Neutron spectrometry and dosimetry by passive detectors:

- Environmental Applications
- Medical Applications

Outline

- Neutron Dosimetry
- Monte-Carlo methods
- Experimental method (ambient and in phantom dosimetry)
- Passive detector system: short range 10keV-20MeV extended range 100keV-100GeV
- Unfolding code
- Anthropomorphic phantom (Jimmy)

Environmental Applications

- High altitude flights
- Stratospheric balloons
- High altitude Observatories

Medical Applications

Radiotherapy

BNCT (**B**oron **N**eutron **C**apture **T**herapy)

Why Neutron Dosimetry?

- Neutrons have high RBE in the range 100 keV - 100 MeV
- Neutrons risk factors have been increased in ICRP 74 (1994)

Environmental application

- Neutrons represent the main component in the atmospheric shower at the altitude of intercontinental flights altitudes
- Secondary neutrons are produced in space by interaction of primary protons with spacecraft shielding
- Neutron dose contribute to the radiation background for people living at high altitude countries

Why Neutron Dosimetry?

Medical applications

- Neutrons represent a crucial component of the undesired dose (outside from the treatment zone) in tumor radiotherapy with high energy linacs
- The new radiotherapy technique based on Boron Neutron Capture Therapy (BNCT) requires an accurate spectrometry to characterize the thermal or epithermal neutron beams.

Neutron Spectrometry and Neutron Dosimetry

The complexity of the experimental neutron dose evaluation is due to many factors:

- *The neutron RBE (Radiation Biological Effectiveness) strongly depends from neutron energy* → Neutron energy spectra measurements

  Threshold detectors + Unfolding codes
- *Neutron fields are mixed with gamma fields* → Detectors able to separate the neutron signal from gamma signal
- *Neutron energy range cover 10 or more order of magnitude: from 0.025 eV to hundred of GeV* → Different interaction mechanisms

  Different detectors for different energy
- *In terference with electromagnetic fields* → Passive detectors – no electronic devices

Quantities for dosimetry and radiological protection

Fluence Φ

$$\Phi = \frac{dN}{dA}$$

Number of particles across the surface A

(cm^{-2})

Absorbed dose D

$$D = \frac{d\bar{\varepsilon}}{dm}$$

(Gray = Joule/Kg)

Mean energy imparted by ionising radiation to matter of mass dm

Equivalent dose H_T

(Sievert= Joule/Kg)

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

T = tissue or organs

$D_{T,R}$= absorbed dose over the tissue or organ

w_R = radiation weighting factor

R = type of radiation

Radiation Weighting factors w_R

(ICRP 74)

Radiation	w_R
Photons	1
Electrons	1
Muons	1
Neutrons	
< 10 keV	**5**
10 – 100 keV	**10**
100 keV – 2 MeV	**20**
2 – 20 MeV	**10**
> 20 MeV	**5**
Protons	5
Alfa particles, fissions fragments, heavy nuclei	20

Quantities for radiological protection

Refence quantity

Effective dose

$$E = \sum_T w_T H_T$$

H_T = equivalent dose
w_T = tissue weighting factor

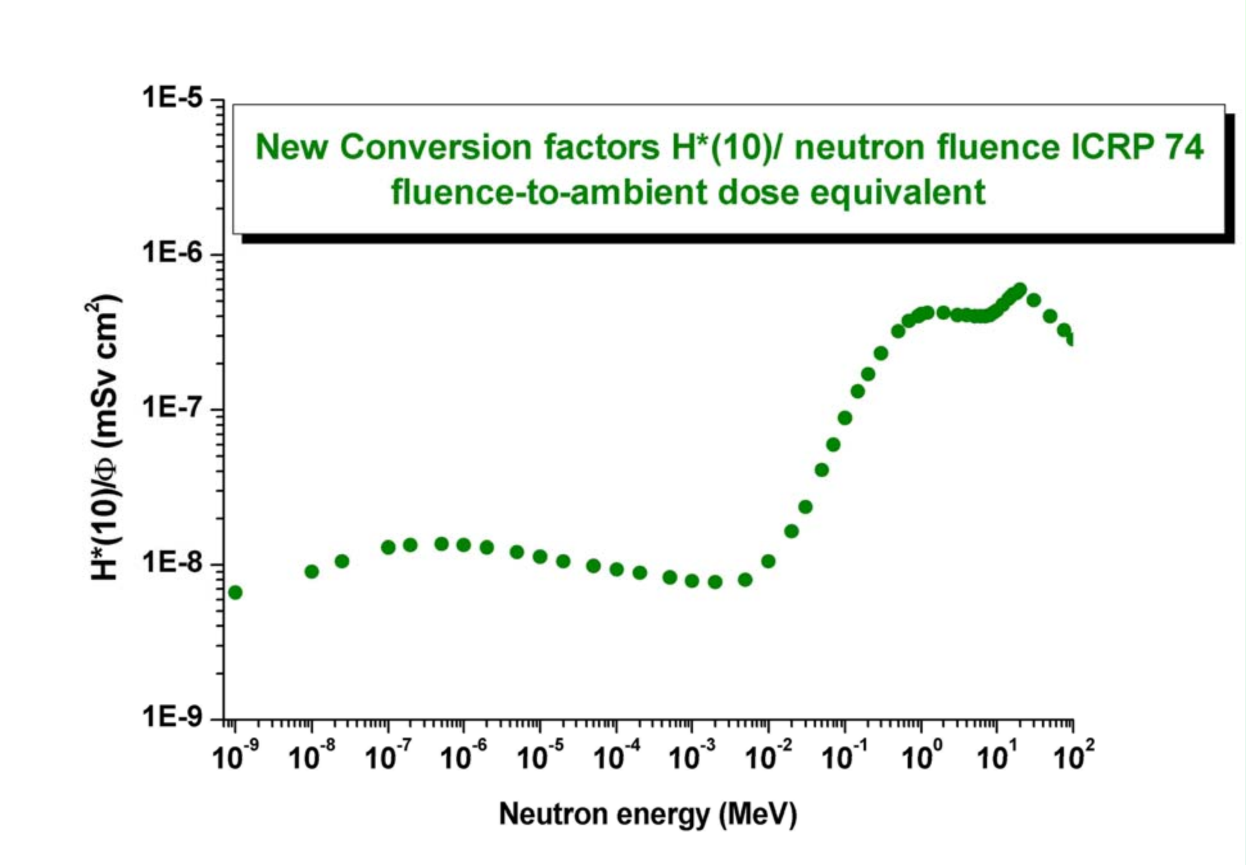
(Sievert= Joule/Kg)

Tissue Weighting Factors

Organs	w_T
Gonads	0.20
Lung	0.12
Stomach	0.12
Colon	0.12
Bladder	0.05
Liver	0.05
Oesophagus	0.05
Breast	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Quantities for dosimetry and radiological protection

Operational quantity



H* Ambient dose equivalent (Sievert = J/Kg)

H* = Φ x Conversion factors

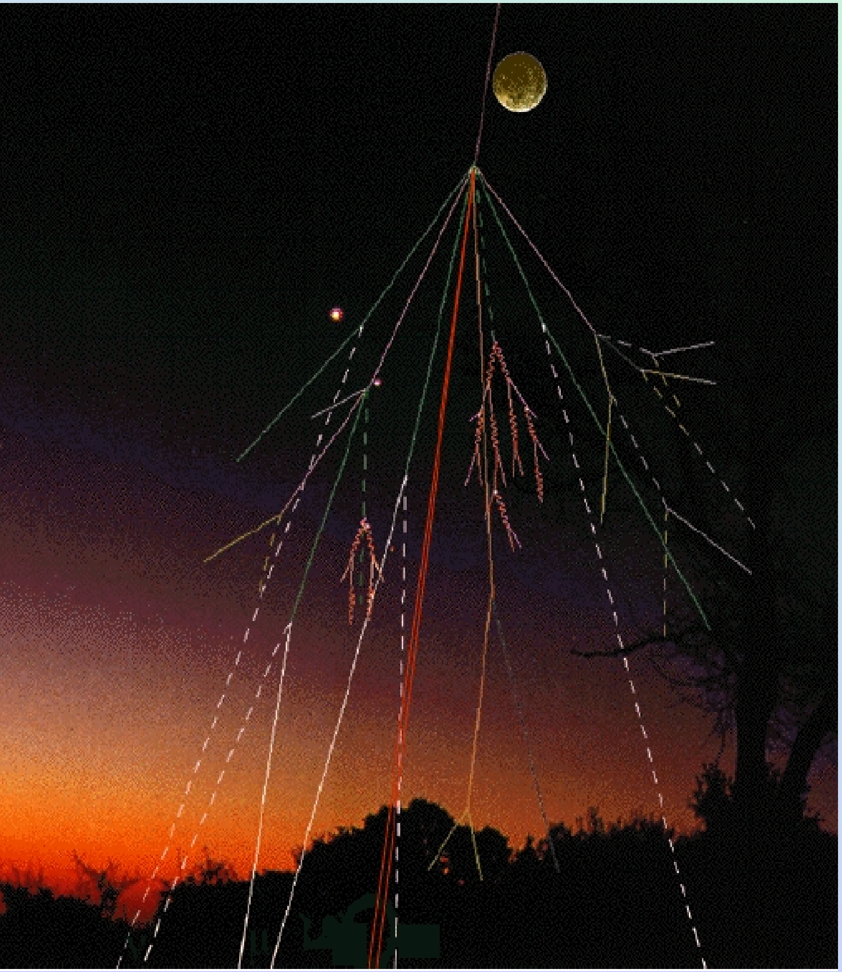
H*>E

H* is conservative to respect to E

Environmental Applications

- *Alitalia intercontinental flights   12000 m*
- *ASI balloon flights   30-40 km*
- *High Mountain Observatories   3000-5000 m*

Cosmic ray neutrons



Neutrons in atmosphere arise from:

1. **Interaction of primary cosmic rays with O and N atmosphere nuclei;**
2. **Nuclear decays like:**

$$\Lambda \rightarrow n + p^{0}$$
$$\Sigma+ \rightarrow n + p^{+}$$
$$\Sigma- \rightarrow n + p^{-}$$

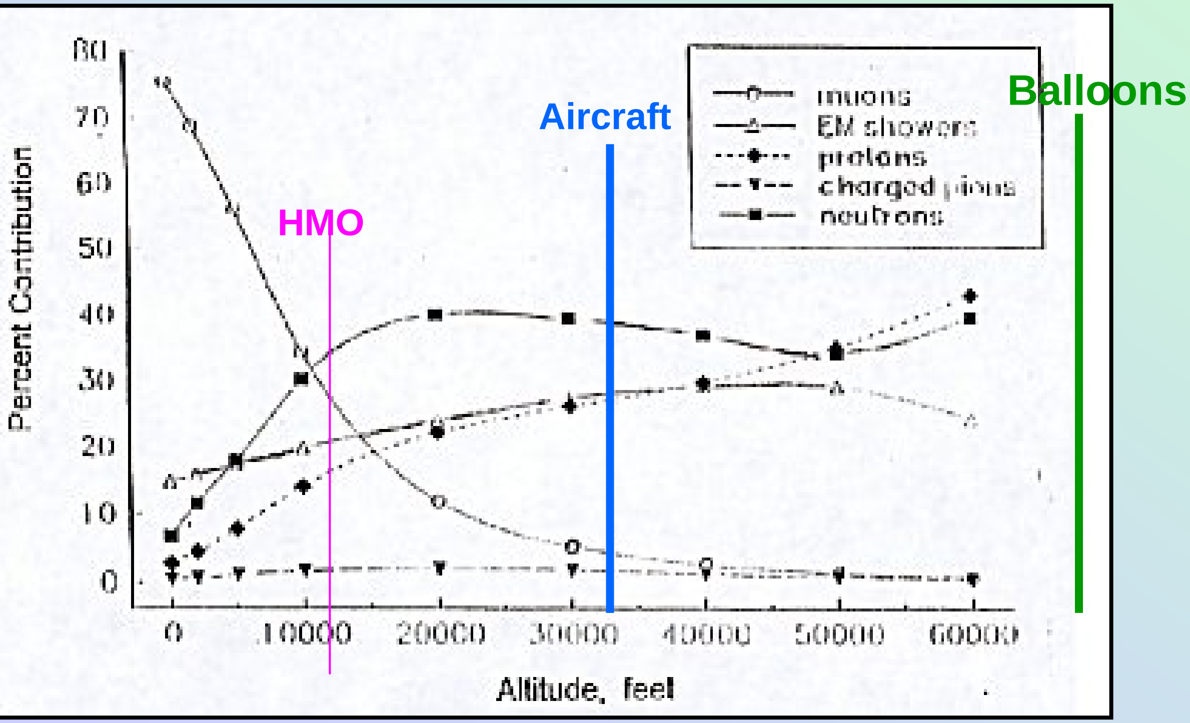
Most of the thermal neutron in atmosphere are absorbed in such processes as:

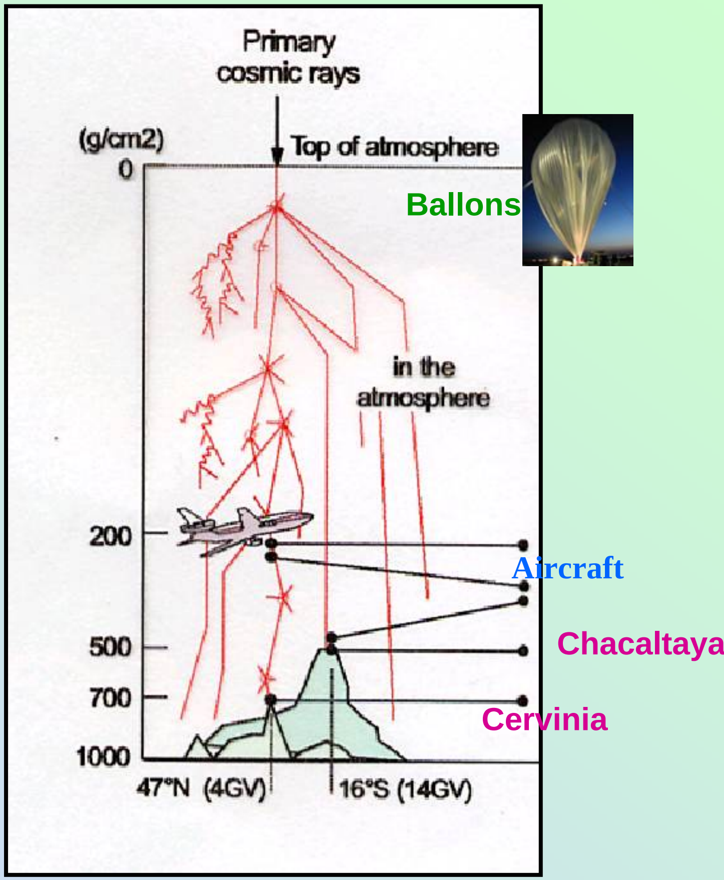
$$^{14}N + n \rightarrow {}^{14}C + {}^{1}H$$

5% of neutron having energies greater than 4 MeV take part in the reaction:

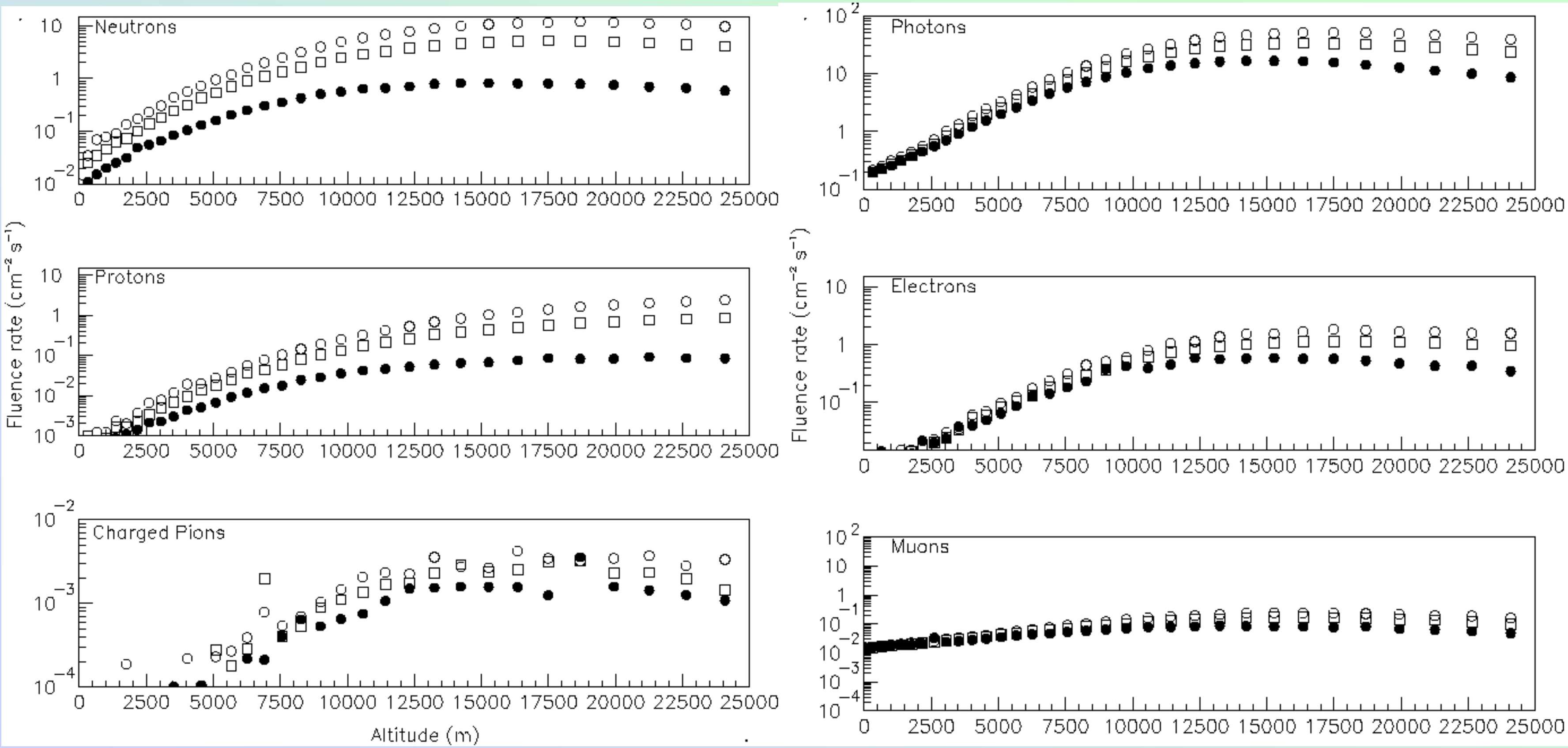
$$^{14}N + n \rightarrow {}^{12}C + {}^{3}H$$

Composition of atmospheric shower





FLUKA simulations



Calculated hadron fluence rates as a function of altitude for different input conditions (○) high latitude, solar minimum activity; (□) high laditude solar maximum activity, (●) low latitude solar minimun activity.

A.Ferrari, M.Pelliccioni, T.Rancati, "Calculation of the Radiation Environment Caused by Galactic Cosmic Rays for Determing Air Crew Exposure", Rad. Prot. Dos. 93, 2, 101-114 Nucl. Tech. Pub. (2001).

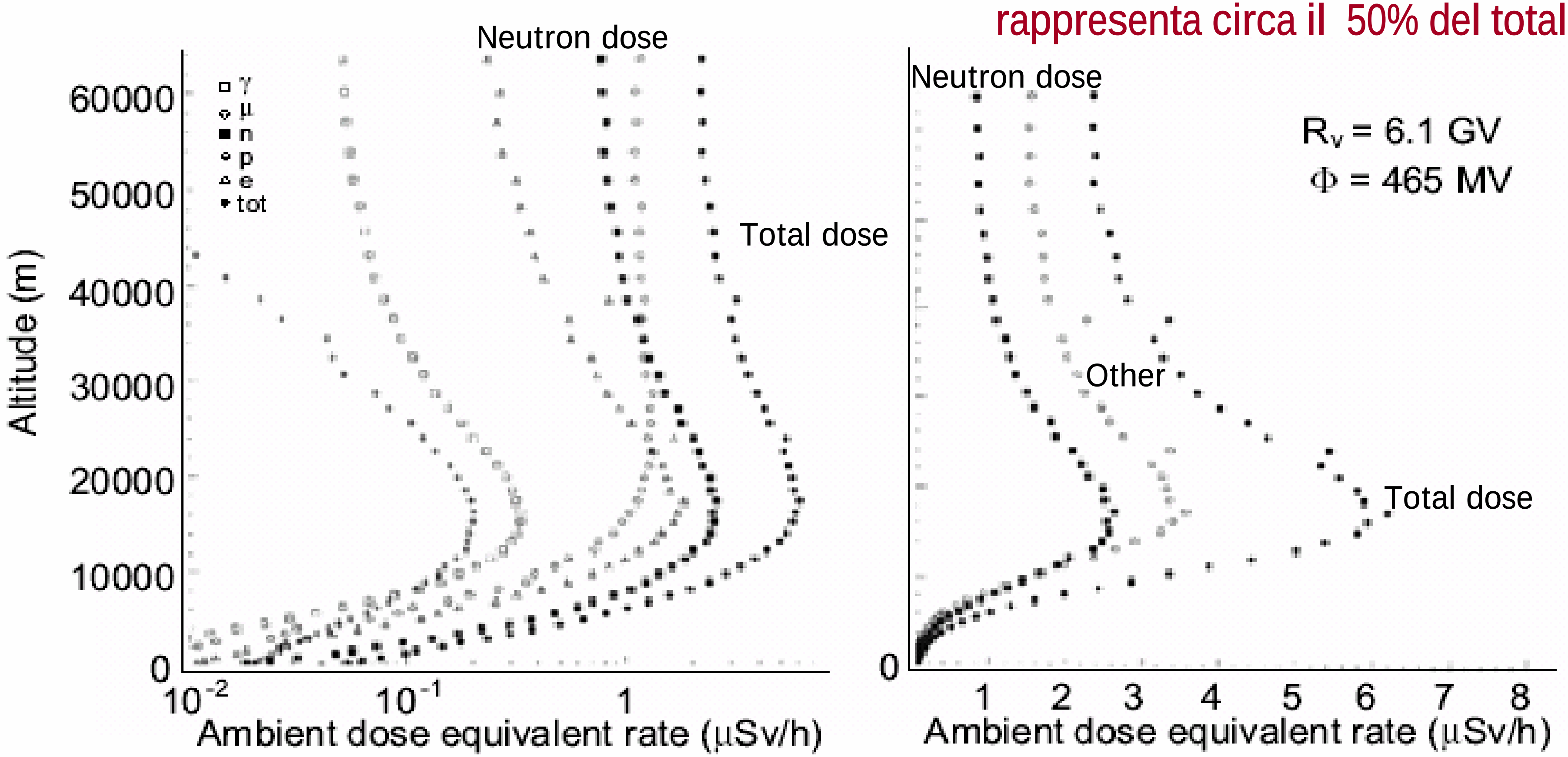
Neutroni in atmosfera

CONTRIBUTO ALLA DOSE TOTALE massimo a ~16 km

quote di volo: 3-6 μSv/h ad alte latitudini,

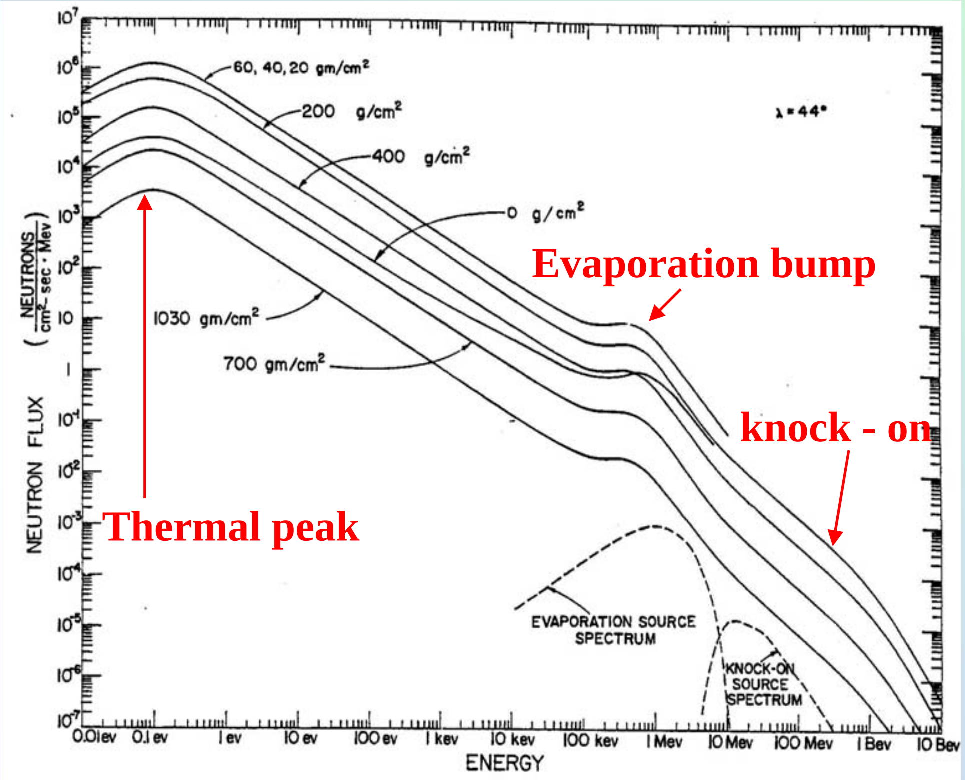
~ 1/2 a basse latitudini;

rappresenta circa il 50% del totale.



Simulazioni codice FLUKA ''Differential Neutron Flux in Atmosphere at Various Geophysical Conditions'' A. Zanini,, M.Pelliccioni, at al., Proc of *The 28th International Cosmic Ray Conference, Tsukuba (July 2003).*

Characteristics of the neutron spectra in atmosphere



- **Low energy peak**

  at about 0.1 eV (the energy shift depends on the capture processes of thermal neutron with formation of radioactive nuclei).

- **Intermediate energy peak**

  at about 1 MeV arising from the evaporation process of the excited nucleus.

- **High energy peak**

  at about 100 MeV. These neutrons derive from the direct interaction of the high energy incident particle with the nucleus.

Neutron dosimetry at high altitudes flights

Calculation

- Monte Carlo codes (FLUKA, GEANT3, GEANT4)
- Transport codes (CARI, LUIN, EPCARD, FREE, PCAIRE, SIEVERT)

Experimental methods

- Tissue equivalent proportional counters (dose from LET)
- Si-semiconductor spectrometers (dose from LET)
- Rem-counters (Alnor th. to 17 MeV, Linus th. to 400 MeV)
- Bubble (super heated-drop) detectors (10 keV-20 MeV)
- Fission stack (Bi^{209}) for high energy neutrons (200MeV – 100 GeV)

Experimental Method

Extended range 100 keV - 100 GeV

(in free air measurements)

- **a wide energy range detection system;**
- **reduced size and no electronic supply (**as required on intercontinental flights).

