MASTER DI II LIVELLO IN RADIOPROTEZIONE

Neutron measurements around accelerators

Adolfo Esposito

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Neutron measurements around accelerators

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Introduction

Since the discovery of the natural and artificial radioactivity, at the end of the 19th century, the use of ionizing radiation in all human practices has known an increase without any break.

Concerning only activities with particles accelerators, a number not less of about 18000 machines are in operation worldwide mainly distributed in industrial countries

Category of accelerators	**Number in use (1994)**	**Number in use (2002)**
Research accelerators	≈ 112	≈ 120
Accelerators in industry	≈ 1500	>1500
Ion implanters+surface modification	≈ 3000	> 7000
Synchrotron radiation source	≈ 50	≈ 50
Radiotherapy	≈ 4000	> 7500)
Medical Research	≈ 800	≈ 1000
Radioisotope production	≈ 200	≈ 200
Total	**≈ 9962**	**≈17370**

80% of increase in 8 years

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During the operation of accelerators, stray radiation fields are generated by beam loss in beam line components and other material that may hit the beam.

At electron machines the secondary radiation is dominated by bremsstralhung photons and high energy electron in the electromagnetic cascade.

At high energy proton accelerators the secondary radiation is dominated by hadronic cascade containing neutrons, charged hadrons, muons, photons and electrons.

Monitoring of ionising radiation around high-energy particle accelerators is a difficult task due to the complexity of the radiation field.

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The ability to distinguish between the high-LET and the low-LET components of the radiation field at workplace and to measure them is of primary importance to evaluate the exposure of the personnel as well as the environmental impact of the accelerators operation.

At proton machines

mainly to neutrons

minor extent to photons and to charged particles

The ambient dose equivalent outside a thick shield is due

At high-energy electron accelerators

mainly to neutrons

minor extent to photons

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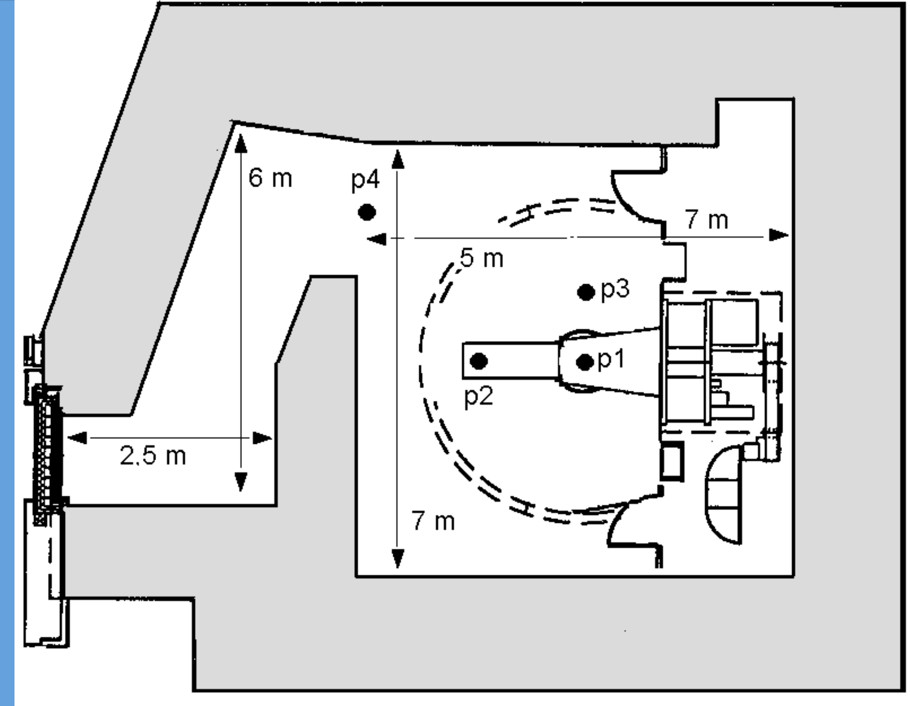
Medical accelerators

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}.

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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

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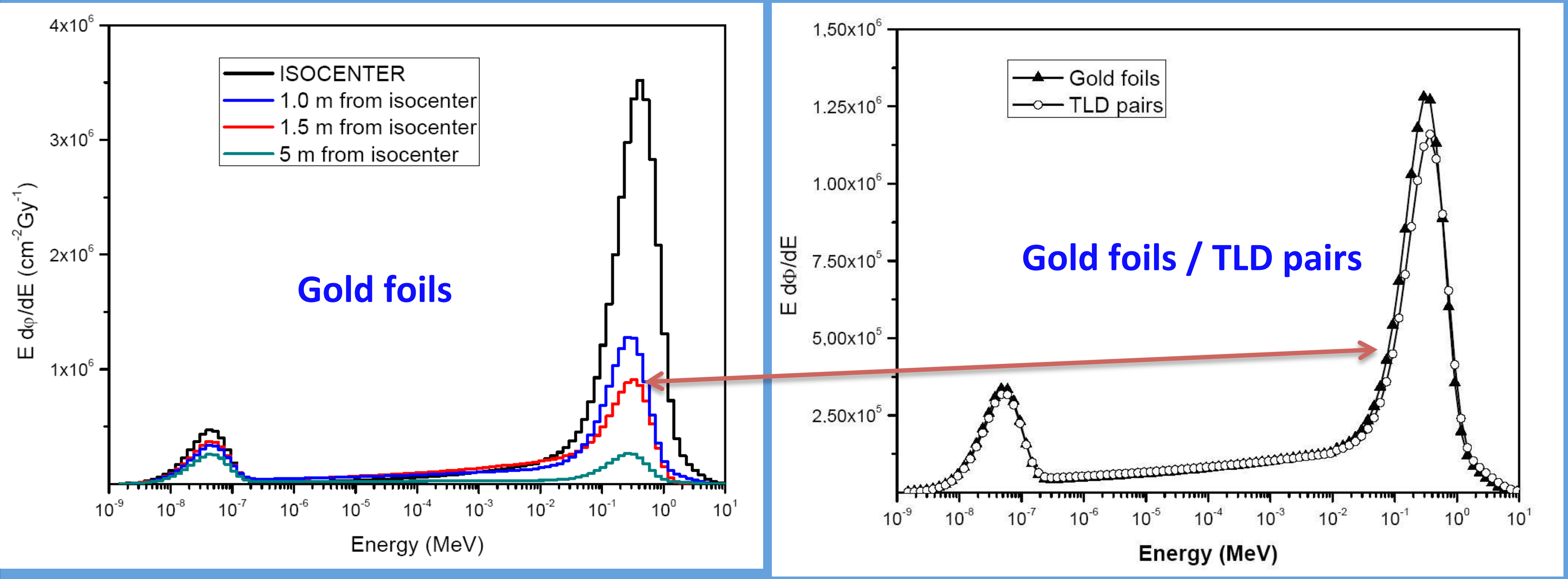

All spectra have an evaporation peak at 0.3 – 0.4 MeV, in agreement with most of the literature works (Thomas et al., 2002; Zanini et al., 2004; Kralik and Turek, 2004; Howell et al., 2005).

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).

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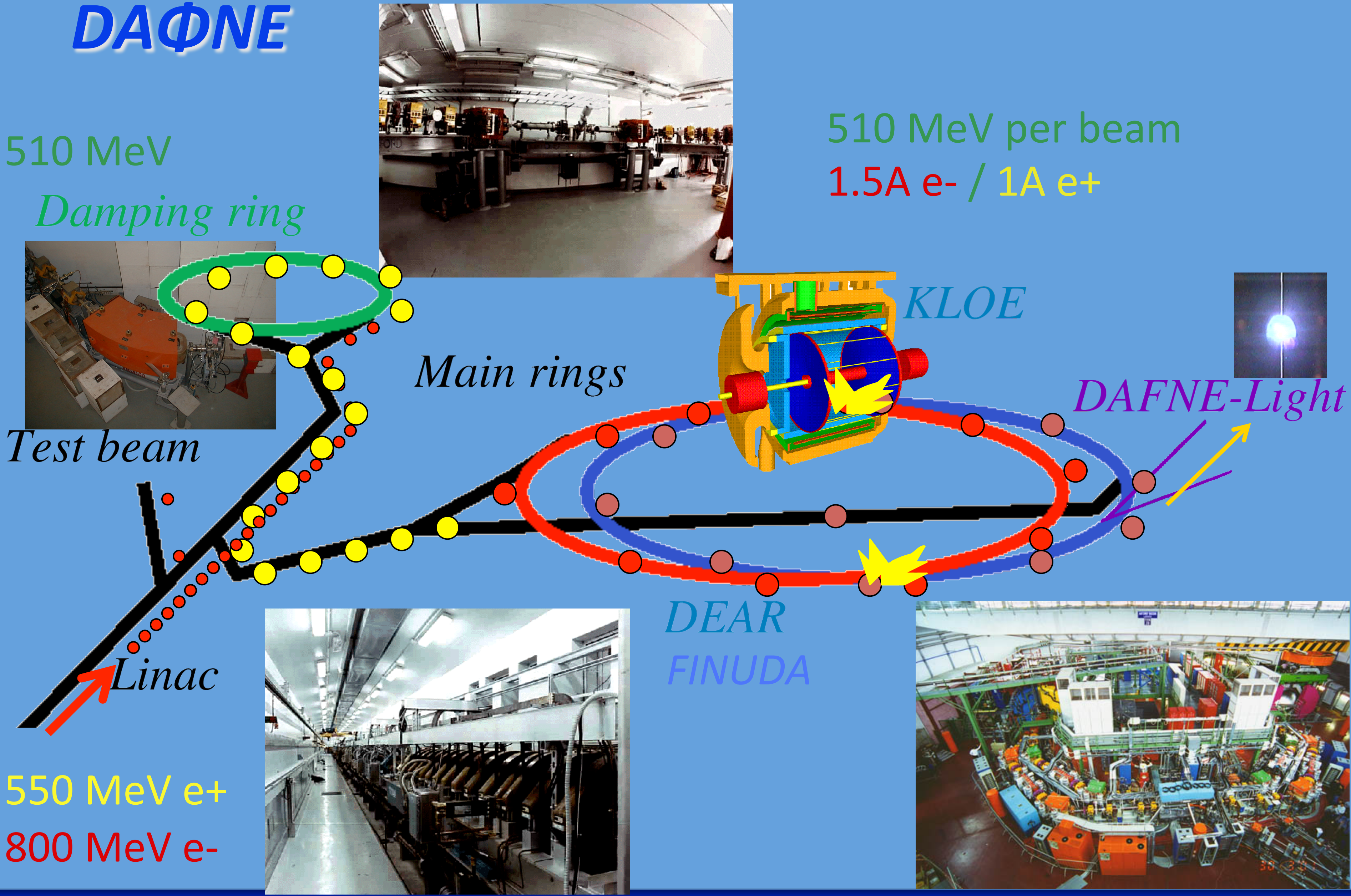
DAΦNE



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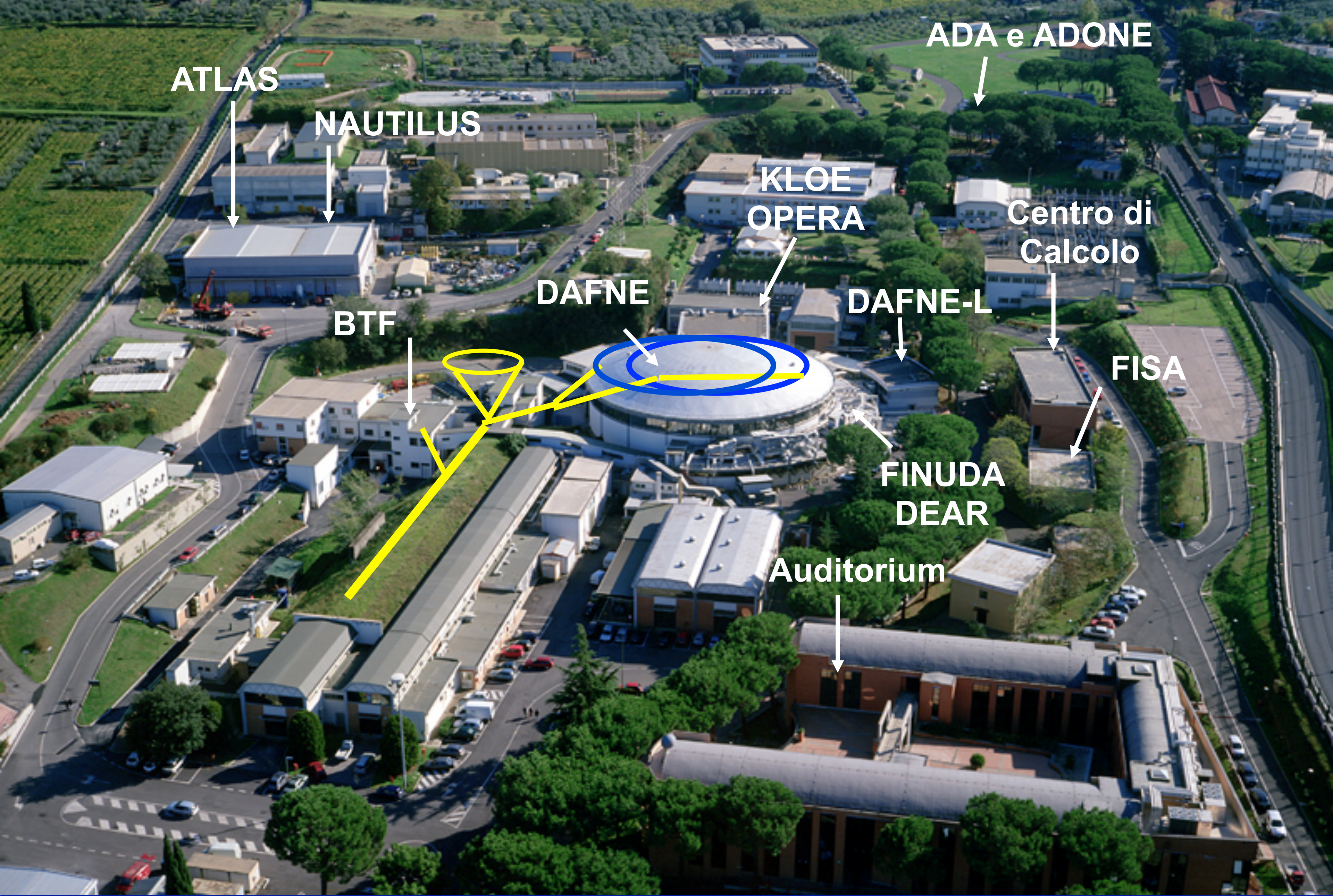

