Development of gamma insensitive semiconductor based diagnostics to qualify intense thermal neutron fields at the e_LiBANS facility

Marco Costa
INFN & UNI Torino
On behalf of e_LiBANS collaboration

Introduction

e_LiBANS [e_Linac Based Actively-monitored Neutron Sources]

I.N.F.N project (Interdisciplinary Applications)

[LNF, Milano, Torino and Trieste]

With the contribution of :

Fisica Torino Dipartimento di Eccellenza

INFN Istituto Nazionale di Fisica Nucleare

Compagnia di San Paolo

FONDAZIONE CRT

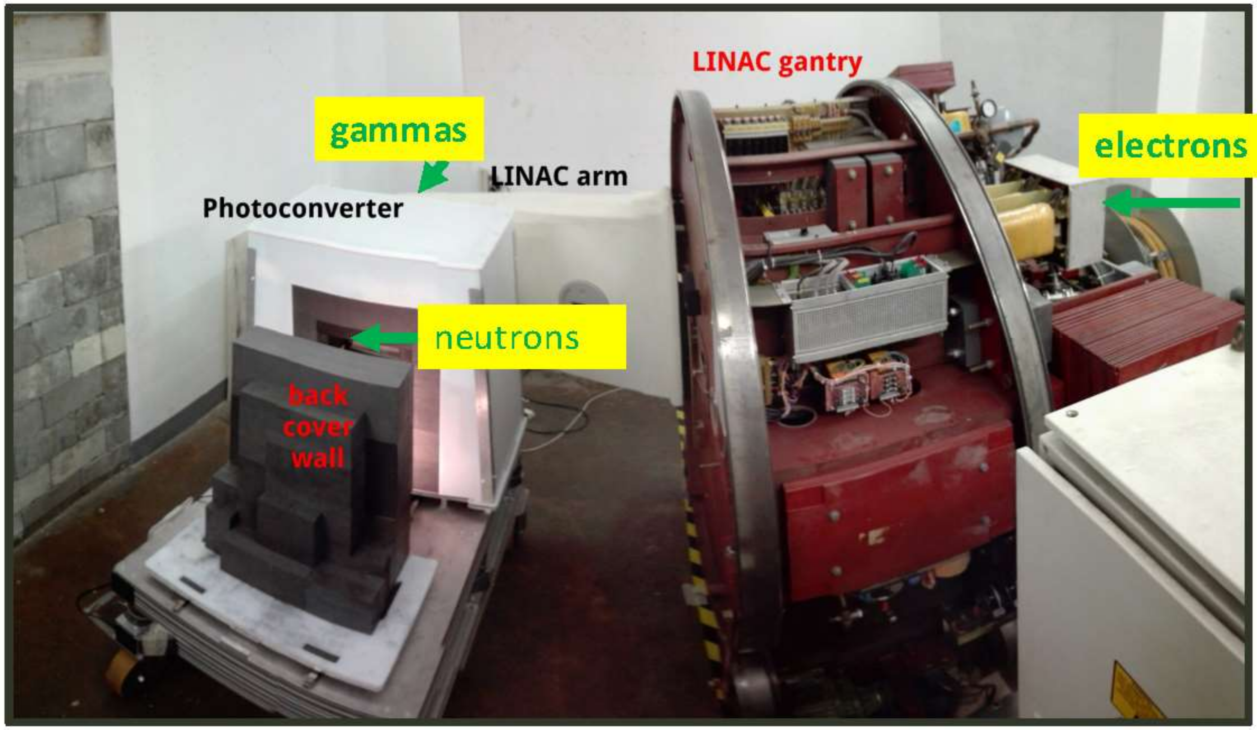
In collaboration with:

Elekta

Azienda Ospedaliero Universitaria S. Luigi Gonzaga Orbassano (To)

AZIENDA OSPEDALIERO - UNIVERSITARIA Città della Salute e della Scienza di Torino

Neutron Facility @ Torino



LINAC ELEKTA SL18 / PRECISE

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- Primary e-Energies: 15MeV / 18MeV
- Electron or gamma output modes
- Tunable rate-Tunable field aperture
- Typical current: $I_e \sim 10^{14}$ e-/s
- PULSED beam (repetition 100-400Hz, duration 2 -3 μs)

Rotating carousel:

- → 5 possible beam configurations in parallel
- Ionization chamber: to give feedback to the injection system
- The output is measured in Monitor Units
- 1 M.U. = 1 cGy at isocenter

Two possible OUTPUTs:

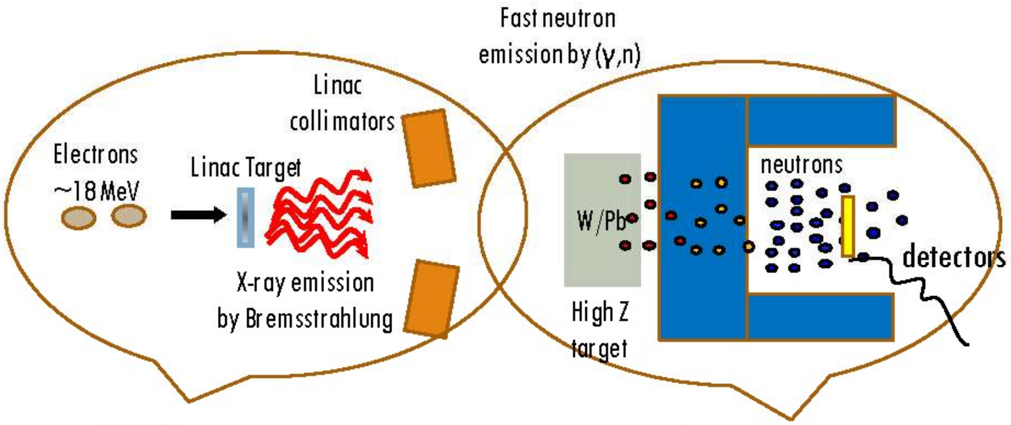
1- mono energetic electron beam (e-mode)

2- Bremsstrahlung photons on a internal target **(γ-mode)**

Set of collimators and filters to shape the beam (for clinical app.)

Flattening filter

Neutrons Production in the Linac γ-mode



LINAC as gamma source

Photo-converter

Aim: to maximise the thermal or epithermal neutrons production limiting **fast neutrons** and **photons** contamination inside the experimental cavity

Photo-neutron conversion

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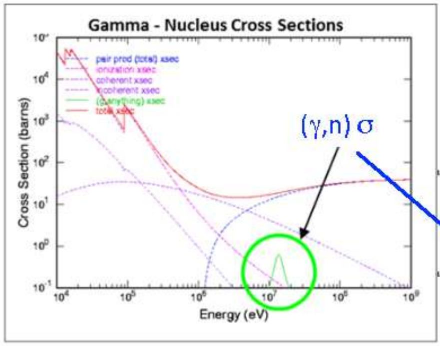
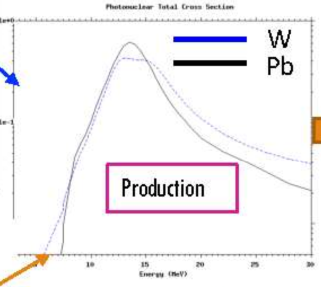


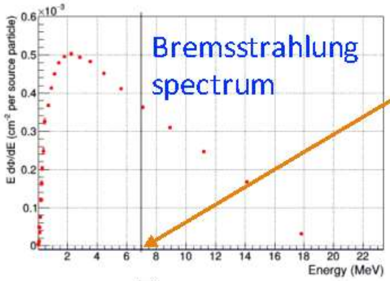
(γ,n) σ

$$\int_0^\infty \sigma_{abs}(E_\gamma)\,dE = \frac{\pi e^2\,h}{Mc}\,\frac{\boxed{NZ}}{A}$$

Photon absorption cross section (γ,n)