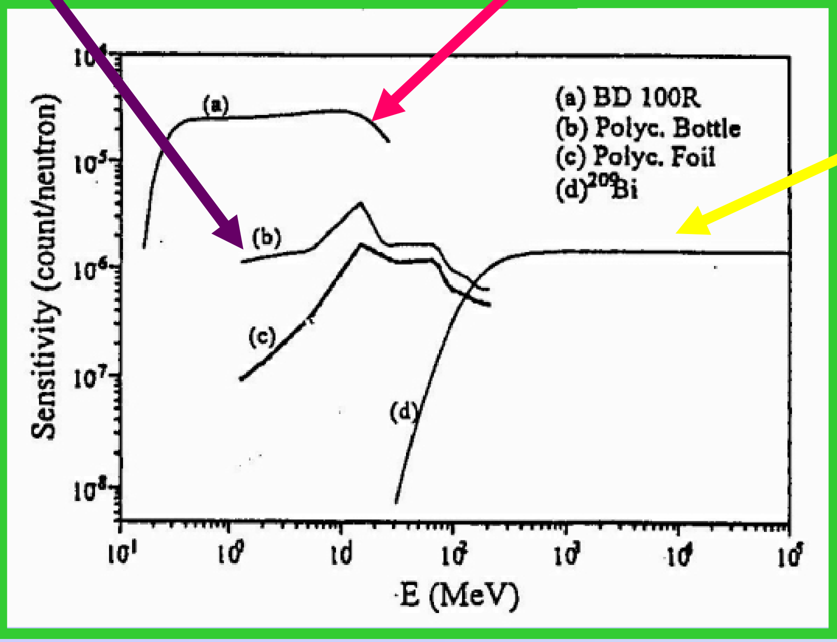
Detector	Energy range	Physical characteristics
1. Bubble dosemeter BD100R	**100 keV- 20MeV**	Polycarbonate vials filled by tissue equivalent gel, in which microdroplets of superheated freon are spread. Charged recoil particles, produced by the interaction of neutron with gel, give raise to visible bubbles.
2. Polycarbonate detectors foil **3. Polycarbonate detector bottles**	**1 MeV- 100 MeV**	Track are left by recoil products, generated by neutron interaction and revealed by etching tecniques.
4. Fission detector ^{209}Bi	**100 MeV- 100 GeV**	Stack of ^{209}Bi layers, deposed on mylar films (100 μ). Fission fragments generated from n- ^{209}Bi interaction generated holes in mylar detected by means of a spark counter

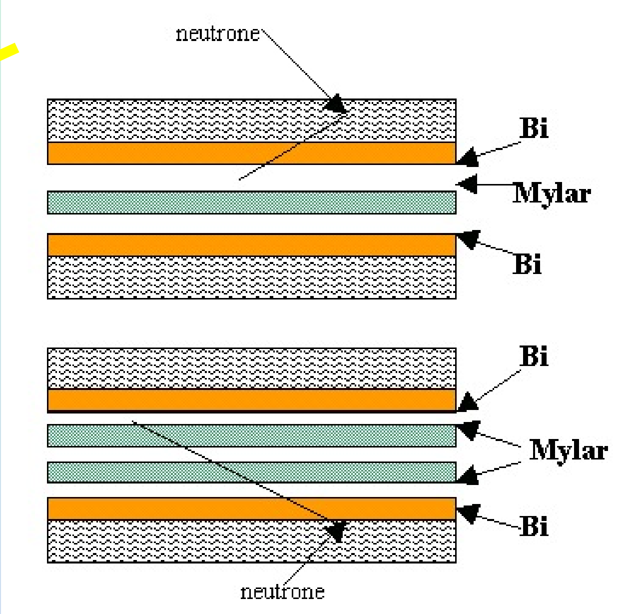
Bubble dosemeter
BD100R 100keV - 20 MeV

Polycarbonate detectors
1MeV-100MeV

Fission detector ^{209}Bi
100MeV -100GeV

RESPONSE CURVES

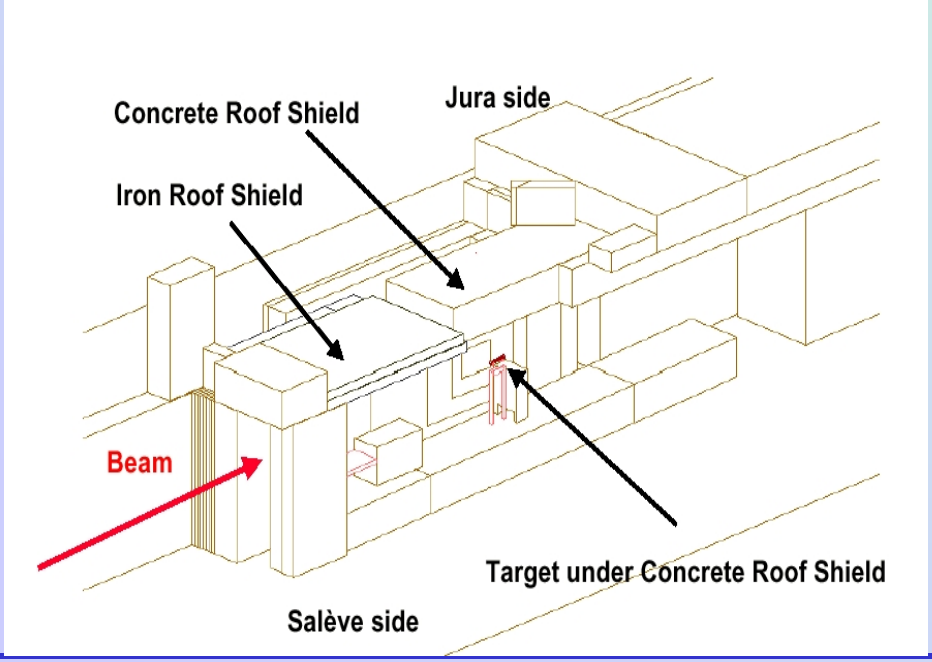


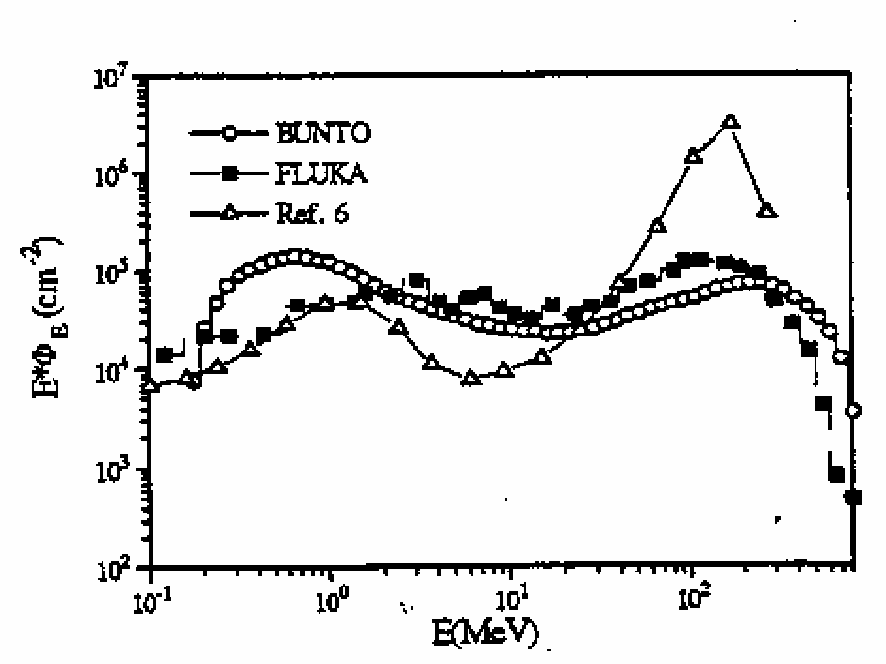


Calibration

- The calibration of the passive detector system has been performed at CERN (T14 position, H-6SPS beam): this facility is a reference field for the calibration of neutron detection systems to be used in the cosmic ray field.

- The passive detector results, unfolded with the BUNTO code, are compared with the MC simulation of the experimental setup; the results are consistent.





Experimental Method

Short range 10 keV-20 MeV

- IN FREE AIR MEASUREMENTS

BDS spectrometer and unfolding code BUNTO → **Evaluation of the neutron spectrum (10 keV – 20 MeV).** → **Evaluation of H*(10) and E from ICRP74 conversion coefficients**

- IN TISSUE EQUIVALENT MEASUREMENTS

Anthropomorphic phantom: JIMMY and bubble detector BD-100R → **Measures of dose equivalents at organ positions in tissue equivalent phantom.** → **Approximation of E from organ dose equivalents**

Experimental Detection System

Bubble detectors for neutron dosimetry

Calibrated in terms of dose equivalent (NCRP 38)

Integral dosemeter:

BDT thermal neutron

BD-100R fast neutron

temperature dependence

BD-PND fast neutron

compensation for sensityvity change with temperature over the operation range of 20-27°C)

Integral dose 100 keV-20 MeV

Neutron spectrometer BDS

Six detectors with different energy threshold

coupled with an unfolding code

Spectral distribution of the neutron field

10 keV - 20 MeV

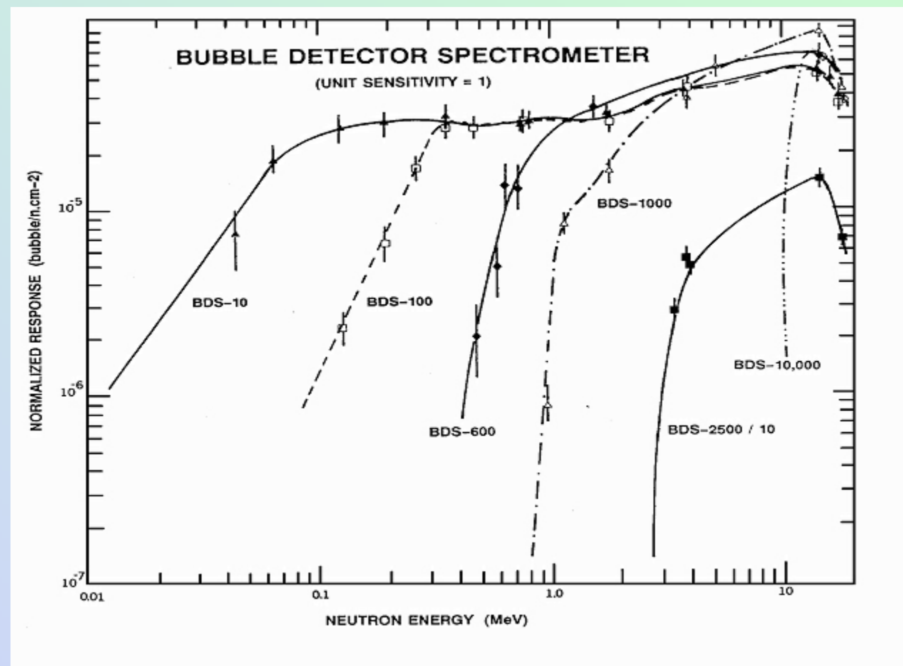
	BD-PND	BD100R	BDT	BDS
Energy Range	< 200 keV to > 15 MeV	< 200 keV to > 15 MeV	Thermal (~ 1/V for epithermals)	Six thresholds: 10, 100, 600, 1000, 2500 and 10000 keV
Dose Range	0.1 - 500 mrem 0.01 - 50 μSv	0.1 - 500 mrem 0.01 - 50 μSv	0.1 - 10 mrem 0.01 - 1 μSv	~ 50 mrem ~5 μSv
Sensitivity (User Selectable)	0.33 - 33 bub/mrem 0.033 - 3.3 bub/μSv	0.33 - 33 bub/mrem 0.033 - 3.3 bub/μSv	~ 30 bub/mrem 3.0 bub/μSv	1 - 2 bub/mrem 0.1 - 0.2 bub/μSv
Automatic Temperature Compensation	Yes	No	Yes	No
Optimum Temperature Range	20 - 37 °C	10 - 35 °C	20 - 37 °C	20 °C
Size	145 mm length x 19 mm diameter	120 mm length x 16 mm diameter	145 mm length x 19 mm diameter	80 mm length x 16 mm diameter
Weight	58 g	33 g	58 g	20 g
Re-use	Yes	Yes	Yes	> 10 cycles
Recompression Method	Integrated assembly	Integrated assembly	Integrated assembly	External recompression chamber required
Notes	Recommended for personal neutron dosimetry	Temperature response curve provided	Thermal:fast neutron sensitivity > 10:1	Ideal for neutron spectral characterization

Neutron spectrometer

BTI (Bubble Tech. Ind., Ontario, Canada)

1. BDS 10	10 keV - 20 MeV
2. BDS 100	100 keV - 20 MeV
3. BDS 600	600 keV - 20 MeV
4. BDS 1000	1 MeV - 20 MeV
5. BDS 2500	2.5 MeV - 20 MeV
6. BDS 10000	10 MeV - 20 MeV

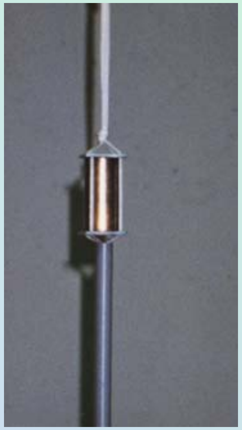
Six different types of superheated drop detector, with different chemical compositions, different thresholds and energetic responses



Three response curves sets in correspondence of different temperatures values (20 °C, 25 °C, 30 °C, 32.5 °C, 35 °C)

Calibration

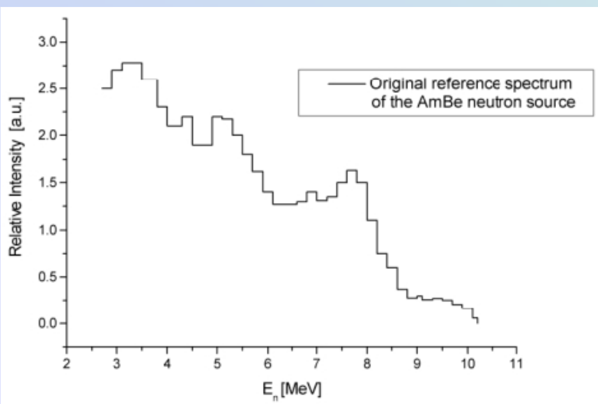
Am-Be source JRC Ispra, VA

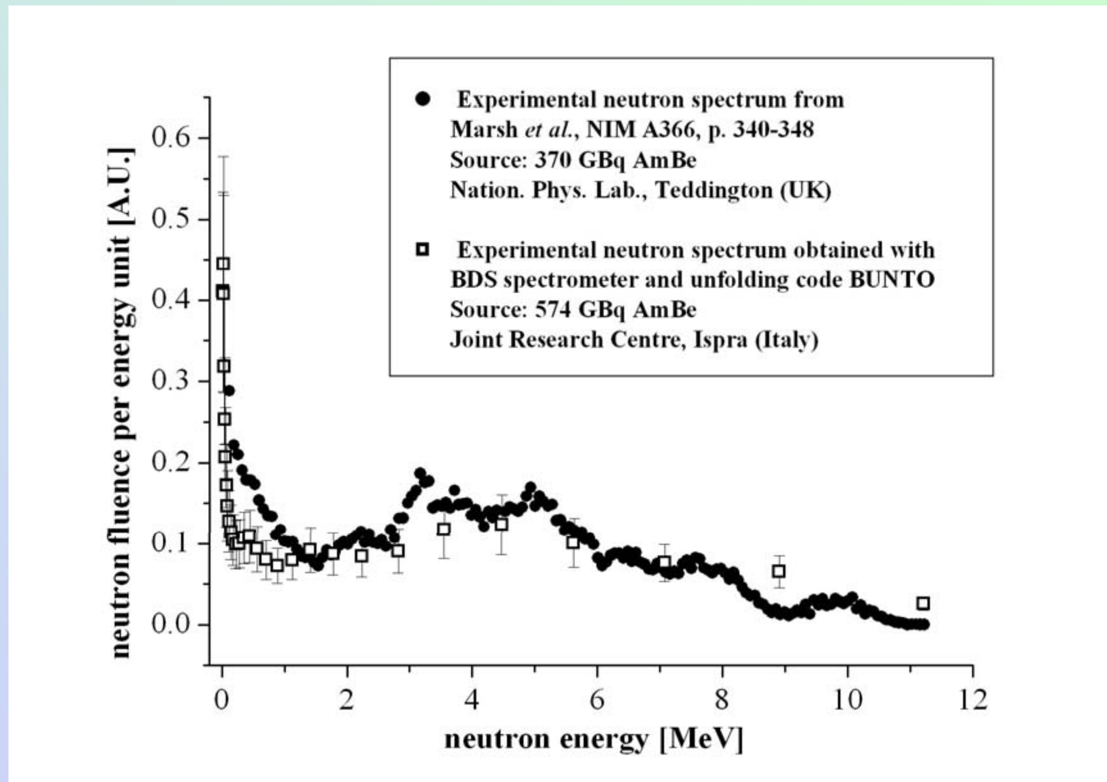


$^{241}Am \longrightarrow {}^{237}Np + \alpha + \gamma$

$E\alpha = 5.49$ MeV, $E\gamma = 29$ keV, Q = +5.64 MeV

$^{9}Be + \alpha \longrightarrow {}^{12}C + n$, Q = +5.7 MeV





Unfolding technique

$$M_j = \int_{E_{\min}}^{E_{\max}} R_j(E)\Phi_E(E)dE \quad j = 1..m$$

Fredholm equations

M_j **: detector response**
R_j (E) **: response curve values**
Φ_E(E) **: differential fluence distribution of neutron energy**
m **: number of energy thresholds**
n **: number of energy intervals**

The analytical function R_j (from the BTI manual instruction) is approximated by the matrix R_{ij}

The system of integral equations is transformed into a matrix system

$$M_j = \sum_{i=1}^{n} R_{ij}\Phi_i \quad i = 1...n$$

BUNTO

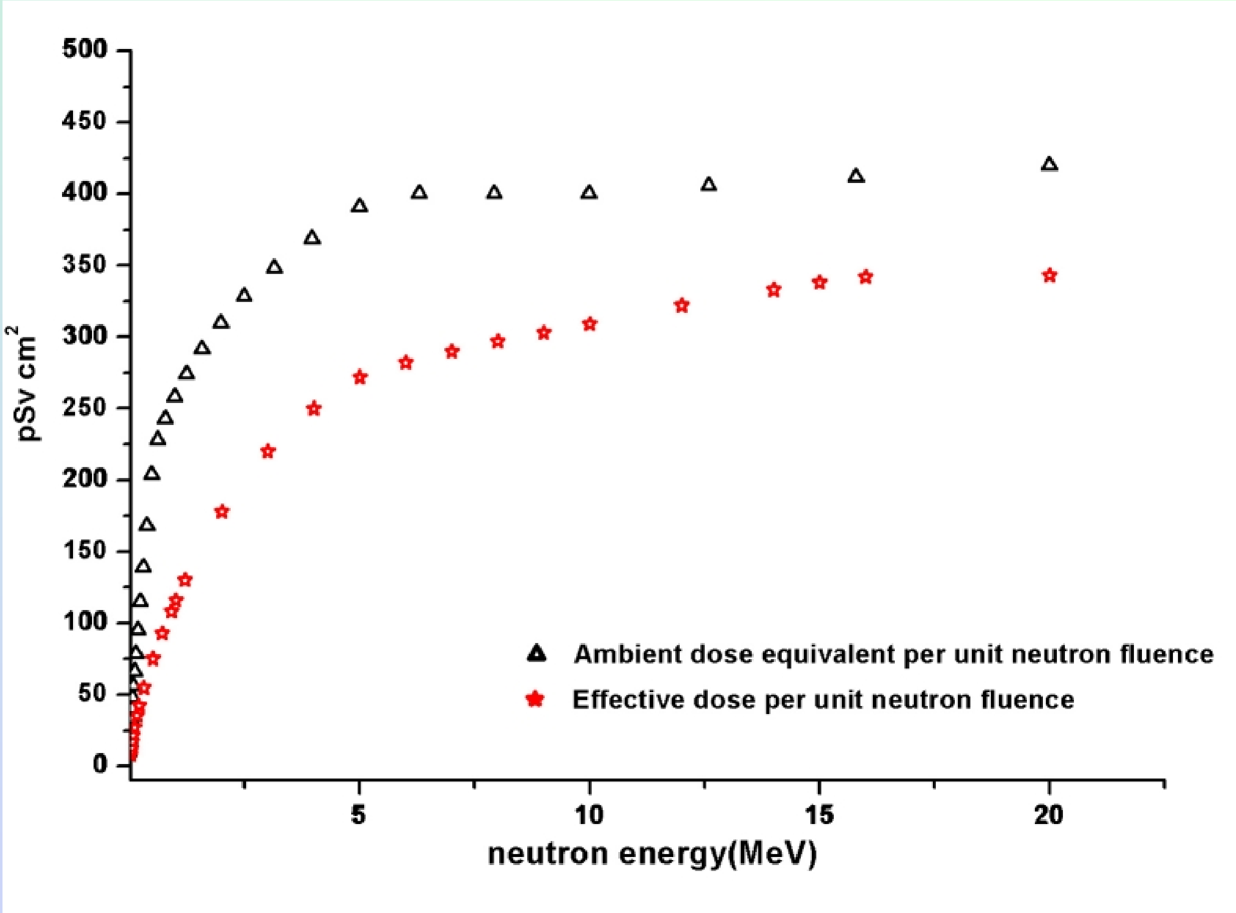
- It is based on BUNKI's algorithm (SPUNIT), which finds the non negative solution through a iterative perturbation procedure.
- It can find a solution using a starting information on the spectrum shape, but it can also work in lack of information on the initial spectrum.
- The solution $\Phi_E(E)$ is the calculated mean from a number of spectra obtained by a random generation of M_j sampled on a normal distribution, whose parameters m and σ are the final value and the associated uncertainty of the j^{th} detector.
- It can be used with different spectrometry systems, if the response matrix of the detectors is known.

<u>BUNTO</u>
is the unfolding code developed in Torino to find a solution to the system of Fredholm equations.

Fluence to dose conversion coefficients

Ambient dose equivalent (H*(10))
at a point in a radiation field is the dose equivalent produced by the corrisponding aligned field in the ICRU sphere at depth 10 mm (ICRP74)

Effective dose (E)
Sum of the weighed equivalent doses in all the tissues and organ of the body (ICRP74)



H*(10) is an operational quantity intended to provide a reasonable estimate of the protection quantity E

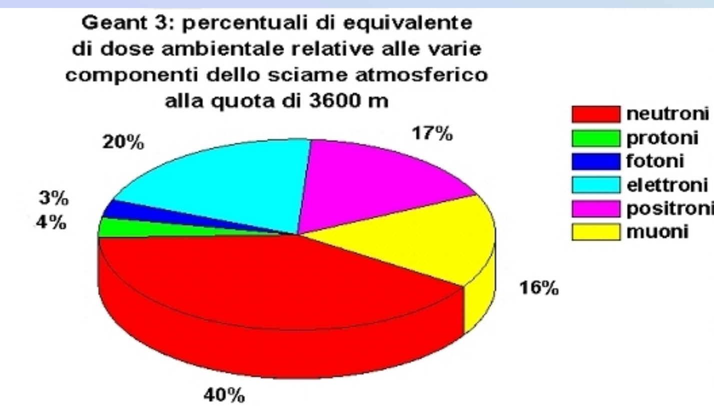
In air measurements

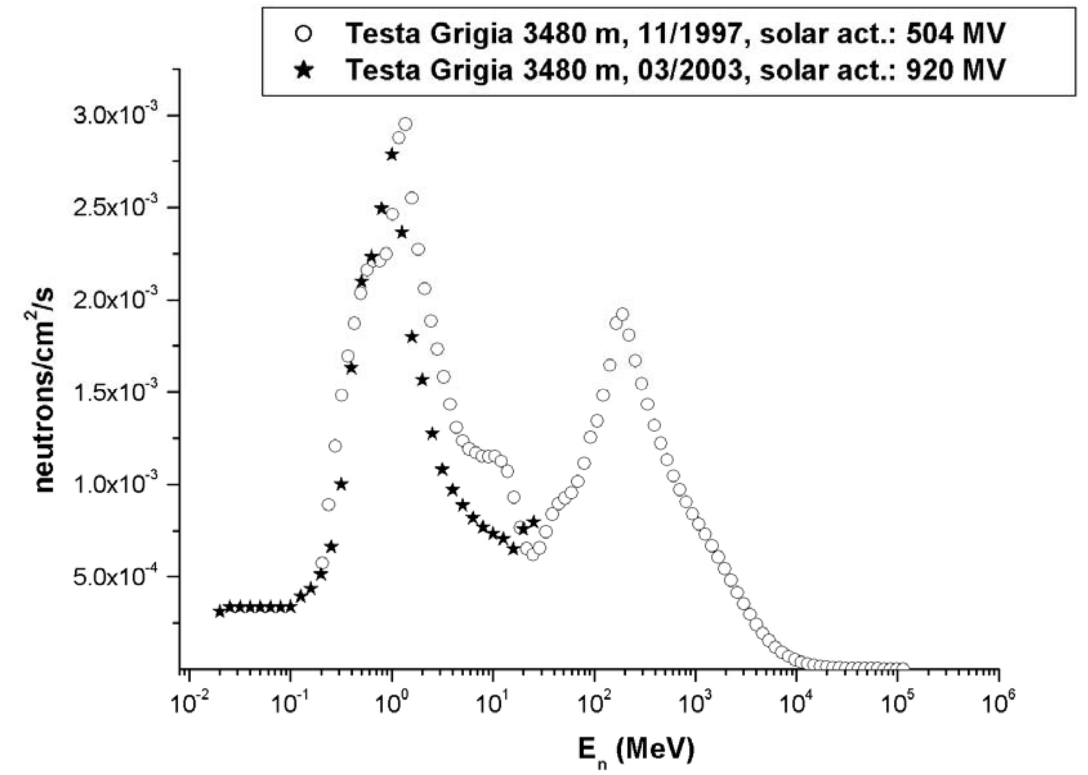
Alitalia intercontinental flights

ASI balloon flights

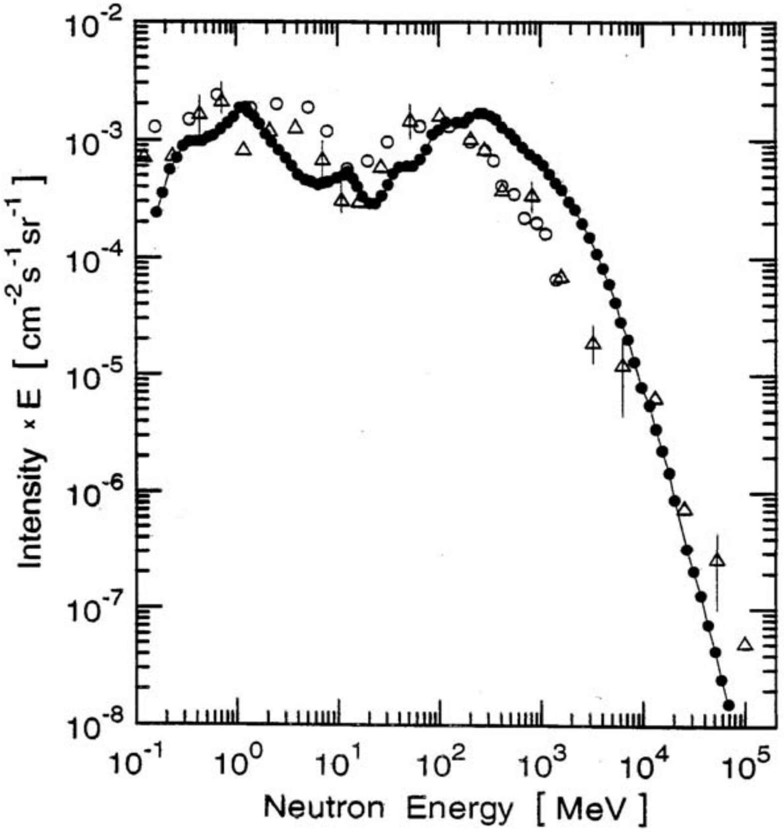
High Mountain Observatories

- ***STAZIONE DI RICERCA TESTA GRIGIA***
- **PLATEAU ROSA' 3480 m. a.s.l.**
- **BREUIL - CERVINIA**
- **ITALY**
- **45°56'03" NORD**
- **07°42'28" EST**





High Mountain Laboratory



Neutron spectrum at high mountain lab.

✐Zanini et al. (1997), Matterhorn 3480m (650 g/cm²)

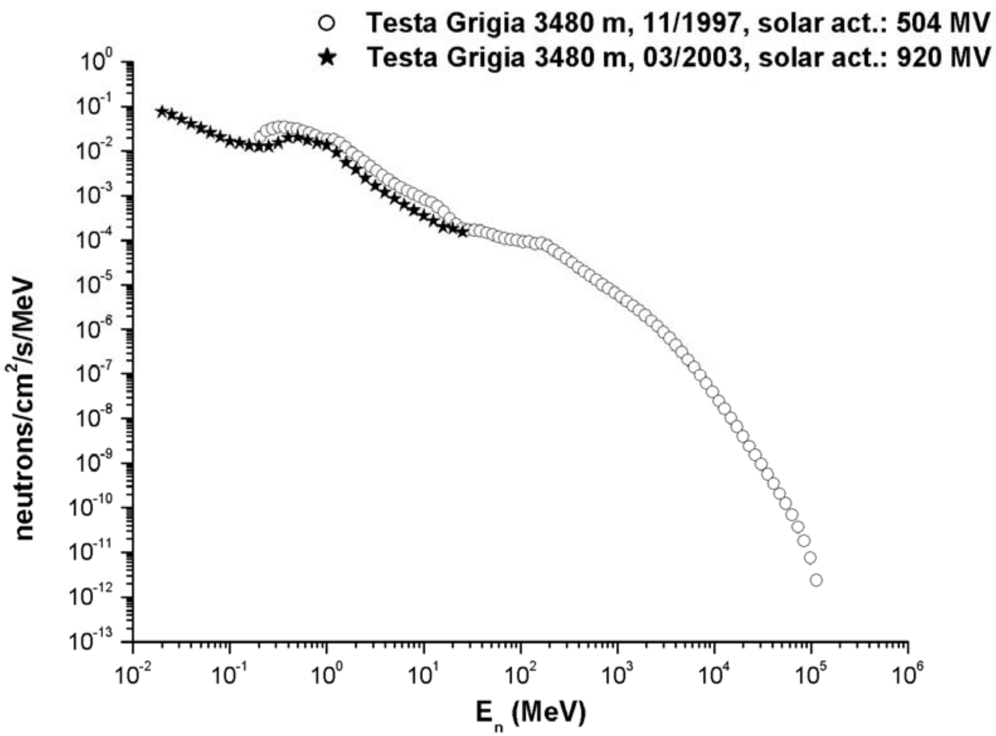
✃Merker (1973) 700 g/cm² (~ 3200 m)

ΔSchraube et al. (1996), Zugspitze 2963 m

STAZIONE DI RICERCA TESTA GRIGIA

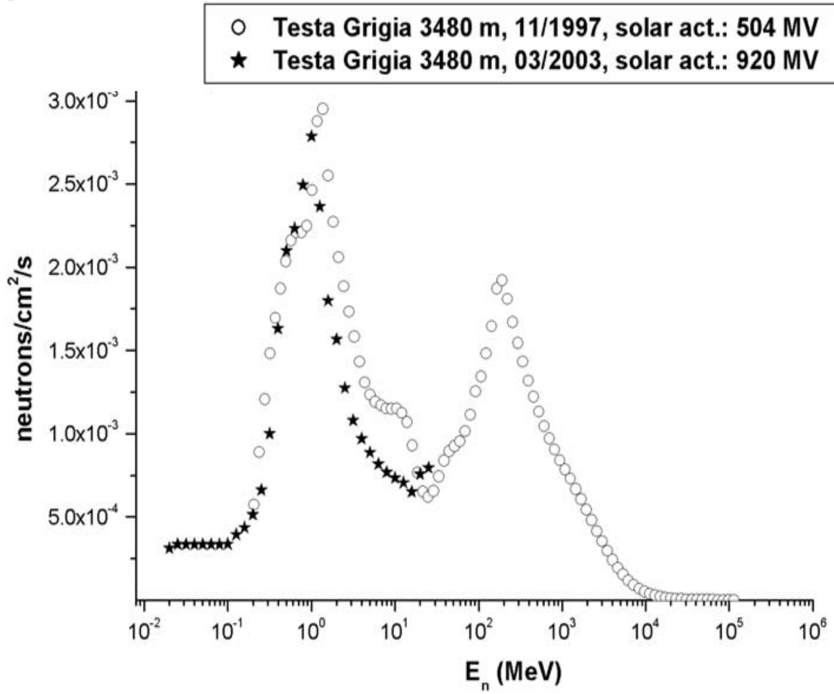
PLATEAU ROSA' 3480 m. a.s.l.

