Measurement of the energy spectrum from the new neutron source planned for IGISOL

R. Bedogni[1], A.Gentile[1], D. Bortot[1], A. Esposito[1], M.V. Introini[2], A. Pola[2],
P. Andersson[3], A. Hjalmarsson[3], M. Lantz[3], **A. Mattera[3]**, S. Pomp[3], V. Rakopoulos[3], A. Solders[3],
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H. Penttilä[5], S. Rinta-Antila[5]

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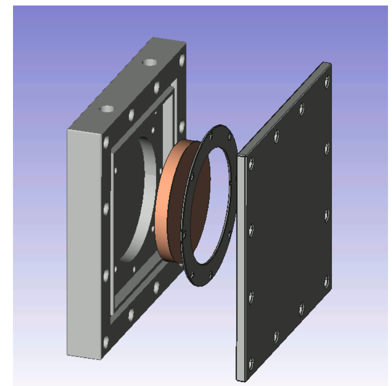
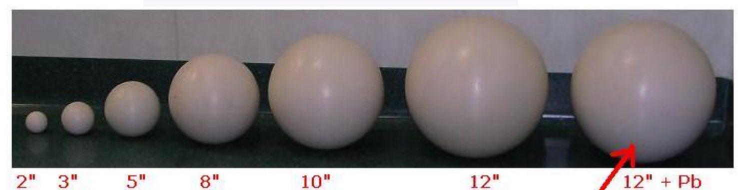
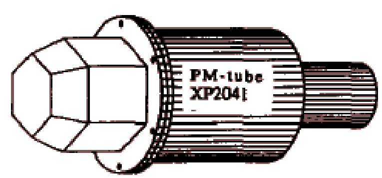
Outline

- Background: measurement of Fission Yields within AlFONS
- N-source design
- Measurement setup
  - BSS
  - ToF
- Analysis & Results
- Outlook
- Published works







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Motivation

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Why ?

- High quality data on independent fission yields
  - will **decrease the uncertainty** about (spent) fuel composition
  - are **relevant for safety measures** (Fission gas production, delayed neutrons, criticality, etc.)
  - **provide information** about core **poisoning**
  - improve burn-up predictions
- Not only for applications: FY data are also useful for a **better understanding of the fission process**

Motivation

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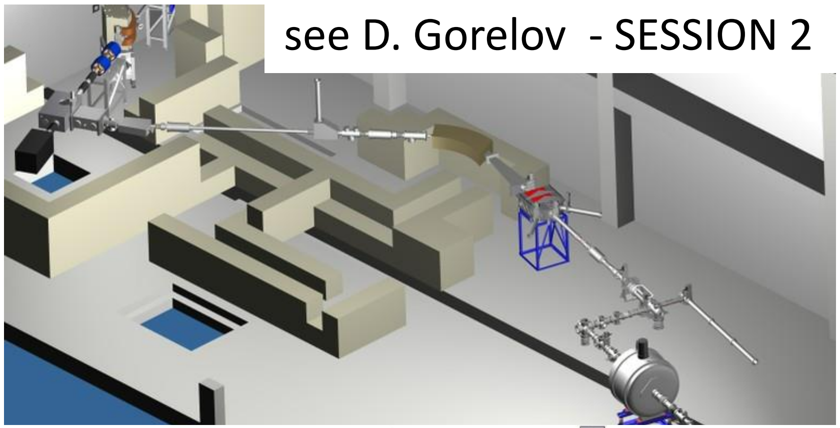
IGISOL-JYFLTRAP @ University of Jyväskylä

see D. Gorelov - SESSION 2



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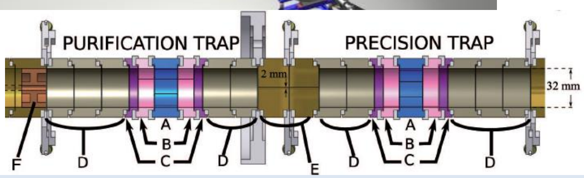

- Penning trap:
  - **q/m** isotope selection (mass spectrometry)
  - coupling with a **Ion Guide & Isotope Separator On-Line** (IGISOL)
- How can it contribute to better nuclear data?
  - ✓ high mass resolution ($M/\Delta M \approx 10^5$), it could also resolve some isomeric states
  - ✓ all isotopes measured in one experiment
  - ✓ fast analysis (≈ 500-1000 ms)
  - ✓ low chemistry dependence

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How ?

Motivation

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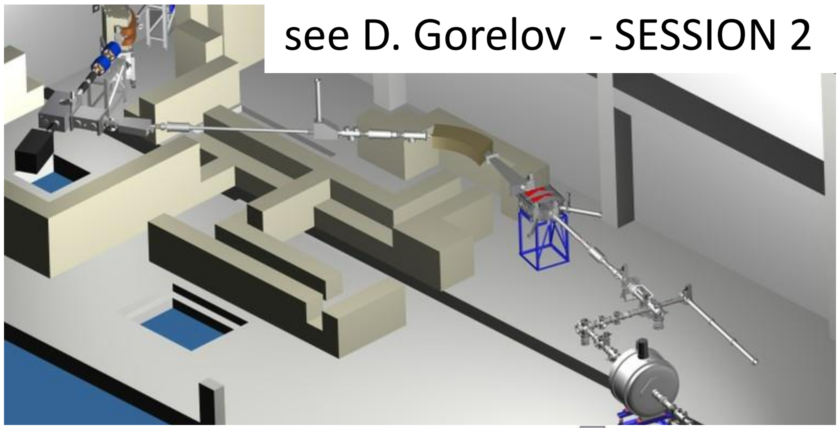

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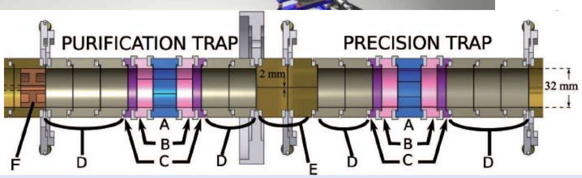

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A **neutron source** is needed

- **Couple a p-n converter to the high-intensity 30 MeV cyclotron at IGISOL**
- **versatile source (low and high energy)**

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Neutron source design

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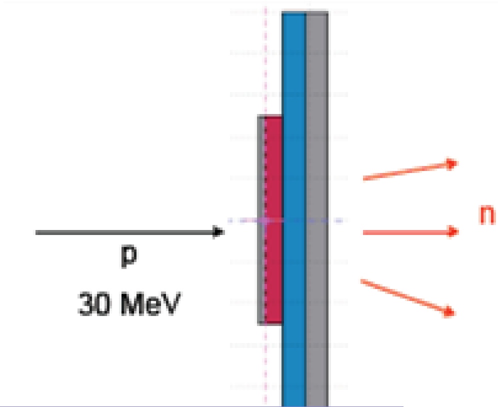
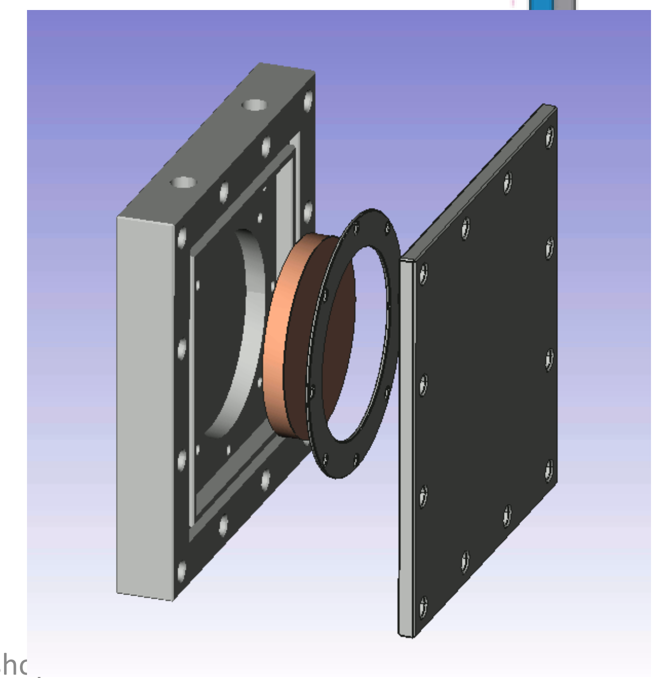
- water-cooled Be-target:
  - 50 mm diameter
  - 5 mm thickness
- 30 MeV protons will **stop in the cooling water**:
  - ✓ **less** effort to remove **heat** (up to 6 kW)
  - ✓ **reduced hydrogen build-up** (lesson learnt from Indiana University)
  - × -5% in neutron yield
- Flexible design: multiple units with different targets





Simulation (FLUKA, MCNPX) to evaluate the neutron yield

see M. Lantz - SESSION 1

Neutron source design

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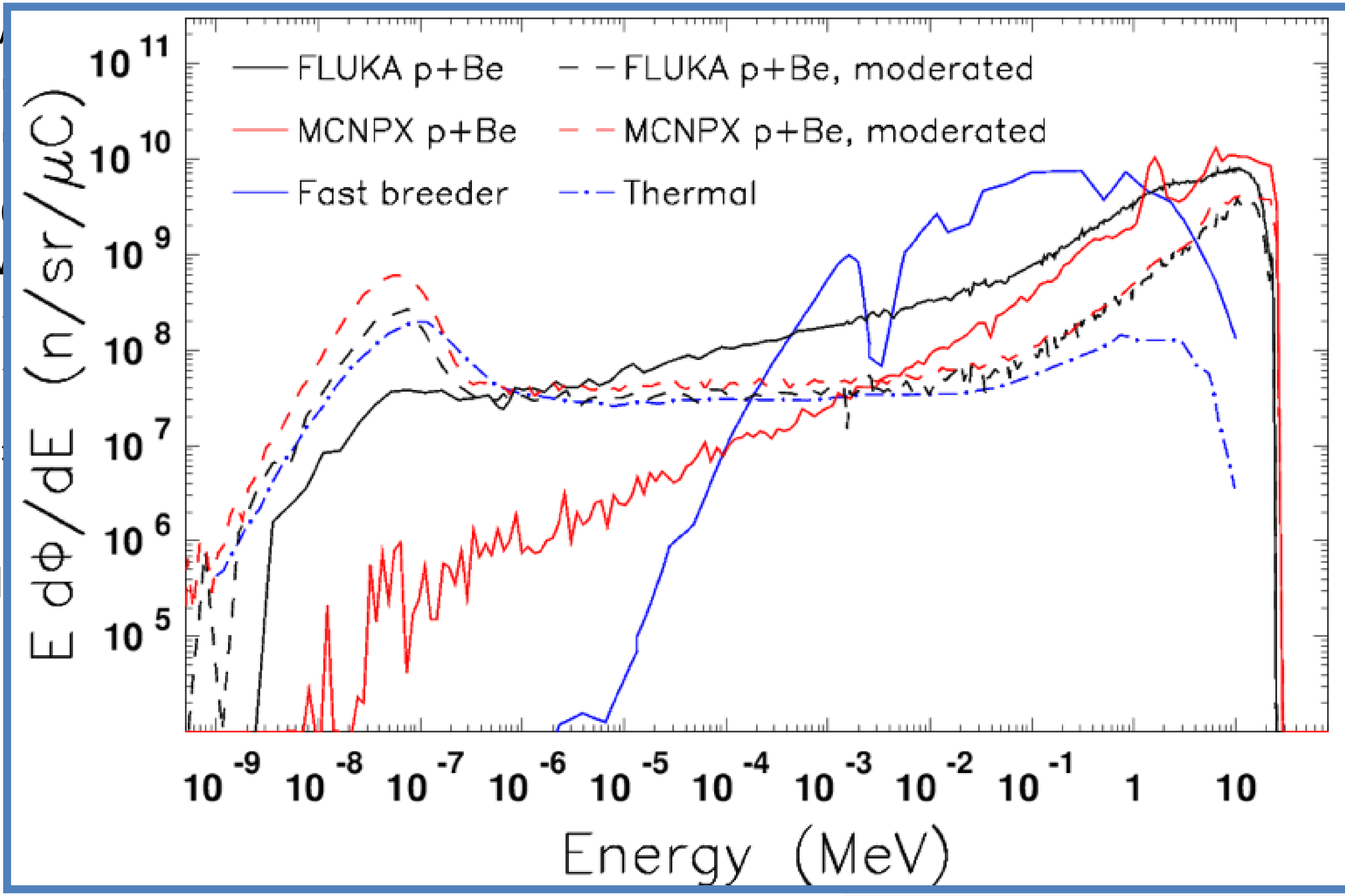

