Training Course:
Neutron dosimetry, radiobiology and instrumentation

Moderator-type neutron detectors

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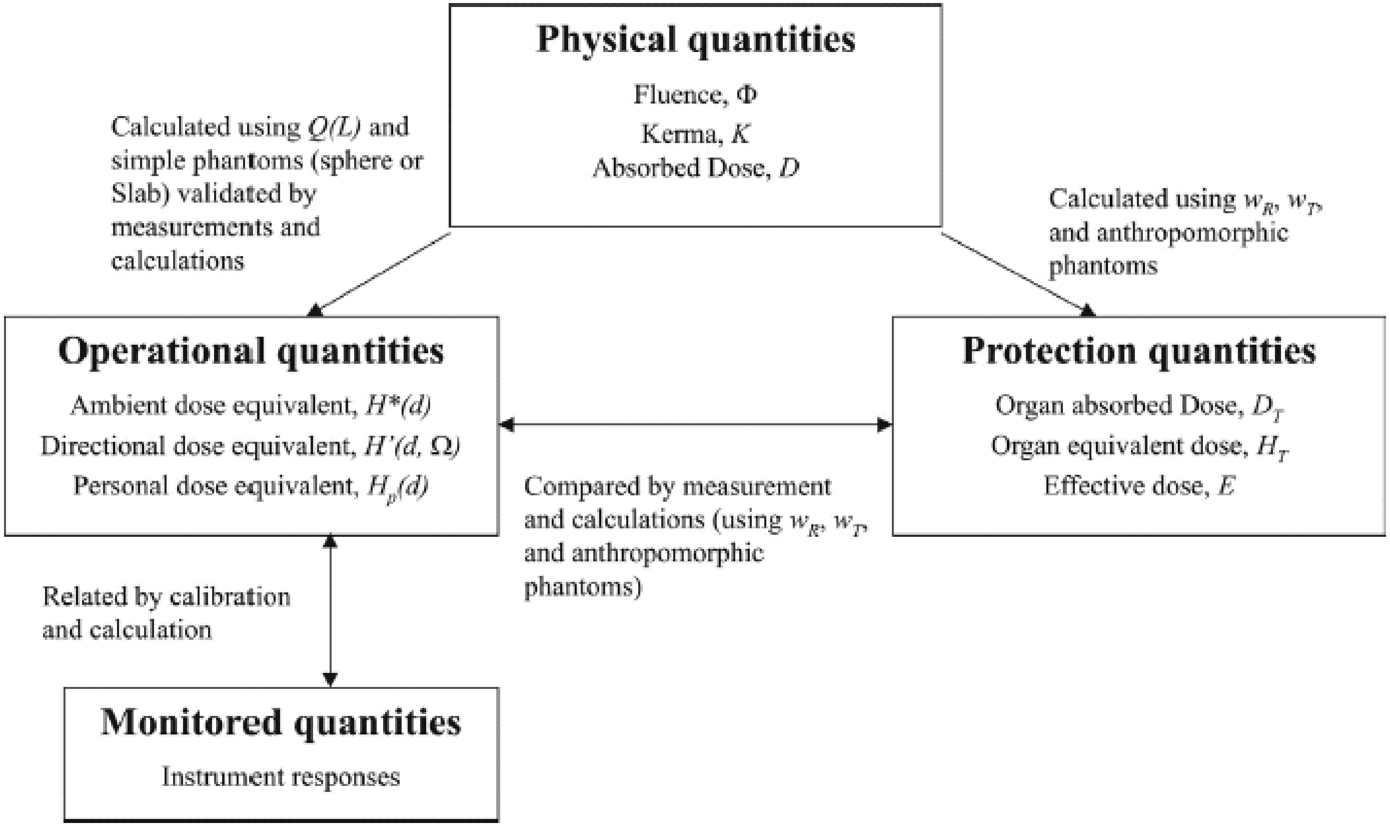
Physical, operational and protection quantities

Relationships of quantities for radiological protection monitoring purposes (ICRP 74)



Physical quantities

Fluence, Φ

Kerma, K

Absorbed Dose, D

Calculated using $Q(L)$ and simple phantoms (sphere or Slab) validated by measurements and calculations

Calculated using w_R, w_T, and anthropomorphic phantoms

Operational quantities

Ambient dose equivalent, $H^*(d)$

Directional dose equivalent, $H'(d, \Omega)$

Personal dose equivalent, $H_p(d)$

Protection quantities

Organ absorbed Dose, D_T

Organ equivalent dose, H_T

Effective dose, E

Compared by measurement and calculations (using w_R, w_T, and anthropomorphic phantoms)

Related by calibration and calculation

Monitored quantities

Instrument responses

Main challenges for instrumentation

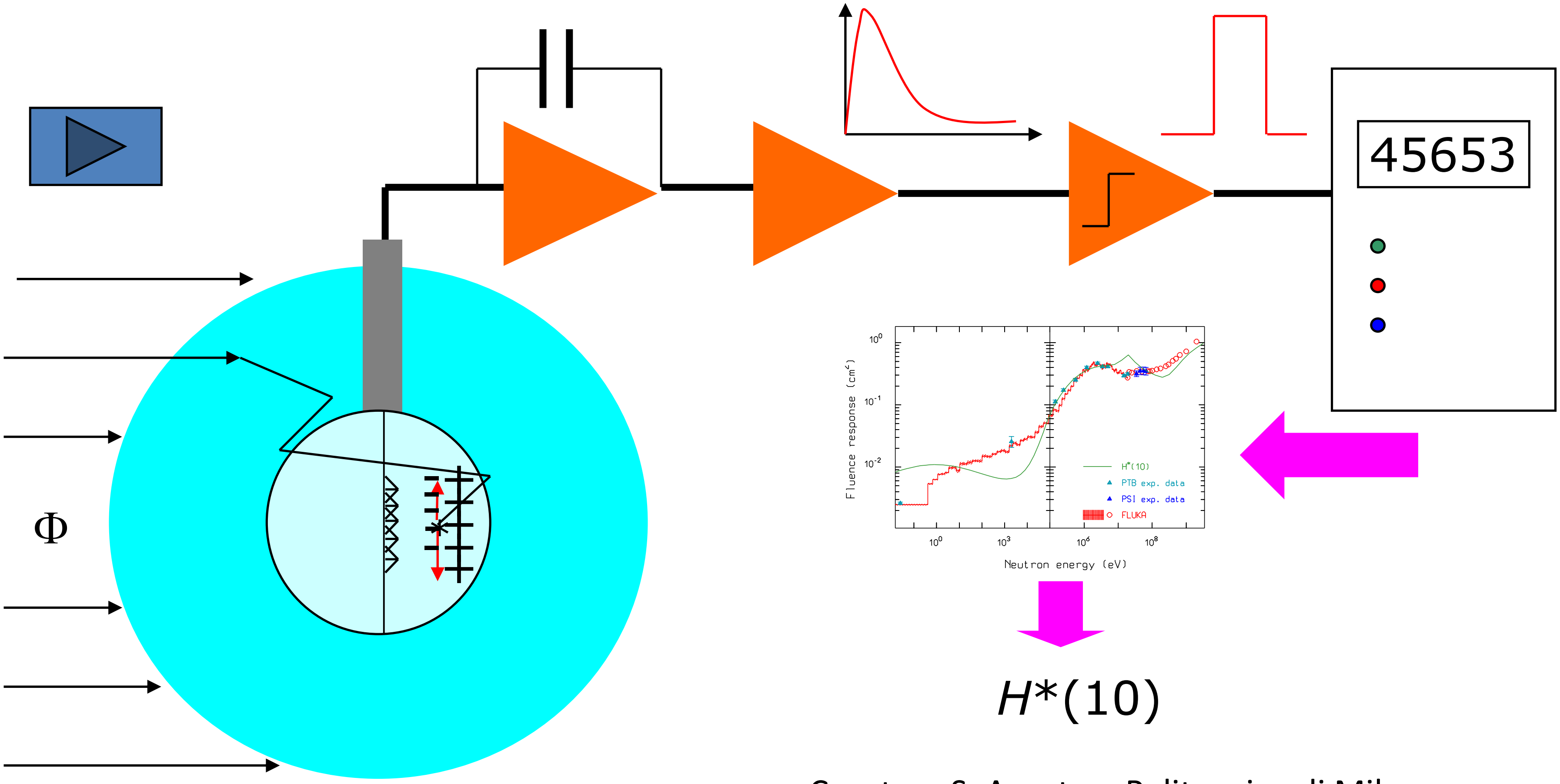
- Distinguish the various components (and their relative importance) of the mixed field
- Have a response function that approximately follows H*(10)
- Measure correctly neutrons with $E_n > 10$ MeV
- Sometimes operate in a (strongly) pulsed radiation field
- Measure ambient dose equivalent rates in the range from a few hundreds of µSv per year to a few mSv per year

Instrument response

- The response of the device can be determined with *Monte Carlo simulations* and:
- with a *proper* calibration with reference (quasi-) monoenergetic radiation sources
- in the radiation field of interest (a ‘field calibration’)
- in an experimental radiation field of sufficiently similar characteristics (a ‘simulated workplace field’)

Measurements

Since the RP quantities are not directly measurable, their estimate involves the measurement of a physical quantity.



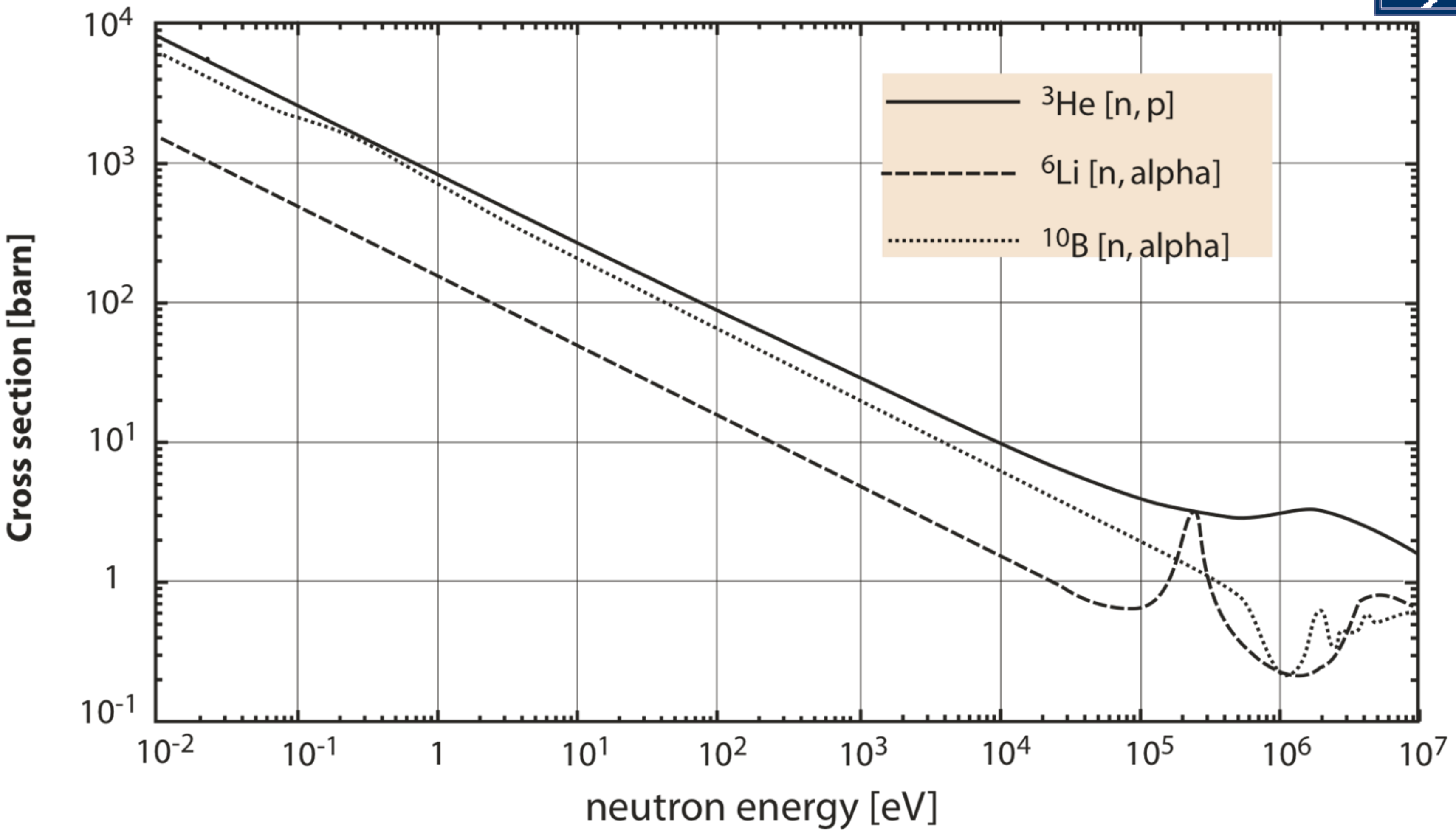
Courtesy S. Agosteo, Politecnico di Milano

Slow neutron detection

Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection

1) Boron	$^{10}B + n \rightarrow {}^{7}Li + \alpha$ $^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$	Q = 2.793 MeV Q = 2.310 MeV
2) Lithium	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	Q = 4.78 MeV
3) ^{3}He	$^{3}He + n \rightarrow {}^{3}H + p$	Q = 764 keV

Neutron cross sections



Mean free path of thermal neutrons

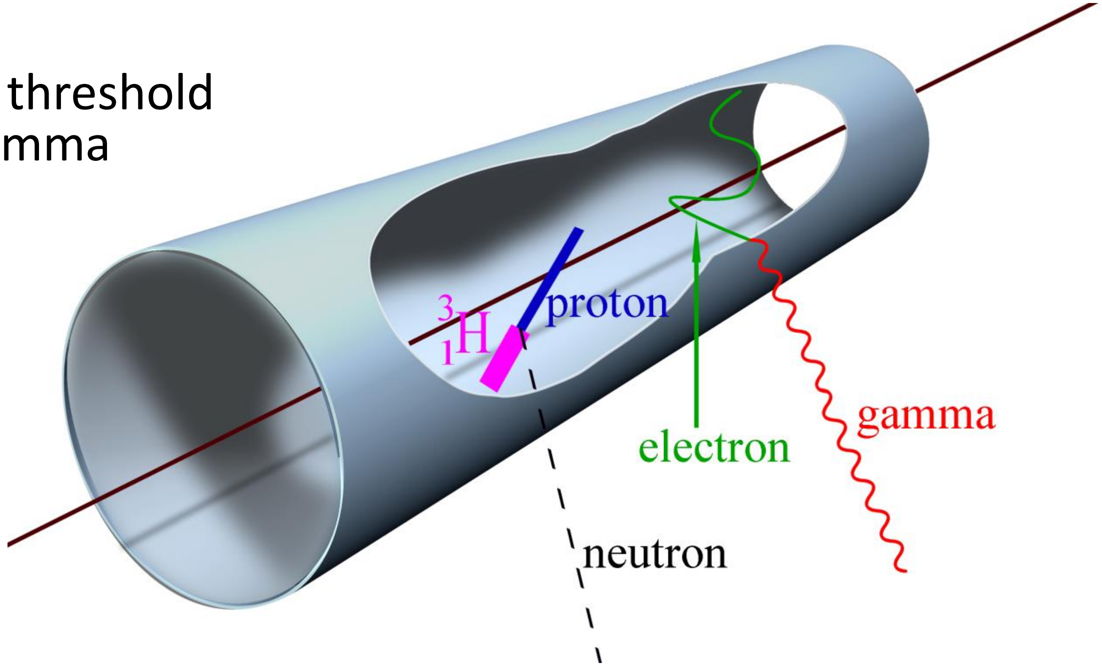
- in ^{3}He gas ≈ 7 cm
- in solid ^{10}B ≈ 70 µm