"COSMIC RAYS AT EARTH - Researcher's Reference Manual and Data Book" ELSEVIER SCIENCE (2001) pp.109-110.

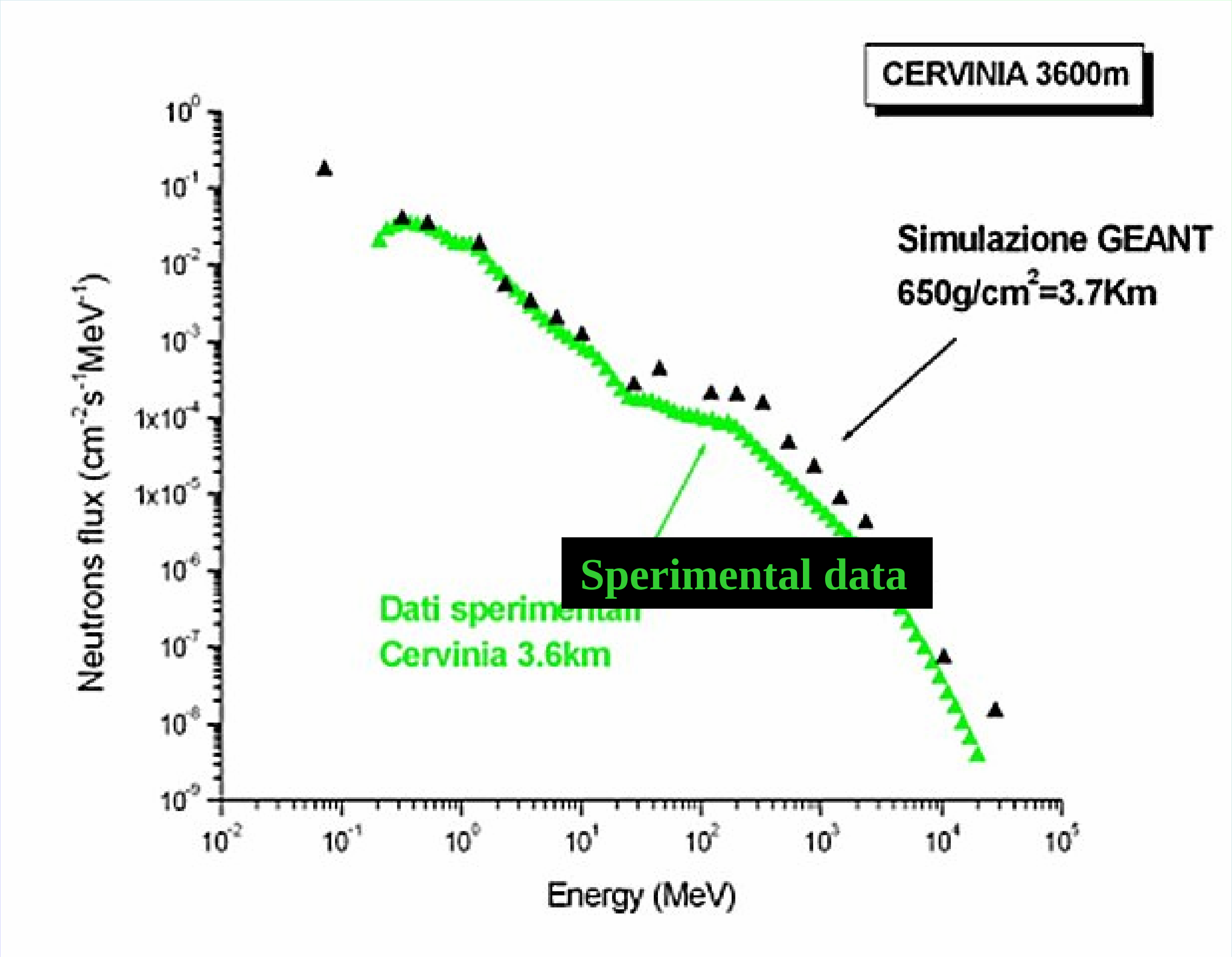


Results at Testa Grigia laboratory

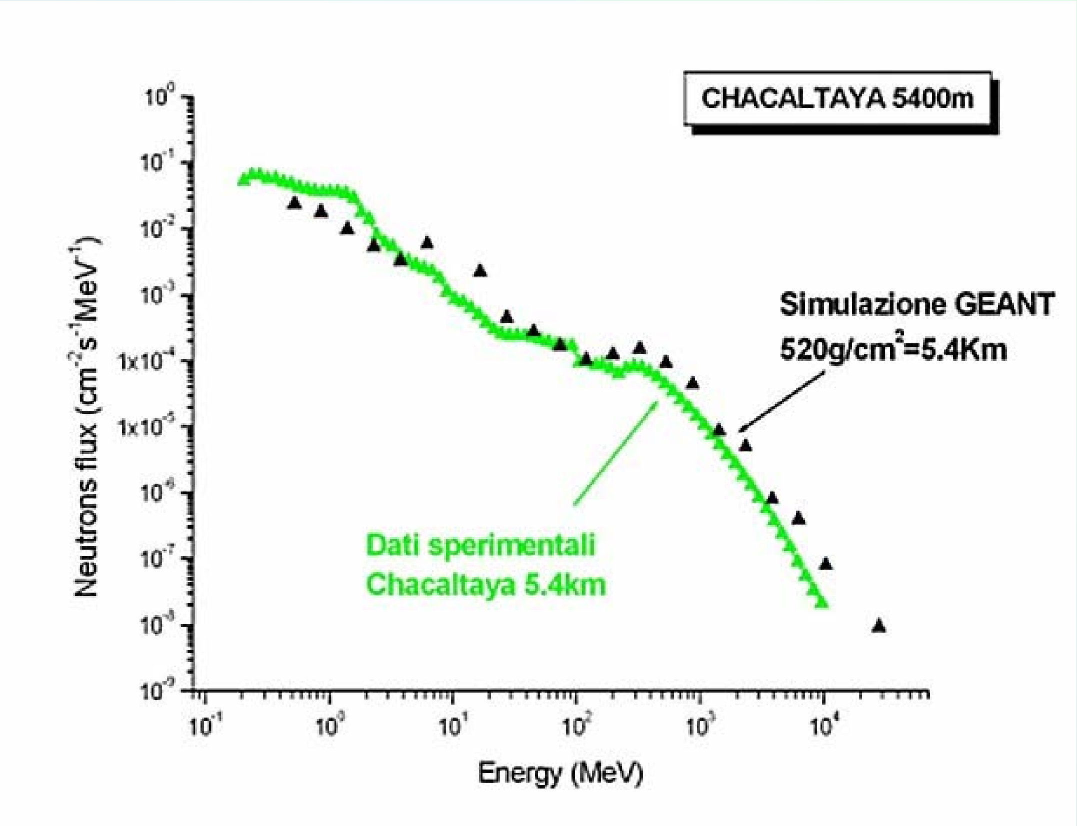
- March 2003 - short range
  compared with
- October 1997- wide range



Neutron spectra at Testa Grigia Laboratory



Comparison between experimental data and simulation (GEANT code)



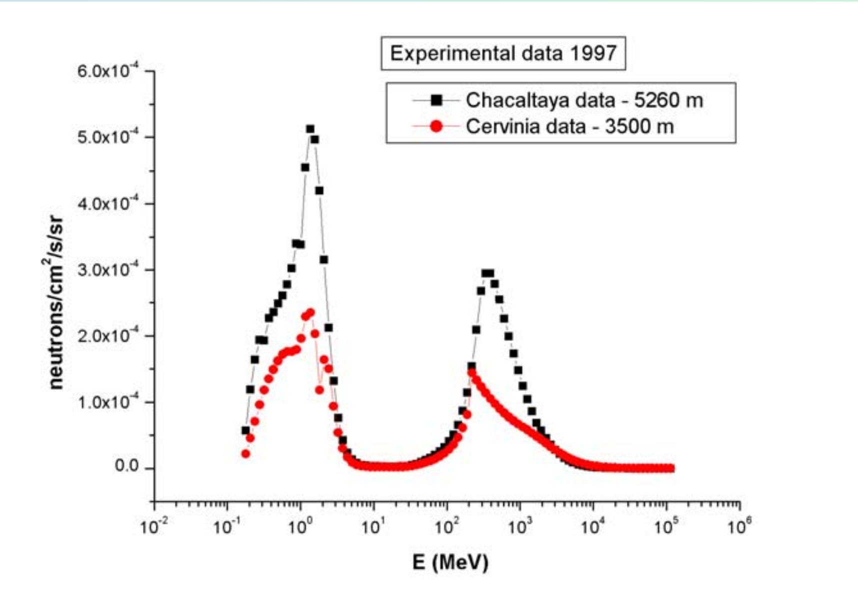
Chacaltaya lab.,

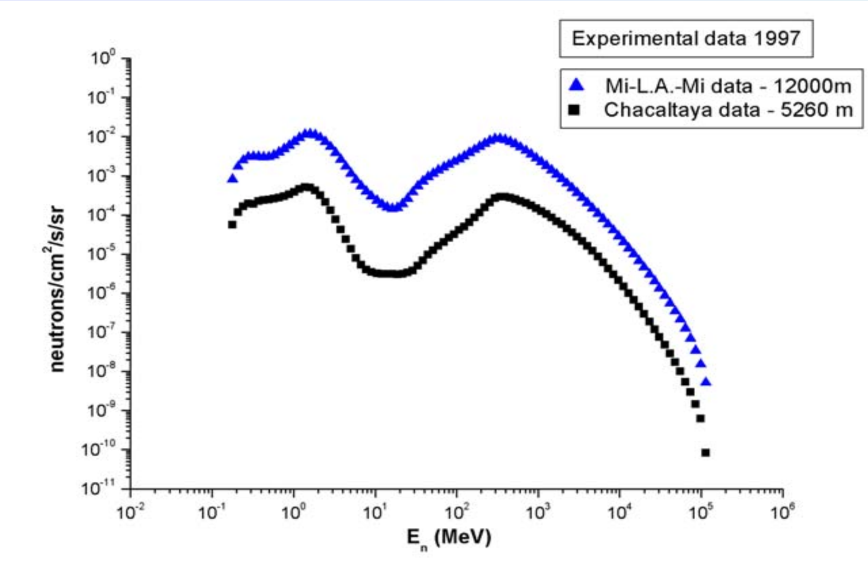
Chacaltaya,
5260 m, 16°S

La Paz,Bolivia

Comparison between experimental data and simulation (GEANT code)

Experimental results using the extended energy range system
(100keV-100 GeV)

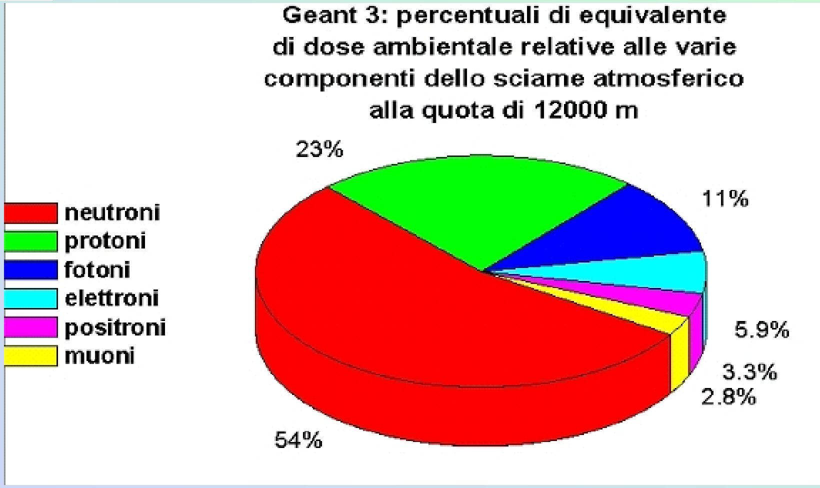


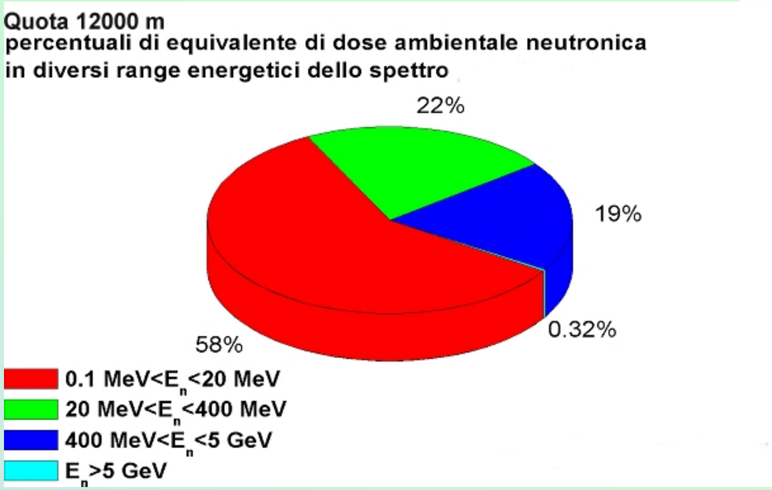


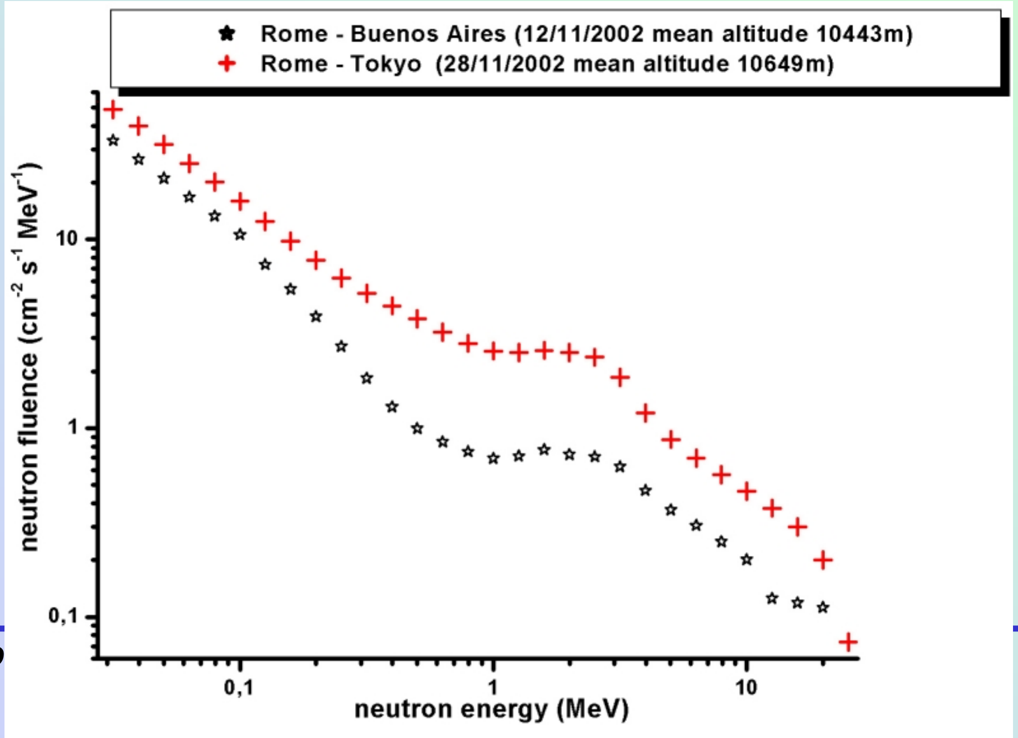
EXPERIMENT	GEOGRAPHIC DATA
Testa Grigia lab., Plateau Rosa, Matterhorn, Italy	3480 m, 45°N
Chacaltaya lab., Chacaltaya, La Paz,Bolivia	5260 m, 16°S
Flight Mi-L.A.-Mi	12000 m

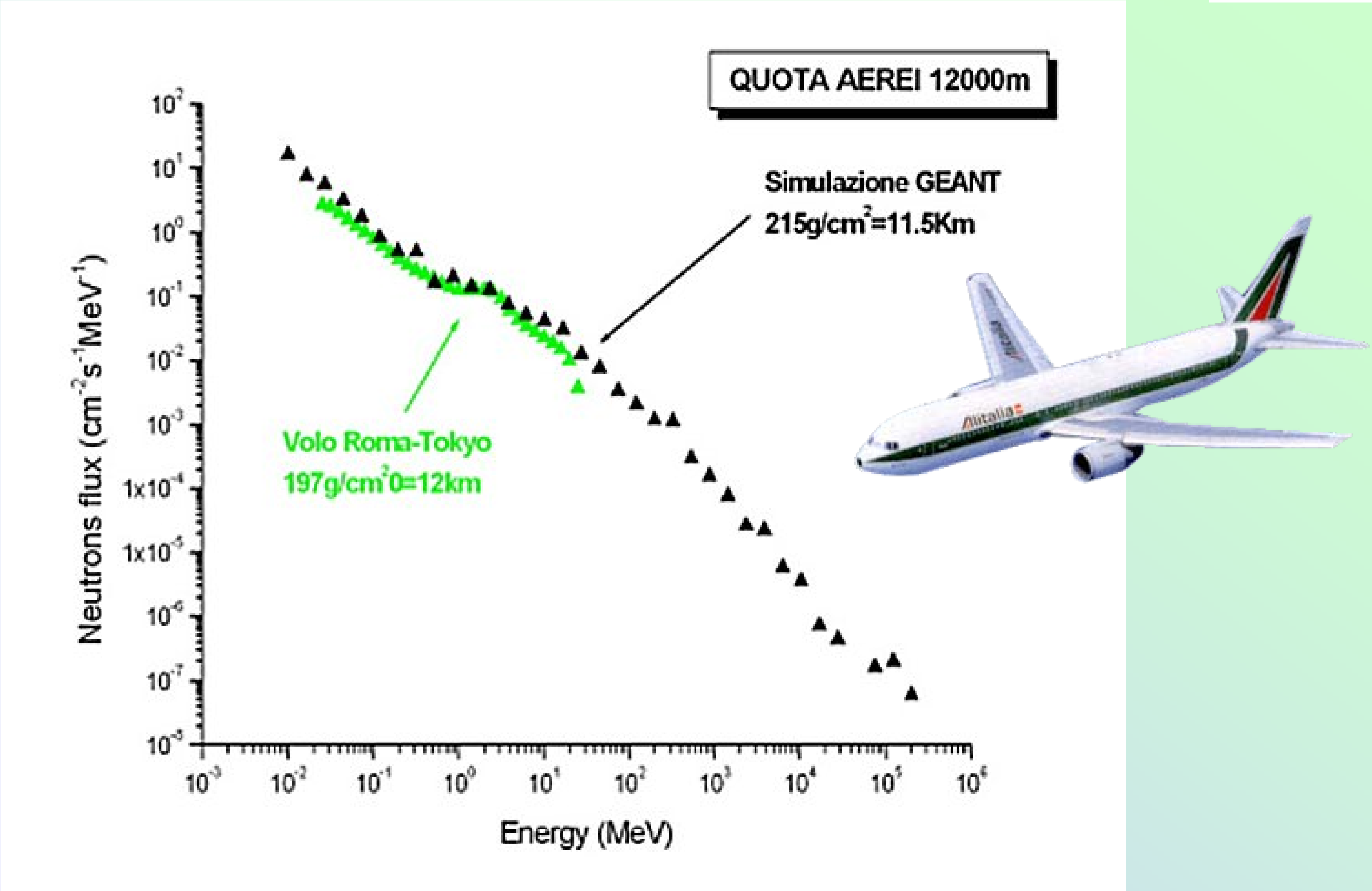
altitude m	latitude	integr. flux n/cm^2/s	dose rates H*(10) (mSv/h)
3480	45° N	0.09	0.12
5260	16° S	0.12	0.15
12000		2.98	1.8

Experimental results using the short energy range system

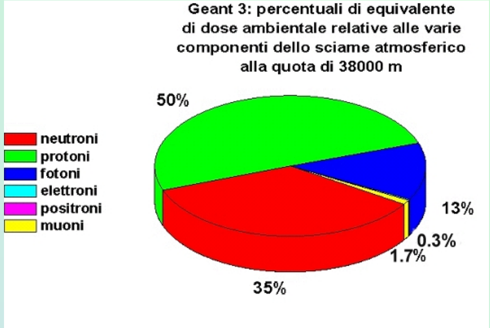


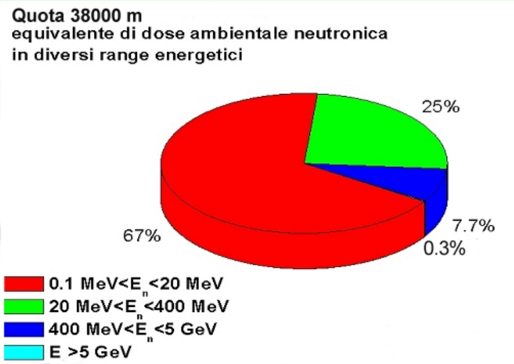


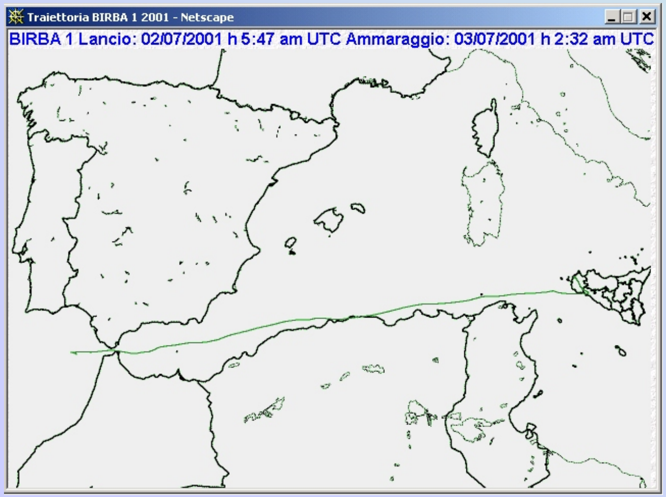


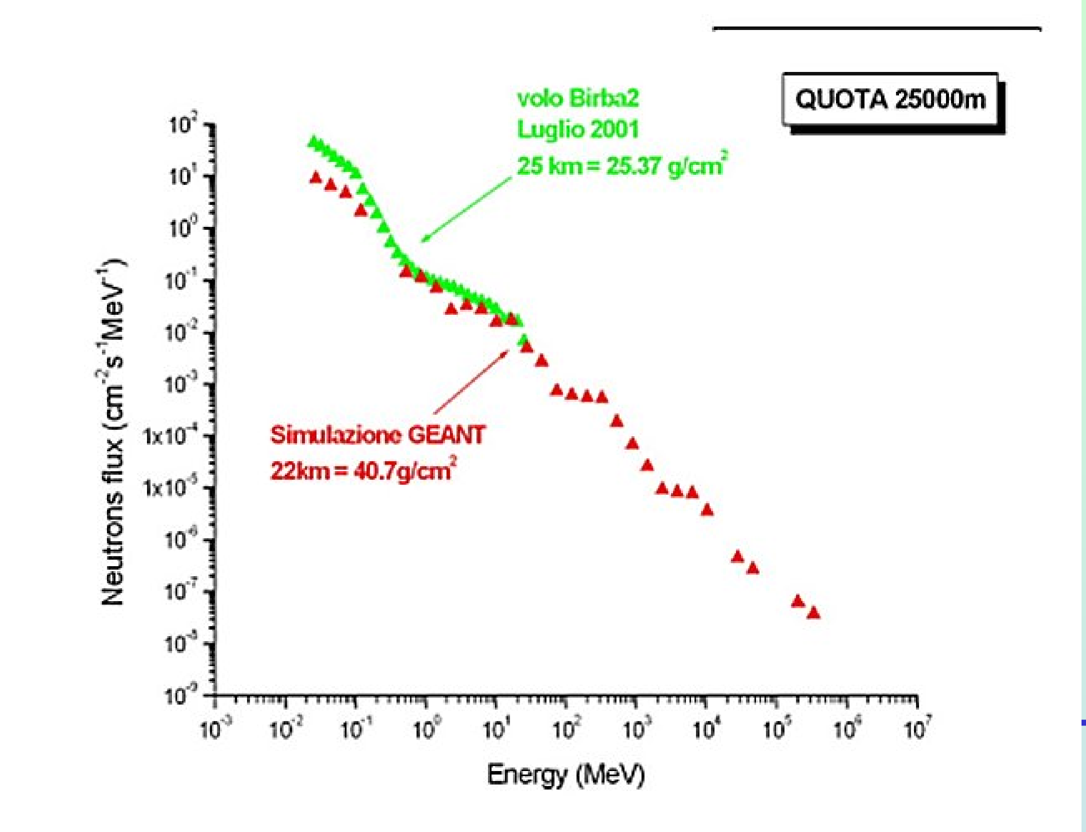

QUOTA AEREI 12000m
Simulazione GEANT
215g/cm²=11.5Km
Volo Roma-Tokyo
197g/cm²0=12km
Neutrons flux (cm⁻²s⁻¹MeV⁻¹)
Energy (MeV)

Stratospheric Balloons ASI base Trapani Italy



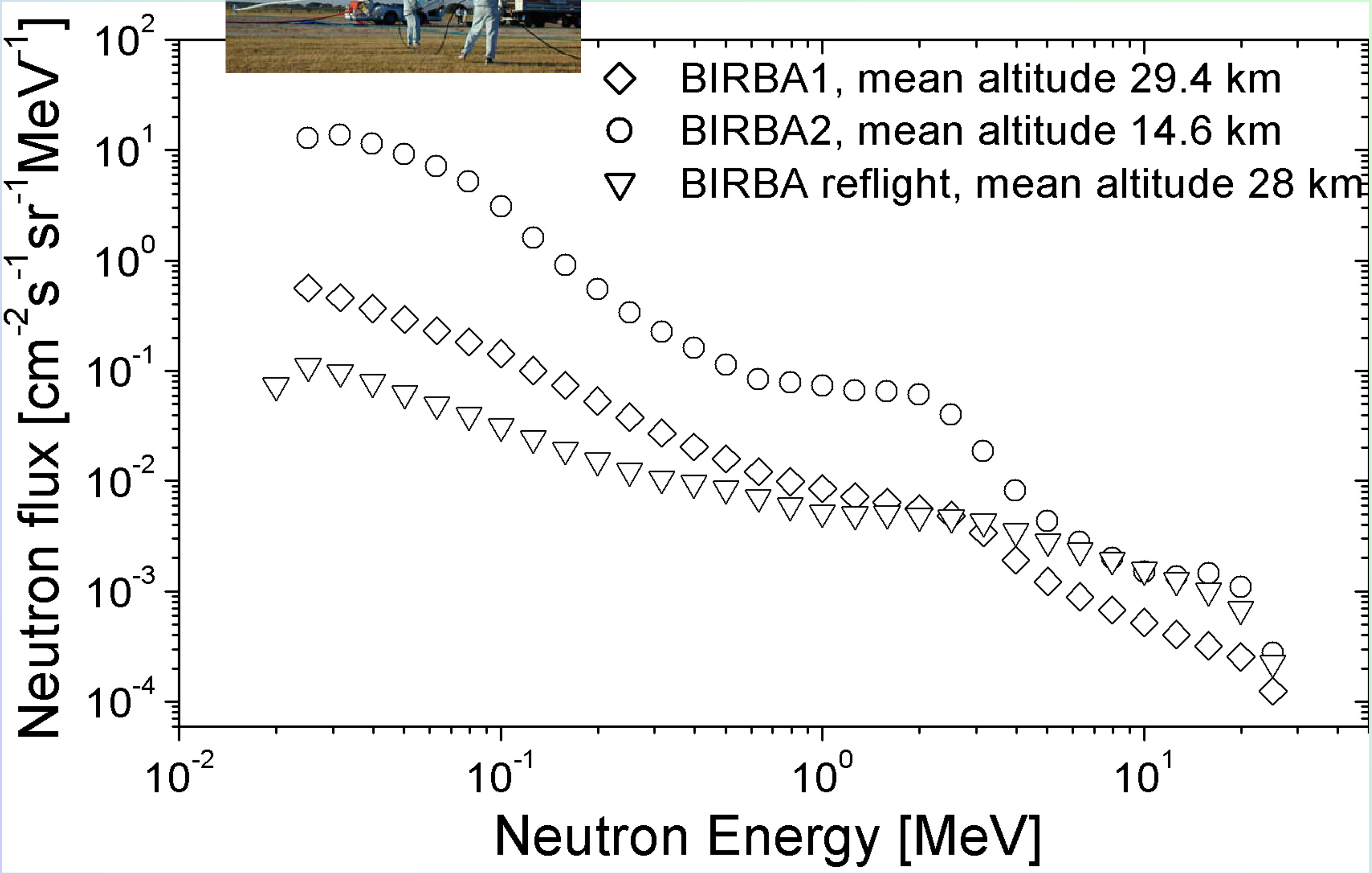






A. Zanini - zanin

Balloon flights



Alitalia intercontinental flights

In phantom measurements

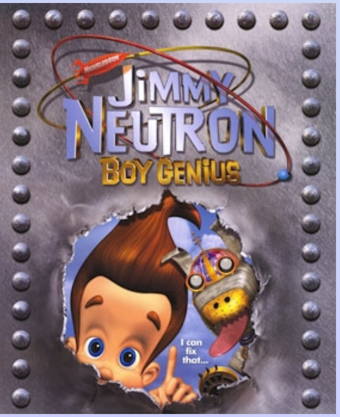
ASI balloon flights

High Mountain Observatories

Jimmy neutron

In an old italian comics Philip Rembrandt, alias Jimmy **Neutron**, is a detective with special abilities due to an **accidental exposure to neutrons**. His girlfriend **Valentina** Rosselli, is the most known character created by **Guido Crepax** one of the greates masters of the italian comic strip genre .