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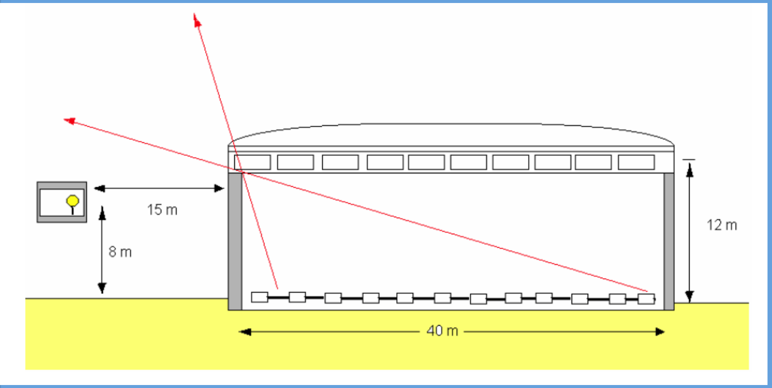
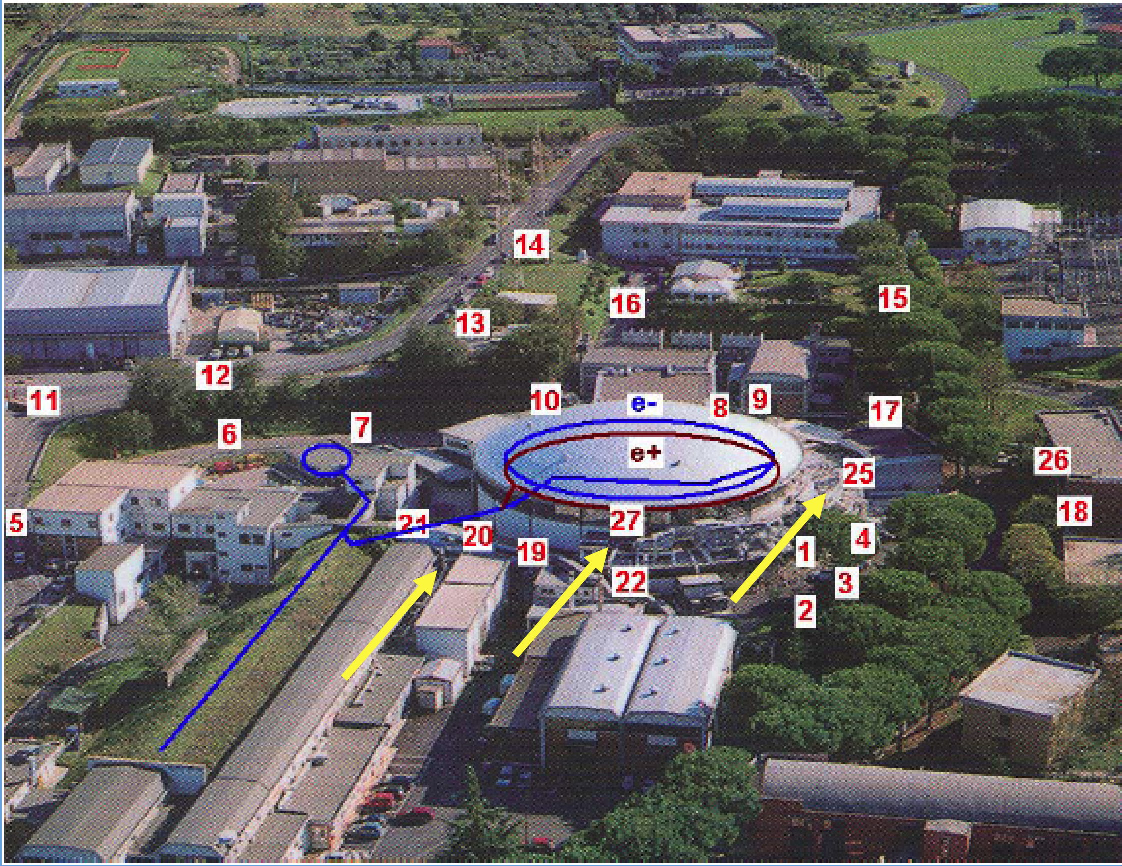
The neutron spectra in points 20, 25 and 27 of the active monitoring network around DAΦNE complex have been measured with BSS spectrometer.

Points 20, 25 and 27 were chosen as representative of different neutron spectra possible.



Irradiation geometry of point 20



Point 25 is located inside a building at 5 m height from ground and 8 m from the big window. It has the same geometry of point 20

Point 27 is located inside DAΦNE building. It faces the accelerator

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The spheres plus the bare detector have been sequentially exposed in the measurement point for one day each.

All BSS reading have been normalized to an independent monitor, in order to eliminate any time variation of the neutron fluence rate.

A rem counter ALNOR 2002B has been used as monitor instrument. Its counts are called "Monitor Units", MU.

The monitor instrument (1) and the complementary devices used in spectrometric / dosimetric measurements around the DAΦNE accelerator complex. The lead loaded LB6411-Pb (3) in presented with only half lead shielding. The Automess 6150 AD-b (4) has been used to estimate the photon dose.

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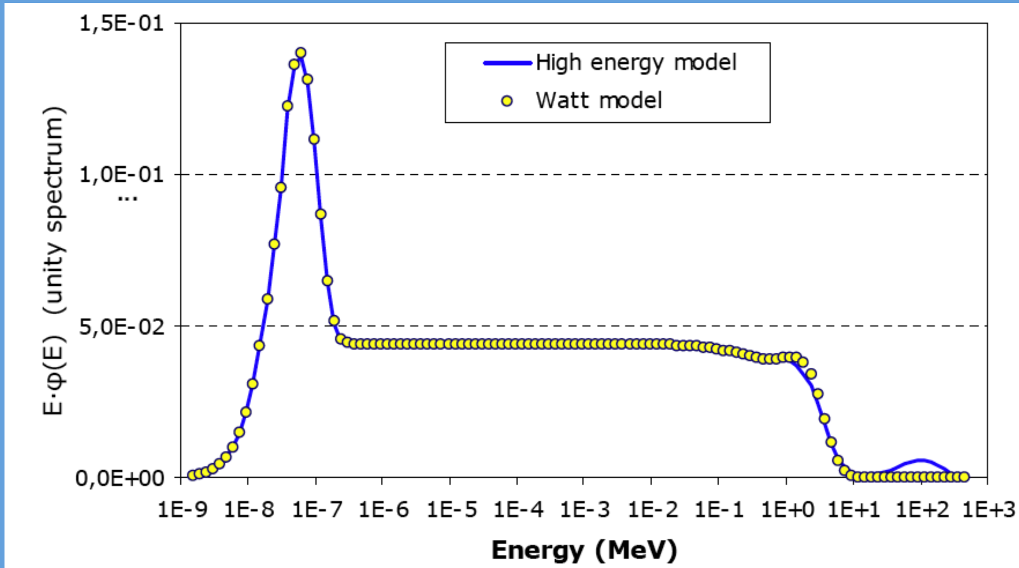

Point 20: Spectrometric and dosimetric characteristics	
E_φ (MeV)	0.16
E_H (MeV)	1.1
h^*_φ (pSv.cm^2)	56
Φ (cm^{-2}.MU^{-1})	16.9±0.6
$H^*(10)^{norm}$ (µSv.MU^{-1})	$(9.5\pm0.3)\cdot10^{-4}$
Monitor unit rate (MU.s^{-1})	0.108±0.016
$\dot{\Phi}$ (cm^{-2}.s^{-1})	1.8±0.3
$H^*(10)$ (µSv.h^{-1})	0.37±0.06

Point 20: complementary measurements	
LB6411^{norm} (µSv.MU^{-1})	$(8.2\pm0.4)\cdot10^{-4}$
LB6411-Pb^{norm} (µSv.MU^{-1})	$(8.5\pm0.4)\cdot10^{-4}$
AUTOMESS^{norm} (µSv.MU^{-1})	$(4.8\pm0.2)\cdot10^{-4}$

Quantity	Watt	Simple evaporation	Evaporation + high energy
h^*_φ (pSv.cm^2)	56	60	58
Φ (cm^{-2}.MU^{-1})	16.9 ± 0.6	17.1 ± 0.6	17.0 ± 0.6
Fluence below 0.4 eV	32%	33%	31%
Fluence above 10 MeV	-	-	1%
H(10)* above 10 MeV	-	-	6%
Δ	2.56	3.98	2.03
ξ^{max}	0.56	0.91	0.54

Comparison of three different unfolding model

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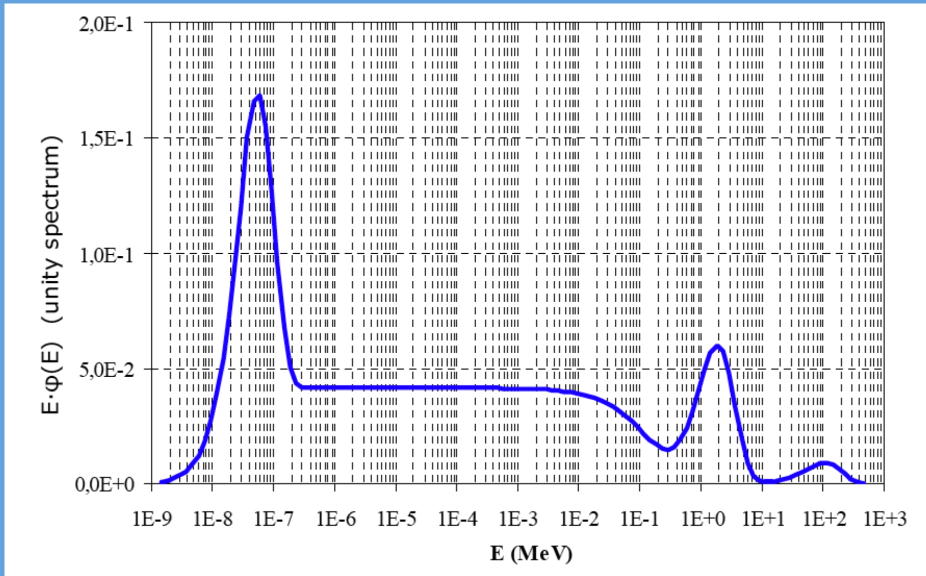

Point 25: summary of the results	
Φ (cm^{-2}.MU^{-1})	12.4 ± 0.4
Monitor unit rate (MU.s^{-1})	0.070 ± 0.017
$\dot{\Phi}$ (cm^{-2}.s^{-1})	0.87 ± 0.21
$H^*(10)$ (μSv·h^{-1})	0.20 ± 0.05
$H^*(10)^{norm}$ (μSv.MU^{-1})	$(7.8 \pm 0.2) \cdot 10^{-4}$
$LB6411^{norm}$ (μSv.MU^{-1})	$(7.1 \pm 0.4) \cdot 10^{-4}$
$LB6411\text{-}Pb^{norm}$ (μSv.MU^{-1})	$(7.5 \pm 0.4) \cdot 10^{-4}$
$AUTOMESS^{norm}$ (μSv.MU^{-1})	$(6.6 \pm 0.3) \cdot 10^{-4}$

Quantity	Watt	Simple evaporation	Evaporation + high energy
h^*_φ (pSv.cm^2)	56	58	63
Φ (cm^{-2}.MU^{-1})	12.5 ± 0.4	12.3 ± 0.4	12.4 ± 0.4
Fluence below 0.4 eV	37%	37%	37%
Fluence above 10 MeV	-	-	1.6%
$H^*(10)$ above 10 MeV	-	-	8.6%
Δ	6.00	5.90	5.20
ξ^{max}	1.70	1.45	1.38

Comparison of three different unfolding model

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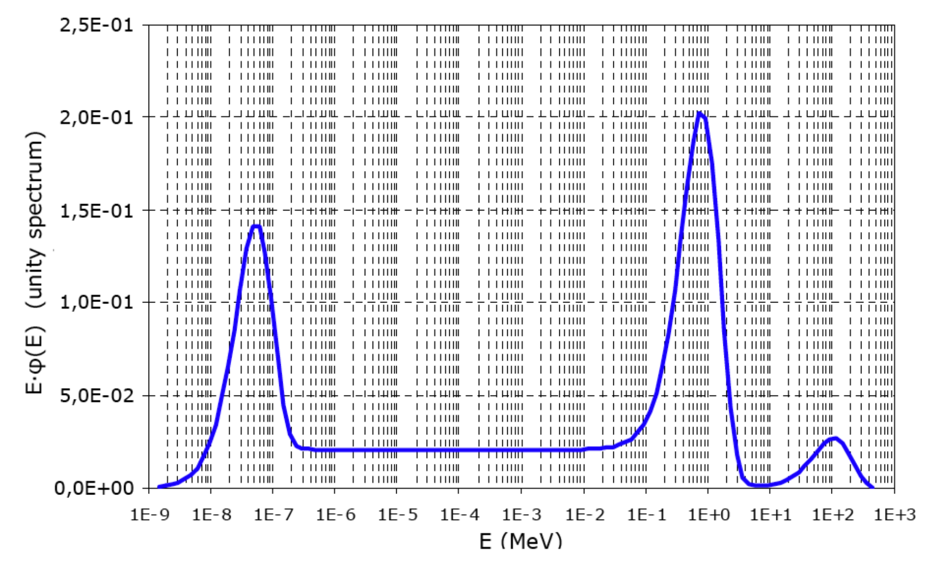

Point 27: summary	
Φ (cm^{-2}.MU^{-1})	27.8±1.0
Monitor unit rate (MU.s^{-1})	2.3±0.4
$\dot{\Phi}$ (cm^{-2}.s^{-1})	64±11
$H^*(10)$ (µSv·h^{-1})	36 ± 7
$H^*(10)^{norm}$ (µSv.MU^{-1})	(4.31±0.15)·10^{-3}
$LB6411^{norm}$ (µSv.MU^{-1})	(3.3±0.2)·10^{-3}
$LB6411\text{-}Pb^{norm}$ (µSv.MU^{-1})	(3.9±0.2)·10^{-3}
$AUTOMESS^{norm}$ (µSv.MU^{-1})	(1.40±0.07)·10^{-3}

The neutron spectrum as expected cover the whole range included in sorce term

Quantity	Watt	Evaporation	High energy
h^*_φ (pSv.cm^2)	124	122	155
Φ (cm^{-2}.MU^{-1})	28.1 ± 1.0	28.3 ± 1.0	27.8 ± 1.0
Fluence below 0.4 eV	30%	33%	29%
Fluence above 10 MeV	-	-	5%
$H^*(10)$ above 10 MeV	-	-	11%
Δ	7.70	8.73	4.90
ξ^{max}	1.90	1.77	1.32

