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EXECUTIVE SUMMARY OF THE THESIS

The light W-PIE neutron spectrometer for soil moisture measurements: design, characterization and preliminary measurements

LAUREA MAGISTRALE IN NUCLEAR ENGINEERING - INGEGNERIA NUCLEARE

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Abstract

Nowadays, the efficient quantification of soil water resources is a crucial task to be addressed for many different fields such as hydrology, agriculture and climate science. The Cosmic-rays neutron sensing technique (CRNS) is a promising technology which can investigate soil moisture on an intermediate scale (i.e, an area of some hectares and a depth of tens of centimeters), thanks to the relation of the intensity of cosmic neutrons above ground and the amount of water content in the soil. The advantages and the potentiality of employing a neutron spectrometer over the traditionally used neutron counters in CRNS are many. Over the last year, an innovative neutron spectrometer for the CRNS technique was developed at Politecnico di Milano, called WEDDING-PIE (Wide Energy Detector for Direct Investigation of Neutron spectrum at Ground level for Precise moIsture Evaluation), abbreviated as W-PIE. The W-PIE has a 2 cm-thick layer of lead in the section detecting neutrons above 20 MeV (high energy section) which makes the system very heavy and therefore quite difficult to manage during its transport and installation. In this thesis work, a new lighter version of the W-PIE has been developed by designing a new coating structure which should lighten the overall structure while maintaining the spectrometric capabilities of the original heavier design. After the manufacturing, the W-PIE was characterized by several irradiations carried out in Laboratory activities in Politecnico di Milano and finally installed in a large park to acquire data for preliminary soil moisture measurements.

1. Introduction

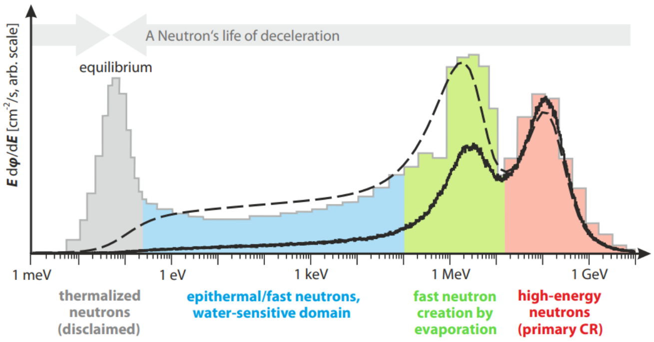


Figure 1: Cosmic neutron energy spectrum, from [4]

1.1. Cosmic ray neutron sensing for soil moisture measurements

The knowledge of soil water content at intermediate scale, over an area of hectares and depth of tens of centimeters, is crucial for a large variety of applications in the fields of hydrology, agriculture and climate science. Nowadays, soil moisture measurements mainly rely in small-scale point measurements and very large-scale satellite remote sensing. The method of Cosmic-Ray Neutron Sensing (CNRS) is a promising tool for determining the environmental water content filling the gap left by the other technologies. The CNRS technique assesses the water content in a field by measuring the cosmic neutron flux at one point. Neutron background radiation is generated in the atmosphere by an incoming flux of cosmic rays made of charged particles interacting with air elements. The neutron density above ground can serve as an efficient probe for the quantity of water in the soil, being the neutron flux extremely sensitive to the moderation caused by hydrogen. The

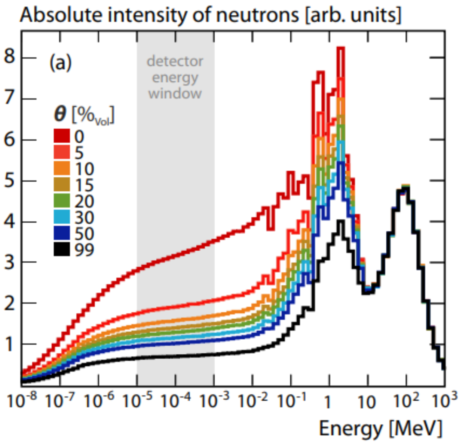


Figure 2: The effect of water content in soil (θ) on the cosmic neutron energy spectrum, from [4]. Dry soils show greater fluxes especially in the epithermal-to-fast energies