n

Characterization of the p-n converter

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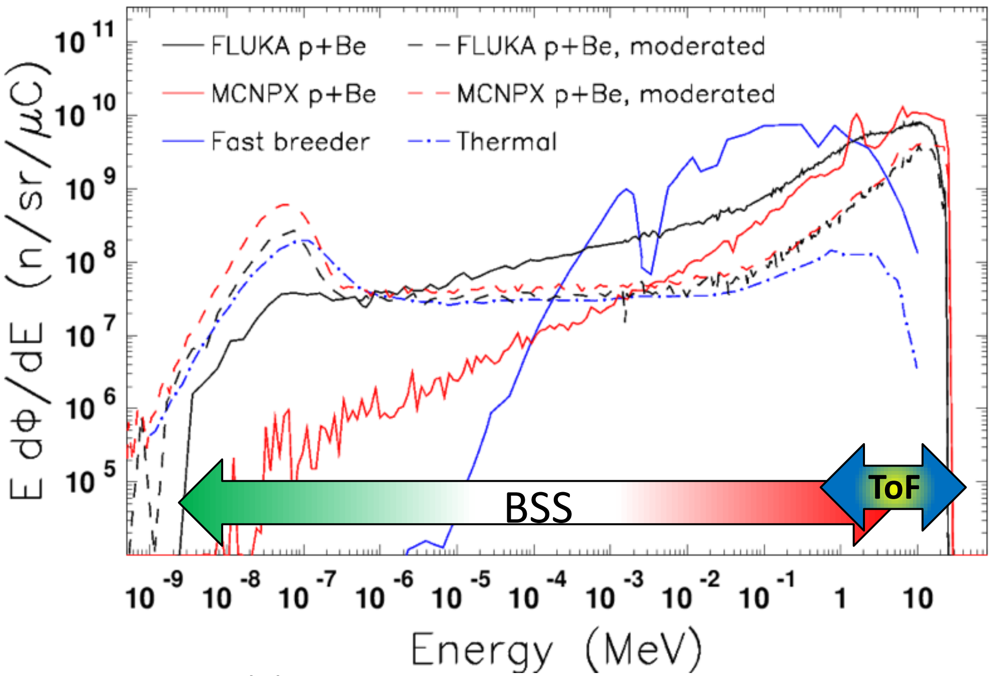
Motivation:

- Validate the simulation for both configurations (bare/moderated target)
- Things will be different in Jyväskylä (Al reaction chamber, concrete, …), but if we know the differences between MC & measurements in a reference geometry, we can have a better idea about the reliability of the simulations at IGISOL

Two different techniques:

- **Bonner Spheres** for the low-energy part (LNF-INFN)
- **Time of Flight** (liquid scintillator) for the high-energy part (UU)



- Background
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    - BSS
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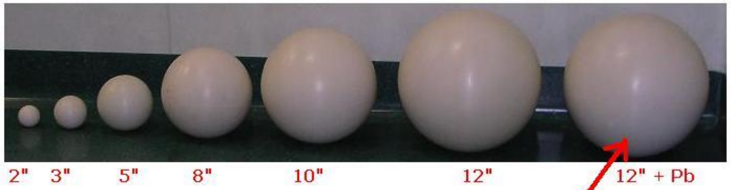
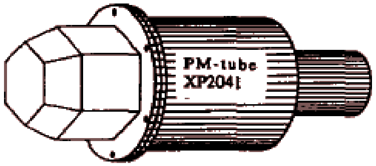
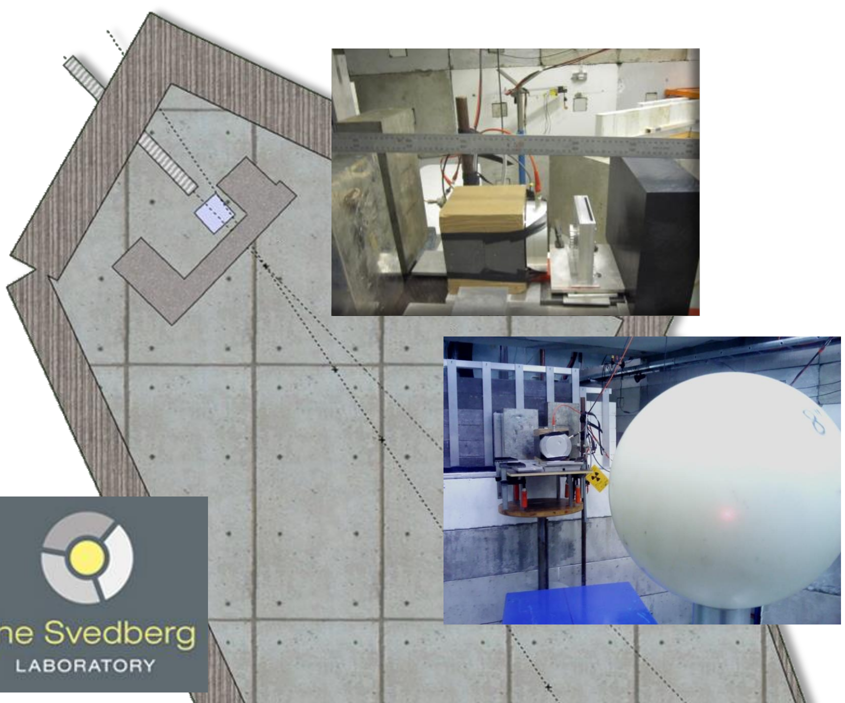




Characterization of the p-n converter

- Measured **energy of accelerated protons**: 37.25 ± 0.5 MeV
- Average **proton energy at target**: 29.62 MeV
- Proton energy spread (FWHM) at target: 0.57 MeV
- Repetition **period of beam micropulses**: 44.2 ns



The PAULA facility at TSL, Uppsala

Measured setups:

- Jyväskylä-like target (TOF & BSS)
- Jyväskylä-like target + 10cm PE moderator (TOF & BSS)
- Thin target (1mm Be) (TOF)
- Full-stop target (6mm Be) (TOF)

Allocated ERINDA beamtime: 44 hrs
Beamtime delivered by TSL: 50 hrs

Measurement of Be(p,n) spectra with an extended range Bonner Sphere Spectrometer (BSS)

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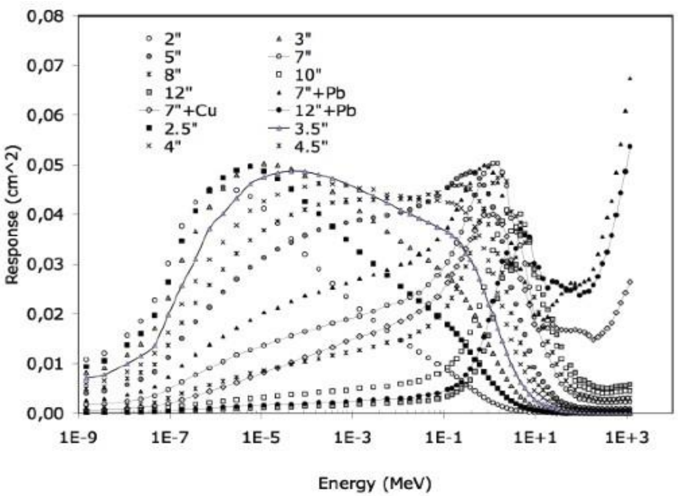
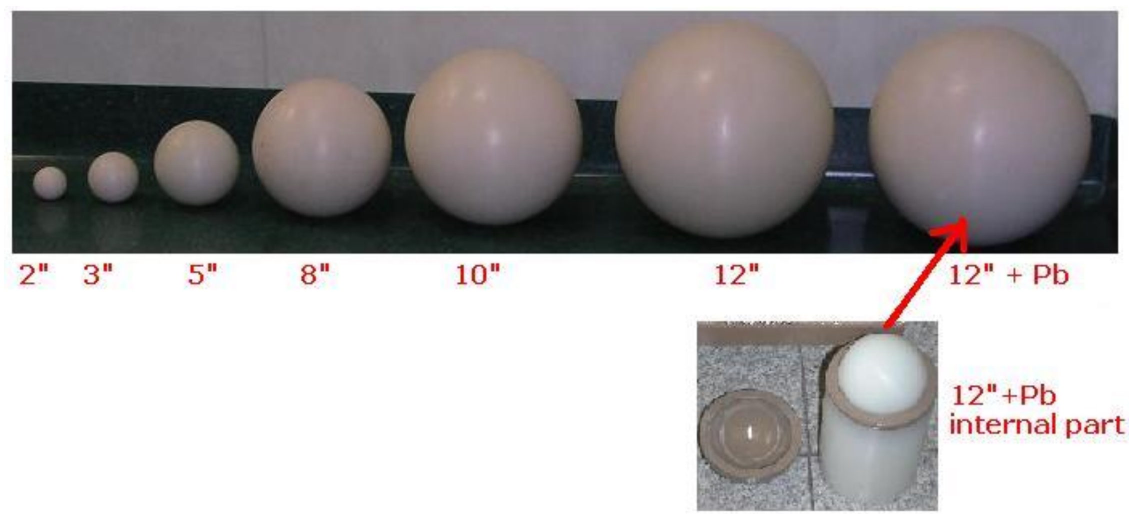
BSS was used to measure neutron spectra obtained from the target assembly in 2 configurations:

- 5mm target
- 5mm target + moderator





13 spheres used (diameter in inches):

2, 2.5, 3, 3.5, 4, 4.5, 5, 7, 8, 10, 12+1cmPb, 7+1cmPb, 7+1cmCu

Measurement of Be(p,n) spectra with an extended range Bonner Sphere Spectrometer (BSS)

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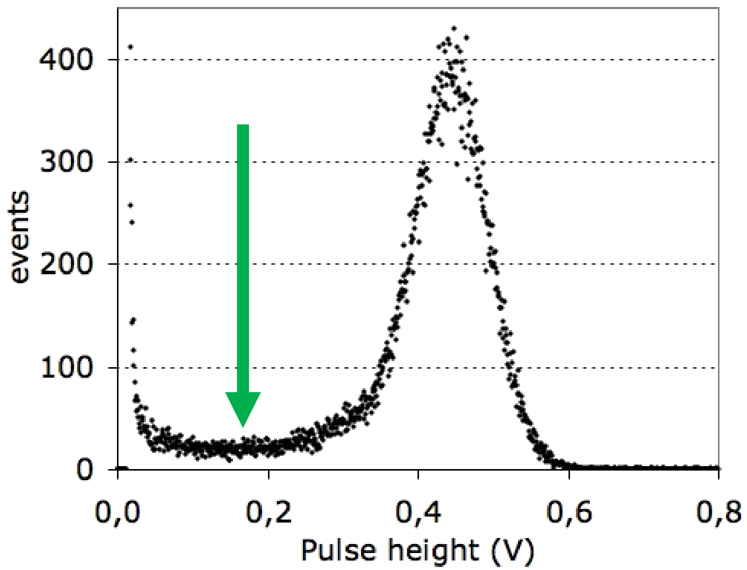
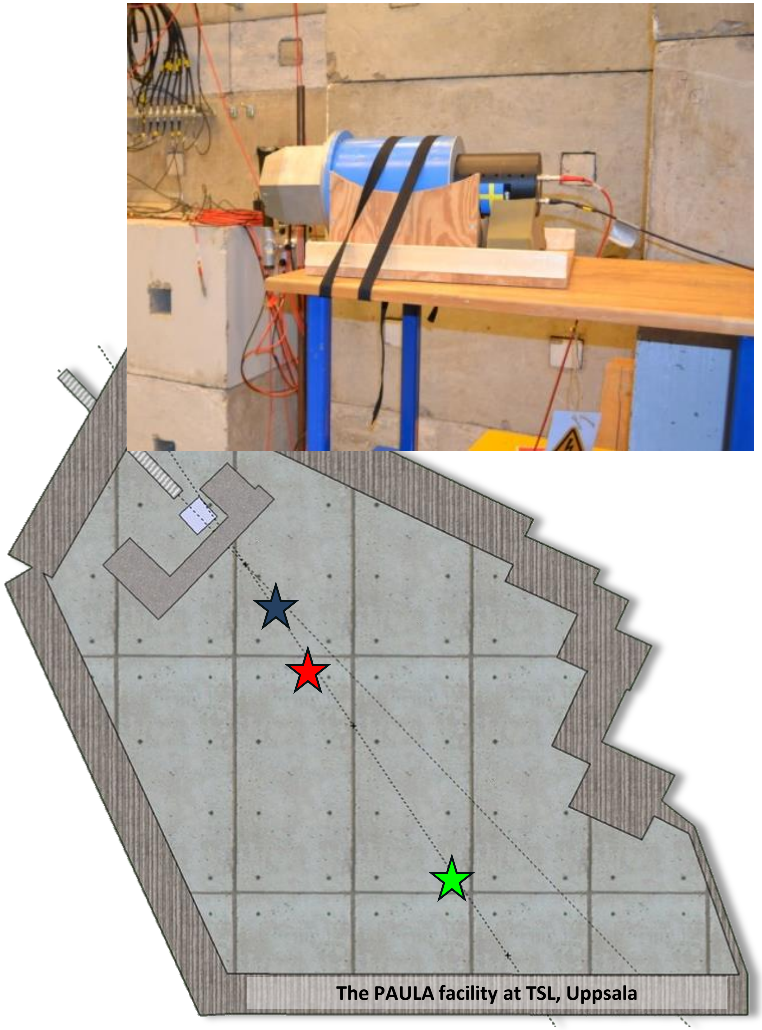
Central detectors (more than one central detectors were used to quality-assure the set of measurements)