Comparison of three different unfolding model

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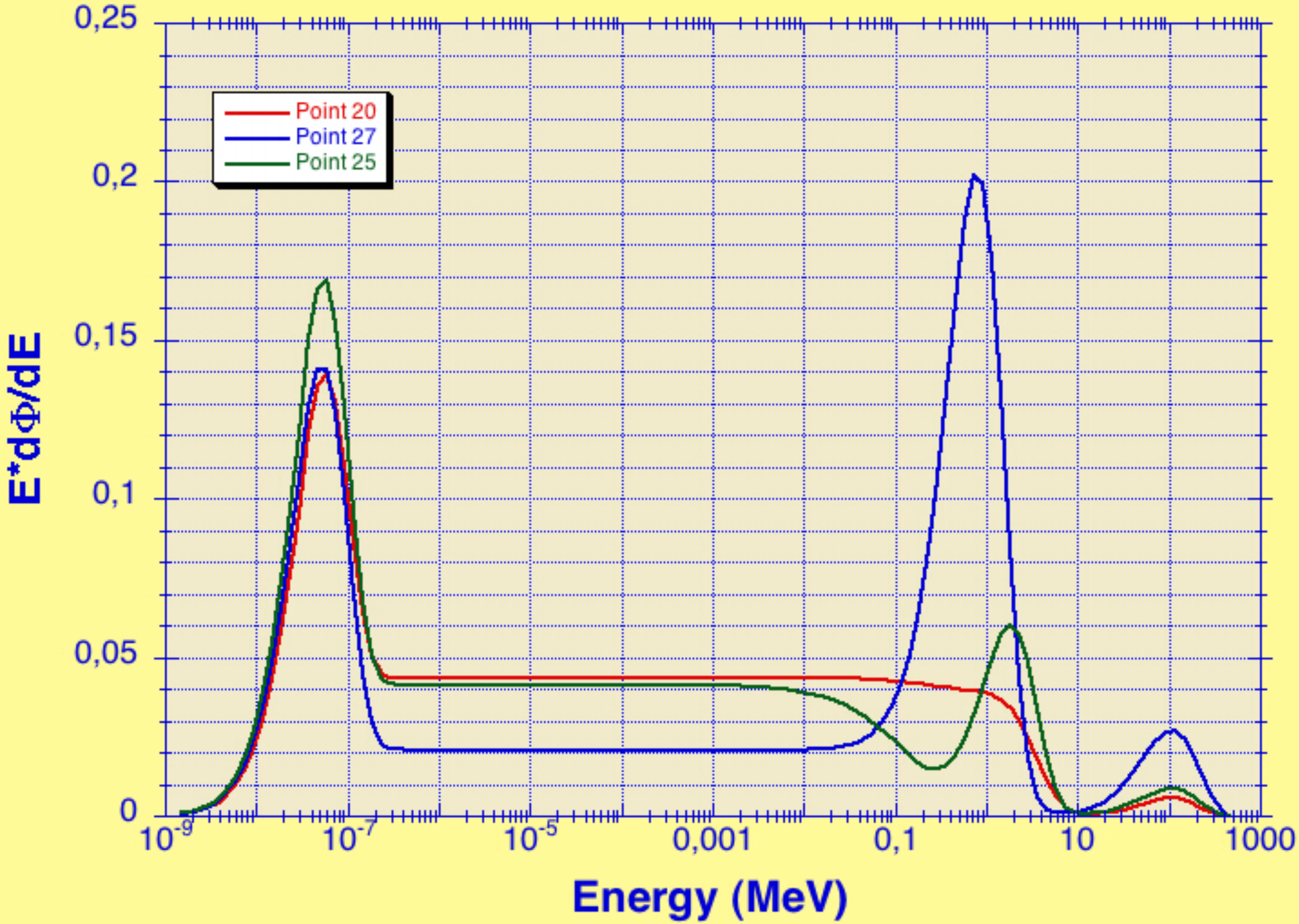
Comparisons of spectra measured in position 20, 25 and 27



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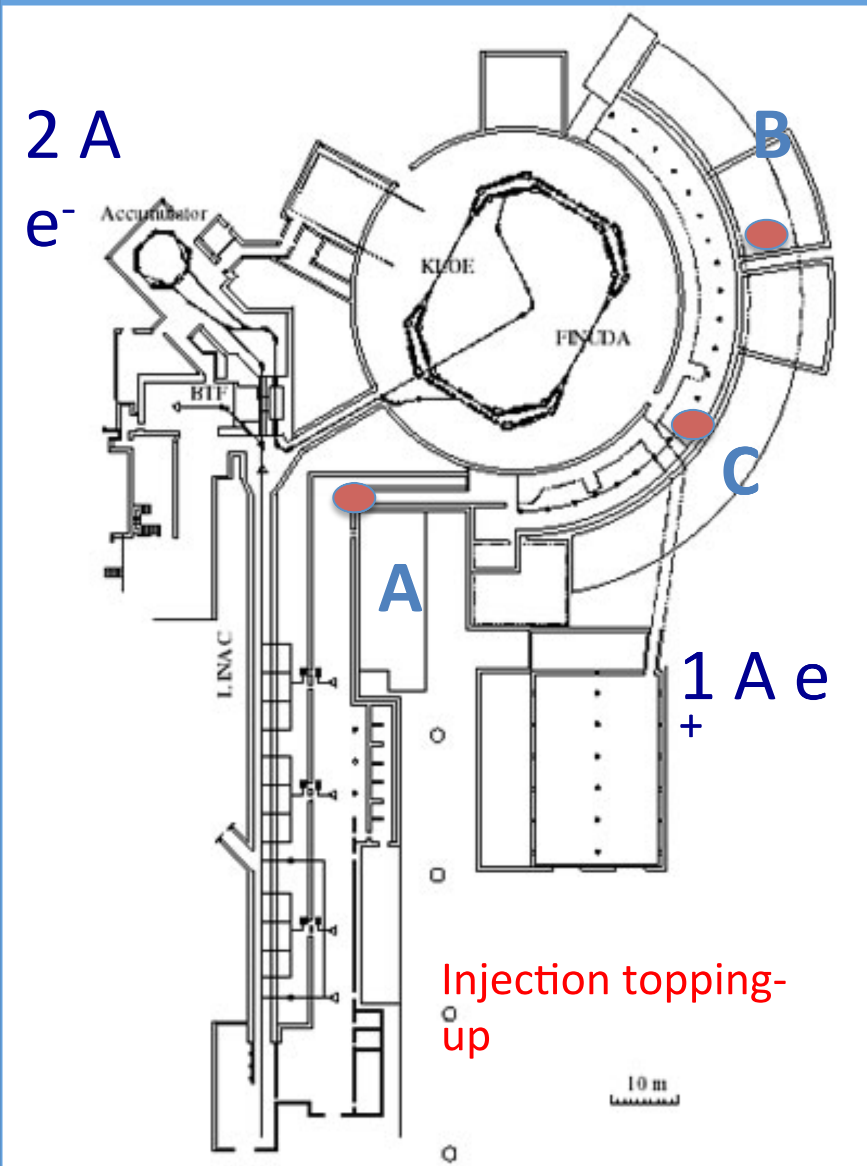
Measurements at DAΦNE



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.

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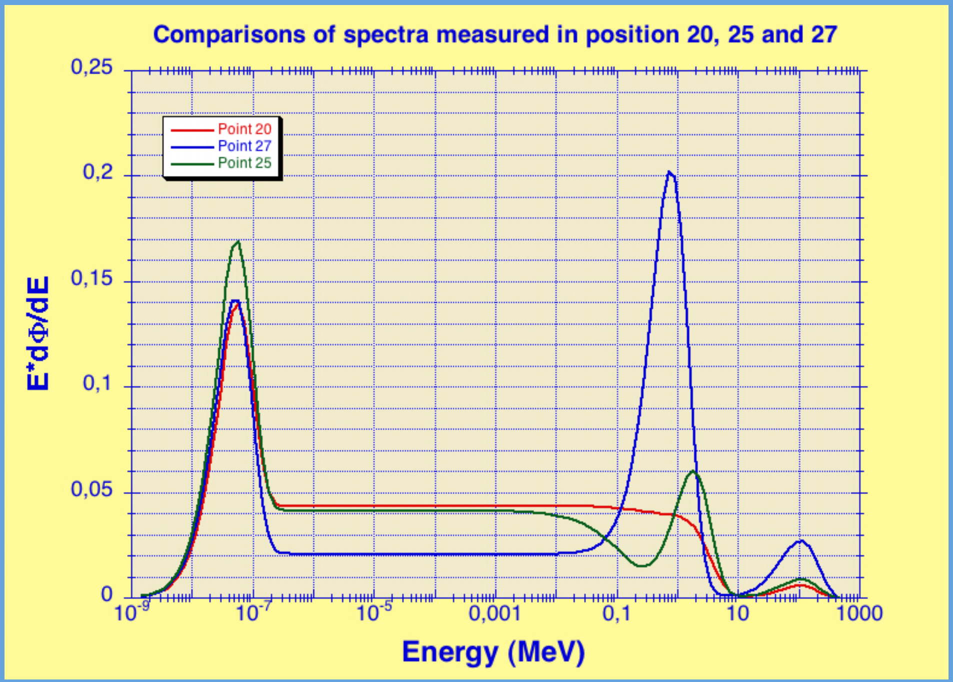
Measurements at DAΦNE

Quantity	(pSv.cm²)
Point A=20	58
Point B=25	63
Point C=27	155

spectrum averaged fluence-to-ambient dose equivalent conversion coefficient

Quantity	Point A	Point B	Point C
h^*_φ (pSv.cm²)	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



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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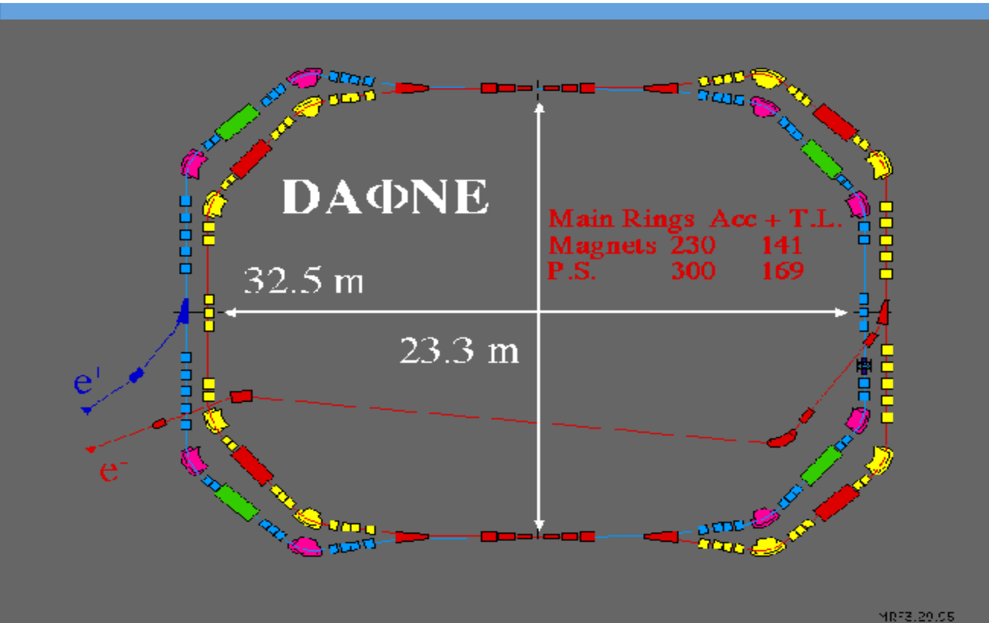
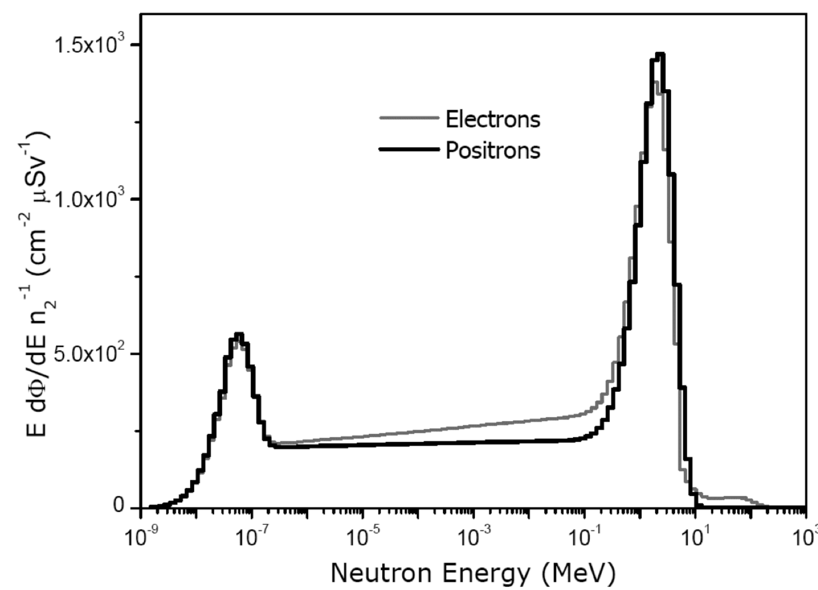
Measurements at DAΦNE

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} μSv^{-1})	$H^*(10)/n_2$	$h^*(10)$ ($pSv \cdot cm^2$)	Fluence fraction (Energy in MeV)			$H^*(10)$ fraction (Energy in MeV)		
				< 0.1	0.1-10	> 10	< 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%





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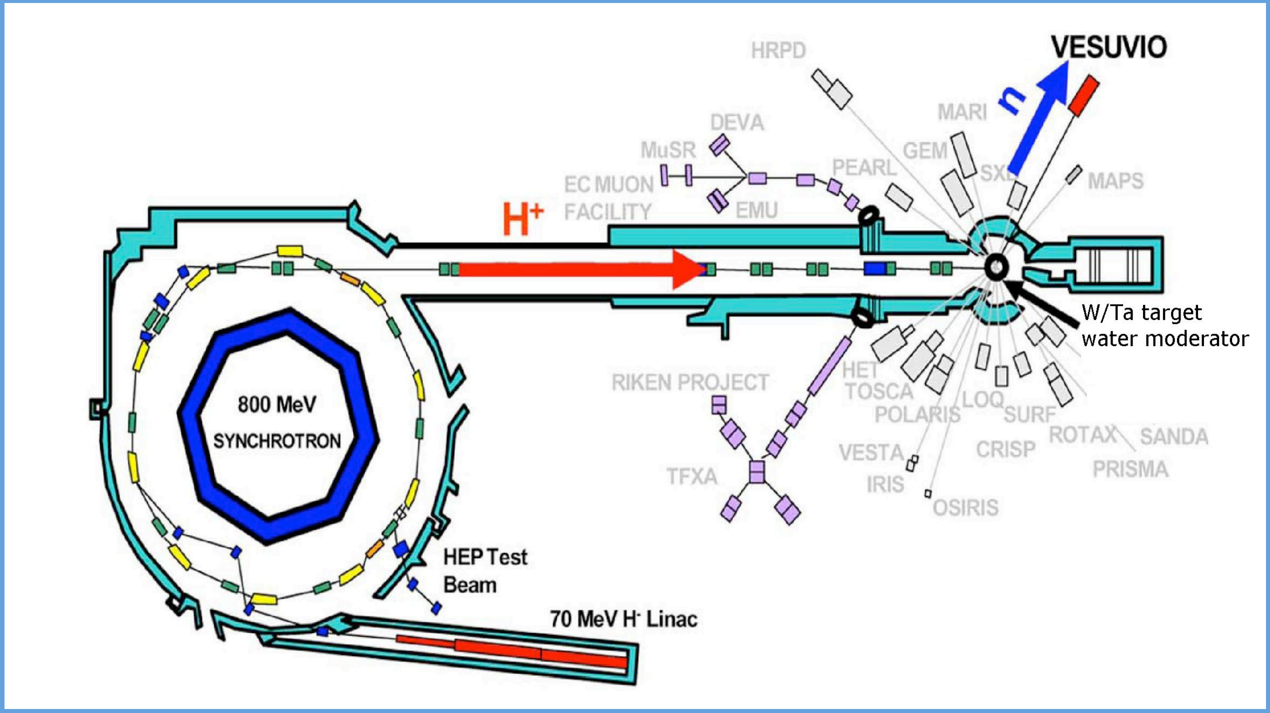
Measurements at VESUVIO

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

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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.