Proportional counters as slow neutron detectors

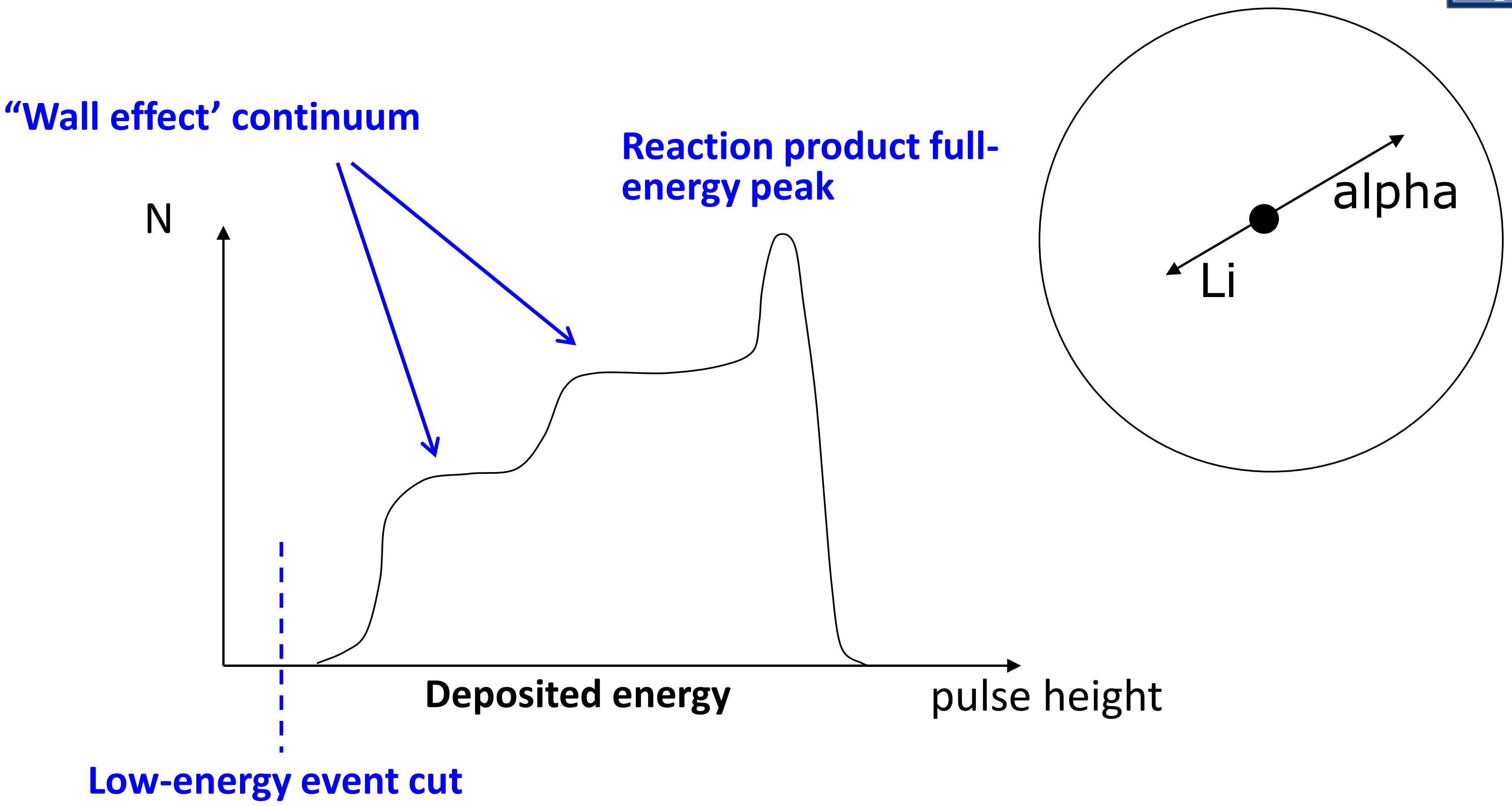
BF_3 gas and ^{3}He gas make detectors for slow neutrons with excellent gamma discrimination

Gamma rays can interact in the walls and produce electrons in the gas, but the energy loss of electrons is small (≈ 2 keV/cm), so that these pulses are much smaller than those due to neutrons

A suitable pulse amplitude threshold can thus eliminate most gamma interactions.



Pulse height spectrum from BF_3 tube



The shape of the pulse height spectrum is due to the energy loss of the recoils in the gas

^{3}He vs BF$_3$ proportional counters

BF$_3$ (cylindrical, 25 mm diameter x 150 mm length)

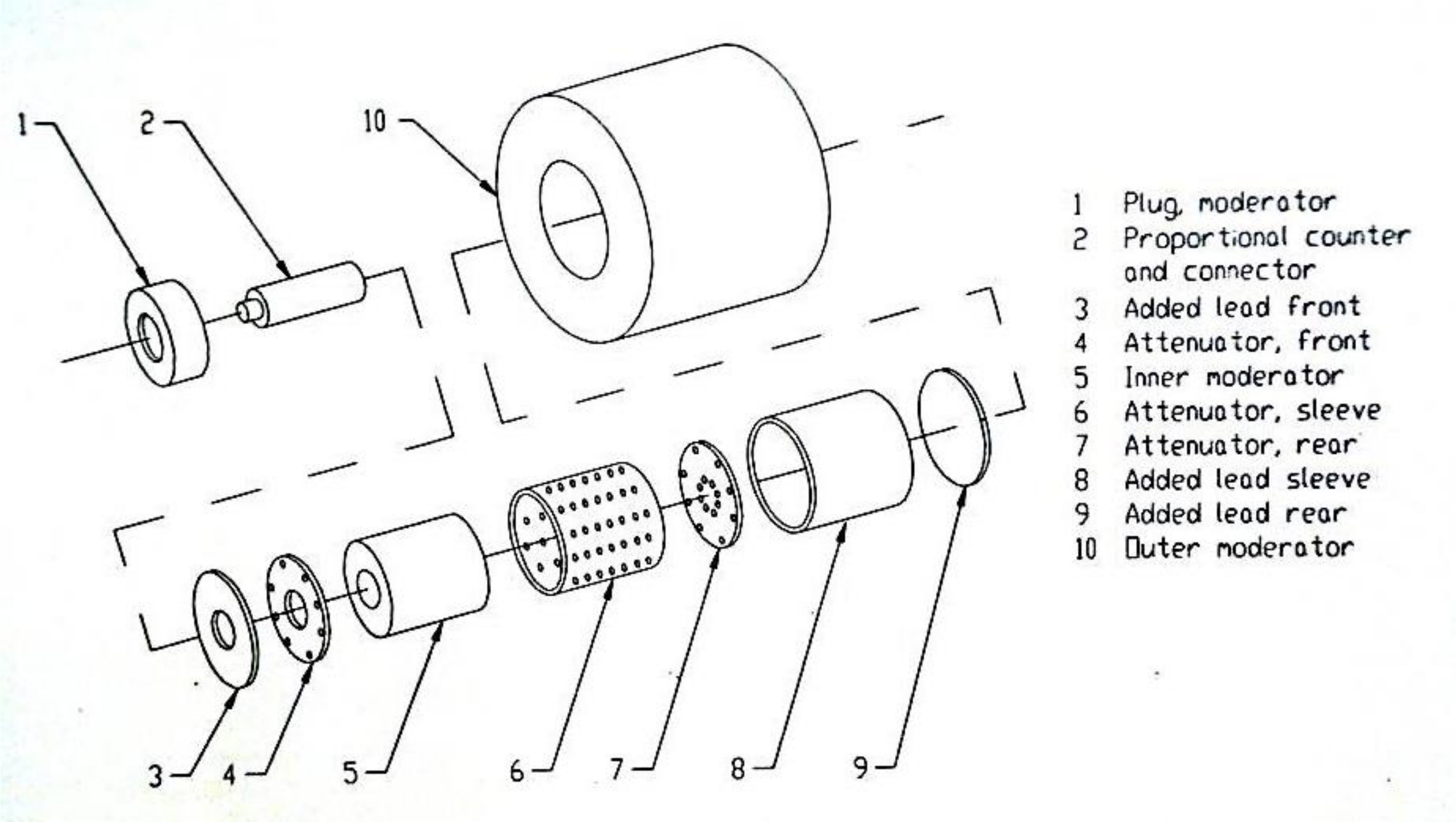
- Higher Q-value of the $^{10}B(n,\alpha)^{7}Li$ reaction w.r.t. the $^{3}He(n,p)^{3}H$ → better photon rejection
- Reduced space charge effects, due to the larger active volume w.r.t. ^{3}He
- Toxic and corrosive

^{3}He (spherical, 31 mm diameter)

- Isotropic response vs non-isotropic (±20% variation in the calibration factor for cylindrical BF$_3$ due to geometry)
- Higher sensitivity
- Harmless but expensive

(Extended range) Rem counter

Exploded view of the original SNOOPY-modified rem counter **L**ong **I**nterval **N**e**U**tron **S**urvey-meter, LINUS



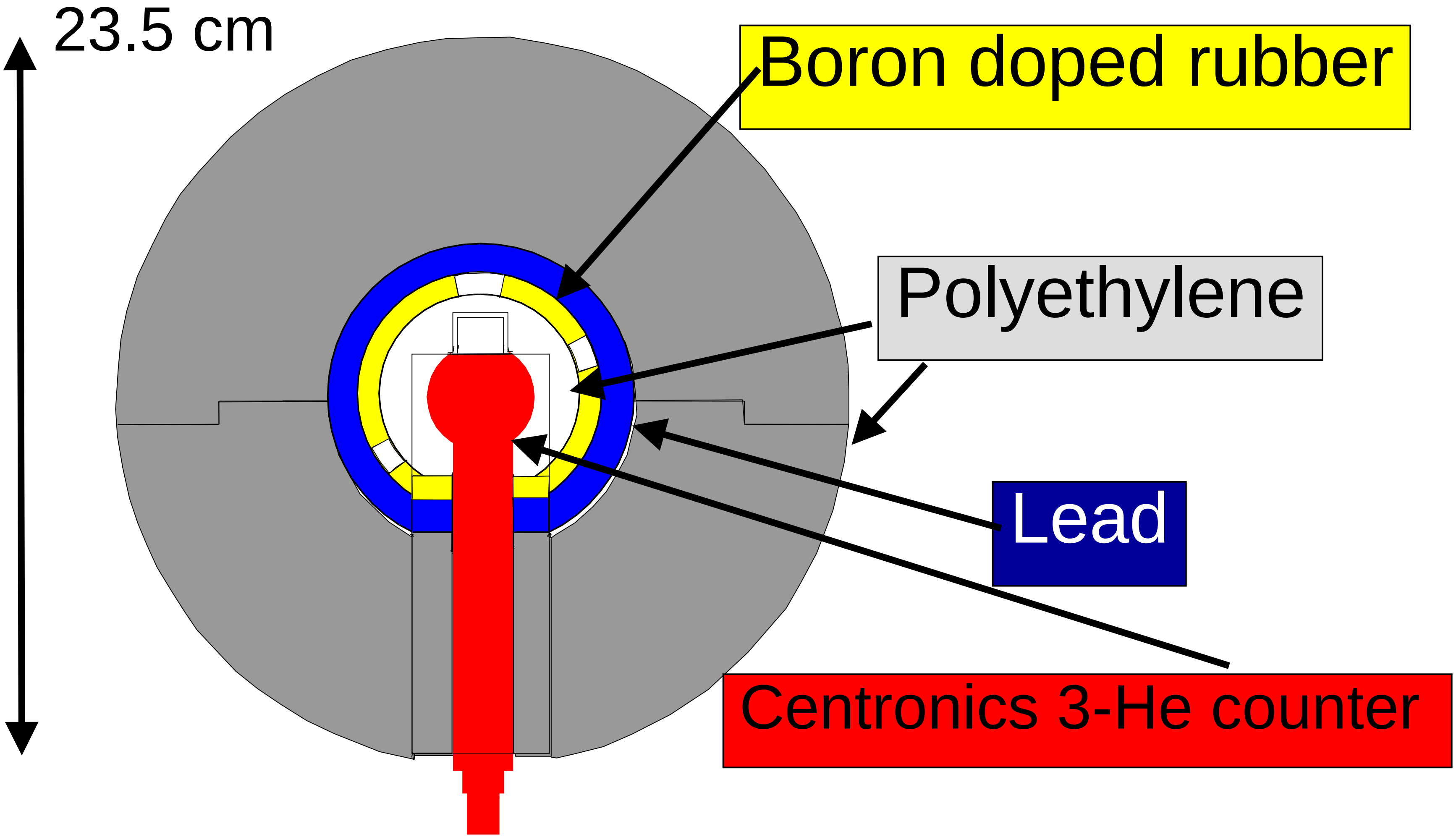
1 Plug, moderator
2 Proportional counter and connector
3 Added lead front
4 Attenuator, front
5 Inner moderator
6 Attenuator, sleeve
7 Attenuator, rear
8 Added lead sleeve
9 Added lead rear
10 Outer moderator

Exploded view of the LINUS detector

C. Birattari, A. Ferrari, C. Nuccetelli, M. Pelliccioni, M. Silari, NIM A 297 (1990) 250-257

(Extended range) Rem counter

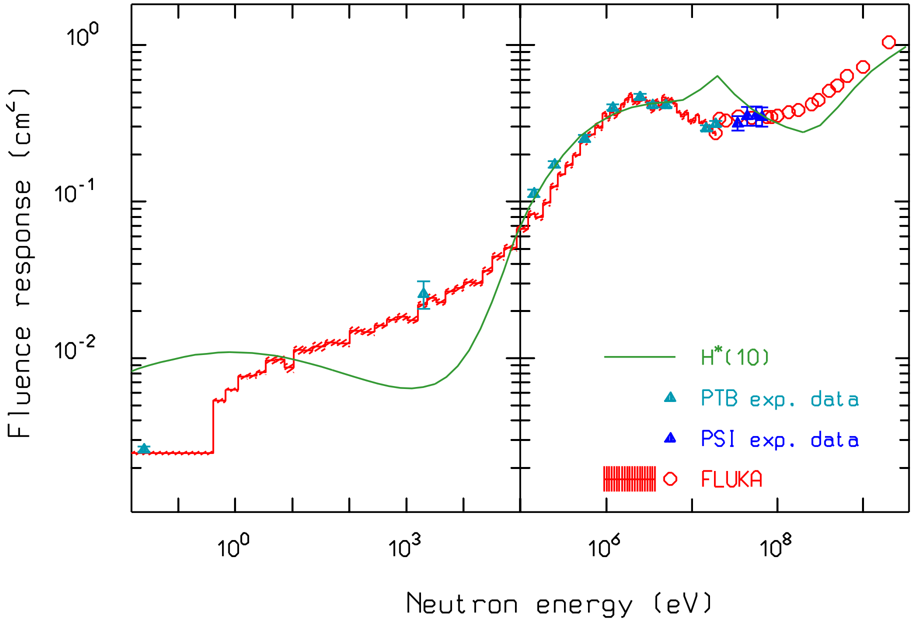
Spherical LINUS



(Extended range) Rem counter

LINUS (extended range)

