Radiation protection studies at LNF: experimental techniques for spectrometric characterization of neutron fields

INFN-LNF Radiation Protection Group

Introduction

Accelerators were first designed and constructed for research purposes.

They have now entered the very fabric of our life

In addition to the application to the fundamental research in cosmology and particle physics, They are now widely applied in

Medicine
- Diagnosis
- Therapy
- Radiopharmaceutical products

Material science

Solid state physics
- Ion implantation
- Radiation damage studies
- Microlithography

Polymerization

Sterilization

Food preservation

Cultural heritage preservation

And so on

Introduction

✧**Most of neutron fields encountered in operational radiation protection exhibit broad energy distribution.**

✧**An accurate knowledge of the neutron spectrum is often necessary for assessing the radiation protection conditions at workplace**

✧**The accuracy of determining the operational quantities with neutron spectrometry depends entirely on the accuracy with the energy and direction distributions of neutron fluences are determined**

✧**The dosimetry of neutron radiation is one of the most complicate task in radiation protection, due mainly to the following causes.**

- **The definition of operational quantities H*(10), $H_P(10)$**
- **Practical problems in the instrument design and calibration**
- **Non ideal properties of dosimeters/non ideal response characteristics**

Radiation measurements

Quantities in Radiological Protection

Primary Physical Quantities

fluence, Φ

energy fluence, Ψ

air kerma, K_a

exposure, X

Calculation for simple phantom (spheres or slab) validation by measurement

Calculation using W_R, W_t and anthropomorphic phantom

interaction coefficients for energy absorption

Operational Quantities

ambient dose equivalent, H*(d)

directional dose equivalent, H' (d,Ω)

personal dose equivalent, Hp (d)

ICRP Protection quantities

absorbed dose,D

equivalent dose, H_T

effective dose, E

Related by calibration and calculation

Estimation by measurements and calculation using usando w_R and anthropomorfic phantom

Monitored quantities

Instruments response

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

Dosimetry of neutron radiation

For area monitoring ICRU recommends the use of H*(10) which is to provide a conservative estimate of effective dose.

H*(10 is not a measurable quantity)

Two approaches are possible to determining the value of the Ambient Dose Equivalent H*(10) in a neutron field.

$$H^*(10) = \int_0^{E\max} \Phi_E(E) h^*_\Phi(E) dE$$

$\Phi_E = \Phi \cdot \varphi(E)$

$\varphi(E)$ is the energy distribution of the neutron fluence normalized to 1 cm^{-2}

h^*_Φ neutron fluence to dose equivalent conversion factor

Deriving $\Phi(E)$ by means of spectrometric techniques

Using an instruments with flat energy response in terms of H*(10)

Dosimetry of neutron radiation

This last approach is possible in a limited energy range.

Due to high energy variability of the fluence-to-ambient dose-equivalent conversion coefficients and the diversity of the interaction mechanisms in the human body and the dosimetric material, the instruments responses usually show a very important energy dependence.

Moreover the energy neutrons in the workplace fields can range over 10 order of magnitude

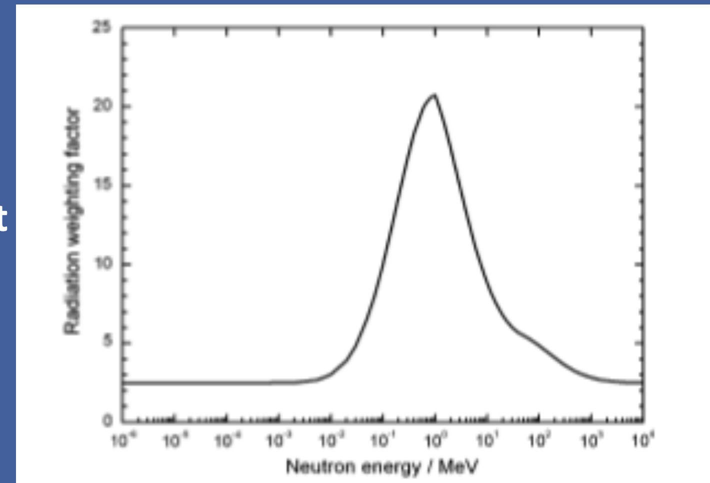
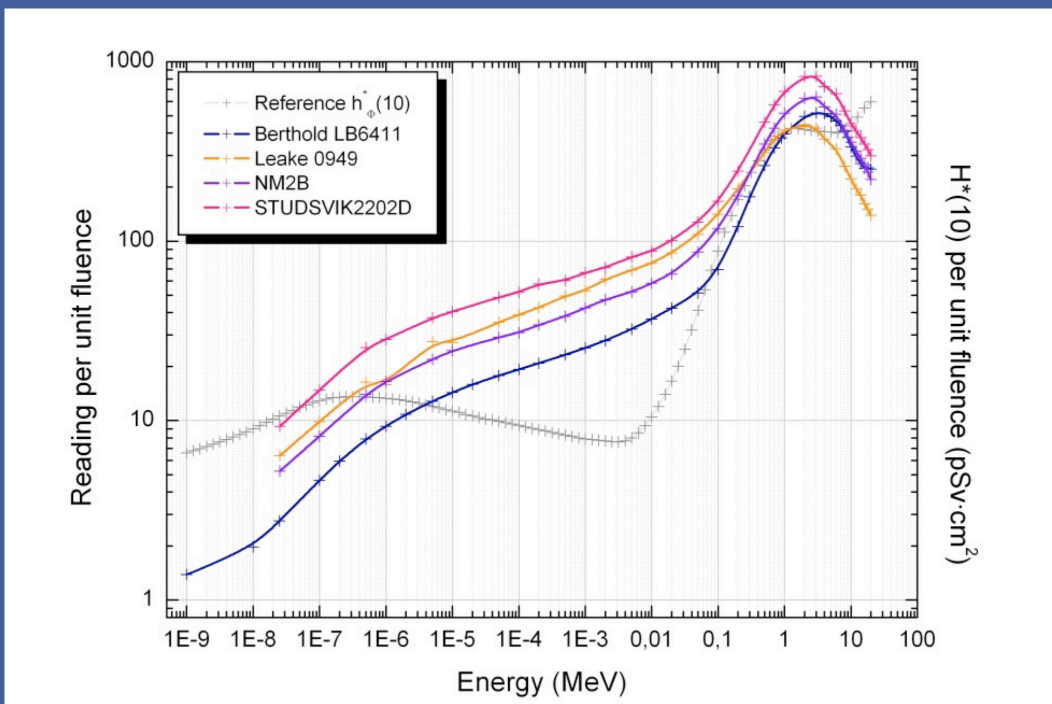
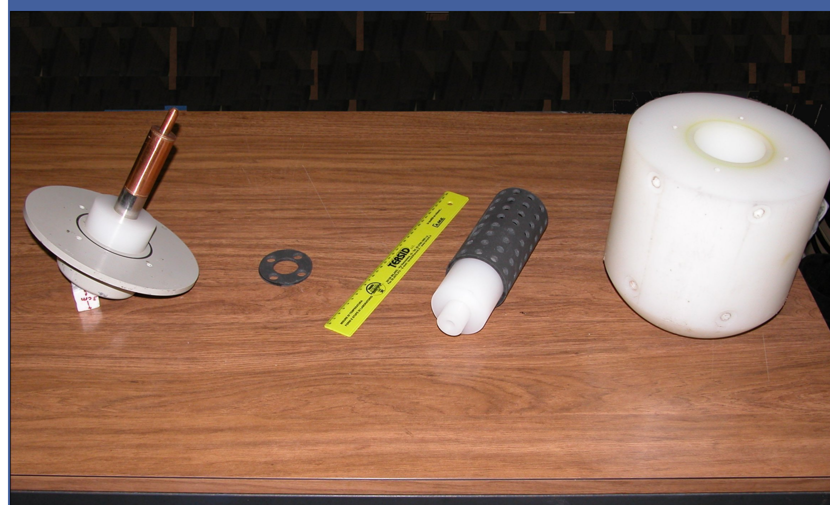


Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.





Dosimetry of neutron radiation

The Long Interval NeUtron Survey-meter (LINUS) is a new type of rem counter developed by INFN (LNF Radiation Protection Group and Section of Milan)

Detector

- cylindrical BF^3 proportional counter (95% 10B enrichment);

- diameter = 2.54 cm;
- active length = 5.08 cm;
- pressure = 8.0×10^4 Pa.

Lead attenuator

- thickness = 1 cm
- outer polyethylene: thickness = 7 cm.

Response

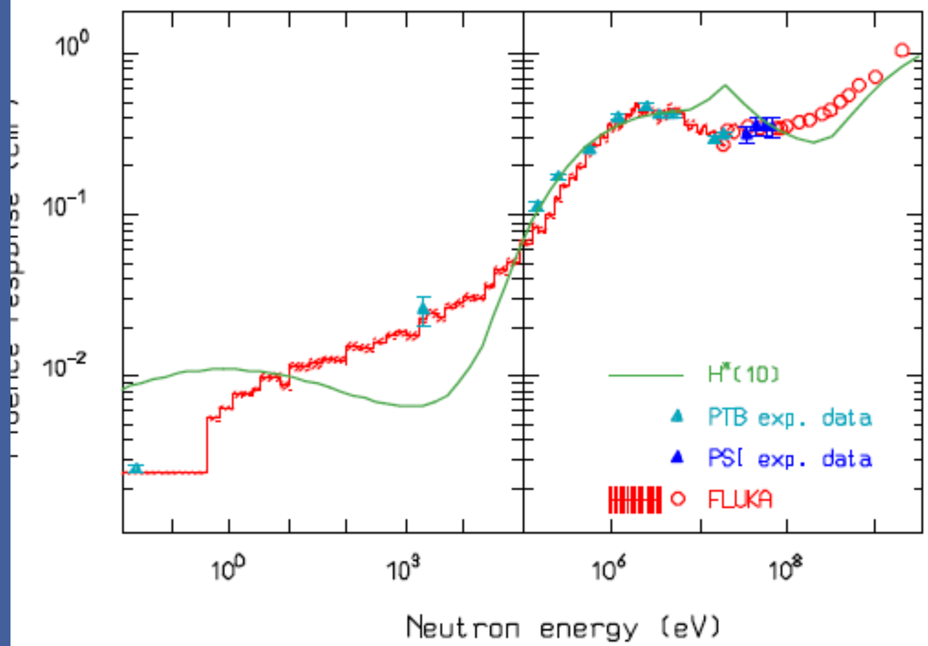
The response function is extended to several hundred MeV.

Moderator

- inner polyethylene : thickness =1.9 cm;
- boron doped synthetic rubber attenuator:
  - outer diameter=7.6 cm;
  - length =14 cm;
  - thickness = 0.6 cm;

The enhancement of instrument response because the reaction (n,xn)

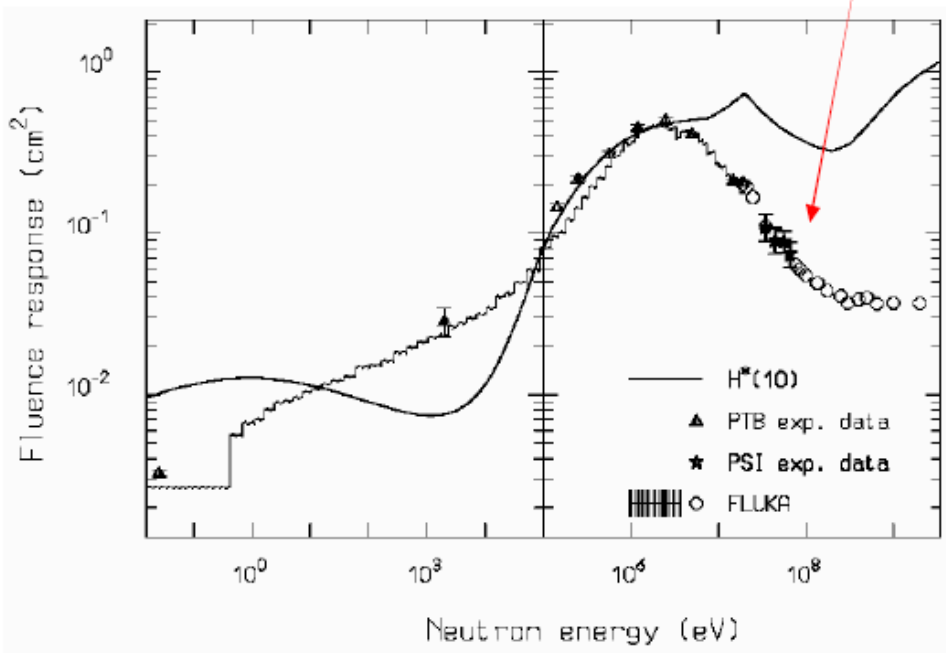
Dosimetry of neutron radiation



LINUS (extended range)

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

Heavily underestimated above a few MeV



SNOOPY (conventional unit)

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

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

Dosimetry of neutron radiation

An accurate determination of H*(10) in workplace field of unknown direction distribution can be achieved through the use of suitable neutron spectrometer.