continuous monitoring of neutron background radiation can provide a non invasive soil moisture measurement which is well representative of the average moisture in the volume of interest. The neutron energy distribution at ground level is the one of Fig. 1: High energy neutrons (red peak) are generated in the upper layers of the atmosphere and are directed towards the surface. They can interact with the atmosphere and soil generating Fast neutrons which are emitted isotropically at energies peaked around 1 MeV (green peak), in the process of evaporation. The scattering process between neutrons and the surrounding nuclei induces fast neutrons to be slowed down and to lose their energy. Slowed down neutrons with energy in the range 0.5 eV and 0.5 MeV are called Epithermal neutrons (blue region). Finally, neutrons are slowed down till they reach the thermal equilibrium with the surroundings. These neutrons are called Thermal neutrons and have an energy of around 10 meV (grey peak). Fig. 2 shows the effect of soil moisture on the cosmic neutrons spectrum. It can be observed that High energy neutrons are basically unaffected by soil moisture. However, the high energy flux values may vary according to oscillations of solar activity, which have a time period of around 11 years, and barometric pressure changes, which affect the amount of atmospheric shielding. Fast and epithermal neutrons are instead strongly affected by soil moisture, in particular, their flux is lowered with increasing soil moisture. This part of the spectrum is therefore the one used for assessing soil moisture with the CRNS technique. Thermal neutrons, which are not showed in the picture, actually are only slightly affected by soil moisture. Moreover, the thermal spectrum is highly dependent on soil chemical composition. For these reasons, thermal neutrons are usually neglected in CRNS. On the other hand, it can be assumed that the evident changes in the epithermal neutron flux intensity are only due to the hydrogen atoms in water, while being independent of the soil chemical composition. Regarding the fast neutrons, they may be generated both in the atmosphere and in the soil. Neutrons generated in the atmosphere which are detected before having interacted with the soil are not useful for probing the soil moisture content. In light of these considerations, CRNS focuses mainly on epithermal neutrons, and the thermal and fast components of the spectrum actually represent contamination for the soil moisture measurements.

1.2. Improving CRNS with neutron spectrometry method

The instrument employed for neutron flux measurements in CRNS are usually counters covered with moderator coatings for enhancing their sensitivity in the epithermal region. In general, neutron counters are optimized for measuring thermal neutrons which are not of interest for soil moisture assessment. Proper moderators made by layers of polyethylene 2-3 cm thick increase the counter response in the epithermal range, as shown in Fig 3. However, the response to thermal and fast neutrons is not null. Hence, the neutron counters selectivity with respect to the energy range of interest is limited. The most used proportional counters are gas-filled detectors which use ^{3}He and ^{10}B, both allowing to reach high sensitivity to neutrons. However, ^{3}He is very expensive due to its worldwide shortage, while large-scaled Boron-lined proportional counters require large surface areas and therefore have a less compact design. During the last two years, a ^{3}He-free cosmic neutron spectrometer able to reconstruct the whole cosmic spectrum such as the one in Fig. 1 was developed at Politecnico di Milano. While counters can provide only numerical information on the flux of cosmic neutrons in the epithermal energy range, a spectrometer allows a clear separation of the four energy regions. The introduction of neutron spectrometry in CRSN can represent a significant improvement. First of all, it makes it possible to extract an epithermal signal free from fast and thermal contamination. In addition, spectrometry allows to correct the neutron signal from its changes due to solar activity. In particular, the high energy peak of the spectrum, which is not affected by soil moisture yet affected by solar activity and air pressure, can be used to monitor this effect. In general, simultaneous measurements of the fluxes with different energies can be exploited to perform new further investigations on the soil water content. [1]. The new innovative neutron spectrometer designed for CRNS purposes is described in the following section.

1.3. Brief overview of neutron spectrometry

Most neutron spectrometers follow the working principles of the Bonner Sphere Spectrometer (BSS). BSS is based on a thermal neutron counter placed at the centre of polyethylene spheres of different diameters (up to 18”). From the readings of the different spheres, and from the knowledge of the spheres response functions, the neutron spectrum can be inferred by means of unfolding algorithms. The unfolding problem can be expressed by:

$$\mathbf{N} = \mathbf{R}\phi \tag{1}$$

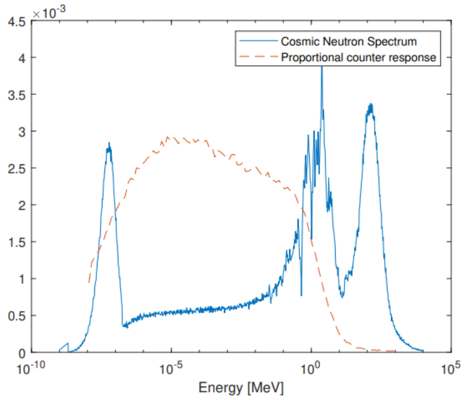


Figure 3: Response function of a proportional counter coated with polyethylene (dashed line), compared to the cosmic neutron spectrum (solid line) that the instrument is supposed to measre. Fig. from [1]

