On the unfolding problem in neutron spectrometry around high-energy electron facilities

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Introduction

❖Monitoring of ionizing radiation around high energy particle accelerators is a difficult task due to the complexity of radiation field.
The capability to distinguish between low LET and high LET components of radiation field at workplace, and measure them, is necessary to correctly evaluate the exposure of personnel.

❖At high energy electron accelerators the dose equivalent outside a thick shield is mainly due to neutrons, with some contribution of bremsstrahlung radiation.

❖The determination of the ambient dose equivalent H*(10) in workplace neutron fields, ranging over a wide energy interval, still constitutes a major concern in operational radiation protection. This is mainly due to the complex energy dependence of the neutron quality factor, leading to practical difficulties in designing survey-meters with adequate response in terms of the operational quantities.

Introduction

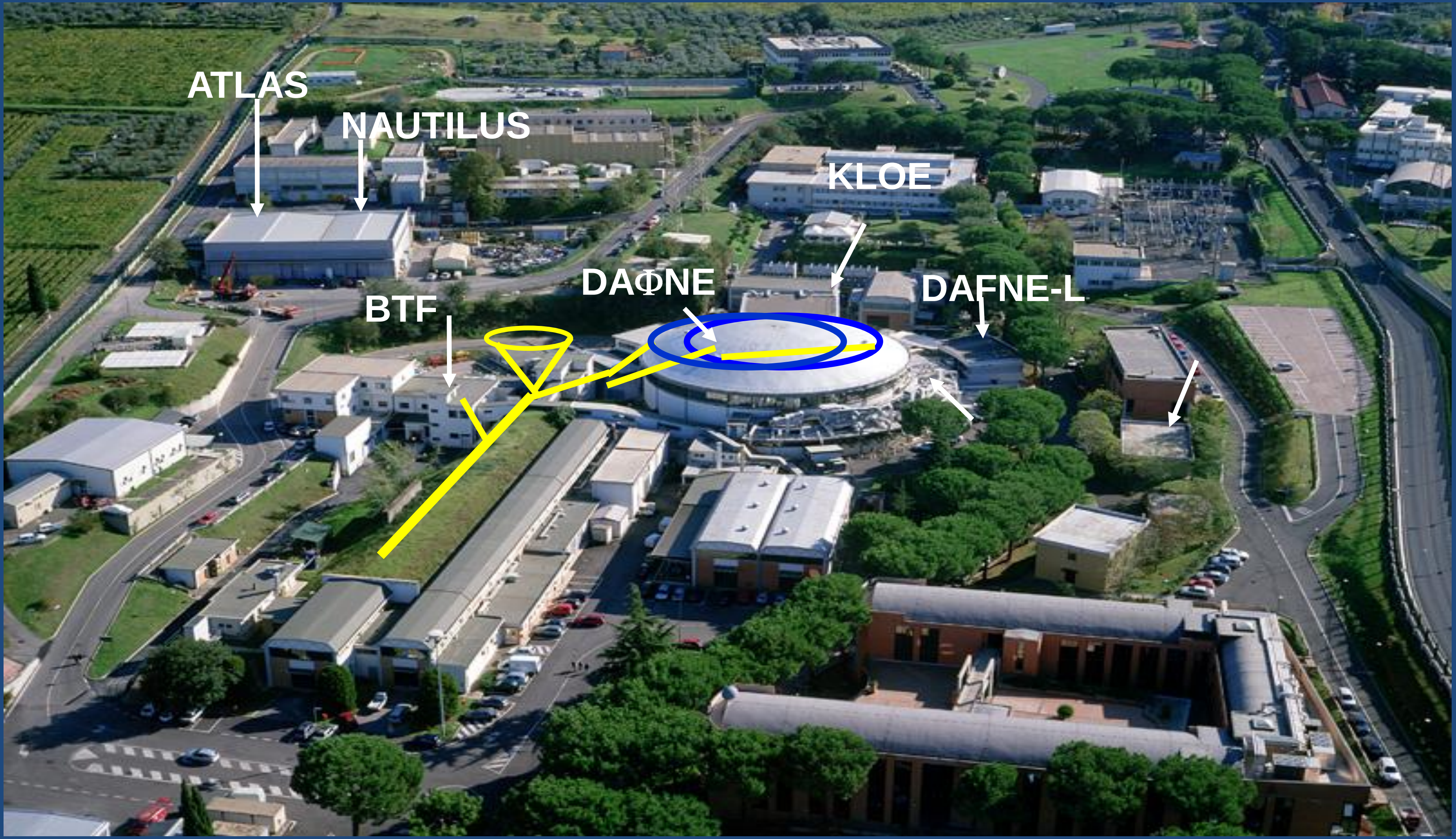
◆ An accurate determination of H*(10) in workplace fields can be achieved through the use of suitable neutron spectrometer.

◆ The most used neutron spectrometry technique in workplaces is the Bonner Sphere Spectrometer (BSS). Its advantages are the isotropy of the response, the possibility to extend the energy range up to GeV neutrons and 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.

This paper presents the main results achieved in the operational monitoring of DA⍰NE, the e^+/e^- high-energy collider of INFN-LNF, and the main characteristics of FRUIT code, used for u folding procedures.