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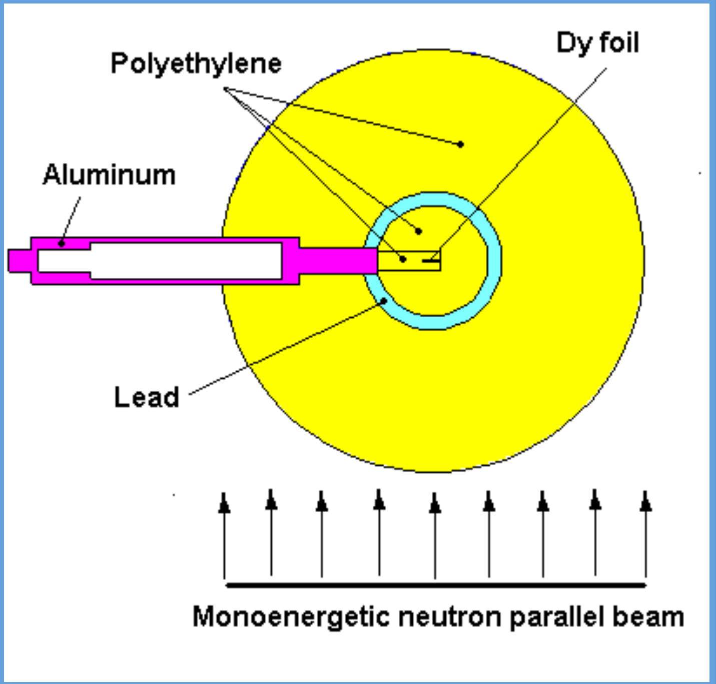
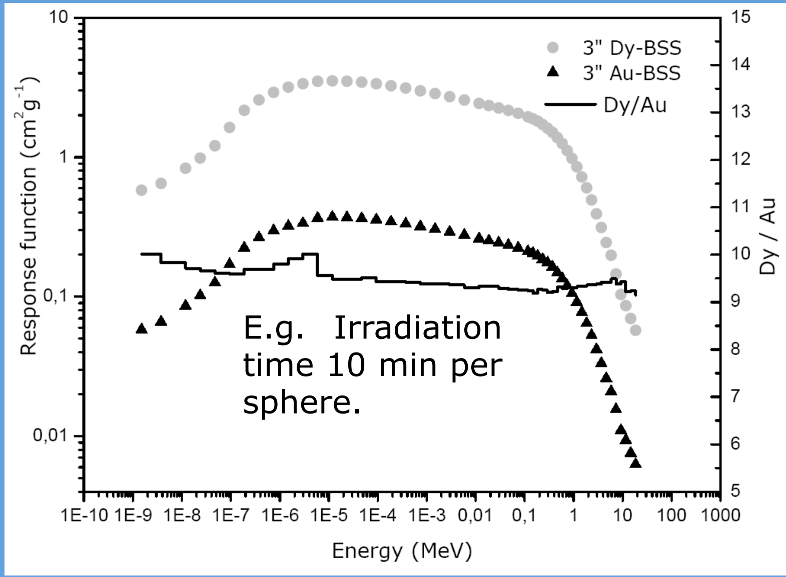
Measurements at VESUVIO

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**

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Measurements at VESUVIO

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

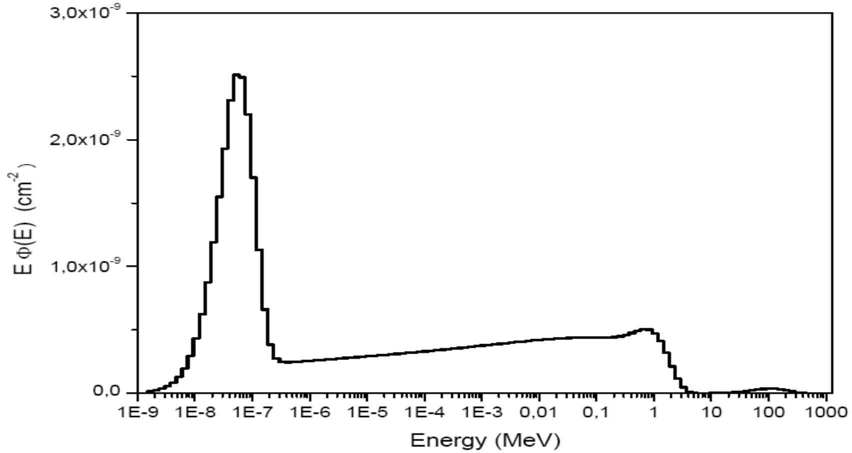
The Dy foils were counted and corrected for: **(1)** exposure to counting delay, **(2)** decay during counting, **(3)** saturation.

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	$(1.07 \pm 0.06) \times 10^{-8}\,\mathrm{cm}^{-2}$
Fluence fraction ($E < 0.4$ eV)	46.9%
Fluence fraction (0.4 eV $< E <$ 100 keV)	40.9%
Fluence fraction (100 keV $< E <$ 10 MeV)	11.5%
Fluence fraction ($E >$ 10 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.



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The European Commission is funding within is 6th Framework Program a three year project (2005-2007) called CONRAD, Coordinated Network for Radiation Dosimetry.

One task within the CONRAD project was to provide

1) the development of new techniques and the improvement of current techniques for the characterization of complex workplace fields;

2) measurement and calculation of particle energy and direction distributions.

Within this task a benchmark irradiation at GSI facility was planned and held during the last week of July 2006, in order to compare measurement and calculations.

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The GSI (Gesellschaft für Schwerionenforschung) accelerator laboratory in Darmstadt, Germany, delivers all type of ion beam, up to and including uranium.

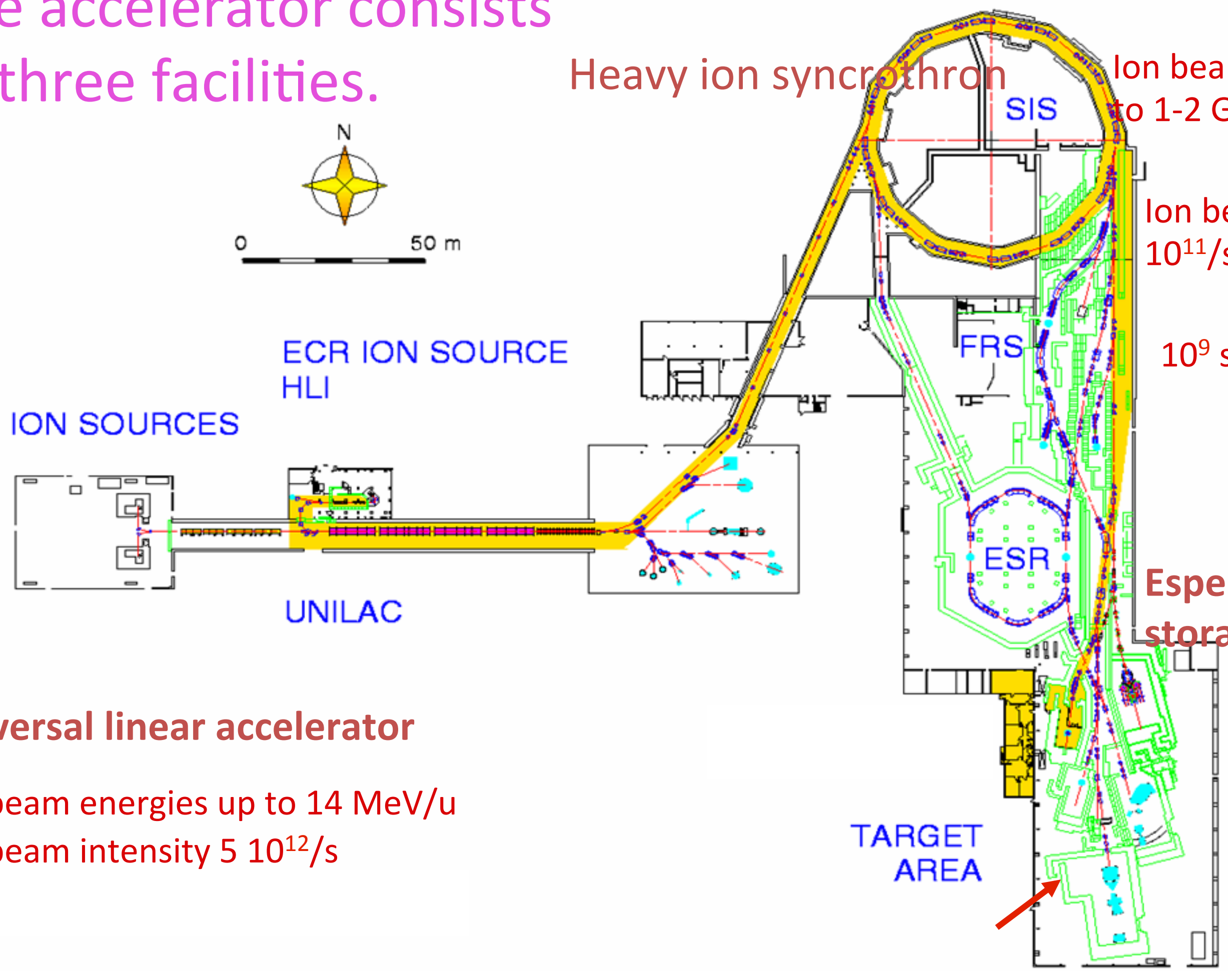
The accelerator consists of three facilities.

Heavy ion syncrothron

Ion beam energies up to 1-2 GeV/u

Ion beam intensity 10^{11}/s - 10^{10}/s

10^{9} stored ion beam



Esperimental storage ring

Universal linear accelerator

Ion beam energies up to 14 MeV/u

Ion beam intensity 5 10^{12}/s

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Participants

INFN-LNF-Italy

Enea-CR Frascati-Italy

Politecnico of Milan-Italy

GSI -Germany

GSF -Germany

PTB -Germany

IRSN -France

NPI-AS - Czech Republic

IAE - Poland

PSI-Switzerland

Cern -Switzerland

ARC-Austria

UAB - Spain

Instruments

TEPC

Active and passive BSS

LIULIN LET spectrometers

Elettronic personal dosimeters

Conventional and extended range rem-counter

Fission track detectors

Bubble detectors

Solid state dosimetry (TLDs, PADC)

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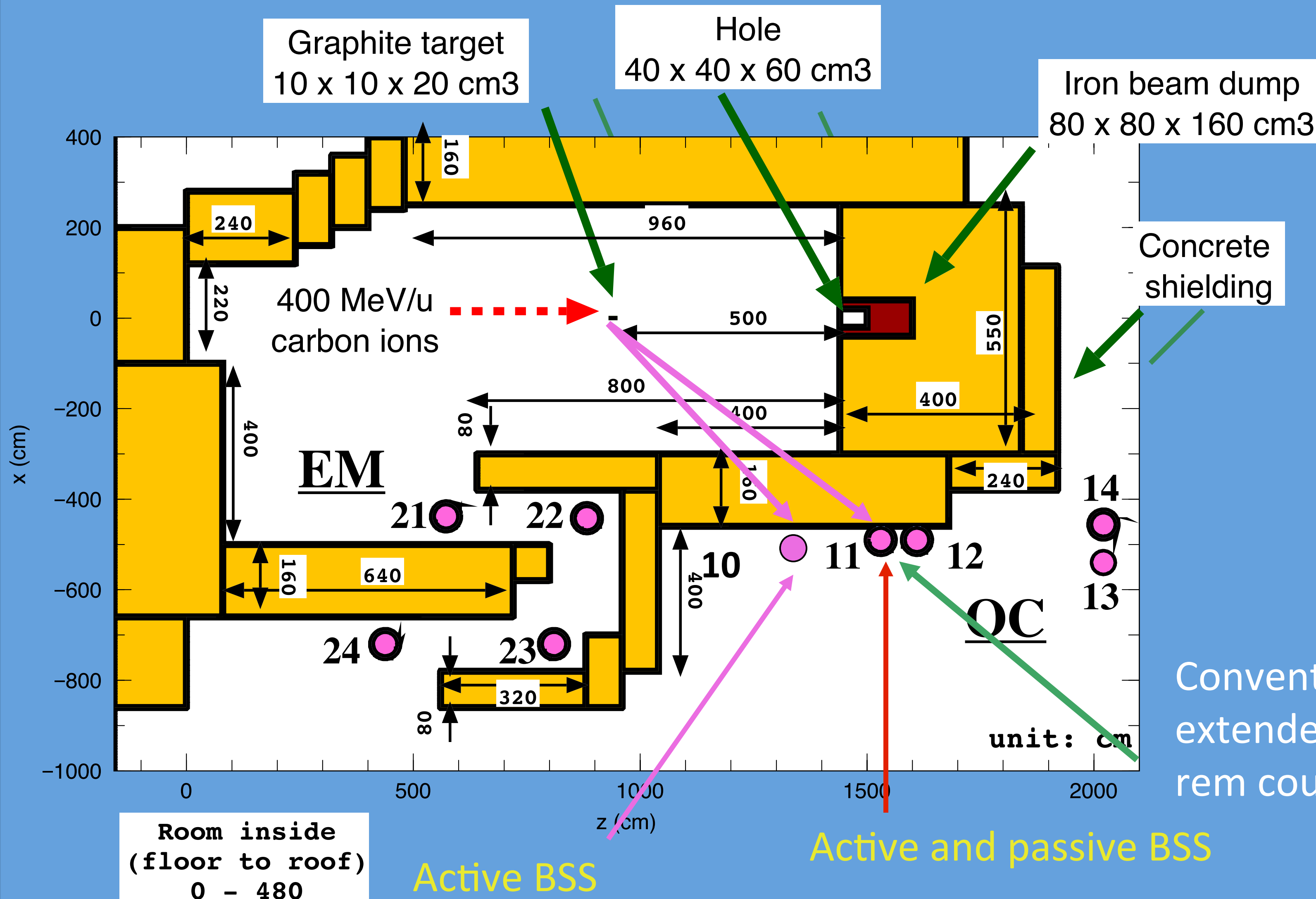
Measurement Points