where $\mathbf{N}$ is the vector of the counts per second recorded in each region of the detector, $\mathbf{R}$ is the matrix containing the response functions for each region and $\boldsymbol{\phi}$ is the energy-binned neutron flux. $\mathbf{N}$ and $\mathbf{R}$ are known, but usually the problem is ill-posed since the number of energy bins, i.e. the dimension of $\boldsymbol{\phi}$ is much larger than the dimension of the vector of counts $\mathbf{N}$. The problem may be addressed in various ways. In this work, the GRAVEL algorithm [5] was adopted. It is an iterative procedure which is fed with an initial guess of the spectrum, $\boldsymbol{\phi_0}$, which iterates until the convergence criterion is reached, i.e. when a statistical variable χ^2 is reduced below a user defined-threshold.

The response functions, in general, are theoretically computed with Monte Carlo simulations and validated experimentally.

The BSS exploits the neutron moderation process within the polyethylene, slowing down neutrons through the reactions with the material which can eventually be detected by the thermal detector. A suitable set of polyethylene spheres of different diameters makes it possible to obtain spectral information over the desired neutron energy range. The spheres can be also equipped with internal metal shells to perform spectrometry of high energy neutrons, for the detection of which the radius of the necessary polyethylene sphere would be too big or even impossible to be manufactured. Materials such as lead are employed to exploit the spallation reactions, which lead to the generation of fast neutrons which can be moderated and then detected by the counter.

2. W-PIE cosmic neutron spectrometer

The WEDDING-PIE (Wide Energy Detector for Direct Investigation of Neutron spectrum at Ground level for Precise moIsture Evaluation) abbreviated as W-PIE, shown in Fig. 4 is composed of a central neutron counter coated with several layers of different materials designed to perform neutron spectrometry. The counter employed is the M800 thermal detector manufactured by ARKTIS, exploiting the neutron reaction of ^{6}Li and the scintillation mechanism of ^{4}He. The gas is sealed in an aluminium tube ⌀15×80 cm divided into eight sectors, which can be read independently by 24 SiPMs (one triplet per sector working in coincidence). The detector is divided into four regions each constituted by two adjacent sectors. Each region is covered with coatings properly designed to maximize its sensitivity to a certain energy range. The thermal-region is bare to detect thermal neutrons up to 1 eV. The epithermal-region is covered with a 2-cm layer of high density polyethylene (HPDE) to detect neutrons from 1 eV to 0.5 MeV. The fast-region is covered with a 7.2 cm of HPDE to detect neutrons from 0.5 MeV to 20 MeV. Finally, the high energy-region is characterized by several layers. From the inner to the outer part (Fig. 4): 4.8 cm of HPDE, 0.2 cm of Cadmium (Cd), 2 cm of Lead (Pb) and 5.9 cm of HPDE. The presence of the lead induces the fragmentation reaction which allows to detect high energy neutrons. The layer of cadmium reduces the sensitivity to thermal neutrons thanks to its absorption cross section. In previous studies [2] the characterization of the W-PIE was performed, showing reliable spectrometry capabilities and a sensitivity to cosmic neutrons of roughly 0.6 cps (summing all regions). However, the W-PIE design has an overall weight of about 100 kg, 90 of which are due to the high energy section where Pb is present. This feature makes the W-PIE quite heavy to be managed throughout its transport and installation. For this reason, the design described above was the starting point for the next optimization, taking into account the weight of the coating system, together with the important properties that the system response functions had to maintain in order to make the system suitable for the soil moisture estimation purpose.

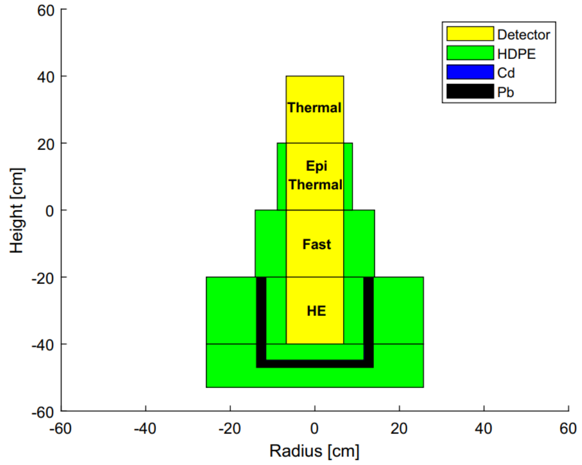


Figure 4: Schematic view of the W-PIE

3. Light W-PIE realization

The objectives to be addressed to optimize the W-PIE response functions (RF), taking into account the RF ideal properties and the weight, are multiples and somehow conflicting. Indeed, the thicknesses of the coatings, to be reduced with the aim to reduce the overall system weight, are the ones ensuring the best RF shape for the W-PIE design. The ideal response functions properties to perform spectrum unfolding are:

- at each energy at least two RFs must be non null
- the RFs shapes should be as different as possible from one another in the energy range of interest
- the RF values must be as high as possible to increase the count rate of the instrument
- all sections should reach good statistics at similar times. If the mean value of the RF of a section is very low compared to the other sections, this would result in a longer time necessary to reach good statistics.