Long **I**nterval **N**e**U**tron **S**urvey meter

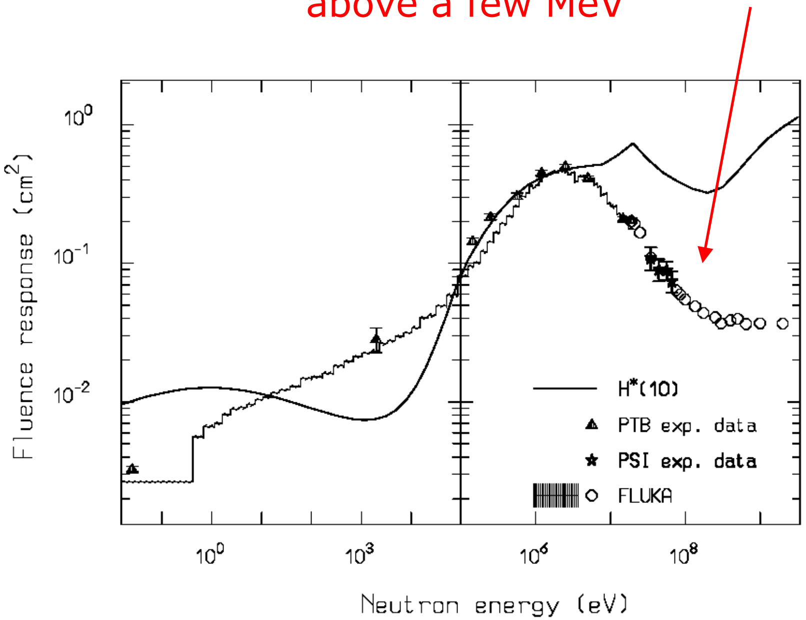


$$M = C\int R_\Phi(E)\,\Phi(E)\,dE$$

Birattari, Esposito, Ferrari, Pelliccioni, Silari, NIM A324 (1993) 232-238

Birattari, Esposito, Ferrari, Pelliccioni, Rancati, Silari, RPD 76 (1998) 135-148

Heavily underestimated above a few MeV

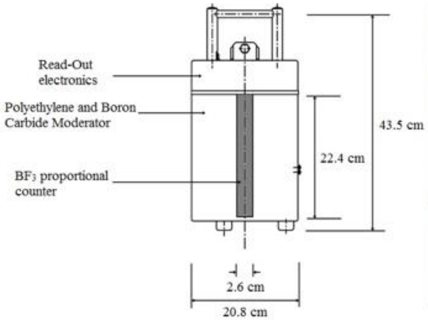


SNOOPY (conventional unit)

Rem counters

- **Conventional rem counter**

BIOREM (good sensitivity up to 20 MeV)

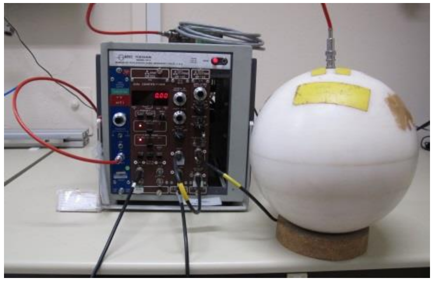


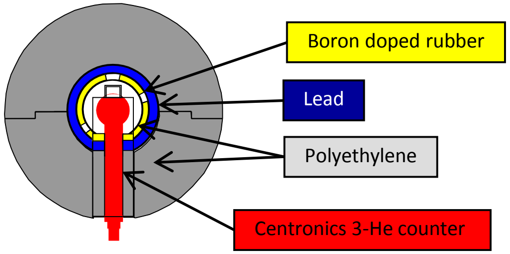
- **Extended range rem counters**

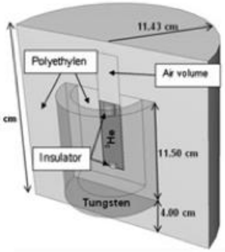
(good sensitivity up to 5 GeV)

LINUS

Wendi-2

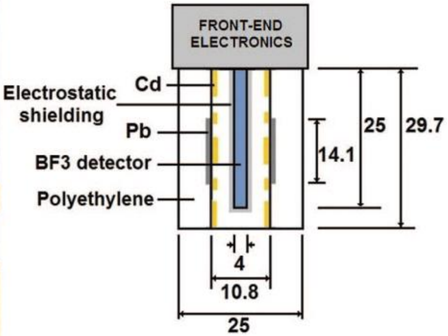






- **Rem counter for pulsed fields**

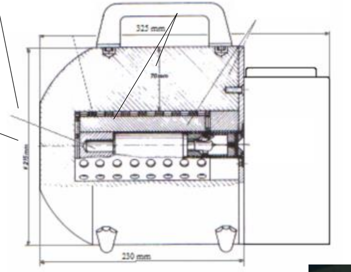
LUPIN, BF_3 version

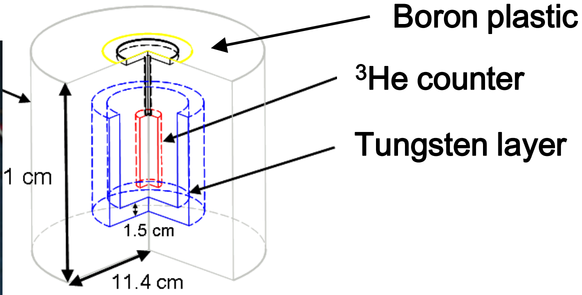


Commercial rem counters

Fuji Electric NSN10014

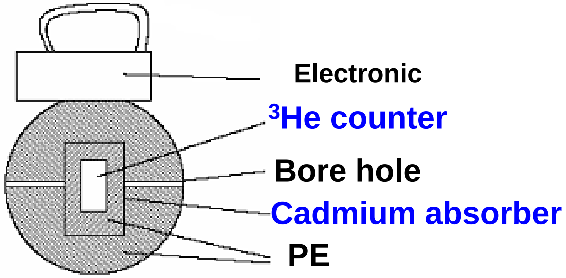
Studsvik 2202D

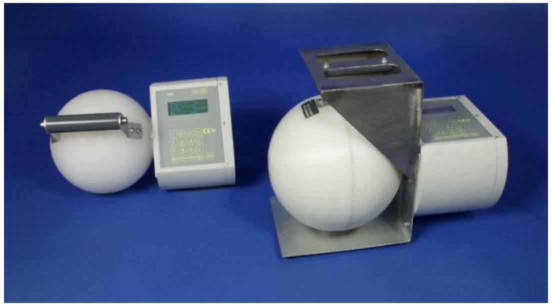




Eberline WENDI-2

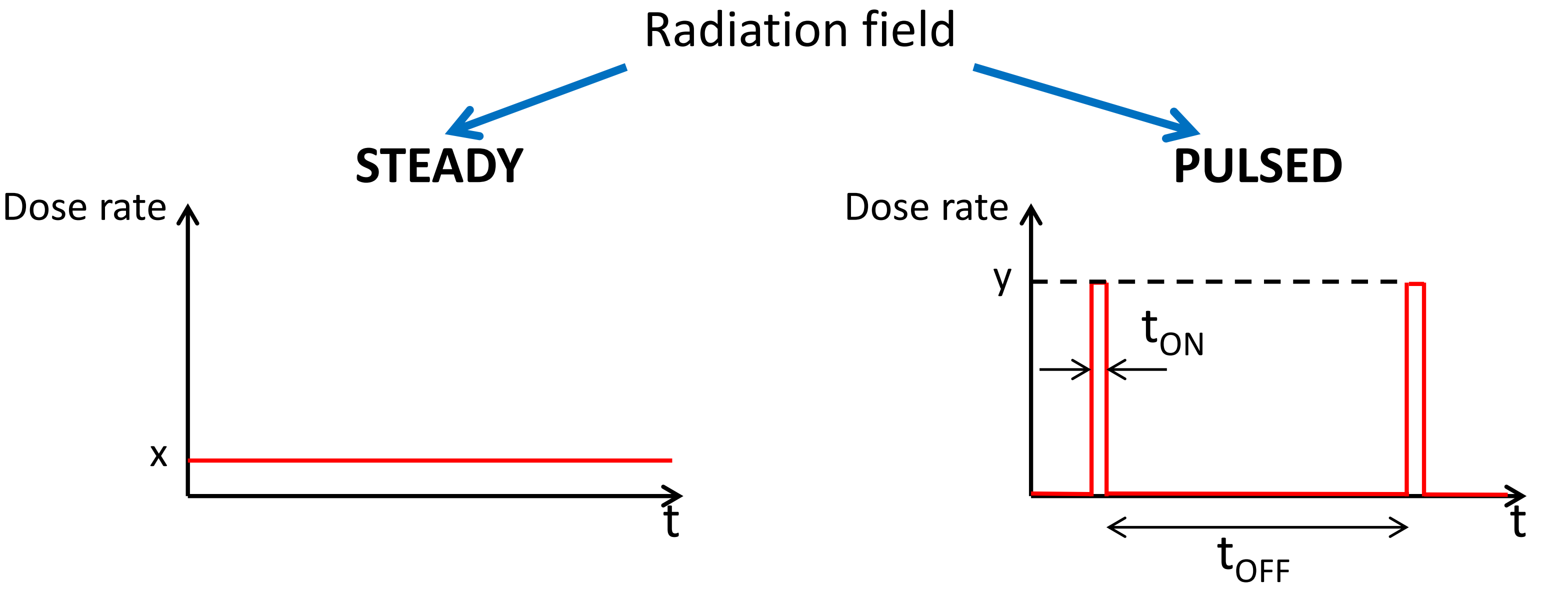
Berthold LB6411 (also LB6411Pb)





MAB SNM500(X)

Measurements in a pulsed neutron field



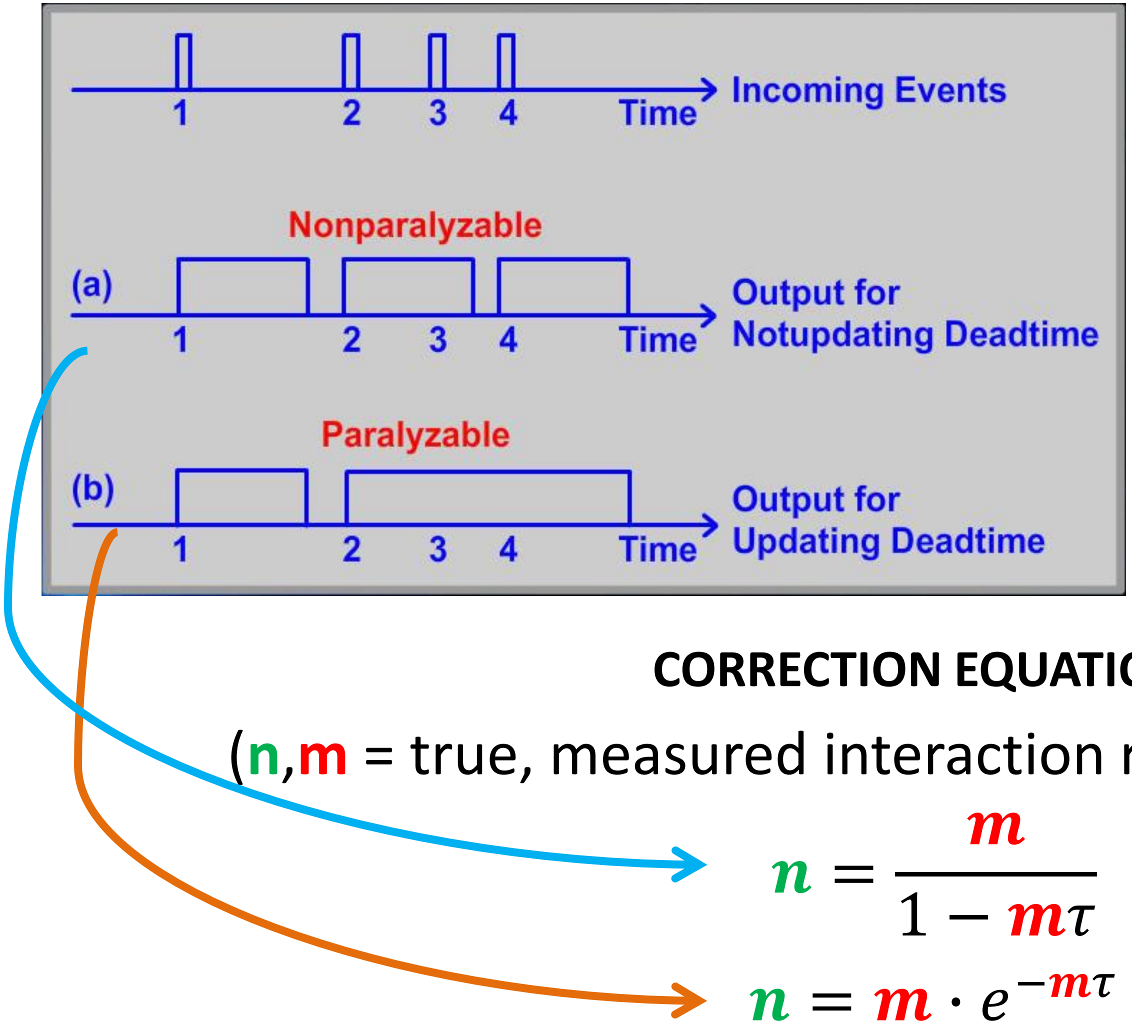
Same **averaged** dose rate but different **instantaneous** dose rates

$$x = y \cdot \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

DUTY FACTOR

Small DUTY FACTORS (=> high instantaneous dose rates) impose severe limitations on the survey meters to be employed