1965



2001

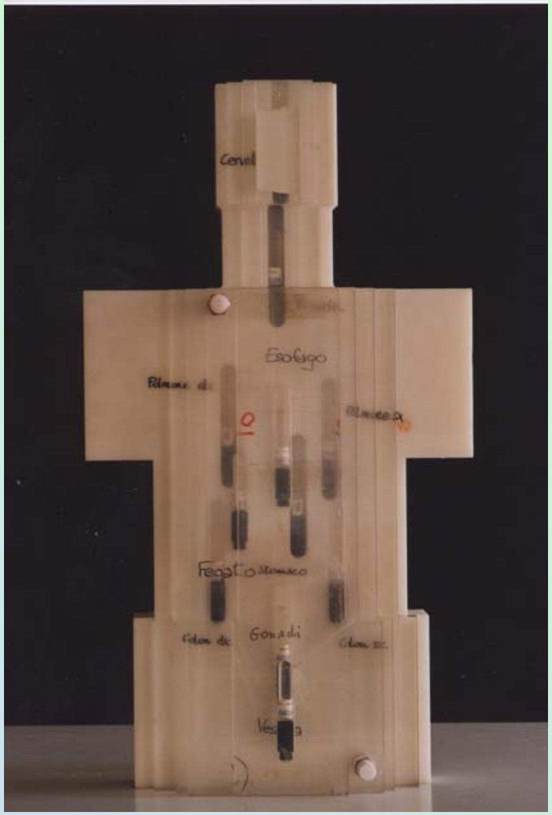
In a recent movie **Jimmy Neutron** is a boy genius and way ahead of his friends, but when it comes to being cool, he's a little behind. All until one day when his parents, and parents all over Earth are kidnapped by aliens, it's up to him to lead all the children of the world to rescue their parents.

Jimmy Phantom

The anthropomorphic phantom Jimmy has been designed and realized by INFN Sez. Torino, in collaboration with JRC Varese.

It consists of a phantom in polyethylene and plexiglas (tissue equivalent material), with inserted human bone in correspondence of column; composition follows the ICRP indications [1] .

Cavities are placed in correspondence of critical organs and are suitable to allocate passive dosemeters such as bubble detectors, TLDs, makrofolds.



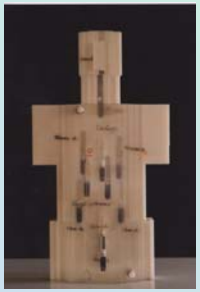
This system allows to evaluate the neutron dose in depth

[1] ICRP -*Recommendation of the International Commission on Radiological Protection*, Pub. n.60, Oxford Pergamon (1991)

Jimmy Phantom

Advantages

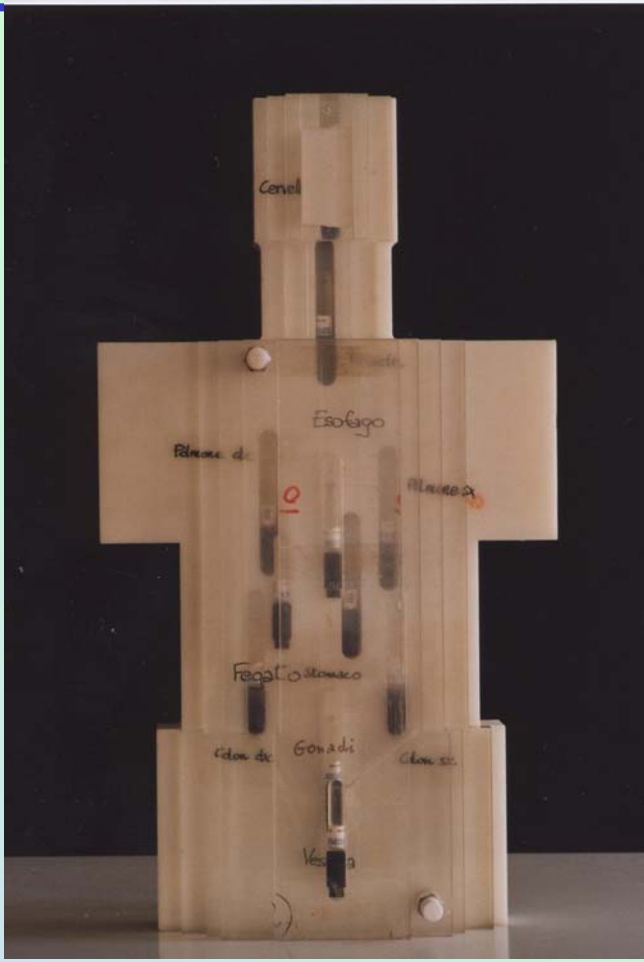
- Cheap and easy-to-hand phantom
- Possibility to obtain an evaluation of the neutron dose in critical organs
- The holes can be used to contain different detectors (TLDs, bubble dosemeters, polycarbonate foils)
- It can be used for biological samples irradiations.



Applications

- Exposure under linear accelerators
- Calibration of personal dosemeters (JRC Second Standard Laboratory for calibration of personal dosemeters; Ispra, VA)
- Dosimetric measurements of cosmic ray neutron: intercontinental flights; high mountains Lab.; balloon flights.

Jimmy Phantom



Main physical characteristics:

- Total weight: 37.1 kg
- 6 plexiglas slabs (21.6 kg)

  8% H, 32% C, 60% O
- 1 big polyethylene slab (14.2 kg)

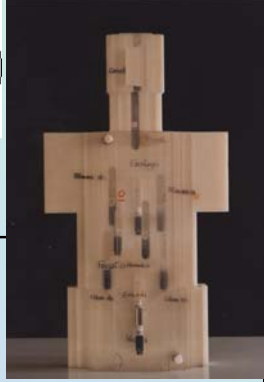
  14.4% H, 85.6% C
- 1 human bone insert (1.2 kg)

  0.2% H, 41.4% O, 18.5% P, 39.9%Ca

  to simulate the spinal column
- Physical dimensions:

  head: 13.5x15x19 cm^3
  neck: 11x10x13.5 cm^3
  trunk: height 59 cm, max width 36 cm, thickness 20 cm

Jimmy Phantom



	H_2O	Polyethylene	PMMA	TE-liquid	Jimmy	ICRU tissue
H	11.2	14.4	8	10.2	10.2	10.1
C		85.6	60	12	67.9	11.1
O	88.8		32	3.6	18.7	76.2
N				74.2		2.6
Bone (H, O, P, Ca)					3.2	
ρ (kg/m^3)	1000	920	1190	1070	1056	1000

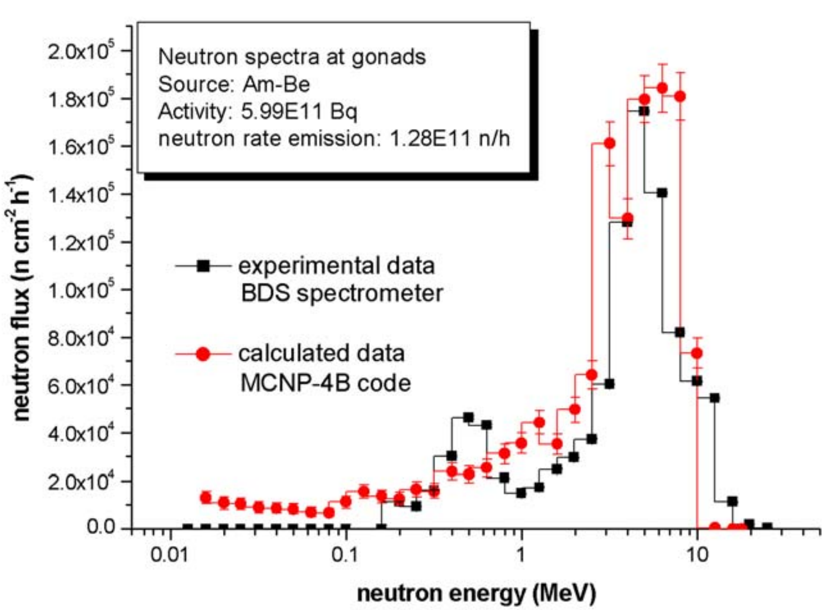
Some commonly used tissue substitutes (mass percentage) and comparison with the reference tissue (ICRU sphere)

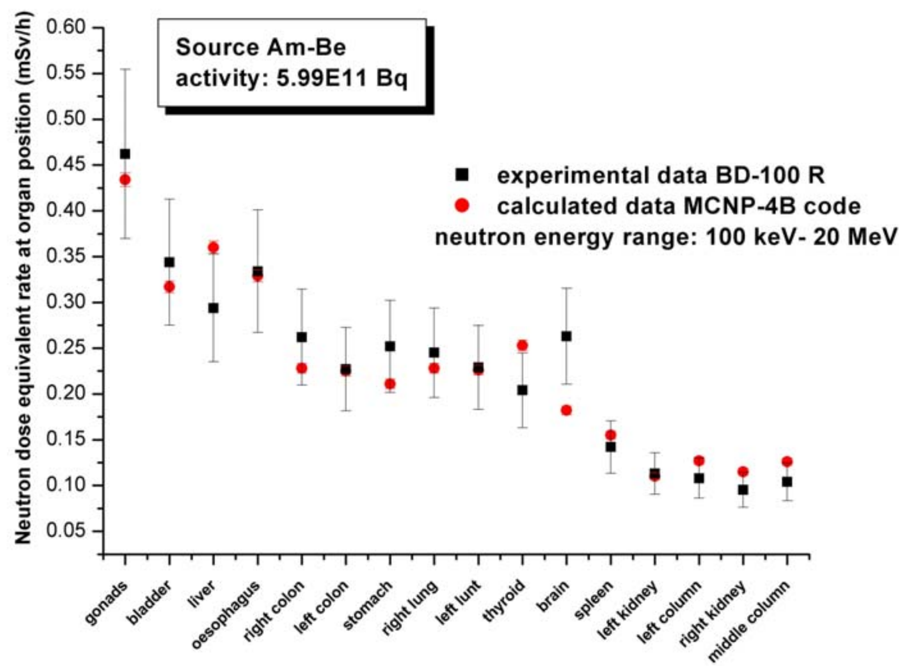
Jimmy Test

Preliminary exposure of the phantom in front of **Am/Be source Ispra, Va (JRC):**

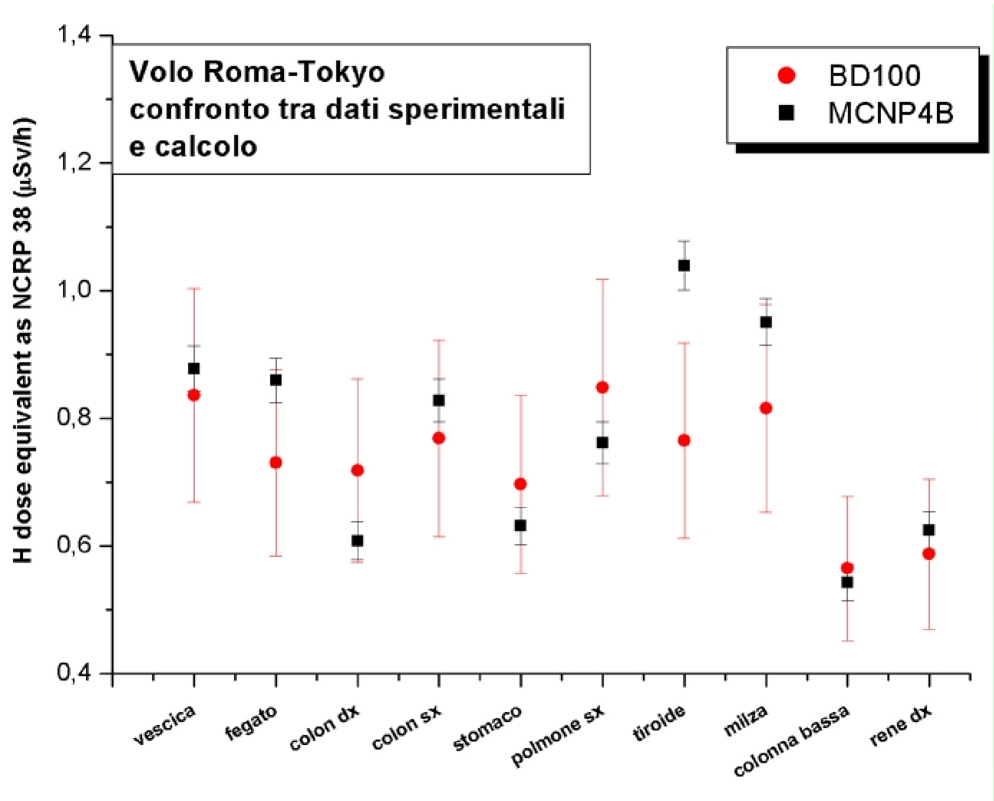
-measure of neutron integral dose (BD-100R) and spectra (BDS) in depth

- comparison with simulation results (MCNP-4B code).



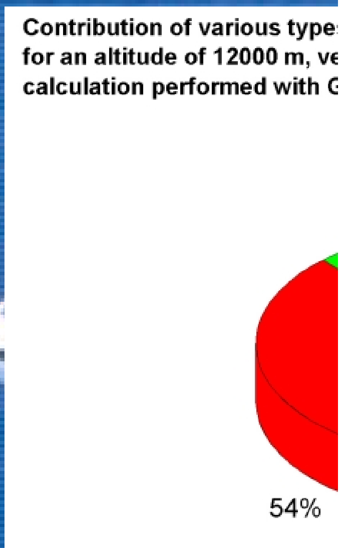


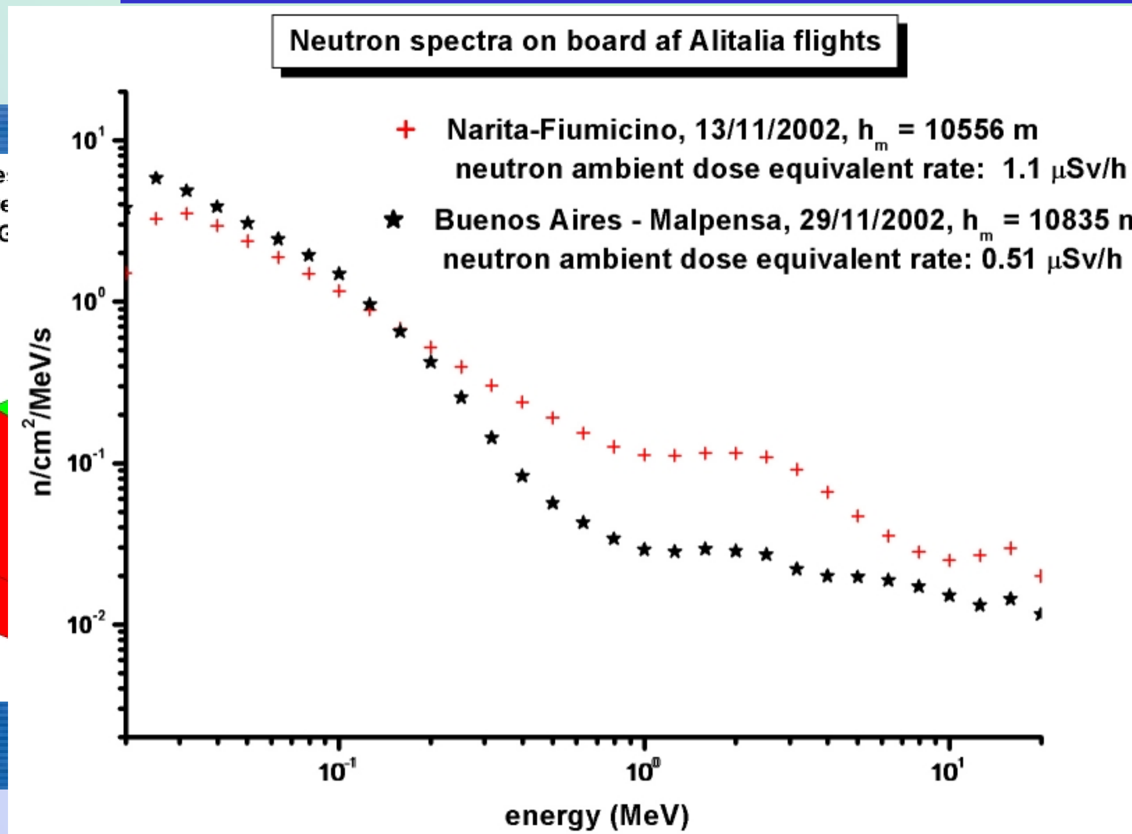
Fantoccio

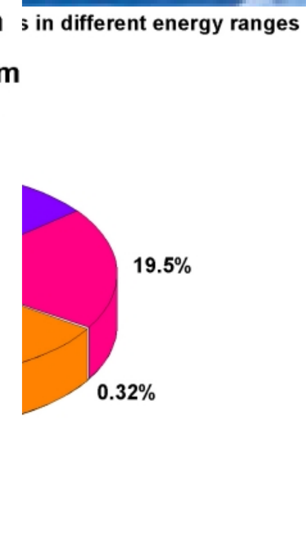


Tratta	h media	BDS H*(10) rate	BDS E rate	E JIMMY rate	CARI 6 E rate	E JIMMY /E CARI
	(m)	(μSv/h)	(μSv/h)	(μSv/h)	(μSv/h)	*100
Roma - Tokyo	10443	1,1	0,76	0,74 ± 0,10	3,6	21
Tokyo - Roma	10556	1,1	0,77	0,83 ± 0,08	3,6	23
Roma - Buenos Aires	10649	0,53	0,36	0,36 ± 0,04	1,7	21
Buenos Aires - Milano	10835	0,51	0,35	0,34 ± 0,03	1,6	21

Neutron spectrum
Intercontinental Alitalia flights

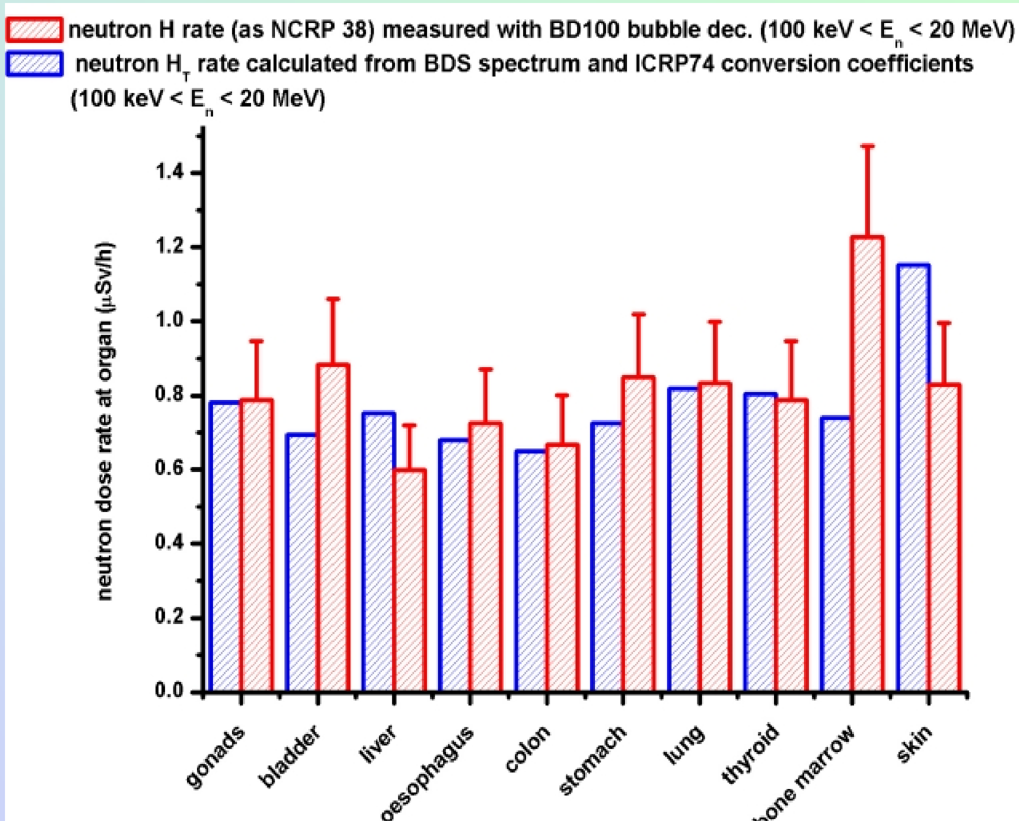






Route	mean alt.	BDS neutron E rate (μSv/h)	CARI 6 total E rate	E BDS/E CARI
	(m)	(100 keV<En<20 MeV)	(μSv/h)	*100
Roma - Tokyo	10443	0,76	3,6	21
Tokyo - Roma	10556	0,77	3,6	22
Roma - Buenos Aires	10649	0,36	1,7	21
Buenos Aires - Roma	10835	0,35	1,6	22

Dose at organs
Tokyo – Rome path

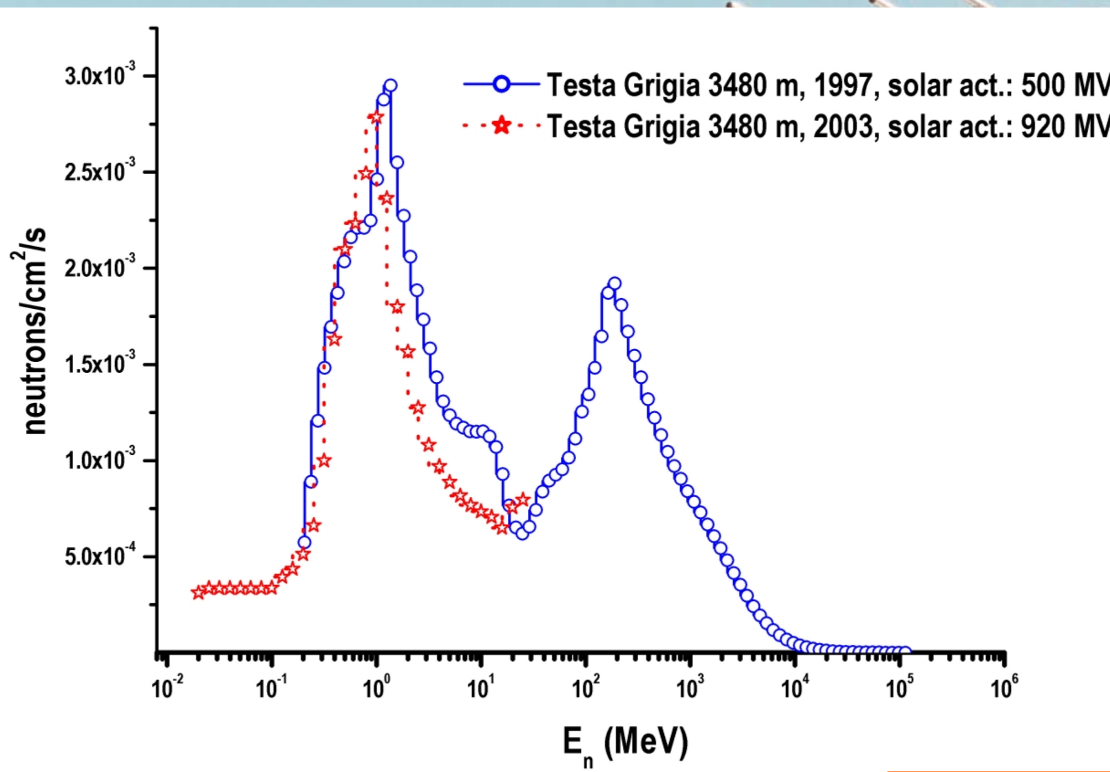


comparison between experimental BD100R H rates at organ position and H_T rates obtained folding the measured spectrum (with ICRP74 conv. coeff. (D_T/Φ and w_T).

comparison between experimental BD100R H rates at organ position and H rates calculated with MCNP4B transport of the measured (BDS) spectrum in the phantom simulation

Neutron spectrum
Testa Grigia research station (3480 m)

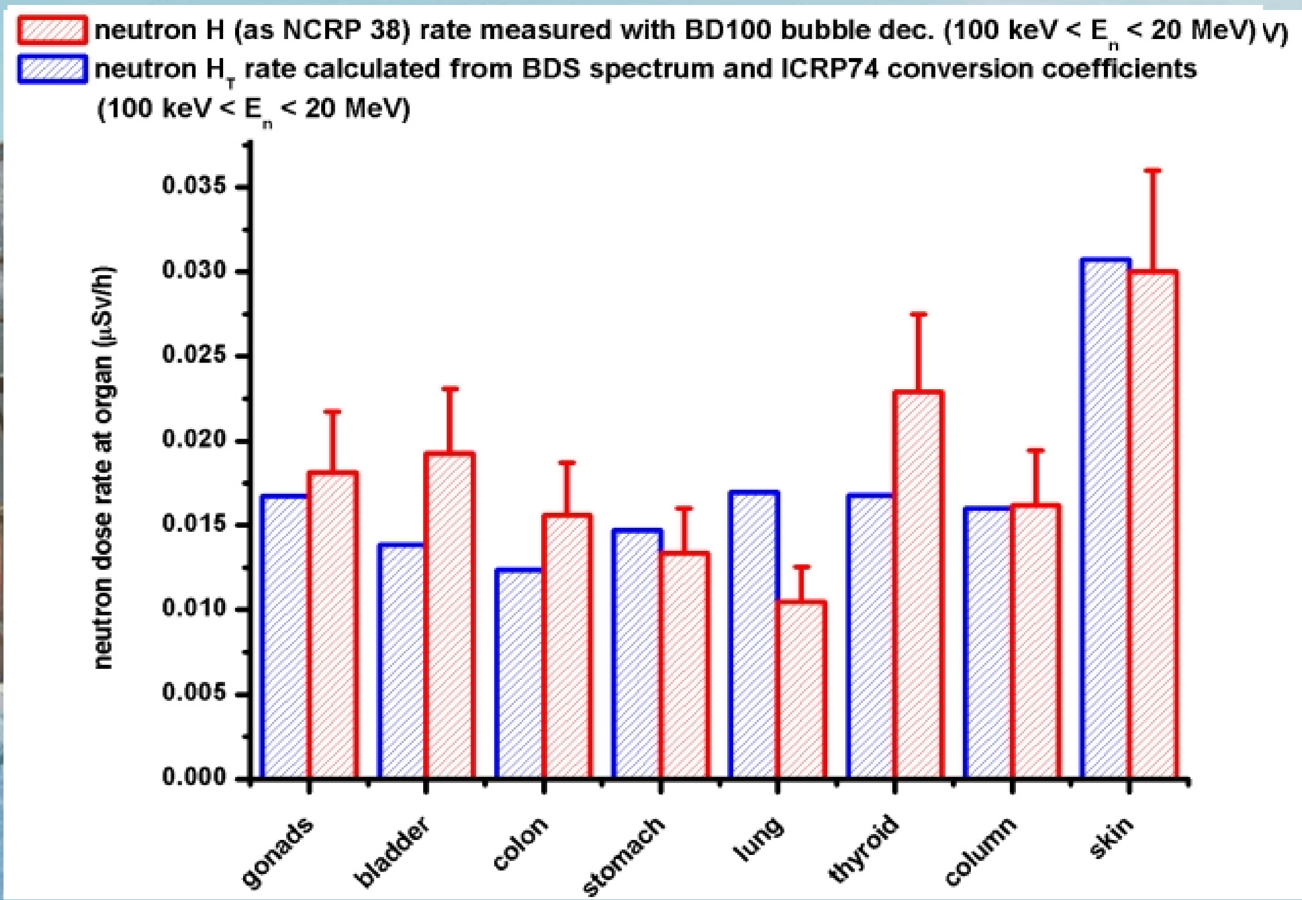
BREUIL – CERVINIA (ITALY) 45°56’03” N, 07°42’28” E