- Neutron scattering and measurement of the energies of recoil nuclei.
- Measurement of the energies of charged particles released in neutron-induced nuclear reactions.
- Methods in which the velocity of neutrons is measured TOF
- Threshold spectrometry
- The most used neutron spectrometry technique in workplaces is the so called Bonner Sphere Spectrometer (BSS).

NUCLEAR INSTRUMENTS AND METHODS 9 (1960) 1–12; NORTH-HOLLAND PUBLISHING CO.

A NEW TYPE OF NEUTRON SPECTROMETER†

RICHARD L. BRAMBLETT, RONALD I. EWING and T. W. BONNER

The Rice University, Houston Texas

Received 4 July 1960

Neutrons are detected in a small $Li^6I(Eu)$ scintillator placed at the center of polyethylene moderating spheres with sizes ranging from 2 to 12 inches in diameter. The efficiency of this neutron counter has been experimentally determined using monoenergetic neutrons from thermal energies to 15 MeV. The counter has excellent energy sensitivity from 0.1 to 2 MeV and is particularly useful for determining the shapes of continuous neutron spectra. The pronounced difference in the efficiencies for the five sizes of spheres which have been calibrated provides a basis for accurate neutron energy determination. The good γ ray discrimination of the counter allows it to be used with a radium-beryllium neutron source. Neutron spectra from a variety of sources have been determined with this counter. These include the two groups of neutrons from the $C^{14}(p,n)N^{14}$ reaction, the evaporation spectrum of the neutrons from the reaction $Rh^{103}(p,n)Pd^{103}$, the energy spectra of inelastically scattered neutrons, and the neutron spectrum from the scattering of fast neutrons by the floor and walls of a building.

Dosimetry of neutron radiation

◆The advantages of such type of spectrometer are

- ◆ the isotropy of the response,
- ◆the possibility to extend the energy range up to GeV neutrons
- ◆the availability of different active or passive central detectors to be chosen according to the field intensity and time structure.

Nevertheless, the unfolding process remains the most difficult task in Bonner Sphere spectrometry, because unfolding codes are usually very complex and require quite detailed "a priori" information on the spectrum to be measured.

With the aim of providing a useful and friendly tool for spectrometry in workplaces, the INFN-LNF Radiation Protection Group developed FRUIT, a new unfolding code specially designed for routine applications where no detailed pre information on the neutron field are available.

The LNF-ERBSS, available from Ludlum Measurements, USA, includes

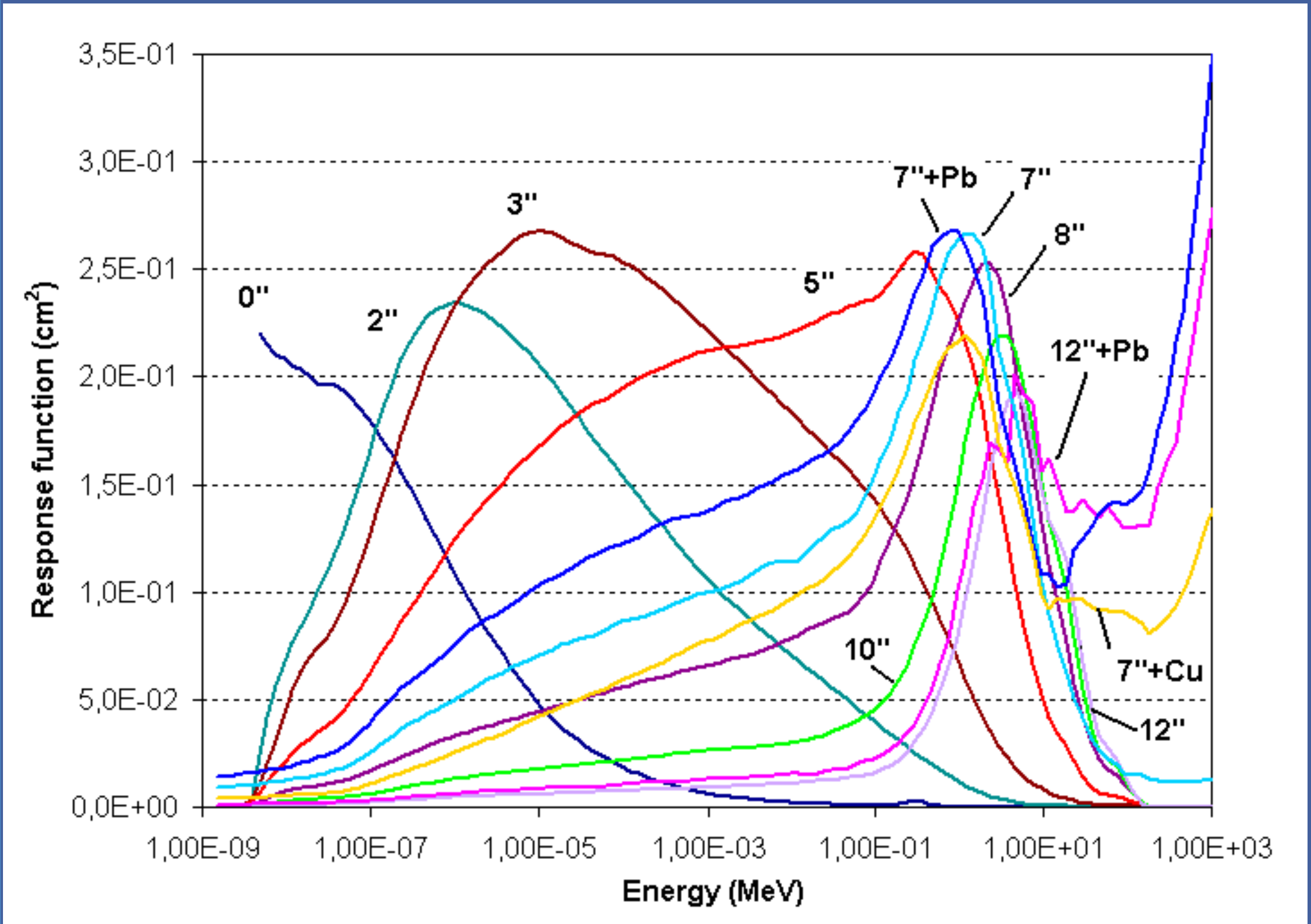
- eleven polyethylene spheres (density 0.95 g·cm^{-3})
  (2", 2.5", 3",3.5", 4.5", 5", 7",8", 10", 12")

- three polyethylene spheres (density 0.95 g·cm^{-3}) loaded with copper and lead
  (7" Cu, 7" Pb, 12" Pb)
- a 4x4 ^{6}LiI(Eu) active scintillator

Special aluminum holders were designed to expose TLD pairs and a gold or dysprosium foil in the same sphere.

All spheres are designed to hold the scintillator

The response functions of the active ERBSS were calculated with MCNPX Monte Carlo transport code.
The data were interpolated to produce a response matrix with 120 logarithmic equidistant intervals from 1.5 meV to 1.16 GeV.



The response matrix of the ERBSS was validated in reference neutron fields (PTB, TSL) and its overall uncertainty was estimated to be σ_{matrix} = ±3%.

The response functions of the high-energy spheres.

The reading C_i, of the thermal neutron sensor inside the i^{th} Bonner sphere, when exposed in a point of a neutron field, can be expressed as

$$C_i = \Phi \int_{E_{min}}^{E_{max}} R_i(E)\varphi(E)dE$$

where:

- ***Φ*** **is the neutron fluence in cm^{-2};**

- ***$R_i(E)$*** **is the response function of the sphere (in cm^{-2}). It is usually derived with Monte Carlo calculations and represents the reading per unit fluence as a function of the monoenergetic neutron energy, E. The set of response functions for all Bonner spheres forms the "response matrix".**

- ***φ(E)*** **is the energy distribution of the neutron fluence normalized to 1 cm^{-2} and its unit is MeV^{-1} (also termed "unit spectrum").**

The energy distribution of the neutron fluence (also termed "spectrum"), is given by

$\Phi_E = \Phi \cdot \varphi(E)$ **and its unit is $cm^{-2} \cdot MeV^{-1}$.**

Dosimetry of neutron radiation

When a set of *m* Bonner spheres is exposed to the same neutron fluence, a set of readings C_1, i=1,..,m is collected. The neutron fluence Φ and its energy distribution $\varphi(E)$ may be derived by inverting a set of *m* equations, that for computer calculation purposes can be expressed in the following discrete form:

$$C_i = \Phi \sum_{J=1}^{N_g} R_{i,j} \varphi_j \Delta E_j \qquad i=1....m$$

Where N_g is the number of energy group

The unfolding problem in Bonner Sphere Spectrometry is under-determined, i.e. the number of independent measurements, *m,* is largely lower than the number of unknowns, N_g.

This implies that a set of infinite mathematical functions could satisfy the equation. Nevertheless, only a limited number of them is physically acceptable.

Many codes have been developed for unfolding neutron spectra .

At LNF we developed the FRUIT (FRascati Unfolding InteRactive code) code

Unfolding code

The neutron spectra were derived from the raw data using the FRUIT (FRascati Unfolding Interactive Tool) developed at the INFN-LNF for the needs of the operational workplace neutron monitoring.

Main features of FRUIT

High level of interactivity

User friendliness and visual operation

No needs of "educated" default spectrum

Uncertainties treatment

And above all

The user doesn't need to be an expert of computer codes

FRUIT is a parametric code written using the Lab-Views software.
It models the neutron spectra with at most seven numerical positive parameters.

Provided the response matrix and the energy the only numerical data required by the code are the Bonner sphere readings and their relative uncertainties.

The type of ''radiation environment'' is selected, using a check-box window, among the following options:

(a) fission-like fields, such as those found in the vicinity of nuclear reactors or fuel elements;

(b) radionuclide neutron sources;

(c) evaporation-based field, such as those found in medical LINACs or PET cyclotrons;

(d) high-energy electron fields;

(e) high-energy hadron accelerators;

(f) Gaussian peak;

(g) user-defined (in this case a parameter file is required).

A neutron spectrum in FRUIT is described as the linear superposition of up to four components

$\phi(E) = P_{th}\phi_{th}(E) + P_e\phi_e(E) + P_f\phi_f(E) + P_{hi}\phi_{hi}(E)$ where

$\phi_{th}(E)$ is the thermal Maxwellian component,

$\phi_e(E)$ the epithermal one,

$\phi_f(E)$ the fast one

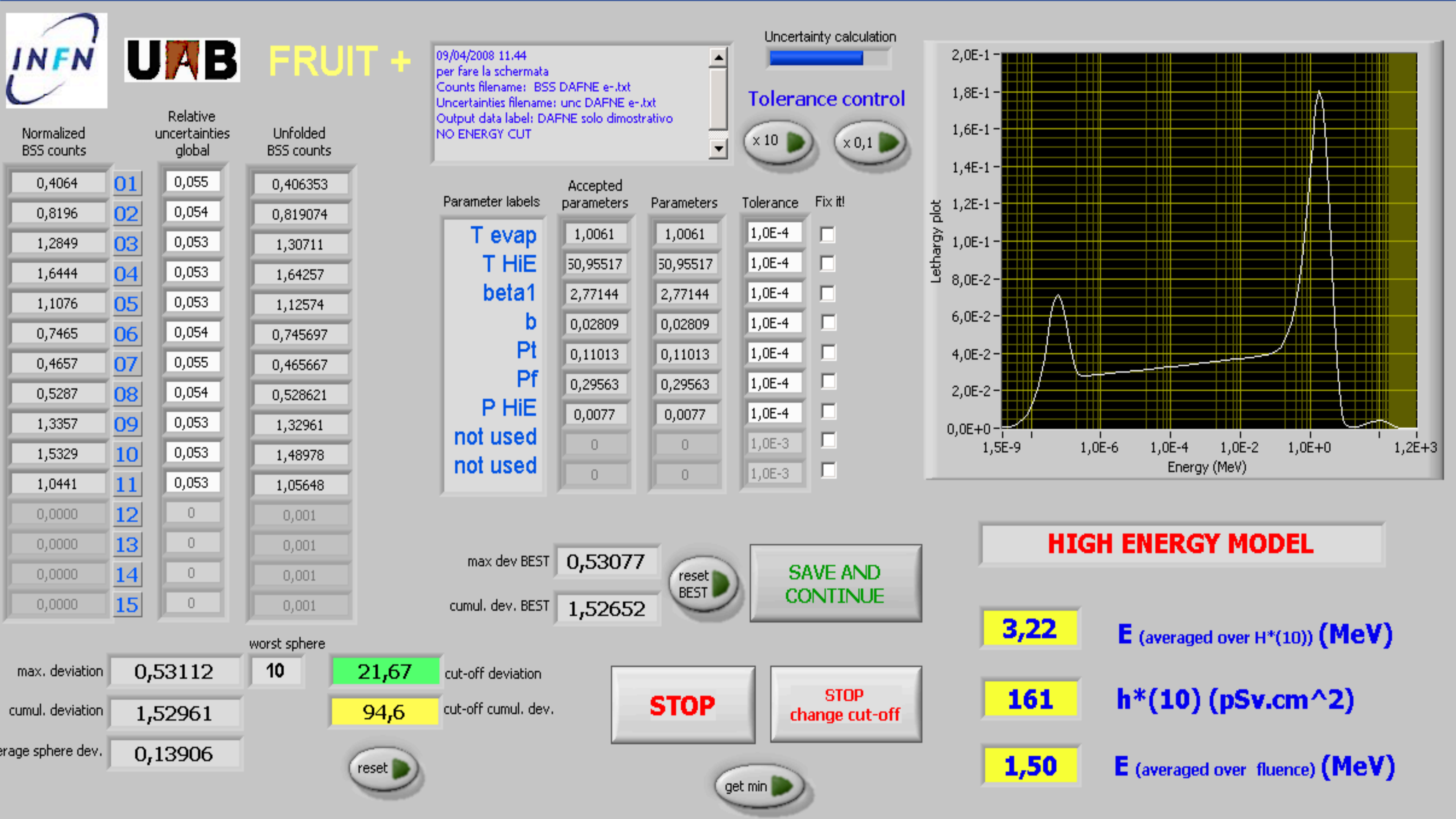
$\phi_{hi}(E)$ the high energy component.