Production



Bremsstrahlung spectrum

E$_{th}$

$\rho_W = 19.2\ gr/cm^3$

$\rho_{Pb} = 11.3\ gr/cm^3$

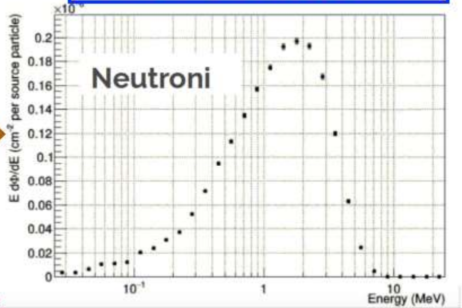
+Gamma shield

but W activation problem

$${}^{184}_{74}W + n \rightarrow {}^{185}_{74}W \rightarrow {}^{185}_{75}Re + e^- + \bar{\nu}_e$$

$$t_{\frac{1}{2}} = 75{,}1\,d$$

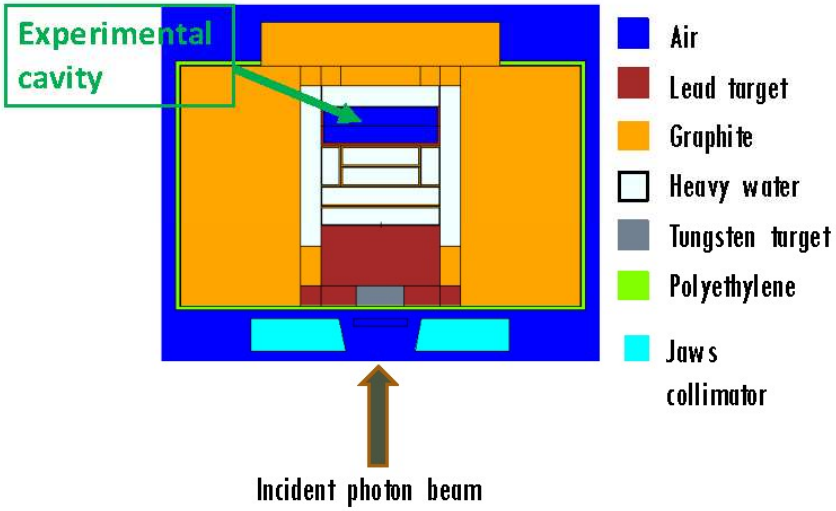
Emitted neutron spectrum



Fast neutrons → Need moderation

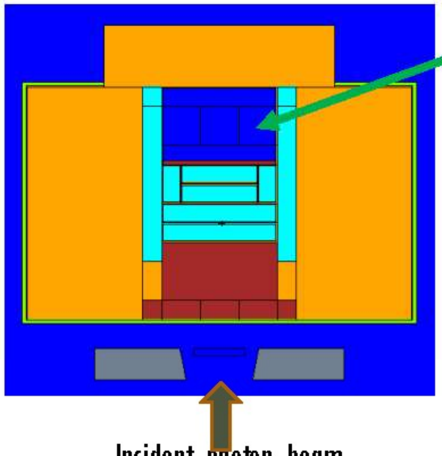
Thermal neutron fotoconverter

Extensive MCNP6 simulation studies
NB. All informations are given per source particle
→ LINAC electron current should be a known parameter

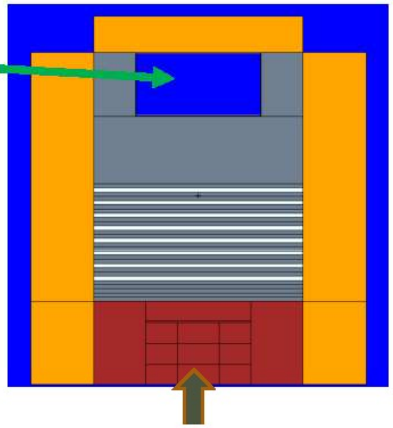


- **W +Pb** target → production and gamma shielding
- **D_2O and Graphite** → moderation and reflection
- **Boron carbide in polyepoxide** → capture of thermal neutron going out of the photoconverter
- **Thin lead shield** → for capture photons from carbon and boron

Thermal vs Epithermal

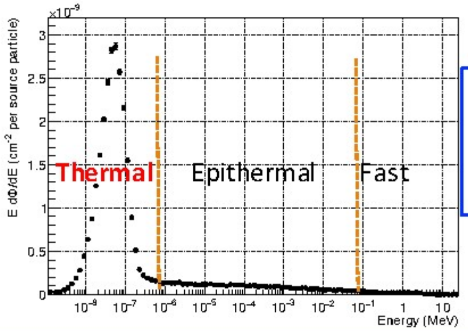


Experimental cavity

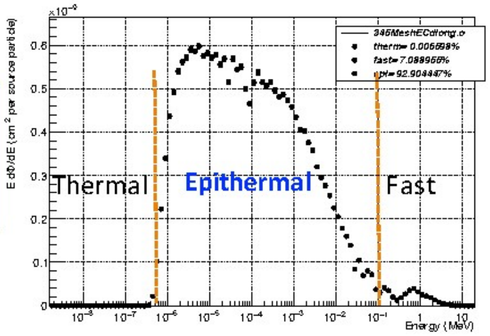


▨ Teflon

☐ Aluminum

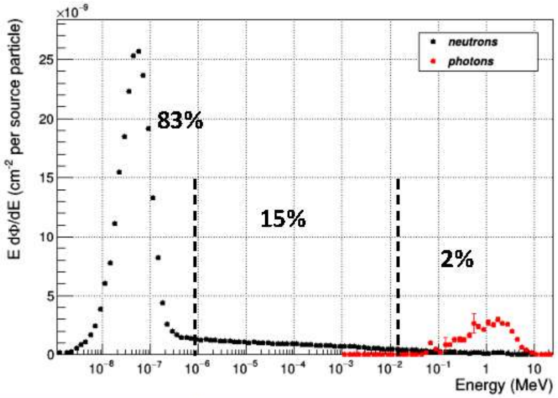


Output neutron Spectra in the cavity



Thermal Photo-Converter E=18 MeV

Neutrons and Photons Energy Spectrum



MNCP6 simulation

Standard working conditions

Assuming working rate at 400 MU/min:

Energy 18 MeV

Electron current on target 1.05×10^{14} e-/s

Distance linac target – γ-converter: 59 cm

IAEA in air free beam parameter:

$$\frac{D_f}{\varphi_{th}} = 1{,}77 * 10^{-13}\, Gy\, cm^2$$

$$\frac{D_\gamma}{\varphi_{th}} = 1.03 * 10^{-12}\, Gy\, cm^2$$

$$\dot{D}_\gamma meas = (6.6 \pm 0.2)\frac{mGy}{h}$$

	Fluence rate in cavity		Dose rate in cavity	
thermal	$(1.8 \pm 0.02) * 10^{6}\ cm^{-2}s^{-1}$	83%	$(6.04 \pm 0.02) * 10^{7}$ pSv s^{-1}	67%
epithermal	$(3.27 \pm 0.04) * 10^{5}\ cm^{-2}s^{-1}$	15%	$(1.04 \pm 0.01) * 10^{7}$ pSv s^{-1}	12%
fast	$(0.46 \pm 0.01) * 10^{5}\ cm^{-2}s^{-1}$	2%	$(1.87 \pm 0.02) * 10^{7}$ pSv s^{-1}	21%
gamma	$8.22 * 10^{5}\ cm^{-2}s^{-1}$		$5.05 * 10^{6}$ pSv s^{-1}	

Thermal Neutron Detector Development

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They should be:
- Active
- Low noise
- Minimal sensitivity to Photons
- Small dimension
- Able to measure rates 10^2 - 10^8 n cm^{-2} s^{-1} and resist an integrated Fluence ~10^{13} n cm^{-2}
- Cheap

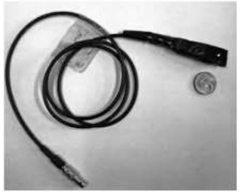
For absolute and punctual fluence rate measurement common silicon substrate devices like TNRD are suitable.

However long exposures or repetitive ones, force us to explore the use of more radiation resistant material → larger Energy gap semiconductor

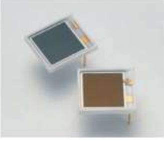
➡ With this aim, Si-carbide (SiC) detectors have been studied

2 substrates have been considered

Si-TNRD



Based on:
S3590-09 HAMAMATSU diodes



Active area: $1cm^2$

Si-Carbide

Based on:
SgLux UV photodiodes
Active area: 0.05 – 7.6 mm^2

✚

Appropriate radiator material

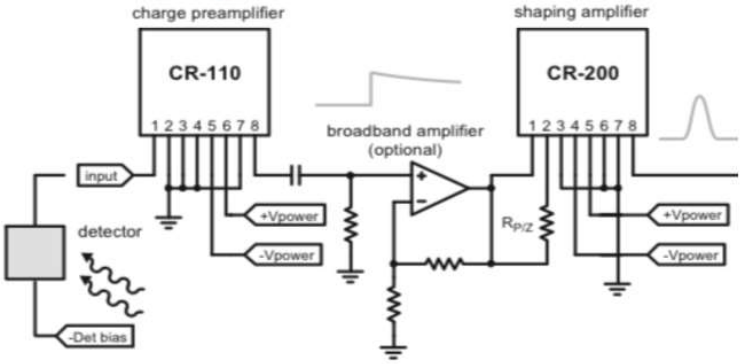
Readout electronics

Can operate in pulse or current mode:

Pulse mode: through a traditional nuclear spectrometry chain formed by a charge sensitive preamplifier (CSP) and a Gaussian shaping amplifier based on CREMAT components.

Current mode: This relies on a custom ultralow current analog board that drives the radiation-induced current (tens of fA or higher) to a resistor, making it measurable as a voltage drop.
By changing this resistor, different amplification values (labeled 1x and 0.1x) can be chosen, according to the different sensitivity of the tested devices.

Commercial digitizers are used in both current and pulse modes to transfer the information to a PC.