1. Standard cylindrical lithium iodide scintillator (^{6}LiI(Eu), 4 mm x 4 mm). *Used in all spheres*
2. 1 cm^2 Silicon diode covered with two different types of thermal-neutron-to-charged-particle radiator, D1 and D2. *Used in few spheres, for the moderated scenario, with QA purposes*

The photon tail is easily separated from the thermal neutron capture peak. Small variations in the treshold position have practically no effect on the results



ToF



- **3.3 l** BC-501 **liquid scintillator** with PSD capabilities
- **3 different distances** to balance energy resolution and wrap-around
- PSD module for **online n-γ** discrimination
- TDC card (sampling time 0.025 ns)
- Digital DAQ in parallel with the TDC card (data under analysis…)

- Background
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- **Analysis & Results**
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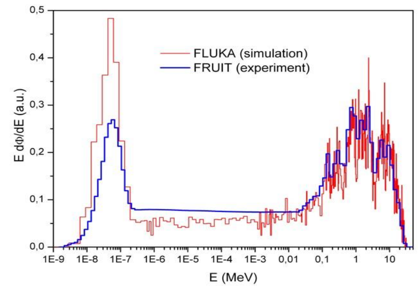
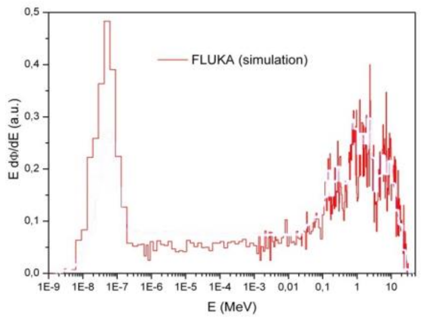
Analysis & Results

BSS



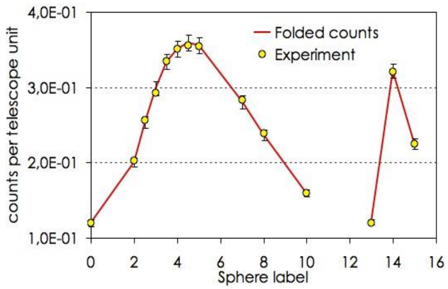


Guess Spectrum

(FLUKA/MCNP simulated and smoothed spectrum used as a starting point)

BSS input data (counts normalized to monitor units)

FRUIT version 7 (adapted to work with a guess spectrum as well as in parametric mode) software **to unfold the spectrum**



Check proposed spectrum against BSS response

Analysis & Results

BSS - unmoderated source

Uncertainties considered:

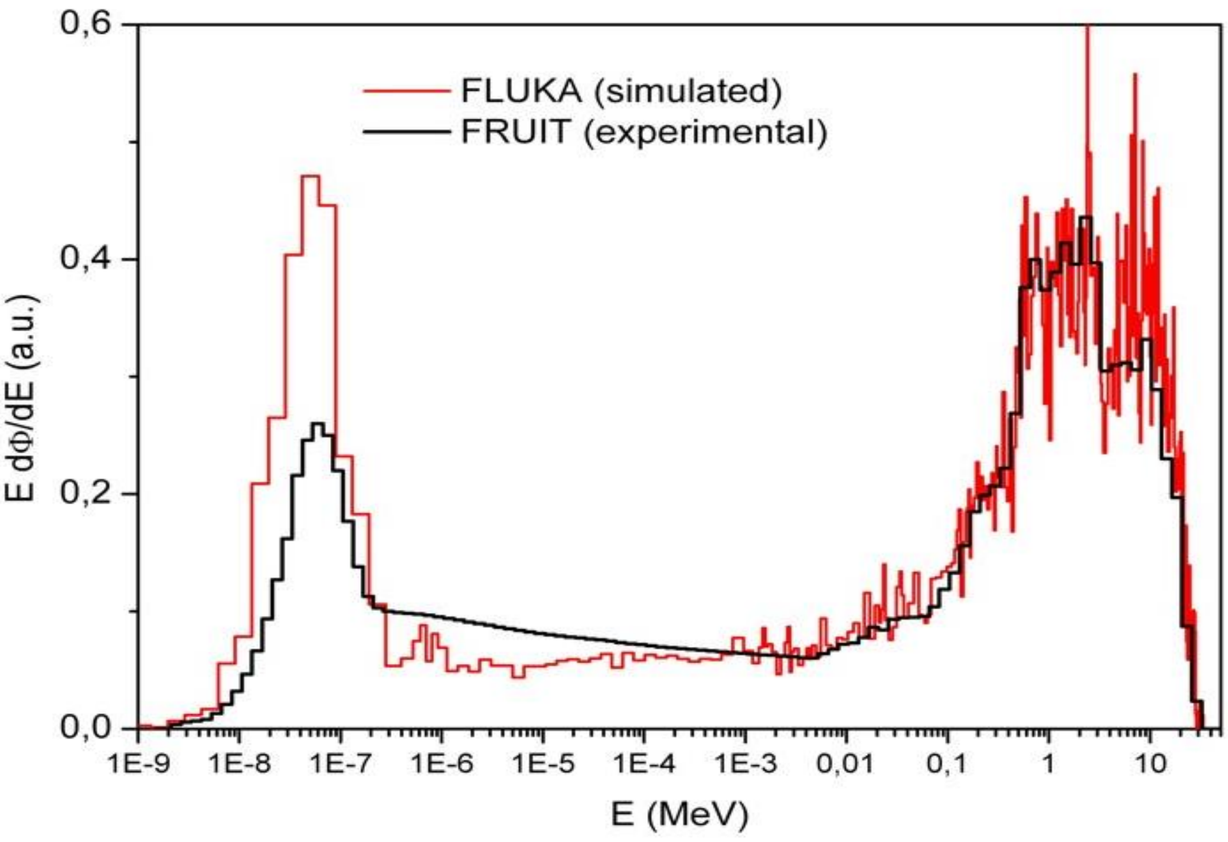
3% beam+monitoring stability (repeated exp. with same sphere)

3% overall unc on BSS response matrix

<1% BSS counting statistics

2% unc on BSS calibration (periodically repeated at LNF)

The discrepancy between FLUKA and the BSS measurement at thermal energies could be attributed to the low-energy (very room-dependant) background in the experimental hall.



Analysis & Results

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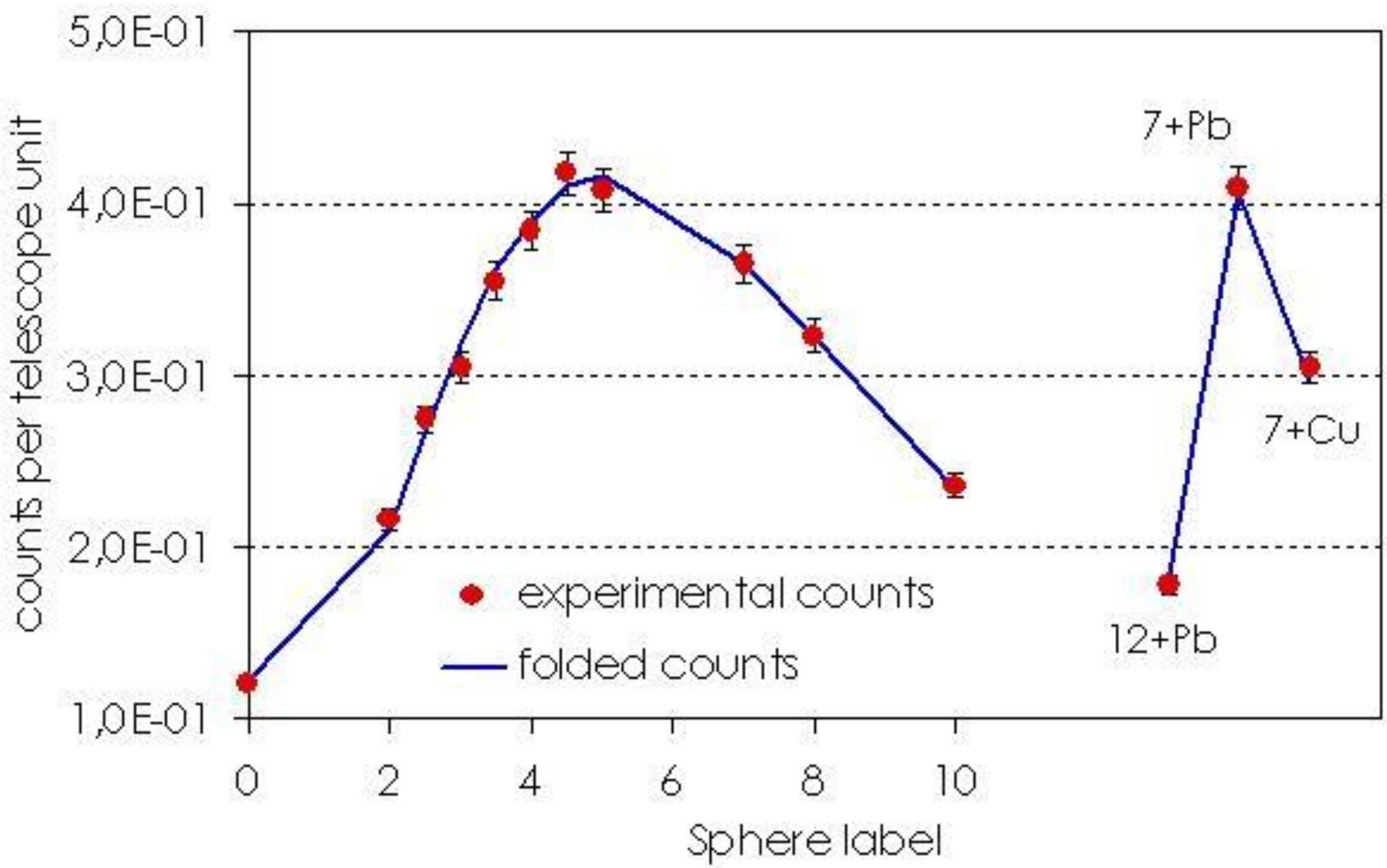
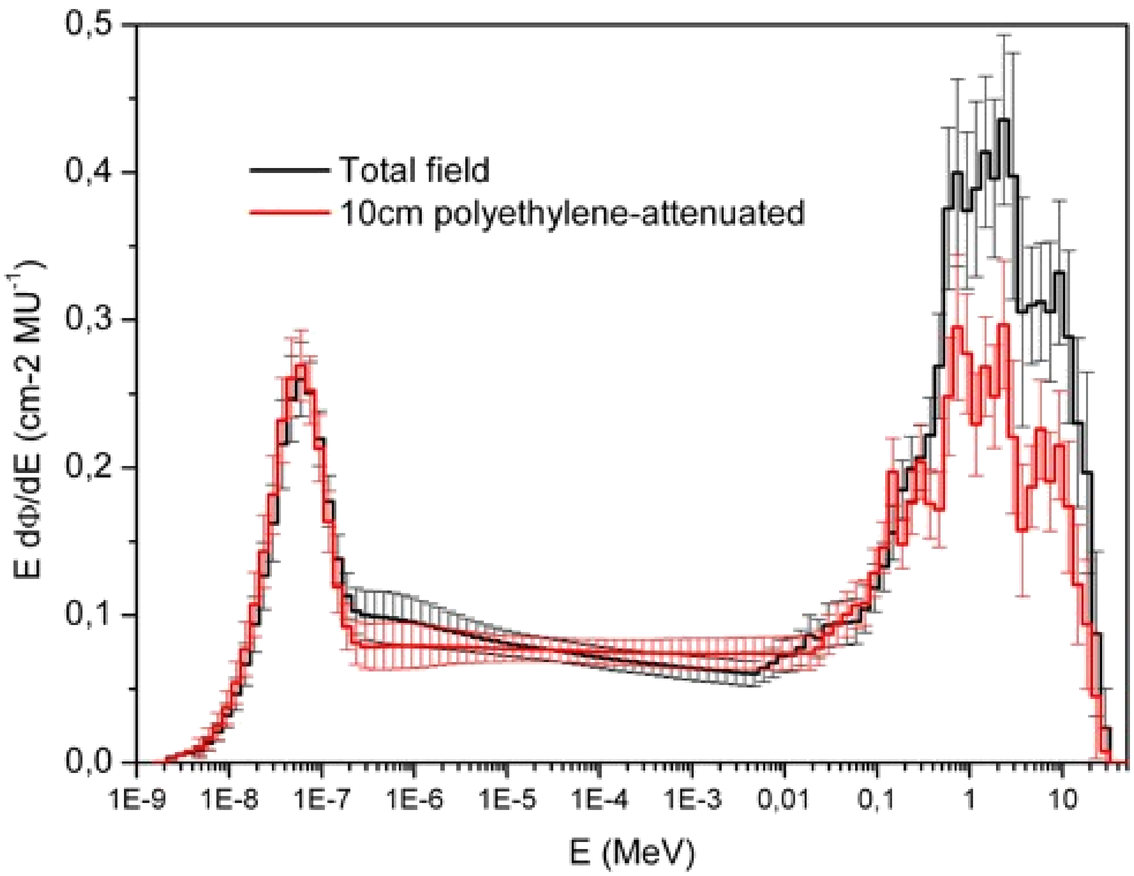
BSS - unmoderated source