Conventional and extended range rem counters

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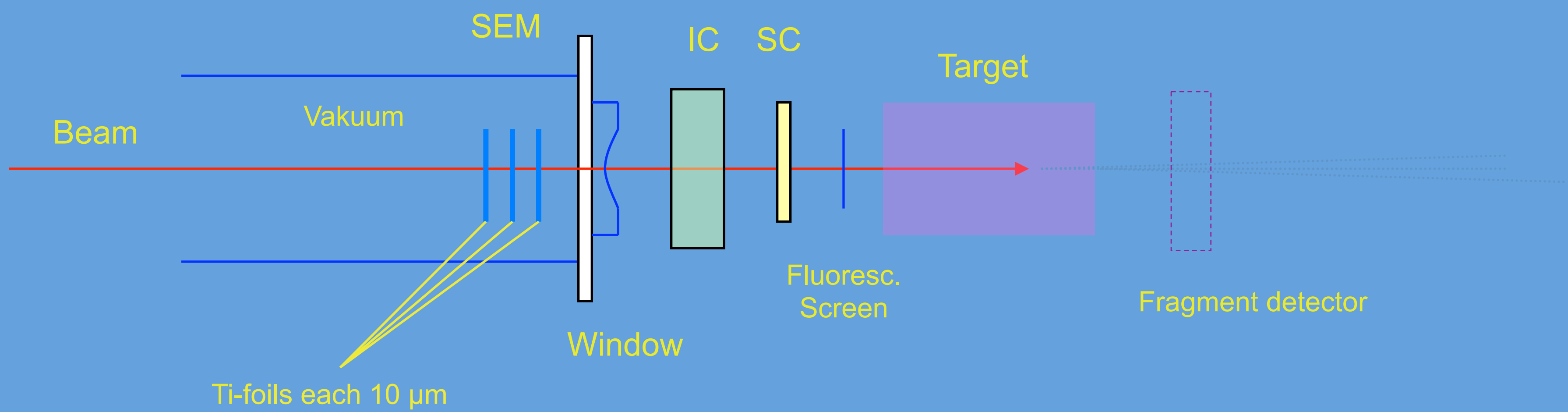
Beam monitoring Cave A



- Sec. Electron Monitor (SEM) > 10E8 pps (no saturation)
- Ionization Chamber (IC) 10E5 -1E8 pps
- Scintillator (SC) < 5x10E5 pps

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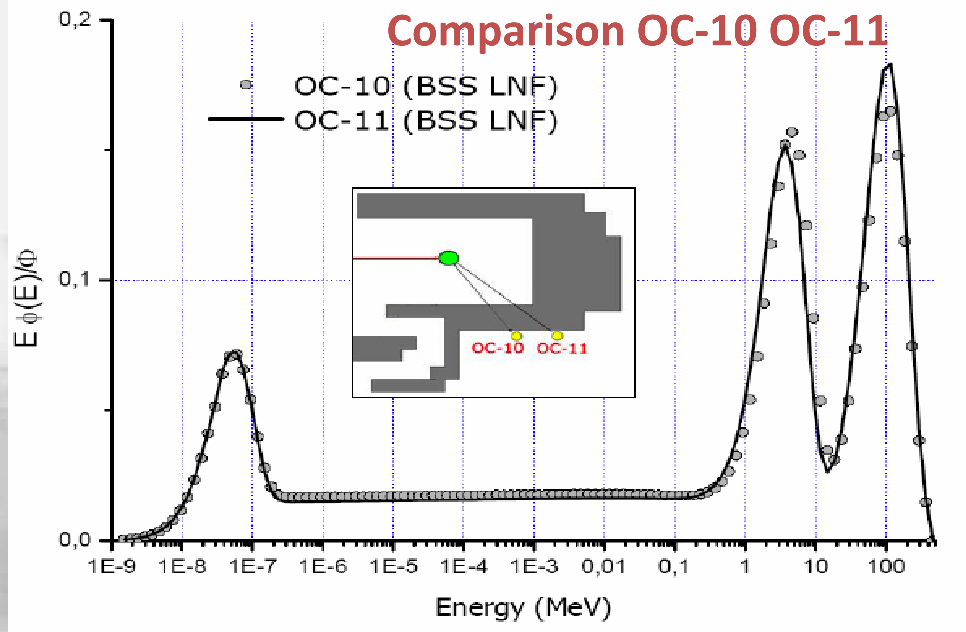

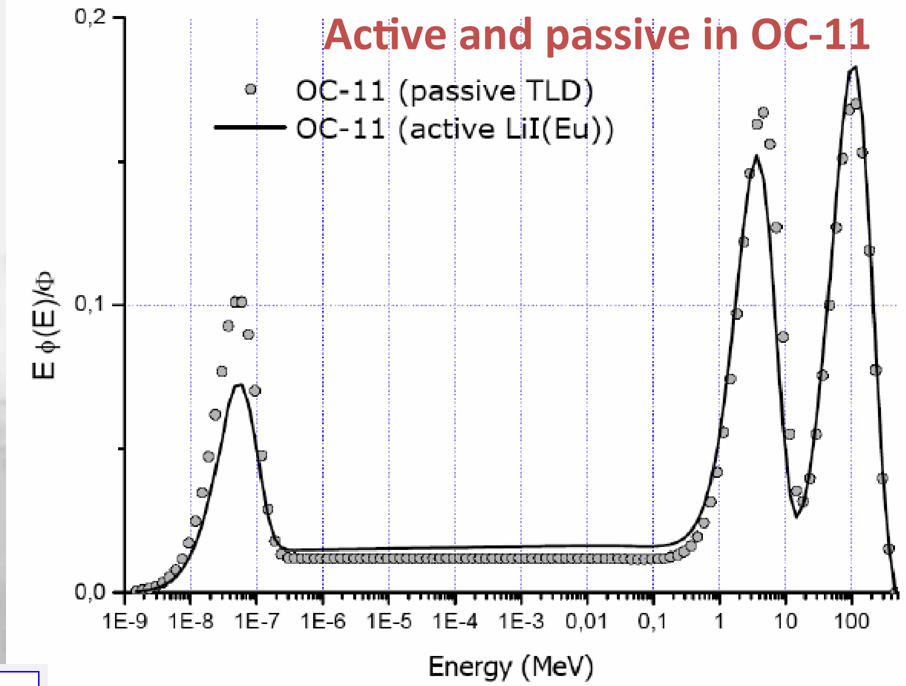

Position and device → Quantity ↓	OC-10 active	OC-11 active	OC-11 TLDs
Φ/MU (cm^{-2} C^{-1})	$(161\pm5)\cdot10^9$	$(151\pm5)\cdot10^9$	
Φ < 0.1 MeV	37%	35%	35%
Φ in [0.1 – 10] MeV	31%	31%	32%
Φ > 10 MeV	32%	34%	33%
$H^*(10)$/MU (Sv C^{-1})	38±2	36±2	
$H^*(10)$ < 0.1 MeV	2%	2%	2%
$H^*(10)$ in [0.1 – 10] MeV	52%	50%	52%
$H^*(10)$ > 10 MeV	46%	48%	46%
h*(10) pSv·cm^2	237±12	242±13	244±28
LB-6411 (Sv C^{-1})	23.7±1.2	-	
LB-6411/Pb (Sv C^{-1})	33.5±1.7	-	

REM COUNTERS results

Rem counter	Position	Average uSv/h	Sv.C^-1
LB6411	OC-10	15,66	23,7
LB6411-Pb	OC-10	22,14	33,5

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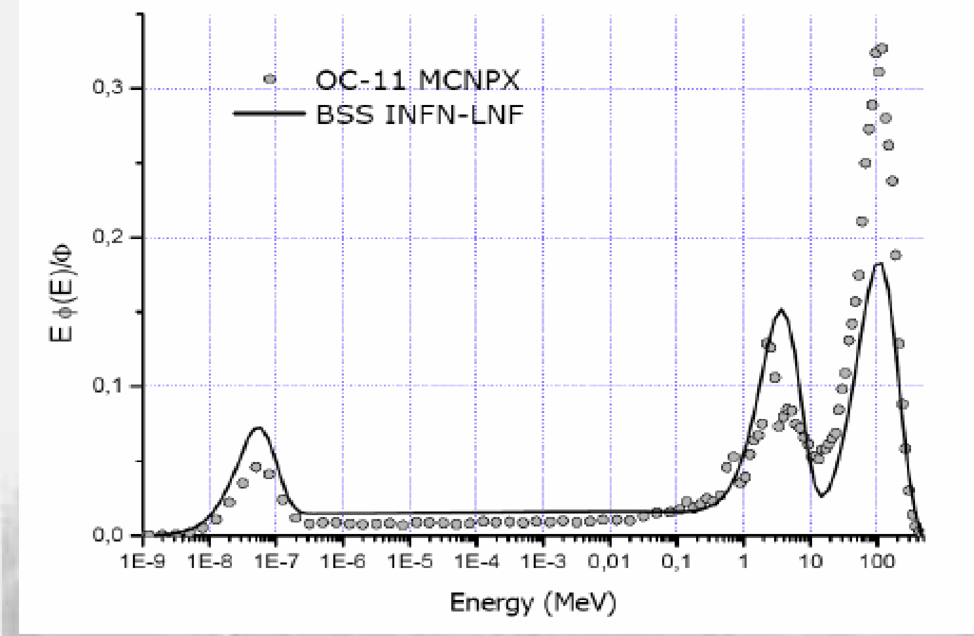
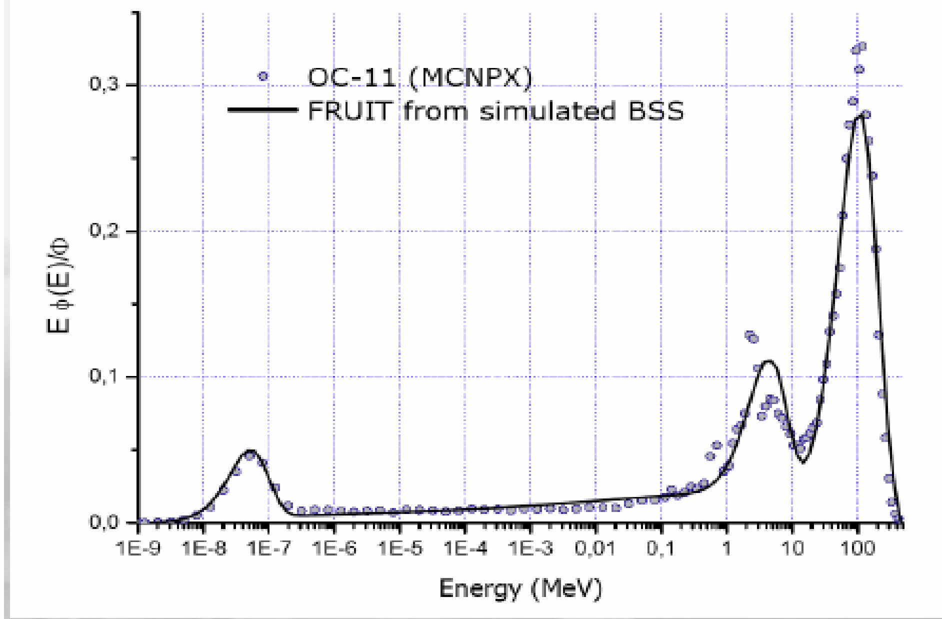
Point OC-11 & MCNP-X

Experimental INFN-LNF data (FRUIT code) compared with MCNP-X simulation (ARCS)



MCNP-X spectrum compared with:

Unfolding [Folding (MCNP-X on LNF-BSS)]



	BSS INFN-LNF	Simulated spectrum	BSS simulated
$\Phi < 0.1$ MeV	35%	21%	23%
Φ in [0.1 – 10] MeV	31%	25%	25%
$\Phi > 10$ MeV	34%	54%	52%
Φ (cm^{-2})	$(151\pm5)\cdot10^9$	1	1.00 ± 0.01
h*(10) pSv.cm^2	242±13	282	276±6