Each component is individually normalized to the unit fluence by mean of an adequate normalization factor.

P_{th}, P_e, P_f and P_{hi} represent the fraction of thermal, epithermal, fast and high-energy neutrons, respectively.

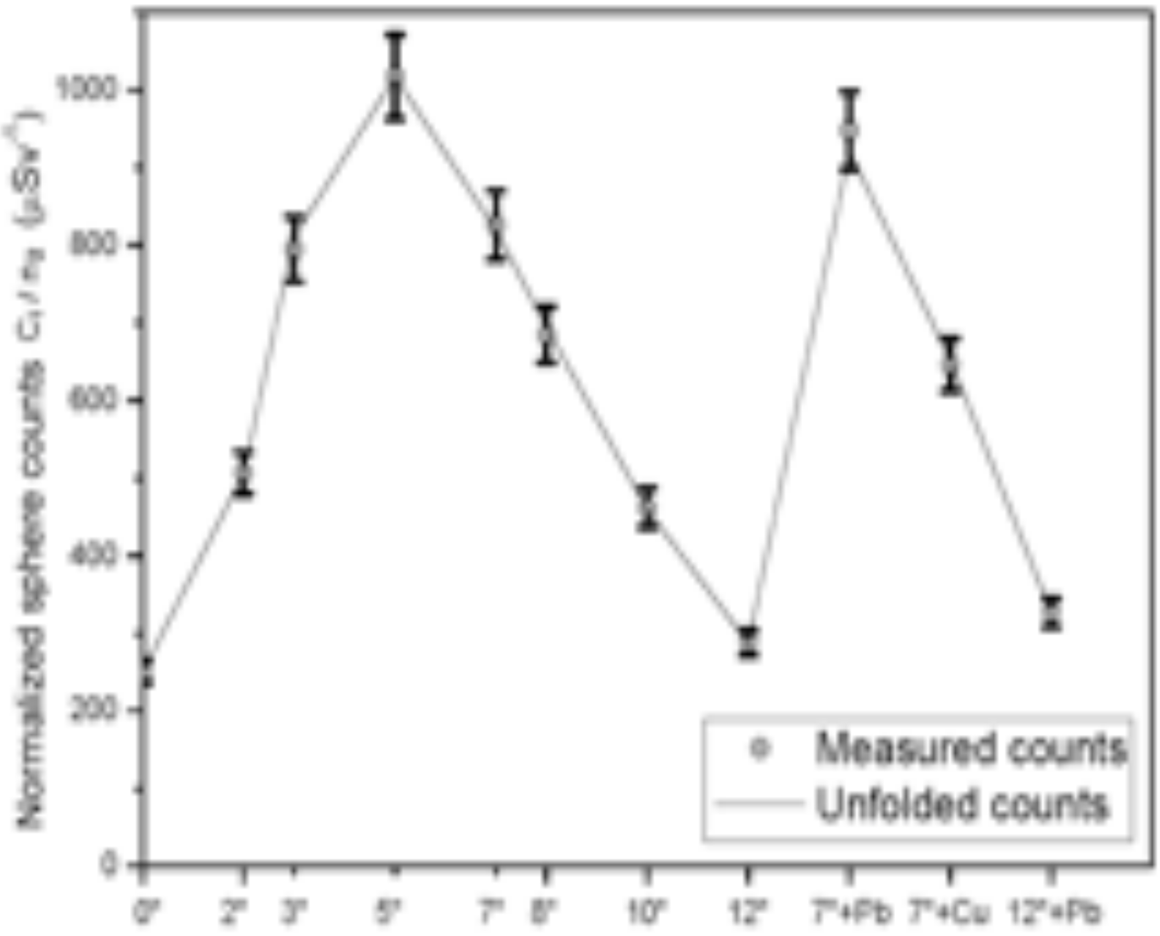
The ‘‘robust convergence theory’’ was modified and adapted to reduce the influence of the initial hypothesis on the results and to speed up the convergence procedure.

 Nuclear Instruments and Methods in Physics Research A 580 (2007) 1301-1309 FRUIT Control Panel



h*(10) = the spectrum averaged fluence-to-ambient dose equivalent conversion coefficient

E_{ϕ}= the fluence-average neutron energy $E_{H*(10}$= the ambient dose equivalent average neutron energy



The "unfolded counts" are calculated by applying the response function of each sphere to the spectrum unfolded with FRUIT.

The maximum difference between "measured" and "unfolded" counts is 3% (7"+Pb).

The figure show the consistency between the unfolded spectrum and the set of sphere counts.

Comparison between measured and unfolded sphere counts, for the different spheres.

Bonner Sphere Spectrometers equipped with passive detectors (activation foils among these) are mainly used in workplaces characterized by one or more of the following element:

High neutron fluence rate
High photon component
Sharply pulsed time structures
Large electromagnetic background

Active BSS may be affected by pile-up, saturation or dead time effects or by noise due to RF

As

research particle accelerators (near targets or inside irradiation room)

medical electron Linacs,

hadro-therapy facilities,

PET cyclotrons

A variety of passive detectors have been employed (TLD pairs, boron-covered PADC, activation foils, semi-active BSS) but the activation foils have been frequently preferred due to their insensitivity to photons and simple management.

The use of Gold, Indium and Dysprosium foils has been reported in literature, but gold foils are definitively the most popular even if

The foils should be chosen on the basis of:

- Neutron activation cross section
- Half-life, radioactive emission and counting system
- Presence of unwanted activation products and competing reactions (γ,n)
- Time structure of the beam

Nuclide	Abundance	Half life	counting
Au-197	100%	2.70 d	γ counters HpGe, NaI. β counters ZnS, GM
Dy-164	28%	2.33 h	β counters
In-115	96%	54 min	γ Counters or β counters

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Design and experimental validation of a Bonner Sphere Spectrometer based on Dysprosium activation foils

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Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Response matrix of an extended range Bonner sphere spectrometer for the characterization of collimated neutron beams

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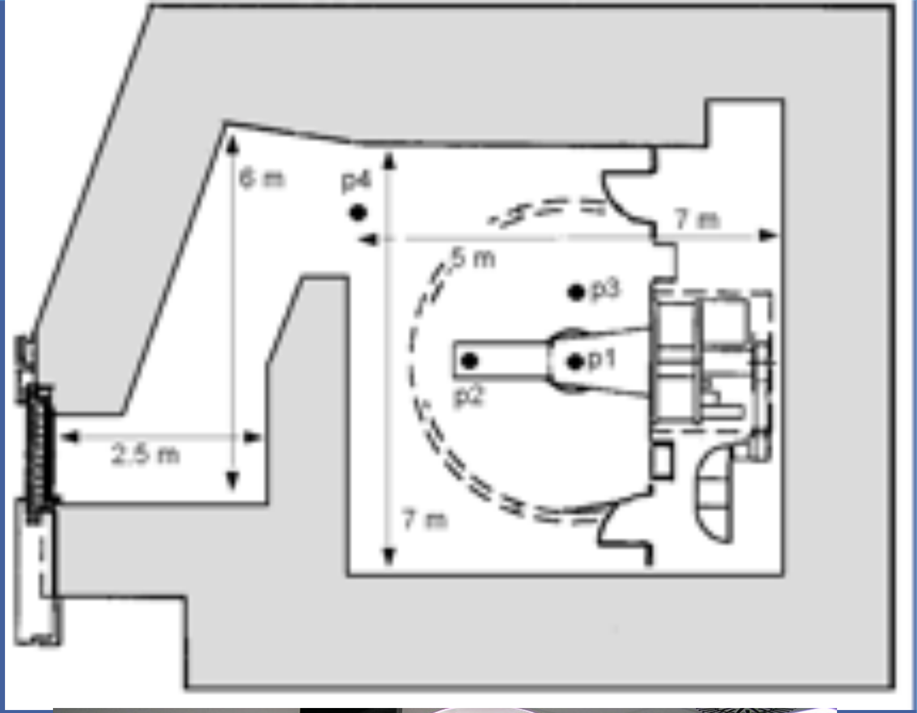
Medical accelerators

The measurement points in the treatment room of the 18 MV Elekta Precise LINAC, installed in the Hospital S. Maria della Scaletta (AUSL Ravenna, Italy) are shown in the figure nearby.



All points are located in the isocenter plane. The isocenter point is P1. P2 (on the patient couch) and P3 are respectively located at 1 m and 1.5 m from P1. P4 is located at 5 m in the maze entrance.

The combined technique was used in P2, P3 and P4, only gold foils were used at the isocenter (P1). Here the copious amount of photons would have probably masked the neutron signal on TLDs.

All spheres were subsequently irradiated to a corresponding isocenter photon dose of 1000 Monitor Units (10 Gy) with a square 15cm x 15cm field at the isocenter plane. The yield of the accelerator was (161±3) MU·min^{-1}.

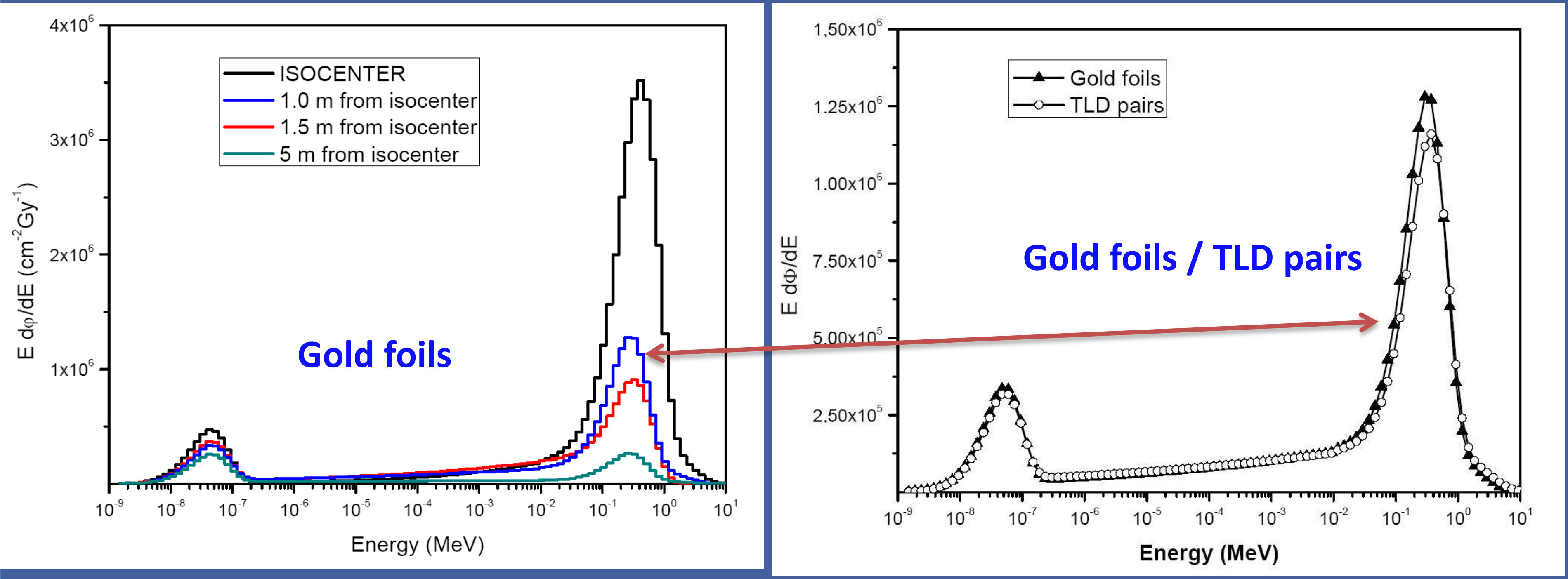
Results

The following quantities, considered important for the radiation protection of either patient or workers, were derived for all studied points and reported in Table 1.