BDS (100 keV-20MeV) and ICRP74 conv. coeff.
H*(10)rate = (0.030 ± 20%) μSv/h
E rate = (0.017 ± 20%) μSv/h

Dose at organs

Testa Grigia research station (3480 m)



comparison between experimental BD100R H rates at organ position and H_T rates obtained folding the measured spectrum with ICRP74 conv. coeff. (D_T/Φ and w_r). in the phantom simulation

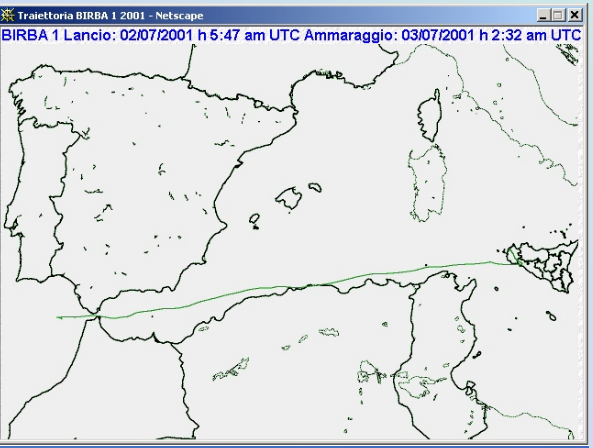
Neutron spectrum
Balloon flight

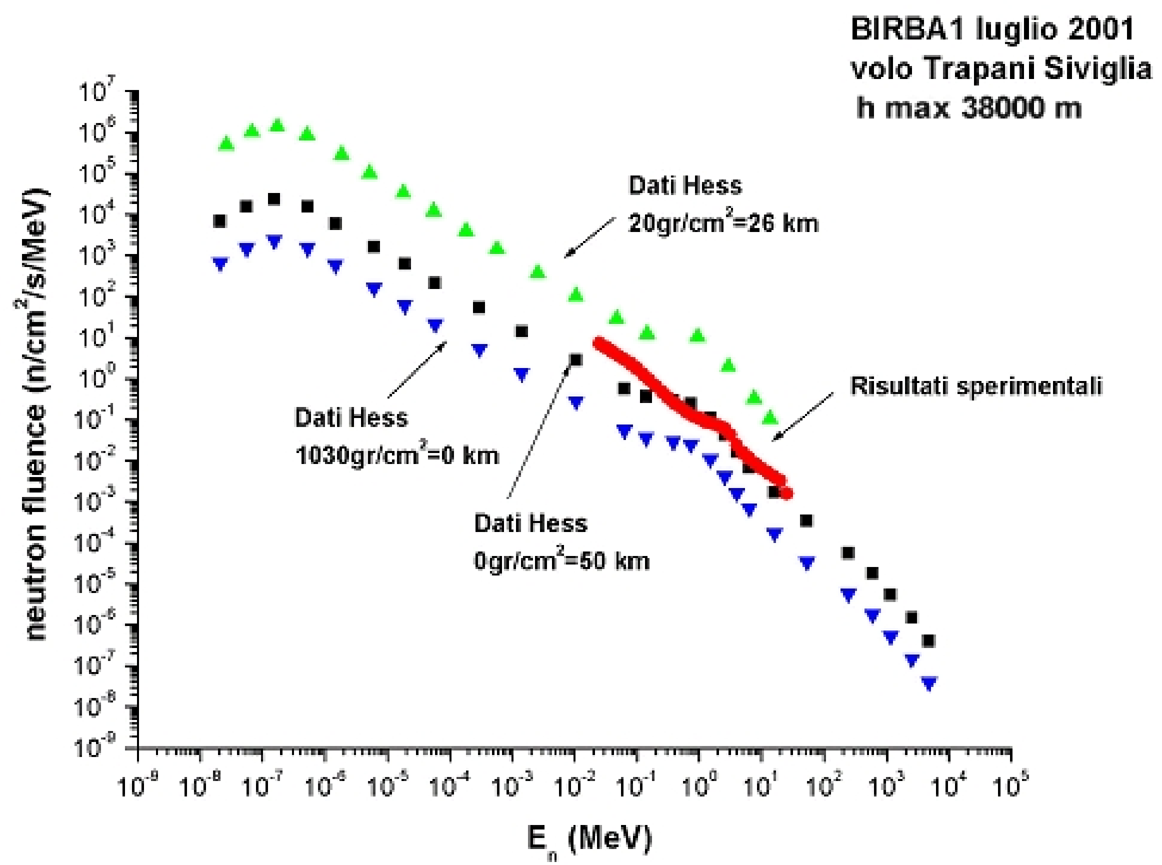
BIRBA ASI flight

Trapani-Sevilla

Max. altitude 38000 m

Mean Alt. 29400 m





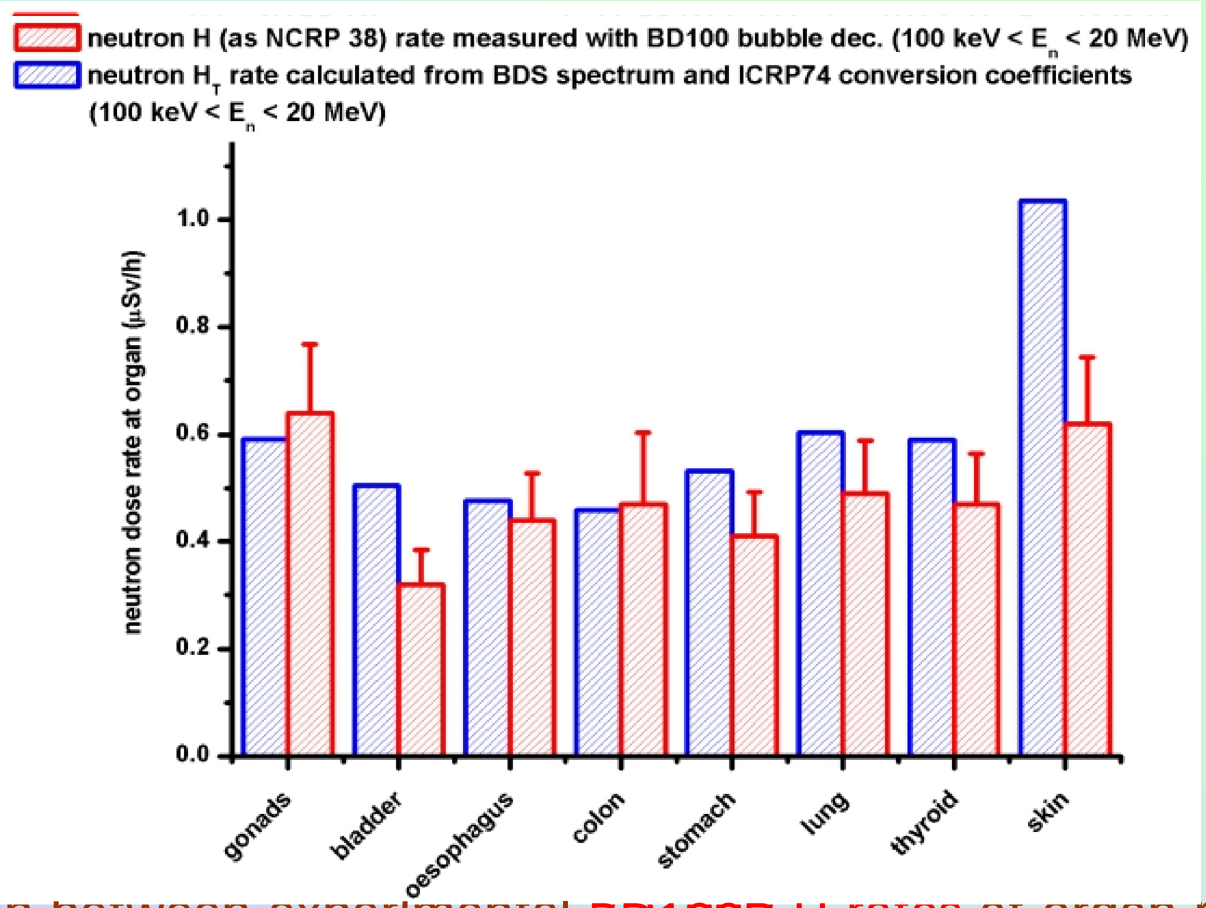
BDS (100 keV-20MeV)

H*(10)rate = (0.62 ± 20%) μSv/h

E rate = (0.29 ± 20%) μSv/h

Dose at organs

Balloon flight

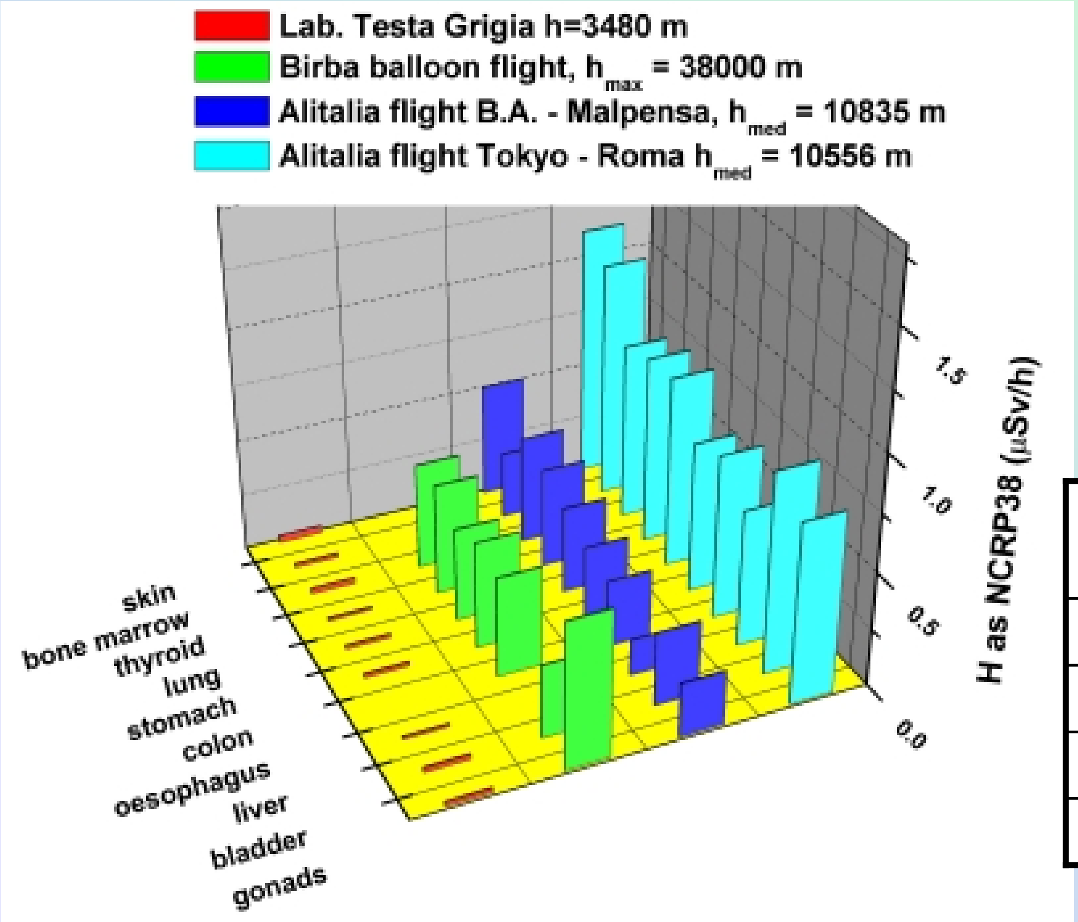


comparison between experimental BD100R H rates at organ positi
and H_T rates obtained folding the measured spectrum with ICRP 74
conv. coeff. (D_T/Φ and w_r).

comparison between experimental BD100R H rates at organ positi
and H rates calculated with MCNP4B transport of the measured (B
spectrum in the phantom simulation

Comparison at different altitudes

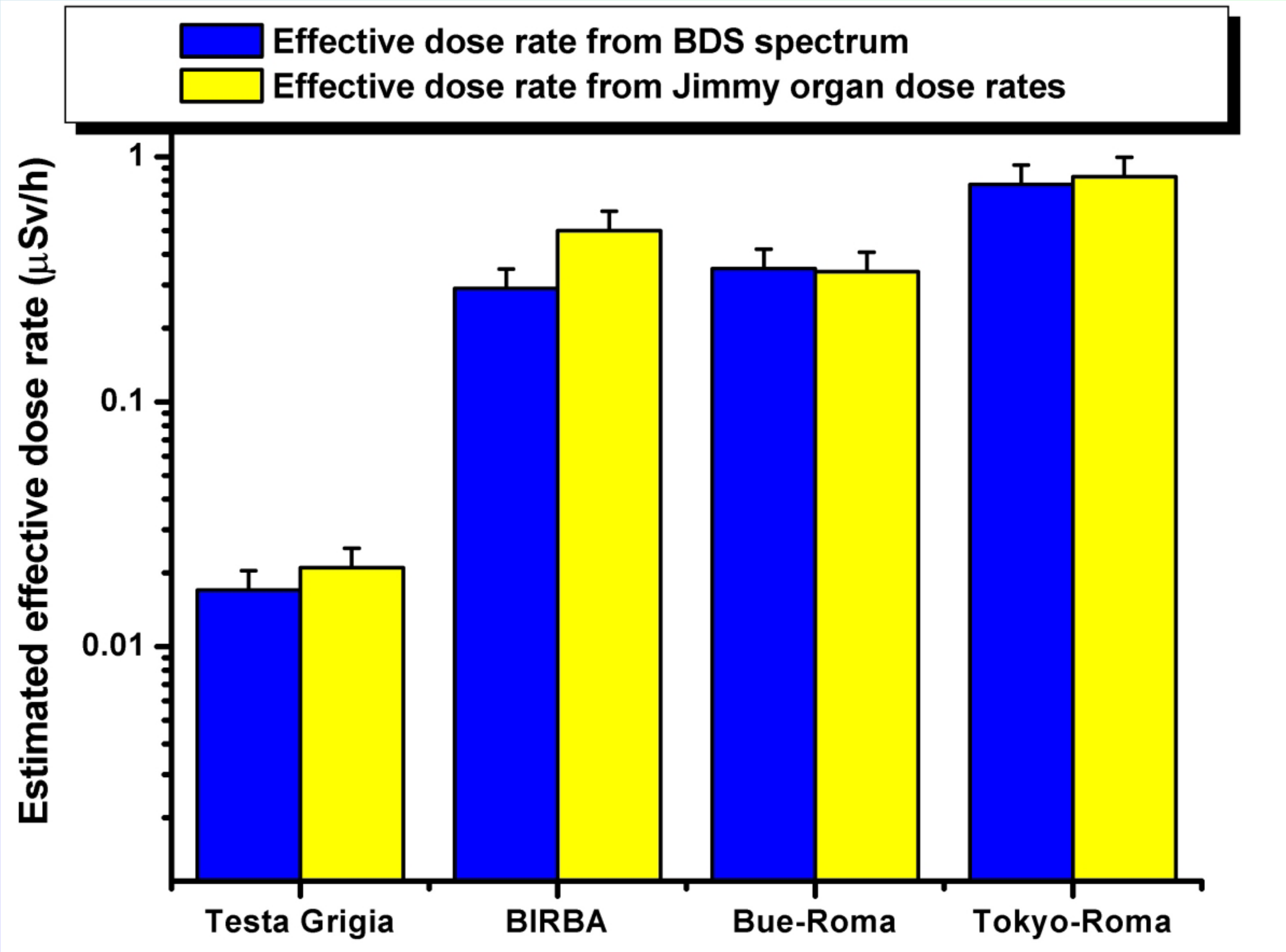
Measured organ dose rates



Approximated effective dose rates

altitude (m)	E_{Jimmy} (µSv/h) (100 keV< En < 20 MeV)
3480 (Testa Grigia)	0.021 ± 0.004
29400 m (mean alt. BIRBA)	0.50 ± 0.11
10835 (B. A. – Malpensa)	0.36 ± 0.07
10556 (Tokyo –Roma)	0.83 ± 0.16

Estimated neutron effective doses
neutron energy (100 keV – 20 MeV)



MEDICAL APPLICATIONS

MonteCarlo simulations — MCNP4C neutron and photon transport

MCNPGN photoneutron production

Experimental method — Bubble detectors BDT, BD-PND

BDS spectrometer (10 keV- 20MeV)

MC code and Experimental Detection System

Simulation code:

MCNP-GN

- **New routine GAMMAN in MCNP4B ⟶ MCNP-GN: photoneutron generation and transport**
- **The new code MCNP-GN especially aimed at modelling complex geometry with suitable variance reduction techniques**

Experimental measurements:

Bubble detectors: BD-100R
BDS spectrometer and unfolding technique: BUNTO

- **Evaluation of neutron spectra at the patient plane.**
- **Evaluation of neutron spectra in tissue equivalent phantom.**

Phantom

Anthropomorphic phantom: JIMMY

- **Tissue equivalent**
- **Cavities in critical organs positions (ICRP 60)**
- **Conservative with respect to standard phantom (ICRU sphere and water phantom)**

Monte Carlo code: MCNP-GN

Developed to treat (γ,n) neutron production in high and low Z elements and transport in matter, for energies below 30 MeV.

Photoneutron production:

The code allows to calculate:

- coordinates of the point of generation
- energetic spectrum
- angular distribution

Photoneutron transport:

Follows the MNCP transport routines

MCNP4B-GN capabilities:

- Cross section "Atlas of photoneutron cross section", Bernan.
- Both (γ,n) and (γ,2n) reactions have been considered.
- Evaporative model: isotropic angular distribution used for low energies.
- Direct model: used for high energies (E_n > 3 MeV), angular distribution:

$$f(\theta) = a + b \sin^2\theta$$

The Monte Carlo code MCNP4B-GN

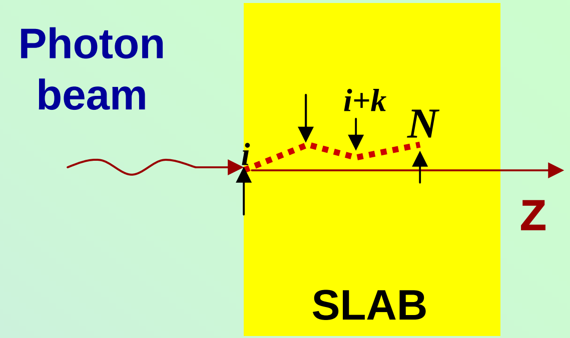
- The method forces at least one neutron to be created in each history

- The neutron creation point *i* is chosen among all the N photon interaction points during the history

- Having forced the neutron production a compensating weight is attached to each source neutron to account for the real neutron creation probability

↓

The weight is calculated employing the neutron production cross sections together with the total photon cross sections



Photoneutron production

$$F(i) = \sum_{j=1}^{i} \frac{\sigma_{(\gamma,n),j}(E_{\gamma,j})}{\sigma_{tot}}$$

$$\sigma_{tot} = \sum_{i=1}^{N} \sigma_{(\gamma,n),i}$$

$$F(i-1) < r < F(i)$$

Statistical weight

$$w = \sigma_{\gamma,n}(E_\gamma) / \sigma_{tot}(E_\gamma)$$

Experimental Detection System

Bubble detectors for neutron dosimetry

Calibrated in terms of dose equivalent (NCRP 38)

Integral dosemeter:

BD-100R fast neutron

temperature dependence

BD-PND fast neutron

compensation for sensityvity change with temperature over the operation range of 20-27°C)

BDT thermal neutron

Integral dose

Neutron spectrometer BDS

Six detectors with different energy threshold

coupled with an unfolding code

Spectral distribution of the neutron field

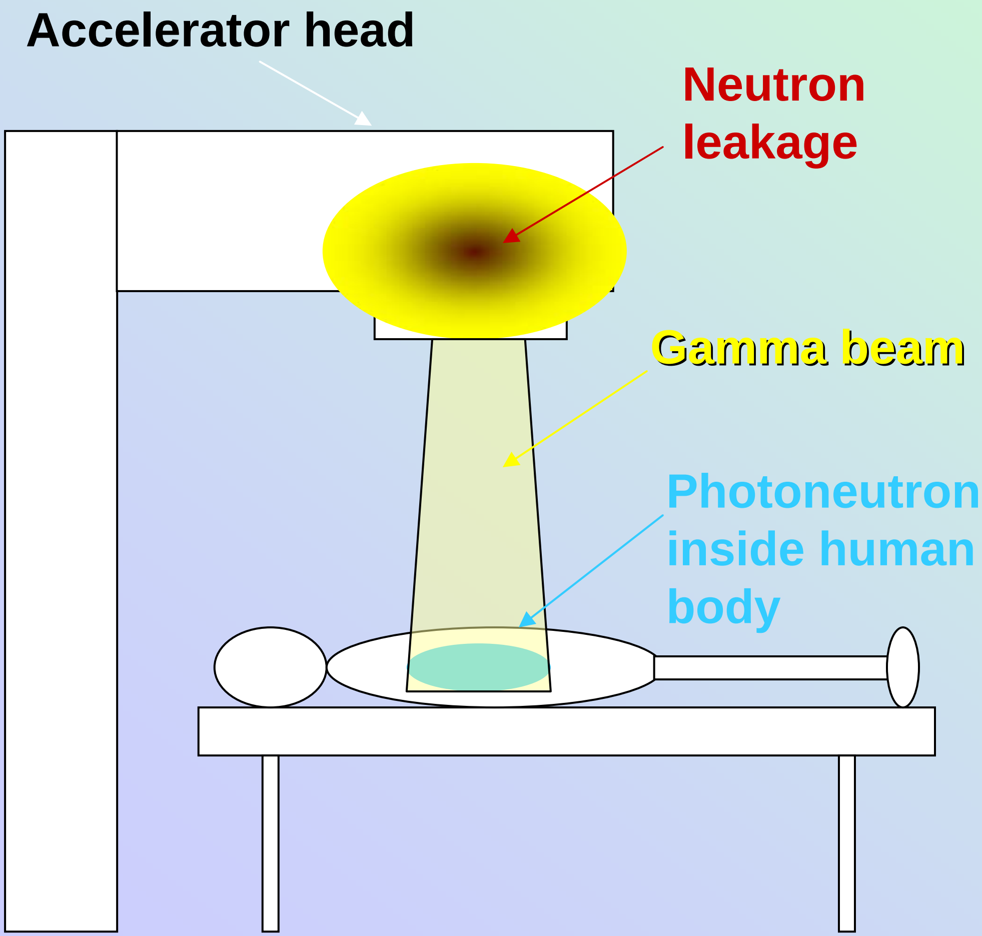
In air measurements

Radiotherapy with Linac's

BNCT treatments

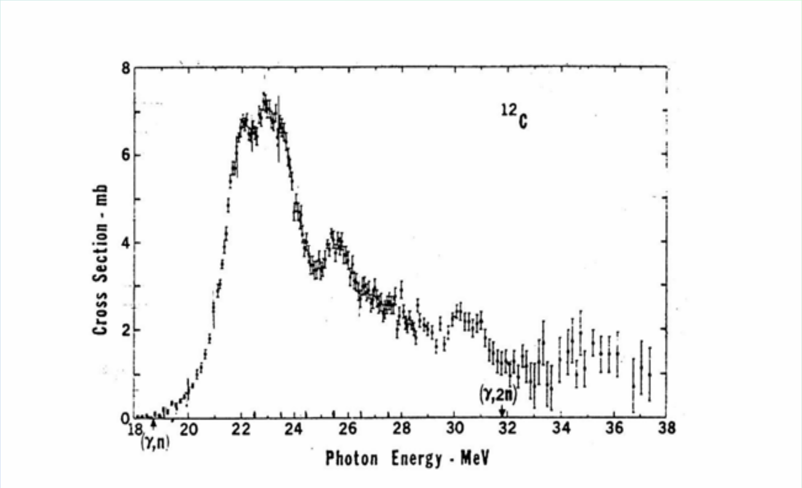
Photoneutron production

WHERE?



Threshold energy (γ,n):

Accelerator head	Human body
W: 7.42 MeV	P: 12.3 MeV
Al: 8 MeV	Ca: 15.6 MeV
Cu: 9 MeV	C: 18.7 MeV
Fe: 10.9 MeV	O: 15.7 MeV



Acceleratore	Modello	MV	Q x10[12] neutroni/Gy	deviaz. standard x10[12] neutroni/Gy	Valori pubblicati di Q (x10[12] neutroni/Gy)
Varian	1800	10			0.06
Varian	1800	15			0.76
Varian	1800	18			1.22
Varian	2100C	18	0.96	0.11	
Varian	2100C**	18	0.87		
Varian	2300CD	18	0.95	0.03	
Varian	2500	24	0.77		
Siemens	MD2	10	0.08		
Siemens	MD	15	0.20	0.02	
Siemens	KD	18	0.88	0.10	
Siemens	KD	20			0.92
Siemens	Primus*	10	0.02		
Siemens	Primus*	15	0.12		
Siemens	Primus**	15	0.21		
Siemens	Primus	15			0.20
Elekta	SL-20	17			0.69
Elekta	SL-20	18	0.46		
Elekta	SL-25	18	0.46		
Elekta	SL-25	22			2.37
Elekta	SL-25	25	1.44	0.31	
GE	Saturne 41	12			0.24
GE	Saturne 41	15			0.47
GE	Saturne 43	18	1.32		1.50
GE	Saturne 43	25			2.40

“*Neutron source strength measurements for Varian, Simens, Elekta, and General Electric linear accelerators*”

David S. Followill et al.

Department of radiation Physics, The University of Texas

Undesired Radiation

- Improvement of collimation techniques : MLF – IMRT
- Better definition of target volume
- Escalation of tumor dose

Increased efficacy of the treatment

BUT…

- Increased number of MU (Monitor Units)
- Increased undesired dose outside the target volume

More photon leakage

Increased photoneutron production

in the accelerator head

Elekta Slit with MLC

Measurements at

Lund Hospital Onkologik Klinik

LINAC: Technical details:

Photon beam: E_{max}: 18MeV

Target: Tungsten

Primary collimator: Tungsten

Flattening filter: Stainless Steel

Multileaf Collimator (x): Tungsten

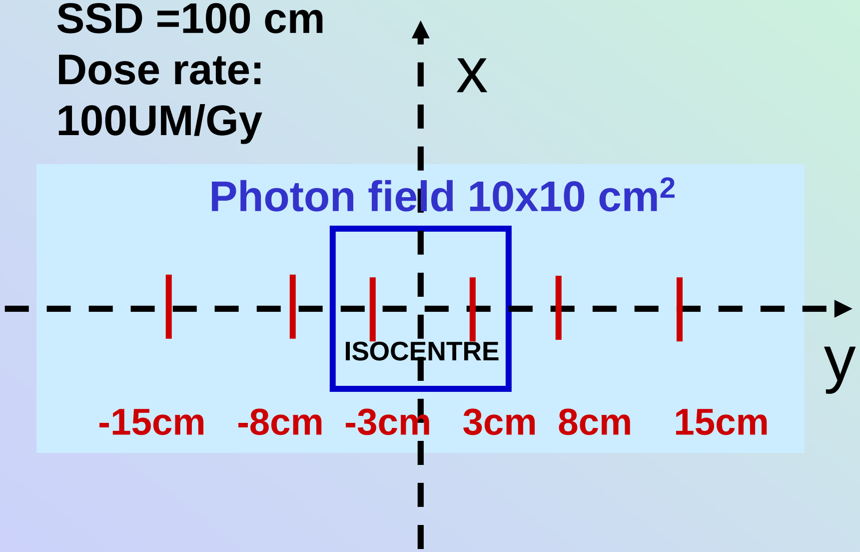
Jaws (x): Tungsten

Jaws (y): Tungsten

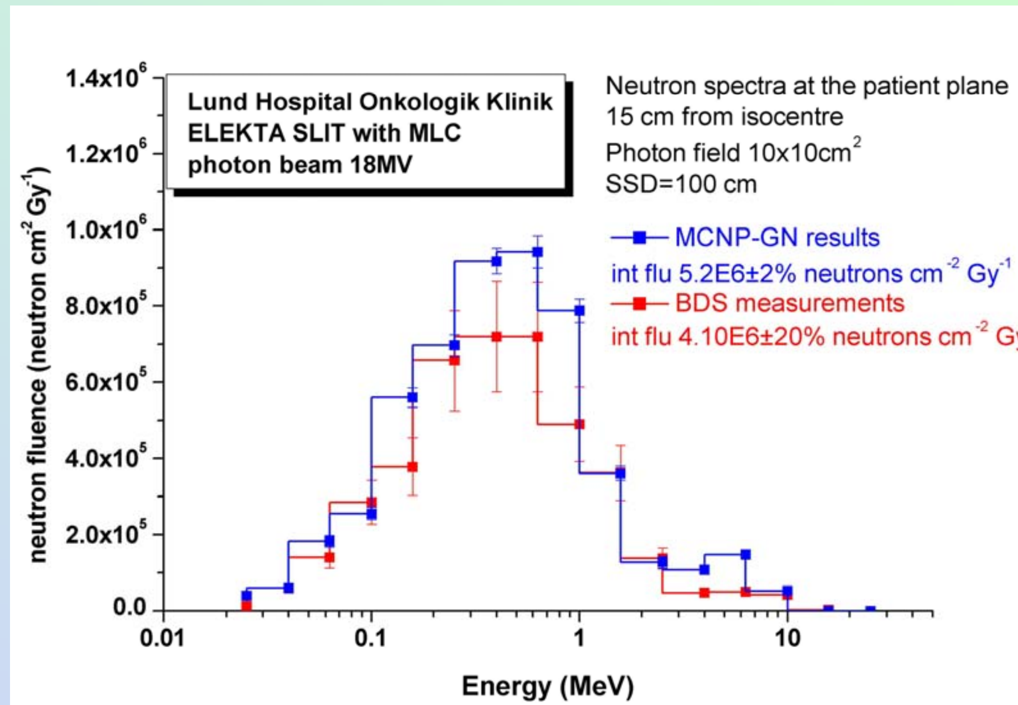
Neutron spectra at patient plane

Patient plane

SSD =100 cm
Dose rate:
100UM/Gy



Comparison between measurements and simulation results



The data are normalized to 1 Gy photon dose that is the energy released at build up in a water phantom.