Detector dead time



Fundamental property for a detector working in pulsed fields

Two response models

Typical values

GM: τ = 100 μs

Rem counter: τ = 1-10 μs

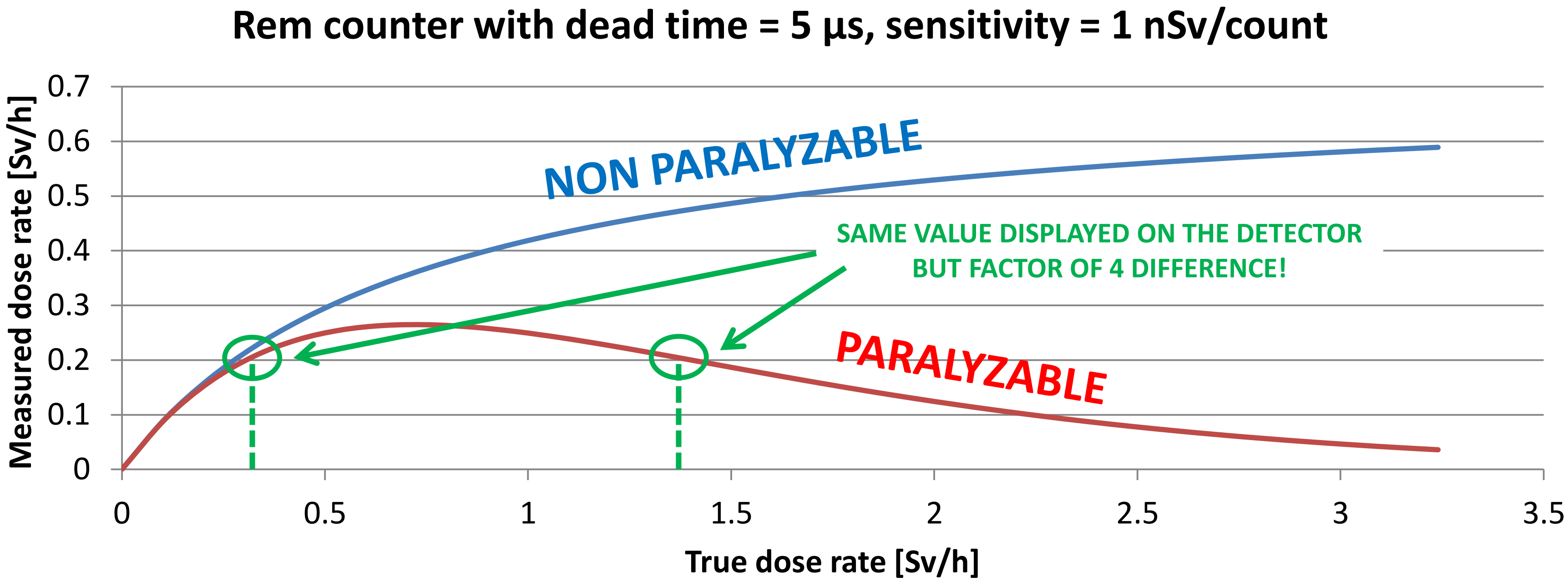
CORRECTION EQUATIONS

(**n**,**m** = true, measured interaction rate; τ = dead time):

$$n = \frac{m}{1 - m\tau}$$

$$n = m \cdot e^{-m\tau}$$

Detector dead time

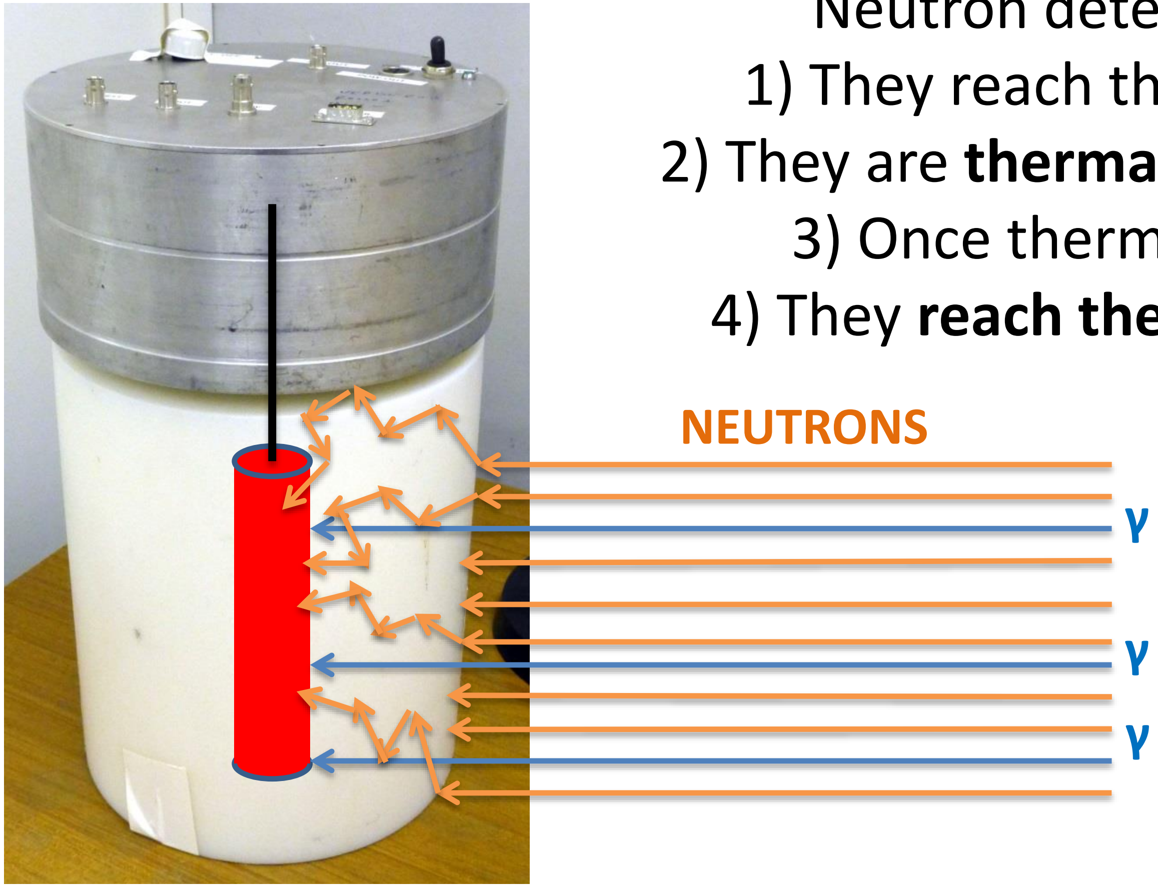


Correction equations work, but…

- Valid only for relatively <u>low dead time losses</u>
- Valid under the assumption that the interactions are <u>uniformly distributed</u> **(=> This is not the case, by definition, for pulsed fields)**

Neutron detection in pulsed neutron field

Detection of pulsed **neutron** fields shows an advantage, if compared to photons



Neutron detection mechanism:

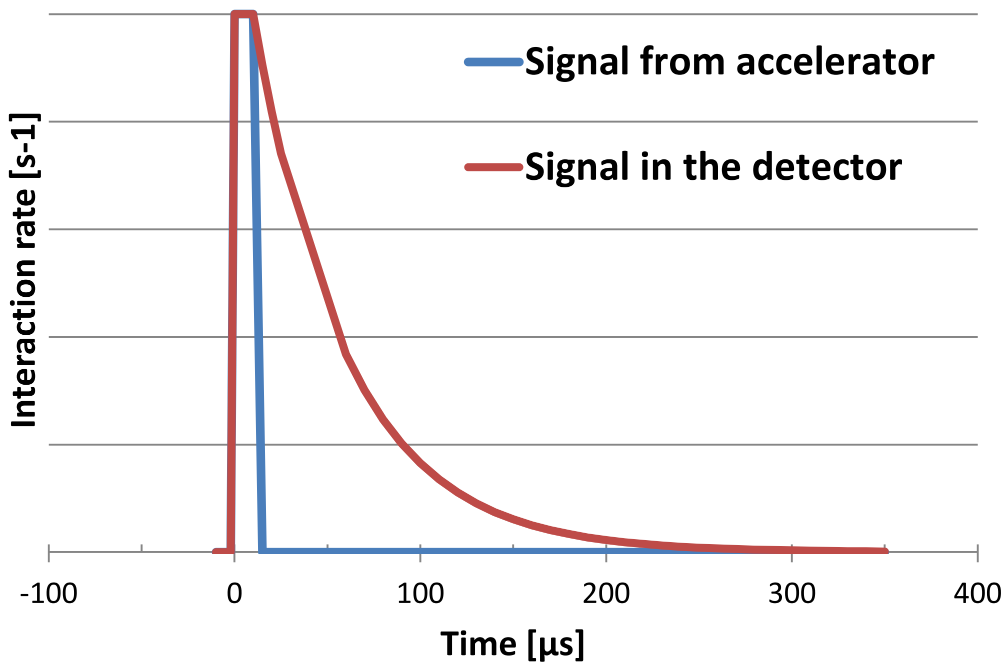
1) They reach the moderator surface
2) They are **thermalized** (scattering events)
3) Once thermalized they **diffuse**
4) They **reach the detector** (BF_3 or ^3He)

Photons do not need thermalization in order to be detected

Neutron diffusion and thermalization

Performances of detectors (rem counters) in pulsed neutron fields:

- **Dead time effects (↓)**
- **Neutrons thermalization and diffusion time (TDT) in the moderator (↑)**



Signal in the detector spread over several hundred µs, regardless of the original pulse width

↓

REDUCED UNDERESTIMATION

Neutron diffusion and thermalization

N(t) = number of thermalized neutrons that reach the gas at a time t:

$$N(t) = N_0 \cdot e^{-t/\tau'}$$

τ’ = decay constant of the neutrons in the moderator
(depends only on materials, size and shape of the moderator)

τ’ ≈ 140 µs for conventional spherical PE moderators (10-inch diameter sphere)

τ’ ≈ 70 µs for cylindrical PE moderators

enriched with Pb and Cd
(extended range detectors)

LUPIN rem counter

LUPIN: **L**ong interval, **U**ltra-wide dynamic, **PI**le-up free, **N**eutron rem counter

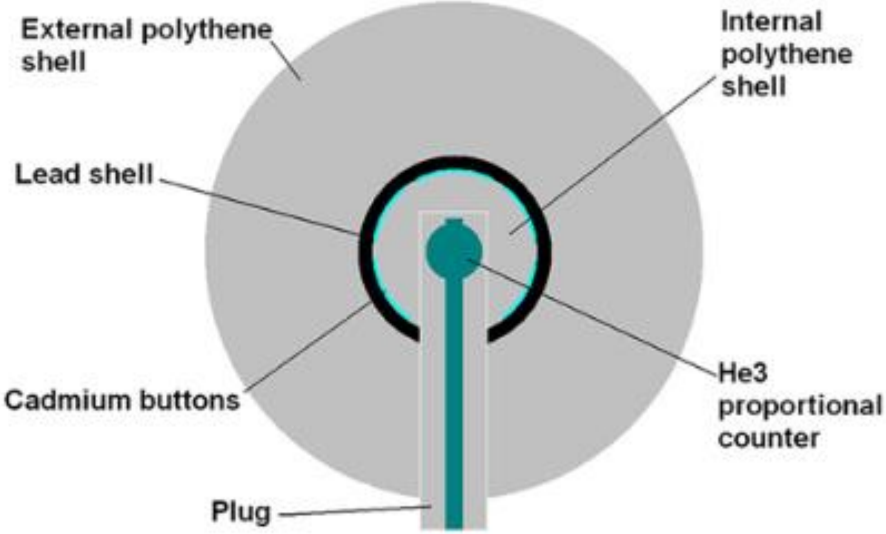
Proportional counter
^{3}He or BF_3

+

Moderator
(response function reproduces the curve of the **neutron fluence to H*(10)** conversion coefficients)

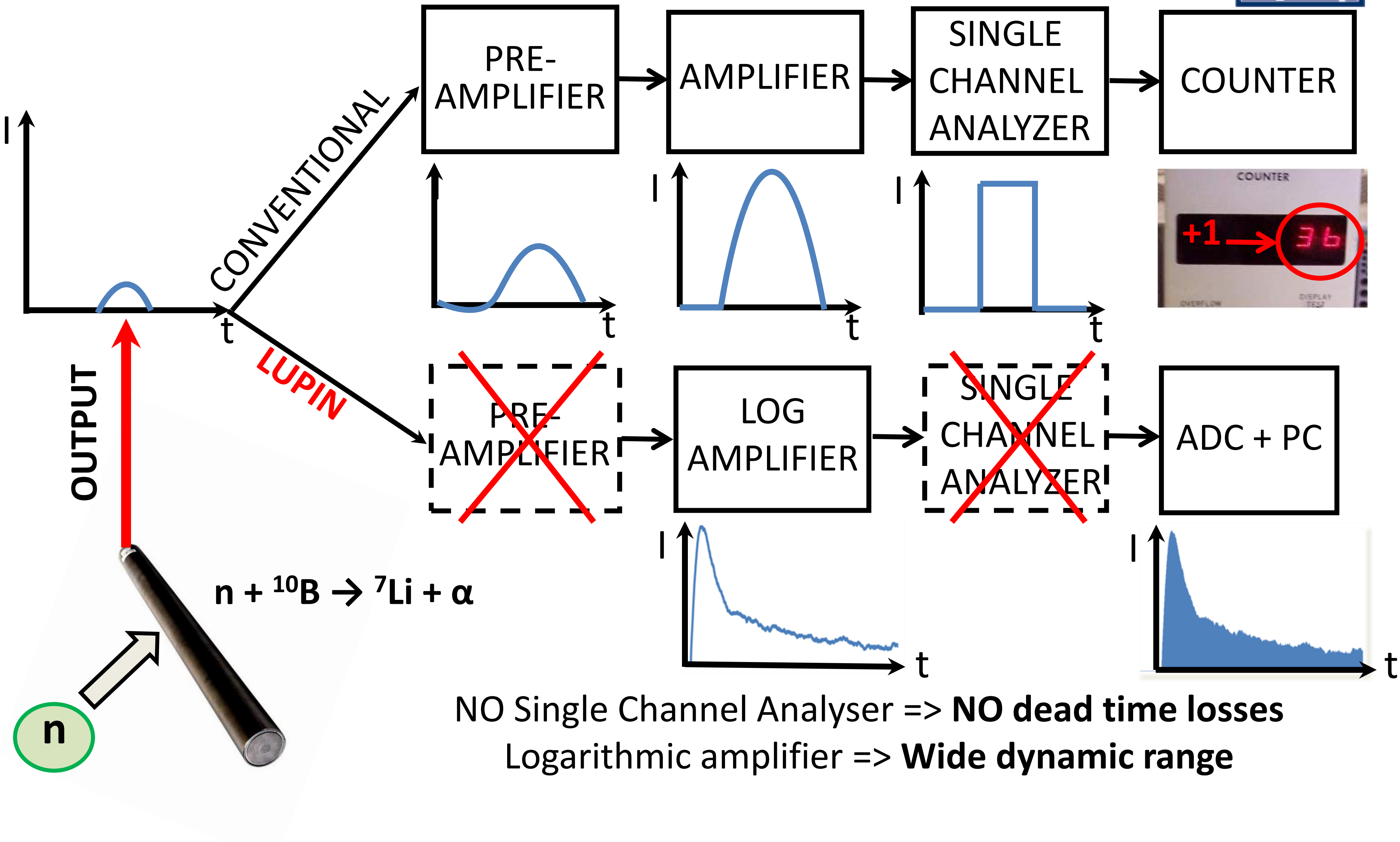
+

Innovative front end electronics



M. Caresana, M. Ferrarini, G.P. Manessi, M. Silari, V. Varoli, LUPIN, a new instrument for pulsed neutron fields, Nuclear Instruments and Methods in Physics Research Section A 712 (2013) 15-26