An "Extended Range" BSS, (ERBSS), obtained by embedding layers of high Z metals, as lead or copper, in the polyethylene moderating spheres, was setup for the neutron monitoring of DAΦNE, a high-energy Φ factory in operation at INFN-LNF since 1997.



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

- eight polyethylene spheres (density 0.95 g·cm^{-3})

- three polyethylene spheres (density 0.95 g·cm^{-3}) loaded with copper and lead

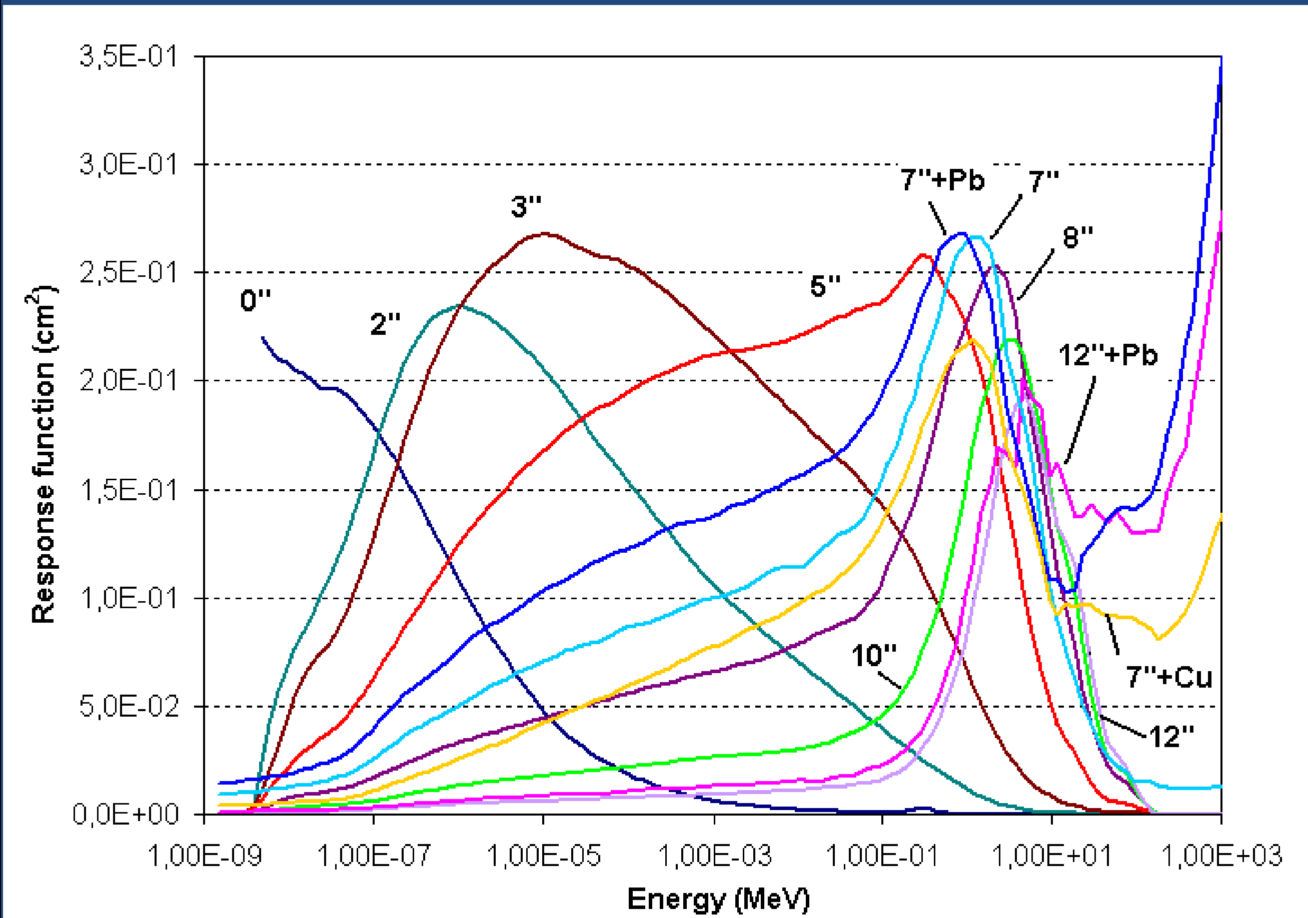
- a 4x4 ^{6}LiI(Eu) active scintillator

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 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 and its overall uncertainty was estimated to be σ_{matrix} = ±3%.

The response functions of the high-energy spheres.