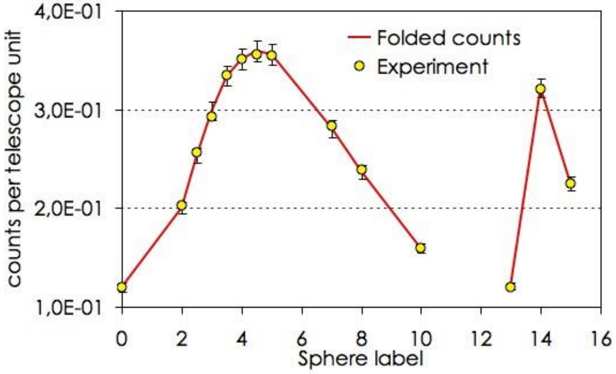
Does the unfolding respect the input BSS data?



Analysis & Results

BSS - moderated source

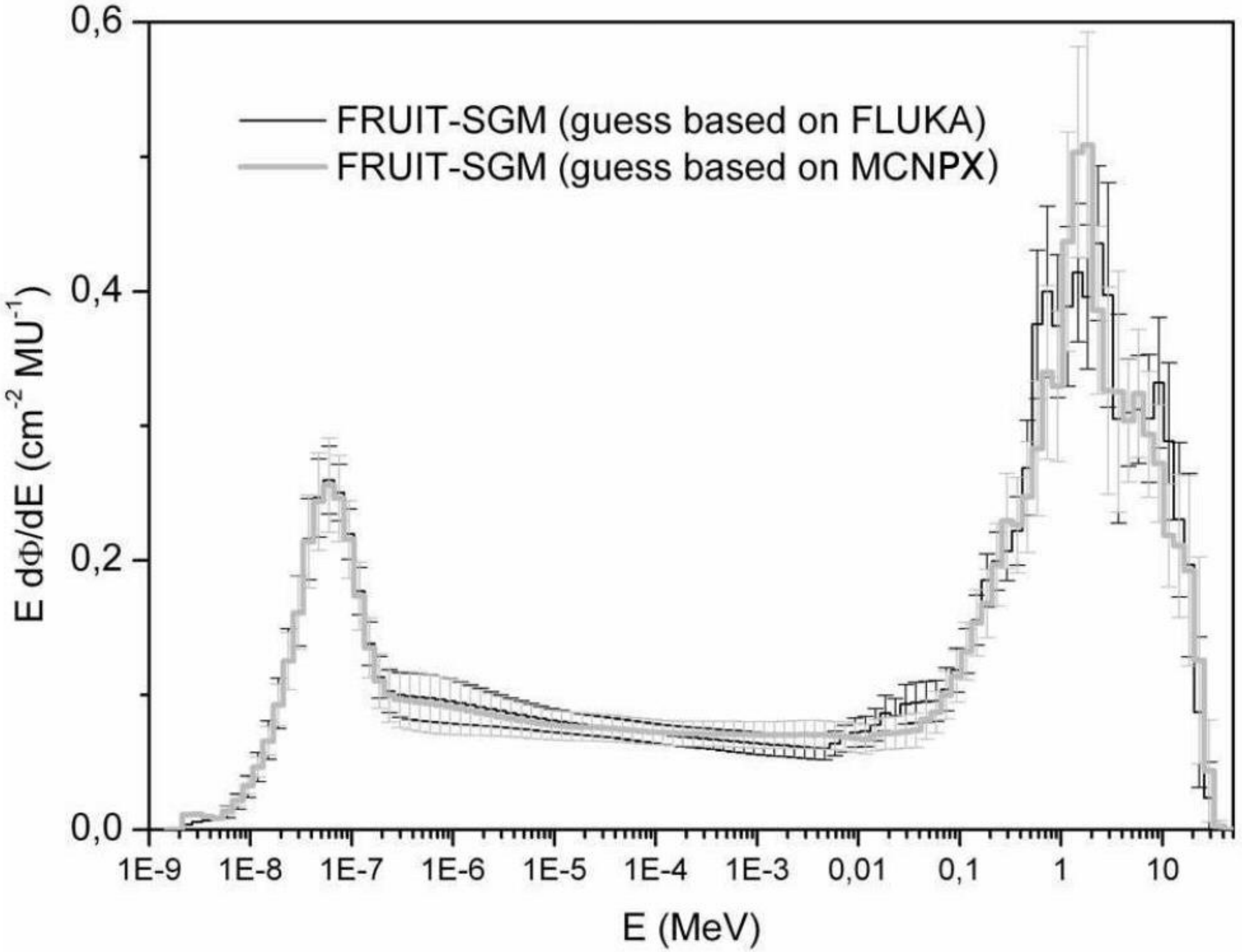




Analysis & Results

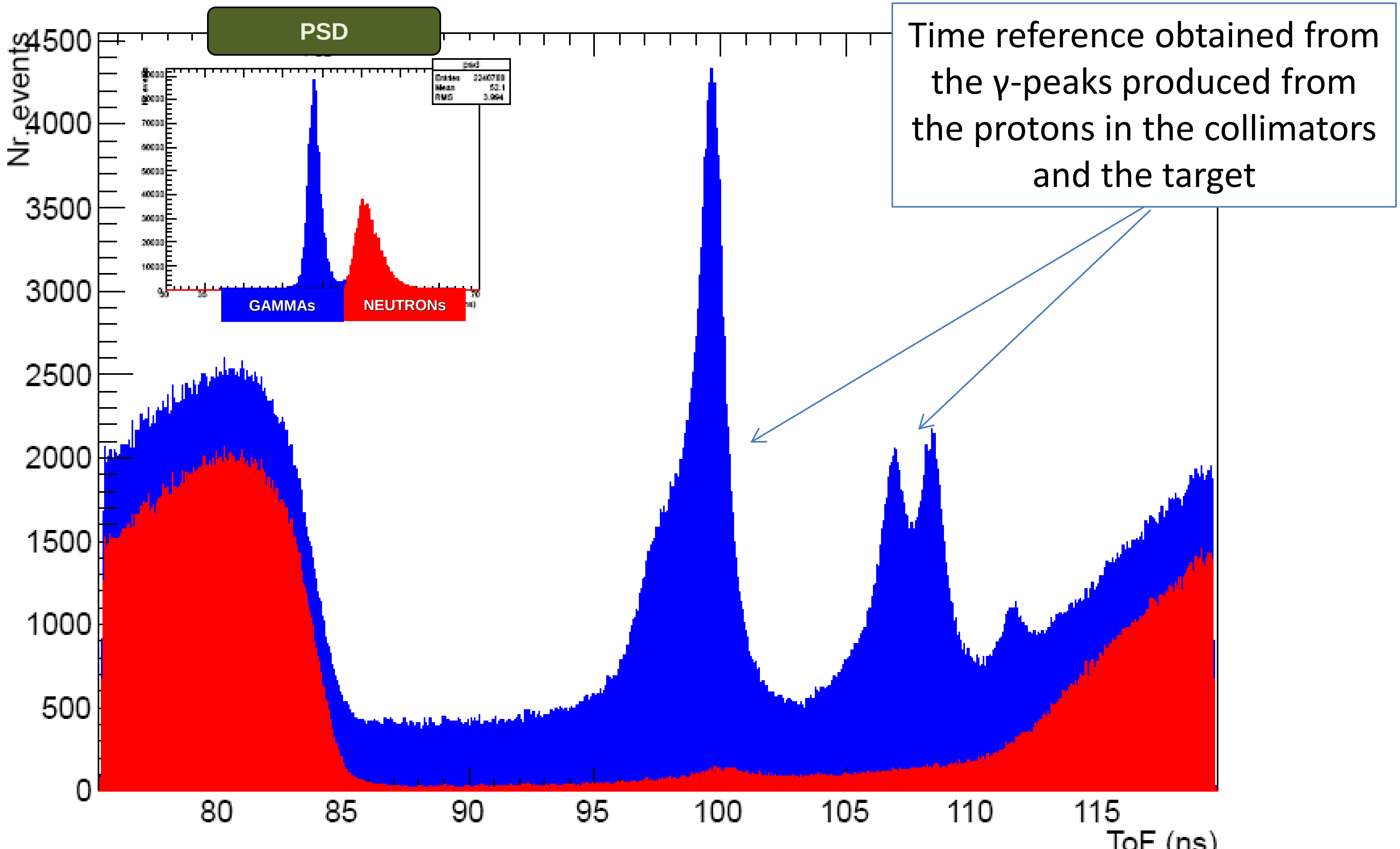
BSS – comparison different input spectra

The results obtained using different input spectra are in agreement within the uncertainties provided



Analysis & Results

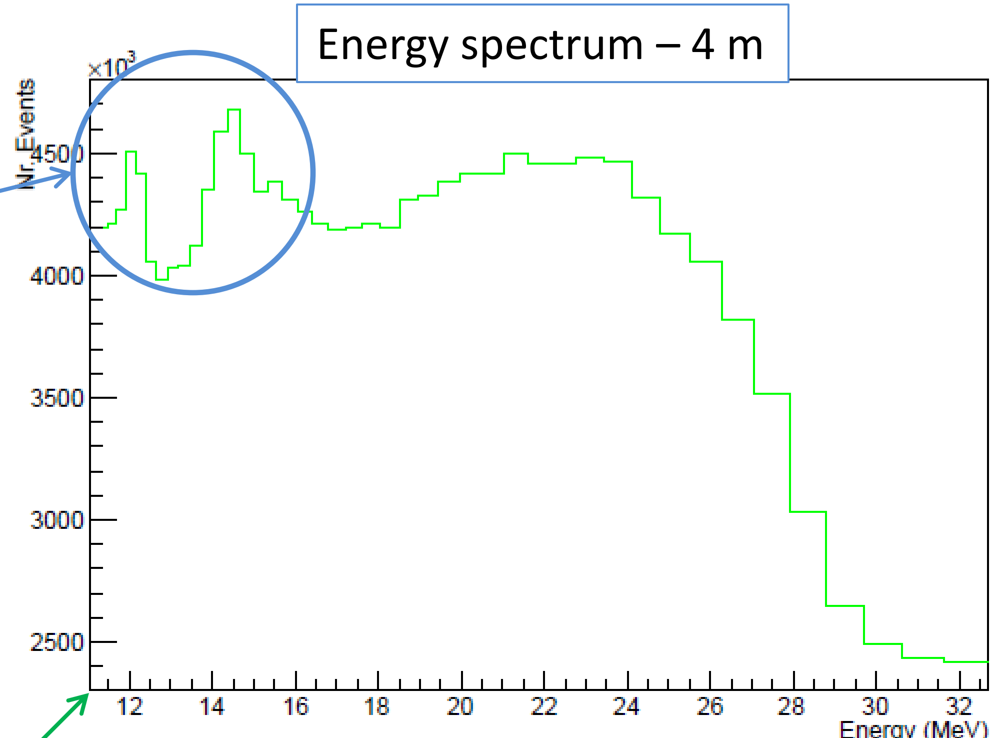
ToF – unmoderated source



Analysis & Results

ToF – unmoderated source

Pulse-shape analysis online is not enough to discriminate between n and gammas at the gamma-peaks