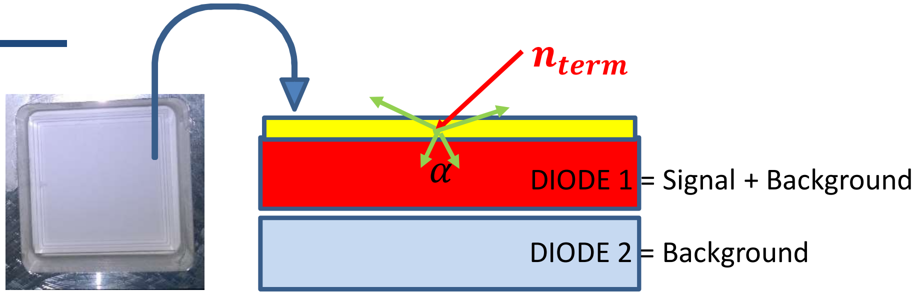
Digitizer NI USB 6366

TNRD Thermal Neutron Rate Detector

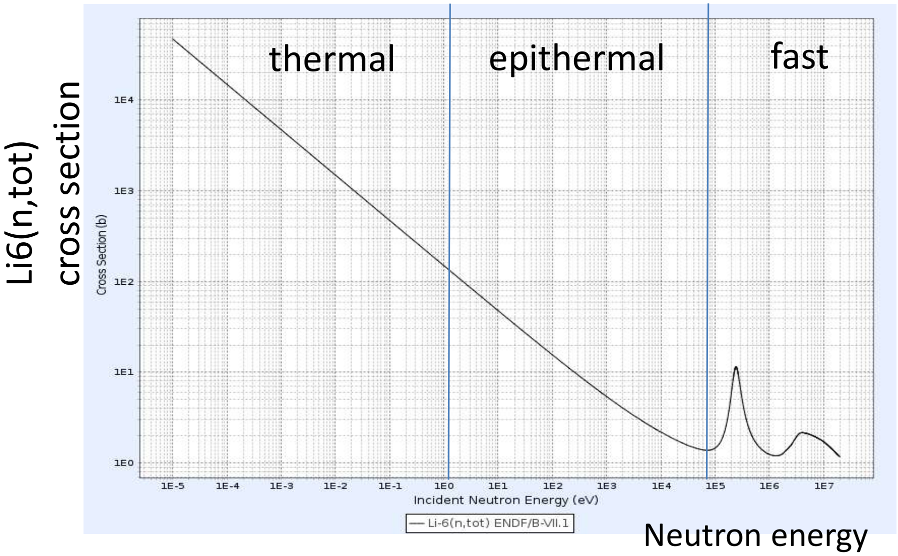
[1] Radiat. Prot. Dosim. (2014) 161 241-244

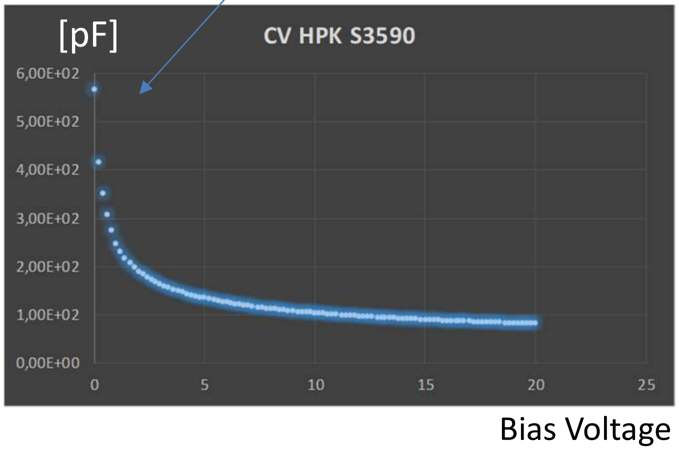
Made out of 2 silicon diodes, one sensitized to thermal neutrons with ^{6}LiF deposition

$$^{6}_{3}Li + n \rightarrow \, ^{3}_{1}H(2.73\ MeV) + \alpha(2.05MeV)$$



- Differential readout
- Minimal gamma sensitivity
- Range: from few cm^{-2} s^{-1} up to 10^{7} cm^{-2} s^{-1}
- Unbiased (20μm depletion depth)



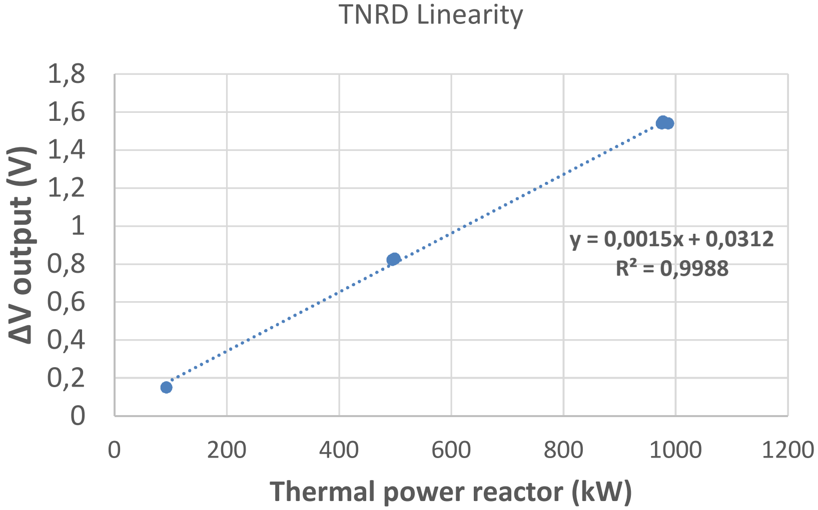


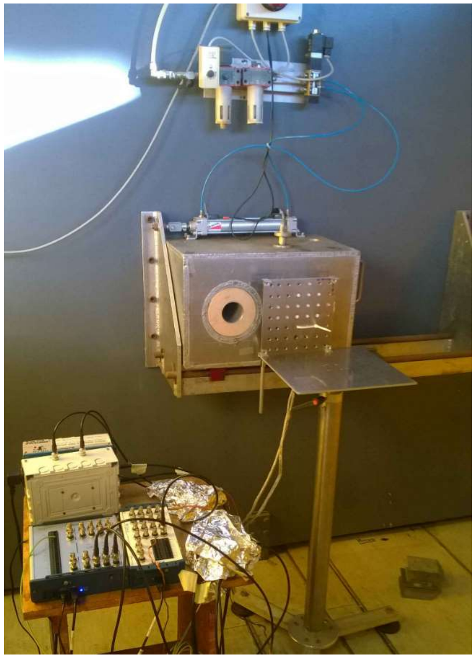
TNRD Calibration

Calibration at ENEA Casaccia (RM) TRIGA Reactor (100kW – 1MW)

Calibration factor:

F = 0.249 μV*cm^2*s (unc. 2%)

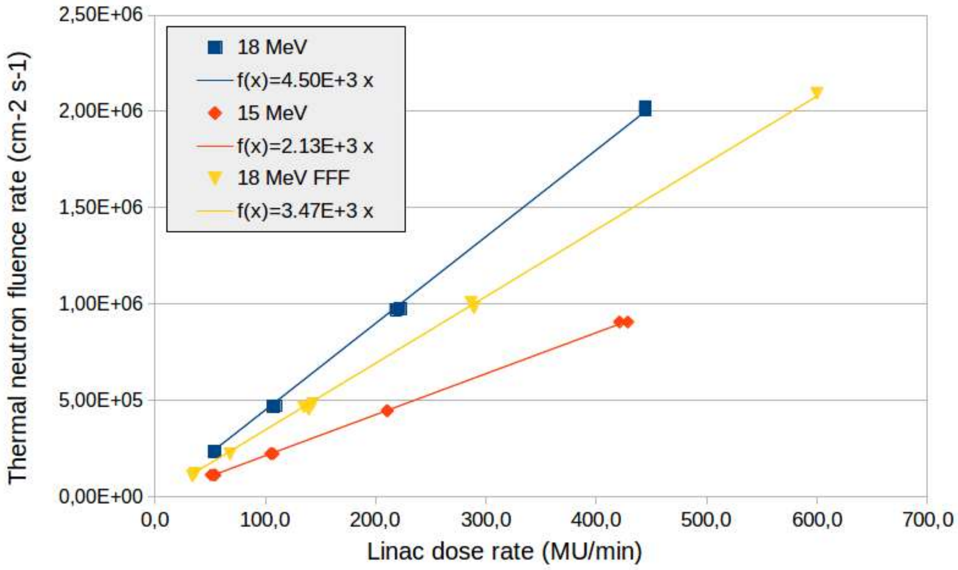




Measurements results - linearity

TNRD detector

Linear dependence of the neutron fluence rate on the linac dose rate (MU/min)