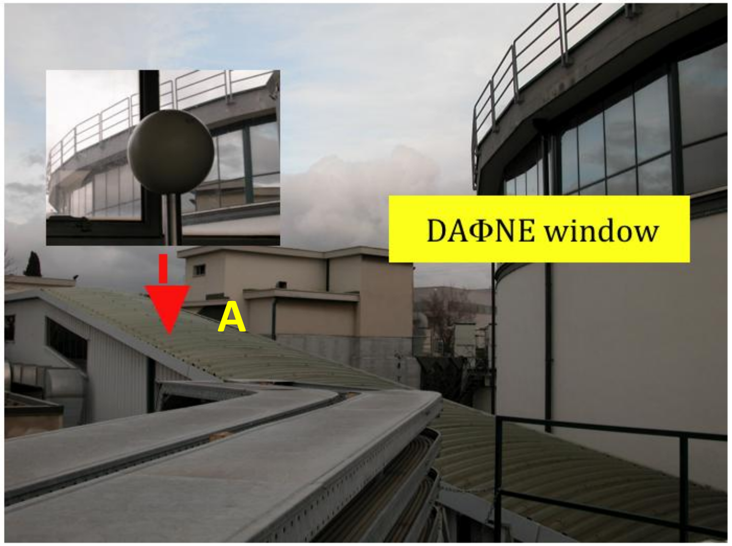
Selection of the points for measuring the neutron spectra

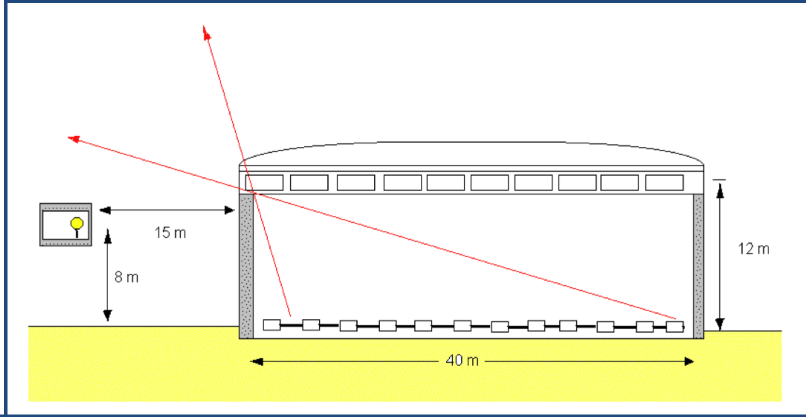
Some "weak point" from the point of view of the radiation shielding have been chosen for measurements. All these points are located in the non shielded upper window of the DAΦNE building (around 12 meters from ground), from which some skyshine radiation arises.

Point A is in a corridor tangential to the DAΦNE building, nearly 4 m below the DAΦNE upper window. The points are directly facing the DAΦNE window at relatively short distance (15 meters). Spectrum expected to be composed by low energy scattered neutrons.

Point B is placed along the DAΦNE circumference in a similar geometry as point A but closer to the building. It is inside the synchrotron light building, at around 5 m height from ground and around 8 m from the DAΦNE upper window. Spectrum expected to be composed by low energy scattered neutrons plus a transmitted components.

Point C is inside DAΦNE, in contact with the upper window. Here the neutron spectrum is expected to cover the whole energy range included in the source term, from thermal up to 10^2 MeV.





Since the neutron fluence rate from the accelerator shows a time variation, depending on a complex set of machine parameters, all BSS readings have been normalized to an independent monitor instrument.

A rem counter ALNOR mod. 2002B has been used as monitor instrument. Its reading (in counts) will be also called “monitor units”, MU. Since each Bonner Sphere has been jointly exposed with the monitor instrument, the neutron fluence normalized to the monitor units (expressed in $cm^{-2}\cdot MU^{-1}$) in the measurement points has been precisely derived (uncertainties are in the order of ±3%).

Complementary dosimetry measurements have been performed using a rem counter Berthold LB6411 and its lead loaded version, the LB6411-Pb.