The first and second requirements above should ease the unfolding procedure. The third and fourth ones are specifically needed for the W-PIE application in soil moisture monitoring, to measure rapid changes in soil moisture.

In this perspective, it was necessary to reach a trade-off between the desirable RF shape and the coatings weight. To embed together these multi-objectives, a figure of merit (f.o.m.) was defined as combination of the following factors: p_1 mean RF in the epithermal region, p_2 mean RF in the fast region, p_3 mean RF in the high energy region, p_4 mean difference between RD of the epithermal region and RF of the fast region, p_5 mean difference between RF of the fast region and RF of the high energy region. Finally, p_6 is the total weight. While factors p_i with i=1,. . . ,5 have to be as high as possible, on the contrary a low p_6, i.e. a low weight is desired. The above factors, and therefore the f.o.m., are functions of all the thicknesses of the layers, x_i. The f.o.m. was defined as:

$$f.o.m.(x_1, ..., x_6) = \sum_{i=1}^{5} p_i - p_6 \qquad (2)$$

With this definition, all the factors p_i have the same importance. The behaviour of the f.o.m. with respect to a chosen set of coatings thicknesses values was investigated by performing more than 1200 Monte Carlo simulations with MCNPX, each corresponding to a different combination of thicknesses. The thickness of the HPDE layer in the epithermal section was maintained fixed at 2 cm. HPDE layer of the fast section was varied from 4 cm to 7 cm with steps of 0.5 cm. The high energy section thicknesses of the four layers were varied in this way:

- internal HPDE thickness = {2, 2.5, 3, 3.5, 4}
- Cd thickness = {0.2}
- Pb thickness = {1, 1.33, 1.66, 2}
- external HPDE thickness = {3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7}

A Phyton script was implemented to perform the 1260 simulations via the MCNPX ver 5.1 code. Each simulation consisted of the generation of the input file describing the M800 geometry and compositions (fixed) and the geometry and composition of the coatings of varying thicknesses. A specific material-file was filled out exploiting the available cross-section libraries to accurately reproduce the detector sensitive volume, as well as the other structural and moderating materials.

Then, to evaluate the RF, a planar neutron source was modelled, generating an expanded and aligned neutron field with energies uniformly sampled from 110 discrete values in the range 0.1 eV - 1 GeV. The source emission direction is perpendicular to the instrument axis, therefore the evaluated response is the radial one. From the data of each output file it is possible to compute the response for each section and for each i-th bin, with i from 1 to 110:

$$RF_i = \frac{RR_i}{\phi_i} \qquad (3)$$

Then, the 1260 values of the f.o.m. were found, summing each of the p_i factors of equation(2) evaluated with the RFs values found by the Monte Carlo simulations. The f.o.m values were normalized and their behaviour was investigated in MATLAB. The coatings design was chosen accounting for:

- the coating performance with respect to the figure of merit value (as high as possible).
- the impact of the new thicknesses, with respect to the old coatings, on the response functions behaviour. This was done both by visual inspection and computing the expected counts detected by each section considering an impinging neutron flux predicted, in a quite approximate way, in Milan through the software EXPACS.
- the thicknesses manufacturing procedure of lead: the mechanical workshop could adopt a standard procedure to produce a layer of a thickness of 0.5 cm. To produce a layer 1.33 cm-thick, a more expensive procedure would be required;
- the overall height of the system had to fit in a proper case, planned for its transportation, which was already available on the market.

The first design chosen had the following thicknesses: 20 mm for the HPDE layer of the epithermal section, 50 mm for the HPDE layer of the fast section. For the high energy region, internal HPDE layer of 20 mm, Cd layer of 2 mm, Pb layer of 10 mm, and external HPDE layer of 63 mm were chosen. Then, the vertical thickness of the external HPDE layer of the high energy section (i.e. the thickness corresponding to the HPDE at the base of the instrument) was reduced by 3 cm with respect to its radial thickness, to comply with the height requirement previously explained. A first instrument outdoor testing for cosmic neutron measurement showed that the cosmic spectrum reconstruction was unsatisfactory. The reconstructed spectrum behaviour suggested that a non-radial contribution, i.e. a contribution not considered in the simulations performed to compute the response functions, was underestimated. To cope with this issue, a further HPDE layer of about 3 cm of thickness was commissioned to increase the thickness of the high energy section (i.e. the base of the instrument). The final light W-PIE design (L-WPIE) is shown in Fig. 5, where the addition of the base can be noted. Its response functions are plotted in Fig. 6. The thickness of the Pb layer was decreased to 1 cm with respect to the heavy version of the W-PIE, and the overall weight