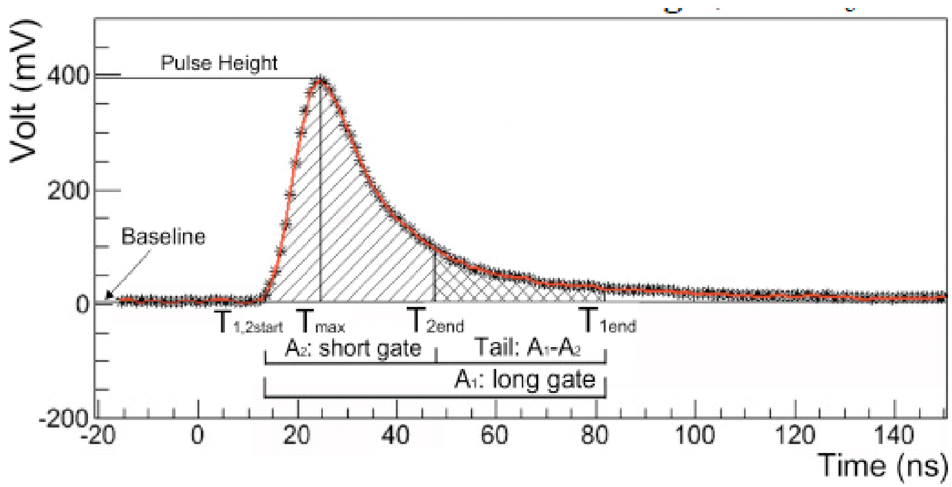


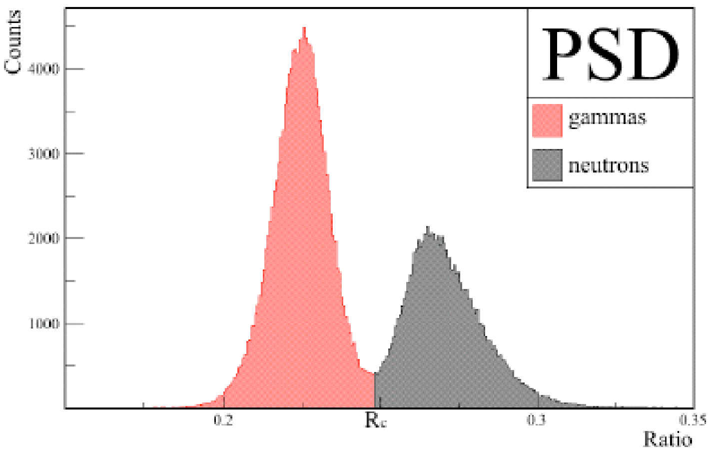
(very) high energy threshold to avoid wrap-around

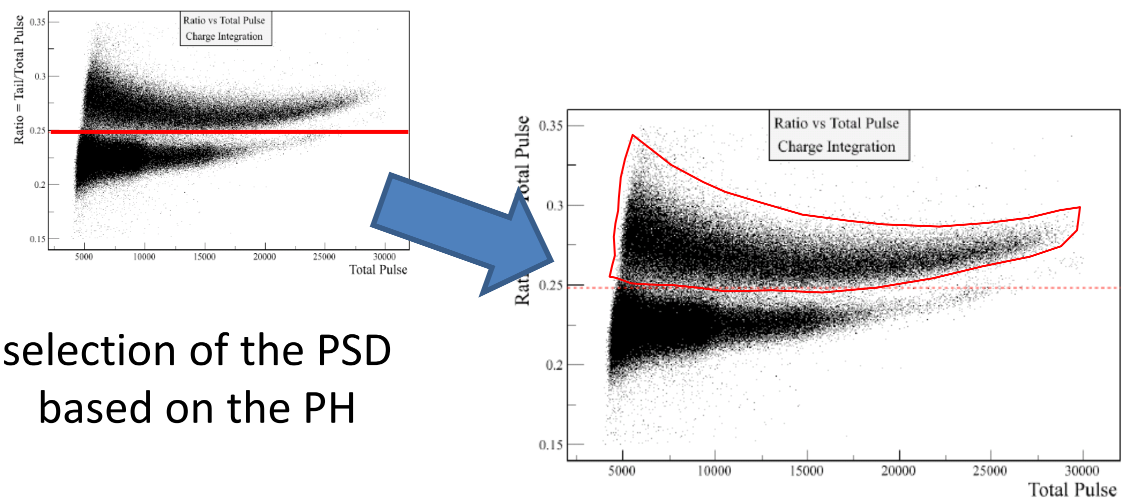
Analysis & Results

ToF – digital DAQ

more "in depth" analysis of the pulse shapes (also Pulse Heights) with digital DAQ



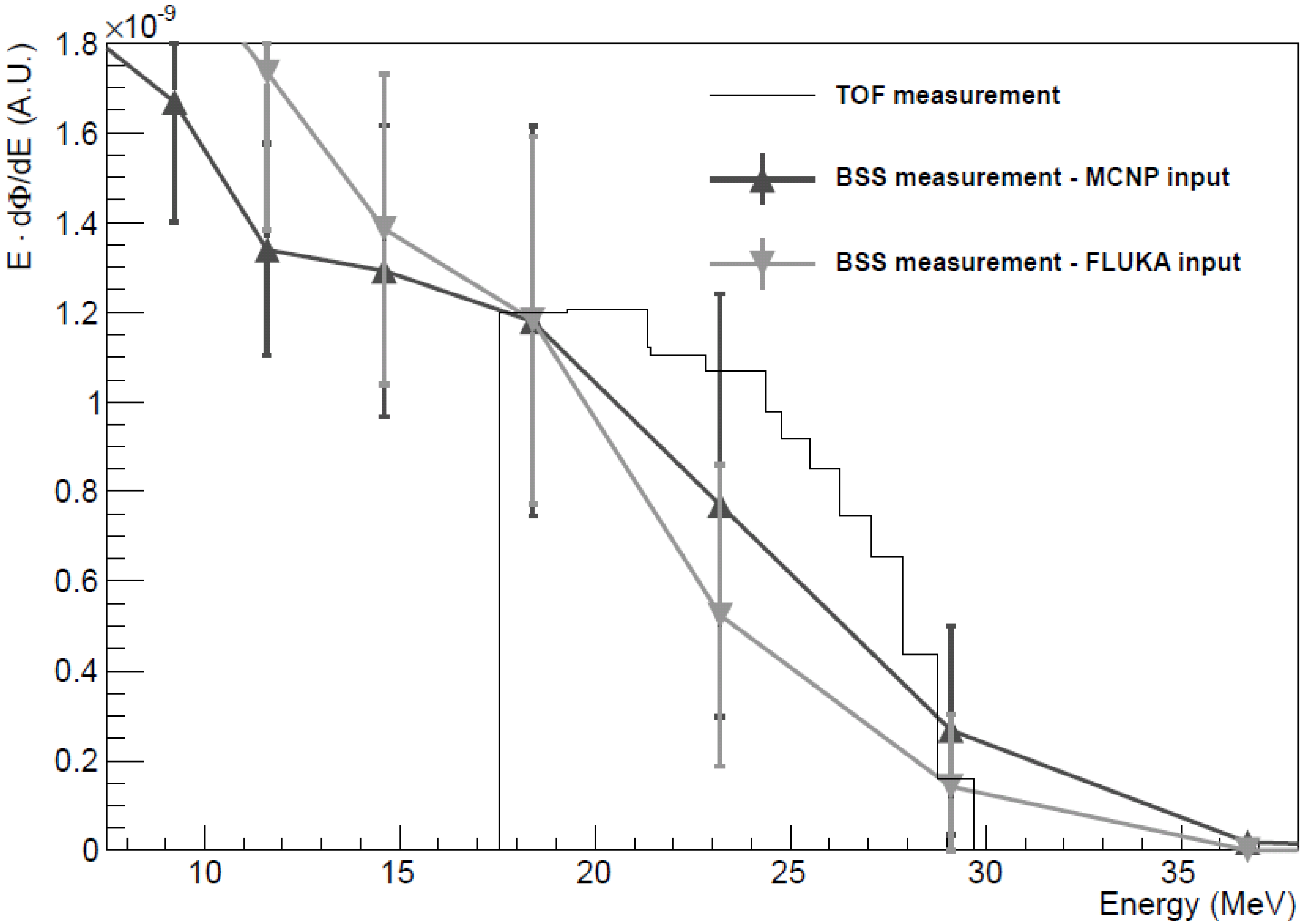




selection of the PSD based on the PH

Analysis & Results

ToF & BSS - unmoderated source



Conclusion & Outlook

Achieved:

- ✓ design (simulation) and construction of a mock-up of the neutron source (p-n converter)
- ✓ Run to measure the energy spectra in two configurations (unmoderated and moderated target)
- ✓ The source shows good features for measurement of n-induced fission yields

Still to do:

- ❑ Full re-scaling with absolute proton intensities (BSS & ToF)
- ❑ Estimation of the Background (BSS & ToF)
- ❑ Correction for the response function (ToF)
- ❑ Finalize analysis of the digital data (low threshold data) (ToF)
- ❑ Comparison of the two methods in the overlapping region

List of Publications

- *V. Rakopoulos, M. Lantz, P. Andersson, A. Hjalmarsson, A. Mattera, S. Pomp, A. Solders, J. Valldor-Blücher, D. Gorelov, H. Penttilä, S. RintaAntila, R. Bedogni, D. Bortot, A. Esposito, A. Gentile, E. Passoth, A.V. Prokofiev, M.V. Introini and A. Pola* **Target thickness dependence of the Be(p,xn) neutron energy spectrum –** proceedings of the International Conference of Nuclear Physics – June 2013.

- *R. Bedogni, A. Mattera, M. Lantz, P. Andersson, A. Hjalmarsson, S. Pomp, V. Rakopoulos, A. Solders, J. ValldorBlücher, D. Gorelov, H. Penttilä, S. RintaAntila, D. Bortot, A. Esposito, A. Gentile, E. Passoth, A.V. Prokofiev, M.V. Introini and A. Pola* **Neutron energy spectra of the Be(p,n) reaction at 30MeV –** proceedings of the 12th Neutron and Ion Dosimetry Symposium.

- *A. Pola, D. Bortot, M.V. Introini, R. Bedogni, A. Esposito, A. Gentile, E. Passoth, A.V. Prokofiev* **Use of semiconductor-based thermal neutron detectors in a Bonner sphere spectrometer –** proceedings of the 12th Neutron and Ion Dosimetry Symposium.

- *A. Mattera, P. Andersson, A. Hjalmarsson, M. Lantz, S. Pomp, V. Rakopoulos, A. Solders, J. Valldor-Blücher, D. Gorelov, H. Penttilä, S. Rinta-Antila, A.V. Prokofiev, E. Passoth, R. Bedogni, A. Gentile, D. Bortot, A. Esposito, M.V. Introini, A. Pola;* **Characterization of a Be(p,xn) neutron source for fission yields measurements –** proceedings of the International Conference on Nuclear Data for Science and Technology 2013 (accepted for publication on *Nuclear Data Sheets*).