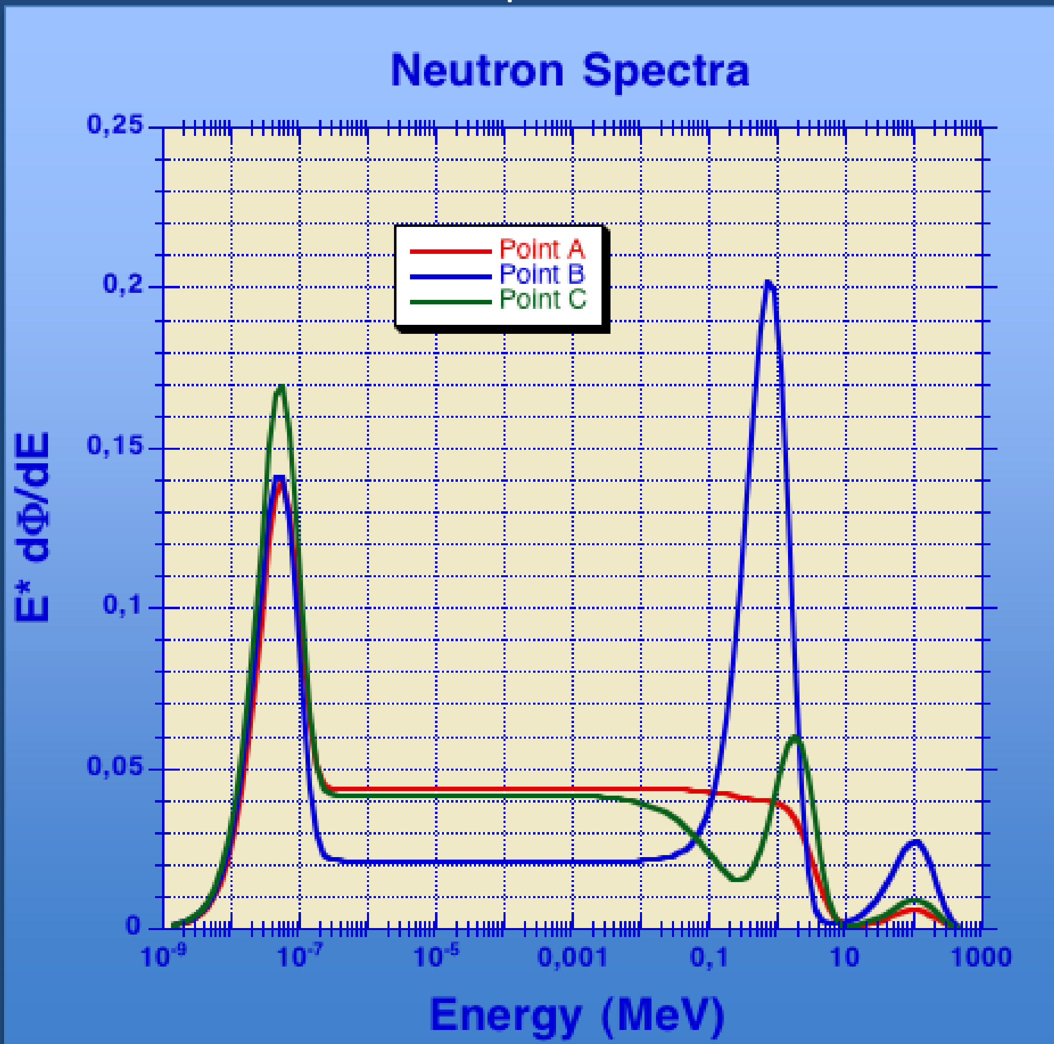
Quantity	Point A	Point B	Point C
h^*_φ (pSv.cm^2)	58	63	155
Fluence below 0.4 eV	31%	37%	29%
Fluence above 10 MeV	1%	1.6%	5%
H(10)* above 10 MeV	6%	8.6%	11%
Φ (cm^{-2}.MU^{-1})	17.0±0.6	12.4 ± 0.4	27.8 ± 1.0
$H^*(10)$ (μSv.MU^{-1})	$(9.5\pm0.3)\cdot10^{-4}$	$(7.8\pm0.2)\cdot10^{-4}$	$(4.31\pm0.15)\cdot10^{-3}$
LB6411 (μSv.MU^{-1})	$(8.2\pm0.4)\cdot10^{-4}$	$(7.1\pm0.4)\cdot10^{-4}$	$(3.3\pm0.2)\cdot10^{-3}$
LB6411-Pb (μSv.MU^{-1})	$(8.5\pm0.4)\cdot10^{-4}$	$(7.5\pm0.4)\cdot10^{-4}$	$(3.9\pm0.2)\cdot10^{-3}$
AUTOMESS μSv.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
$H^*(10)$ (μSv.h^{-1})	0.37±0.06	0.20 ± 0.05	36 ± 7

Each sphere was exposed for half a day in the same location during DAΦNE operation (e- and e+ injection accumulation phase and loss of the beams stored)