Spectra normalized to 1 cm^{-2} and in equilethargic representation

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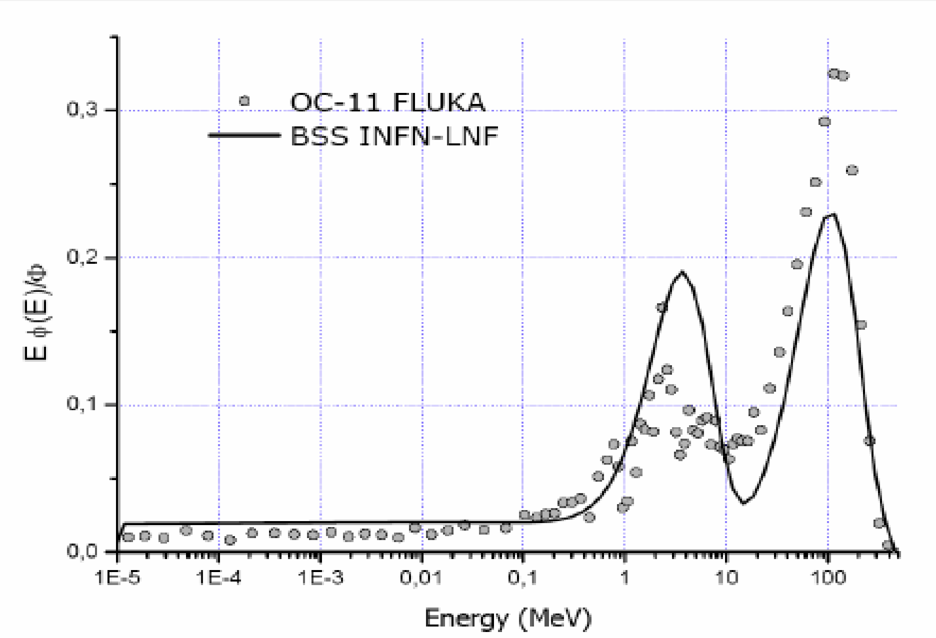
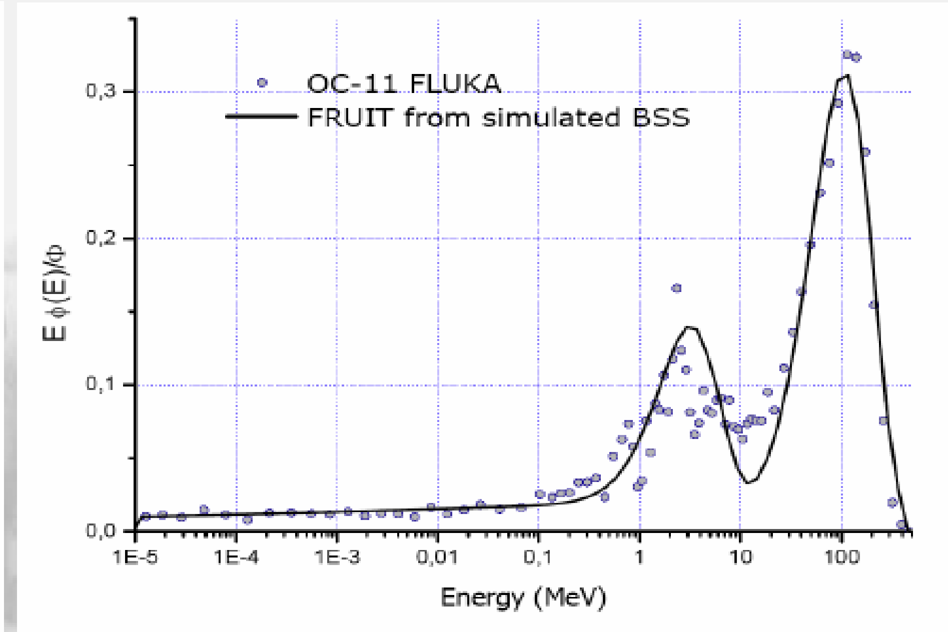
Point OC-11 & FLUKA

Experimental INFN-LNF data (FRUIT code) compared with FLUKA simulation (ARCS)



FLUKA spectrum compared with:

Unfolding [Folding (FLUKA on LNF-BSS)]



	BSS INFN-LNF	FLUKA	BSS simulated
Φ < 0.1 MeV	18%	12%	13%
Φ in [0.1 – 10] MeV	39%	29%	30%
Φ > 10 MeV	43%	59%	57%
h*(10) pSv.cm^2	301±15	320	313±8

Only the > 1E-5 MeV energy region is considered

Spectra normalized to 1 cm^{-2} and in equilethargic representation

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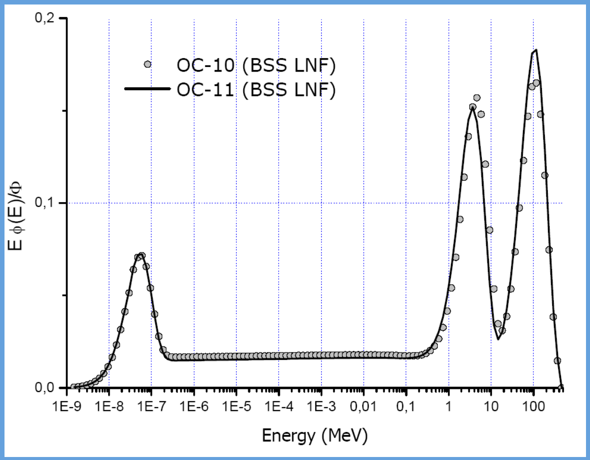
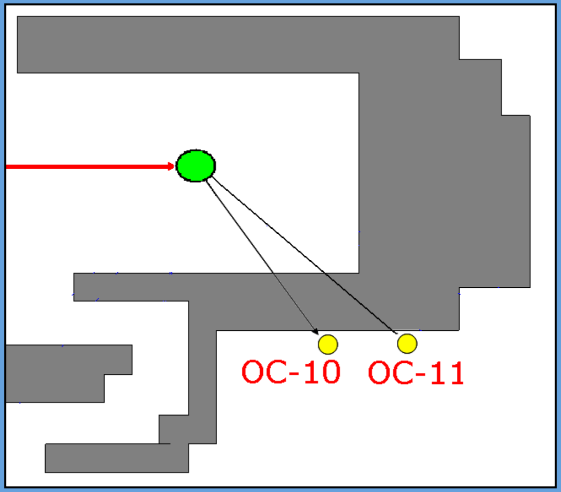
Measurements at GSI

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

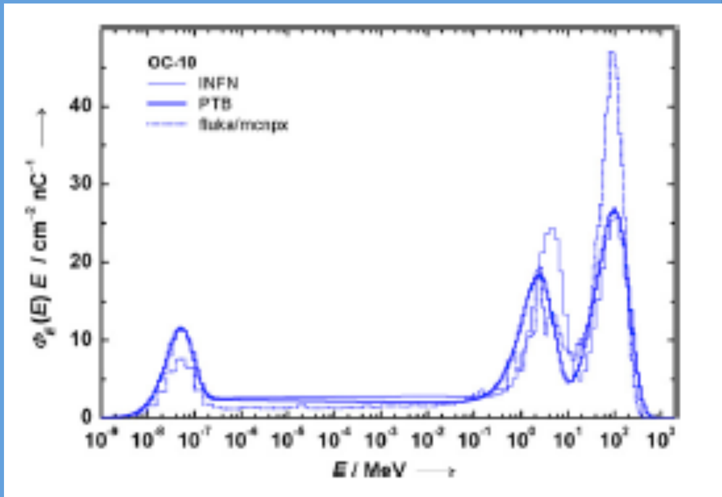


Fig. 6. Neutron spectra at position OC-10, measured by INFN and PTB and calculated with FLUKA/MCNPX.

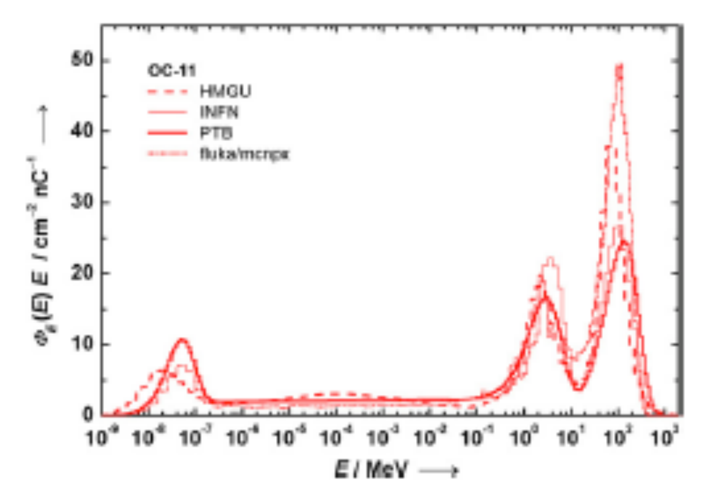


Fig. 7. Neutron spectra at position OC-11, measured by HMGU, INFN and PTB and calculated with FLUKA/MCNPX.

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

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

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The spherical spectrometer

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Nuclear Instruments and Methods in Physics Research A 584 (2008) 196–203
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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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

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[a]CIEMAT, Av. Complutense 22, 28040 Madrid, Spain
[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

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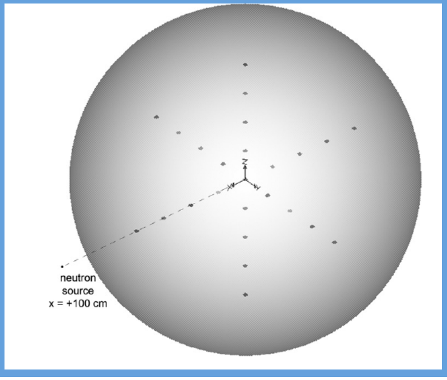
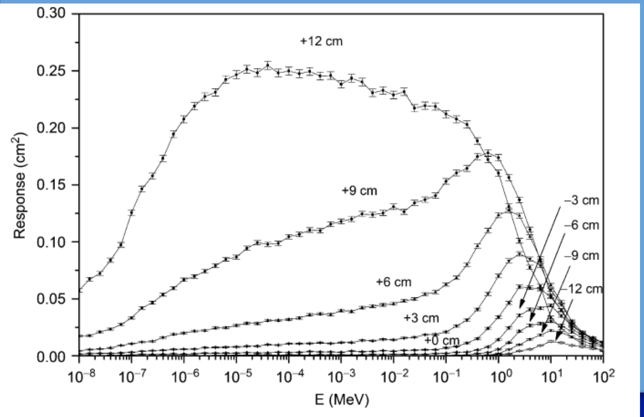
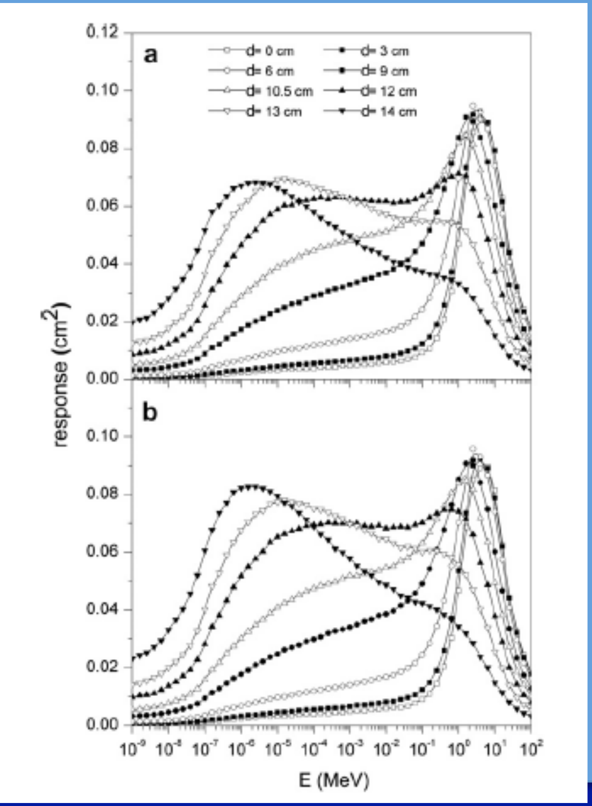
[a]CIEMAT, Edif. 36, Av. Complutense 22, E-28040 Madrid, Spain
[b]IFNF, LNF Frascati National Laboratory, U.F. Fisica Sanitaria, via E. Fermi n. 40, 00044 Frascati, Italy

Radiat. Meas. (2010) 45 1220-1223

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







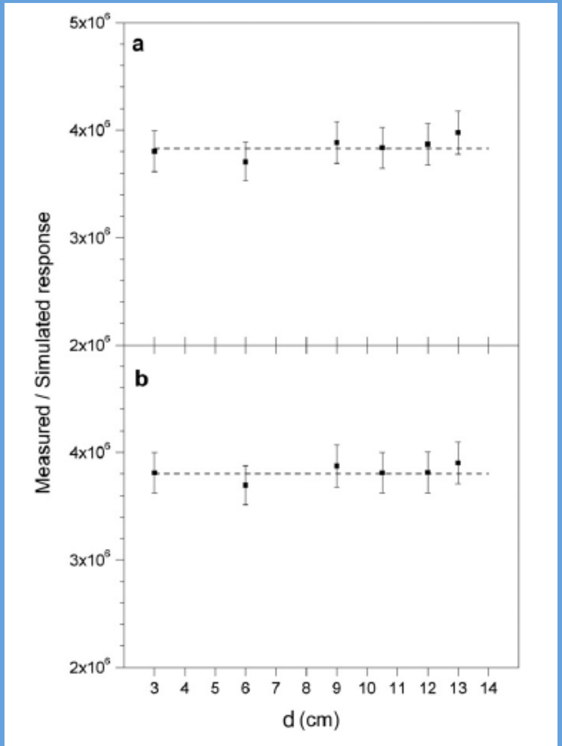
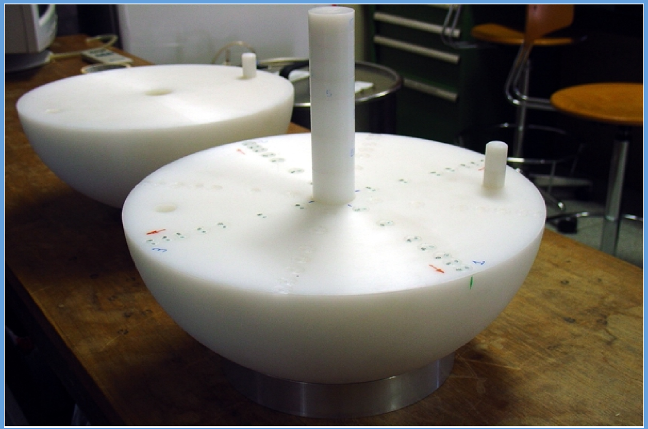


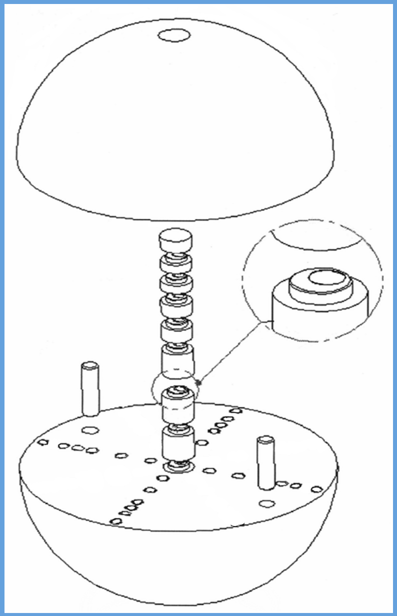
Fig. 4. Measured/simulated response ratio for: a) monodirectional response matrix; b) isotropic response matrix. Experimental uncertainties are around 5% for each data point.