- **The total neutron fluence per unit photon absorbed dose at the isocenter, Φ, measured in $cm^{-2} \cdot Gy^{-1}$;**
- **the evaporation, epithermal and thermal components of the neutron fluence (expressed as a fraction of the total fluence) P_{ev}, P_{epi} and P_{th};**
- **the fluence to ambient dose equivalent average conversion factor, $h^*(10) = H^*(10)/\Phi$, measured in $pSv \cdot cm^2$;**
- **the ambient dose equivalent per unit photon absorbed dose at the isocenter, $H^*(10)$, measured in $mSv \cdot Gy^{-1}$;**

Dosimetric and field quantities derived in the measurement points with the gold foil or TLD pairs-based BSSs

BSS type	Point	Φ ($cm^{-2}\,Gy^{-1}$)	P_{ev} (%)	P_{epi} (%)	P_{th} (%)	$h^*(10)$ ($pSv\,cm^2$)	$H^*(10)$ ($mSv\,Gy^{-1}$)
Gold foils	1	$9.11 \times 10^6 \pm 2.1\%$	64	27	9	$214 \pm 3\%$	1.95 ± 0.07
	2	$4.36 \times 10^6 \pm 2.1\%$	48	38	14	$141 \pm 7\%$	0.61 ± 0.05
	3	$3.98 \times 10^6 \pm 2.4\%$	36	47	17	$125 \pm 7\%$	0.50 ± 0.04
	4	$1.35 \times 10^6 \pm 4\%$	33	33	34	$98 \pm 11\%$	0.130 ± 0.015
TLDs	2	$4.15 \times 10^6 \pm 4\%$	45	41	14	$144 \pm 14\%$	0.60 ± 0.09
	3	$3.89 \times 10^6 \pm 4\%$	37	47	16	$136 \pm 10\%$	0.53 ± 0.05
	4	$1.33 \times 10^6 \pm 4\%$	32	35	33	$90 \pm 11\%$	0.120 ± 0.014

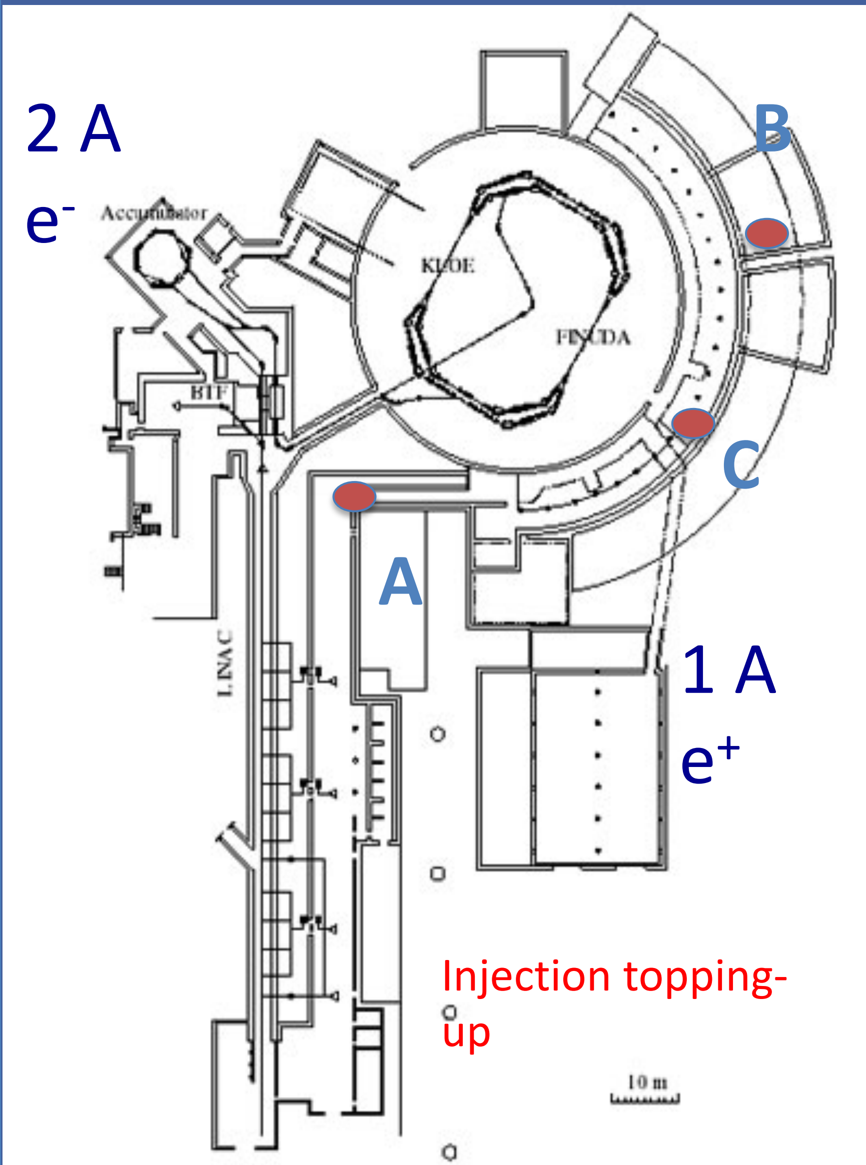


All spectra have an evaporation peak at 0.3 – 0.4 MeV, in agreement with most of the literature works (Thomas et al., 2002; Zanini et al., 2004; Kralik and Turek, 2004; Howell et al., 2005).

The spectra in the treatment room become softer as the distance from the isocenter increases.

In fact the factor $h^*(10)$ decreases from about 200 at the isocenter down to 100 at 5 m distance as shown in the previous table.

It is worth noticing that, whilst the fluence due to the direct "evaporation" component roughly decreases with the inverse square distance from the isocenter, the thermal fluence is roughly constant. This agrees with the formulation from McGinley (1998).



How to select the points for measuring the neutron spectra?

We chose for measurements some "weak point" from the point of view of the radiation shielding.

All these points are located in the non shielded upper window of the DAΦNE building (around 12 meters from ground), from which some skyshine radiation arises.

Measurements at DAΦNE

Quantity	($pSv.cm^2$)
Point A	58
Point B	63
Point C	155

spectrum averaged fluence-to-ambient dose equivalent conversion coefficient

Quantity	Point A	Point B	Point C
h^*_φ ($pSv.cm^2$)	58	63	155
Fluence below 0.4 eV	31%	37%	29%
Fluence above 10 MeV	1%	1.6%	5%
$H^*(10)$ above 10 MeV	6%	8.6%	11%
Φ ($cm^{-2}.MU^{-1}$)	17.0±0.6	12.4 ± 0.4	27.8 ± 1.0
$H^*(10)$ ($\mu Sv.MU^{-1}$)	$(9.5\pm0.3)\cdot10^{-4}$	$(7.8\pm0.2)\cdot10^{-4}$	$(4.31\pm0.15)\cdot10^{-3}$
LB6411 ($\mu Sv.MU^{-1}$)	$(8.2\pm0.4)\cdot10^{-4}$	$(7.1\pm0.4)\cdot10^{-4}$	$(3.3\pm0.2)\cdot10^{-3}$
LB6411-Pb ($\mu Sv.MU^{-1}$)	$(8.5\pm0.4)\cdot10^{-4}$	$(7.5\pm0.4)\cdot10^{-4}$	$(3.9\pm0.2)\cdot10^{-3}$
AUTOMESS $\mu Sv.MU^{-1}$)	$(4.8\pm0.2)\cdot10^{-4}$	$(6.6\pm0.3)\cdot10^{-4}$	$(1.40\pm0.07)\cdot10^{-3}$
Monitor unit rate ($MU.s^{-1}$)	0.108±0.016	0.070 ± 0.017	2.3±0.4
$\dot{\Phi}$ ($cm^{-2}.s^{-1}$)	1.8±0.3	0.87± 0.21	64±11
$H^*(10)$ ($\mu Sv.h^{-1}$)	0.37±0.06	0.20 ± 0.05	36 ± 7

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A

C

Point B. As expected, the giant resonance peak is more evident here than in point A

Point C. The main difference between this point and points A and B is the importance of the evaporation peak, due to the unshielded irradiation condition

The so called "workplace specific calibration factor" of the LB6411 in point

A is 1.16 B is 1.10 C is 1.31

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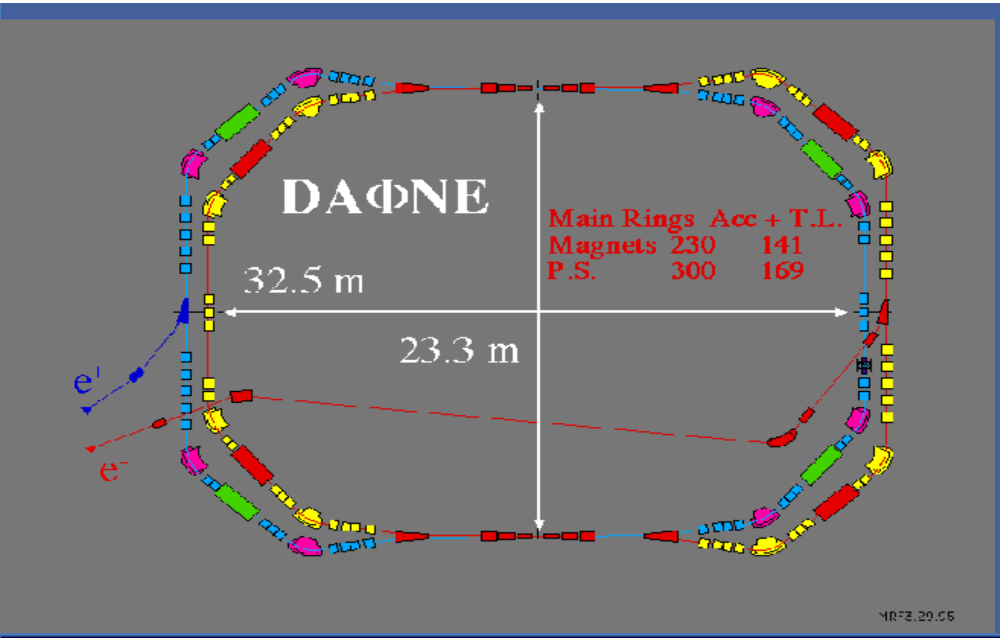
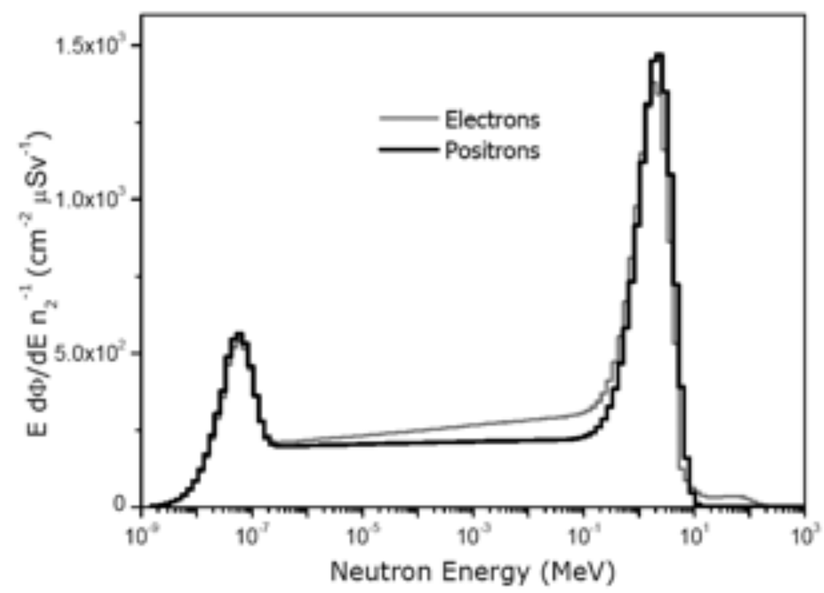
Measurements at DAΦNE

Some special run of the DAΦNE complex was devoted to a neutron spectrometry benchmark. The aim of such measurements was to study the neutron spectrum in an unshielded irradiation condition using only e- or e+. The ERBSS was placed inside the DAΦNE building, along the main axis of the collider.