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

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

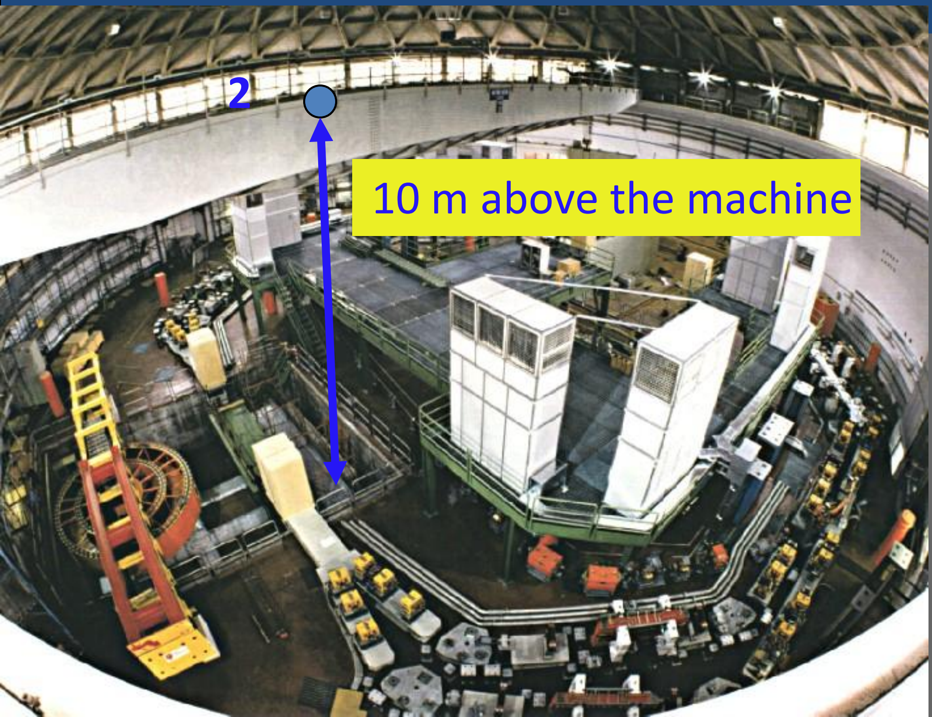


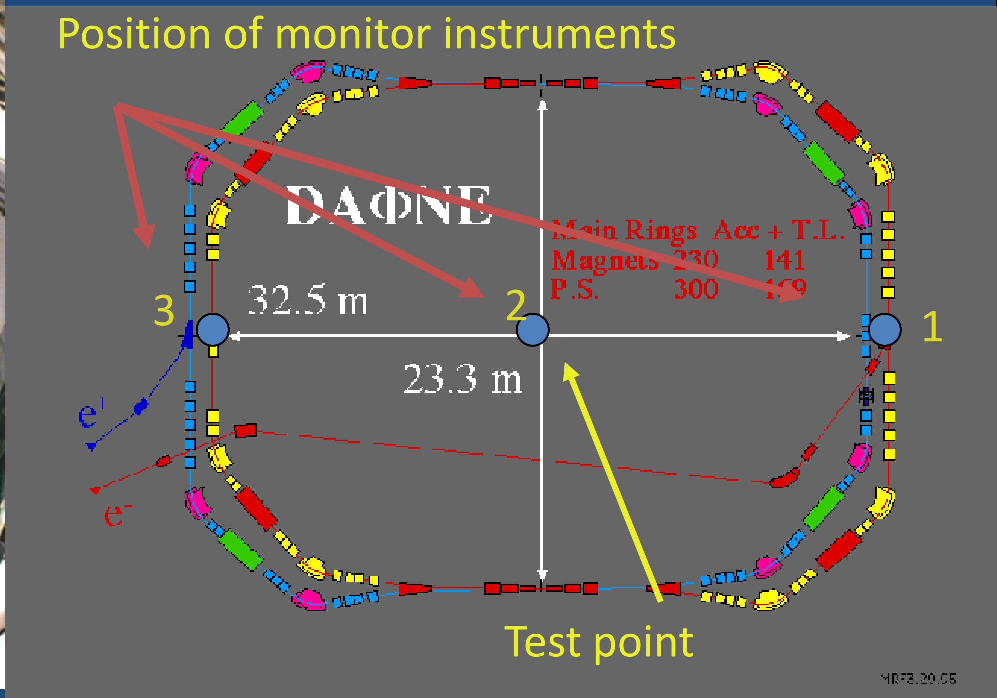
The so called "workplace specific calibration factor" of the LB6411 in point
A is 1.16
B is 1.10
C is 1.31

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.

The spheres have been sequentially exposed in the test point.

Since the neutron leakage from the accelerator varied with time, a neutron survey meter (Berthold LB6411) was exposed, together with the spectrometer, as a normalization instrument.