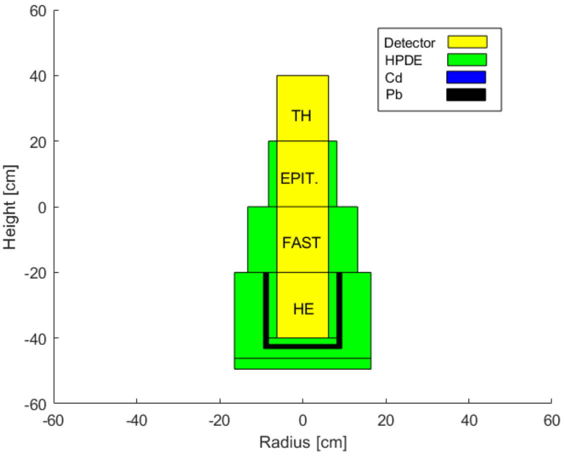


Figure 5: Schematic view of the light-WPIE

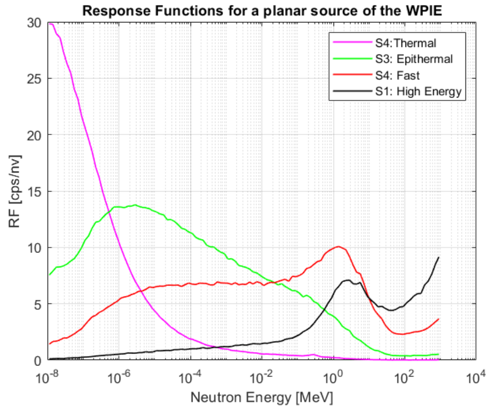


Figure 6: L-WPIE response functions for the four regions

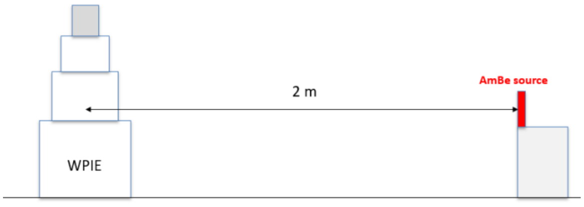
of the final design is about 50 kg.

4. Experimental measurements

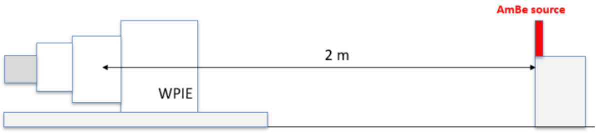
In the following sections the laboratory activities and the outdoor campaign are reported. W-PIE refers to the very first and heavy W-PIE desing. L-WPIE refers to the light optimized W-PIE coated with the final moderators, i.e. with the High Energy section having a total polyethilene base about 6 cm thick. Then, when referring to the L-WPIE version prior to the addition of the 3 polyethylene base, this aspect is specified.

4.1. Laboratory activities

The L-WPIE was characterized performing several measurements in a Laboratory room of the building of the Department of Energy of Politecnico di Milano. The original W-PIE (the heavy one of Fig. 4) and the L-WPIE without the addition of the 3 cm polyethilene base were also irradiated to compare the results. Measurements for the three instruments were performed in the two configurations which are depicted in Fig. 7 employing an AmBe neutron fast source. The three instruments were irradiated in each configuration for 10 minutes. The spectrum reconstruction was performed by means of the GRAVEL algorithm [5], fed by the response functions of each instrument (such as the ones in Fig. 6) and by two guess spectrum options: the first one has a peak centered at the AmBe neutron emission energy, while the second one has a distribution corresponding to the ^{252}Cf neutron emission energy. This allowed us to investigate the unfolding algorithm capability to approach the real spectrum emitted by the source, even with less information associated with the guess spectrum.



(a) Vertical configuration



(b) Horizontal configuration

Figure 7: AmBe irradiations experimental set-up

Considering the rather small dimensions of the rooms in which the measurement was taken, the radiation field detected is a sum of a direct component coming from the source plus a scattering component of lower energy. In this activity, no scattering correction strategies were adopted since the aim was to evaluate the spectrometer performance and there was no calibration purpose.

