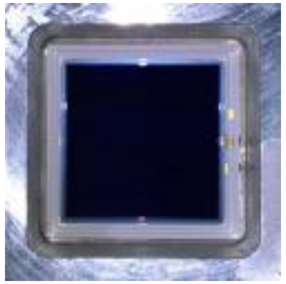
TNPD – thermal neutron pulse detectors

1-cm^2 Si-diode covered by 30 µm ^{6}LiF

Slightly biased to improve noise gamma rejection

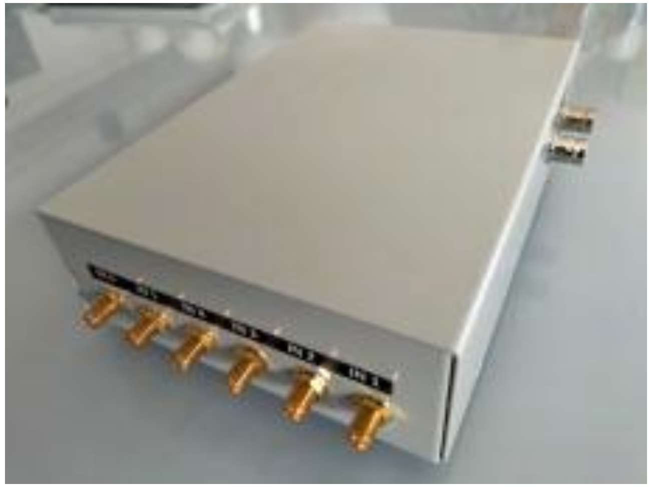
Custom multi-detector analog board (charge preamp. + shaper amp.)

Digital elaboration using commercial digitizer and laptop



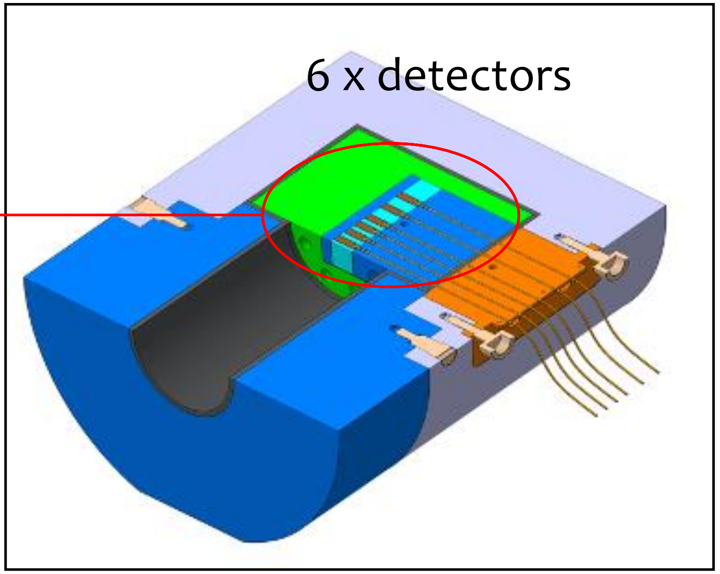
Bare Si diode

Si + ^{6}LiF diode



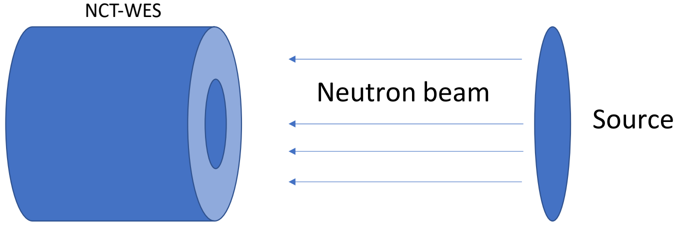
NIM A 1018 (2021) 16585, NIM A 780 (2015) 51-54, Radiat. Prot. Dosim. 161 1-4 (2014) 229-232