LUPIN operating principle



CONVENTIONAL

PRE-AMPLIFIER → AMPLIFIER → SINGLE CHANNEL ANALYZER → COUNTER

LUPIN

~~PRE-AMPLIFIER~~ → LOG AMPLIFIER → ~~SINGLE CHANNEL ANALYZER~~ → ADC + PC

OUTPUT

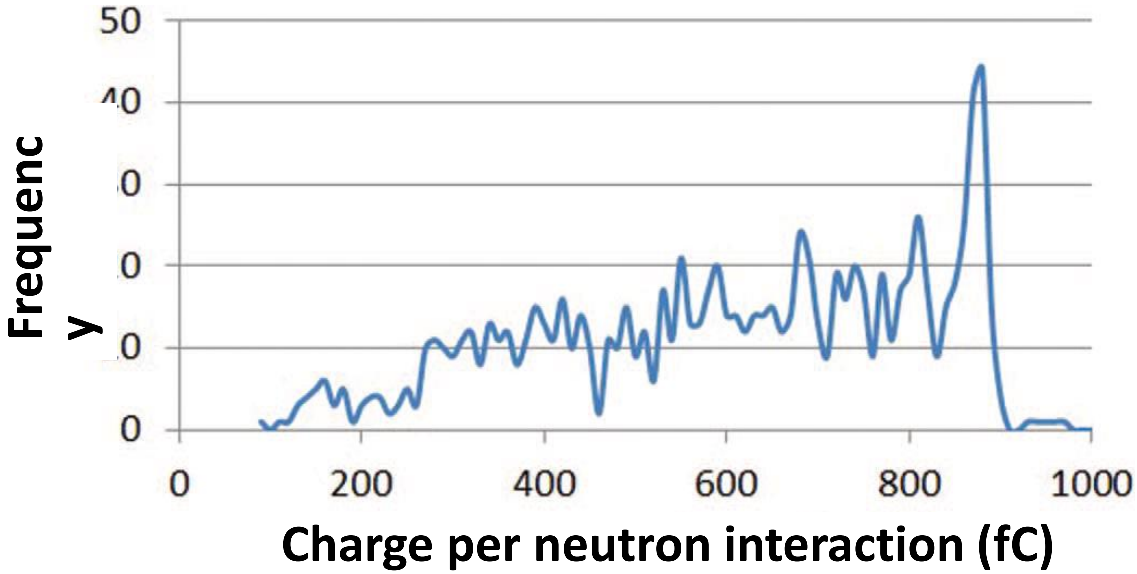
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$

NO Single Channel Analyser => **NO dead time losses**

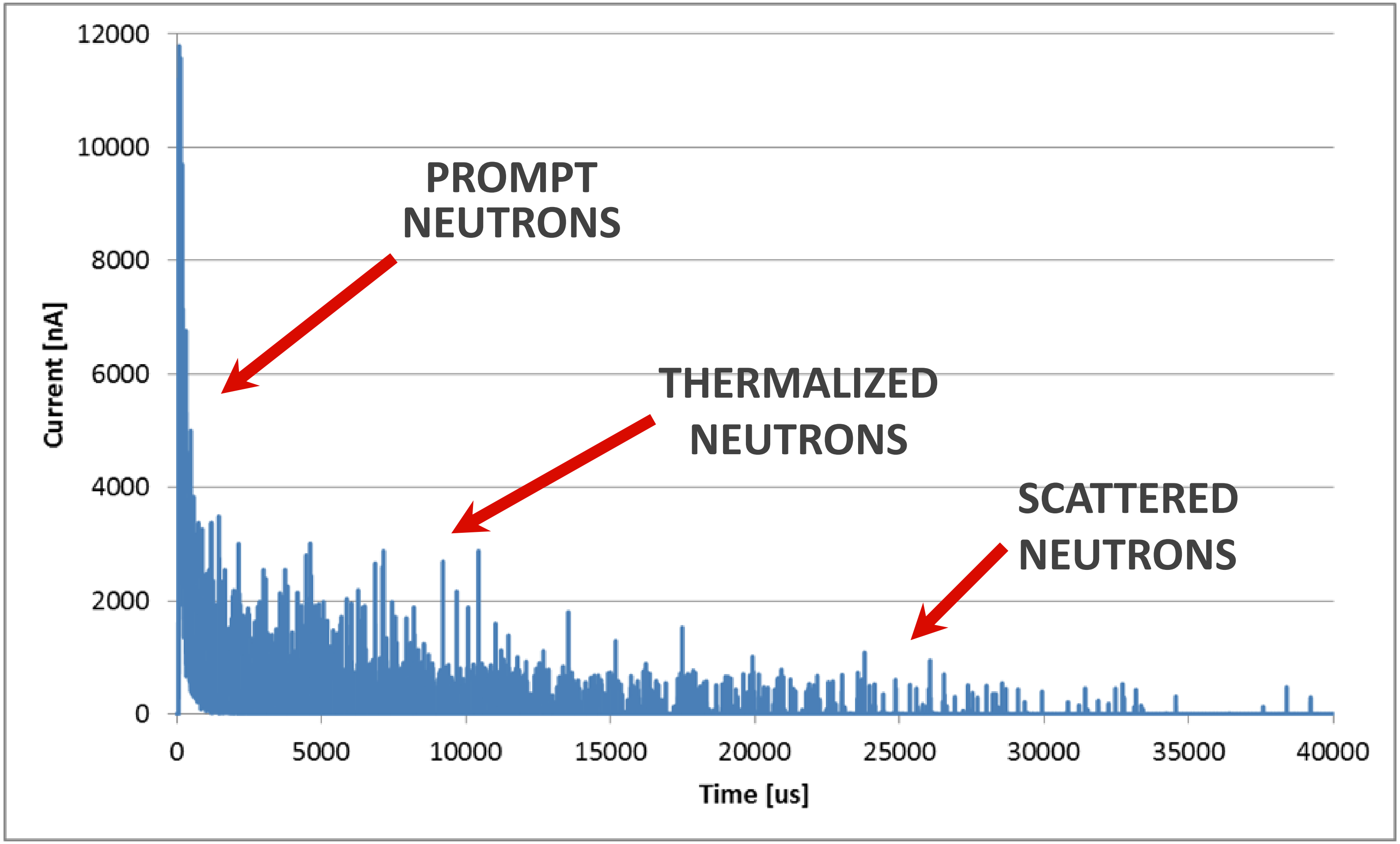
Logarithmic amplifier => **Wide dynamic range**

LUPIN operating principle

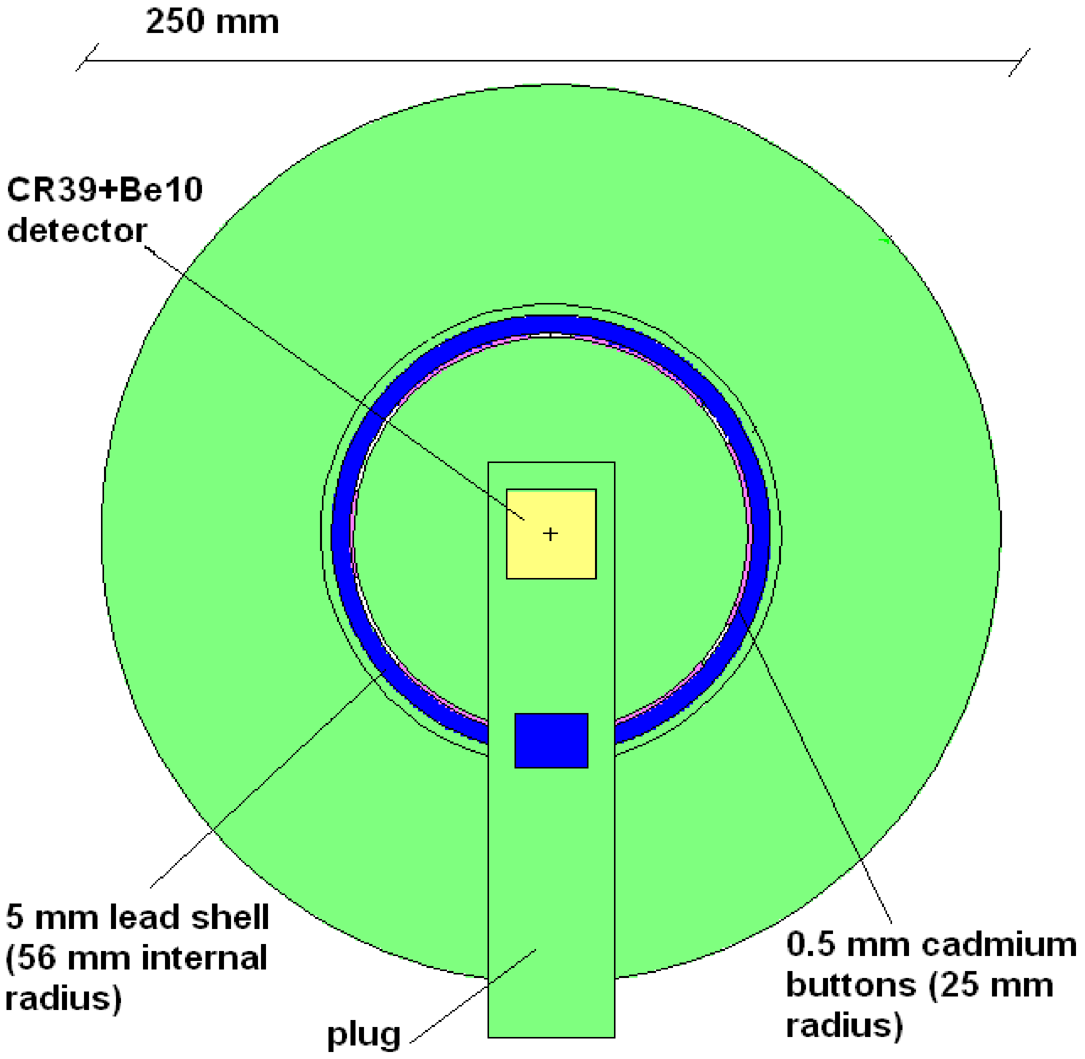
- Signal treated digitally, charge produced in the gas calculated by integrating the current over a settable time base
- Allows measuring the generated charge even if the neutron interactions pile up
- The total charge divided by the average charge expected by a single interaction represents the number of interactions occurring during the integration time
- Calibration of detector needs
  - knowledge of the mean collected charge (MCC) in fC, i.e., the average amount of charge generated in the detector by a neutron interaction
  - conversion coefficient from neutron interactions to H*(10), in nSv^{-1}



Example of signal acquired with LUPIN



Passive rem counter – POLIMI passive LINUS



Courtesy M. Caresana, Politecnico of Milano

Passive rem counter – POLIMI passive LINUS

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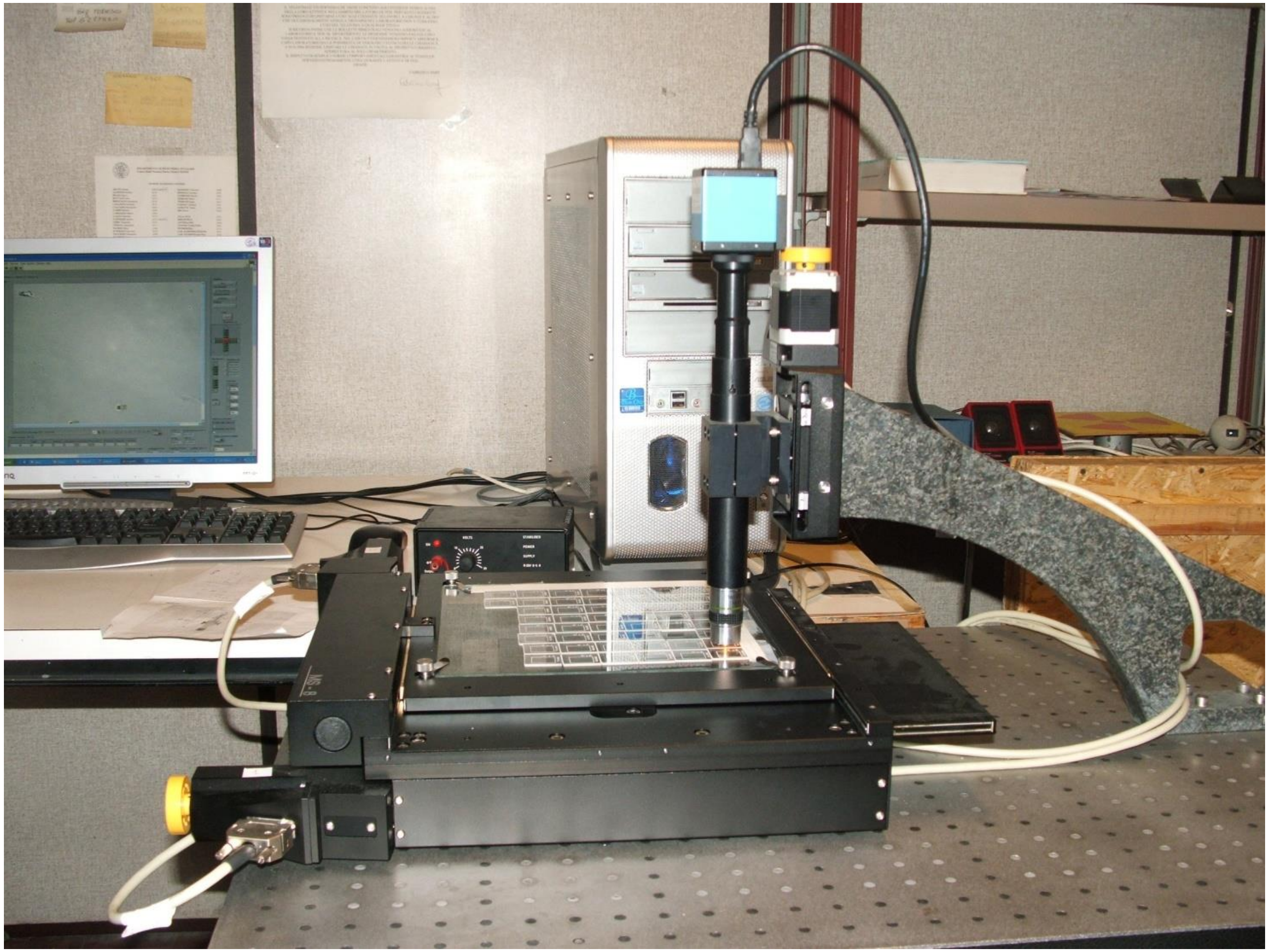