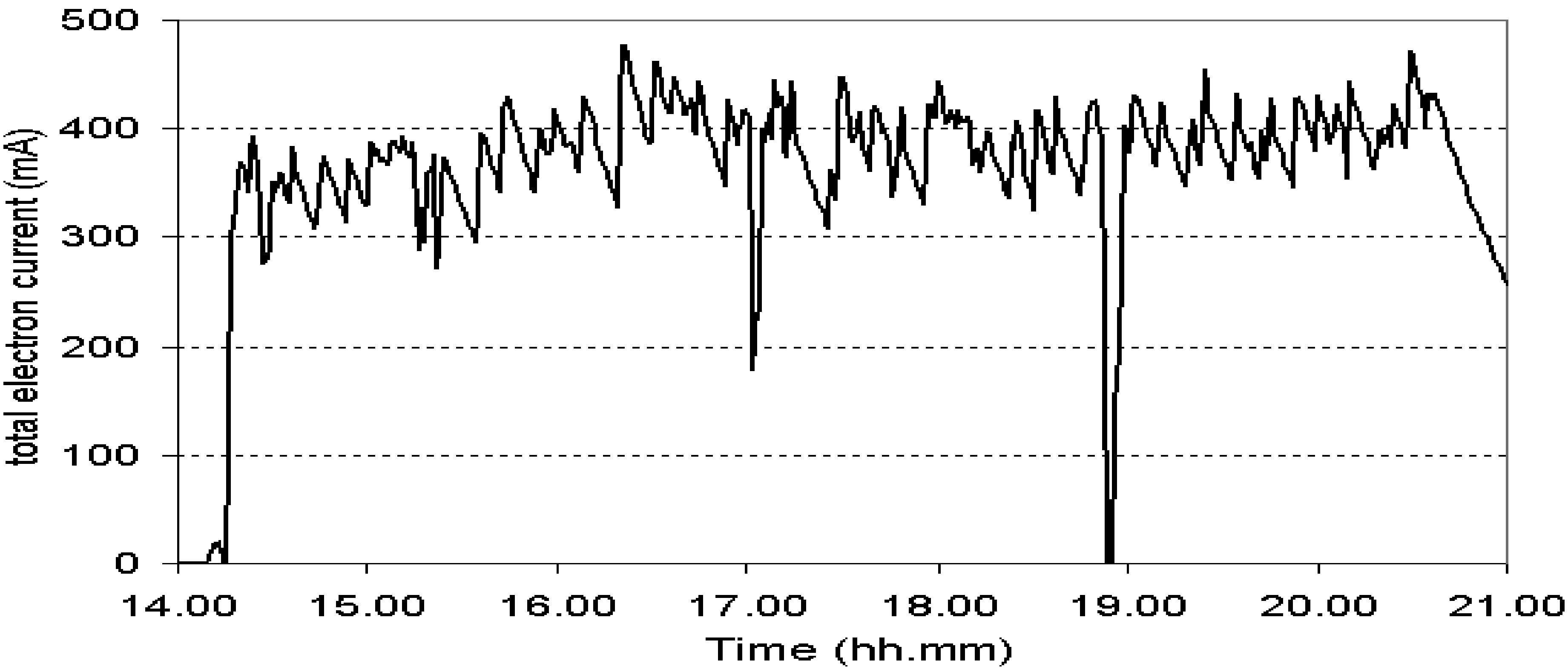




Measurements with only positrons operation have been made. The data are under elaboration

The time dependence of the electron current in the DAΦNE ring during the measurement session is shown in figure.

The rising fronts correspond to injection processes, whilst the falling fronts express the natural current decay (mean life ~ 20 min) due to bremmstrahlung, gas-bremmstrahlung and synchrotron light emission. Each sphere was exposed for about 20 min (3 injections).



The radiation leakage from DAΦNE depends in a complex way from the injection parameter, the stored current, its temporal variability and a series of non predictable events such as the beam losses.

To obtain meaningful data with sequentially exposed Bonner spheres, the energy and direction distribution of the neutron fluence should not vary in between the various exposures.

The reproducibility of the fluence energy distribution, obtained by a repeated exposures of a pair of devices with different energy dependence showed a variability of ±3% (1 s.d.)

The reproducibility of the fluence direction distribution obtained by repeated exposures of the three neutron survey meters placed in three different positions (points 1, 2 and 3) showed the ratio n_1/n_2 and n_3/n_2 nearly constant during the whole measurement session. The variability was σ_Ω= ±3% for n_1/n_2 and ±2% for n_3/n_2

Being the irradiation conditions reproducible, the neutron spectrum was determined using, as input data for the unfolding procedure, the sphere counts divided by reading of the normalization instrument installed in position 2.

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

$\phi(E)= P_{th}\prod_{th}(E) + P_e\prod_e(E) + P_f\prod_f(E) + P_{hi}\prod_{hi}(E)$ where

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

$\prod_e(E)$ the epithermal one,

$\prod_f(E)$ the fast one

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

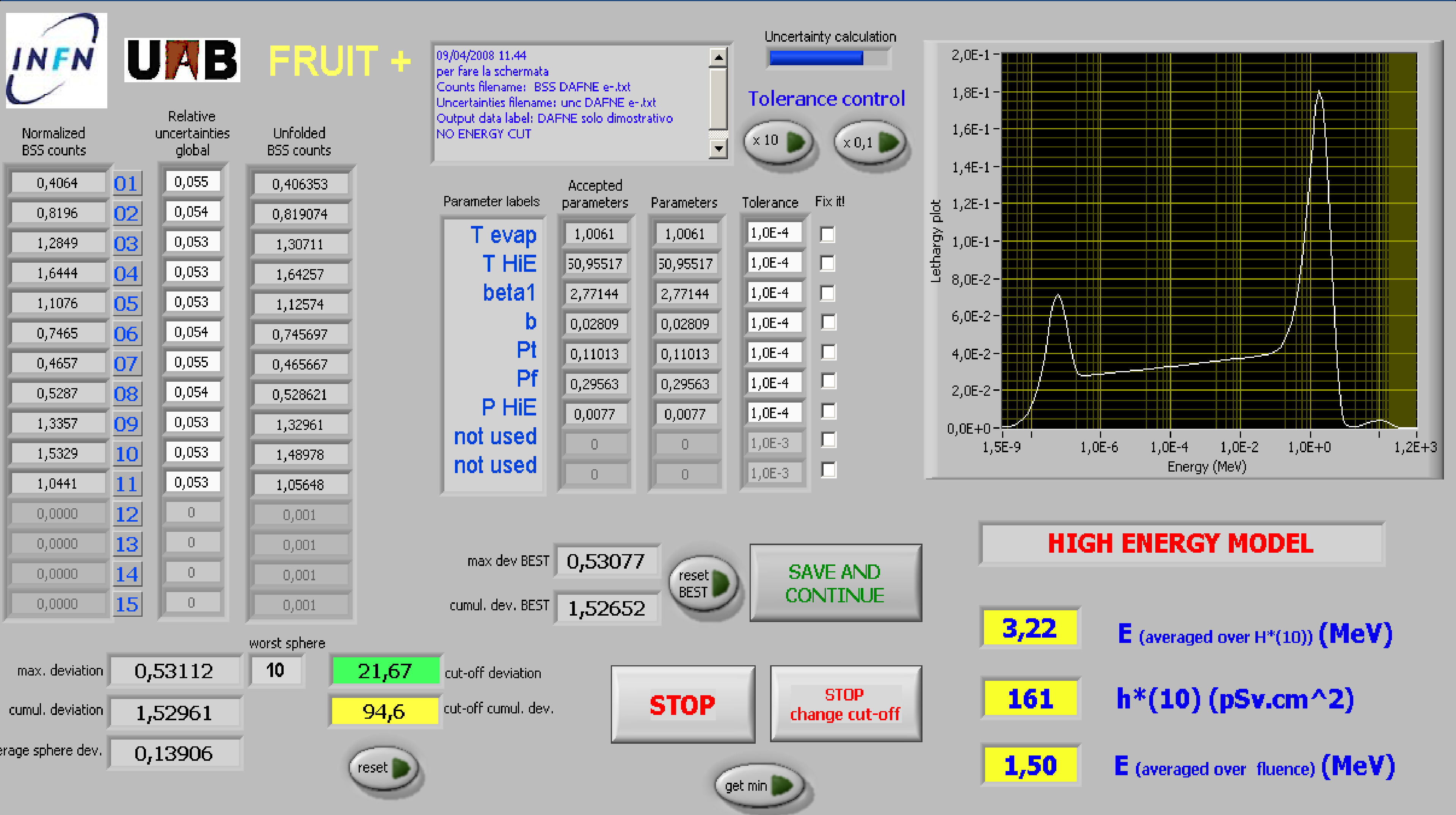
Each component is individually normalized to the unit fluence by mean of an adequate normalization factor.