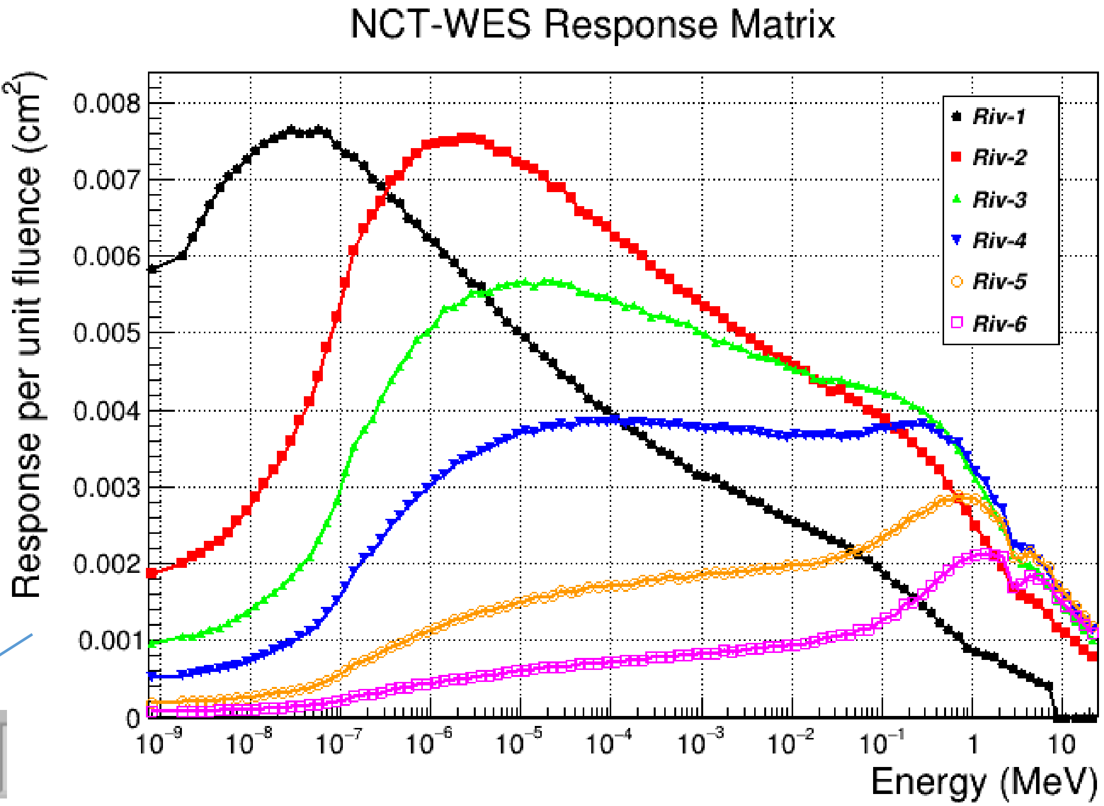
NCT Wide Energy Spectrometer



The energy spectrum is obtained by measuring thermal neutrons at 6 different depth

MCNP6 simulations to calculate the Response Matrix and optimize the geometry to have the best response in the epithermal energy range





Unfolding

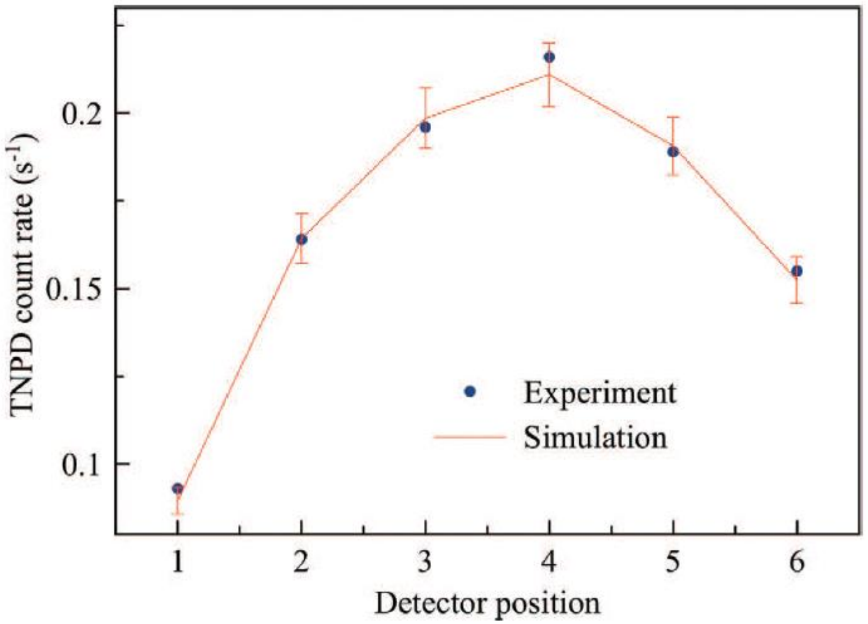
FruitSix

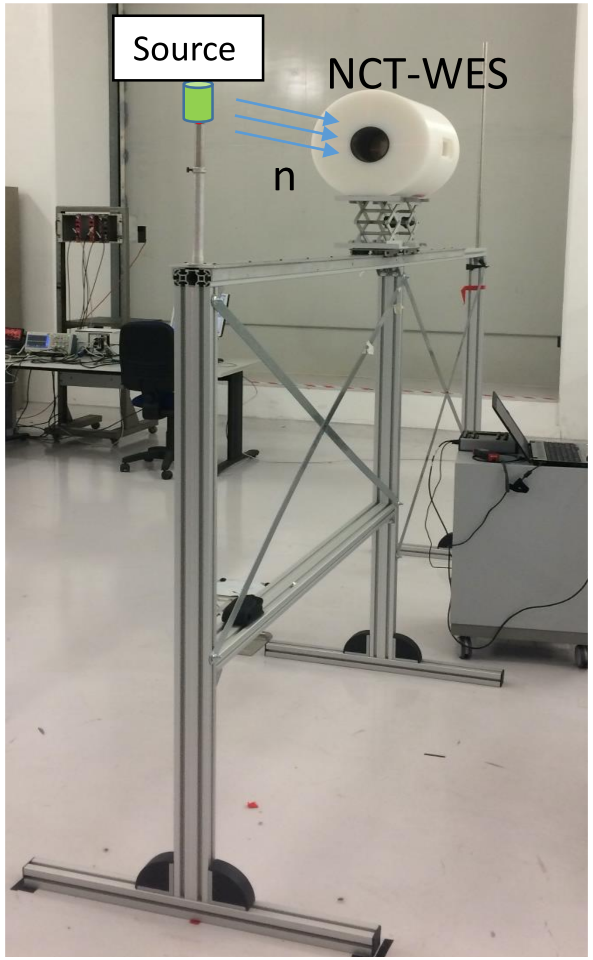
NCT-WES calibration

1. Every inner detector calibrated in the thermal neutron reference field of HOTNES (moderated Am-B source @ LNF-ENEA Frascati)

$$\varepsilon_{TNPD} = \frac{\dot{N}_{Experiment}}{\dot{N}_{^6Li(n,\alpha)^3H}} = (23.8 \pm 0.4)\%$$

2. NCT-WES test at the AmBe reference neutron field at PoliMi Response matrix validation





Am-Be irradiation at PoliMi

NCT-WES calibration

3. Response matrix validation at monoenergetic neutron beams at NPL (UK)

$$R_{exp} = \frac{C_{tot}}{N_{tot}} - \frac{C_{cone}}{N_{cone}}$$

C_{tot}, C_{cone} counts without and with the shadow cone
N_{tot}, N_{cone} monoenergetic neutrons emitted by the target as if they were isotropically distribuited, without and with the shadow cone.

