NEURAPID
NEutron RAPId Diagnostics

2014 Activity Report

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INFN-Milano / Politecnico di Milano

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See website https://sites.google.com/site/csn5neurapid/ for more details
1. **Project introduction**

NEURAPID has the objective of developing instruments to measure neutron spectra in “emerging” fields, i.e. those fields where the neutron detection is made especially difficult due to the following aspects

- **Very low fluence fields**: fields with very low fluence rate such as the neutron component of the cosmic rays at ground level. Cosmic ray field at ground level is characterized by:
  - a continuous spectrum ranging from thermal up to GeV neutrons (12 orders of magnitude in energy)
  - a very low fluence rate, in the order of $10^{-2} \text{ cm}^{-2} \text{ s}^{-1}$ (integrated on the whole energy interval).
This constraint opens serious problems of detector efficiency, especially when a complete spectrum measurement is expected to be performed in minutes. This is the case of the GLE (Ground Level Enhancement) detection. Real-time detection of GLE with ground-based instruments has substantial impact on aircrew radiation protection and prevention of failures in electronic equipments of aircrafts.

- **SPF (Single Pulse Fields)**: fields with “extreme” pulsed structure, such a single pulses with femtosecond duration. Examples are the neutron fields produced by bombarding suitable gaseous or solid targets with ultra-intense (TW-PW) / ultrashort (fs) lasers
  SPF environments present:
  - more than 10 order of magnitudes in neutron energy.
  - An expected spectrum-integrated fluence per pulse in the order of $10^2$-$10^5 \text{ cm}^{-2}/\text{shot}$. In this case a major measurement problem is the very shot pulse duration (fs), likely to cause serious pile-up problems in any combination of active detector + analog electronics.

**Major scientific challenges of NERAPID are:**

**Challenge 1.**
Measuring a neutron spectrum over more than ten order of magnitudes in energy (from thermal up to GeV).
This problem is in common to cosmic ray and SPF environments, and a validated solution consists in the spectrometer geometries CYSP and SP² developed and tested already in the NESCOFI@BTF project (2011-2013).

**Challenge 2.**
Measure thermal neutrons with the highest possible efficiency. This is needed to
- speed up measurements in very low intensity fields
- collect the maximum possible amount of information about a “single pulse” of neutrons. With respect to the one-cm$^2$ thermal neutron detectors established within NESCOFI, a major technology challenge is to increase the thermal neutron efficiency, of more than a factor of ten.

**Challenge 3.**

Developing efficient thermal neutron counting system for pulses of $10^2$-$10^5$ cm$^2$/shot, which would cause serious pile-up problems in any combination of active detector + analog electronics. After thermalization in the polyethylene, an ultra-short pulse of neutrons will be spread over tens of microseconds (dye-away time). However, even if the detector pulses are shaped to fractions of microsecond, there is still a serious risk of pile-up for the stated values of fluence per pulse. Two counting alternatives are foreseen:

**FAST ELECTRONICS**

Acquisition with large-area semiconductors covered with $^6$Li compounds, connected to a fast electronics: the NEURAPID group has experience in designing multi-detector analog boards for nuclear spectroscopy, including for every detector (one channel) a bias regulator, a charge pre-amplifier chosen according to the electric characteristics of the detector, and Gaussian-shaper amplifier. Dedicated multi-detector boards will be developed using short shaping times (100 ns or lower), and the analog signal will be digitally filtered and sampled with high-speed digitizers (50 MS/s or more).

**BETA RADIATORS**

Using conventional electronics (shaping time in the order of 1-2 microseconds and low-speed digitizers, such as 2 MS/s) coupled with new types of thermal neutrons detectors INTRINSICALLY able to dilute in time the pulsed information. To achieve this objective, large-area semiconductors will be covered with beta-emitting radiators with large thermal neutron capture cross-section. The betas from the radiator, emitted with decay times in the order of seconds (or more), will be efficiently detected from the large area detector without causing no pile-up. In and Dy radiators will be tested (See Table 1)