- Extended paper (with final results and detailed description of the experimental setup) planned for NIM A

Measurement of the energy spectrum from the new neutron source planned for IGISOL

Thank you!

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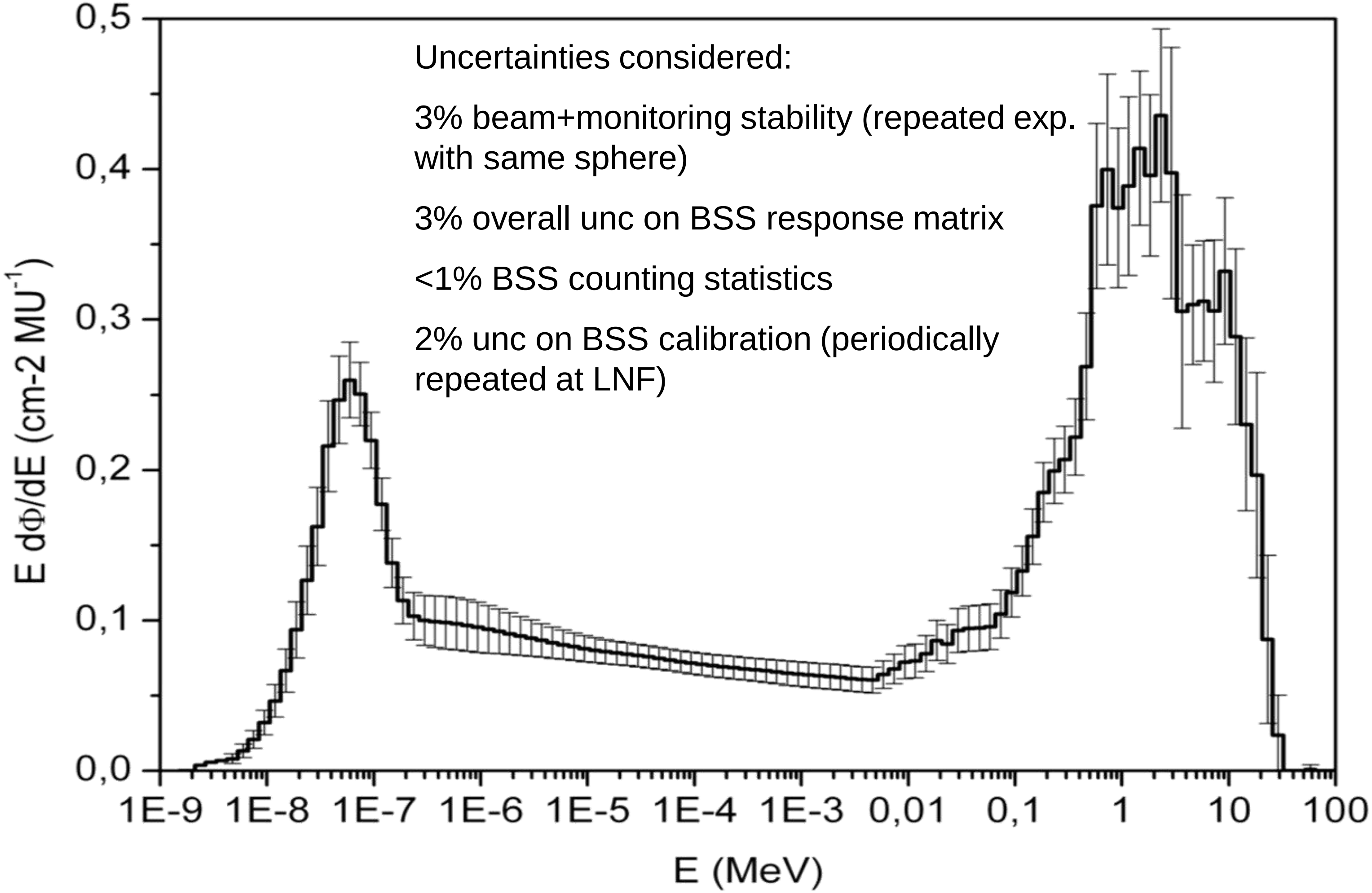
Analysis & Results

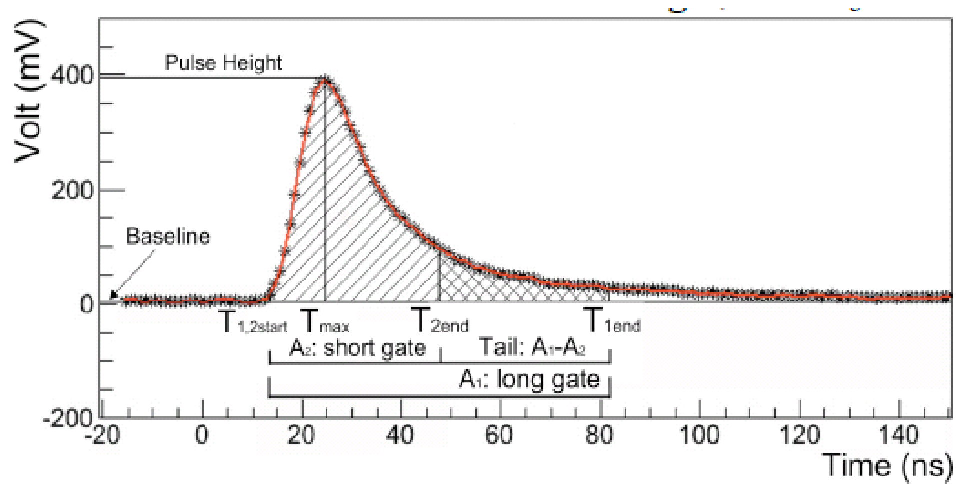
unmoderated source

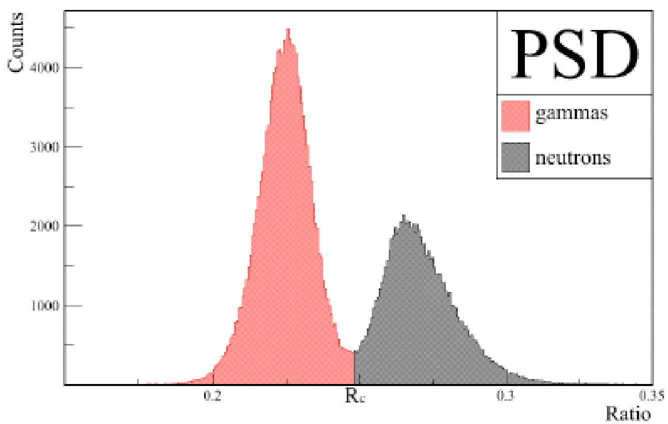


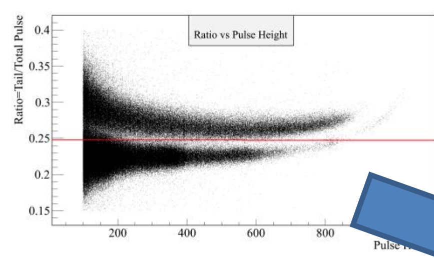
Analysis & Results

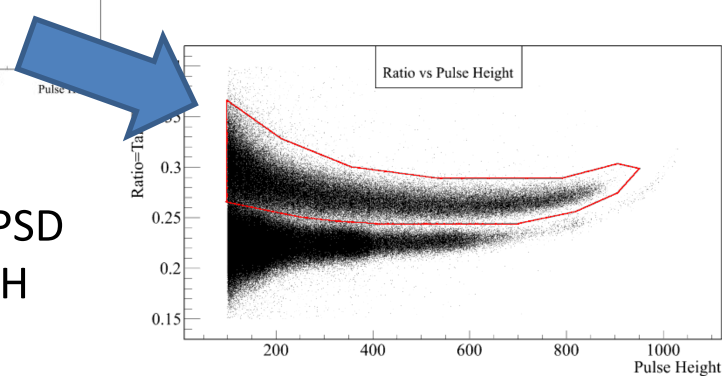
ToF – digital DAQ

more "in depth" analysis of the pulse shapes (also Pulse Heights) with digital DAQ









selection of the PSD based on the PH

TOF

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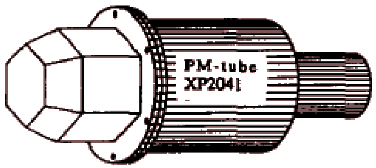
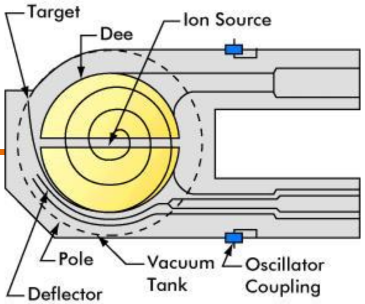
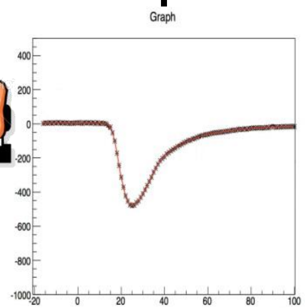
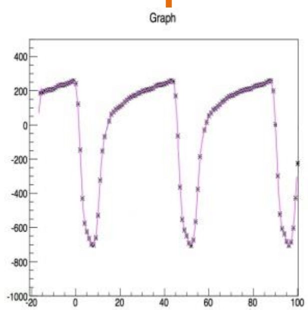
DIGITAL DAQ





Signal from the liquid scintillator





RF signal from the cyclotron (44.25 ns rep rate)

Pulse Shape Discrimination

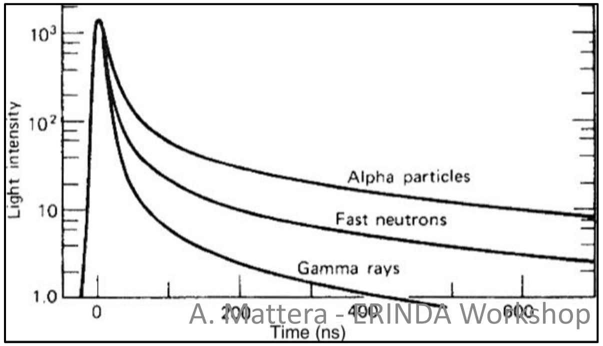
T D C

TRIGGER from scintillator

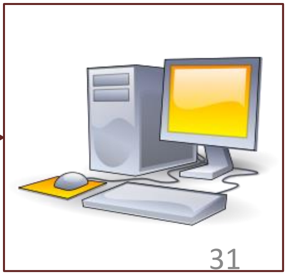
ToF STOP from RF

Pulse Shape information

THE PSD MODULE CONVERTS DIFFERENT PULSE SHAPES (n/γ) IN DIFFERENT DELAYS FROM A SET T_0



TIME-TO-DIGITAL CONVERSION



TOF Statistical Uncertainties

Source of uncertainty	% uncertainty @ 1.3 m		% uncertainty @ 4.9 m	
	30 MeV	5 MeV	30 MeV	5 MeV
Beam spread (≈ 3 ns)	**35.0 %**	**14.3 %**	**9.3 %**	**3.8 %**
TDC sampling time (25 ps)	0.3 %	0.1 %	0.1 %	< 0.1 %
Detector positioning (≈ 0.5 cm)	0.8 %	0.8 %	0.2 %	0.2 %
Detector thickness (6 cm)	**9.2 %**	**9.2 %**	**2.5 %**	**2.5 %**
TOTAL	**36.2 %**	**17.0 %**	**9.6 %**	**4.5 %**