N E S C O F I

NEutron Spectrometry in COmplex FIelds

(SP)² **SP**herical **SP**ectrometer





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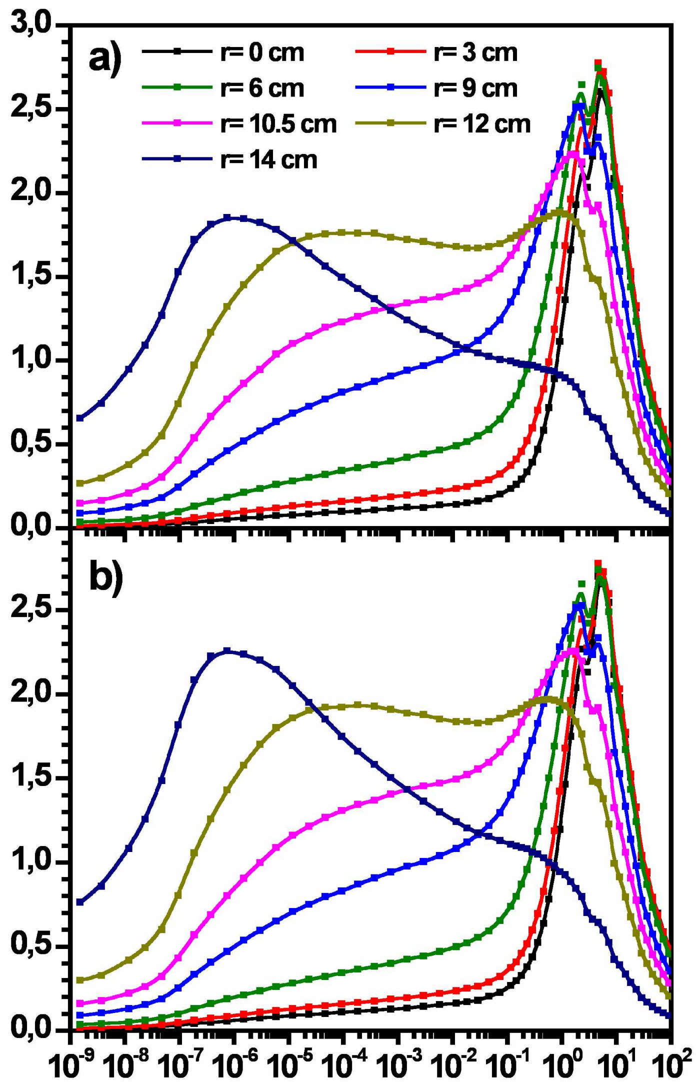
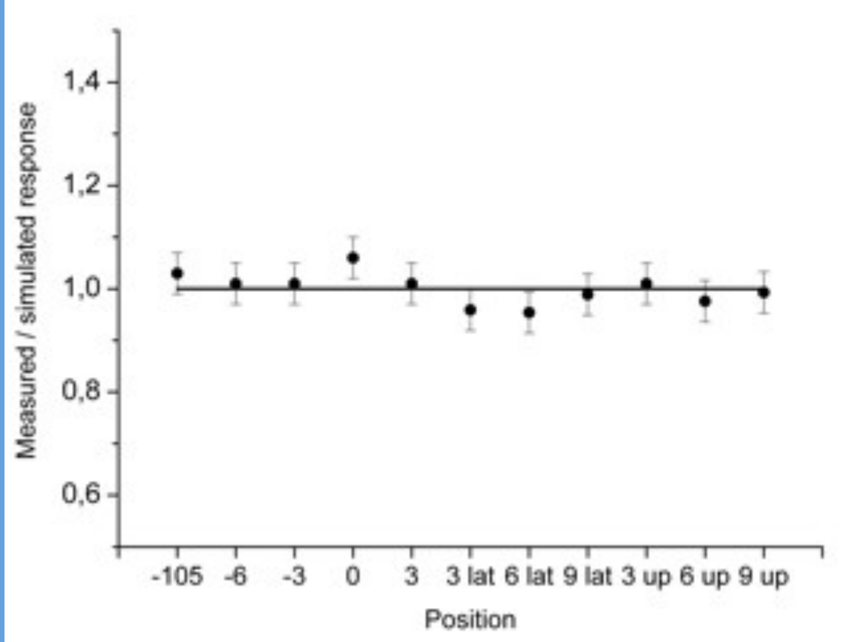
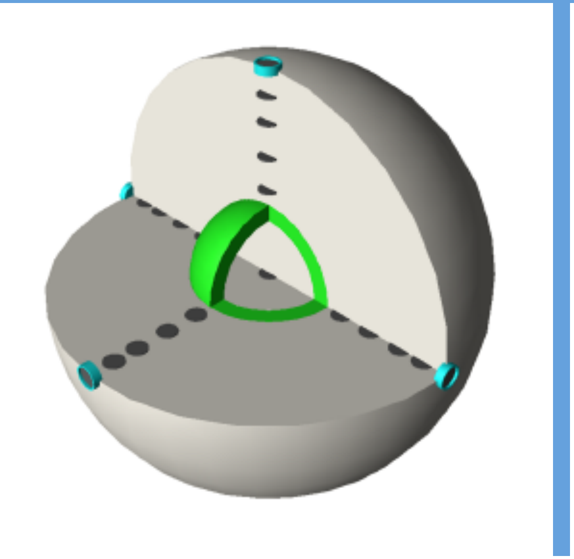
Stesso spettrometro con lamine di attivazione

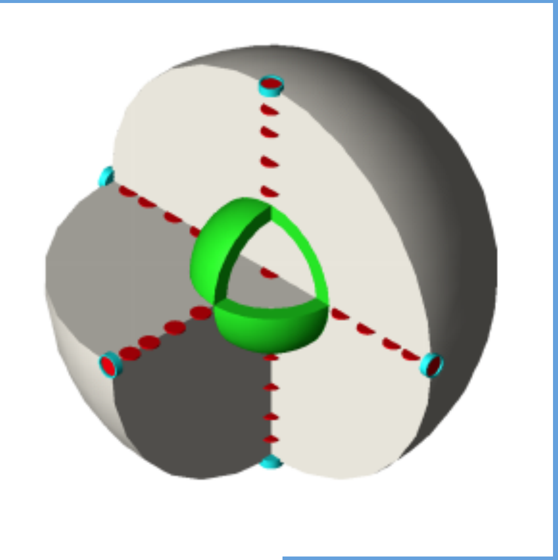
Design and validation of a photon insensitive multidetector neutron spectrometer based on Dysprosium activation foils
Radiation Measurements (2011), doi: 10.1016/j.radmeas.2011.06.037



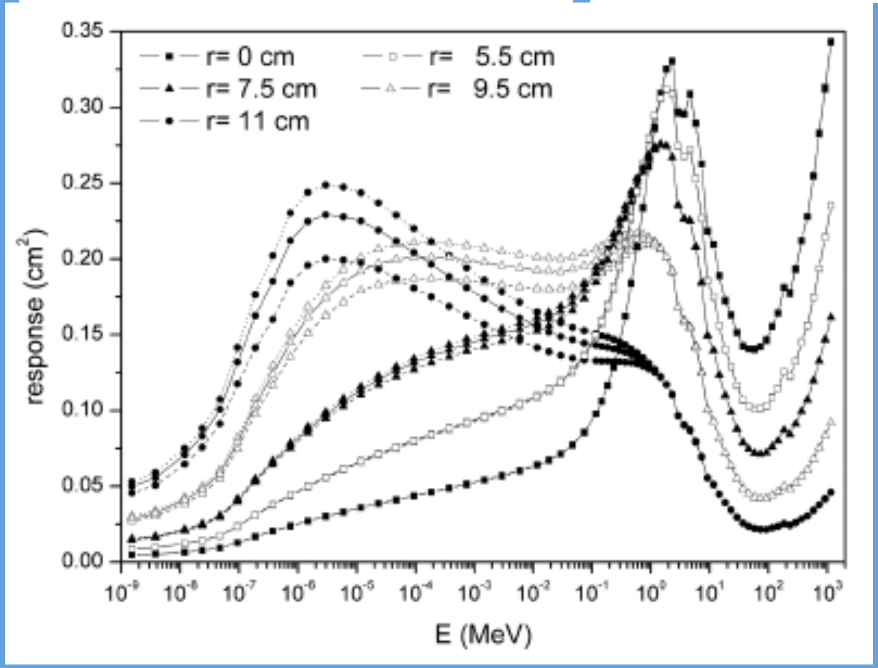
Test performed at the FNG







Final layout of SP^2



Number and positon of detectors

Energy response functions to monoenergetic incident neutrons, averaged over the detectors located at the same distance from the center, for three different irradiation geometries:

- along the (1 0 0) axis (dashed lines), -
isotropic (continuous lines)
- along the (1 1 1) axis (dotted lines)

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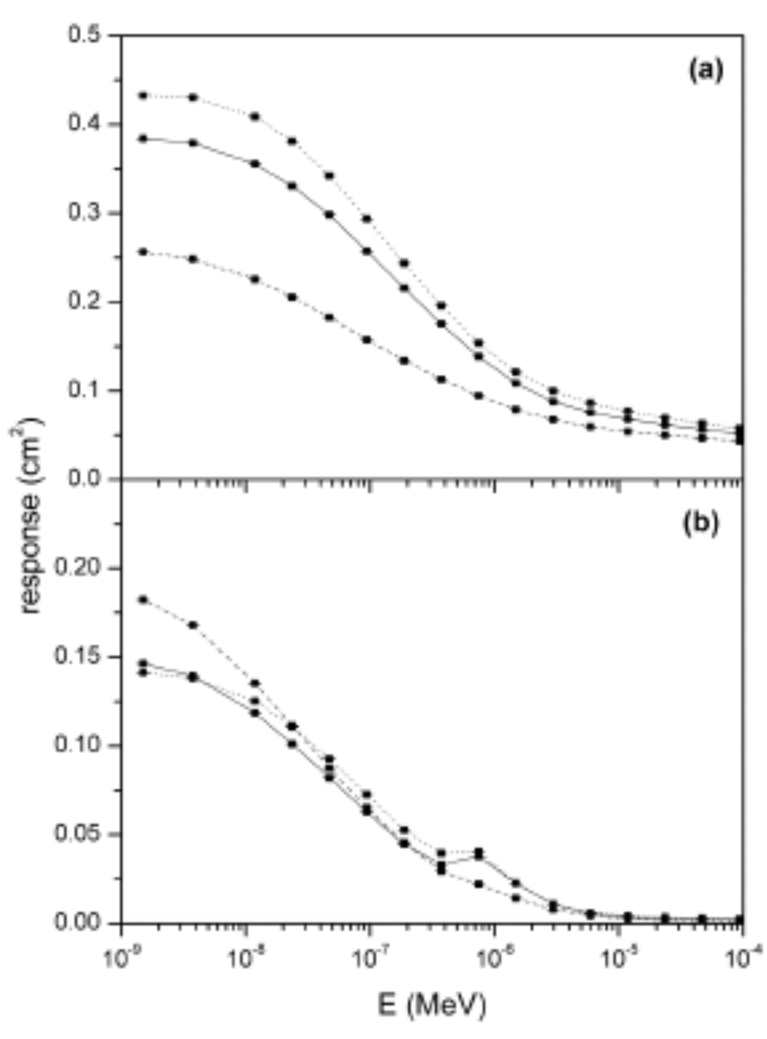

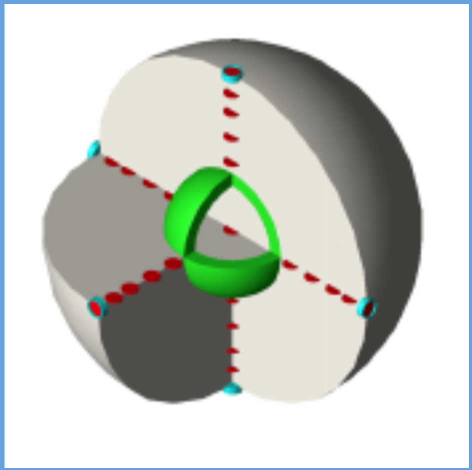

Energy response function to monoenergetic incident neutrons, averaged over the detectors located on the surface of the sphere, for three different irradiation geometries:

- along the (1 0 0) axis (dashed lines) - isotropic (continuous lines)
- along the (1 1 1) axis (dotted lines)

a) Without Cadmium
b) With Cadmium

Anisotropy of low energy neutrons

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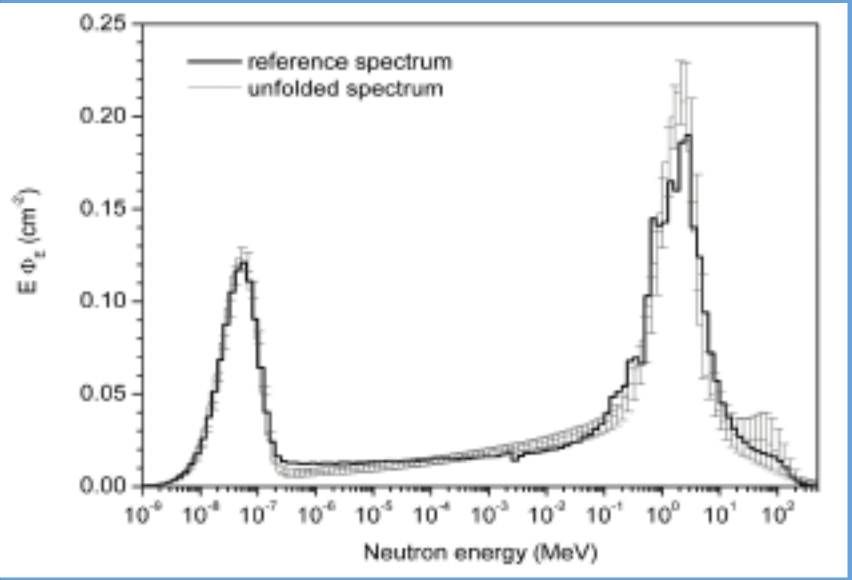

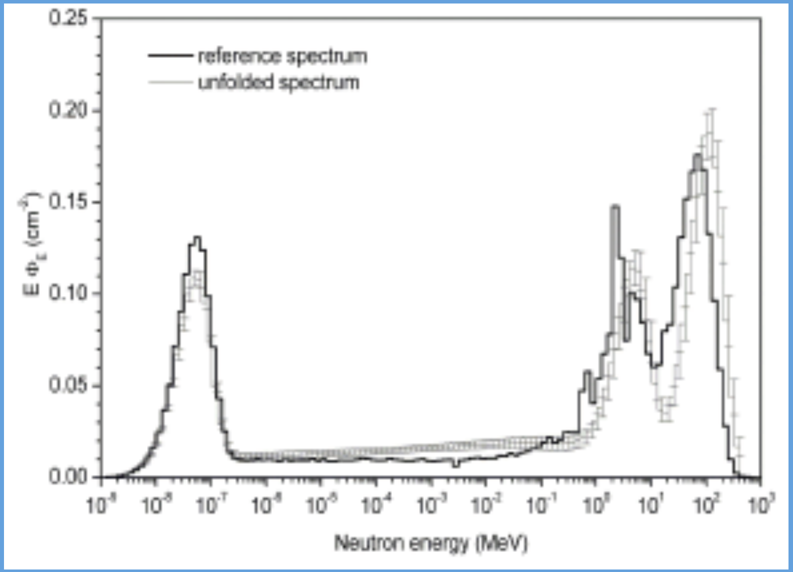

Simulated exposure to a high energy neutron field (unshielded high energy electron source).