The build up is at 3cm depth for a 18 MeV end point beam

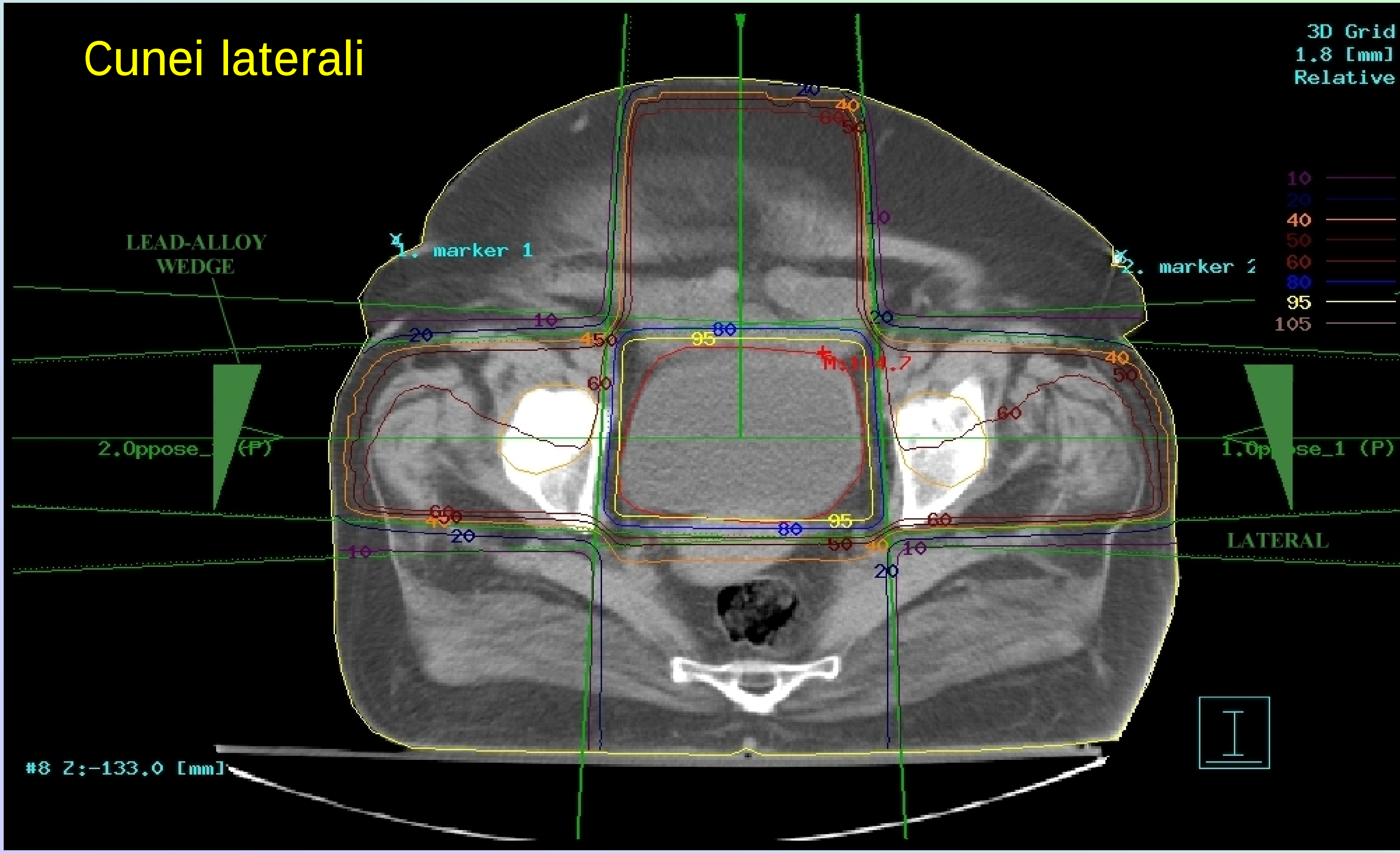
Collimation Techniques

- **Wedges**
- **MLC (Multi-Leaf Collimators)**
- **IMRT (Intensity Modulated Radiotherapy**

The number of MU (Monitor Units) to give 1 Gy gamma dose at build up depends from collimation

The undesired neutron dose depends from collimation and it is related to MU

Tecniche di collimazione (Blocchi)



Metodo di collimazione tradizionale esterno alla testata

Usato in trattamenti con fasci incrociati

Tecniche di collimazione (MLC)

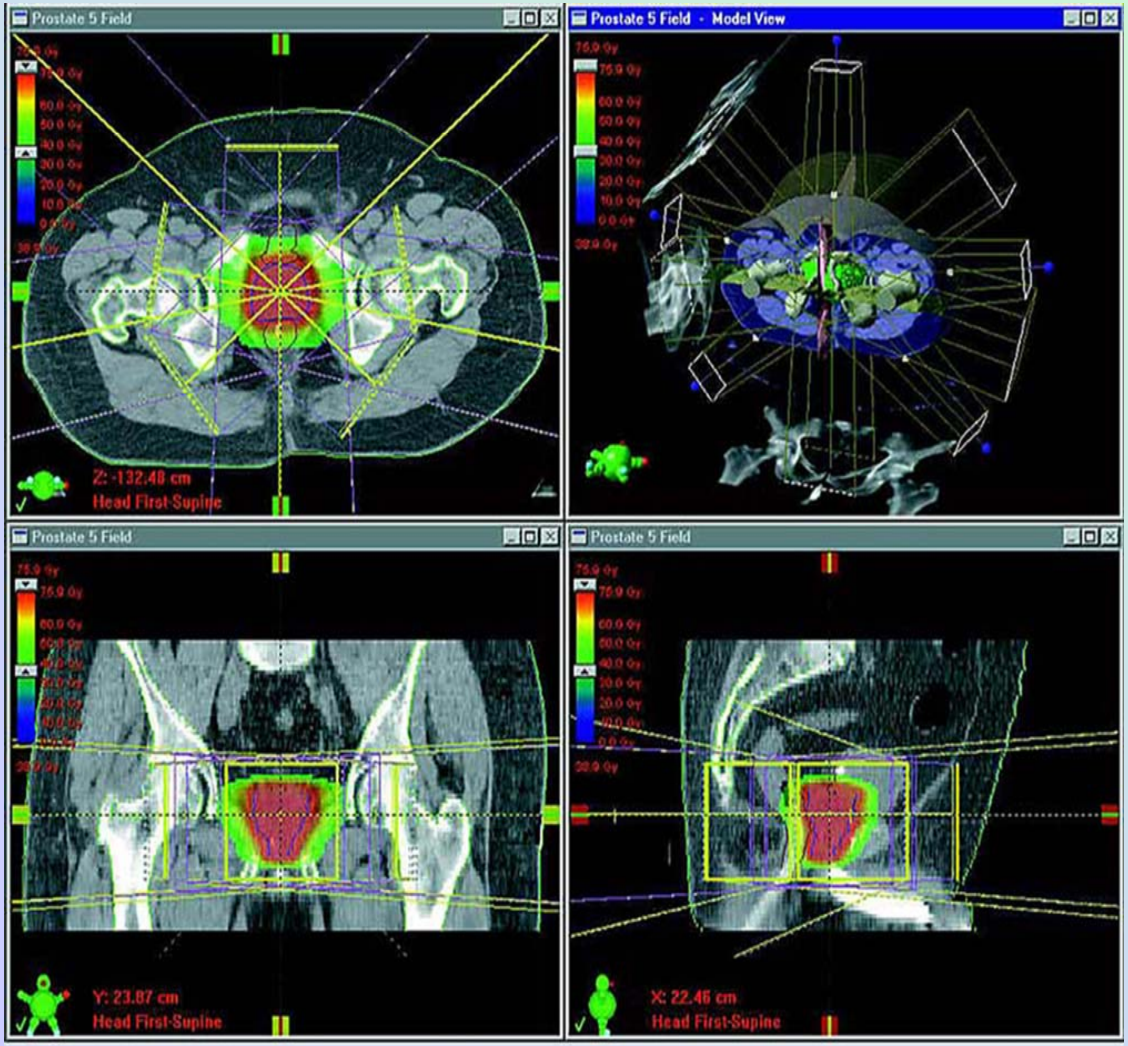
• Il Multi-Leaf Collimator (sagomatore di fascio multilamellare) è un accessorio, gestito da un computer dedicato, che consente di creare schermi personalizzati in tempi brevi e con la massima precisione.

• Il Multi-Leaf Collimator è posto all'interno della testata dell'Acceleratore Lineare ed è costituito da un numero variabile di lamine di materiale ad alto Z, opaco alle radiazioni, poste in modo speculare.

• Posizionando in modo diverso le singole lamine, si possono ottenere campi di irradiazione anche molto complessi.

• La grande innovazione apportata dal Multi-Leaf Collimator, tuttavia, risiede nella possibilità di variare la forma del campo di irradiazione anche durante "l'esecuzione" di una singola seduta di radioterapia.

Tecniche di collimazione (IMRT)



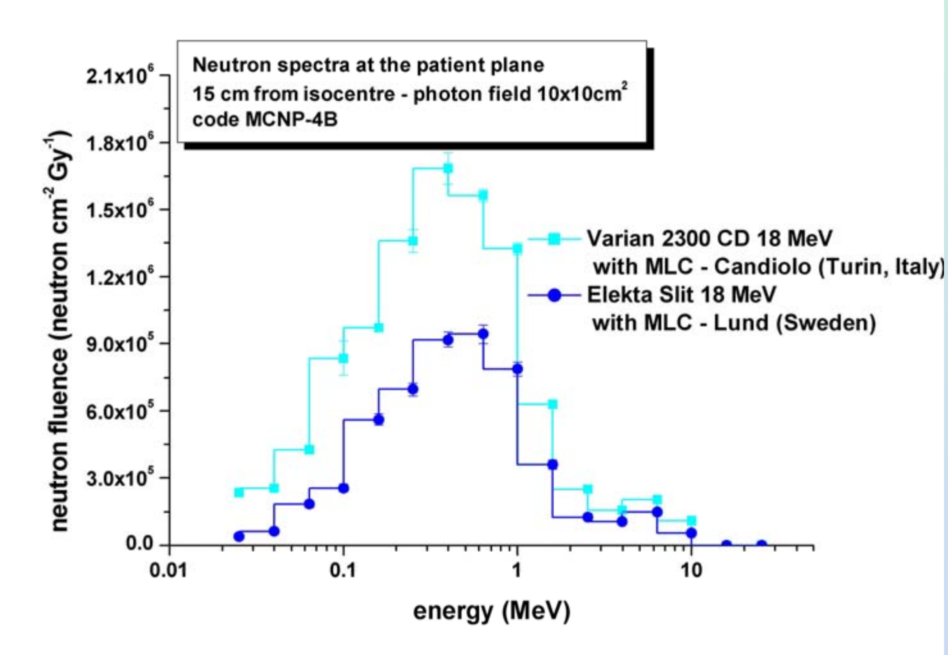
Radioterapia con fasci ad intensità modulata (IMRT)

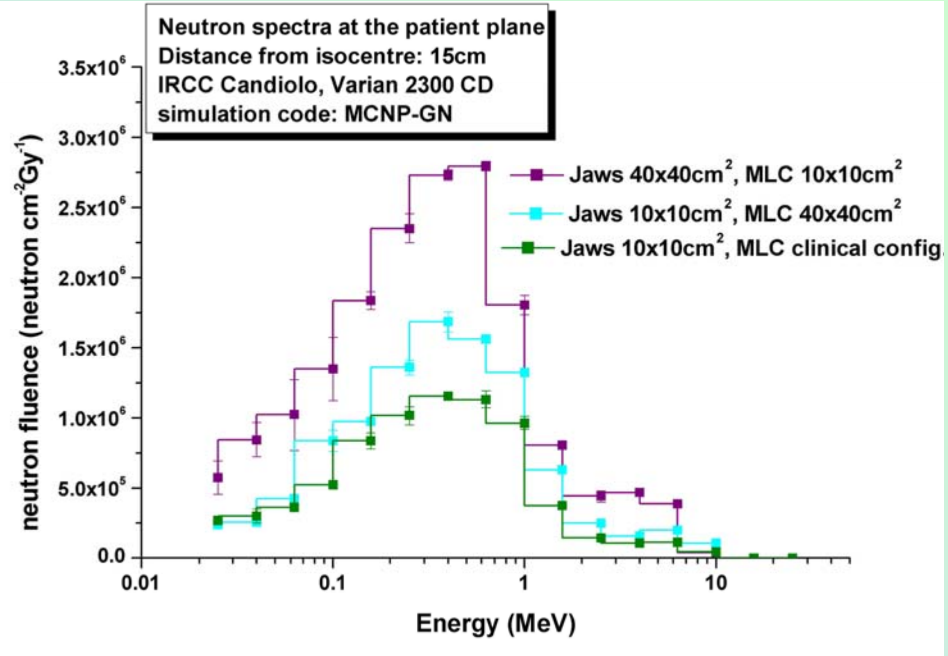
Questa modalità di radioterapia prevede l'utilizzo di collimatori multilamellari. Nel corso del trattamento le lamelle del collimatore si muovono sull'area da irradiare con una sequenza stabilita e controllata da un computer, mentre la macchina eroga il fascio di radiazioni. In questo modo è possibile conformare la fluenza del fascio di radiazioni all'area da irradiare con una maggiore precisione rispetto alla radioterapia conformazionale.

Neutron spectra at patient plane

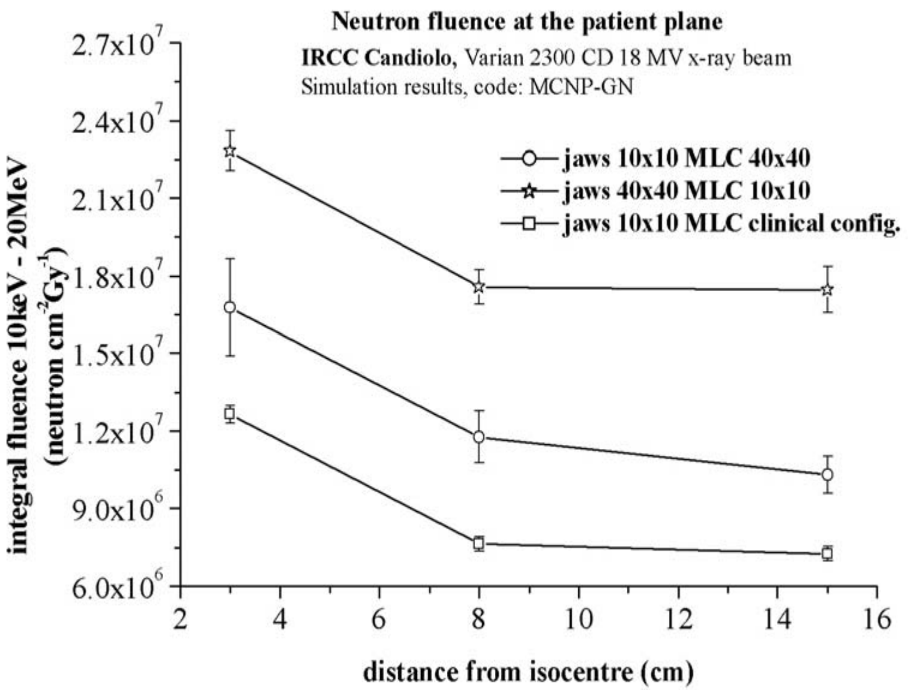
Comparison between different accelerators

Neutron spectra at the patient plane carried out with different collimator configurations

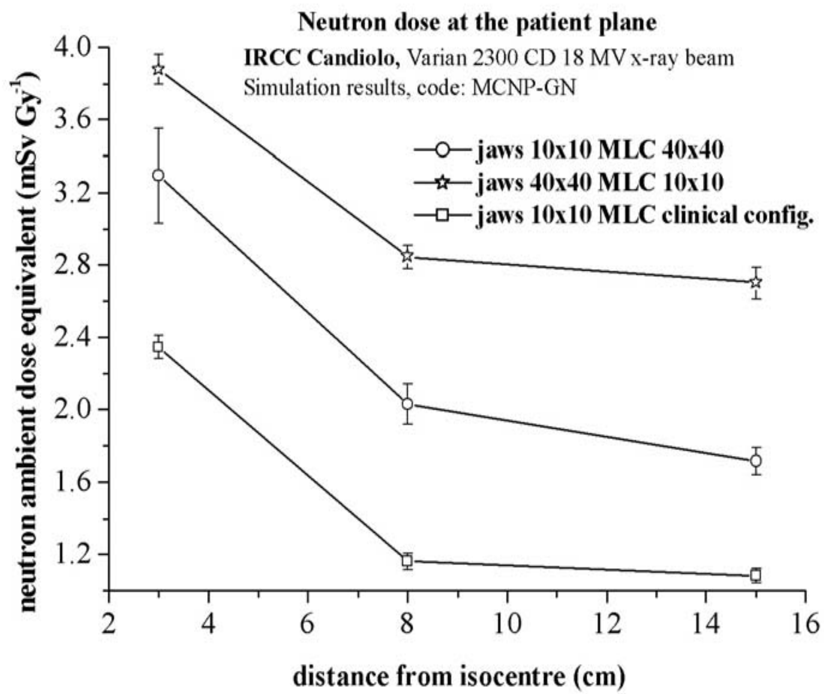




Neutron spectra at the patient plane



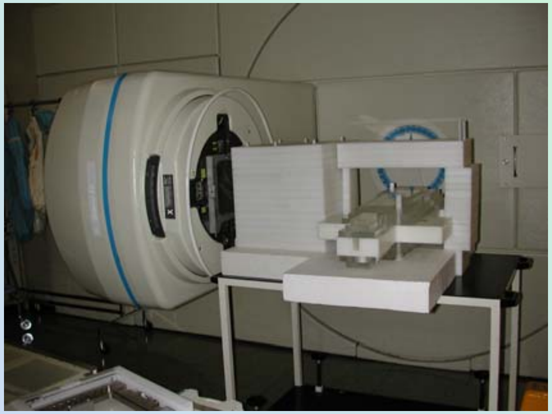
Undesired neutron ambient dose equivalent at the patient plane, calculated with MCNP4B-GN.



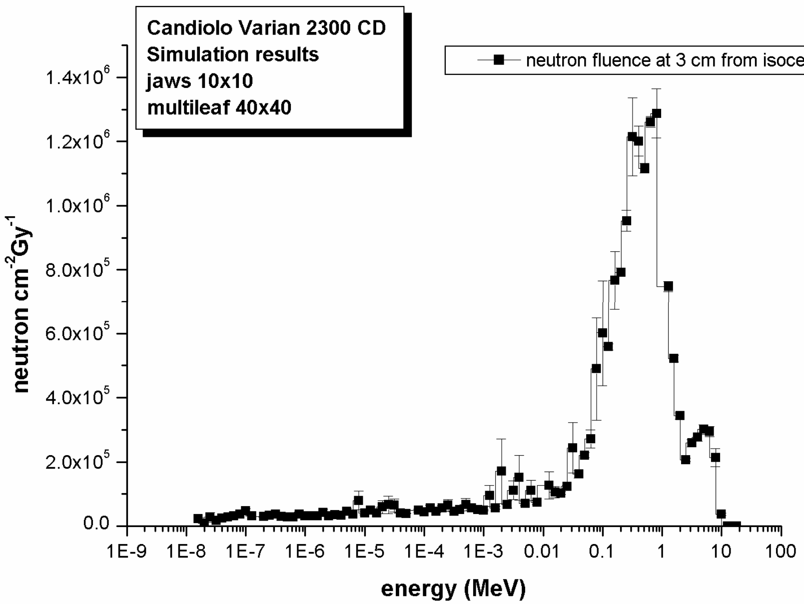
Comparison between neutron integral fluences at different positions with respect to the axis, for three different collimation systems, calculated with MCNP4B-GN

“Monte Carlo simulation of the photoneutron field in linac radiotherapy treatments with different collimation system” A. Zanini et al. Phys. Med. Biol. 49 (2004) 571-582

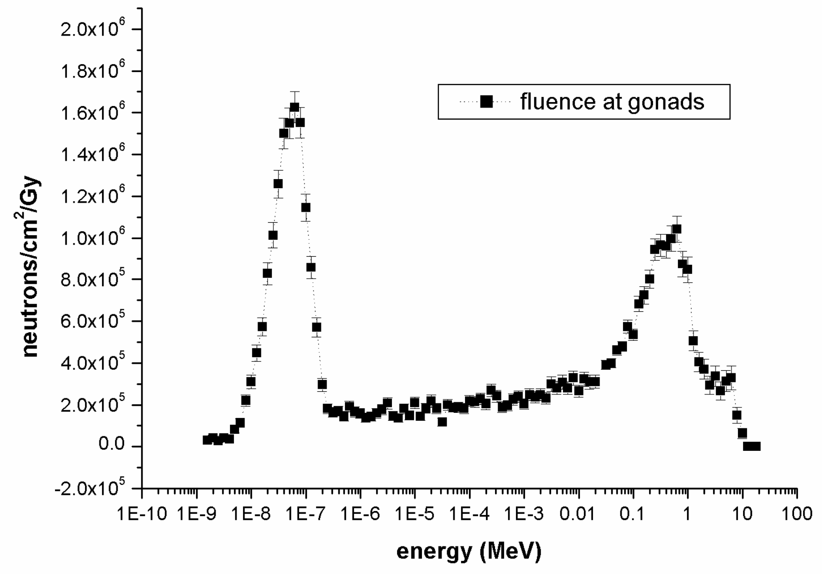
In phantom measurements



Influenza del fantoccio antropomorfo



Spettro neutronico
alle gonadi (z = 2 cm)



La presenza del fantoccio comporta:

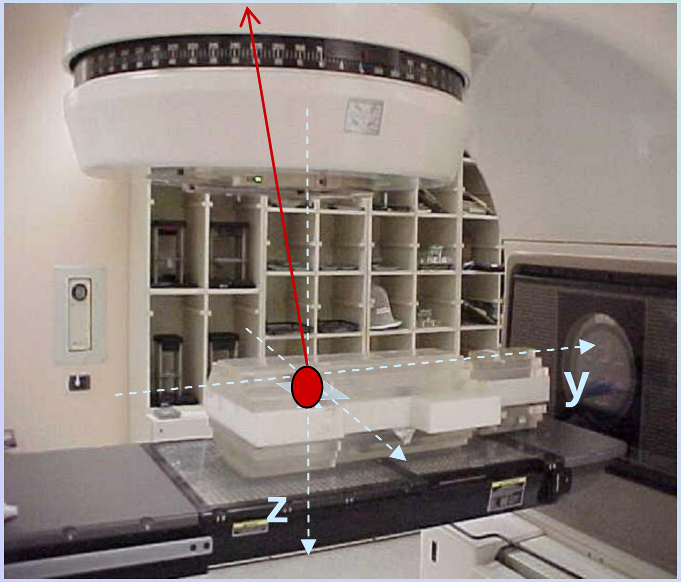
- aumento della componente termica

Neutron spectra in depth

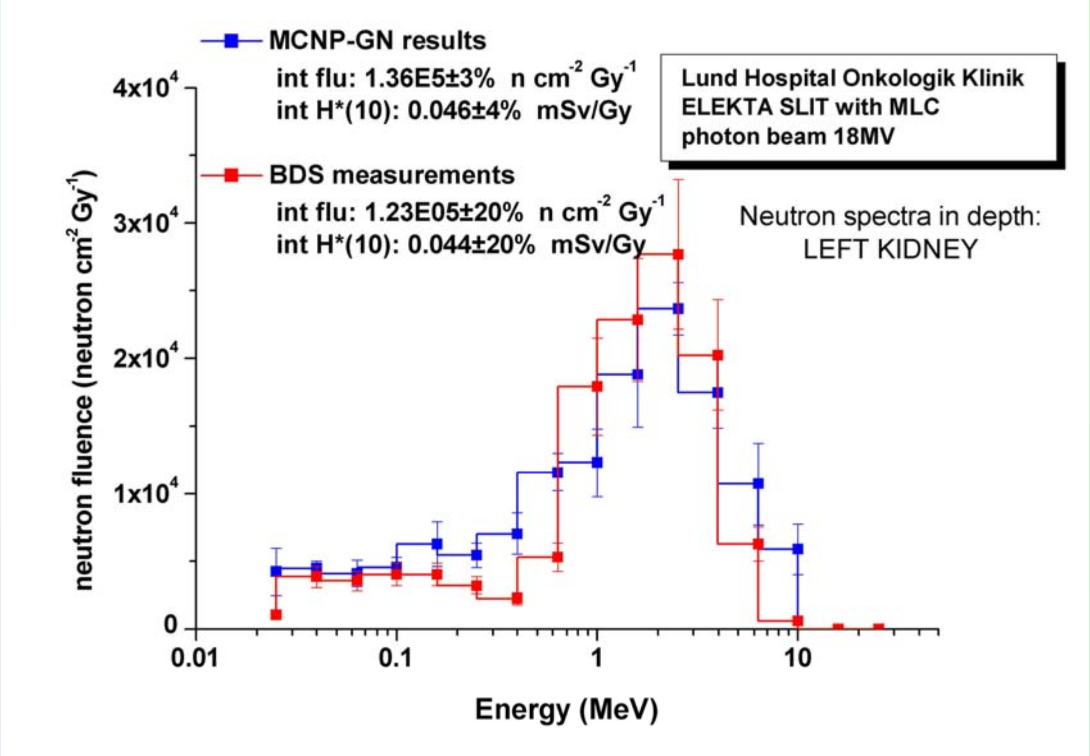
Organ	x	y	z
Left kidney	4	17.8	16

Comparison between measurements and simulation results

Irradiation at gonads SSD 1m



Photon field at the patient plane 10x10 cm^2



The data are normalized to 1 Gy photon dose that is the energy released at build up in a water phantom.