Particle injected	Φ/n_2 ($cm^{-2}\ \mu Sv^{-1}$)	$H^*(10)/n_2$	$h^*(10)$ ($pSv\cdot cm^2$)	Fluence fraction (Energy in MeV) < 0.1	0.1-10	> 10	$H^*(10)$ fraction (Energy in MeV) < 0.1	0.1-10	> 10
e^-	$(7.54\pm0.19)\cdot10^3$	1.20±0.06	159±7	58.6%	40.4%	1%	5.3%	91.7%	3%
e^+	$(6.99\pm0.24)\cdot10^3$	1.22±0.07	176±12	55.4%	44.5%	0.1%	4.4%	95.5%	0.1%

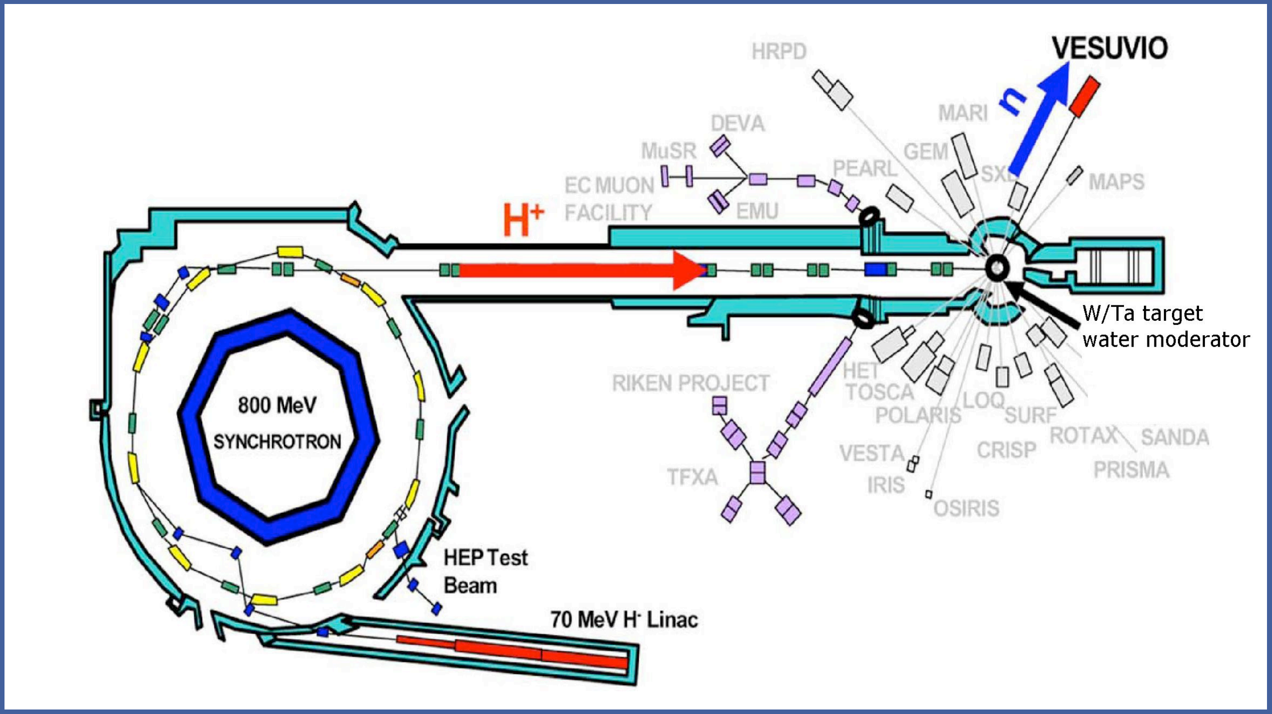




Measurements at VESUVIO

ISIS is the multi-purpose spallation neutron source of the *Rutherford Appleton Laboratory, Oxfordshire, UK*.

At ISIS, an accelerator complex formed by an H^- injector and a synchrotron allows bombarding a W/Ta target with 800 MeV protons.



The target is surrounded by four reflector/moderator assemblies (H_2O, liquid CH_4@100 K and liquid H_2 @ 20 K)

Chip Irradiation Beamline

Measurements at VESUVIO

The thermal neutron detector for the ERBSS was chosen according to:

- Intensity of the field
- photon component
- Pulsed time structure of the field

- Active counters could not be used.

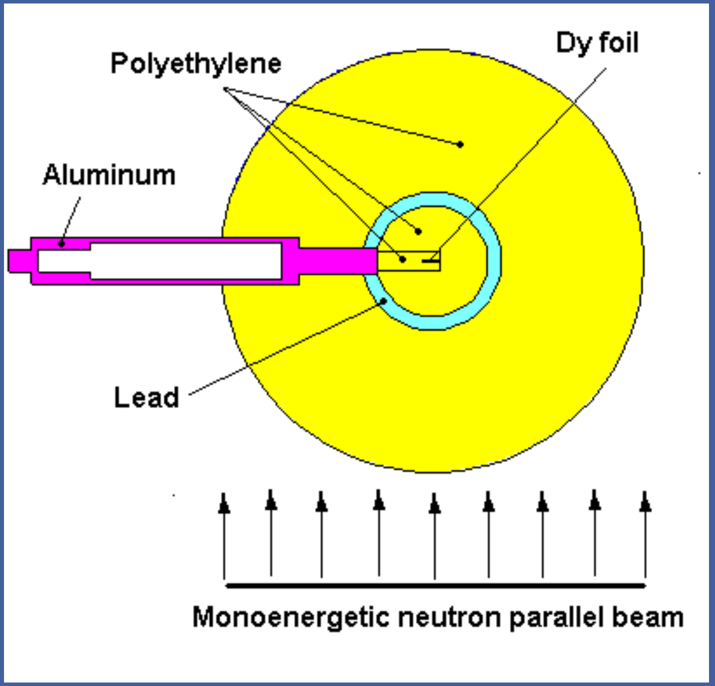
- TLD pairs ($^{6}Li/^{7}Li$) could be affected by large uncertainties due to the presumably large photon component.

- Activation foils:

The traditional gold-foils based BSS has several advantages (well established, validated) but the activation signal, especially in large or metal loaded spheres (high-energy component) could be insufficient to be counted in situ, with good statistics, using a portable counter.

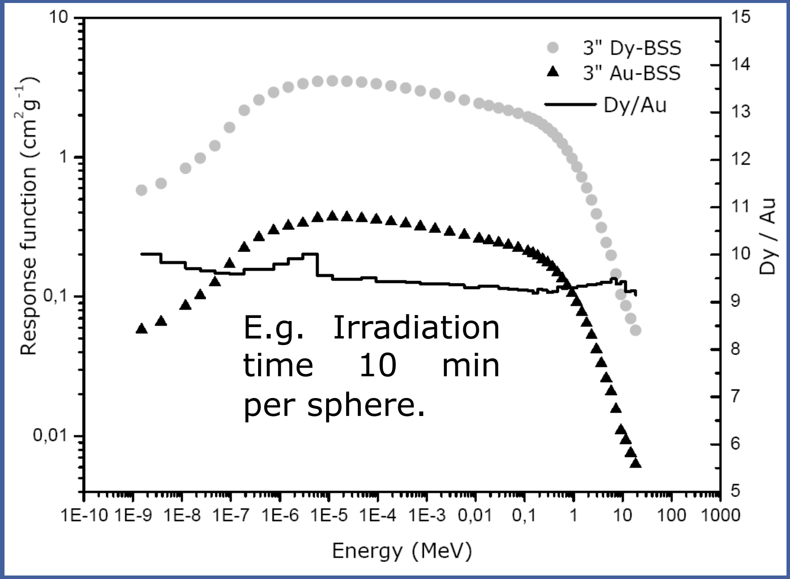
Measurements at VESUVIO

A Dy-foils based ERBSS for **rapid, in-situ** measurements in medium-high intensity fields (>10^2 $cm^{-2}s^{-1}$) such as medical LINACs, PET cyclotron or nuclear plants were used for Vesuvio measurements



The foils have diameter 12.7 mm, 25 μm thickness and purity > 99.9%.

With respect to Au:
Higher σ_{act} (2700 barn vs. 99 barn)
Lower $T_{1/2}$ (2.34 h vs. 2.7 d)



The percentage of the saturation activity reached by Au or Dy is 0.2% or 4.8% respectively.
The effective advantage in terms of measurable activity is therefore **9 * 4.8/0.2 ~ 220**

Measurements at VESUVIO

The ISIS proton current ranged from 170 to 190 μA.
Each sphere was exposed for about 20 minutes.

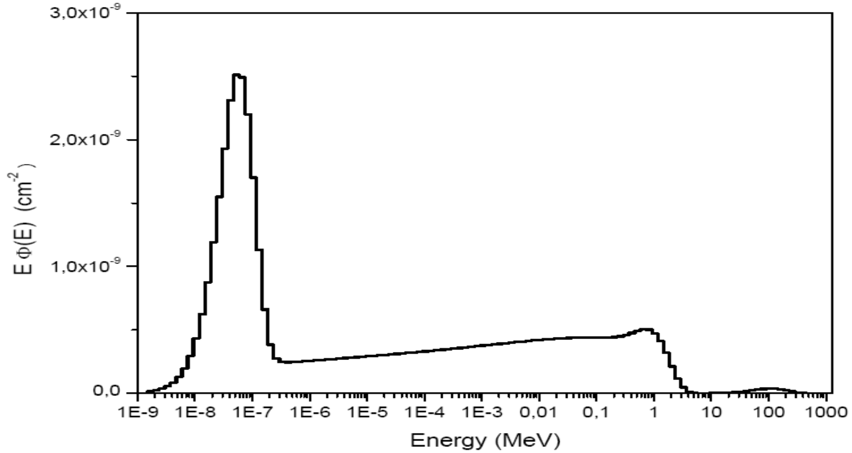
The Dy foils were counted and corrected for: **(1)** exposure to counting delay, **(2)** decay during counting, **(3)** saturation.

The saturation specific activities (10^3 to 10^5 Bq.g^{-1}) were normalized to the proton current and unfolded with FRUIT

Integral quantities related to the neutron spectrum of the VESUVIO beam-line.

Total fluence normalized to one incident proton	$(1.07 \pm 0.06) \times 10^{-8}\,\text{cm}^{-2}$
Fluence fraction ($E < 0.4\,\text{eV}$)	46.9%
Fluence fraction ($0.4\,\text{eV} < E < 100\,\text{keV}$)	40.9%
Fluence fraction ($100\,\text{keV} < E < 10\,\text{MeV}$)	11.5%
Fluence fraction ($E > 10\,\text{MeV}$)	0.7%

The uncertainty of the total fluence (about 5%) is mainly due to the uncertainty of the ^{152}Eu source (4%) used to calibrate the beta counter.



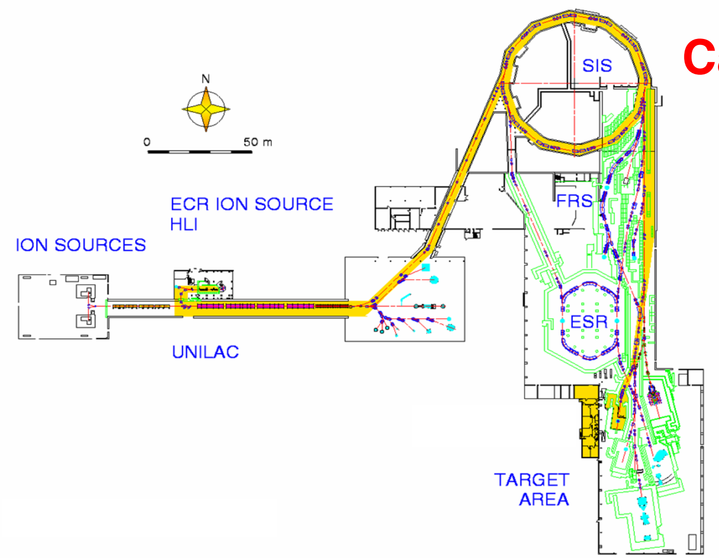
Measurements at GSI

❖The European Commission has funded within its 6th Framework Programme a three-year project (2005–2007) called CONRAD, COordinated Network for RAdiation Dosimetry.