Simulated exposure to a high energy neutron field (shielded high energy proton source).

neutron spectrum		total fluence (cm^{-2})	h*(10) (pSv.cm^{2})	fluence fractions (%)			
				E < 0.4 eV	0.4 eV < E < 10 keV	10 keV < E < 20 MeV	E > 20 MeV
high-E electrons unshielded point	reference	1	216	12.6	26.2	57.2	4.0
	unfolded	0.98±0.02	218±11	14.0	24.2	56.9	4.9
high-E protons shielded point	reference	1	247	12.8	21.8	35.1	30.3
	unfolded	1.07±0.05	238±15	11.6	22.9	29.5	36.0

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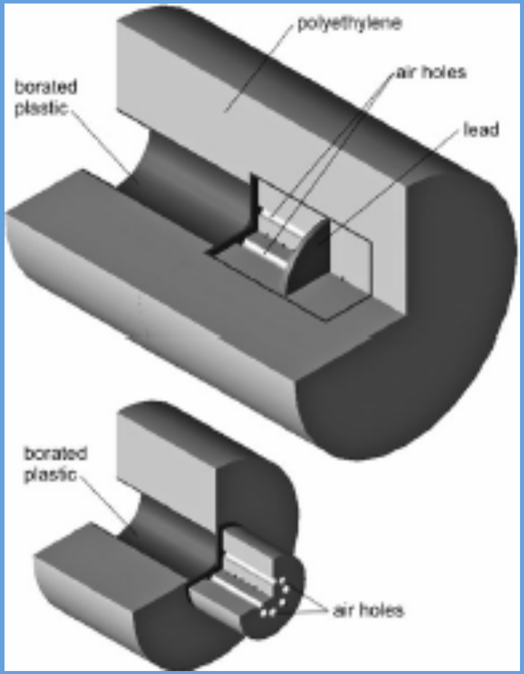
CYSP CYlindrical SPectrometer

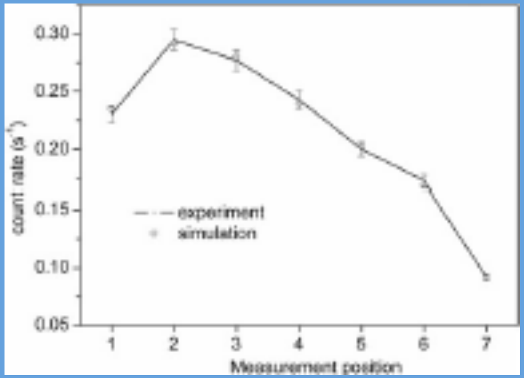
CYSP is a cylindrical moderator with seven TNDs located at different depths along the axis. An internal 1-cm-thick lead shell allows detecting high-energy neutrons. The CYSP response is sharply directional, and its collimating aperture defines the acceptance solid angle.

The dimensions of the cylinder as well as the location of detectors have been optimized to achieve spectral resolution and practically eliminate the eventual contribution from epithermal neutrons coming from lateral directions. The collimator and the additional shielding made in borated plastic are included to eliminate such lateral contributions over the whole energy range.



A 3D model of the CYSP spectrometer

The first part of the CYSP is a collimator 50 in diameter 30 cm in length made of polyethylene. The hole diameter is 8 cm, and is covered by 5-mm-thick borated plastic SWX-238. The main body of the spectrometer (right part in the figure) is a 35-cm-diameter polyethylene cylinder with seven detectors located along the axis. A lead disc has been inserted between 6th and 7th positions to in-crease the response to high-energy neutrons.



Profile of the count rate along the seven measurement positions of the CYSP. Uncertainty bars are 3%.

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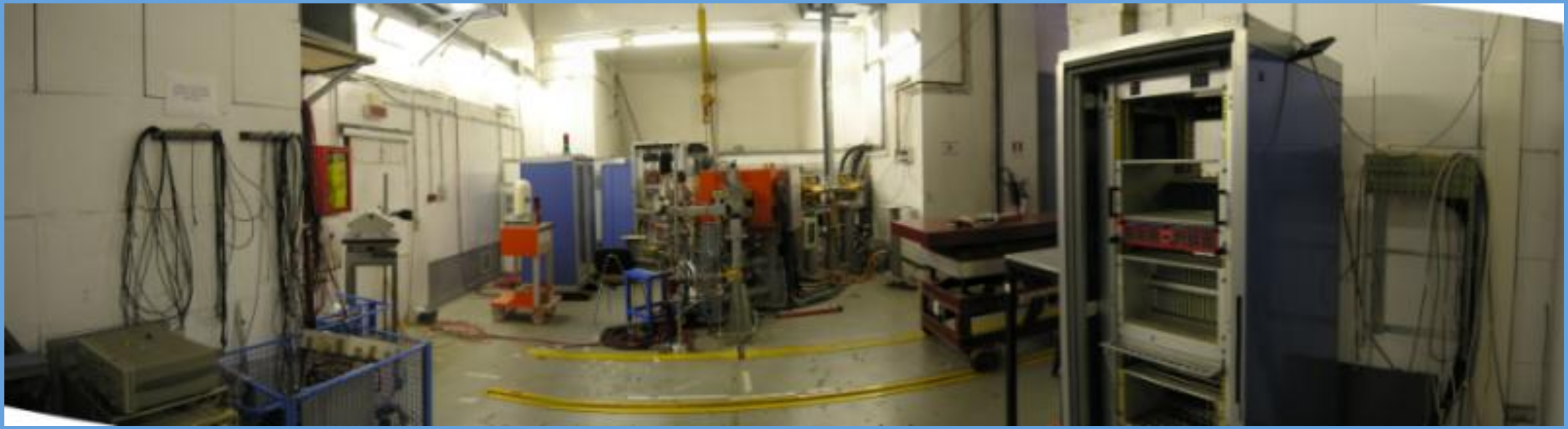
"n@BTF"

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



Roma 17-18/4/15 Master II livello "Sicurezza nel campo delle Radiazioni Ionizzanti, Radiazioni Non Ionizzanti e Risonanza Magnetica Ionizzanti"

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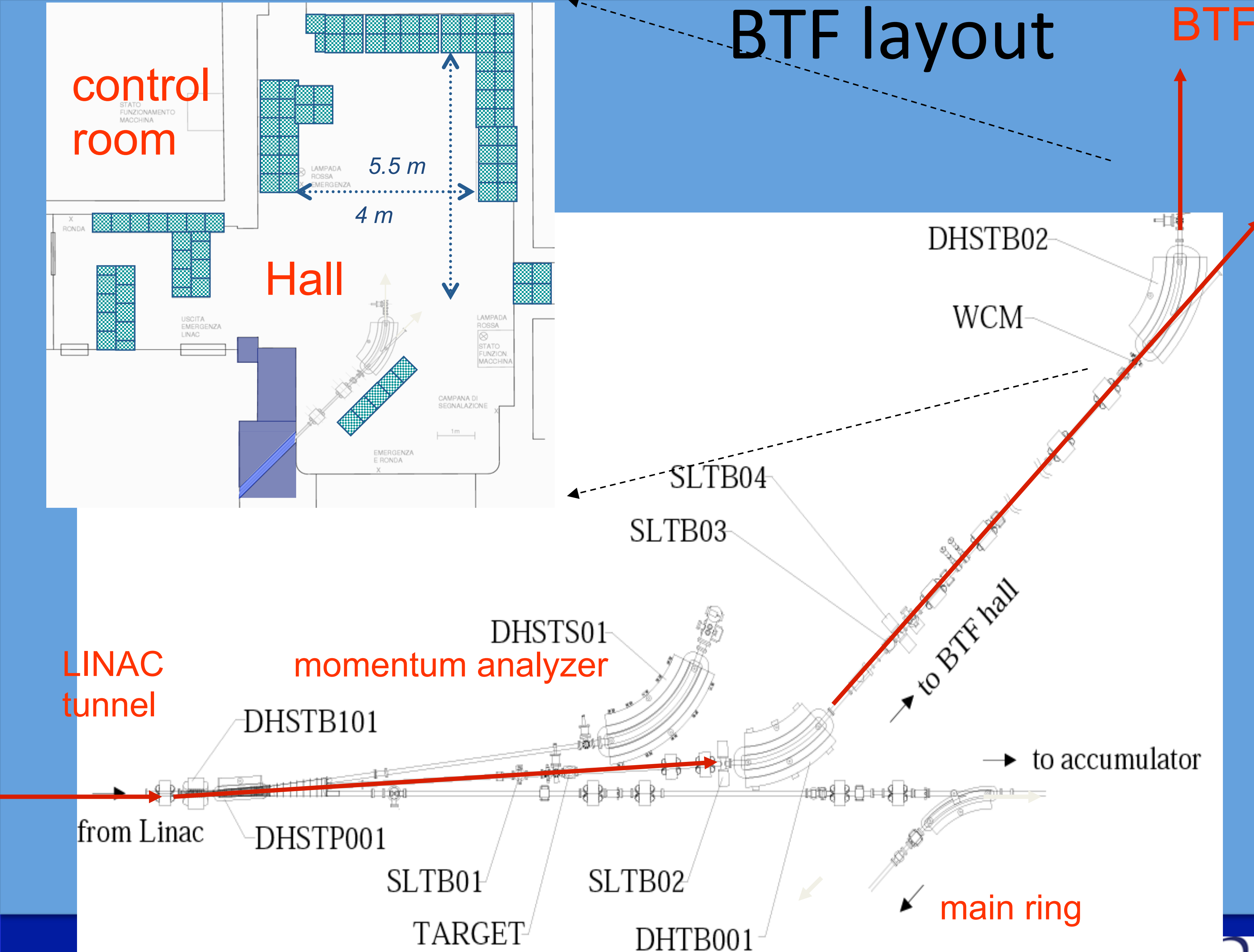
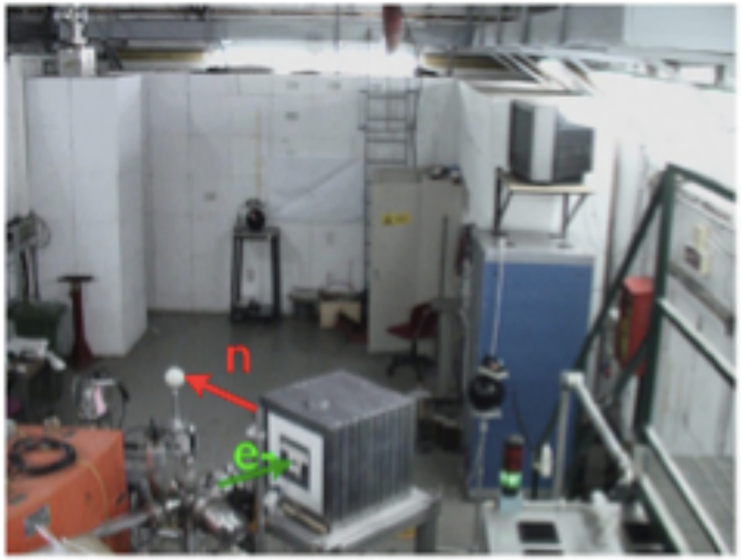
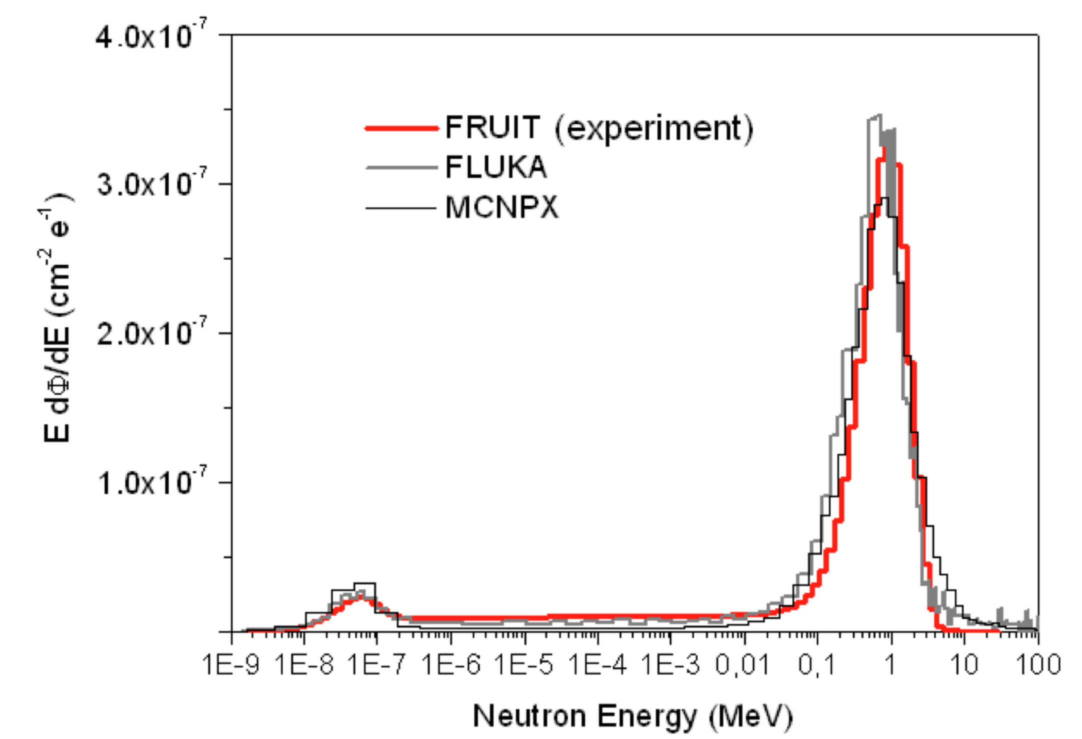
BTF layout



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}

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