Trasmission microscope coupled with a 1024 x 768 CCD camera

Bonner Sphere Spectrometry (BSS)

All started in 1960 with Bramblett, Ewing and Bonner

Neutrons are detected in a ^{6}LiI(Eu) scintillator after being moderated in polyethylene spheres of various sizes…

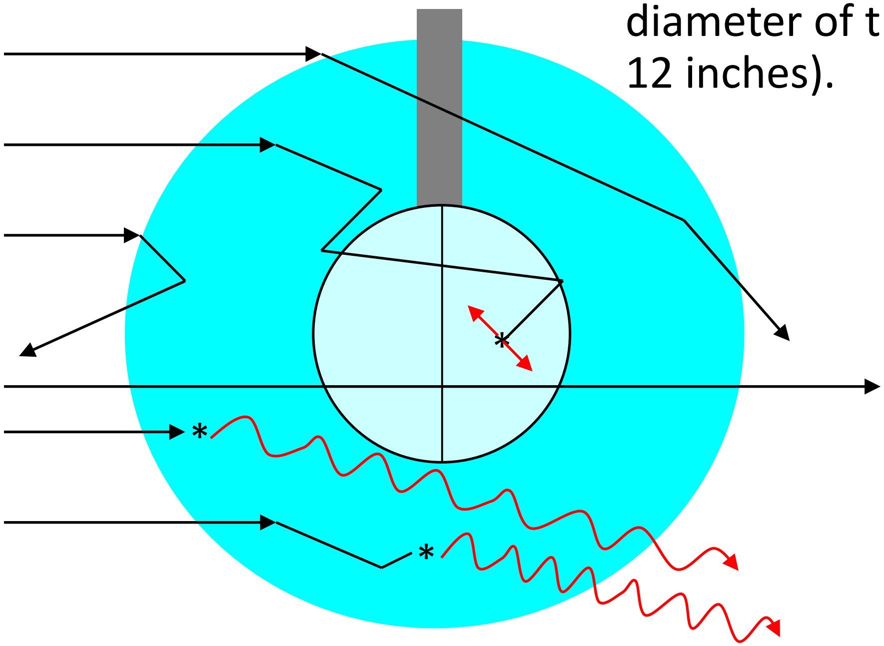
The counter can give information about the energy of neutrons over a wide range of energies

Since the neutron detector is sensitive to all energies of neutrons, it might well be applied to problems in neutron dosimetry

R.L. Bramblett, R.I. Ewing and T.W. Bonner, Nucl. Instr. Meth. 9 (1960) 1-12

Bonner Sphere Spectrometer (BSS)

- The BSS consists of a set of **moderating spheres** of different diameter housing a thermal neutron detector at their centre.
- The spherical shape allows approaching an **isotropic angular response.**
- The moderator is usually made of **polyethylene** (PE). The diameter of the spheres usually varies from 5 to 30 cm (2 to 12 inches).

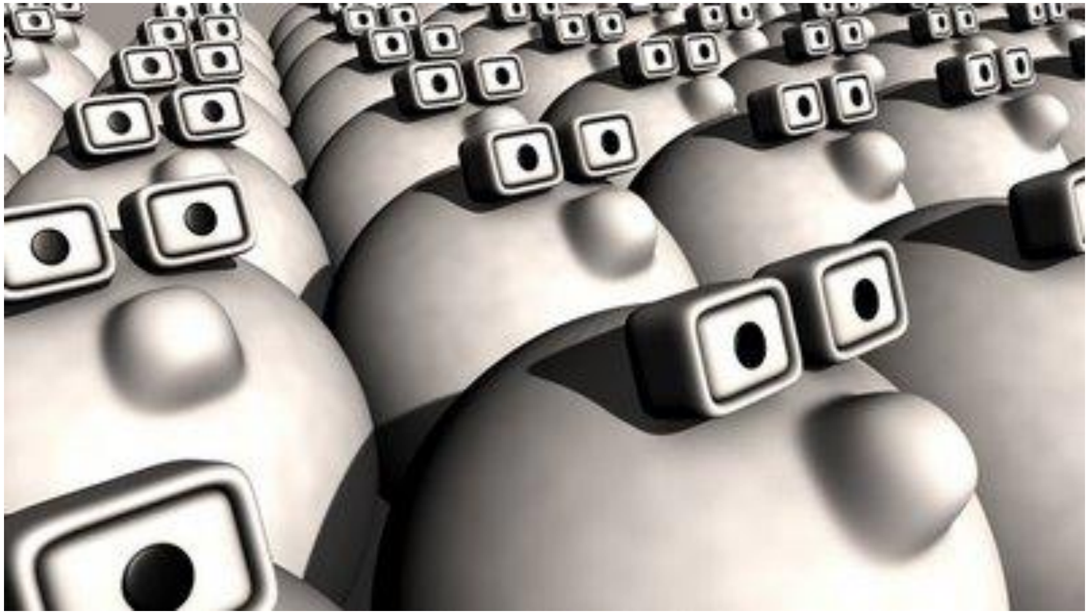


Courtesy S. Agosteo, Politecnico di Milano

- For a sphere of a given diameter, the **response** represents the number of events acquired by the thermal neutron detector per unit fluence of neutrons of a given energy impinging on the moderator.
- The response variation versus neutron energy is the **response function** of a sphere of a given dimension.
- The set of response functions of all the spheres of a BSS constitutes its **response matrix.**

Bonner Sphere Spectrometry (BSS)

A BSS can be made up by as few as 5 spheres and up to around 15

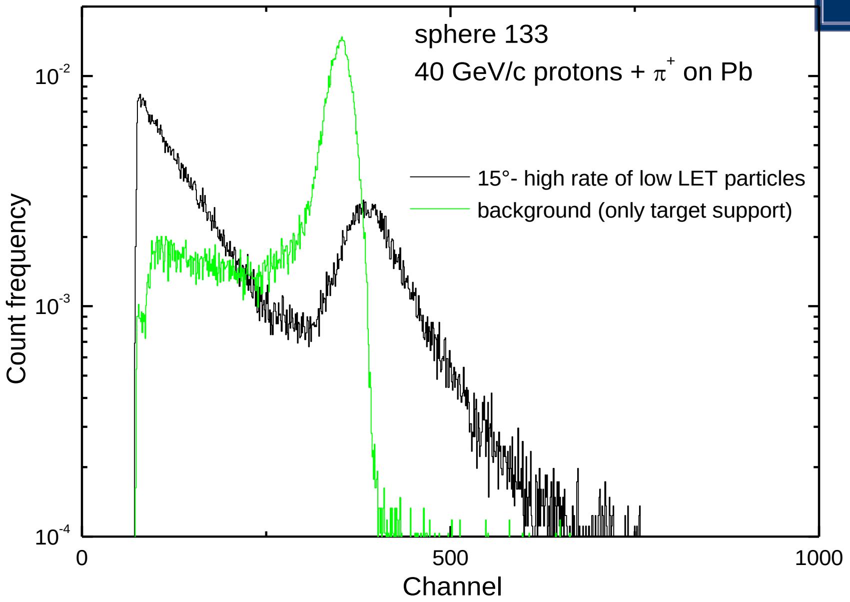


BUT

the response from the spheres may not be necessarily all independent (correlation)

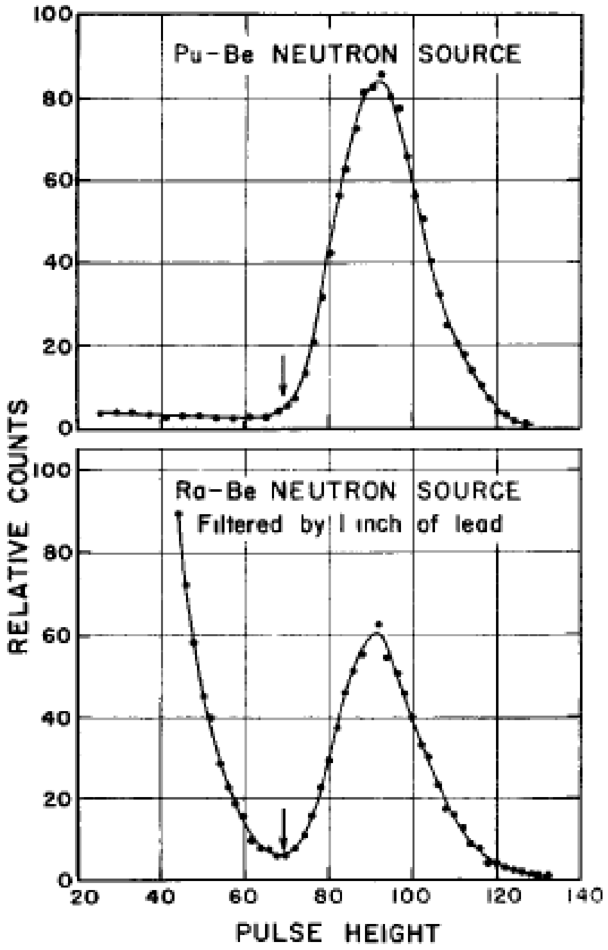
Bonner Sphere Spectrometer (BSS)

- Active thermal neutron detectors:
  - ✓ LiI(Eu) scintillators (original BSS);
  - ✓ BF_3 proportional counters;
  - ✓ ^{3}He proportional counters.
- Passive thermal neutron detectors:
  - ✓ TLDs;
  - ✓ activation foils (Au mainly);
  - ✓ track detectors coupled to ^{10}B radiators.



- All these techniques should exclude any response to photons.
- For active detectors, this requirement can be met by setting a threshold to the acquired electric signals.
- Care should be taken in radiation fields where the photon contribution is relevant, since pulse pile-up from photon detection may produce pulses over the threshold.
- A multi-channel analyzer measuring the spectrum of energy deposited in the detector can be helpful for this purpose.
- The contribution of photons can be assessed in TLD-based BSS, by employing a pair of detectors enriched in ^{7}Li and ^{6}Li.

Gamma-ray discrimination of ^{6}Li(Eu) counter



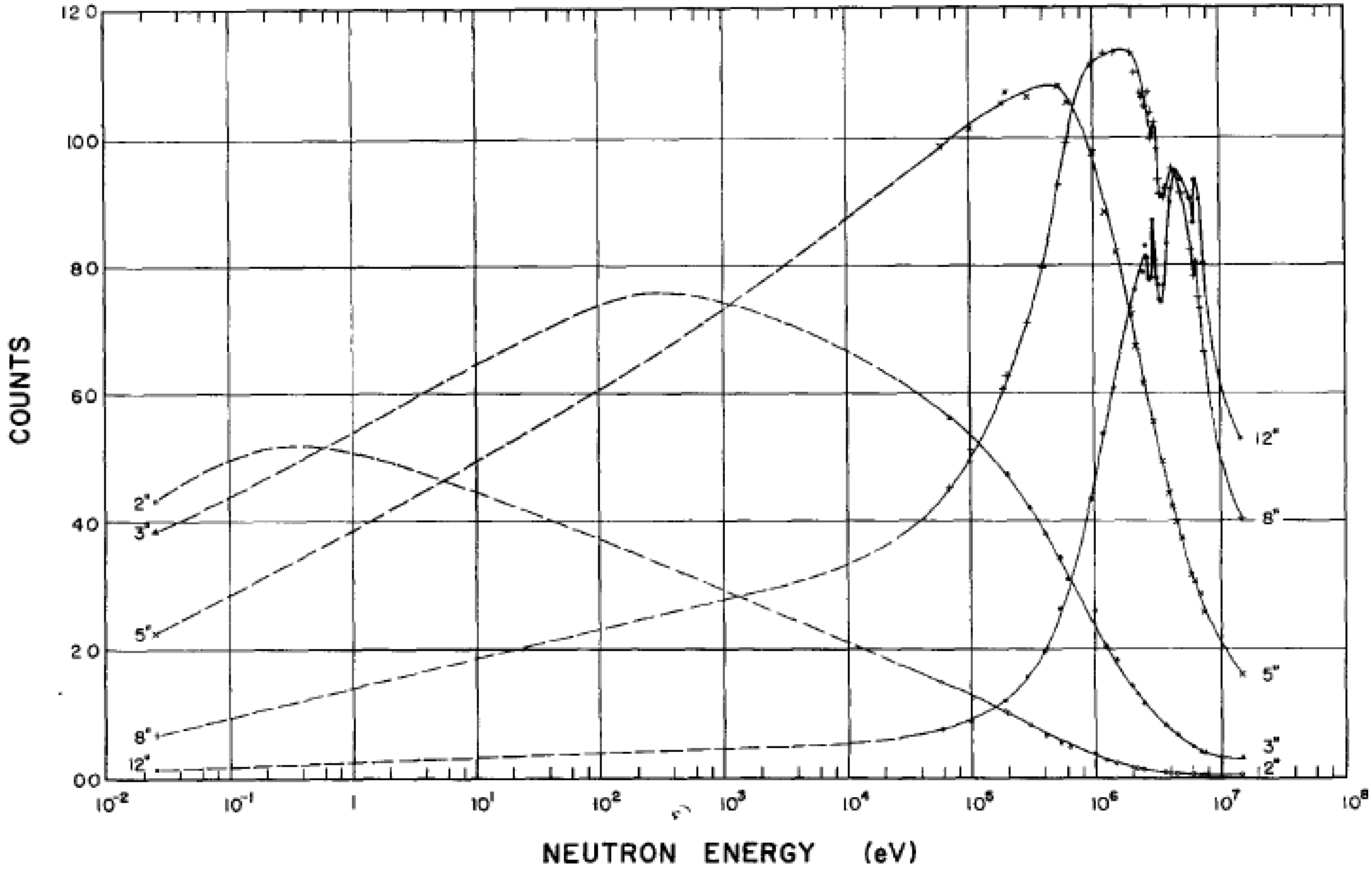
Pulse spectra obtained with 8 inch counter showing the effect of a large number of γ rays