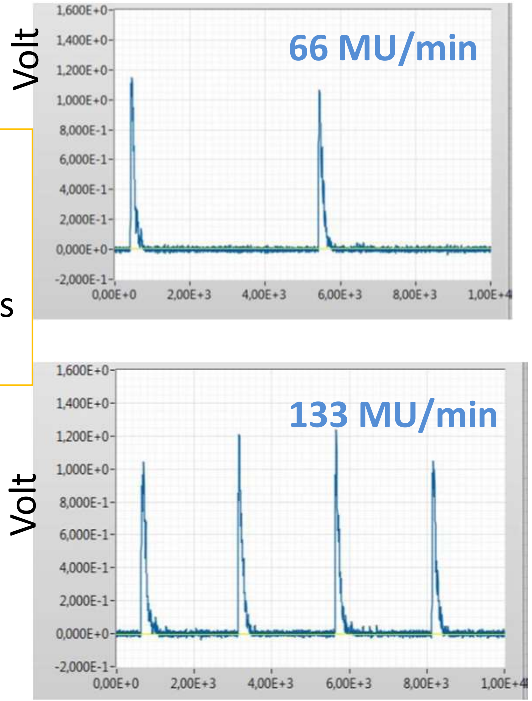


e-Linac pulses

⬇

neutron pulses in the cavity

TNRDs work in a pulsed field



sample number

E-LiBANS thermal cavity central position, 18 MV, 400 MU/min:

$$\dot{\Phi}_{th} = (1.75 \pm 0.04\,)10^{6}\; cm^{-2}\; s^{-1}$$

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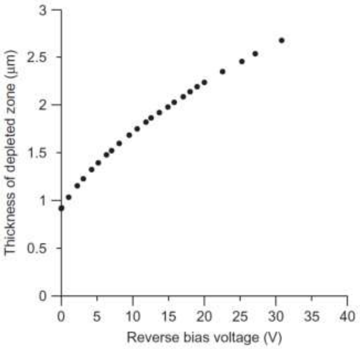
Based on commercial Silicon Carbide Detector

- SG01XL by SGLux *gmbh*
- 7.6 mm^2 active area
- TO_5Ni plated housing h=4.7 mm Unfiltered & *Uncovered*
- leakage current smaller <1 pA & C in the order of hundreds of pF when the bias voltage is 20 V or lower.

- Typical depletion layers are of the order of few microns at few tens of volts bias voltage.

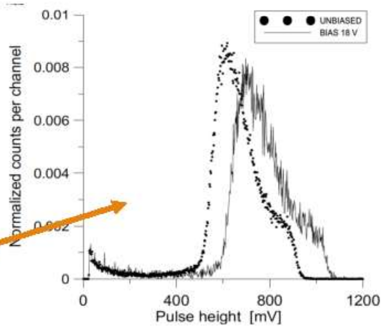


- It can work UNBIASED:

☐ 1 micron depletion depth @ Vbias =0 V

☐ Enough for highly ionizing particles
Tests with alpha particles from ^{241}Am

☐ Minimize photon sensitivity



Convert Thermal Neutrons to Alphas….

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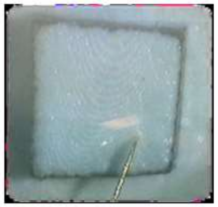
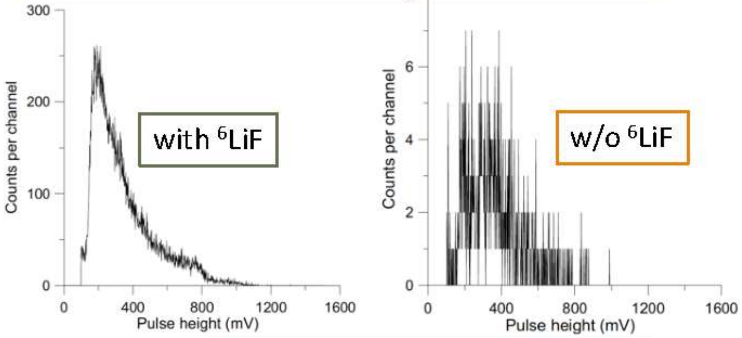
$$^{6}_{3}Li + n \rightarrow {}^{3}_{1}H(2.73\,MeV) + \alpha(2.05MeV)$$

^{6}LiF deposit process optimized to maximize the thermal neutron capture probability

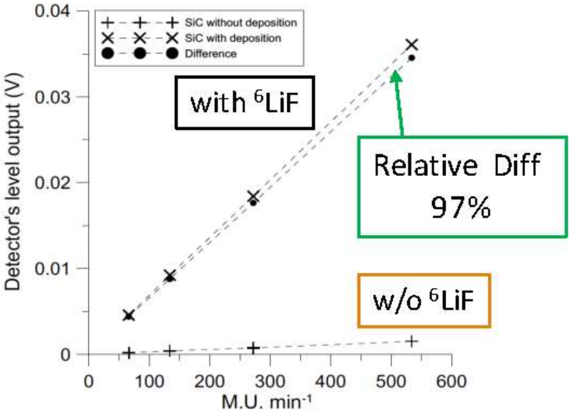


Exposed to **e_LiBANS** field

UNBIASED



Pulse mode (meas.time 180s)



Relative Diff 97%

Current mode

4x4 Si-Carbide Matrix

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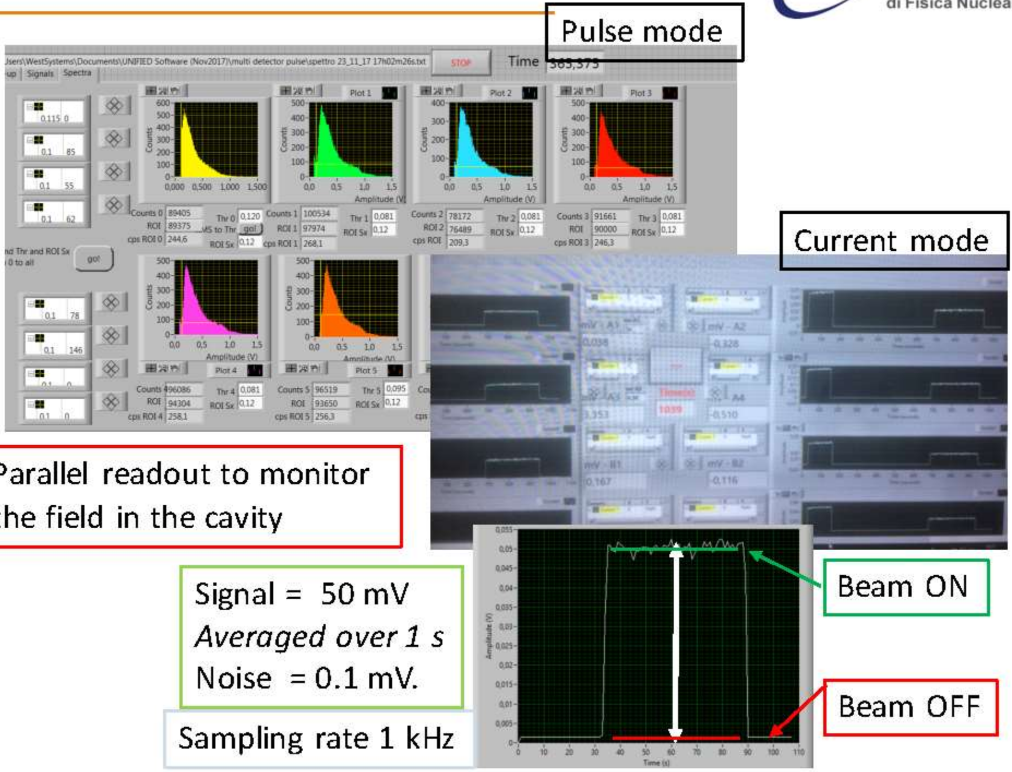
Field of view 10 x 10 cm2



Parallel readout to monitor the field in the cavity

Signal = 50 mV
Averaged over 1 s
Noise = 0.1 mV.

Sampling rate 1 kHz

LINAC Measurements results - linearity

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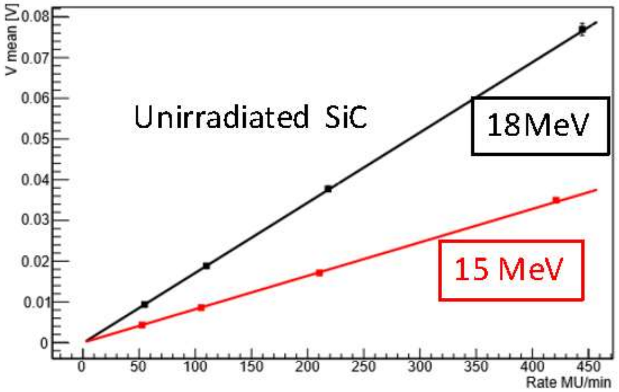