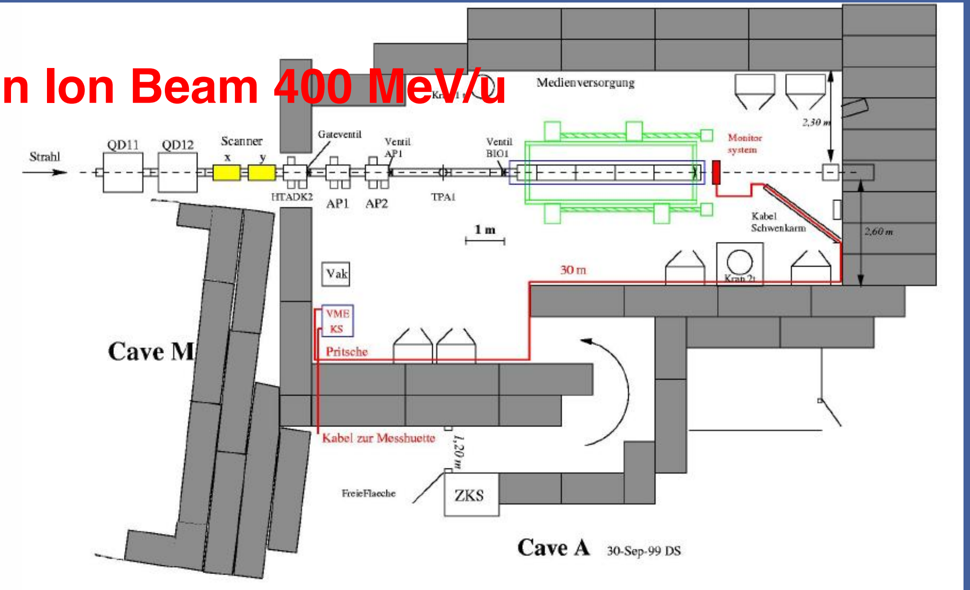
❖A major task of the CONRAD Work Package “complex mixed radiation fields at workplaces” was to organise a benchmark exercise in a workplace field at a high-energy particle accelerator where neutrons are the dominant radiation component. The CONRAD benchmark exercise took place at the Gesellschaft für Schwerionenforschung mbH (GSI) in Darmstadt, Germany in July 2006.

Radiation Measurements
Volume 44, Issues 7-8, August-September 2009, Pages 660-672

Intercomparison of radiation protection devices in a high-energy stray neutron field. Part III: Instrument response

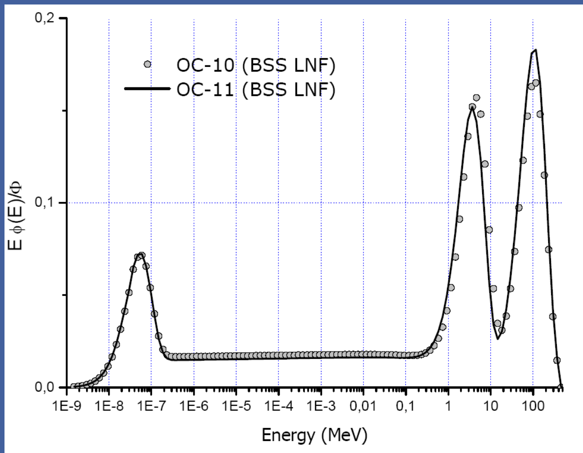


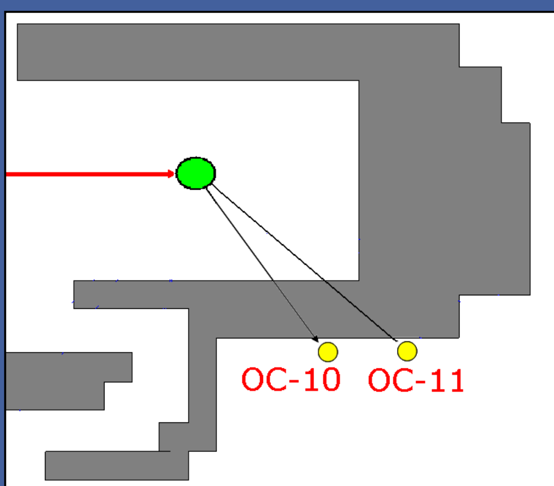
Carbon Ion Beam 400 MeV/u



Measurements at GSI

Comparison OC-10 & OC-11





Quantity	OC-11
HMGU	
$\Phi/\mathrm{cm}^{-2}\,\mathrm{nC}^{-1}$	142.5 ± 1.2
$\Phi_{thm}/\Phi/\%$	13.1
$\Phi_{int}/\Phi/\%$	19.5
$\Phi_{fst}/\Phi/\%$	28.5
$\Phi_{hgh}/\Phi/\%$	38.9
INFN (act. BSS)	
$\Phi/\mathrm{cm}^{-2}\,\mathrm{nC}^{-1}$	146 ± 4
$\Phi_{thm}/\Phi/\%$	6.2
$\Phi_{int}/\Phi/\%$	28.6
$\Phi_{fst}/\Phi/\%$	33.1
$\Phi_{hgh}/\Phi/\%$	32.1
PTB	
$\Phi/\mathrm{cm}^{-2}\,\mathrm{nC}^{-1}$	139.2 ± 6.3
$\Phi_{thm}/\Phi/\%$	15.6
$\Phi_{int}/\Phi/\%$	18.6
$\Phi_{fst}/\Phi/\%$	30.7
$\Phi_{hgh}/\Phi/\%$	35.1
FLUKA/MCNPX	
$\Phi/\mathrm{cm}^{-2}\,\mathrm{nC}^{-1}$	151.7 ± 7.6
$\Phi_{thm}/\Phi/\%$	9.7
$\Phi_{int}/\Phi/\%$	11.9
$\Phi_{fst}/\Phi/\%$	28.5
$\Phi_{hgh}/\Phi/\%$	49.9

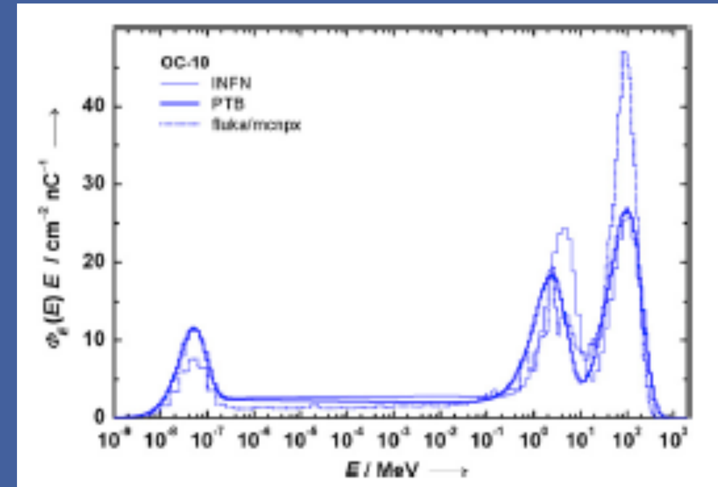


Fig. 6. Neutron spectra at position OC-10, measured by INFN and PTB and calculated with FLUKA/MCNPX.

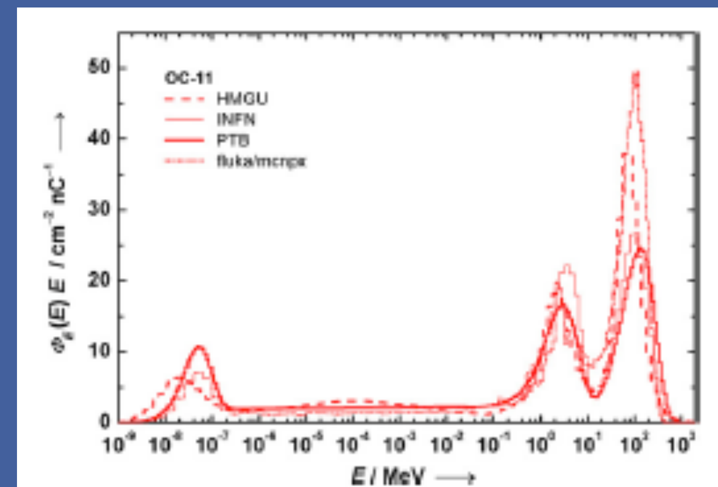
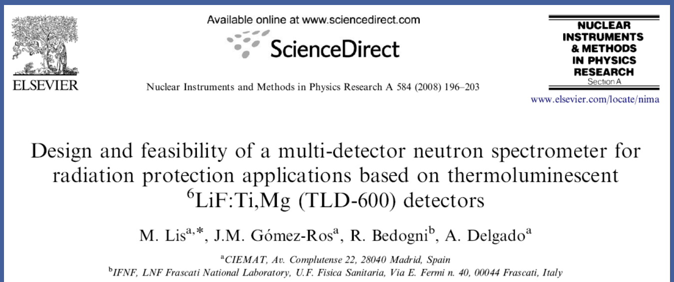


Fig. 7. Neutron spectra at position OC-11, measured by HMGU, INFN and PTB and calculated with FLUKA/MCNPX.

The spherical spectrometer



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
Nuclear Instruments and Methods in Physics Research A 584 (2008) 196–203
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Design and feasibility of a multi-detector neutron spectrometer for radiation protection applications based on thermoluminescent ^{6}LiF:Ti,Mg (TLD-600) detectors

M. Lis[a],*, J.M. Gómez-Ros[a], R. Bedogni[b], A. Delgado[a]

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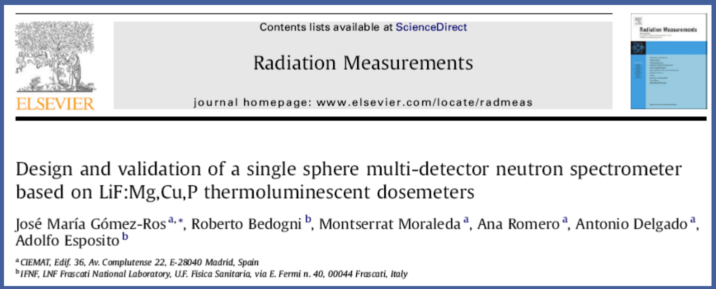
[b]IFNF, LNF Frascati National Laboratory, U.F. Fisica Sanitaria, Via E. Fermi n. 40, 00044 Frascati, Italy



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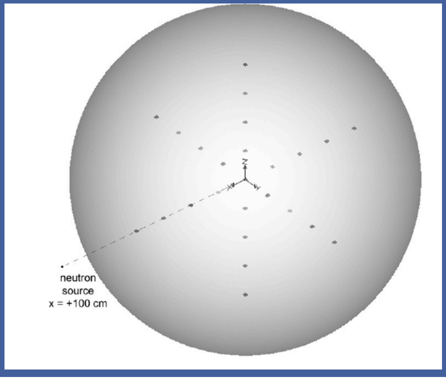
Design and validation of a single sphere multi-detector neutron spectrometer based on LiF:Mg,Cu,P thermoluminescent dosemeters

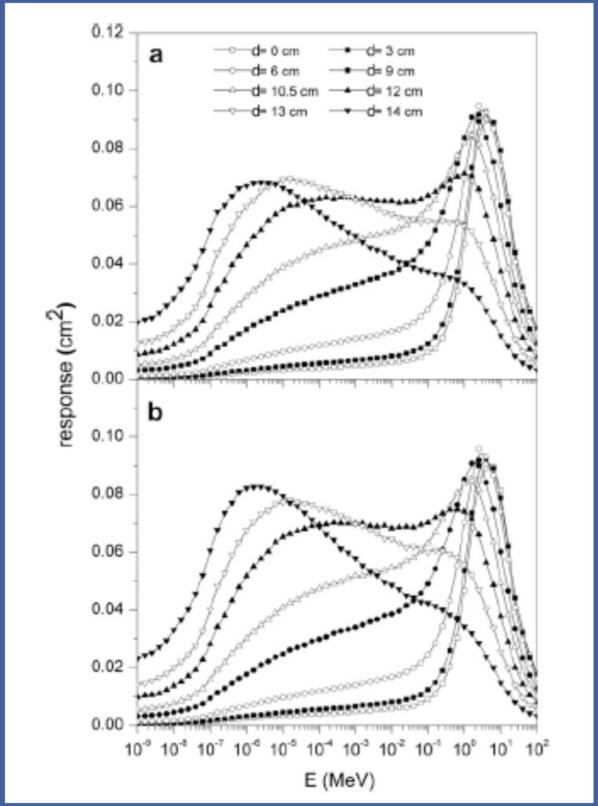
José María Gómez-Ros[a],*, Roberto Bedogni[b], Montserrat Moraleda[a], Ana Romero[a], Antonio Delgado[a], Adolfo Esposito[b]