0.6 γ-ray per neutron

30,000 γ -rays per neutron

R.L. Bramblett, R.I. Ewing and T.W. Bonner, Nucl. Instr. Meth. 9 (1960) 1-12

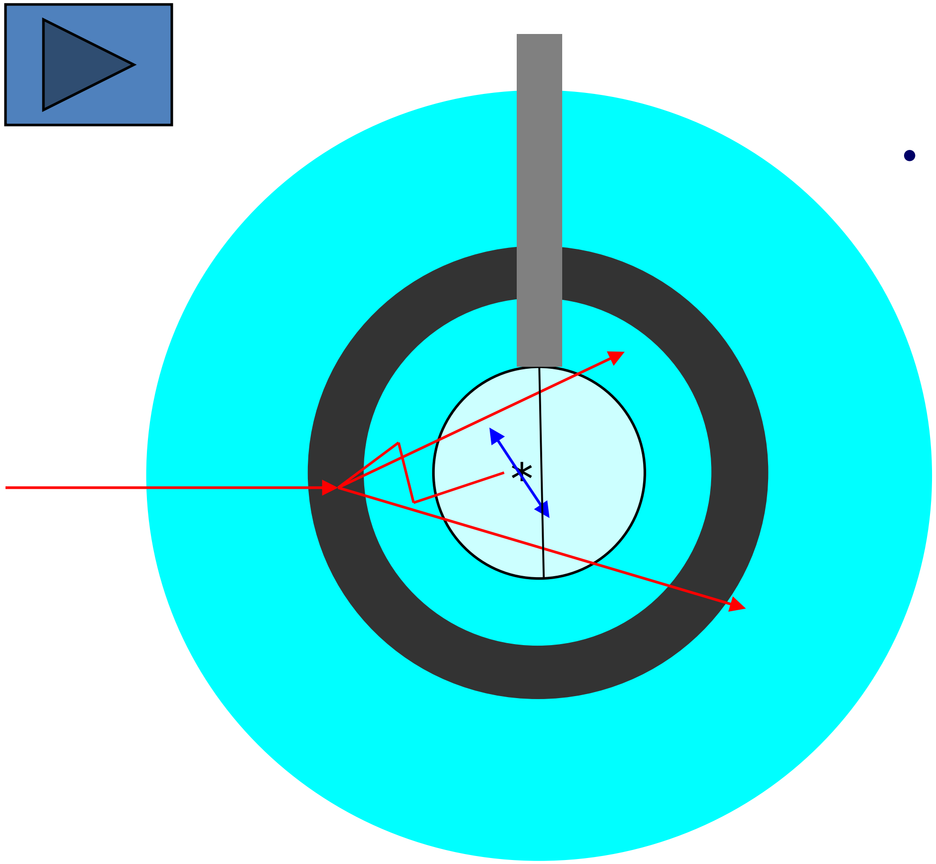
Response function of the original 1960 BSS



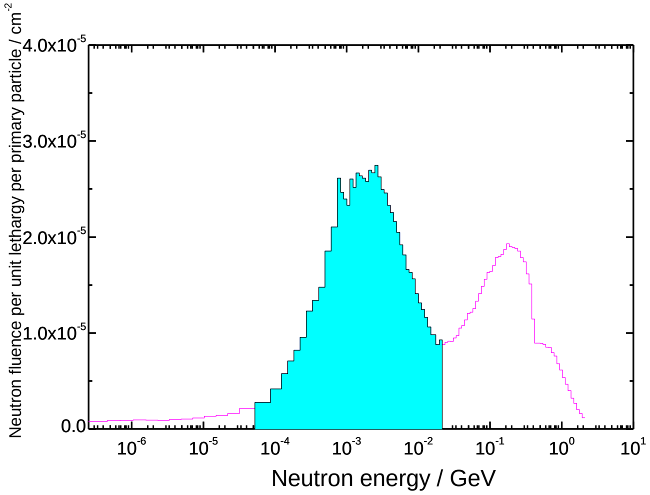
R.L. Bramblett, R.I. Ewing and T.W. Bonner, Nucl. Instr. Meth. 9 (1960) 1-12

Extended-range BSS

Same concept as the LINUS rem counter

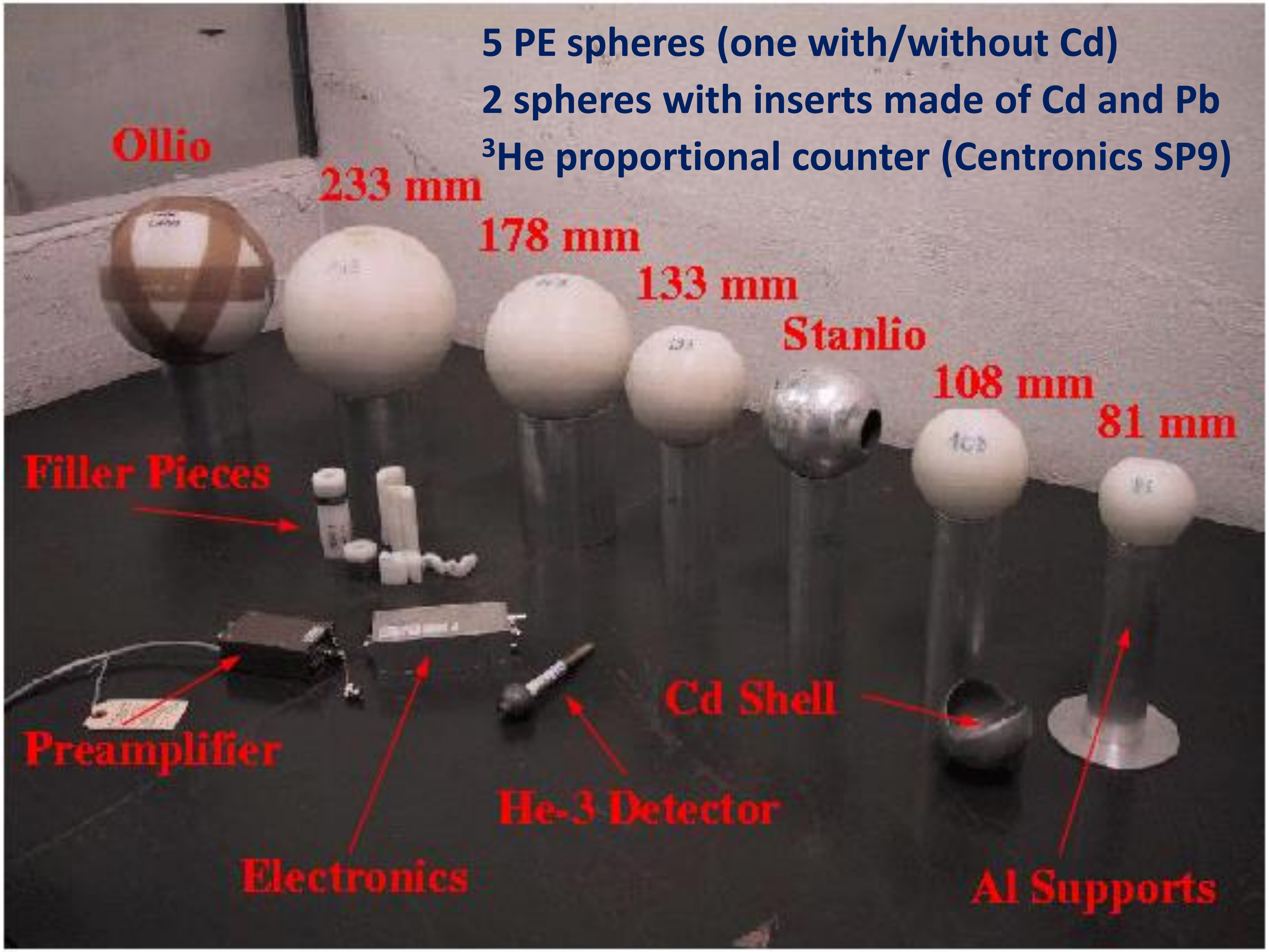


- A conventional BSS constituted only by PE spheres housing a thermal neutron detector can be used for assessing neutron spectra from thermal energies up to about 20 MeV.
- The response can be extended to high-energy neutrons (up to a few GeV) by coupling an attenuator shell of high-mass number to the moderator. Evaporation neutrons play a fundamental role for improving the response to HE neutrons.



Courtesy S. Agosteo, Politecnico di Milano

CERN extended-range BSS

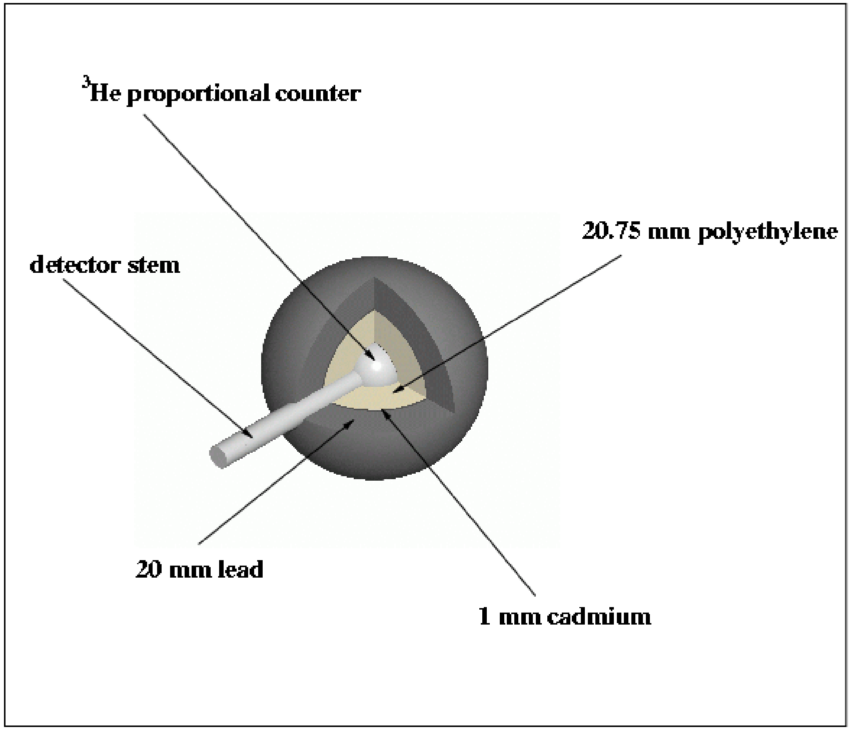


5 PE spheres (one with/without Cd)

2 spheres with inserts made of Cd and Pb

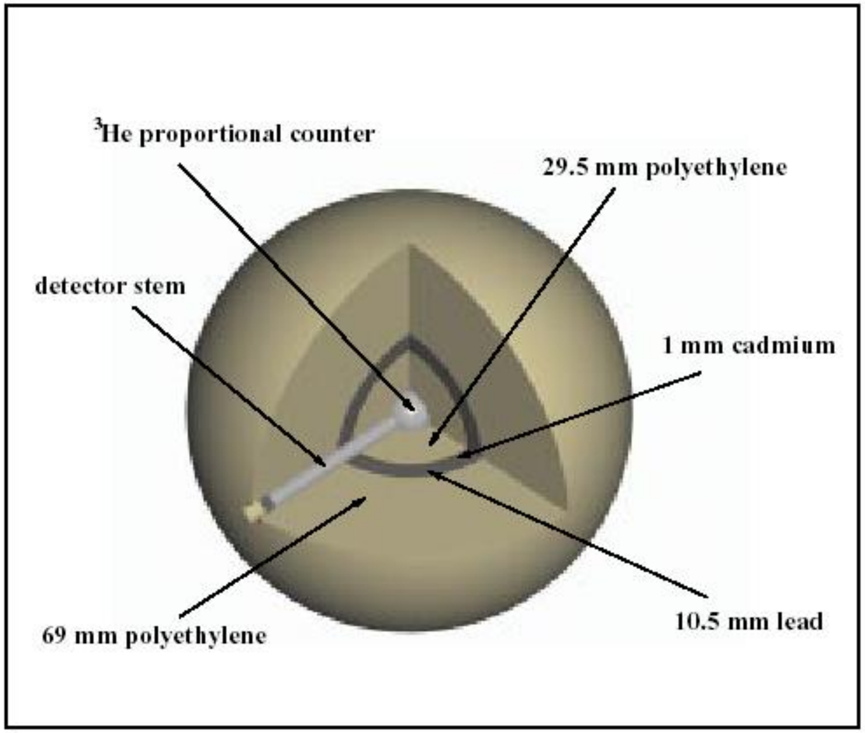
^{3}He proportional counter (Centronics SP9)

The CERN BSS high-energy detectors



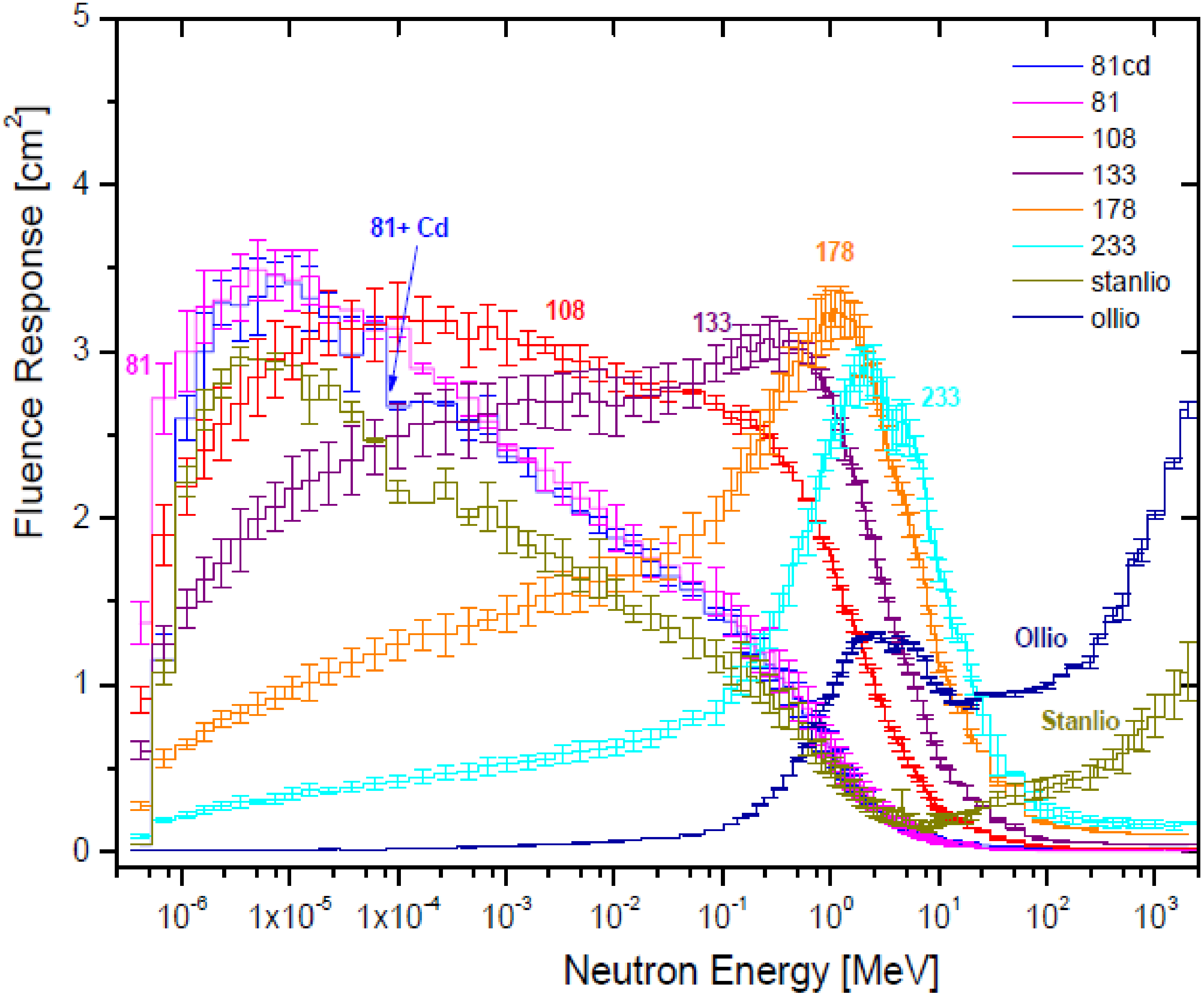
Stanlio (Stan)