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.

Results

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

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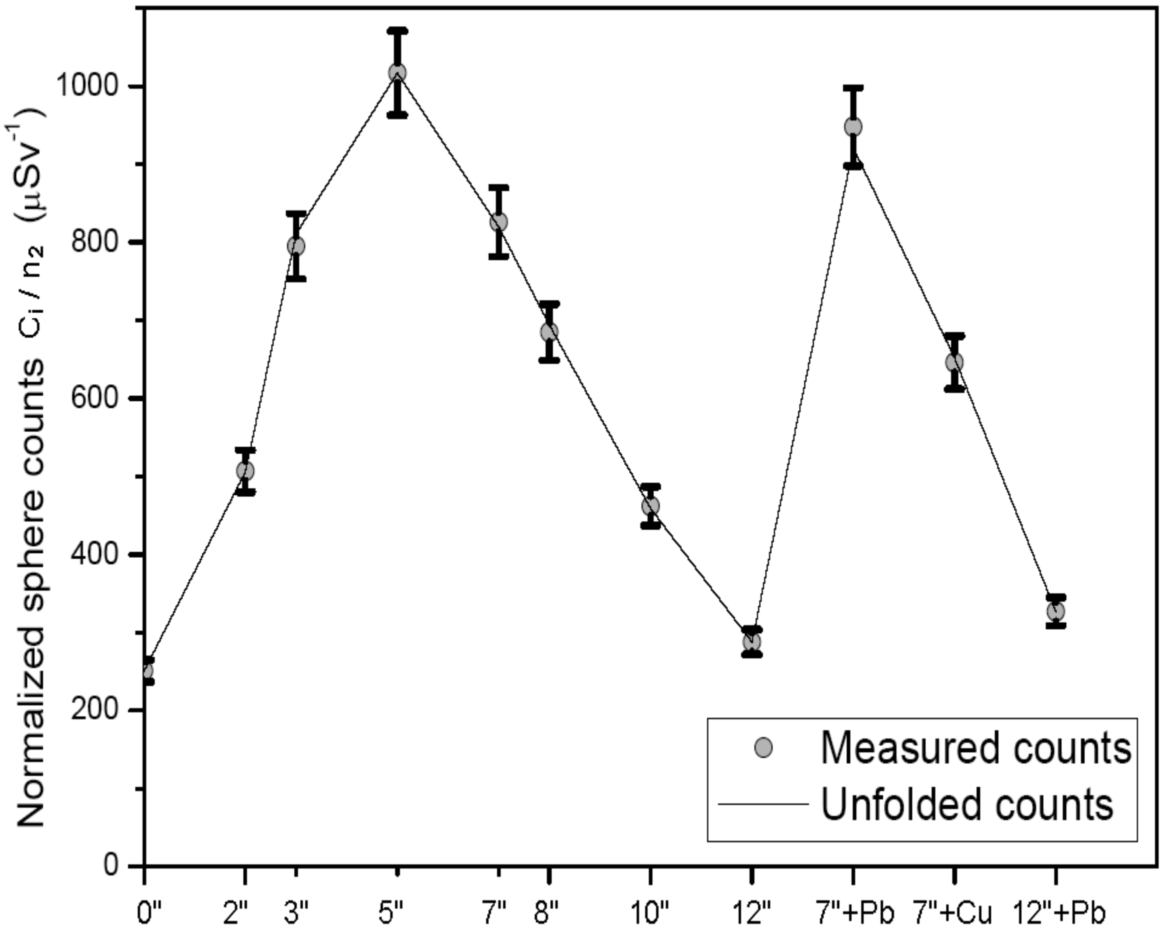


The "unfolded counts" are calculated by applying the response function of each sphere to the spectrum unfolded with FRUIT.