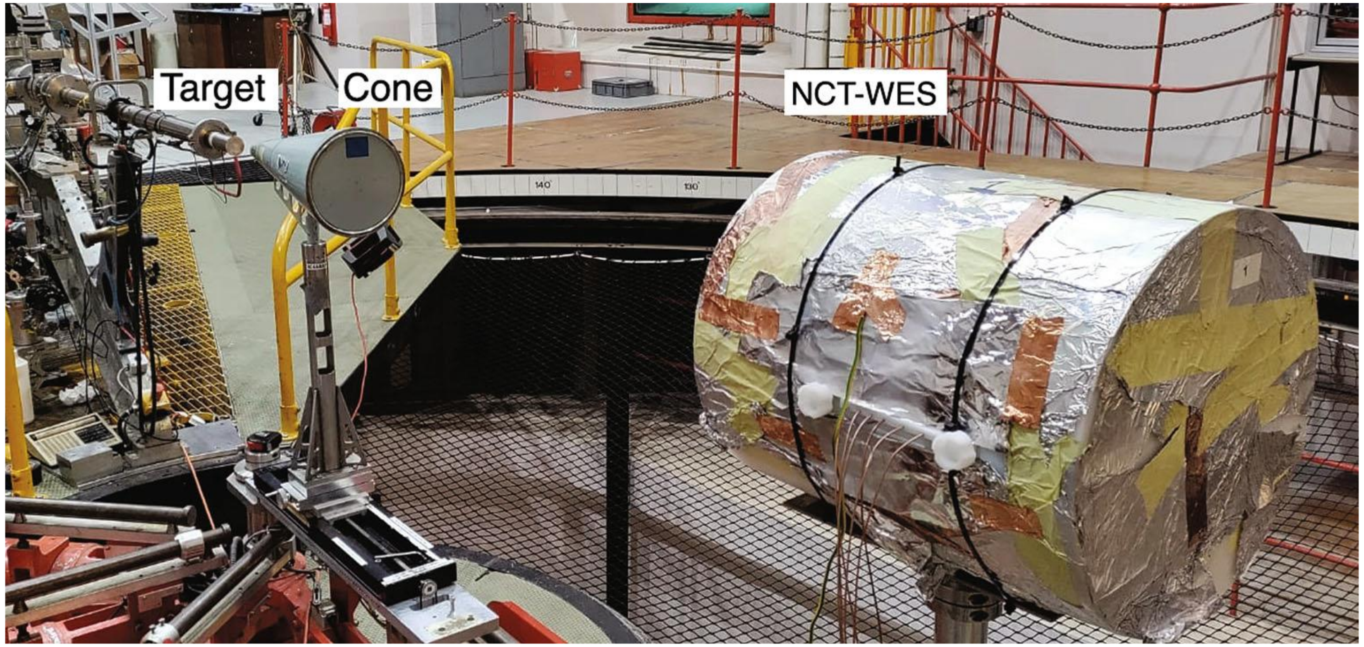
71.5 keV,
144.2 keV
565.1 keV
841.9 keV
1200.4 keV

Neutron beams obtained by a 3.5 MV Van De Graaf proton accelerator on 7Li or Tritium target

$$\frac{R_{i,sim}}{R_{i.exp}} @ \ 841.9\ keV$$

P1	1.03 ± 0.04
P2	1.00 ± 0.04
P3	1.04 ± 0.04
P4	0.98 ± 0.04
P5	1.04 ± 0.04
P6	0.99 ± 0.04

- Accuracy of the response matrix
- Minimal energy and detector dependance (Distribution of all the ratios within 4%, average 1.002+-0.008)