Photoneutron spectra in depth

Comparison between neutron spectra at different depths calculated with MCNP-GN

Liver:

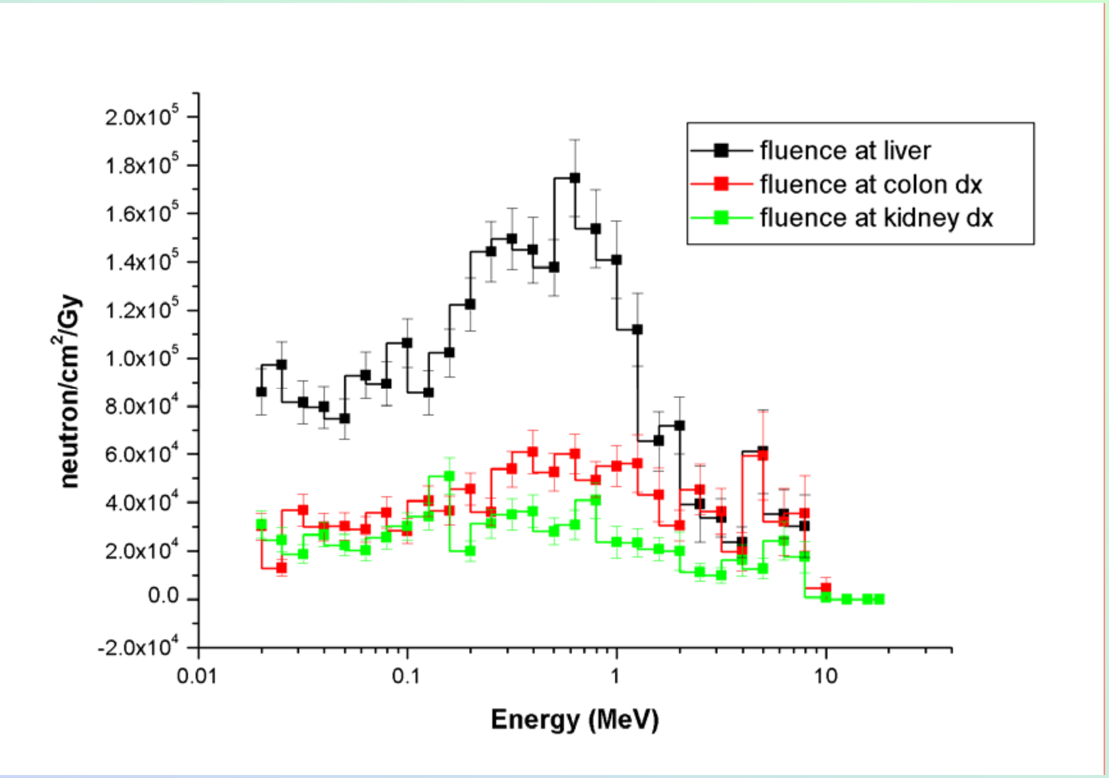
x= -5; y= 36.5; **z= 6** cm

colon dx:

x = -7.5; y= 26.7; **z= 10.1** cm

kidney dx:

x= -5.5; y= 29; **z=16** cm



Attenuazione dei neutroni nel materiale

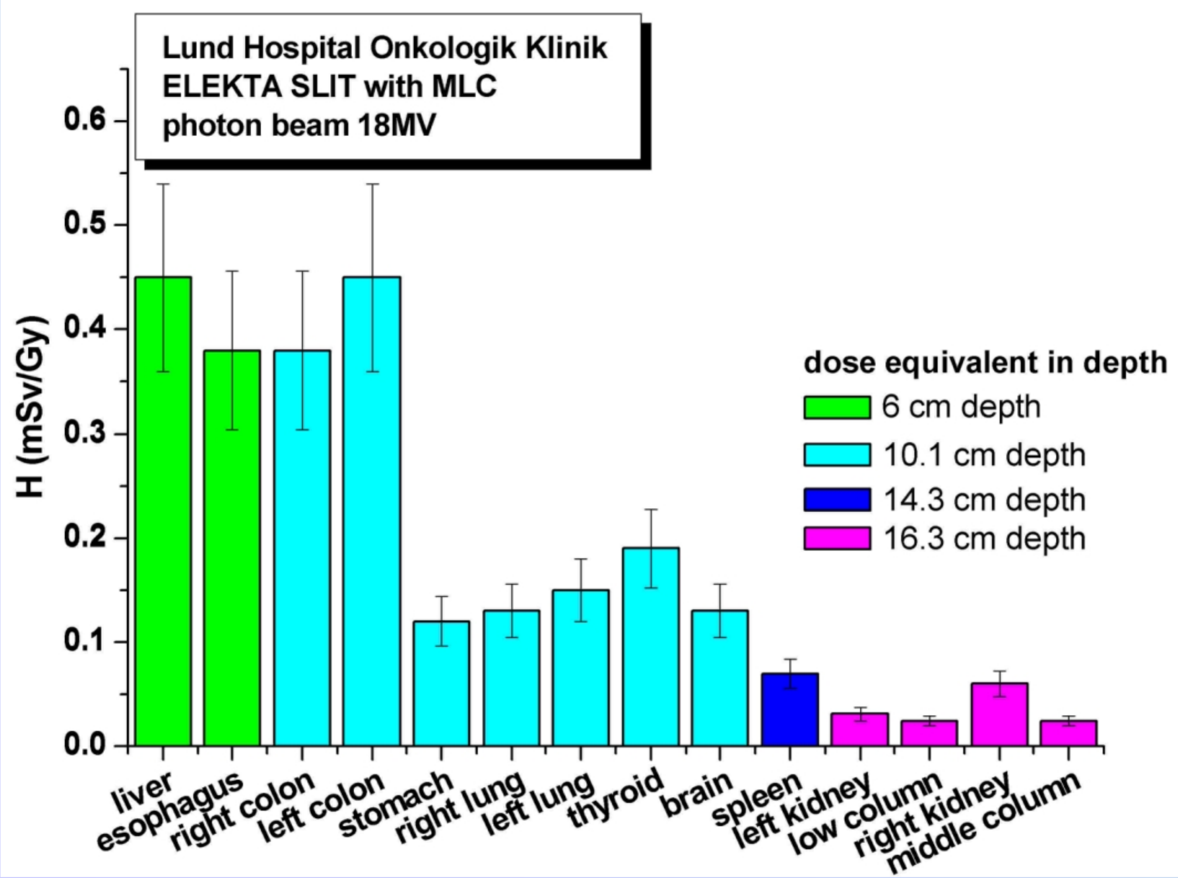
↓

al crescere della profondità l’altezza del picco diminuisce

Experimental neutron dose in depth

- Photon field =10x10 cm^2
- dose rate = 100 UM/Gy

- SSD = 100 cm
- Energy range: 100 keV – 20 MeV



- The organs are arranged layer by layer
- The organs in each layer are arranged in increasing distance from isocentre

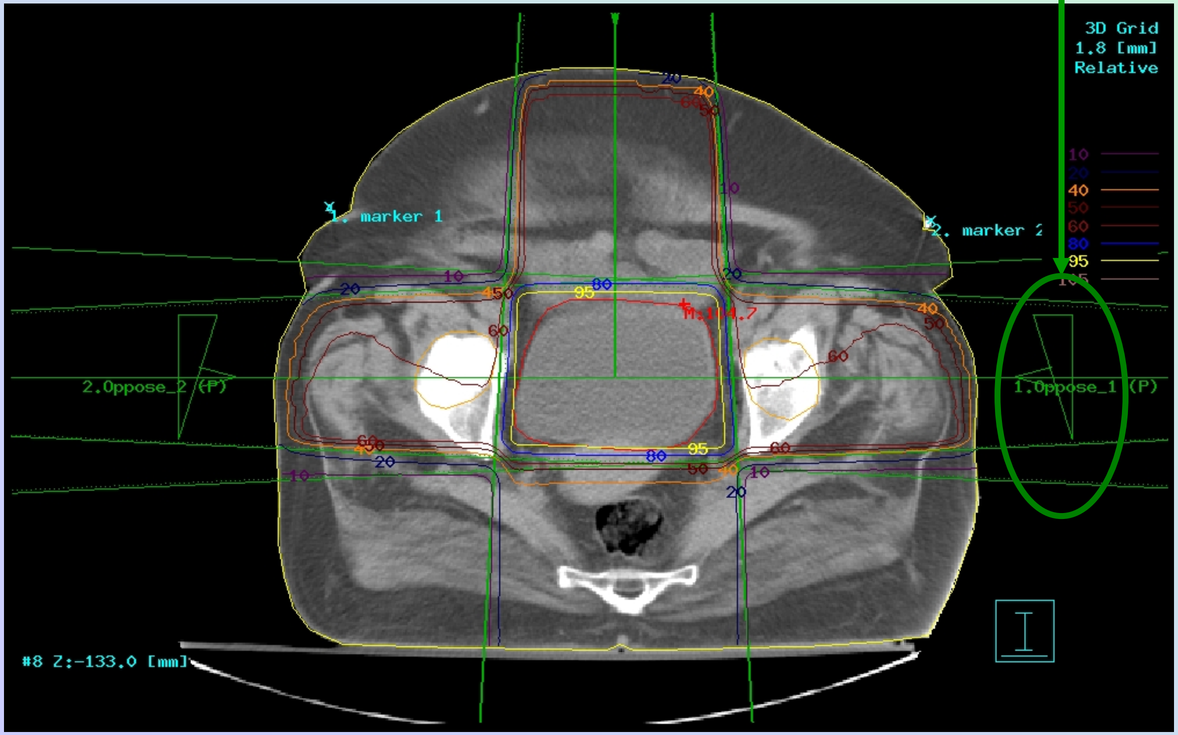
Integral measurements: BD-100R, calibrated in H (HCRP 38)

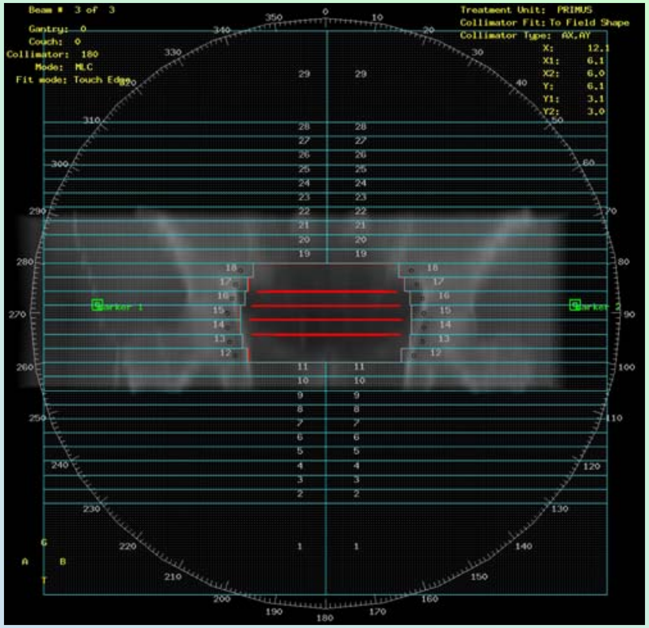
Crossed beams treatment to bladder

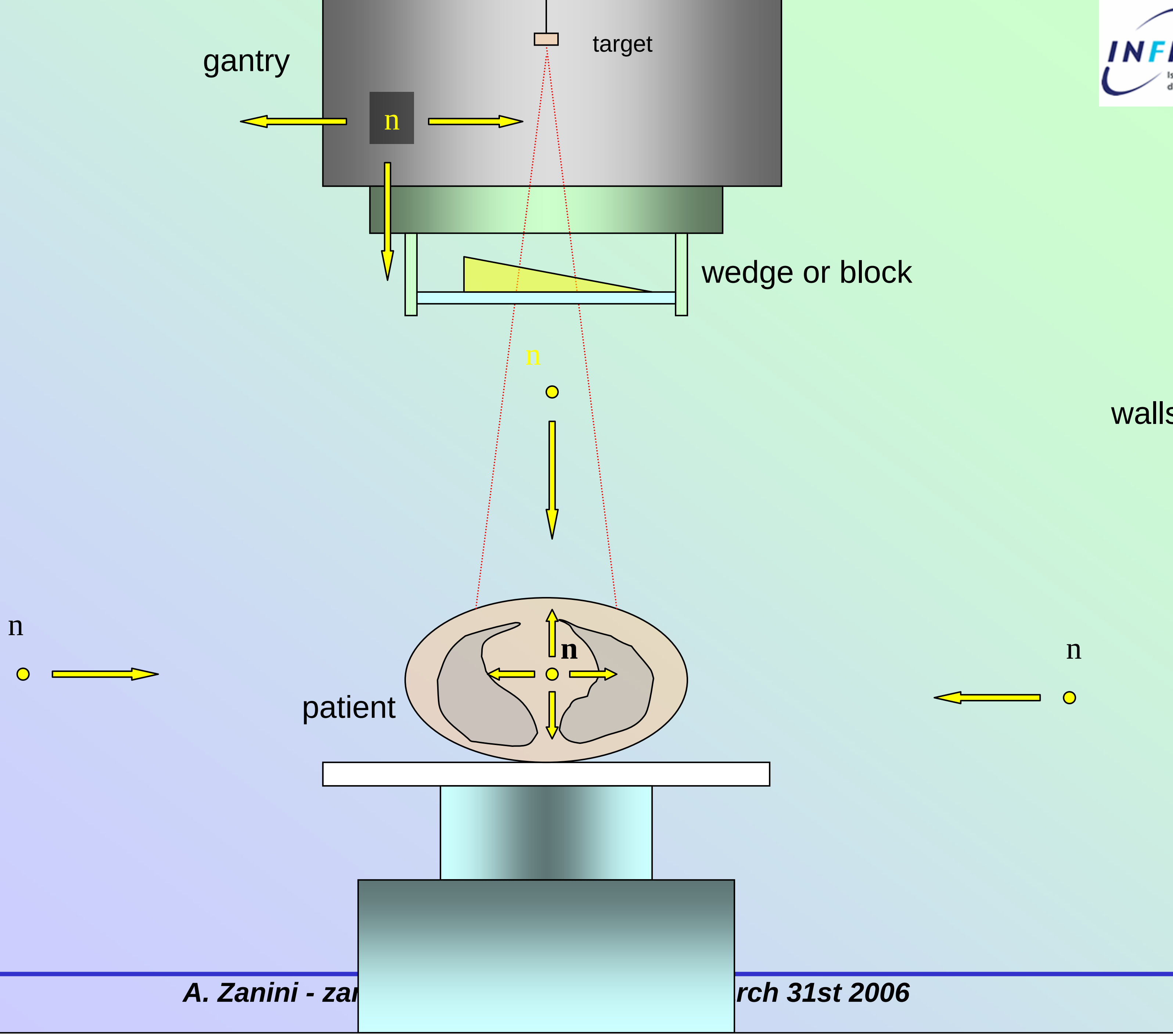
Three photon fields:
0° AP irradiation
90° lateral irradiation
270°lateral irradiation

treatment planning to bladder in a patient

Lead alloy wedges are used in lateral photon fields for a better dose distribution






target
gantry
n
wedge or block
n
walls
n
n
patient
n

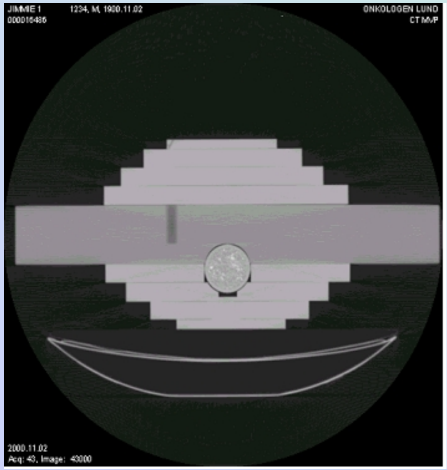
Crossed beams treatment to bladder

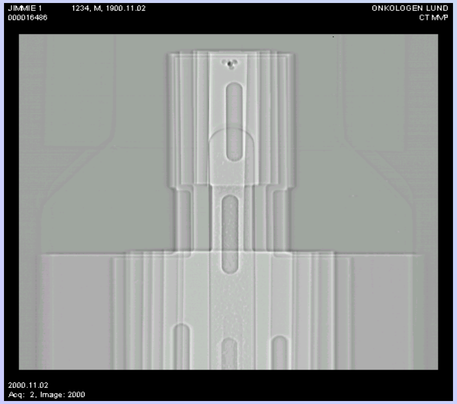
Dose rate: 100 UM/Gy

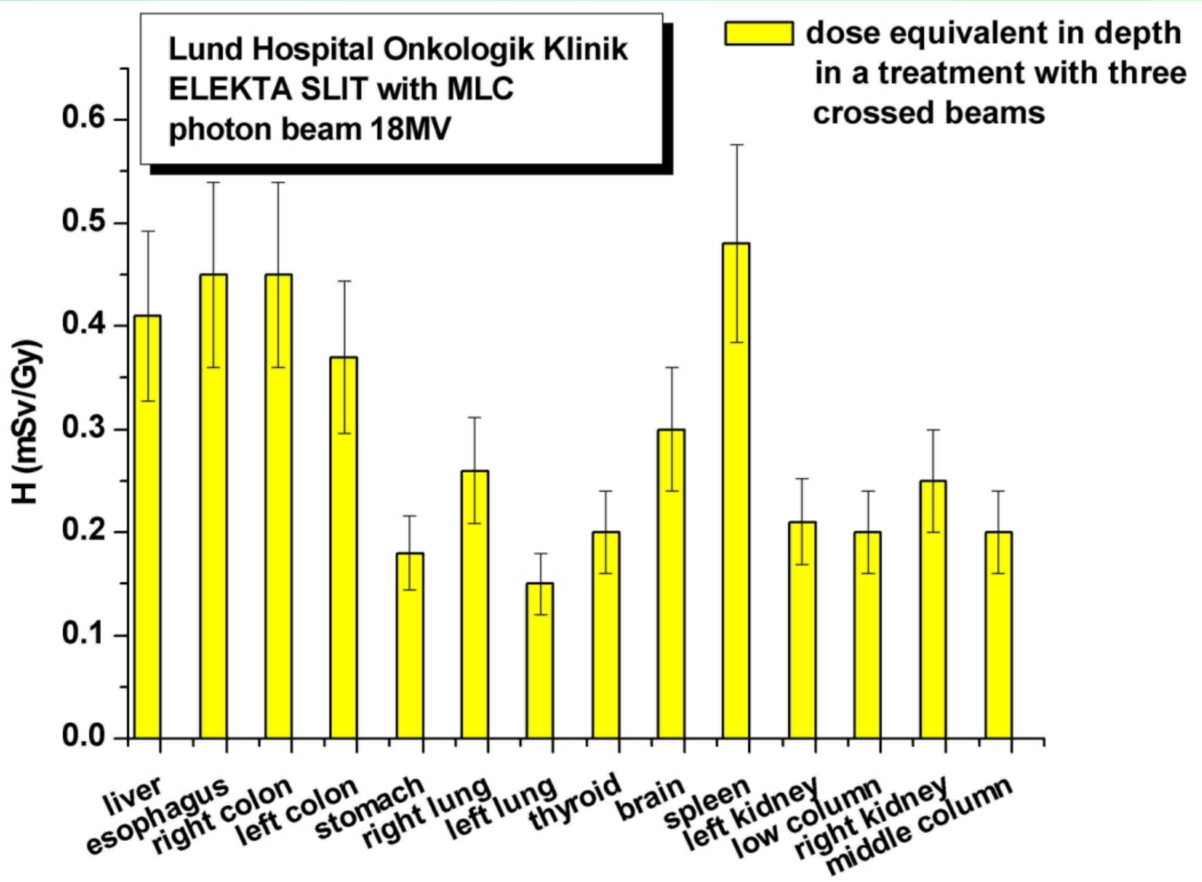
3 photon field 10x10cm^2

dose delivered in the tumor area 0.1 Gy

treatment planning to bladder in a phantom **Neutron Energy range detected: 100 keV – 20 MeV detector: BD100R**



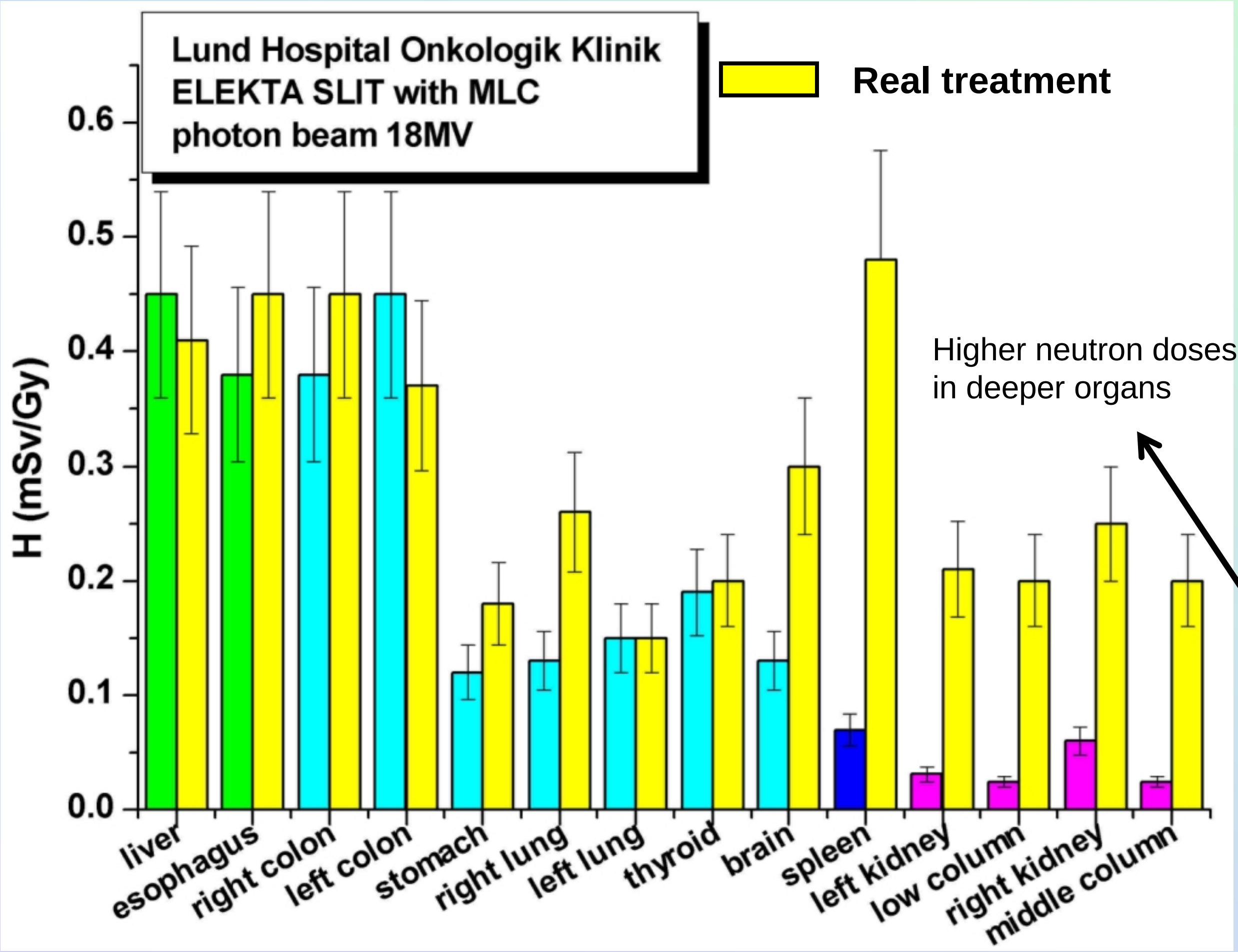




Crossed beams treatment to bladder

Undesired neutron dose in a real treatment compared with the neutron dose measured during an exposure to ONE photon beam

Neutron Energy range detected : 100 keV – 20 MeV



	one γ beam	RT
Organ	H	mSv/Gy
liver	0.45	0.41
esophagus	0.38	0.45
right colon	0.38	0.45
left colon	0.45	0.37
stomach	0.12	0.18
right lung	0.13	0.26
left lung	0.15	0.15
thyroid	0.19	0.20
brain	0.13	0.30
spleen	0.07	0.48
left kidney	0.031	0.21
low column	0.024	0.20
right kidney	0.06	0.25
middle column	0.024	0.20

Conclusions

- The spectrometry based on passive detector system gives good results both
- in the extended range

  100 keV-100 GeV (environment neutron dosimetry)
- in the short range

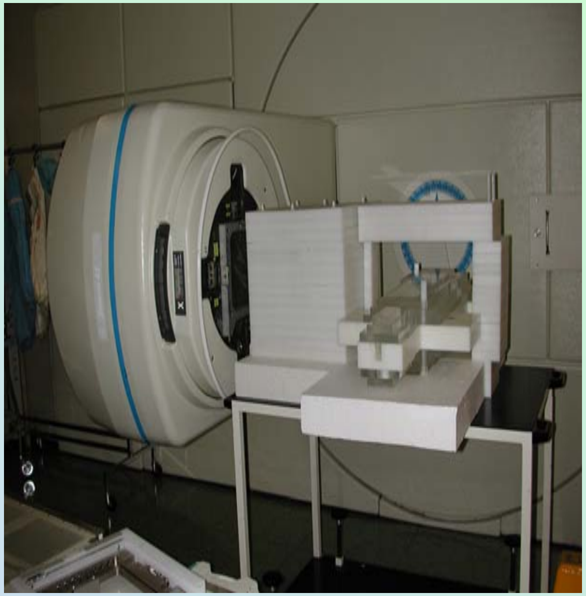
  10 keV-20 MeV (medical end environment dosimetry)
- The use of anthropomorphic tissue-equivalent phantom allows the evaluation of dose equivalent distribution in critical organs.

- Work in progress
- Extension of spectrometry energy range to low energies

  (Thermal -10 keV) by new detectors based on BDT bubble detectors shielded by layers of Cd and polyetilene

Compact sources for in-hospital BNCT treatment

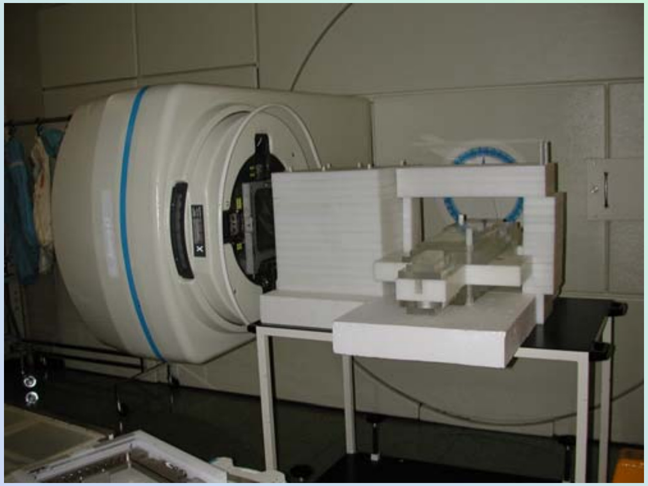
D-D fusion source



Photoconverter for Linac Saturne 18 MV

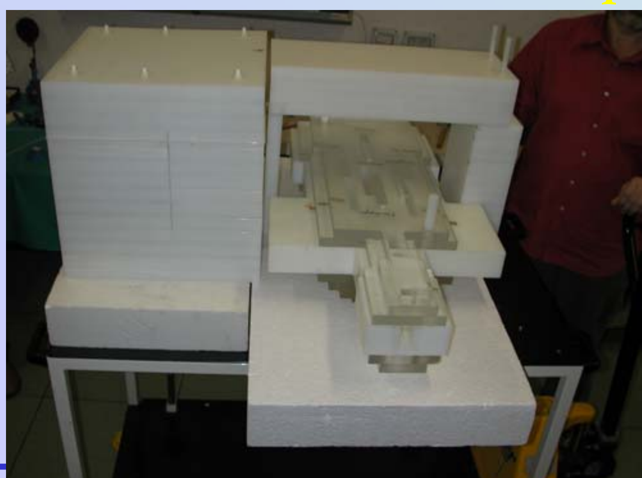
Photoconverter

MISURE PRELIMINARI (INFN TS)



LINAC: SATURNE 43 18MV

Installazione del collimatore presso l'ospedale Gemelli di Roma



“Small Prototype” Measurements in Como S.Anna Hospital (8/2005)

Mounting Lead and Graphite Blocks.

Filling the Heavy Water Box

Transporting in the hospital radiotherapy room.

Positioning in front of the accelerator head.