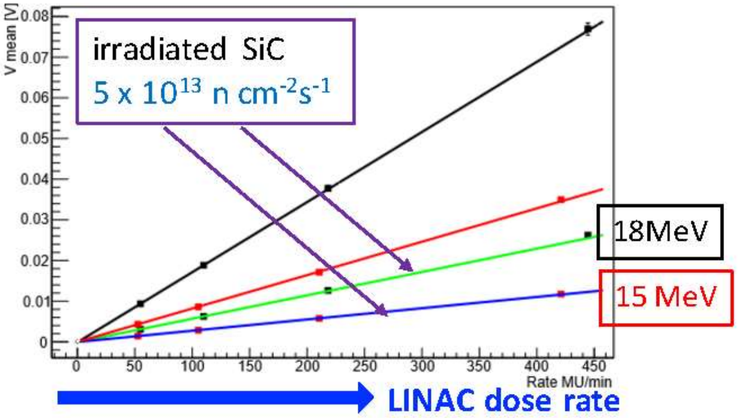

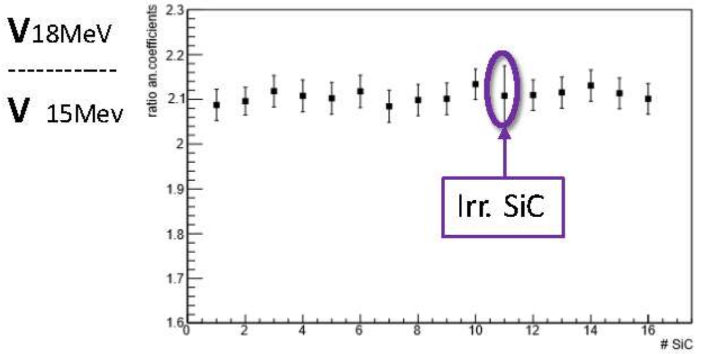

- SiC linearity with the LINAC dose rate is proved
- Dependence on LINAC energy as expected
- Irradiated SiC keeps working correctly

Detector Calibration and photon sensitivity

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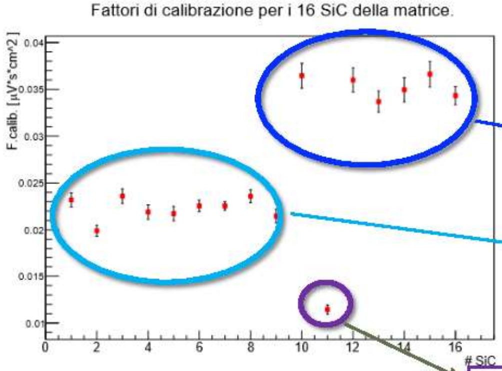
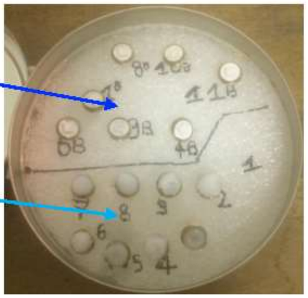
Calibration at ENEA Casaccia (RM) TRIGA Reactor (100kW – 1MW)
1 MW → (1.59 +- 0.03)10^6 $cm^{-2}s^{-1}$ (Thermal neutron)





irradiated to 5 x 10^{13} n $cm^{-2}s^{-1}$

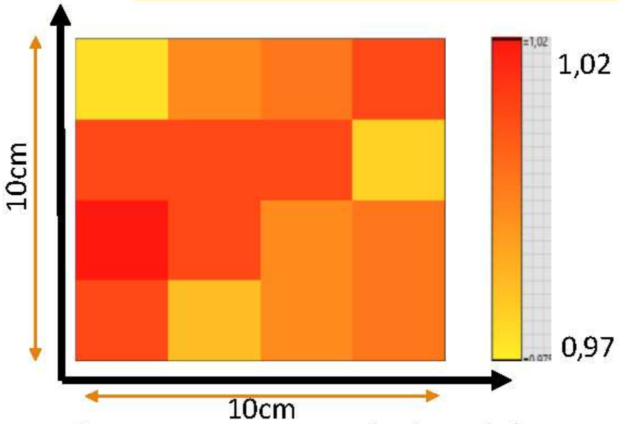
2 different ^{6}LiF deposit recepies give different response sensitivity

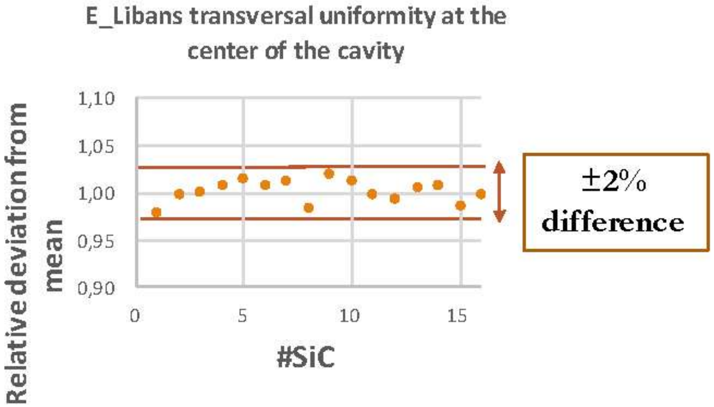
Calibration accuracy 5-8%
being improved

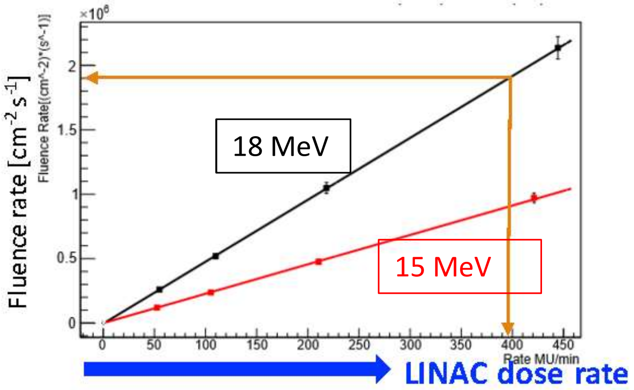
^{137}Cs and ^{60}Co sources

PHOTON SENSITIVITY
1 unit of thermal fluence rate (1 cm-2 s-1) produces a signal equivalent to 70 μGy/h of photon signal
Photon to neutron sensitivity ~10^{-4}

LINAC Measurements results - uniformity







- ☐ Good neutron field uniformity in the e_LiBANS cavity
- ☐ Mean fluence rate 1.9 x 10^6 n cm^{-2} s^{-1} @ 400 MU/min nominal 18 MeV beam
- ☐ Calibration accuracy ~5%
- ☐ The 4 x 4 SiC matrix allows to explore a 10 x 10 cm^2 field of view with a single acquisition, in real time

Neutron Spectrometers

TREDI 2019

Bonner Sphere System + TNRD

- Insensitive to LINAC RF
- Sequential exposition of the spheres in the cavity

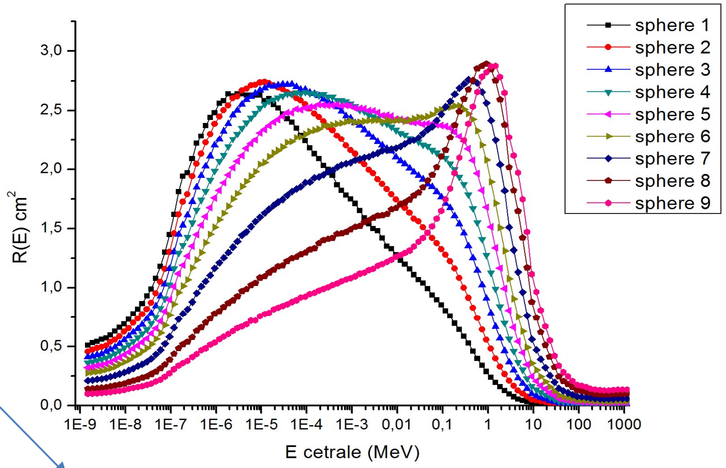
- Unfolding of the detector readings

M_i

$$M_i = \sum_{j=0}^{n} R_{ij} \Phi_j$$

- Unfolding code → heuristic process

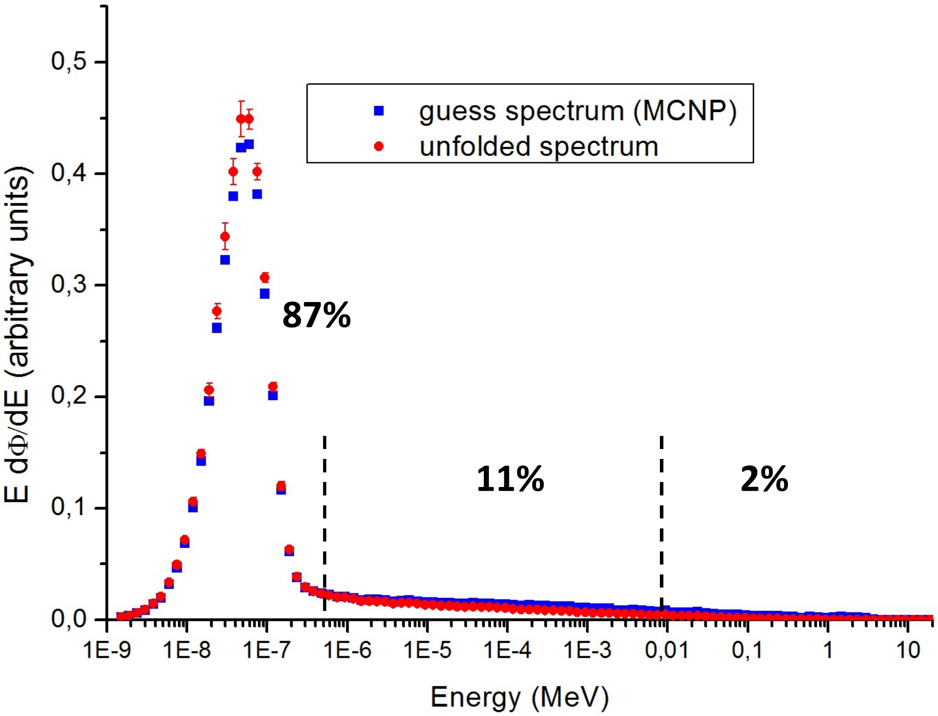
Bonner Spheres System (BSS)