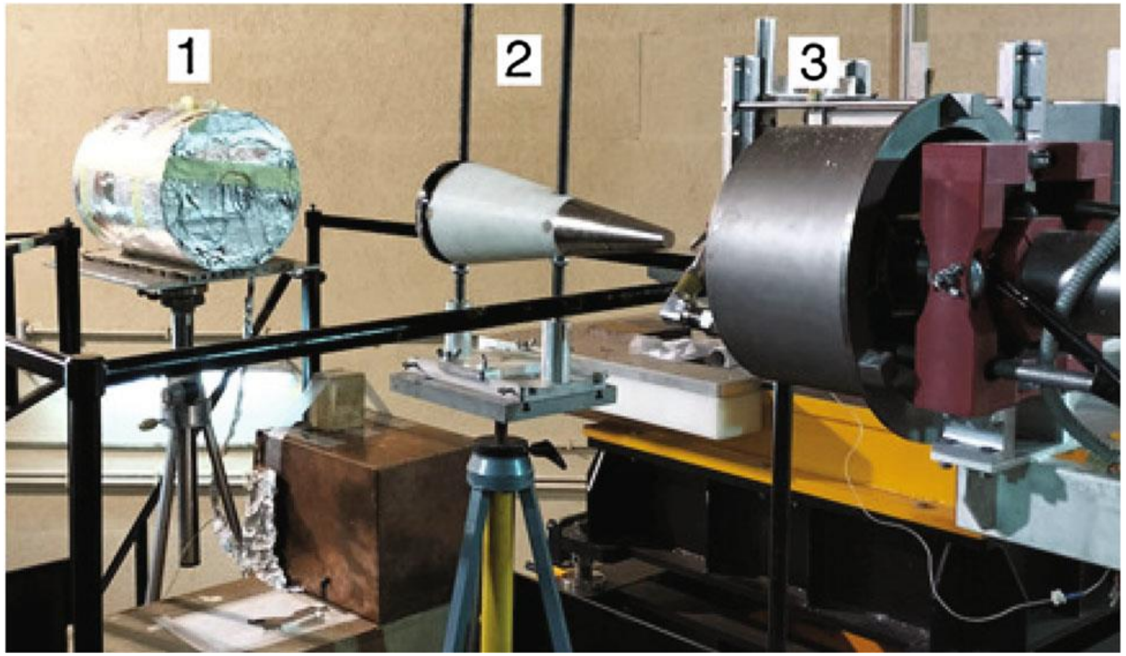


Low scatter irradiation room at NPL. NCT-WES exposed at 0°with the shadow cone.

[Ref. Eur. Phys. J. Plus (2023) 138:270]

NCT-WES first experiment

“Measuring the near-target neutron field of a D–D fusion facility with the novel NCT-WES spectrometer»
R. Bedogni et al.
Eur. Phys. J. Plus (2022) 137:773



NCT-ACS

Neutron **C**apture **T**herapy **A**ctivation **C**ompact **S**pectrometer

NCT Activation Neutron Spectrometer

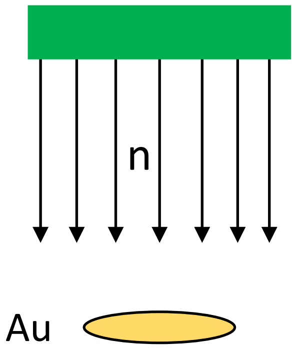
Small, passive detector for in phantom measurement of the neutron field with spectrometric capability.

Based on activation foils → n,γ absorption resonances in the epithermal range

Different elements show resonances at different energies → quantitative analysis of the activation gives information about the neutron energy through an unfolding procedure.

NCT-ACS

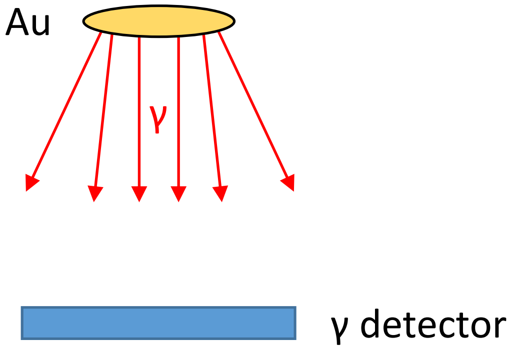
Phase 1:



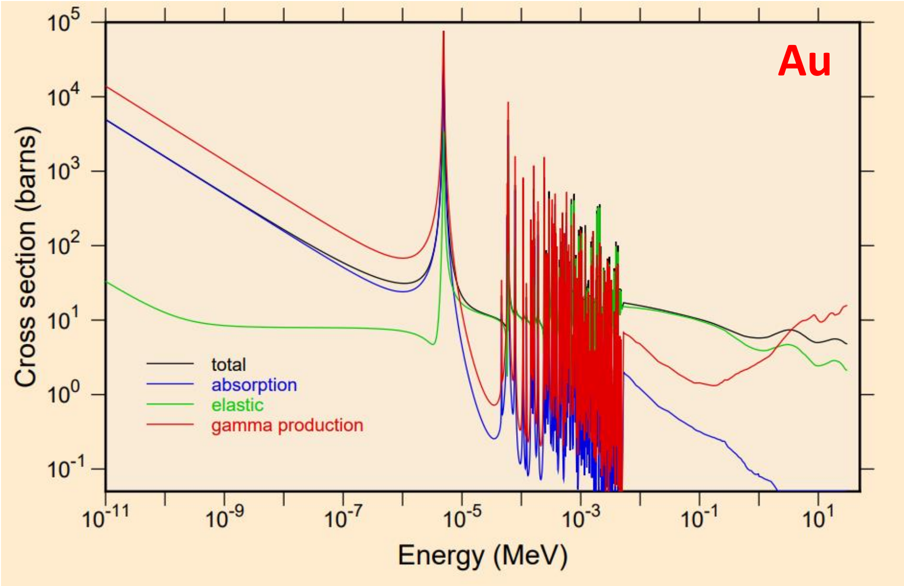
Foil irradiation with neutrons.

+

Phase 2:



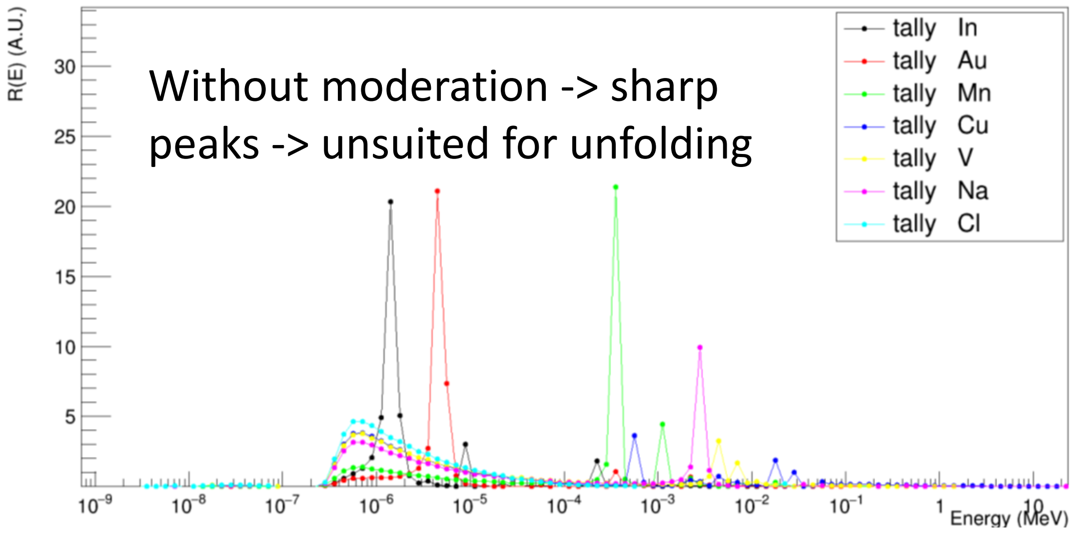
Gamma analysis with a HPGe detector.