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

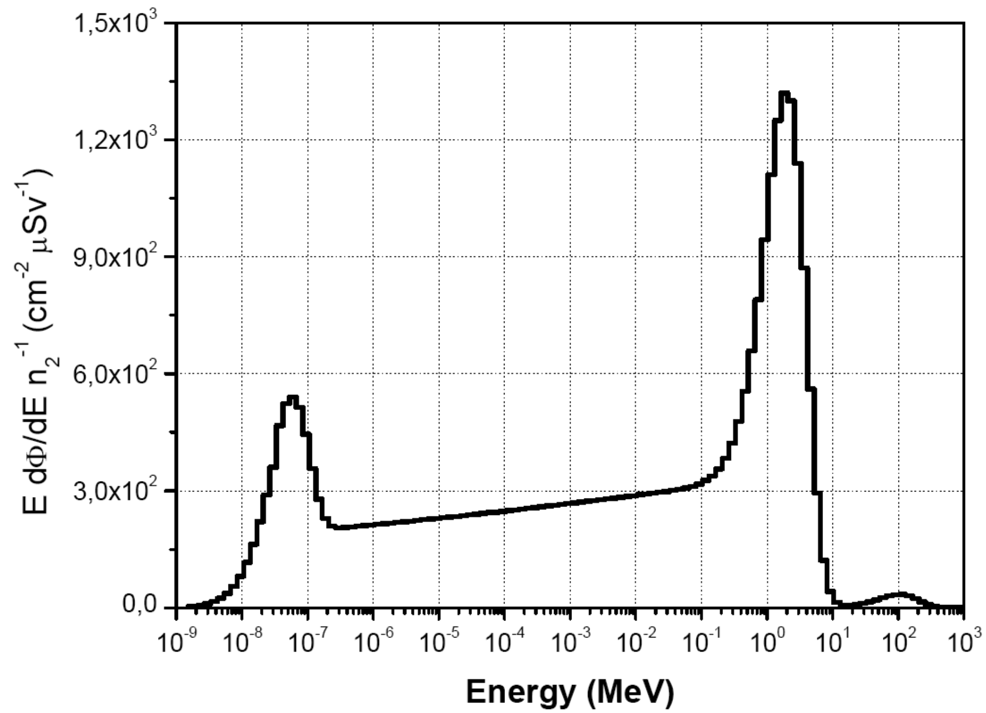
The figure show the consistency between the unfolded spectrum and the set of sphere counts.

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

The spectrum presents a huge evaporation peak at 2 MeV

The peak at 100 MeV is only 0.8% in terms of fluence

The high-energy neutrons only contribute to 1.6% in terms of H*(10).



Quantity	
Neutron fluence, Φ/n_2 (cm^{-2} μSv^{-1})	$(7.54\pm0.19)10^3$
$<d\Phi/dt>$ ($cm^{-2}s^{-1}$)	109±32
$H^*(10)/n_2$	1.20±0.06
$<dH^*(10)/dt>$ ($\mu Sv\ h^{-1}$)	62±19
Spectrum averaged conversion coefficient, h*(10) (pSv cm^2)	159±18
$\Phi_{E<0.4\ eV}/\Phi$	16.4%
$\Phi_{0.4\ eV<E<0.1\ MeV}/\Phi$	42.2%
$\Phi_{0.1\ MeV<E<20\ MeV}/\Phi$	40.6%
$\Phi_{E>20\ MeV}/\Phi$	0.8%
$H^*(10)_{E<0.4\ eV}/H^*(10)$	1.2%
$H^*(10)_{0.4\ eV<E<0.1\ MeV}/H^*(10)$	4.1%
$H^*(10)_{0.1\ MeV<E<20\ MeV}/H^*(10)$	93.1%
$H^*(10)_{E>20\ MeV}/H^*(10)$	1.6%

It is worth noting that, in spite of the large temporal variability of the current in DAΦNE and the related leakage radiation, the adoption of a suitable normalization technique allowed measuring the quantities Φ/n_2 and $H^*(10)/n_2$ with reduced uncertainties (±2.5% and ±5%, respectively).

Conclusion

The photo-neutron spectrum around the DAΦNE collider was measured in different location within a dedicated runs using a new LNF-ERBSS.

The experimental data were unfolded with FRUIT, a recently ad hoc developed unfolding code equipped with specific facilities for the operational radiation protection needs.

The measured spectra show a prominent evaporation peak and a limited high-energy fraction.

This campaign allowed deriving important data for use in radiation protection, such as "workplace specific" calibration factors to be applied to routine neutron survey-meters.

The very reduced amount of high-energy neutrons allow us to conclude that non-extended range routine instruments could be used, if properly calibrated.

An autonomous neutron survey-meter, without a specific workplace calibration, would underestimate of about 20%

Thank you for your attention