Forth configuration

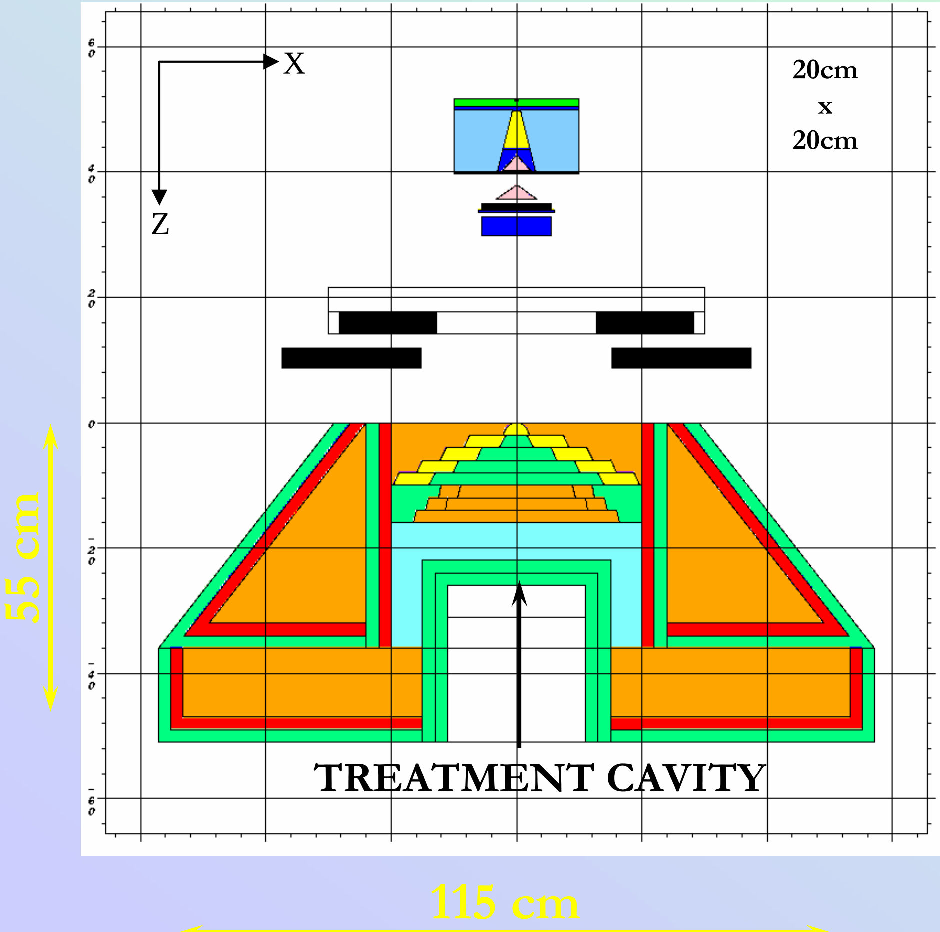
TUNGSTEN

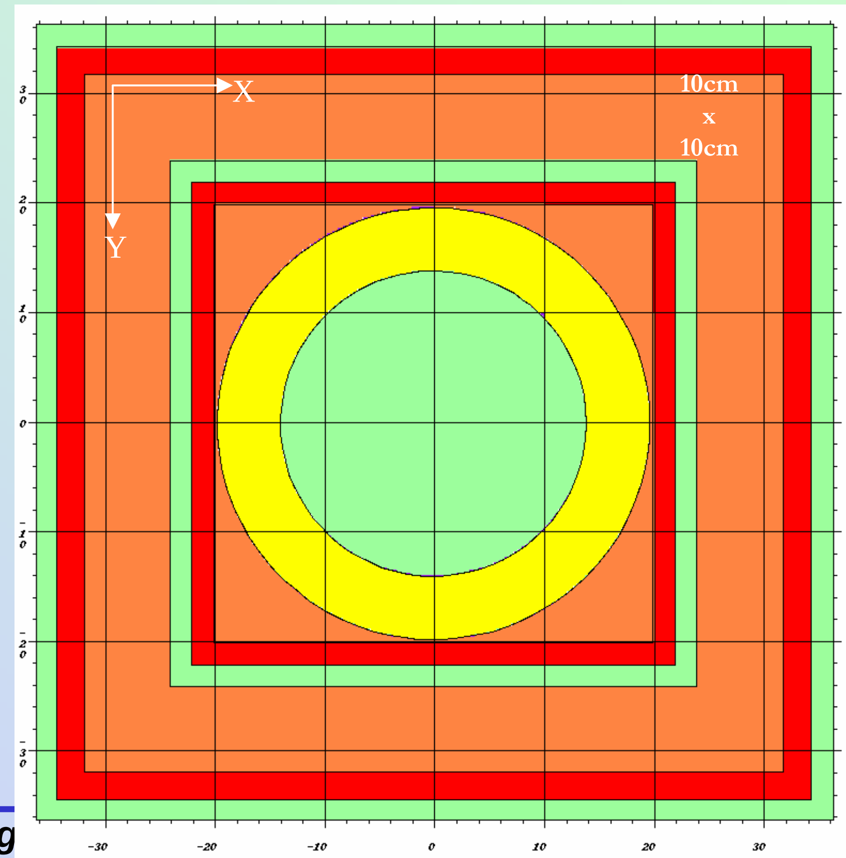
LEAD

CARBON

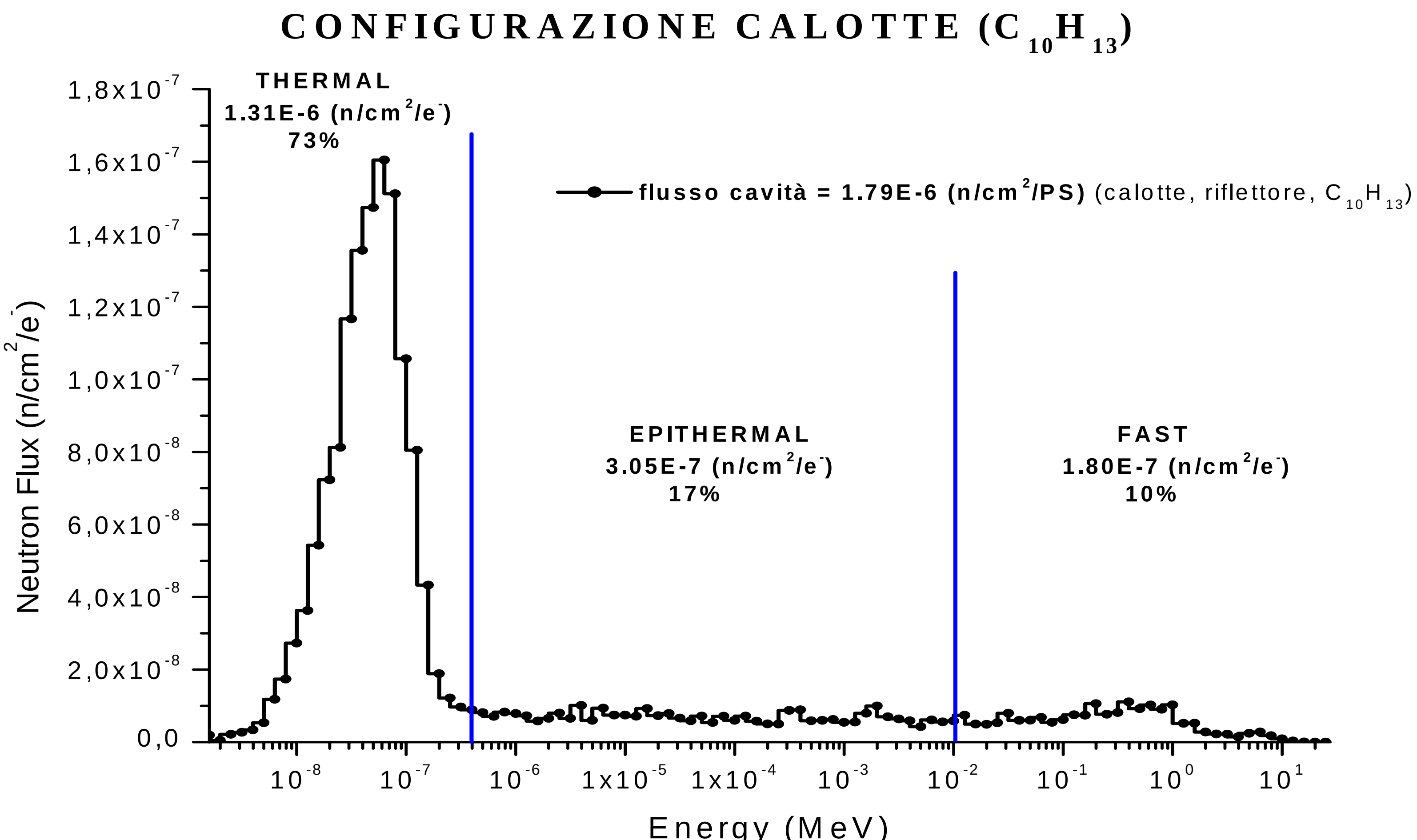
BISMUTH

HEAVY WATER



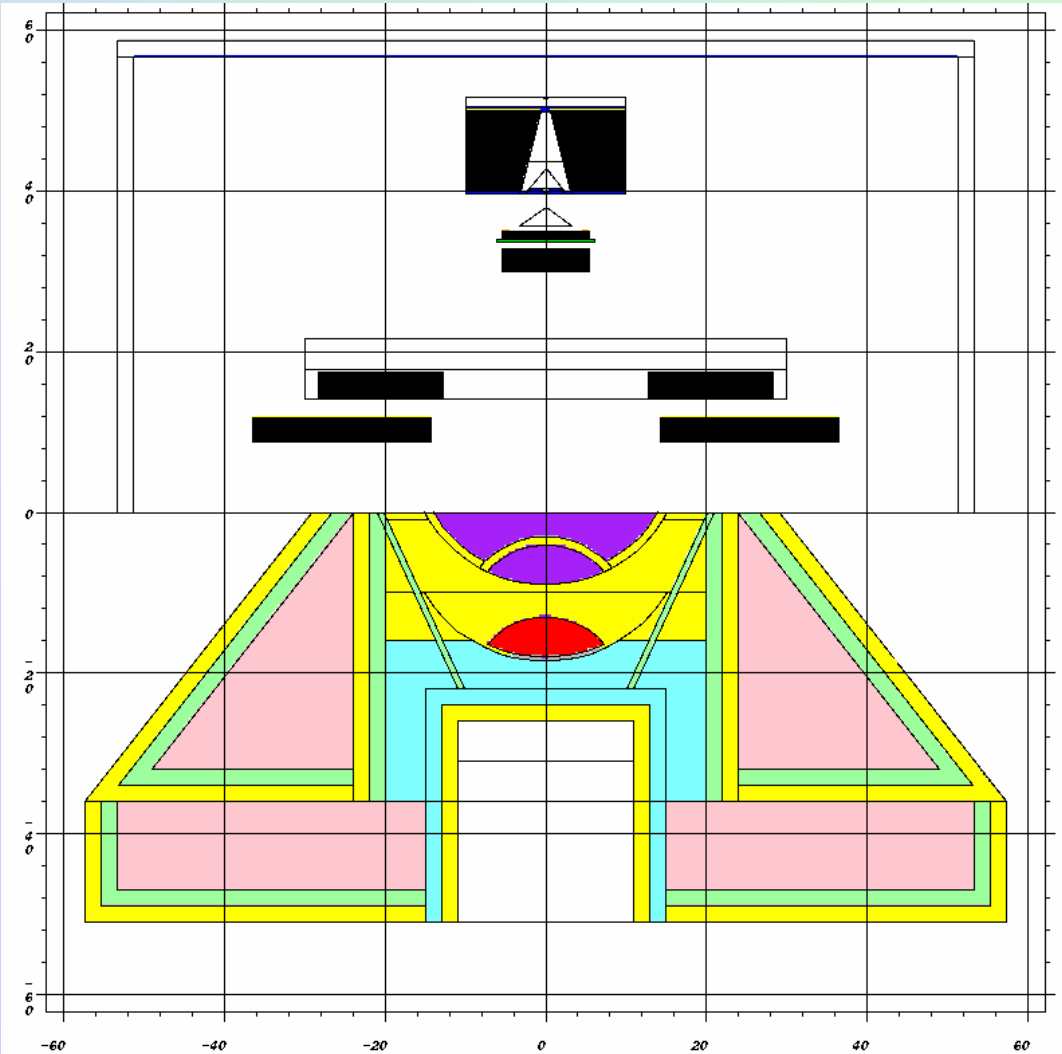


CONFIG. CALOTTE ($C_{10}H_{13}$)



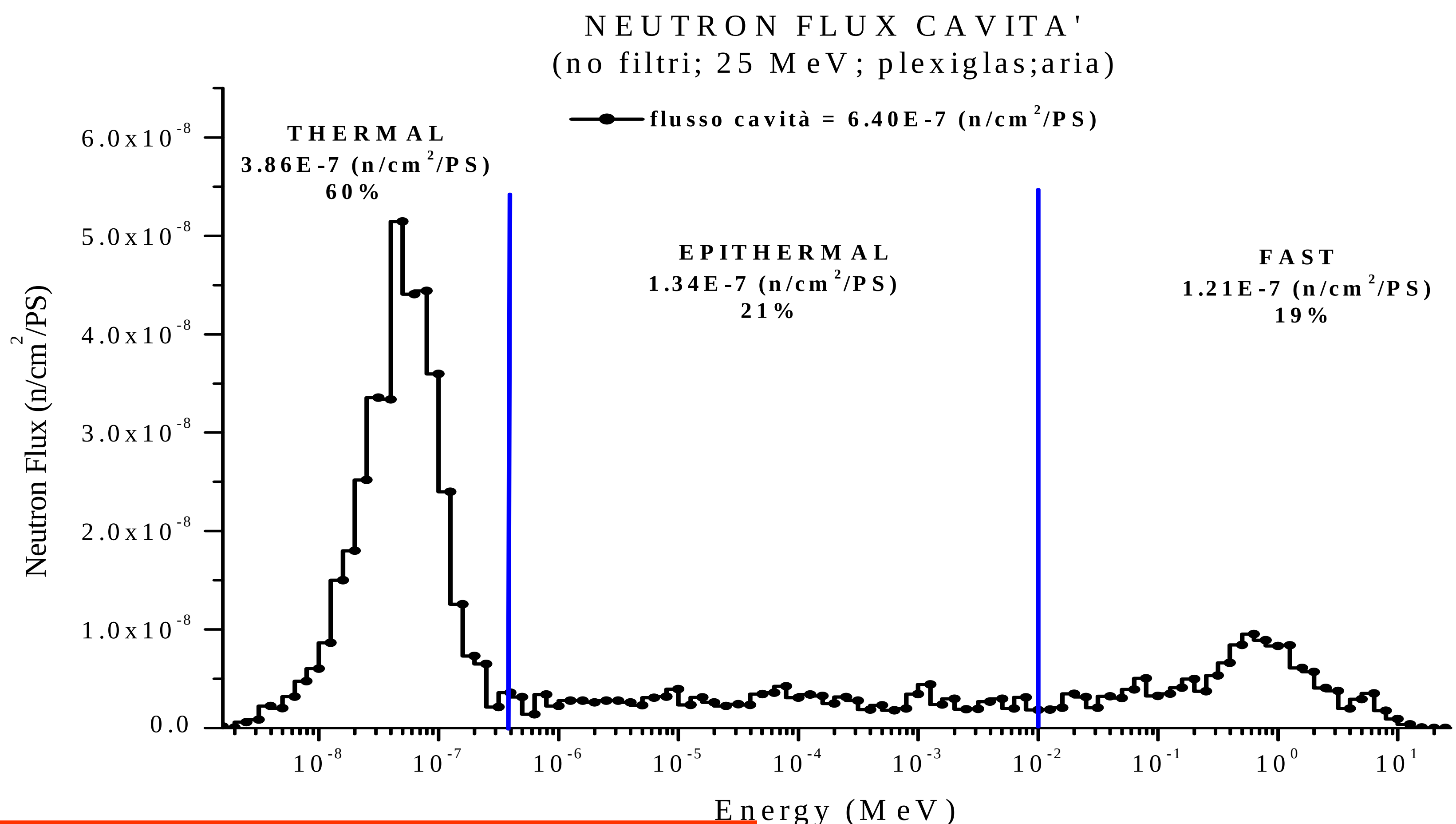
Flusso terapeutico = 2.82E8 n/cm²/s

Nuova configurazione



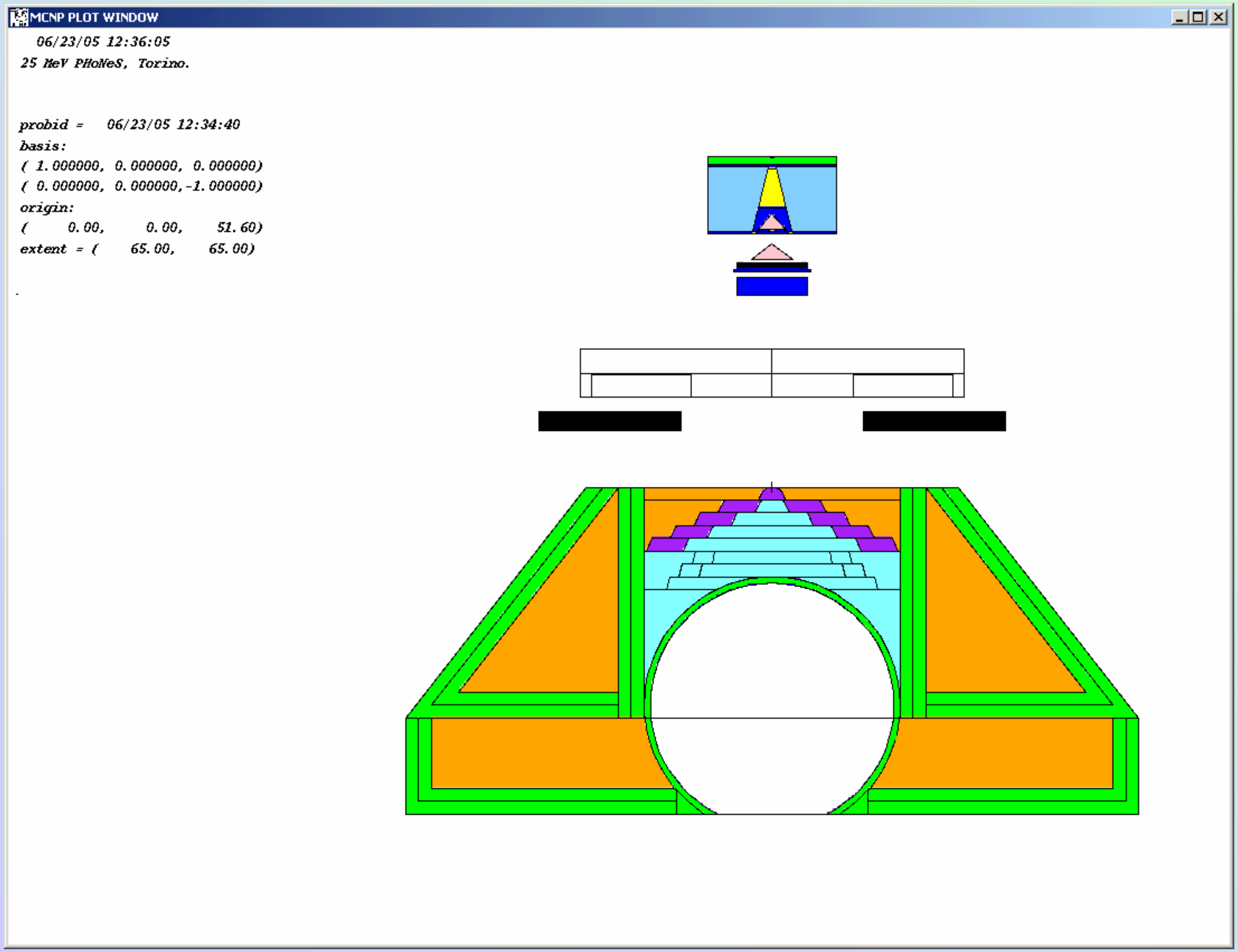
- PIOMBO
- GRAFITE
- BISMUTO
- TUNGSTENO
- PLEXIGLAS
- MATERIALE IDROGENATO ($C_{10}H_{13}$)

Spettro neutronico all'interno della cavità (no filtri)



Flusso terapeutico = 9.05E7 n/cm^2/s

New Configuration (photon)



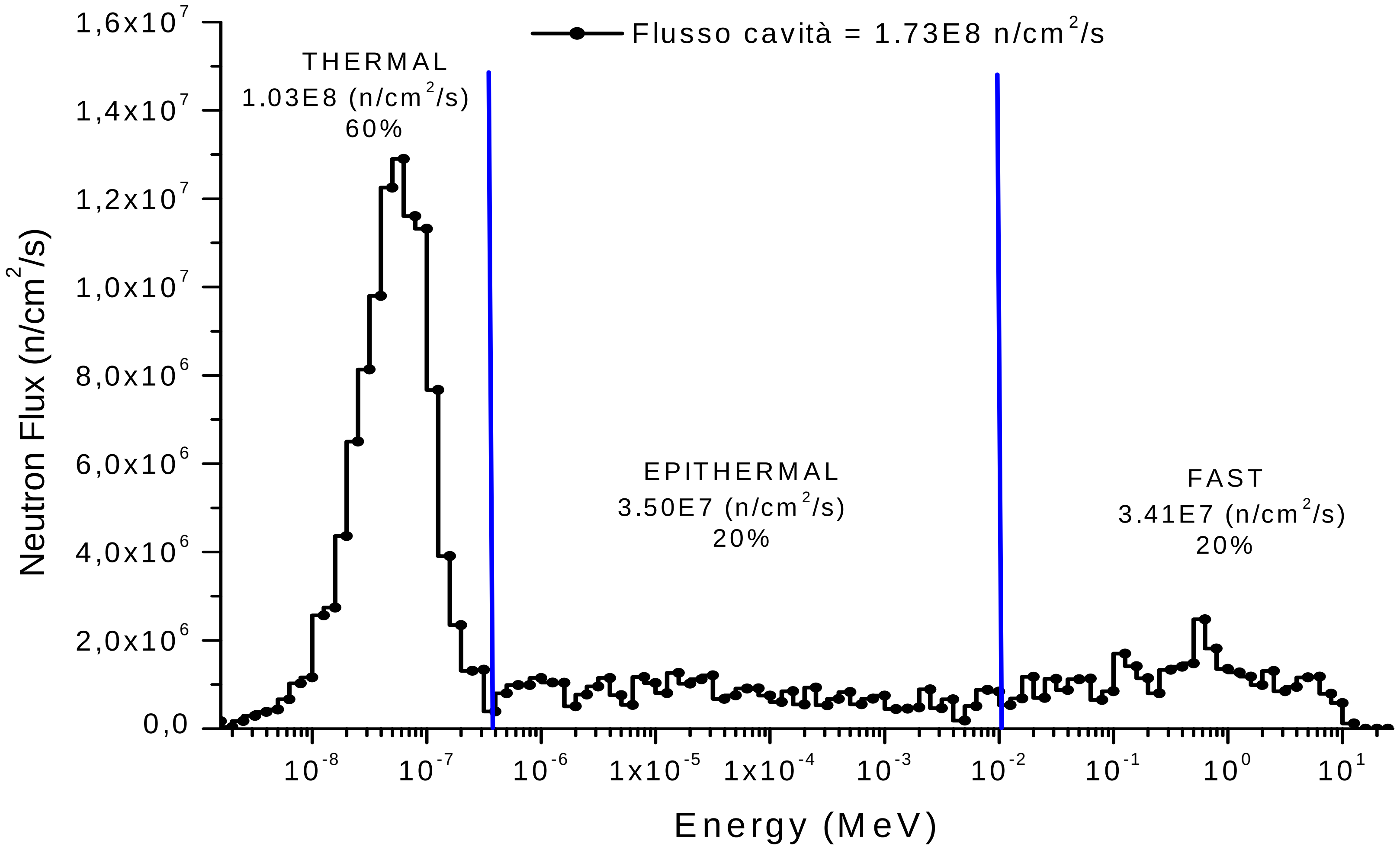
LEAD

CARBON

TUNGSTEN

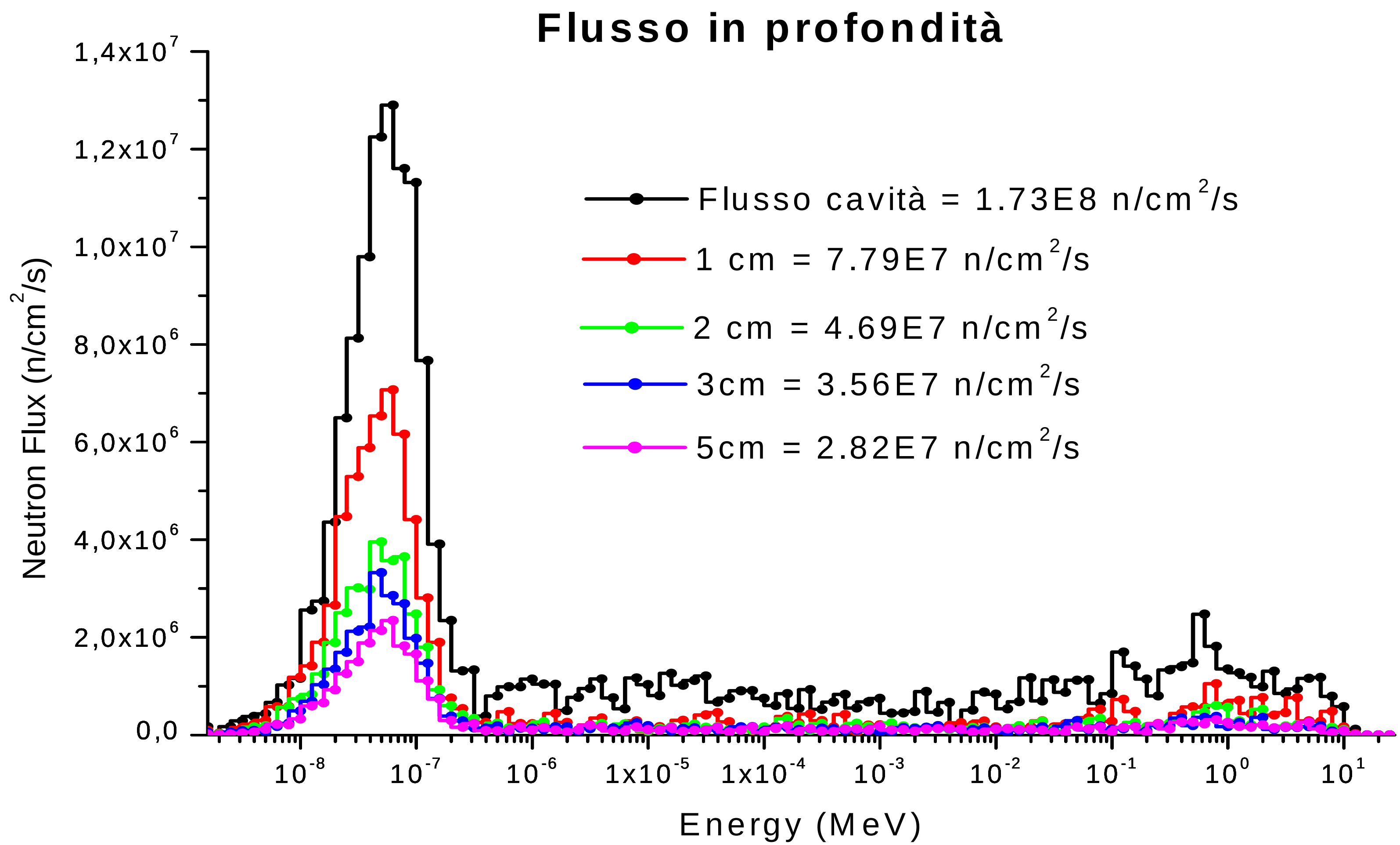
PLEXIGLAS

Neutron spectra inside the treatment cavity



Therapeutic flux = 1.38E8 n/cm^2/s

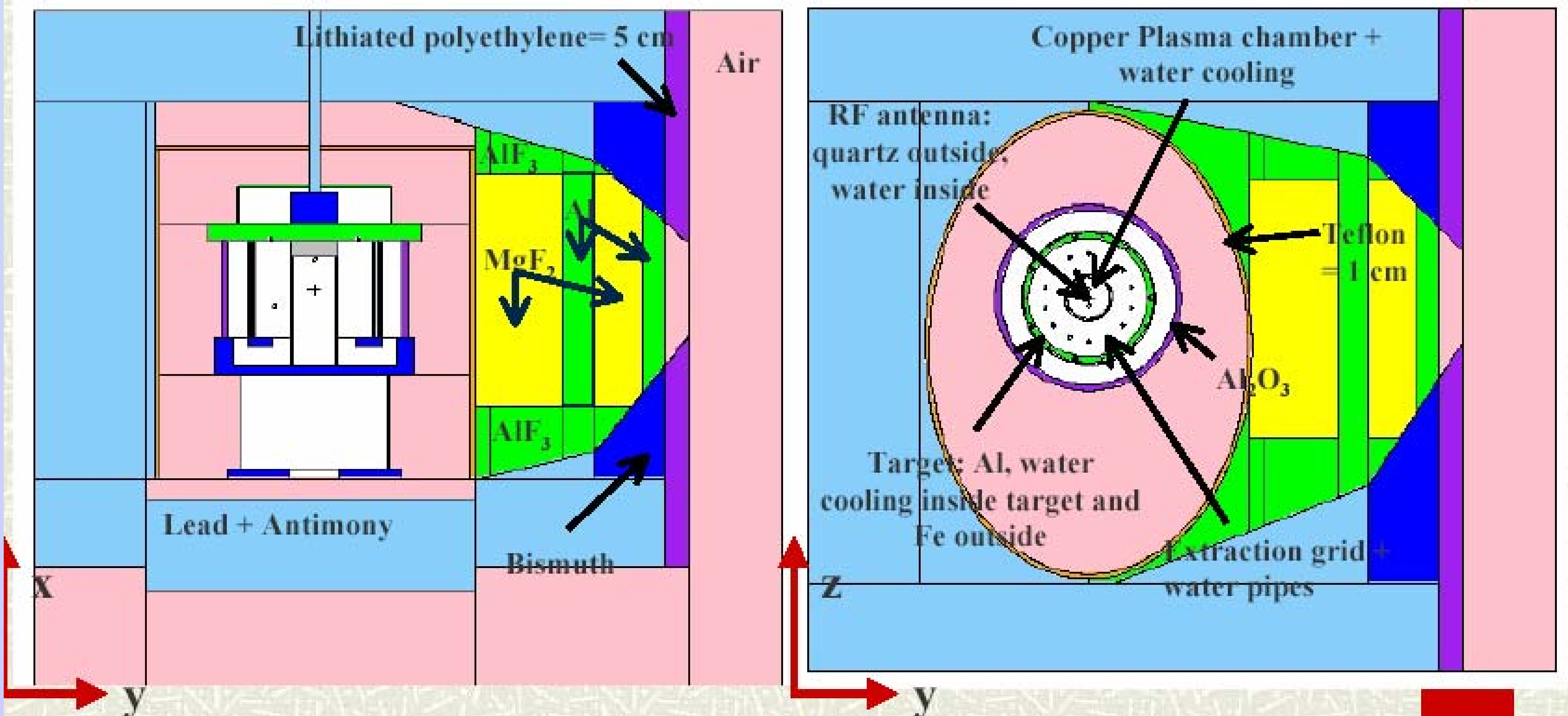
Flusso in profondità (nuova configurazione)



BSA realizzato con MCNP-4C

Colonna epitermica: 19 cm MgF_2 + 6.5 cm Al + 10 cm MgF_2 + 5 Al + 5 air; dimensione del fascio 20x20 cm^2

Distanza tra il centro della sorgente e la finestra di uscita del fascio= 80 cm



Neutron spectrum at beam exit window

(Neutron yield 1E11 s^{-1})