NCT ACS geometry

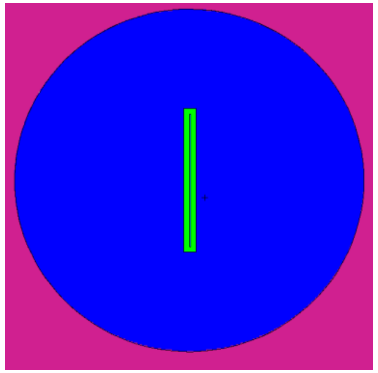
Elements selection criteria:

- Resonance energy
- $t_{1/2}$ of the activated nucleus
- Energy and B.R. of the γ decay
- Decay chain
- γ spectrum complexity
- Cross section for n-capture
- Toxicity

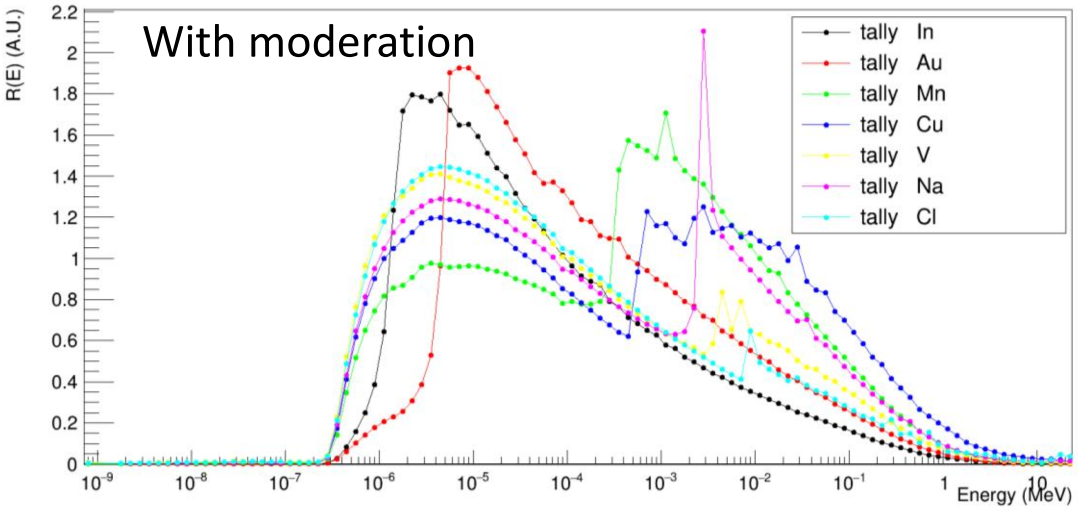


Small moderator to improve the response curves shapes

Cadmium cover to suppress the response in the thermal range



Polyethylene sphere (blue) 6 cm diameter, cadmium foil cover (green).



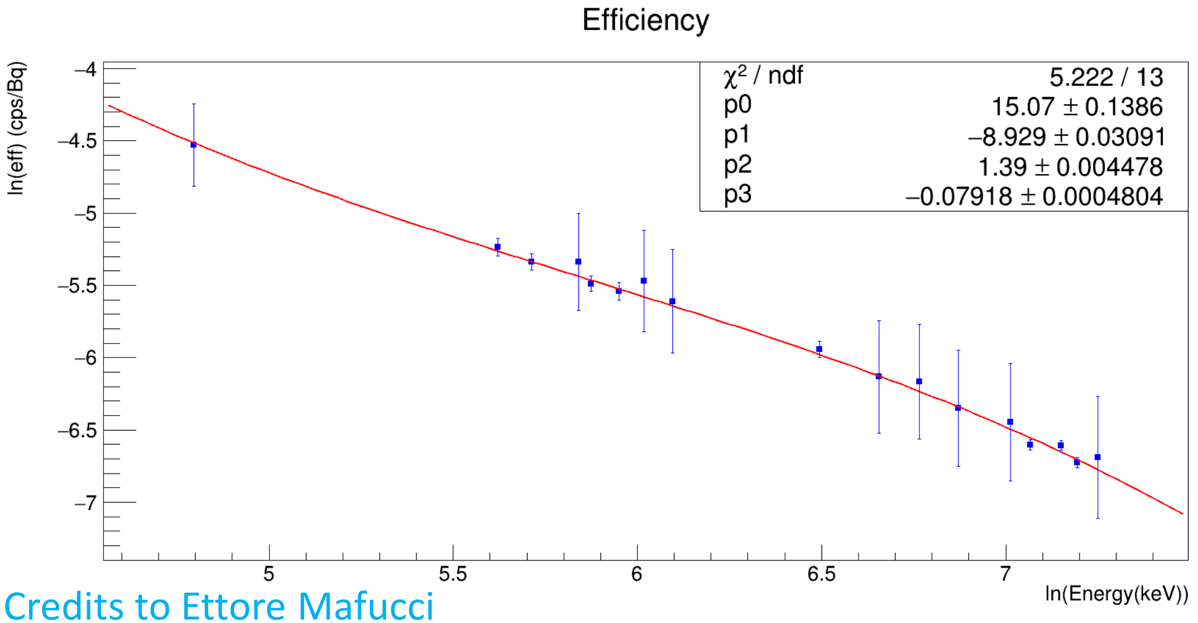
Credits to Ettore Mafucci

NCT ACS analysis

Gamma activation analysys is performed with an **HPGe detector**

Energy and efficiency calibration performed using **calibrated sources (^{152}Eu, ^{60}Co, ^{137}Cs, ^{133}Ba, ^{22}Na)**.