<table>
<thead>
<tr>
<th>Parent</th>
<th>Abundance</th>
<th>Daughter</th>
<th>Capture Xs (barn)</th>
<th>$T_{1/2}$</th>
<th>Max. beta energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{115}$In</td>
<td>95.7%</td>
<td>$^{116}$In</td>
<td>202</td>
<td>14 s</td>
<td>3.3</td>
</tr>
<tr>
<td>$^{164}$Dy</td>
<td>28.2%</td>
<td>$^{165}$Dy</td>
<td>2640</td>
<td>78 s</td>
<td>0.9 - 1.0</td>
</tr>
</tbody>
</table>

In both FAST ELECTRONICS and BETA RADIATORS approaches, large area silicon diodes will be used.

A thermal neutron field with uniform flux profile over a large area (as large as several tens of cm$^2$) is needed for testing and calibration purposes.

Being the efficiency of the large area thermal neutron detector a key-issue, this should be measured
as accurately as possible. Therefore this thermal neutron field should have metrological quality.

With this philosophy, the development of a large-area and highly uniform thermal neutron fields was included among project’s activities: ETHERNES (Extended THERmal Neutron Source)

2. Prototypes to be developed

a. Large area thermal neutron detectors (LATND)
b. Extended Thermal neutron source (ETHERNES)
c. CYSP-C (Cosmic) (*)
d. CYSP-P (Pulse) (*)
e. SPEEDY

(*) CYSP means a cylindrical moderating structure embedding up to ten thermal neutron detectors and showing spectrometric capability along a specific direction, identified by a collimator. A CYSP prototype equipped with one-cm$^2$ Silicon diodes covered with $^6$LiF was successfully tested during NESCOFI.

For cosmic rays application:
CYSP-C will be able to accumulate sufficient information to compute a whole neutron spectrum (eV-to-GeV) in approx. one hour of acquisition at flux in the order of 0.01 cm$^{-2}$ s$^{-1}$.

For single-pulse neutron fields (such as lasers):
CYSP-P will perform neutron spectrometry in specific direction of interest
SPEEDY will perform area monitor measurements with isotropic response. It will be a spherical device and will contain thermal neutron detectors symmetrically arranged along the three axes.

CYSP-C, CYSP-P and SPEEDY will take advantage of moderating geometries developed in NESCOFI. However, for the three of them new thermal neutron detectors with large area (LATND) need to be developed in the framework of NEURAPID.

3. 2014 Activities

The 2014 activities were focused on achieving two milestones, namely:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishing the ETHERNES facility</td>
<td>31-10-2014</td>
</tr>
<tr>
<td>Calculation of the response matrix of CYSP-C and CYSP-P</td>
<td>31-12-2014</td>
</tr>
</tbody>
</table>

In addition, studies on LATND were undertaken.
3.1 **ETHERNES design**

**Notes:**
- The executive design of ETHERNES is not published here because under evaluation for patent/s (in collaboration with Technology Transfer Office of INFN-LNF)
- For more details about ETHERNES, see presentations BEDO NEURAPID RB 8-7-14.pdf and BEDOGNI NEURAPID RB 4-12-14x.pdf at 8 July 2014 and 4 December 2014 NEURAPID meetings, available on project website.

Table 2. List of existing (or recently decommissioned) source-based thermal facilities with open space field in Europe

<table>
<thead>
<tr>
<th>Facility and Institution</th>
<th>Moderator</th>
<th>Useful flux ((\text{cm}^2 \text{s}^{-1}))</th>
<th>Am-Be ((\text{Ci}))</th>
<th>Field Uniformity and size ((\text{cm}))</th>
<th>Thermal Performance ratio ((\text{cm}^2 \text{s}^{-1} \text{Ci}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIGMA (CEA) France 8 m³ graphite</td>
<td>1500</td>
<td>≈ 100</td>
<td>10% in 30x30</td>
<td>88%</td>
<td>15</td>
</tr>
<tr>
<td>PTB Germany 4 m³ graphite</td>
<td>80</td>
<td>27</td>
<td>10% in 20x20</td>
<td>99%</td>
<td>3</td>
</tr>
<tr>
<td>ENEA Italy 1 m³ HDPE</td>
<td>500</td>
<td>15</td>
<td>5% in 10x10</td>
<td>60%</td>
<td>33</td>
</tr>
</tbody>
</table>