Results showed that the L-WPIE in vertical configuration performed a satisfactory spectrum reconstruction, especially using a realistic guess spectrum (Fig. 8). the presence of the real thermal component, result of the fast component moderation in the room, even if not suggested by the guess spectrum, is correctly detected. This result is particularly important, since soil moisture measurement by cosmic neutron is based on the moderating power of soil.

The unfolding reconstructions performed with the ^{252}Cf guess spectrum (Fig. 9) demonstrate the algorithm capability to shift the peak towards the real energy of the emitted source and, again, to identify the thermal component. No relevant difference could be detected between the L-WPIE and the W-PIE performance.

Comparing the values of the flux measured by the three instruments, the L-WPIE and the W-PIE showed optimal agreement, as can be seen from Table 1

AmBe detected fast flux $[cm^{-2}s^{-1}]$

ϕ_{L-WPIE}	ϕ_{W-PIE}	$\phi_{L-WPIE,w/o,base}$
0.1887±0.0174	0.1891±0.0063	0.2323±0.0095

Table 1: AmBe flux measured by the three instruments

The L-WPIE without the addition of the 3 cm- thick polyethylene fast flux measurement was instead af-

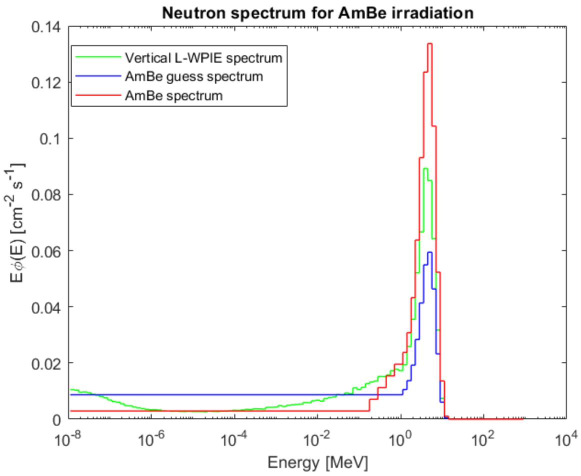


Figure 8: Reconstructed spectrum (green), guess spectrum of AmBe (blue). In red, the AmBe emission expressed in arbitrary units for better showing the energy range in which the source emission falls. The realistic guess spectrum allows a fine spectrum reconstruction

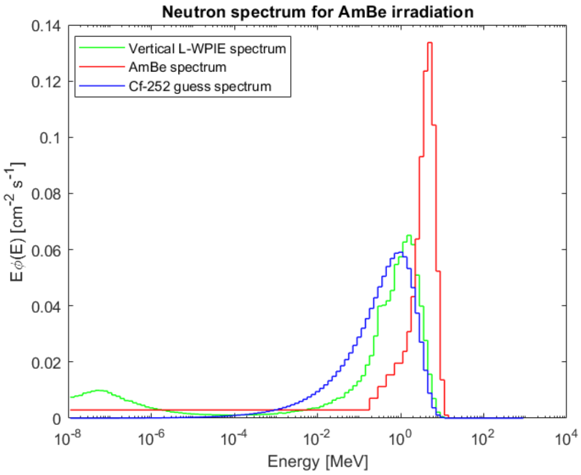


Figure 9: Reconstructed spectrum (green), guess spectrum of Cf-252 (blue), AmBe emission (red). The reconstructed spectrum is shifted towards the realistic emission energy

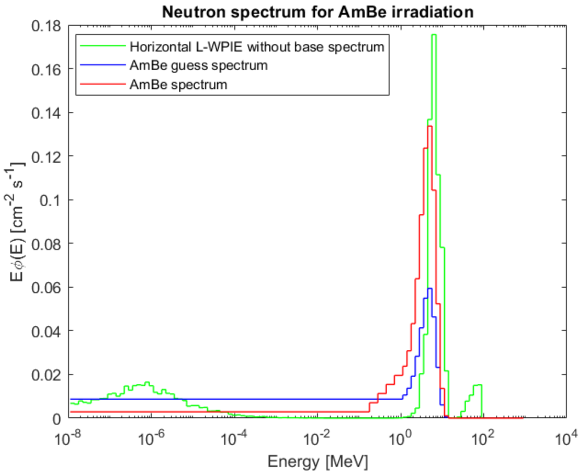


Figure 10: Reconstructed spectrum (green), guess spectrum (blue), AmBe emission (red). A non-physical peak can be observed at high energies due to the too low vertical thickness of the external HPDE layer of the high energy section