Efficiency function $\ln \epsilon = \sum_{j=0}^{n} a_j (\ln E)^j$ n=3.



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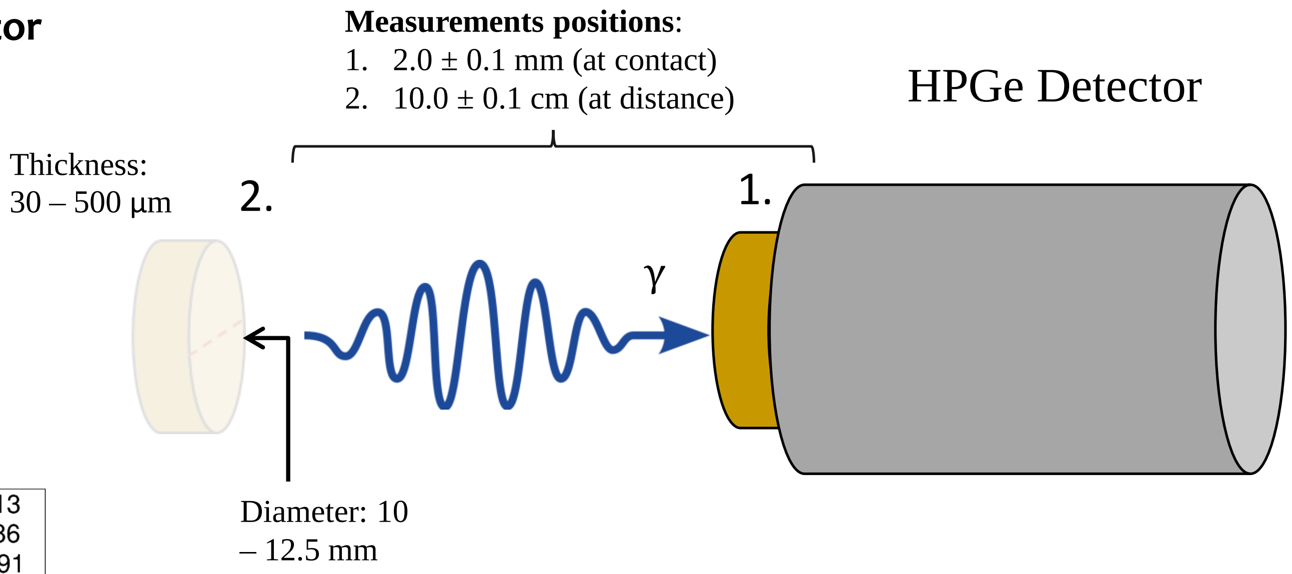


Sources placed at 10 cm from the detector face in order to minimize the error induced by the finite dimension of the foils.