Thermal neutron fields in the range of \(10^2\text{-}10^3\) of \(\text{cm}^2 \text{s}^{-1}\) are easily achieved in small cavities (few cm) within moderating assemblies embedding radionuclide neutron sources. This is normally suited for irradiating small samples like activation foils and TLDs. Small cavities are not suited to test complex detecting systems, including multiple-sensors, large 2D screens, cables and phantoms. For these purposes, thermal fields in **open large spaces** are preferred, with the following characteristics:
- uniform field over large sizes (tens of cm in side)
- Gamma background as low as possible
- Low fast neutron contribution

Thermal fields in open large spaces have been achieved in the past by allocating large neutron sources (typ. several tens of Ci of Am-Be) in the geometrical centre of big moderating blocks (several m³ of graphite or polyethylene).

The leakage field was used for testing and calibration purposes. To achieve a satisfactory level of thermalisation, the field must be highly attenuated, thus requiring very big sources (tens of Ci of Am-Be) to get thermal fluence rates in the orde of tens of hundreds of \(\text{cm}^2 \text{s}^{-1}\).

Due to the increased difficulties in getting large neutron sources (cost 10-20 k€/Ci (!!), commercial availability, authorizations), the development of new thermal facilities should include new design concepts,
able to maximize the ratio between useful thermal flux and Am-Be activity (performance ratio).

Targets for ETHERNES designs were:
- Achieve flux in the range of $10^2$-$10^3$ cm$^{-2}$s$^{-1}$ (design goal about 600)
- Availability of a single 2.6 Ci source of Am-Be
- 30 cm x30 cm homogeneity area in open-space

Available material: one cubic meter of polyethylene in sheets 1 m x 1 m x 10 cm

The idea was to produce thermal neutrons by multiple scattering rather than transmission in a moderating block, thus the polyethylene sheets were used to build a large cavity rather than a “traditional” moderating block. ETHERNES was designed after an extensive calculation campaign with MCNP. See Figs 1 and 2.

Figure 1. Lateral view of ETHERNES.

Figure 2. ETHERNES irradiation cavity (45 x 45 x h=63 cm$^3$), from top.

In Fig. 3 the neutron spectrum, at height 15 cm from the cavity bottom, is shown. The thermal fraction is in 74%.
According to the simulations, the thermal flux linearly decreases with height in the irradiation cavity, with gradient -2% cm\(^{-1}\).

The field uniformity improves as the height from the cavity bottom increases, see Fig. 4. At 5 cm from cavity bottom the thermal flux variation over 30 cm x 30 cm is ±2.5%, whilst at 15 cm (reference height) is ±0.25% only.
The gamma component at the reference height (15 cm from cavity bottom) is lower than 3 uSv/h (MCNP simulation) and the expected spectrum is that of Fig. 5.

Fig. 5. Gamma spectrum at the reference height (15 cm from cavity bottom). The field is dominated by the 2.2 MeV component, coming from the thermal neutron capture in Hydrogen.

To conclude, the following design goals were achieved:
- Very high performance ratio, about 230 cm$^{-2}$ s$^{-1}$ Ci$^{-1}$ (more than a factor of seven higher than “leakage”-based facilities, see Table 2).
- Very large homogeneity area (±0.25% flux variation over 30 cm x 30 cm at ref. height)
- Reduced gamma background
- High thermal fraction (74%)

3.2 ETHERNES experimental validation

The homogeneity area at ref. height was experimentally verified using a one-cm$^2$ Si-diode covered with 30 µm of $^6$LiF, finding satisfactory agreement with the simulation, See Figg. 6 and 7.

Fig. 6. Verifying the thermal field homogeneity area at ref. height, along the apothem of the irradiation
Fig. 7. Verifying the thermal field homogeneity area at ref. height, along the diagonal of the irradiation plane.