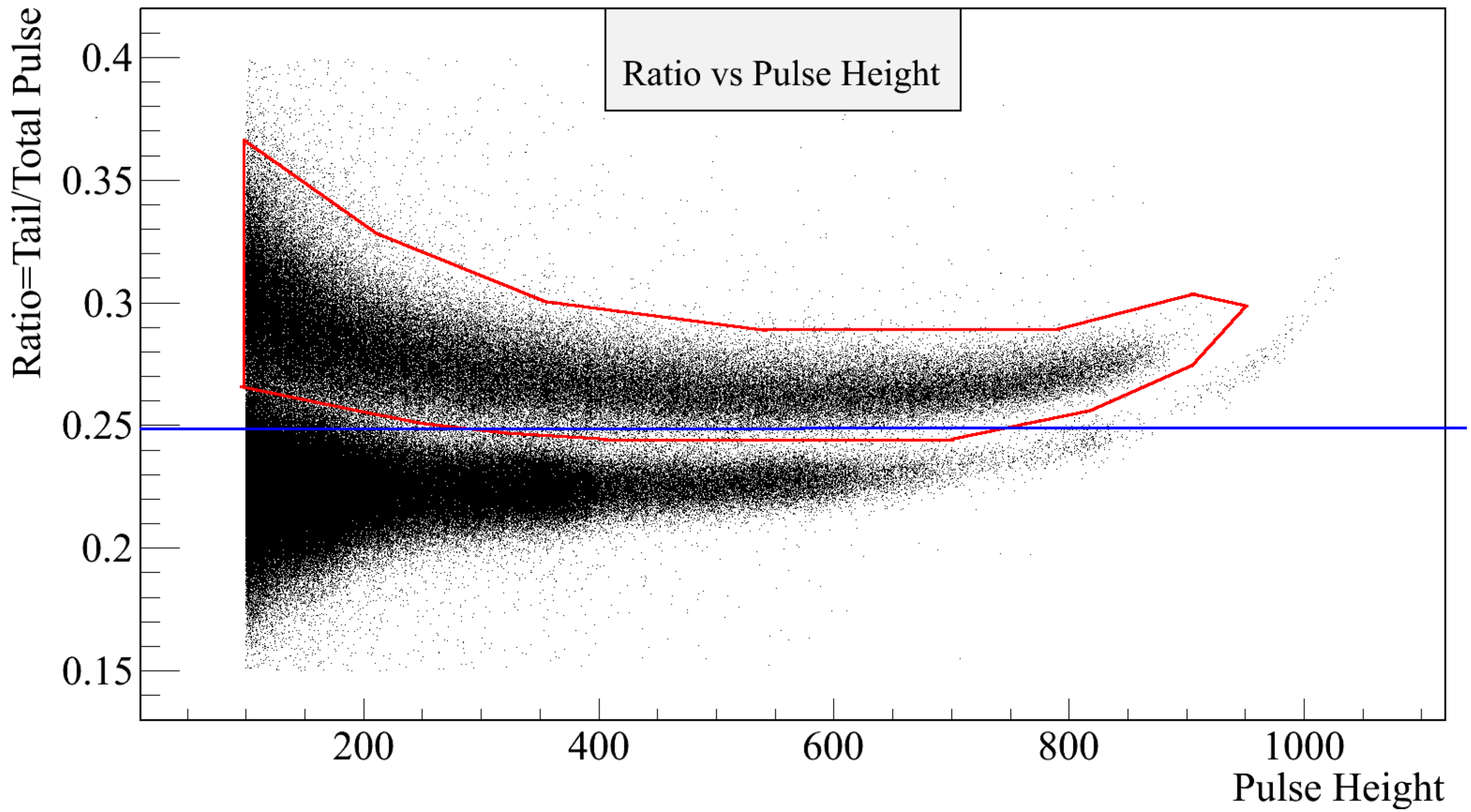
TOF Statistical Uncertainties

UPPSALA UNIVERSITET

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Source of uncertainty	% uncertainty @ 1.3 m		% uncertainty @ 4.9 m	
	30 MeV	5 MeV	30 MeV	5 MeV
Beam spread (≈ 1.5 ns)	**17.5 %**	**7.1 %**	**4.6 %**	**1.9 %**
TDC sampling time (25 ps)	0.3 %	0.1 %	0.1 %	< 0.1 %
Detector positioning (≈ 0.5 cm)	0.8 %	0.8 %	0.2 %	0.2 %
Detector thickness (6 cm)	**9.2 %**	**9.2 %**	**2.5 %**	**2.5 %**
TOTAL	**19.8 %**	**11.7 %**	**5.3 %**	**3.1 %**

Digital DAQ – PSD



Results

NO-cone configuration

Guess spectrum: Fluka after smooting (uncertainty-affected highly discontinuous structures disturb unfolding)

BSS input data: BSS counts normalized to monitor units (telescope)

Spheres used (diameter in in.):

2, 2.5, 3, 3.5, 4, 4.5, 5, 7, 8, 10, 12+1cmPb, 7+1cmPb, 7+1cmCu

Central detector: 6LiI(Eu) 4 mm x 4 mm. Neutron/gamma discrimination operated on the basis of the pulse height spectrum

Uncertainties considered:

3% beam+monitoring stability (repeated exp. with same sphere)

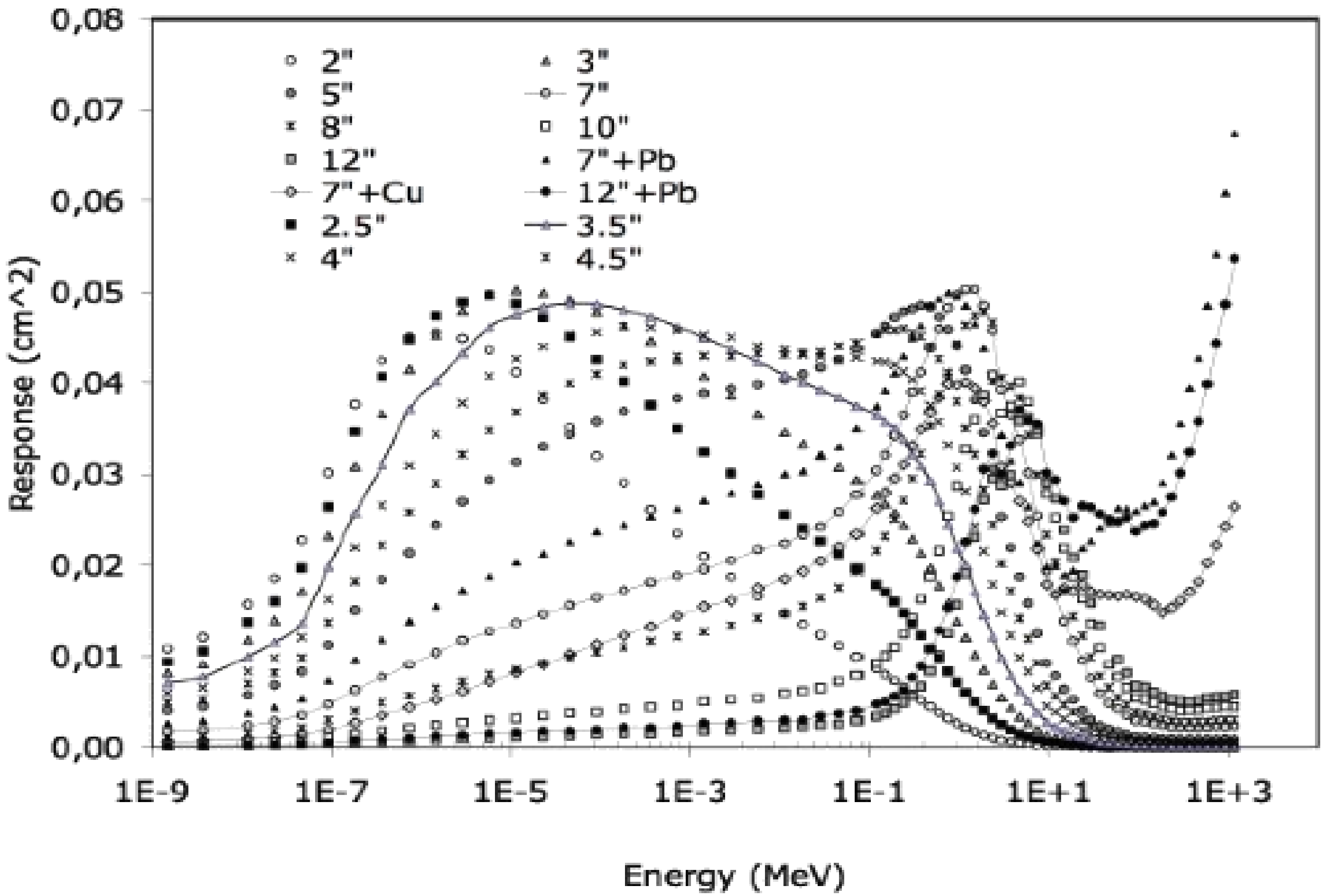
3% overall unc on BSS response matrix

<1% BSS counting statistics

2% unc on BSS calibration (periodically repeated at LNF)

Code used: FRUIT-SGM

Typical response function for spheres of different diameter



Unfolding 30 MeV Be(p,n) data with BSS

Guess spectrum: Fluka (Mattias) after smooting (uncertainty-affected highly discontinuous structures disturb unfolding)

BSS input data: BSS counts normalized to monitor units (telescope)

Spheres used (diameter in in.):

2, 2.5, 3, 3.5, 4, 4.5, 5, 7, 8, 10, 12+1cmPb, 7+1cmPb, 7+1cmCu

Central detector: 6LiI(Eu) 4 mm x 4 mm. Neutron/gamma discrimination operated on the basis of the pulse height spectrum

Uncertainties considered:

3% beam+monitoring stability (repeated exp. with same sphere)

3% overall unc on BSS response matrix

<1% BSS counting statistics

2% unc on BSS calibration (periodically repeated at LNF)

Code used: FRUIT-SGM

Integral values

Total fluence **3.16 cm-2 MU-1 ± 3.2%**

Fluence Fractions (errors below 10%)

> 0.4 eV	**18.3%**
0.4 eV – 10 keV	**24.1%**
> 10 keV	**57.6%**

Integral values

	TOTAL	MODERATED
Total fluence(cm-2 MU-1)	3.16 (± 3.2%)	2.65 (± 3.0%)
Fluence Fractions (errors below 10%)		
E> 0.4 eV	18.3%	21.8%
0.4 eV – 10 keV	24.1%	38.4%
E> 10 keV	57.6%	39.8%

Note: the impact of polyethylene is an attenuation of the high-E component, whilst the epithermal and thermal ones remain constant because they basically come from the room (wall, floor, air scatter)

Integral values

Total fluence 3.16 cm-2 MU-1 ± 3.2%

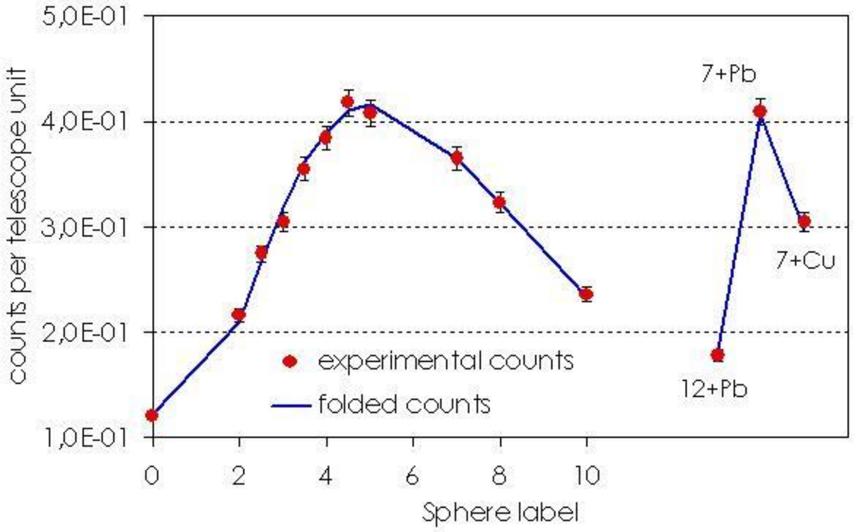
Fluence Fractions (errors below 10%)