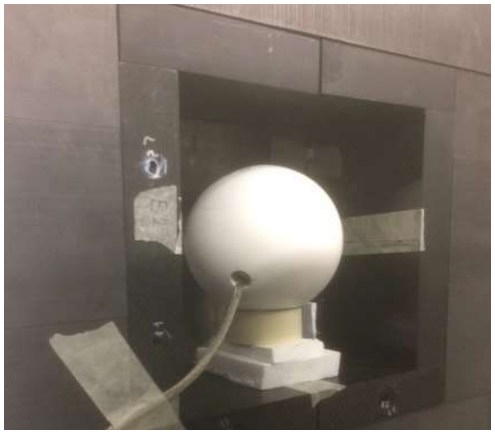


Response curves for of Bonner Spheres + TNRD system

e_LiBANS thermal Cavity Spectrum measurement

Neutron energy spectrum measured with Bonner Sphere System + active TNRD





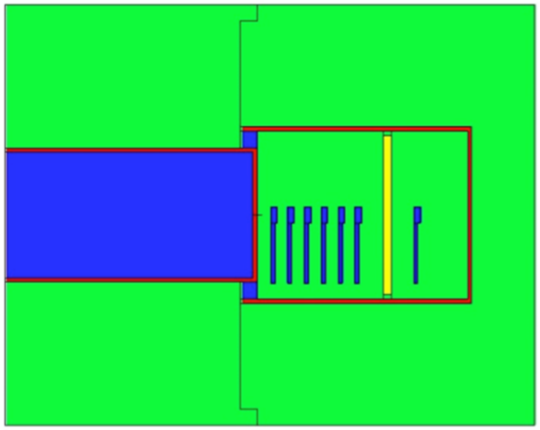
Unfolding with FRUIT convergence procedure starting from a guess spectrum

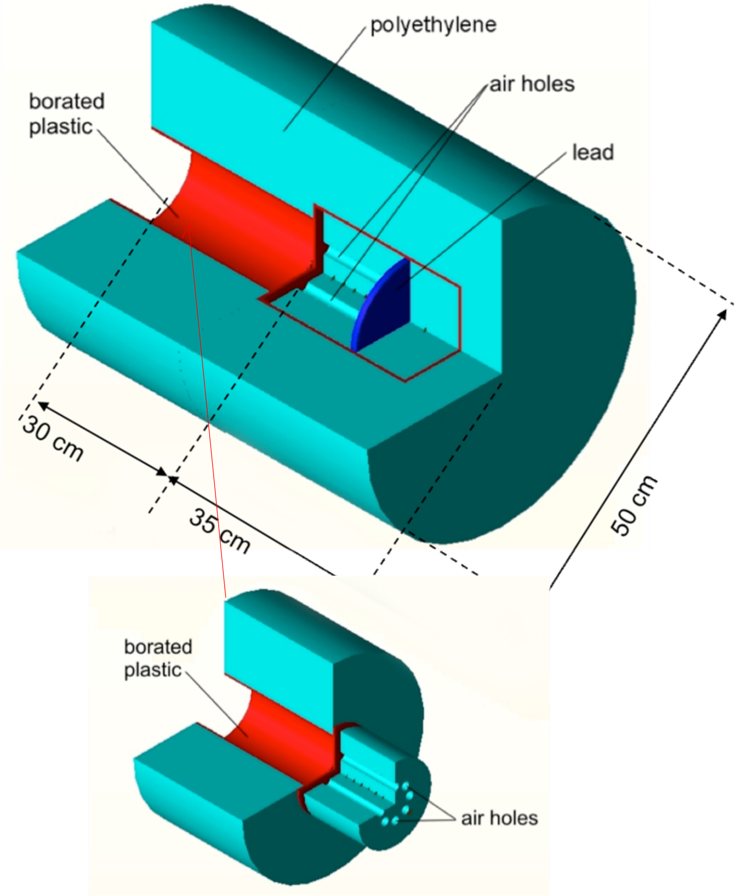
True thermal neutron fluence rate: $\Phi_{th} = (2.07 \pm 0.07)10^6\ cm^{-2}\ s^{-1}$

Cylindrical SPectrometer design

- Seven TNDs along the axis
- Spectral resolution and lateral rejection
- HPDE Collimator 50 cm diam x 30 cm h
  Hole diameter 16 cm, B-plastic lined
- 35 cm h x 50 cm diam detectors part
- Capsule for detectors: 20 cm diam,
  includes one cm lead disk (high-E)
- Air holes to increase deep response

HDPE AIR Pb B-plastic

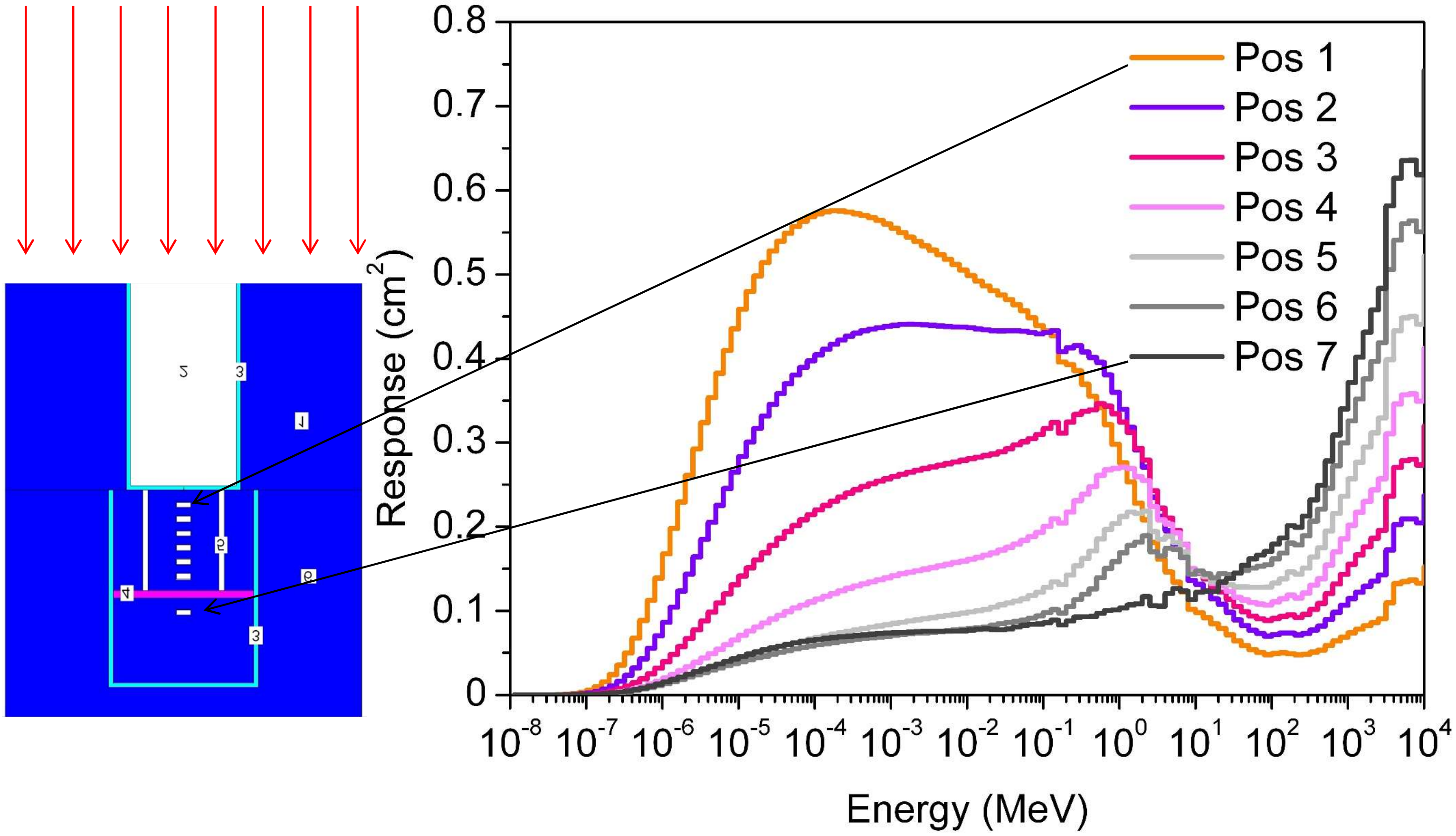




Radiat. Meas. 82, 47-51 (2015)