**Thermal neutron images from the ETHERNES cavity were acquired** to map the field uniformity across the whole irradiation plane at 15 cm height. This was done using Gafchromic self-developing films (XRQA2 type) coupled with a 1 mm thick Cd radiator, according to the scheme of Fig. 8.

Figure 8. Measurement sandwich developed for measurements in ETHERNES. The radio-chromic film is back-irradiated by the Cd radiator. The measurement sandwich was preliminarily tests at the ENEA-Triga (Casaccia) ex-core thermal channel, obtaining the images shown in Fig. 9 with different values of thermal fluence.

Fig. 9. Radiochromic films exposed in the ENEA TRIGA ex-core thermal channel.
The related calibration curve is shown in Figure 10.

![Calibration Curve](image)

**Figure 10.** Thermal fluence vs. grey level calibration curve for radio-chromic films.

After a two months exposure in ETHERNES at the reference height (15 from cavity bottom), the grey profiles and false color images of Figg. 11 and 12 were obtained.

![Grey Profile](image)

**Figure 11.** Grey profile of the ETHERNES irradiation plane at reference height. Variability in the plateau region is 0.3% only, fully in agreement with the 0.25% figure obtained from the simulations.
The thermal neutron fluence rate at the centre of the irradiation plane was measured with the gold-foils technique (with and without Cd cover), using very thin foils (0.01 mm x 15 mm diam) counted in a HPGe detector.

According to the formalism developed in NPL Report DQL RN008 (2005), a sub-Cd flux of $589\pm12 \text{ cm}^{-2} \text{s}^{-1}$ was achieved.

A comparison with NPL (Teddington, UK) to inter-compare this value is under conclusion.

In addition, a complete spectrum measurement was performed at the reference point using a Bonner spheres spectrometer operated by the Universitat Autonome de Barcelona. The BSS data were unfolded using the FRUIT code [1,2]. According to the adopted unfolding model, slightly different results can be obtained, but the overall agreement with simulations is always highly satisfactory, see Fig. 13.
Fig. 13. Neutron spectrum at the ref. point of ETHERNES (centre of the plane located at reference height 15 cm), simulated with MCNP and measured with Bonner spheres. Data were unfolded using either a physical parameterized model (parametric) or a pure numerical convergence algorithm (SGM, special gradient method). Although slightly different results can be obtained from different unfolding approaches, the agreement with the simulated spectrum is highly satisfactory.

3.3 Determining the response matrix of CYSP-C and CYSP-P

The design of the cylindrical spectrometer CYSP was adapted to allocate large area thermal neutron detectors LATNDs. On the basis of the current status of the studies to define the final structure of the LATND, we assumed a 3 cm x 3 cm silicon-based sensitive area covered with a prompt (6LiF) or delayed (beta emitting activation foils) radiator, corresponding to the largest format for commercially available windowless p-i-n diodes. The final objective is to arrange two 3x3 Silicon detectors in a sandwich structure, with the radiator in the middle. See Section 3.4 for characterization of these configurations.

To date, there are no reasons to differentiate the structure of the CYSP-C from that of CYSP-P, because in both cases one or two 3x3 Silicon detectors will be used to register the particles from a radiator. Whilst the CYSP-C will certainly adopt a prompt \(^6\)LiF radiator, the CYSP-P will possibly adopt an In or Dy delayed radiator. Because both radiators approximately show 1/E cross-section dependence, a single response matrix is enough for design evaluation purposes. When the final detector for the cosmic or pulsed version of CYSP will be reached, the response matrix will be specialized for those configurations and this will be
experimentally verified using a real prototype. At this stage the important question to solve is the amount of perturbation (self absorption) generated by large detecting structures in the detector cavities.

Fig. 14. CYSP general design.