[a]CIEMAT, Edif. 36, Av. Complutense 22, E-28040 Madrid, Spain
[b]IFNF, LNF Frascati National Laboratory, UF. Fisica Sanitaria, via E. Fermi n. 40, 00044 Frascati, Italy

Radiat. Meas. (2010) 45 1220-1223

Nucl.Instrum.Meth. A 584 (2008) 196–203





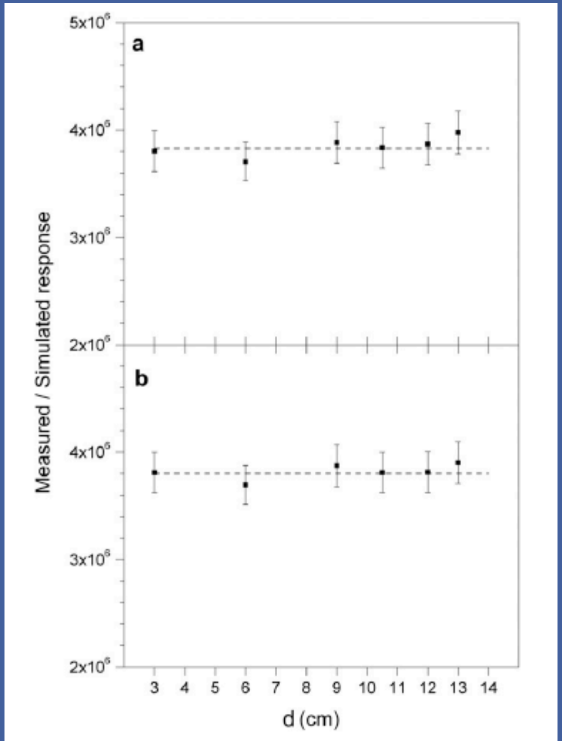
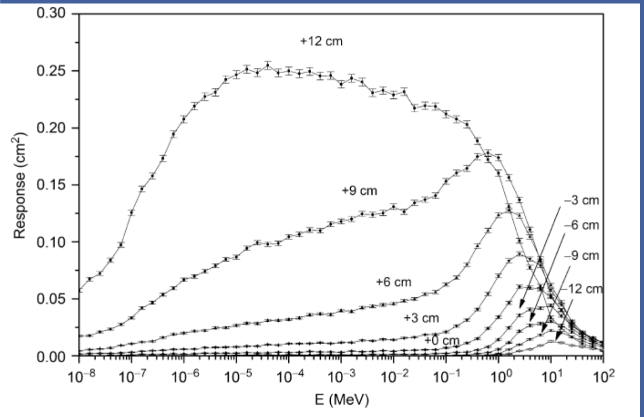


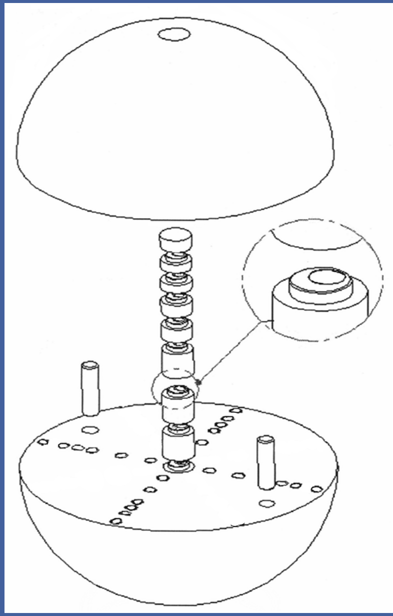
Fig. 4. Measured/simulated response ratio for: a) monodirectional response matrix; b) isotropic response matrix. Experimental uncertainties are around 5% for each data point.



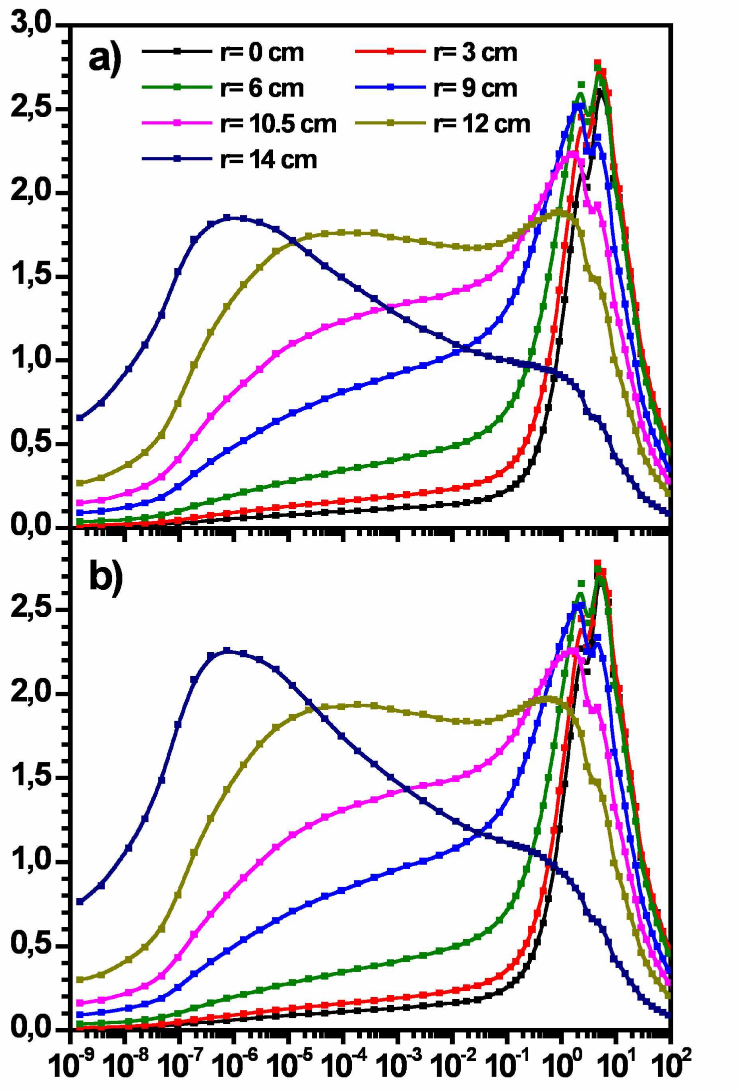
N E S C O F I

NEutron Spectrometry in COmplex FIelds

(SP)² **SP**herical **SP**ectrometer



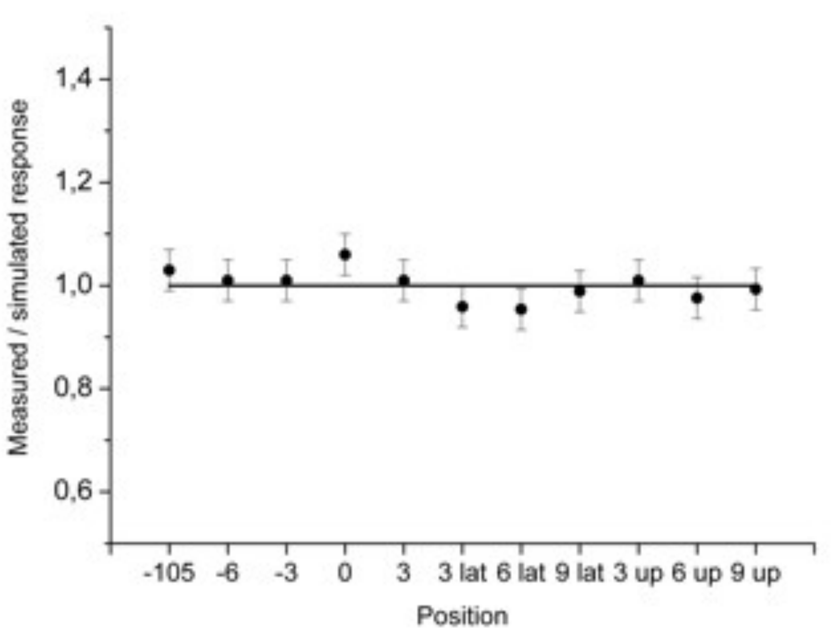
Stesso spettrometro con lamine di attivazione

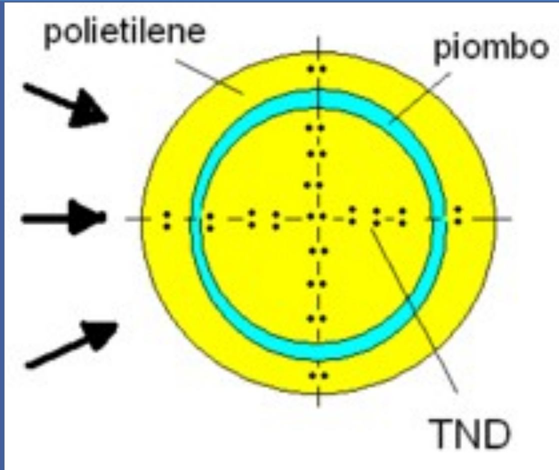


Design and validation of a photon insensitive multidetector neutron spectrometer based on Dysprosium activation foils