> 0.4 eV	**18.3%**
0.4 eV – 10 keV	**24.1%**
> 10 keV	**57.6%**

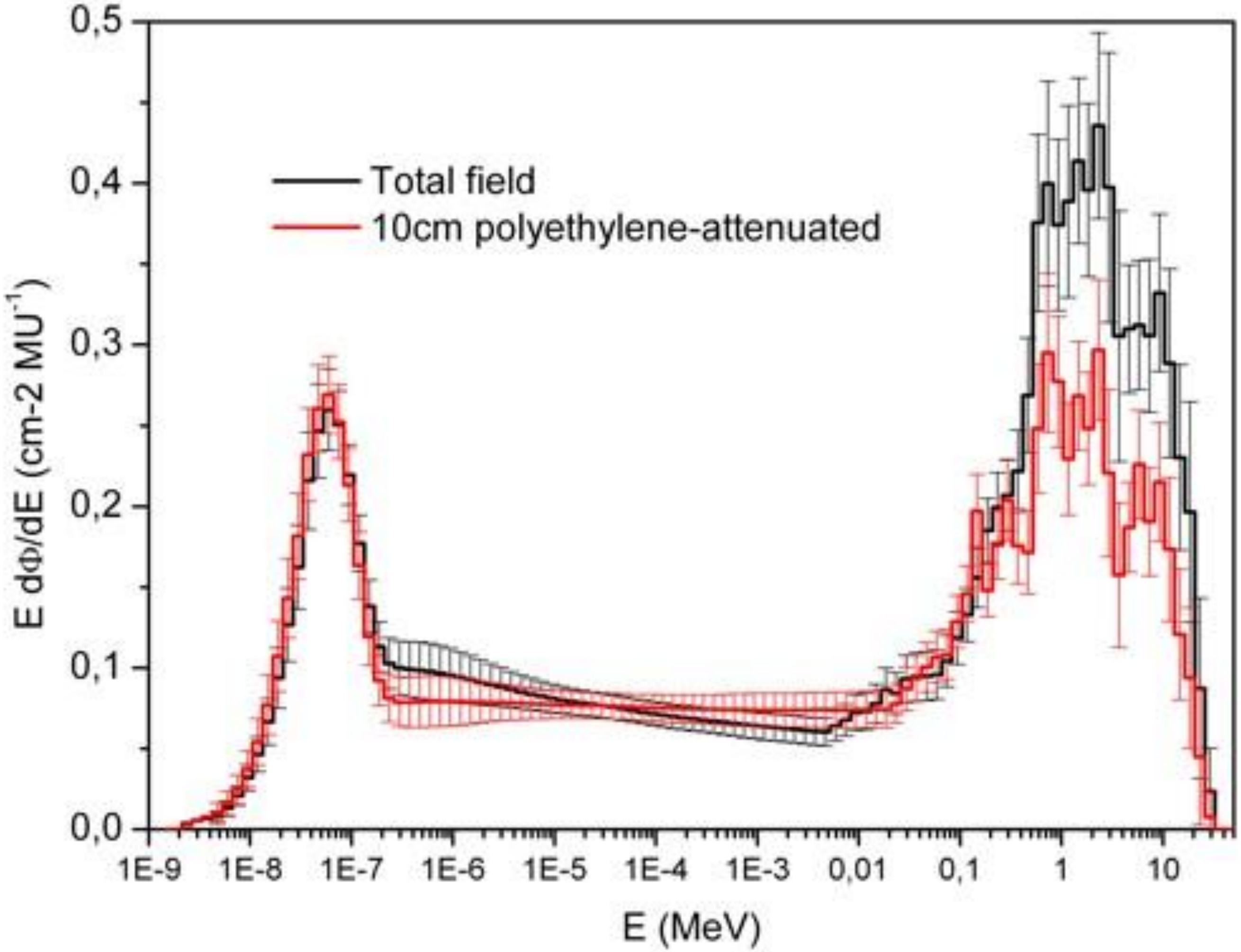
Does the unfolding respect the input BSS data?

Note: “Folded counts” means calculated by folding the BSS theoretical response matrix (Energy dependent, previously determined with MCNPX) with the unfolded spectrum.

Good agreement means the results of unfolding process respected the experimental data.



Neutron spectrum (in lethargy representation)

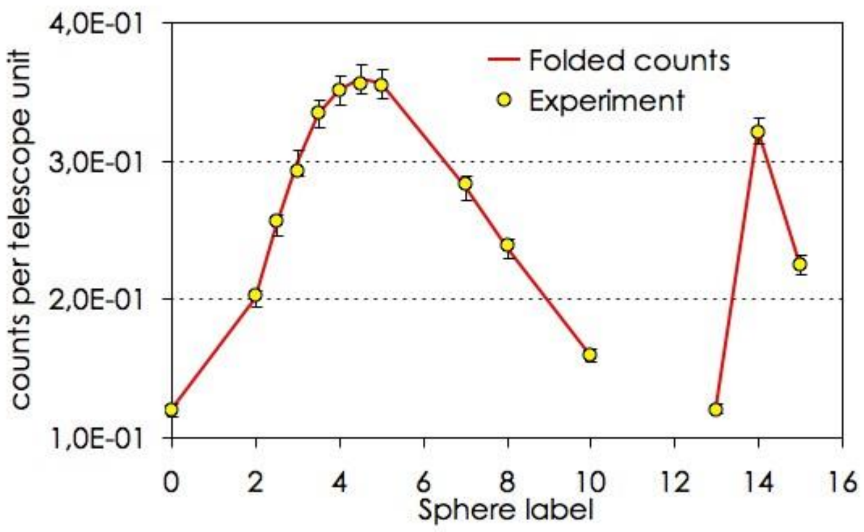


Does the unfolding respect the input BSS data?

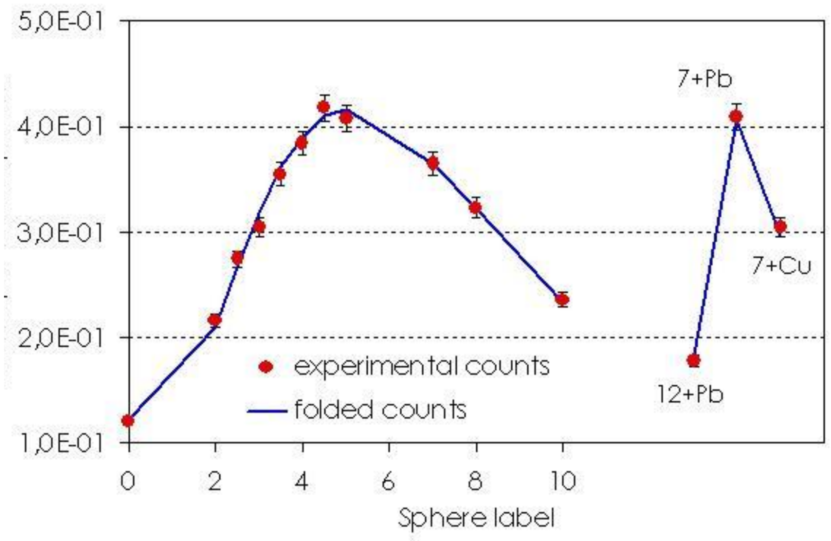
Note: “Folded counts” means calculated by folding the BSS theoretical response matrix (Energy dependent, previously determined with MCNPX) with the unfolded spectrum.

Good agreement means the results of unfolding process respected the experimental data.

Moderated field



Total field



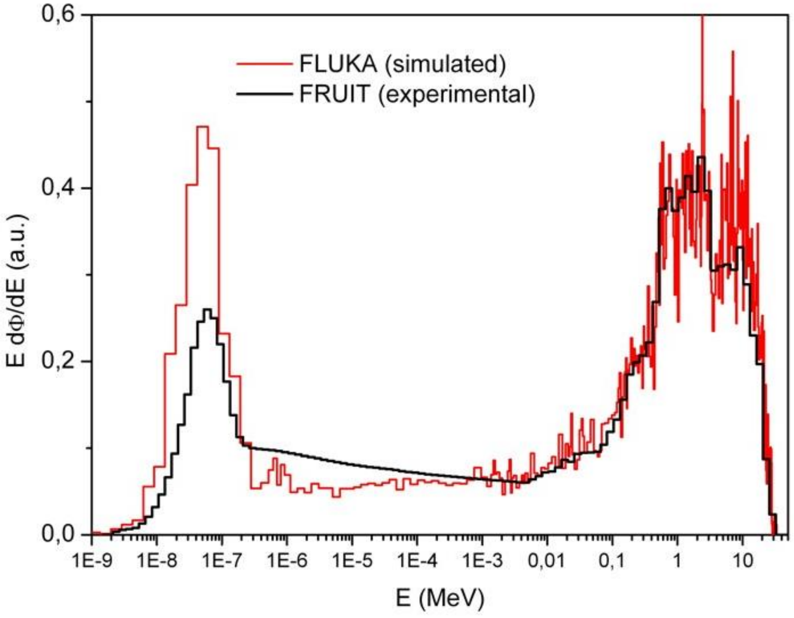
Focusing on the high-E part

(thermal and epithermal is very room-dependent, so difficult to predict correctly)

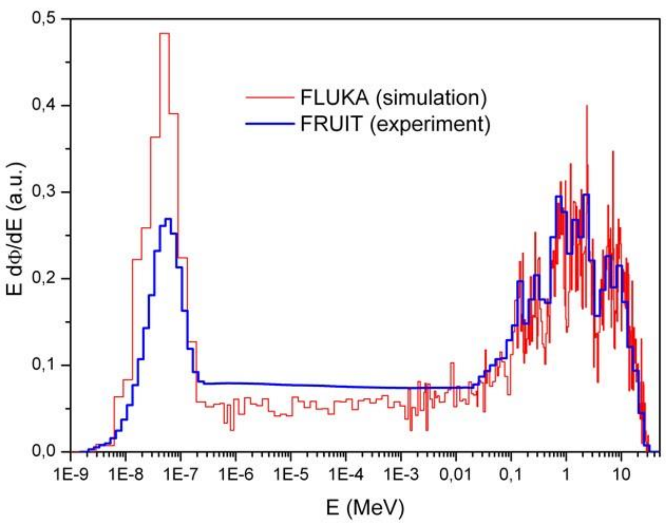
(In absence of absolute calibration of p+ beam, the simulation was rescaled to allow comparison)

It seems the relevant structures (E>0.01 MeV) predicted by Fluka simulations are well preserved in the final spectrum.

So as a conclusion: Both BSS experimental data and FLUKA simulations are respected in the final results.



Total field



moderated field

Unfolding results in NO-cone configuration

Guess spectrum: Fluka (Mattias) after smooting (uncertainty-affected highly discontinuous structures disturb unfolding)

BSS input data: BSS counts normalized to monitor units (telescope)

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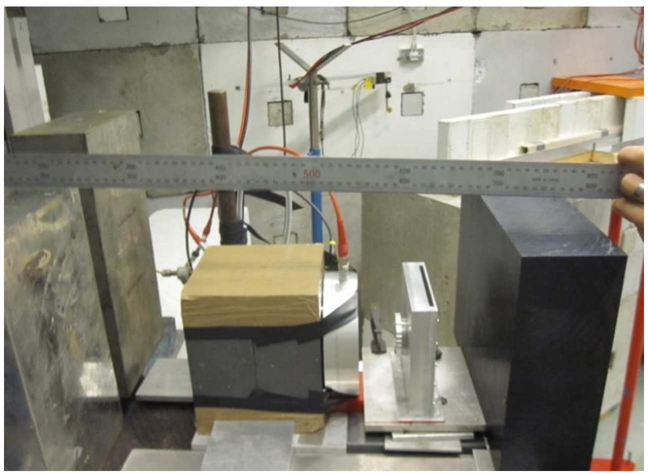
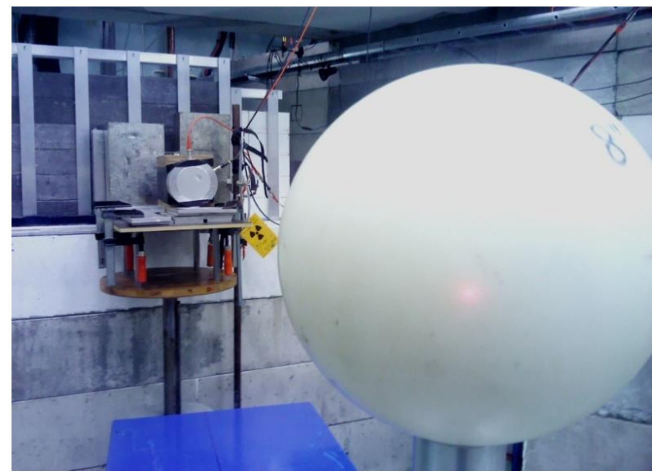
Code used: FRUIT-SGM

Measurement of Be(p,n) n spectra with an extended range Bonner Sphere Spectrometer (BSS)

BSS was used to measure neutron spectra obtained from:

- the target + 10 cm polyethylene moderator
(moderated spectrum)
total field condition





The Bonner Sphere Spectrometer (BSS) covers the energy range from thermal to 30 MeV neutrons and uses a ^{6}LiI(Eu) scintillator as thermal neutron detector.