CYSP response

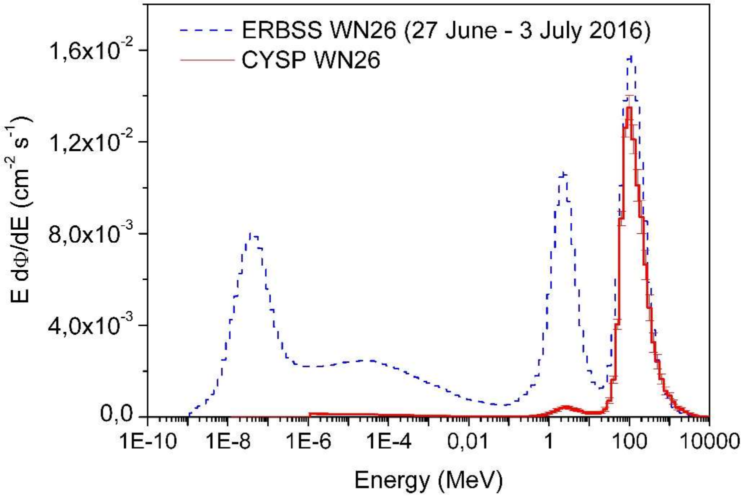
Radiat. Meas. 82, 47-51 (2015)



CYSP workplace testing

The HMGU measurement station at UFS Schneefernerhaus (2650 mt, 4.1 GV)

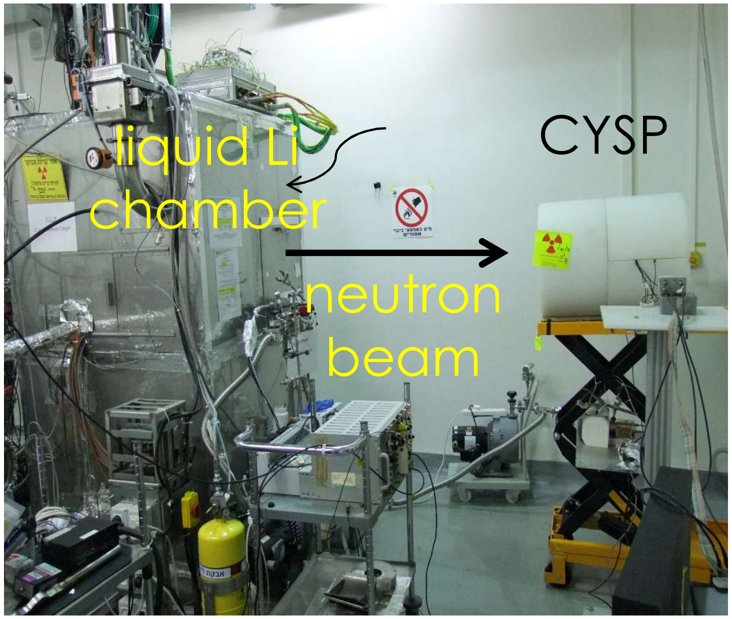
1. Compare with the HMGU Extended Range Bonner Sphere Spectrometer (^{3}He-based, 15 spheres, 2 of which with extended range + 1 bare detector).
2. Eliminate the omnidirectional “albedo” component affecting the ERBSS

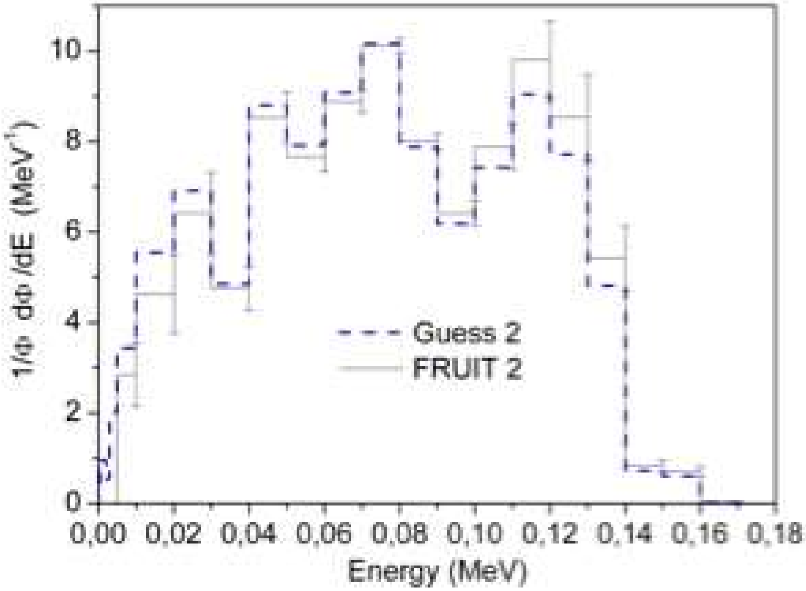


CYSP workplace testing

The neutron beam at SARAF (SOREQ, Israel)

1.92 MeV protons on a liquid Lithium target
peak current 500 μA
Different pulse durations and repetition rates





Conclusions

The e_LiBANS facility in Torino provides intense and well characterized neutron fields, tunable in intensity by varying the beam current and energy

Thermal neutron detectors were developed by depositing ^{6}LiF on Si/ SiC devices (in-house process, satisfactory n/γ, sensitivity scales with area, able to work in pulsed fields, good linear response)

Accurate calibration campaigns (Casaccia, NPL) allowed to determine their response curves at 3% level

Silicon carbide devices proved to be radiation resistant up to 5×10^{13} n cm^{-2} with a neutron to photon sensitivity 10^{-4}

Multi detector systems have been developed:

- 4 x 4 matrix of SiC’s as neutron field transverse uniformity monitor
- Bonner Sphere System Spectrometers with TNRD can span thermal to 20 MeV neutron energy
- Cylindrical Spectrometers (for directional neutron sources) on an extended neutron energy range

Developments of new detectors are ongoing mostly for biomedical applications (BNCT among others)

Thank you for your attention!

e_LiBANS collaboration:

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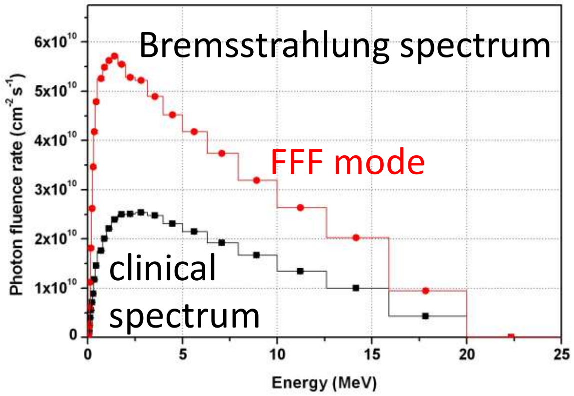
BACKUP

“Options” to increase Fluence rate

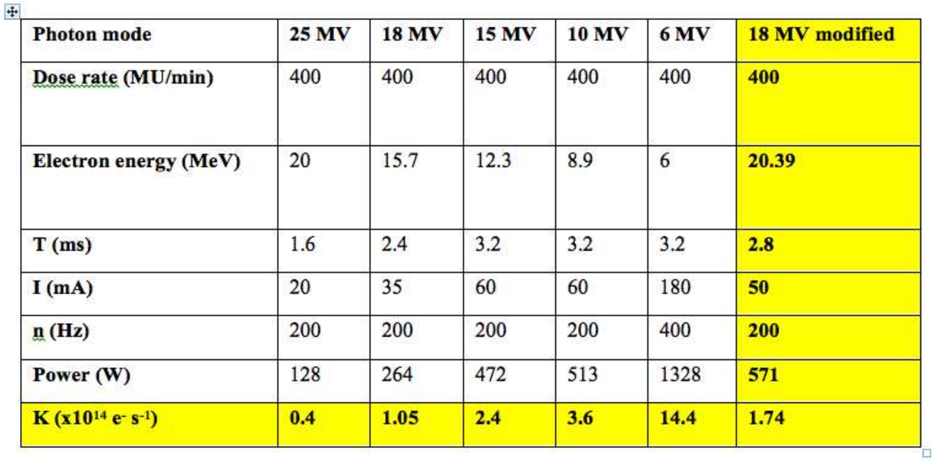
1-Removal of Flattening filter (implemented):
- g-mode 18 MV FFF →
- e-mode 18 MeV FFF

Expected a factor 2 increase (to be measured)



M. Costa INFN Torino

ELEKTA



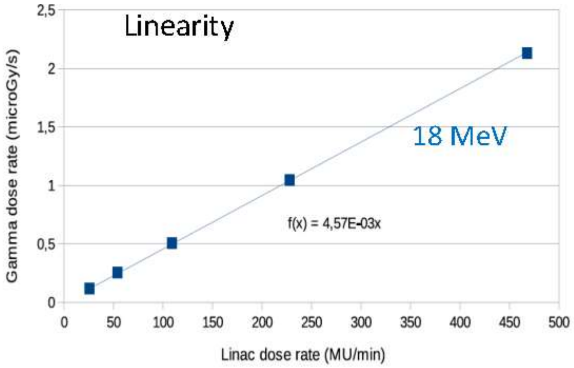
Photon mode	25 MV	18 MV	15 MV	10 MV	6 MV	18 MV modified
Dose rate (MU/min)	400	400	400	400	400	400
Electron energy (MeV)	20	15.7	12.3	8.9	6	20.39
T (ms)	1.6	2.4	3.2	3.2	3.2	2.8
I (mA)	20	35	60	60	180	50
n (Hz)	200	200	200	200	400	200
Power (W)	128	264	472	513	1328	571
K ($\times 10^{14}$ e$^-$ s^{-1})	0.4	1.05	2.4	3.6	14.4	1.74