CYSP is a HDPE cylinder with overall diameter 50 cm and total length 65 cm. The dimensions of the cylinder as well as the location of detectors have been chosen to maximize the “spectrometric capability” of the device, i.e. the degree of differentiation between the response functions associated to different detector positions. The collimator (label 1) is 30 cm in length and its collimating hole (label 2), 16 cm in diameter, is covered by 5 mm of borated plastic SWX-238 (label 3, www.shieldwerx.com). The seven thermal neutron detectors, located along the cylindrical axis, are contained in a HDPE capsule (20 cm in diameter, 30 cm in length). An external shield made of 5 mm of SWX-238 (label 3) plus 15 cm of HDPE (label 6) protects the sensitive capsule from lateral contributions over a broad energy range. A one cm thick, 20 cm in diameter, lead disk (label 4), has been inserted between 6th and 7th positions to increase the response to high-energy neutrons. The distance between two adjacent detector cavities is 2 cm (centre to centre). The seven detectors are located at depths 4, 6, 8, 10, 12, 14 and 21 cm from the end of the collimator. The latter is located under the one-cm lead filter. Label 5 symbolizes eight cylindrical air cavities, one cm in diameter, designed to enhance neutron streaming towards the deeper detectors.

The HDPE capsule was dimensioned to allocate LATNDs made of a single or double 3 cm x 3 cm silicon diode coupled with a thermal neutron radiator.

An extensive simulation campaign was performed to derive the response matrix of the CYSP with large area detectors and to compare it with the low-sensitivity version, equipped with one-cm² diodes. See Figures 15 and 16. As expected, the 9 cm² to 1 cm² response ratio slightly depends on detector position and on neutron energy.
In general, a roughly constant ratio of seven can be considered, in the hypothesis that only one silicon diode is used per position. If two $9\,\text{cm}^2$ diodes are coupled to the same radiator, this ratio is expected to reach fourteen.

Figure 15. Response matrix of the CYSP-C / -P with $9\,\text{cm}^2$ silicon diodes compared with the one-$\text{cm}^2$ diode based response matrix of the CYSP.

Figure 16. Ratio between the response matrix of the CYSP-C / -P with $9\,\text{cm}^2$ silicon diodes and the one-$\text{cm}^2$ diode based response matrix of the CYSP.
3.4 State of art of large area thermal neutron detectors, LATND

From the initial single one-cm$^2$ diodes covered with 6LiF, as adopted in previous project NESCOFI, an evolution towards larger area diodes was undertaken as follows:

1. Single 1 cm$^2$ (1 cm x 1 cm) diode covered with 6LiF
2. Single 3.24 cm$^2$ (nearly 1.8 cm x 1.8 cm) diode covered with 6LiF
3. Single 7.84 cm$^2$ (nearly 2.8 cm x 2.8 cm) diode covered with 6LiF
4. Double 7.84 cm$^2$ (nearly 2.8 cm x 2.8 cm) diode covered with 6LiF, total sensitive area 15.6 cm$^2$

The deposited layer is always around 30 microns, corresponding to the maximum detection efficiency \([3,4]\). As low as possible bias voltage was chosen to achieve a good photon-to-neutron discrimination capability but, at the same time, to preserve the maximum efficiency. Signal processing was performed using specially manufactured boards, including for every detector a bias regulator, a charge pre-amplifier and a Gaussian-shaper amplifier (2 µs time constant). The data were acquired on a PC through a commercial 2 MS/s digitizer.

The spectra acquired in the four cases, positioning the detector at the reference position in ETHERNES (centre of irradiation plane at reference height 15 cm from cavity bottom), are reported in Fig. 17.

As expected, the count rate associated with the thermal neutrons (Region of Interest above 0.6 V) linearly increases with the sensitive area, see Fig. 18.
Fig. 18. Response of the four detecting configurations, covered with 6LiF, as a function of the sensitive area

3.5 Preparing cosmic measurements

To start understanding the problems connected with long-term acquisitions, as will be the case of cosmic neutron measurements with CYSP-C, a test was performed with the current CYSP (equipped with 1 cm$^3$ LiF covered single diodes) exposed at the SVIRCO cosmic-ray measurement station of Roma 3 University, see Fig. 19.

Fig. 19. The CYSP exposed to the vertical component of the cosmic-ray-induced neutron field at SVIRCO, Roma 3.
The acquisition took place from December 2014 to February 2015, data under elaboration.
The following interventions were developed to ensure reliable long-terms acquisitions:
- very stable DC supply for electronics,
- additional energy generators,
- remote control of equipments, vis TeamViewer.