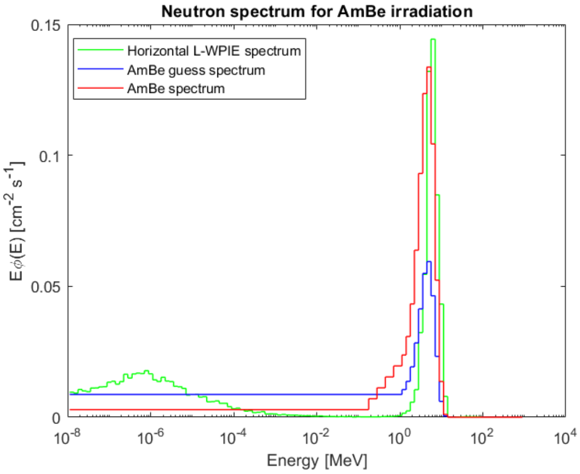


Figure 11: Reconstructed spectrum (green), guess spectrum (blue), AmBe emission (red). The non-physical peak at high energy of Fig. disappear with the addition of the 3 cm thick HPDE base

fected by the lower thickness of the base and the fast flux was overestimated. This may be due to the contribution of neutrons scattered by the floor and detected by the high energy section, due to the smaller thickness of the HPDE external layer on the base. The simulations for the response functions calculation did not include this contribution because they assumed the detector was irradiated in the void.

Irradiations performed in the horizontal configuration were done to investigate how much the inevitable anisotropy of the system (which is cylindrical in its general shape) affected the measurement for the three instruments. The response functions adopted to unfold the spectrum were the radial ones because the instrument was designed to be irradiated laterally. Results showed that:

- the counts, with respect to the vertical configuration, decreased in all sections for the three instruments, as expected, due to the geometry of the set-up, which acted as a shield for the source.
- for the three cases the principal emission of the AmBe fast source was correctly identified in the fast energy range from 1 MeV to 20 MeV.
- a small non-physical peak was reconstructed at about 100 MeV by the heavy W-PIE and the L-WPIE without the base (Fig. 10). The L-WPIE spectrum did not show the non physical peak (Fig. 11). This behaviour was expected since the RF used in the unfolding are the radial ones, and the L-WPIE with the base high energy response in the horizontal configuration is more similar to the simulated one.

4.2. Outdoor experimental campaign

The L-WPIE neutron spectrometer was tested with respect to the soil moisture measurement purpose by detection of neutron cosmic rays. Cosmic neutron flux can be used to investigate soil moisture on a scale of areas of hectares and depths of tens of centimeters. Therefore, measurements were carried out in an open field in the northern part of Milano,

Figure 12: L-WPIE installation in the Parco Nord site in Milano

Italia, allowing to test the L-WPIE in a properly large area. The L-WPIE was connected to a field computer by an Ethernet cable. It was controlled by a Python script allowing to set the measurement duration and number. For each measurement, a file containing the counts and the cps acquired in each section, named with the date and time of the acquisition start up, is created by the script. After each count measurement, the unfolding algorithm is performed providing the neutron spectrum in the output. The flux values in the four energy regions (thermal, epithermal, fast and high energy) are then calculated from the spectrum and saved in a file. The spectrometer system was integrated with a weather station and with two point scale soil moisture probes FDR (Frequency Domain Reflectometry), allowing to have remotely exportable information on precipitation levels, temperature, other environmental parameters and soil moisture. The system (Fig. 12) is powered by a solar panel. Flux measurements and environmental parameters were acquired from 15/02/2023 to 30/03/2023.

The values of the measured epithermal flux were normalized to the high energy flux. This was done to correct the epithermal flux value, affected by water content in the field, from the variations induced by the solar activity and atmospheric pressure changes. The high energy flux was adopted for this correction since it is not affected by soil moisture, as can be seen in Fig. 2.

Data of the normalized epithermal flux averaged over one and three days were first investigated with respect to the precipitation trend. Results were compared to the W-PIE campaign carried out from July to October 2022 which can be found in [1]. In the heavy W-PIE campaign, precipitations were of about 25 mm/day on dry soil and the instrument resulted more sensible to soil moisture variations. It has to be said that the L-WPIE campaign instead was characterised by minimal precipitations (up to 9 mm/day) on an already moist ground. The first days flux measurements showed oscillations (the first points of Fig. 13) which could not be attributed to the occurrence of precipitations. In the subsequent days, the flux actually showed a decrease when precipitations were revealed. This flux decrease is quite comparable to the decrease due to the statistical fluctuations of the first days. This means that probably the instrument is not able to discern the soil moisture changes from the background fluctuations in case of poor precipitations dynamic. The soil moisture estimation was done via the universal calibration function developed by Franz et al. [3]:

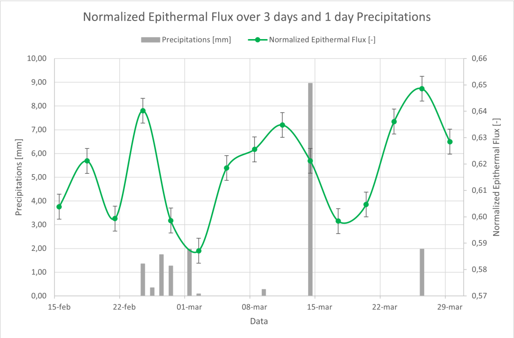


Figure 13: L-WPIE measured flux averaged over three days plotted together with daily precipitations

$$\theta - \theta_{off} = \frac{a_0}{\phi/\phi_0 - a_1} - a_2 \tag{4}$$

where θ is the soil moisture, ϕ the normalized epithermal flux, ϕ_0 the calibration parameter, θ_{off} the offset contribution to neutron moderation (stationary source). Finally, a_0, a_1 and a_2 are physical parameters found in [1] for the W-PIE spectrometer performing Monte Carlo simulations with the code URANOS. The calibration parameter ϕ_0 is the measured flux corresponding to a known value of θ. In this case, it was found inverting the universal equation and substituting the θ parameter with the mean soil moisture measured by the two SM probes. θ_{off} was estimated as a fitting parameter. Indeed, its evaluation is not trivial and would require a detailed analysis of the soil and vegetation around the detector. In this case, it was evaluated fitting the obtained data. In particular, training days from 25/02 to 09/03 were selected to minimize the statistical variable χ^2 computed with respect to the soil moisture measured by the FDR probes ($\theta_{SMprobes,i}$) and the soil moisture estimated through the L-WPIE flux and the universal calibration function formula ($\theta_{L-WPIE,i}$):

$$\chi^2 = \sum_i \frac{(\theta_{L-WPIE,i} - \theta_{SMprobes,i})}{\theta_{L-WPIE,i}} \tag{5}$$

where i refers to the training days. Soil moisture results are affected by the considerations previously made for the detected epithermal flux. In addition, the soil moisture probes were installed very near the ground surface. This means that the flux measurement and the soil probe measurement are representative of soil moisture at different penetration depths. Water at the surface evaporates much faster than the water in depth: this effect, together with the water

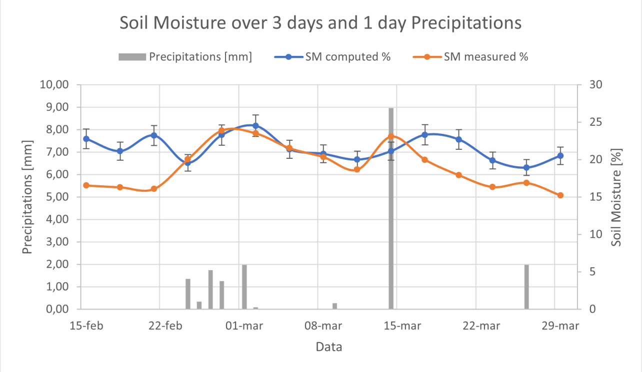


Figure 14: Comparison between the calculated soil moisture values (blue line) and the average of the point measurements (orange line)

permeation in the soil could explain the discrepancy between the soil moisture probes and the estimation of L-WPIE.

5. Conclusions

In this work, a new light version of the W-PIE cosmic neutron spectrometer was designed and tested. The W-PIE heavy design was the starting point of the new optimization implemented to reduce the thicknesses of the various coatings with the aim to lighten the overall system. A multi-objective figure of merit was defined, taking into account the desired ideal properties of the spectrometer set of response functions, and including the low-weight objective. The final design reduced a lot the weight of the system, in particular, thanks to the reduction of the thickness of the layer of lead, which was reduced from 2 to 1 cm.

The light W-PIE was irradiated by an AmBe fast source in Laboratory activities showing satisfactory spectrometric capabilities in view of its role as a soil moisture probe. The fast emission of the source was recognized even if the unfolding guess spectrum was not the AmBe one (the ^{252}Cf one). When the algorithm was provided with a more realistic distribution (the AmBe fast peak), a finer reconstruction of the spectrum was obtained.

Preliminary soil moisture measurements carried out in an outdoor campaign showed that the instrument is not reasonably able to discern the soil moisture changes from the background fluctuations in case of poor precipitation dynamics. In the future, further investigations are necessary to compare the W-PIE and the L-WPIE acquiring real cosmic flux data simultaneously in the same location, and therefore the same soil conditions. These future measurements are planned to be taken in a field close to Ferrara which will be better characterized from the point of view of the traditional soil moisture measurement: both CRNS and traditional point-scale technologies will be used to compare the various methods.

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