Ollio (Oliver)



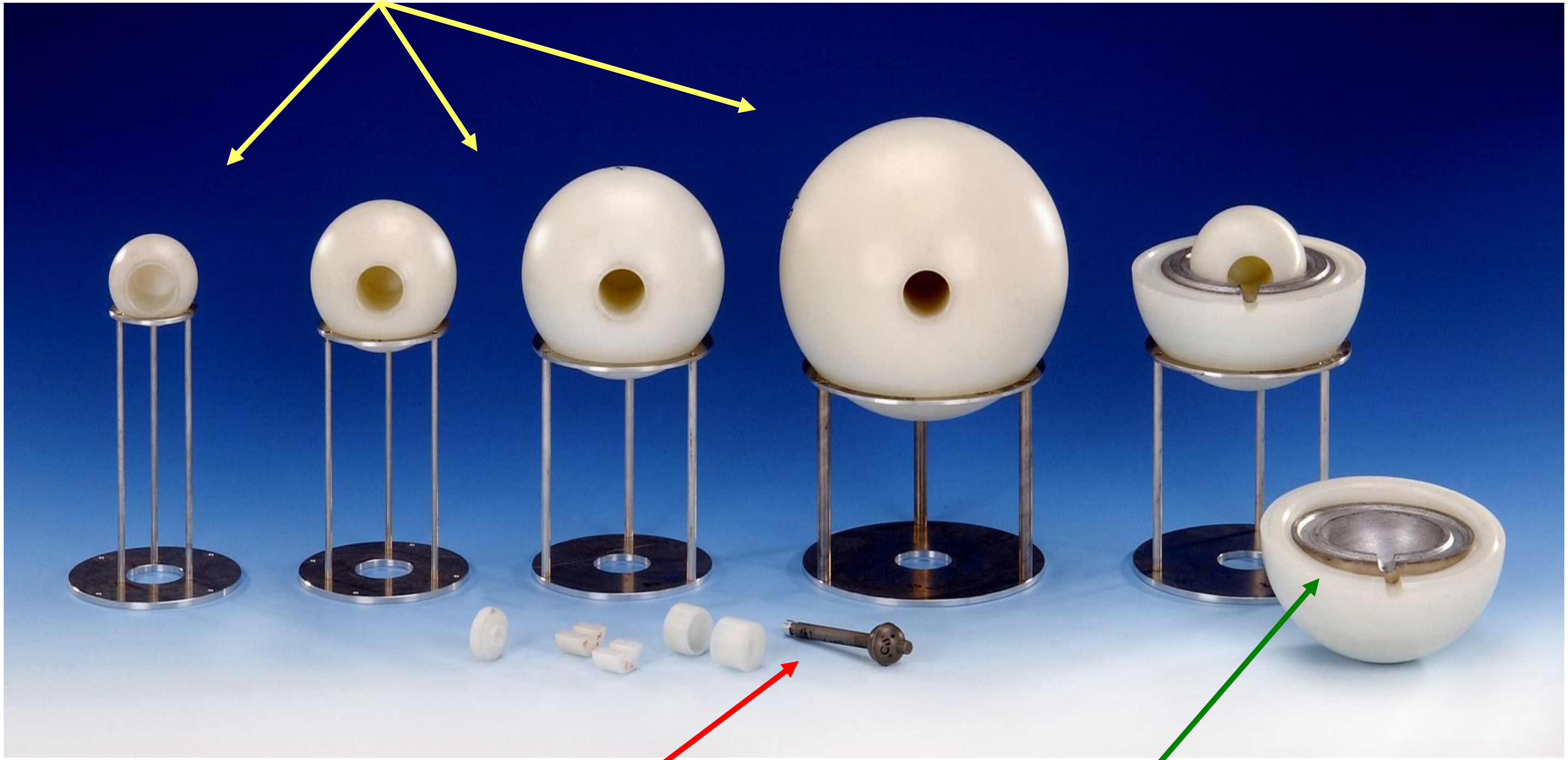
A. Mitaroff, PhD thesis (CERN and University of Vienna)
E. Dimovasili, PhD thesis (CERN and EPFL Lausanne)
C. Birattari et al, Proc. of Monte Carlo 2000, Lisbon, October 2000.

Absolute neutron fluence response of CERN BSS



PTB NEMUS (neutron multisphere spectrometer)

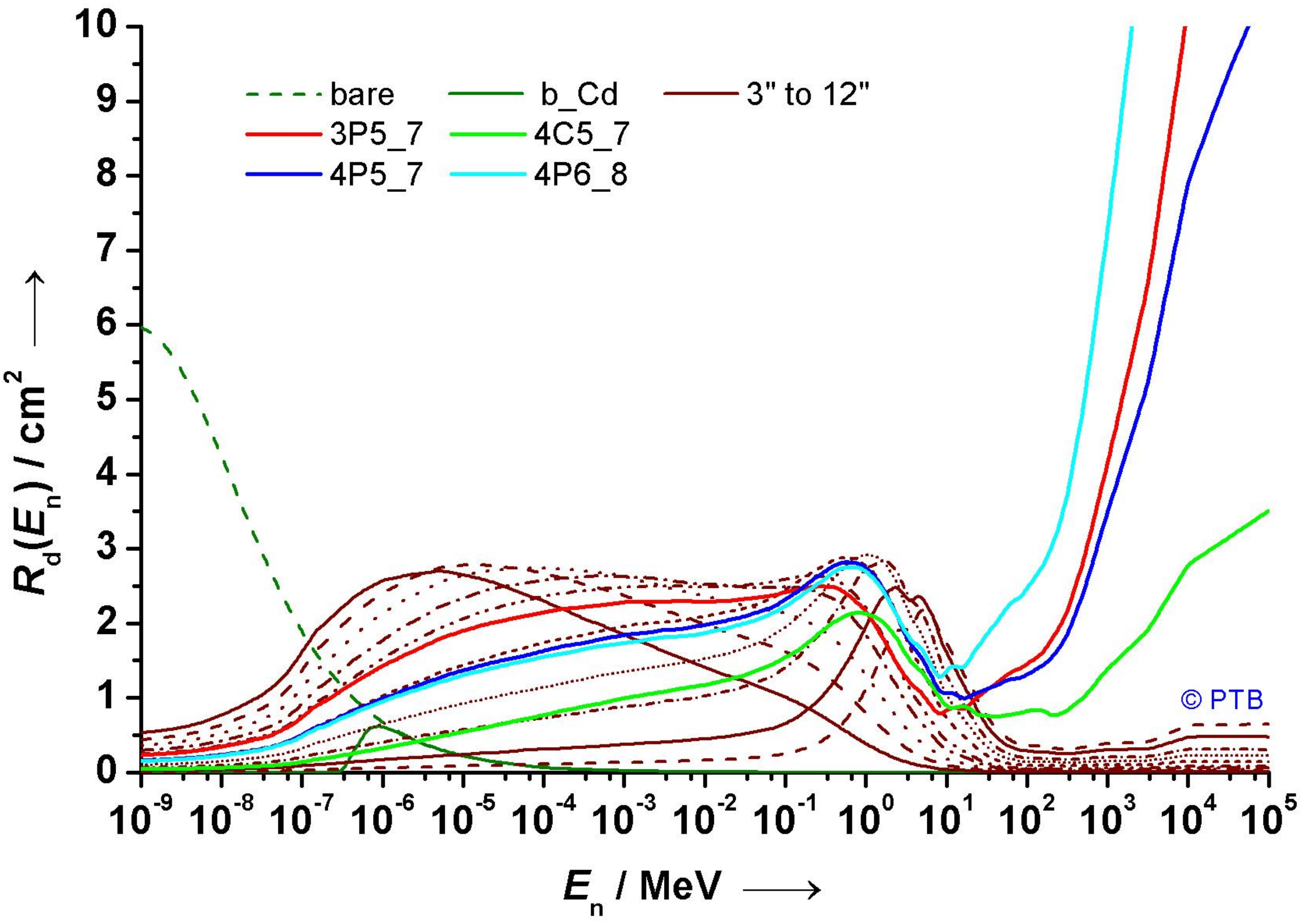
10 moderator spheres (polyethylene), ***d*** : 7.62 cm to 30.48 cm



^{3}He proportional counter as central thermal neutron sensor

4 modified spheres with copper or lead shells

Absolute neutron fluence response of NEMUS



Spectrum unfolding

- The fluence can be reconstructed by unfolding the experimental data. This procedure is based on a system of integral equations:

$$C_i = \int_{E\min}^{E\max} f_{i,E} \Phi_E dE + \varepsilon_i \qquad \text{i = 1,....., m}$$

- In general the unfolding techniques calculate a spectral fluence which maximizes the probability of giving the measured set of count rates C_i.
- The ambient dose equivalent can be determined by folding the measured spectrum with the fluence to dose conversion coefficients

$$H^*(10) = \int h_E^*(10) \Phi_E dE$$

Unfolding codes

GRAVEL

M. Matzke, PTB, Braunschweig PTBN-19, 1994.

MAXED

M. Reginatto and P. Goldhagen, Health Phys. 77 (1999) 579-583

FRUIT

R. Bedogni, C. Domingo, A. Esposito and F. Fernandez, Nucl. Instr. Meth. A 580 (2007) 1301-1309.

BONDI-97

B. Mukherjee, Nucl. Instr. Meth. A 432 (1999) 305-312

BUNKIUT

K.A. Lowry and T.L. Johnson, Health Phys. 47 (1984) 587-593.

Codes using algorithms based on artificial intelligence

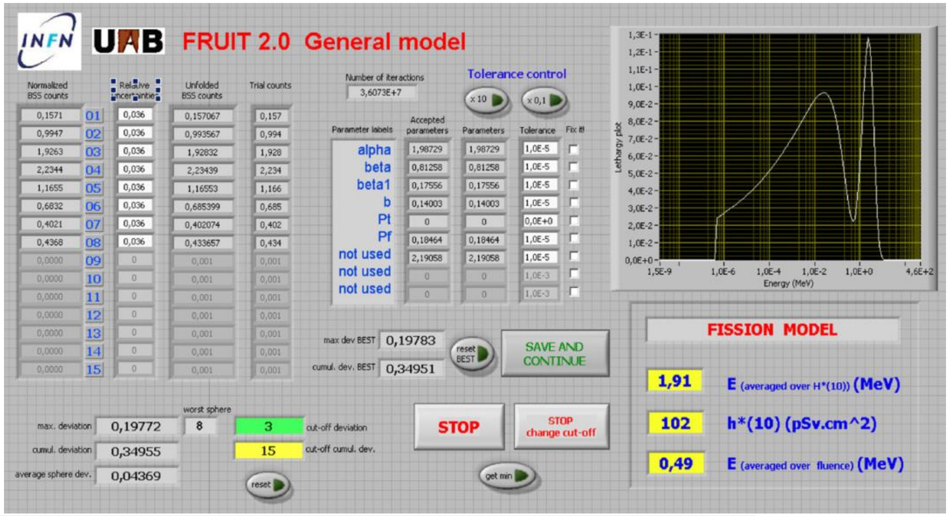
H.R. Vega-Carrillo, M.R. Martinez-Blanco, V.M. Hernandez-Dávila and J.M. Ortíz Rodriguez, J. Radioanal. Nucl. Chem. 281 (2009) 615-618

The U.M.G. package (M. Reginatto, PTB)

- Two versions
  - “multichannel”
  - “few channels”
- Two algorithms
  - MAXED (written specifically for unfolding BSS data)
  - GRAVEL (a modification of SAND-II)
- The user can choose whether any re-binning of spectra and/or response functions is linear with respect to the energy or linear with respect to the logarithm of the energy
- Four energy structures can be used for the unfolding (fine energy bin structure, four bins per decade, energy bin structure of the default spectrum, energy bin structure of the response functions)
- Required input files: measured data, BSS response functions, default (“guess”) spectrum
- Output: solution spectrum and parameter file

FRUIT (R. Bedogni, INFN)

- FRUIT models a generic neutron spectrum as the superposition of elementary spectra described by a set of parameters
- Limited amount of “a priori” information needed: measured data, BSS response functions and qualitative information on the type of ‘‘radiation environment’’ (no default spectrum)
- The iterative convergence procedure varies the parameters describing the spectrum on the basis of a ‘‘variable tolerance’’ which may be changed by the user during the run
- User-friendliness and visual operation



FRUIT 2.0 General model

Normalized BSS counts		Relative uncertainties	Unfolded BSS counts	Trial counts
0,1571	01	0,036	0,157067	0,157
0,9947	02	0,036	0,993567	0,994
1,9263	03	0,036	1,92832	1,928
2,2344	04	0,036	2,23439	2,234
1,1655	05	0,036	1,16553	1,166
0,6832	06	0,036	0,685399	0,685
0,4021	07	0,036	0,402074	0,402
0,4368	08	0,036	0,433657	0,434
0,0000	09	0	0,001	0,001
0,0000	10	0	0,001	0,001
0,0000	11	0	0,001	0,001
0,0000	12	0	0,001	0,001
0,0000	13	0	0,001	0,001
0,0000	14	0	0,001	0,001
0,0000	15	0	0,001	0,001

Number of iteractions 3,6073E+7

Tolerance control

Parameter labels	Accepted parameters	Parameters	Tolerance	Fix it!
alpha	1,98729	1,98729	1,0E-5	☐
beta	0,81258	0,81258	1,0E-5	☐
beta1	0,17556	0,17556	1,0E-5	☐
b	0,14003	0,14003	1,0E-5	☐
Pt	0	0	0,0E+0	☐
Pf	0,18464	0,18464	1,0E-5	☐
not used	2,19058	2,19058	1,0E-5	☐
not used	0	0	1,0E-3	☐
not used	0	0	1,0E-3	☐

max dev BEST 0,19783

cumul. dev. BEST 0,34951

max. deviation 0,19772

worst sphere 8

cumul. deviation 0,34955

average sphere dev. 0,04369

3 cut-off deviation

15 cut-off cumul. dev.

FISSION MODEL

1,91 E (averaged over H*(10)) (MeV)

102 h*(10) (pSv.cm^2)

0,49 E (averaged over fluence) (MeV)

Bonner Sphere Spectrometry - Summary

- BSS is used in operational radiation protections since many years
- Its energy resolution depends to a certain extent on how many detectors (spheres) is made of, but it is anyhow rather coarse (but sufficient for RP purposes)
- Isotropic response
- A conventional BSS made only of polyethylene moderators has an intrinsic upper energy limit around 15 MeV (same as with conventional rem counters)
- Extended-range BSS employing one or more moderators made by a combination of polyethylene and a high-Z material (Pb, W, Cu) have an enhanced response up to hundreds of MeV
- Unfolding the experimental data require some knowledge of the expected neutron spectrum or at least of the radiation environment
- Sometimes the solution spectrum is “biased” by the guess spectrum