The activity of each element + response matrix

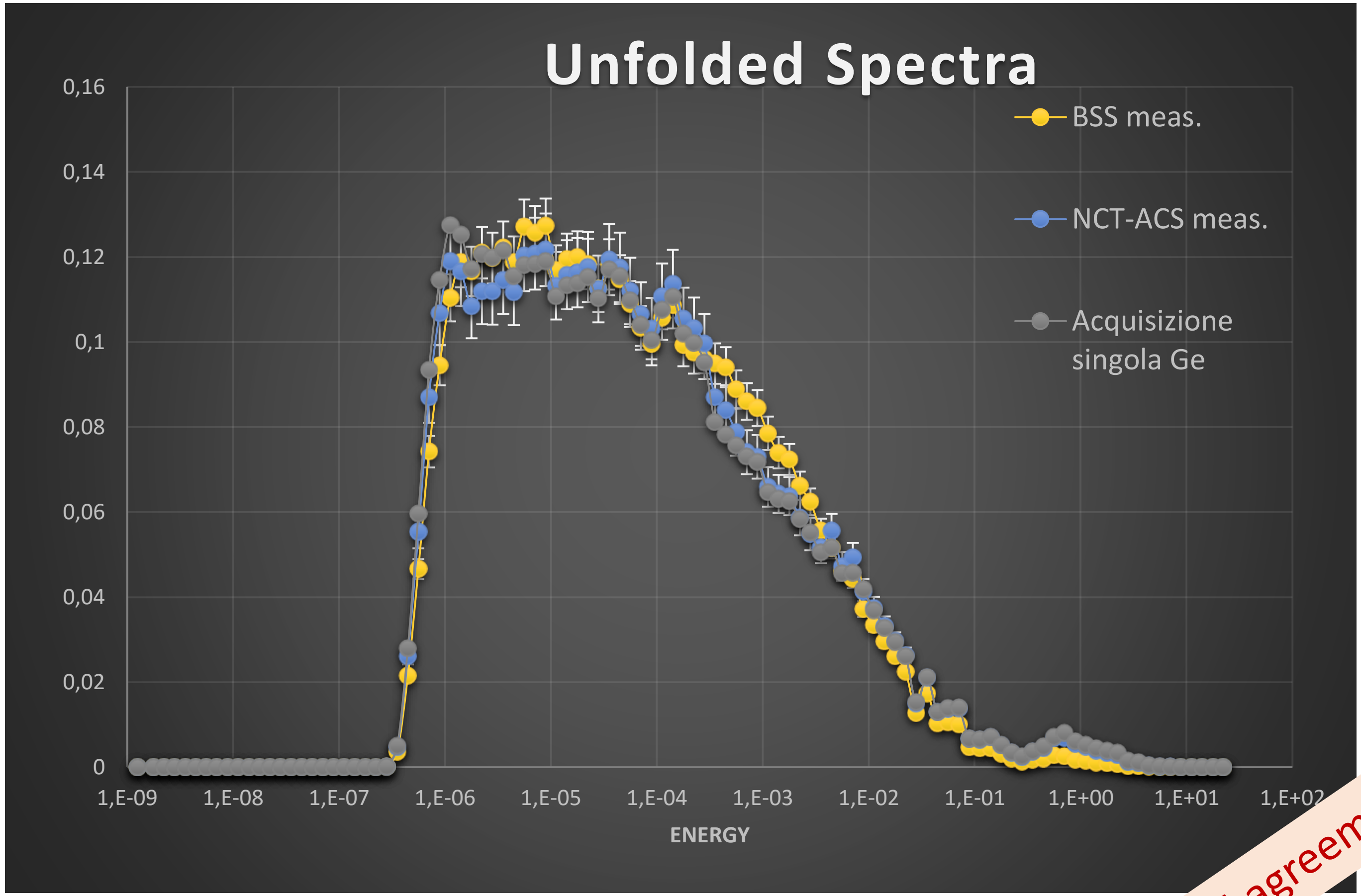
Unfolding code

Neutron energy spectrum reconstruction

NCT ACS analysis

Test @ the 18 MV Linac based epithermal neutron source in Torino [1]

Comparison with a calibrated Bonner Sphere System neutron spectrometry



Very good agreement

[1] Nuclear Inst. and Methods in Physics Research A, 953 (2020) 163154

Conclusions

Two neutron spectrometers have been developed to fulfill the BNCT beam quality assurance.

NCT-WES allows real time measurements of neutron beam spectra with a single exposure and with good rejection of the room-scattered component. Accuracy below 5%

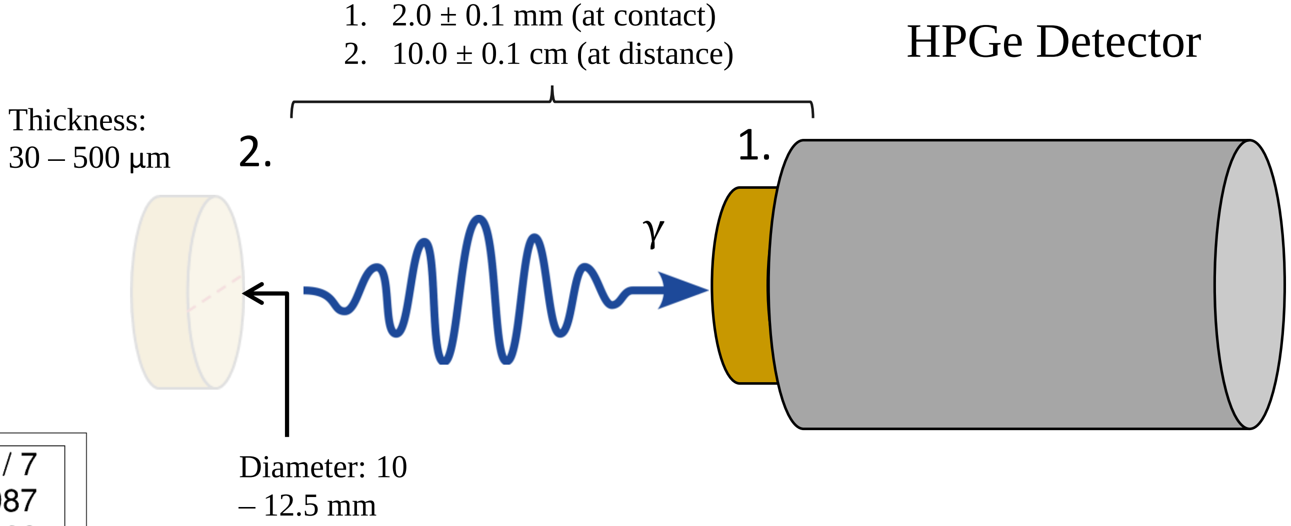
NCT-ACS is a passive device, its small dimensions and isotropical response allow its use for in phantom measurements.

Both instruments have been succesfully tested in different neutron fields and have prooved to be able to give accurate results.