Using CYSP-C, equipped with LATNDs (total sensitive area per position 15.6 cm$^2$) the time needed for a complete spectrum acquisition will be considerably reduced.

### 3.6 Collaborations

- CIEMAT Madrid: 35,000 equiv-hours CPU time on EULER cluster for response matrix calculations
- Roma3 University, support for CYSP cosmic measurement test.
- Politecnico di Milano: support for electronics design and testing
- Azienda Ospedaliera San Camillo-Forlanini (Roma) and Ospedale Santa Maria delle Croci (Ravenna): usage of 15 MV electron LINACs for testing Silicon detectors under very intense high-Energy gamma field.
- LNF support: 2 man*month at mechanical workshop, experiments performed at FISMEL laboratories.
- UAB Barcellona: donating the HDPE for building ETHERNES, spectrum measurement in ETHERNES with Bonner spheres.

### 3.7 Project meetings

(See website for downloading presentations)
- NESCOFI@BTF closure & NEURAPID start up meetings, INFN-LNF, 26 February 2014
- NEURAPID 2014 Midyear meeting, INFN-LNF, 8-7-14
- NEURAPID 2014 end of year meeting, INFN-LNF, 4-12-2014

### 3.8 International Review Panel

The panel produced a mid-year report during the 8th July meeting, see enclosed text.

Prof. Carles Domingo, Profesor Titular Universitat Autonoma de Barcelona, carles.domingo@uab.cat
Dr. D.J. Thomas, Head of Neutron Metrology Group of NPL (UK)
Reviewer's report on NEURAPID review meeting
8th July 2014

We were impressed with the activities of the NEURAPID group. It was good to see a group of people working in a planned and coordinated way on a topic area (neutron detection) where little work is presently being undertaken. It was also good to see that the group were being innovative and not following the route which many labs are going down of simply copying work which has been done in the past, e.g. the development of Bonner spheres based on the designs developed in the 1980s and 1990s by PTB, GSF, NPL and others.

The presentations by the various speakers were logically laid out and outlined the goals and achievements of the project in a clear and understandable way. The project appears to be on track in terms of achieving its objectives with the milestones fulfilled in advance in many cases.

The introduction by Bedogni presented the aims in the areas of pulsed field measurement and very low intensity field measurements, and fully justified these as areas of importance.

Bartol then described the quality control issues for the TNDS detectors which are a very useful addition to the range of detectors available for detecting thermal neutrons with options for different areas and hence sensitivities.

The ETHERNES facility, presented by Bedogni, makes use of multiple scatter approach to thermal neutron production rather than the more conventional approach of moderation and appears to produce excellent results. Further measurements are planned to validate the extensive simulation calculations with MCNP.

The ETHERNES imaging system, described by Sacco, presented a novel technique for using a proton sensitive Gafchromic to detect thermal neutrons by using a cadmium sheet to produce gamma rays. Despite its very low sensitivity it should provide a very useful visual measure of the uniformity of the field within the ETHERNES facility.

Gonzales Roa described calculations of the response expected for the CYSIP detector with new larger area detectors. They raised some interesting questions and further work is planned. Fabrication of the larger area detectors to being approach cautiously as the large silicon diodes are expensive.

The activities of NEURAPID-Milan were outlined by Pola. This group have been concentrating on the electronics aspects of the project and have produced novel electronic devices which will probably have applications outside the project.

The reviewers felt that the goals of the project were fully justified and that progress on the project was well on track which was to be applauded for such a complex multidisciplinary venture.

Fracati, 8-7-2014

D. J. Thomas

C. Domingo

3.9 Website

https://sites.google.com/site/csn5neurapid/

3.10 2014 Publications

Nucl. Instr. and Meth. 746 (2014) 59-63
Nucl. Instr. and Meth. 763 (2014) 547-552
NEURAPID activity was also presented Workshop on accelerator based neutron production (14-15 April 2014, INFN-LNL)

4. Bibliography