Radiation Measurements (2011), doi: 10.1016/j.radmeas.2011.06.037

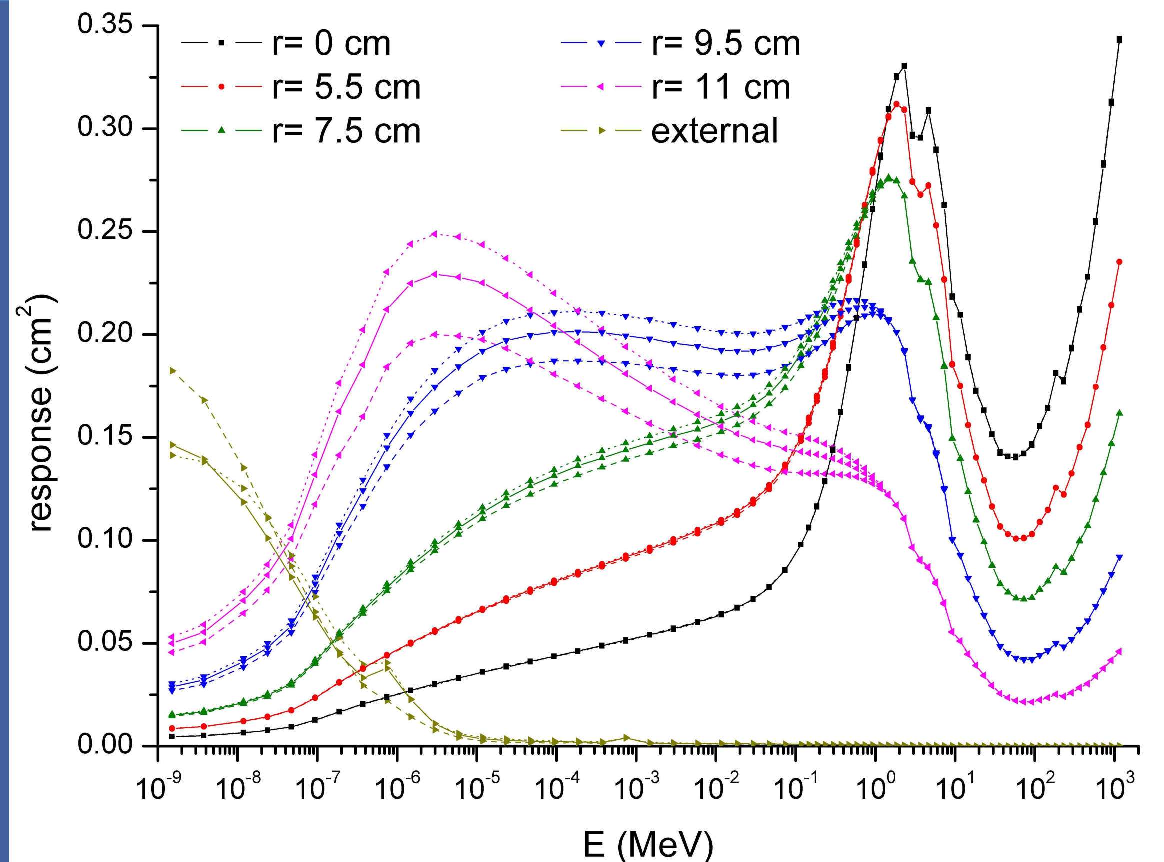
Test performed at the FNG

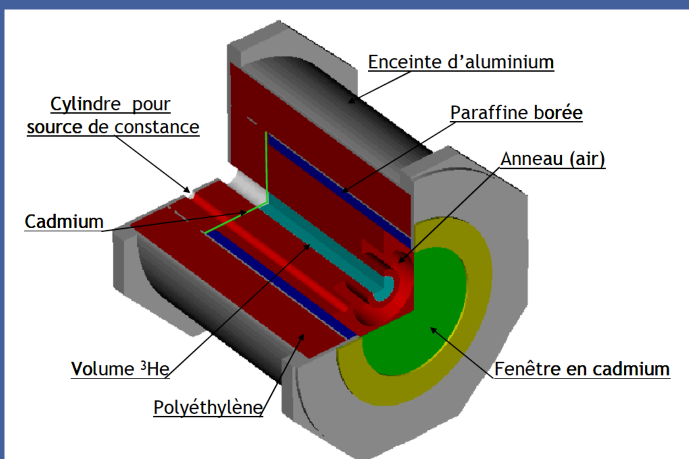




Diámetro: 25 cm

Pb: **3.5 - 4.5 cm**





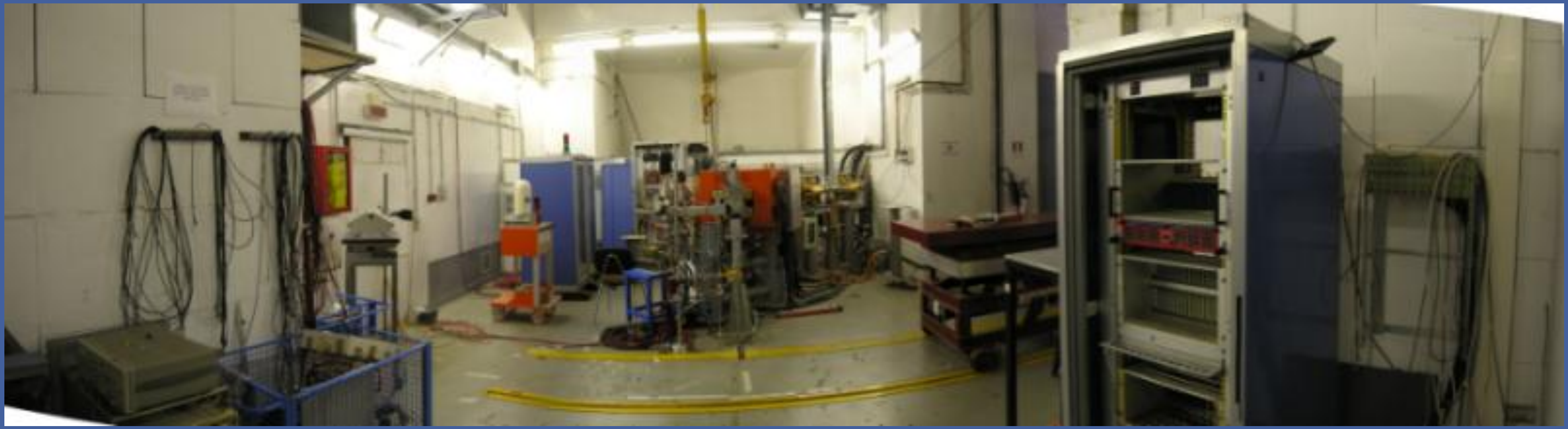
CYSP CYlindrical SPectrometer

Test of a single polyethylene **Bonner Cylinder** with multiple activation foils as a suitable spectrometer for collimated beams.

The development of such spectrometric techniques is part of the design effort for the CHIPIR beam line on TS –II, and VESUVIO beam line provides a unique tool for testing.

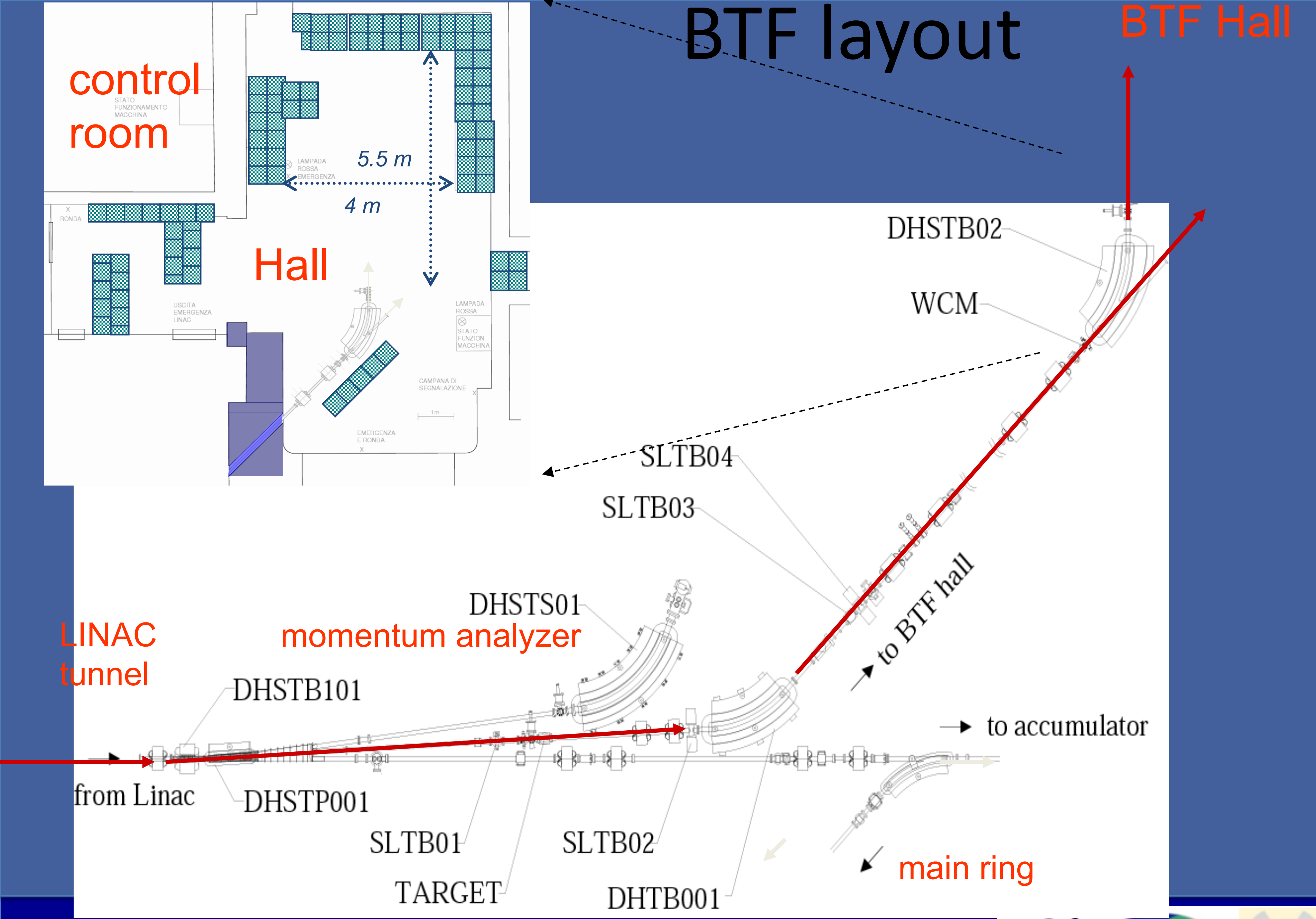
"n@BTF"

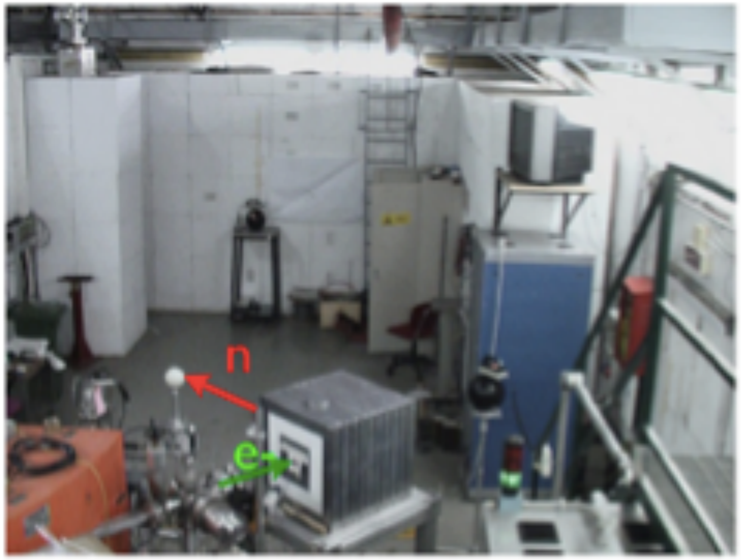
Produzione di neutroni alla Beam Test Facility (BTF) dei Laboratori Nazionali di Frascati



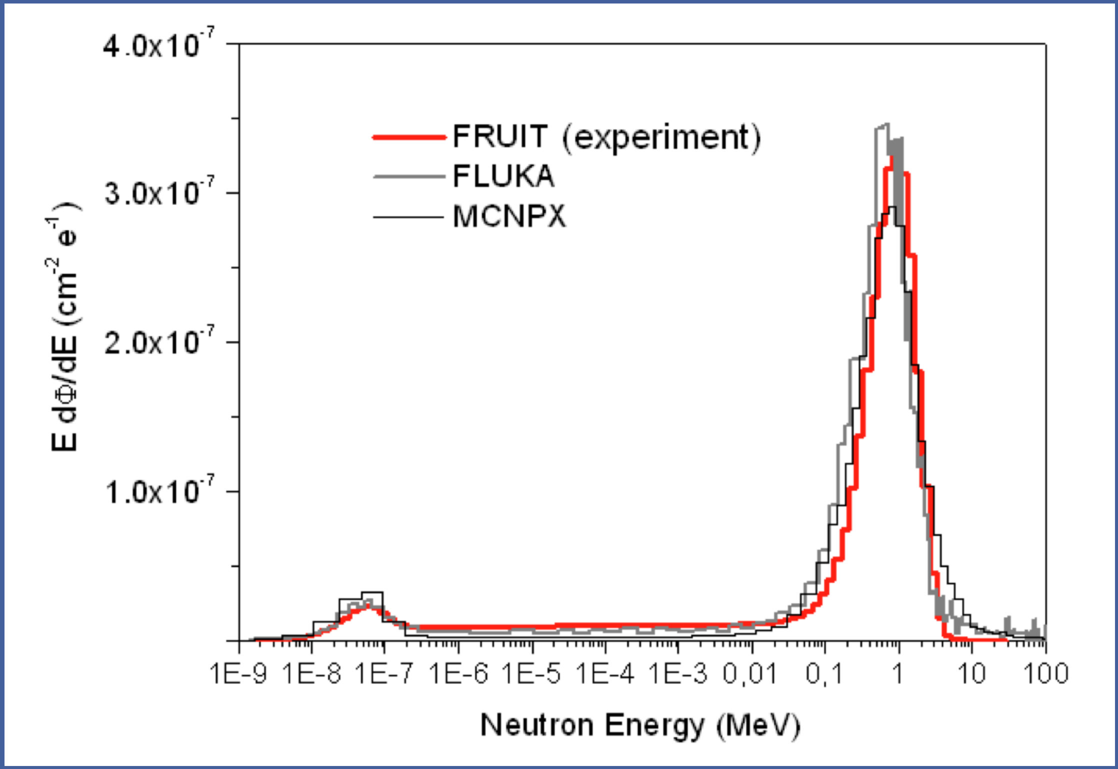
 Adolfo.Esposito@lnf.infn.it
INFN LNF Radiation Protection Group

BTF layout


BTF Hall
control room
STATO FUNZIONAMENTO MACCHINA
LAMPADA ROSSA EMERGENZA
5.5 m
4 m
RONDA
Hall
USCITA EMERGENZA LINAC
LAMPADA ROSSA
STATO FUNZION MACCHINA
CAMPANA DI SEGNALAZIONE
1m
EMERGENZA E RONDA
DHSTB02
WCM
SLTB04
SLTB03
to BTF hall
DHSTS01
LINAC tunnel
momentum analyzer
DHSTB101
to accumulator
from Linac
DHSTP001
SLTB01
SLTB02
main ring
TARGET
DHTB001



4.5×10^5 n cm^{-2} s^{-1}



Conclusion

✧**An accurate knowledge of the neutron spectrum is often necessary for assessing the radiation protection conditions at workplace.**

✧**The accuracy of determining the operational quantities with neutron spectrometry depends entirely on the accuracy with the energy and direction distributions of neutron fluences are determined**

✧An accurate determination of H*(10) in workplace field of unknown direction distribution can be achieved through the use of the Bonner Sphere Spectrometer (BSS), an appropriate central detector and a suitable unfolding code.

✧I have shown

- ✧ the results obtained with the ERBSS of LNF and FRUIT code
- ✧the future improvements of such technique: a spherical Spectrometer and cylindrical spectrometer
- ✧ the characteristic of n@BTF

Thank you for your attention