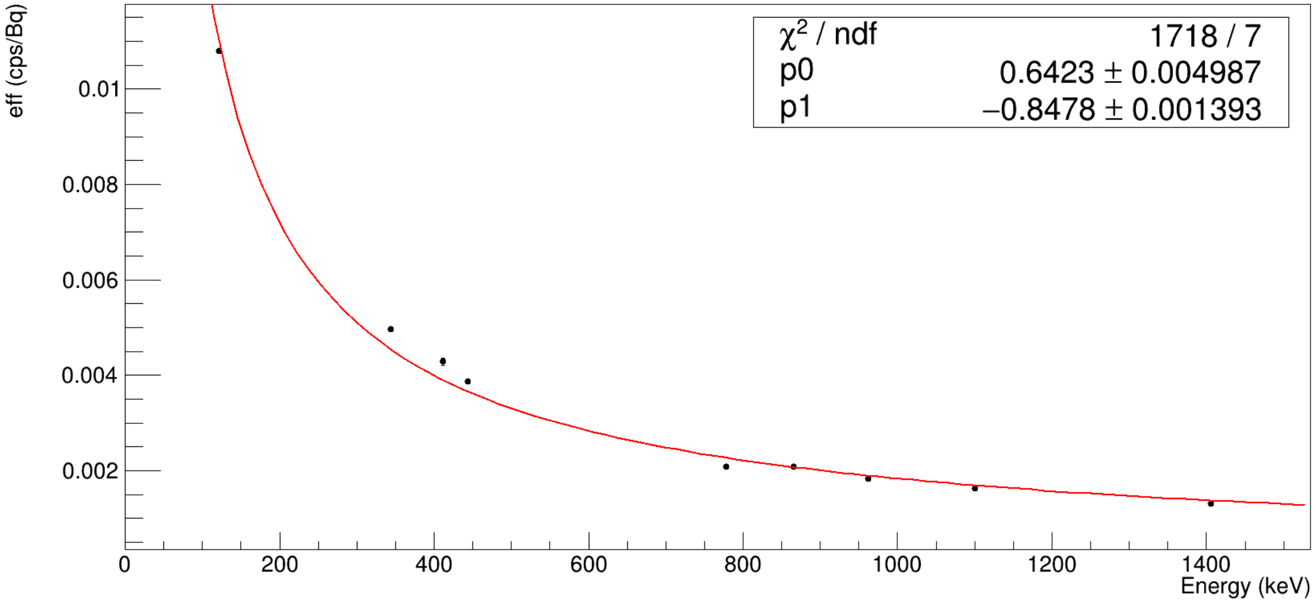
Back-up

$$\varepsilon^{Ge}_{contact} = \varepsilon^{Ge}_{10cm} * F_{geom}$$

Measurements positions:
1. 2.0 ± 0.1 mm (at contact)
2. 10.0 ± 0.1 cm (at distance)



Efficiency



Calibrated source at 10cm

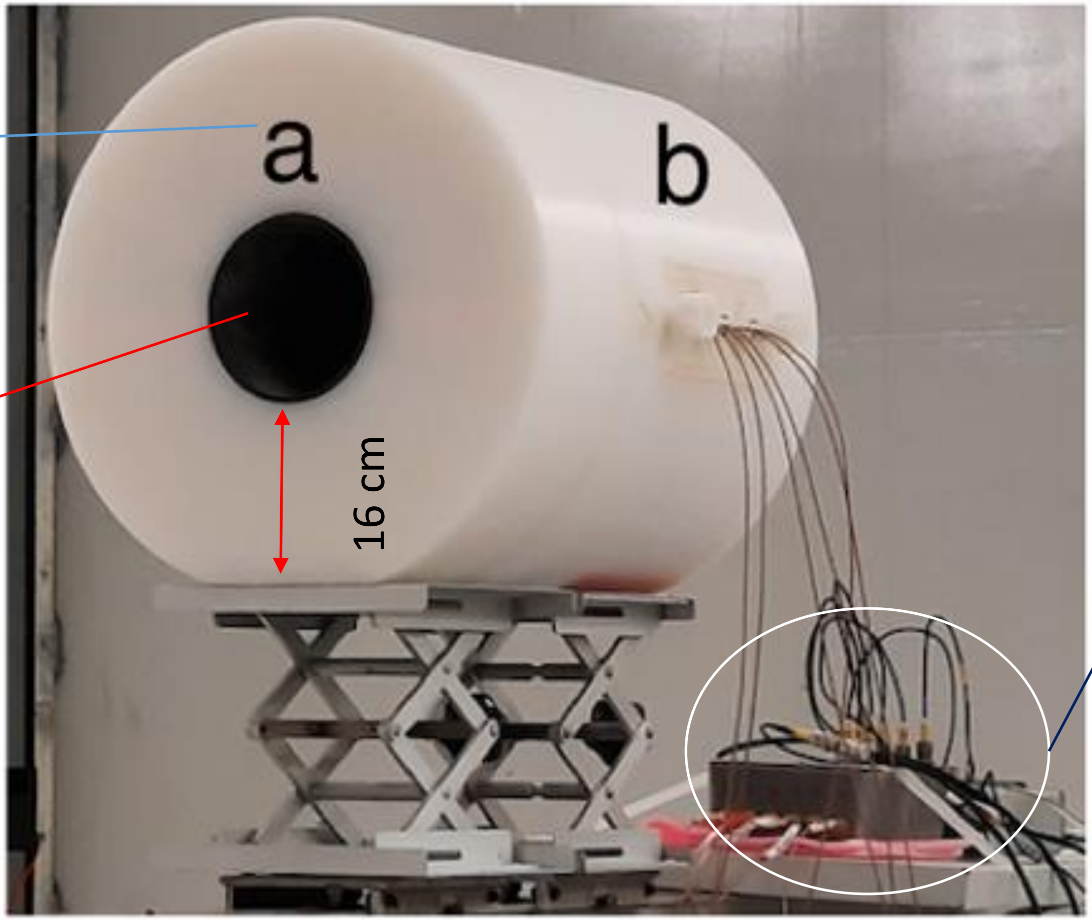
F_{geom} is the ratio between the saturation activity measured at contact and at 10 cm.
The assumption is that at 10 cm the point source like approximation is good enough.

NCT Wide Energy Spectrometer

a: polyethylene collimator
b: polyethylene moderator block containing the neutron detectors

Borated rubber to shield from thermal neutrons

Dimension:
Length 41.5 cm
External diameter 36 cm
Inner collimator diam 12 cm
Weight 40 kg



Dedicated electronic and Labview acquisition software