2- Beam energy increase up to 20 MeV is feasible but under discussion with ELEKTA

Expected a factor 2 increase in the neutron Fluence rate

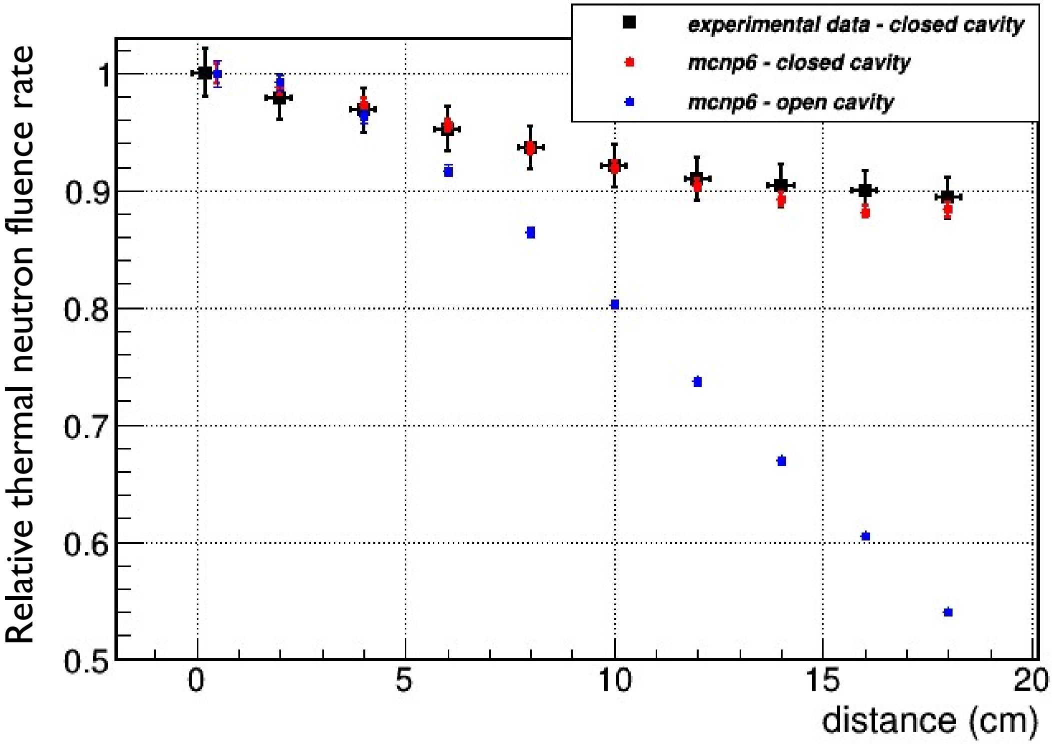
Gamma Dose measurement

Use Far West Technology's energy compensated Geiger Muller counter (GM-1 Geiger counter)
The calibration factor of the detector is known from a previous calibration with a ^{60}Co source.
Its value in terms of air kerma is: f = 207 μGy^{-1}, with 5% of uncertainty.
A bias voltage of 500 V has been applied to the GM counter.



γ beam	D_g μ**Gy MU**$^{-1}$	st.dev %	D_g @400MU/min **mGy/h**	Φ_{th} @400MU/min **cm**$^{-2}$**s**$^{-1}$	ratio D_g/Φ_{th} **Gy cm**^{2}
18 MV	0.277	2.05	6.65	$1.80\ 10^{6}$	$1.03\ 10^{-12}$
15 MV	0.204	0.38	4.88	$8.52\ 10^{5}$	$1.59\ 10^{-12}$
18 MV FFF	0.211	0.65	5.06	$1.39\ 10^{6}$	$1.01\ 10^{-12}$

Thermal neutron field depth gradient



Fluence rate decrease: 5% over 20 cm in closed cavity condition

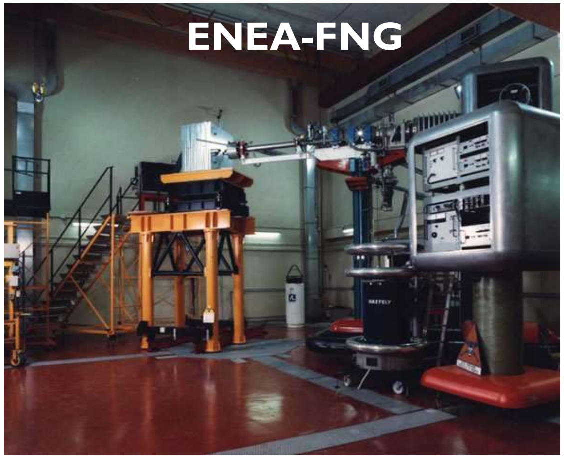
Data uncertainties include detector sensibility and position measurement

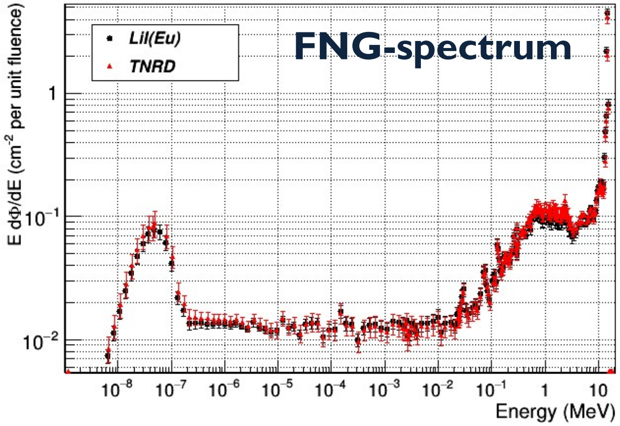
Calibration of the BSS + TNRD system

- Bonner Spheres + LiI(Eu) scintillator calibrated at NPL UK (primary standard) with mono-energetic beams 144 keV, 545 keV, 1.2 MeV [*]

- Response matrix of the BSS+TNRD system calculated by MCNP

- Validation and calibration by exposing the two systems to the same spectrum at ENEA Frascati Neutron Generator (FNG)



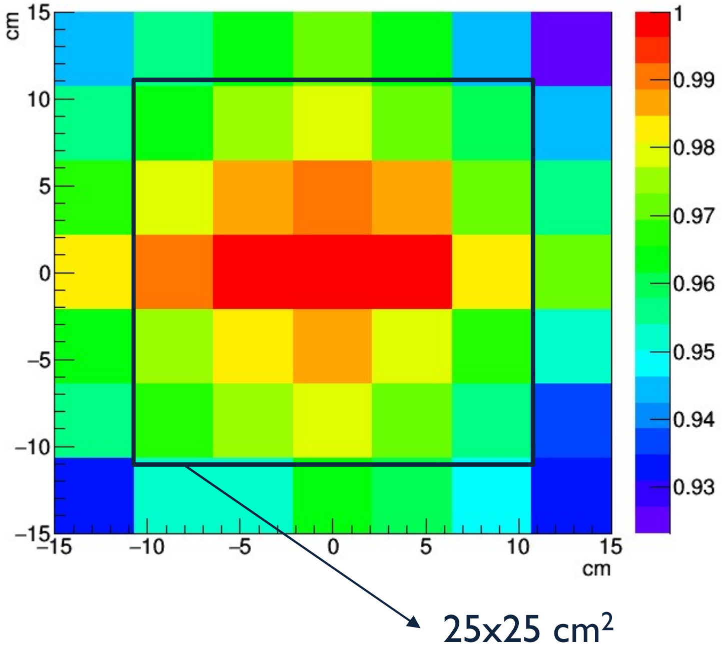


[*] R. Bedogni, A. Pola, M. Costa V. Monti, D. J. Thomas . Nucl. Instrum. Methods A 897 1821, 2018.

Thermal neutron field uniformity

TNRD measurement on 49 positions in the central cross plane of the cavity (18 MV)

Relative Thermal Fluence Rate



25x25 cm^2
uniform within the 4%

	TNRD	MCNP6
Maximum deviation	7%	8%
Standard deviation	2%	2%

E-LiBANS thermal cavity central position, 18 MV, 400 MU/min:

$$\Phi_{th} = (1.75 \pm 0.04\,)10^{6}\ cm^{-2}\ s^{-1}$$

CYSP prototype

2013: Mono-energetic neutron fields from 144 keV to 16.5 MeV at NPL (UK)

Overall uncertainty of Response matrix estimated as < ±2% (comparison between observed and calculated count rates).

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