A BONNER SPHERE SPECTROMETER FOR PULSED FIELDS

E. Aza^{1,2}, N. Dinar¹, G. P. Manessi^{1,3} and M. Silari^{1,*}

¹CERN, Geneva 23 CH-1211, Switzerland

²Department of Physics, Aristotle University of Thessaloniki, Thessaloniki GR-54124, Greece

³Department of Physics, University of Liverpool, Liverpool L69 7ZE, UK

*Corresponding author: marco.silari@cern.ch

Received 13 January 2015; revised 23 February 2015; accepted 27 February 2015

The use of conventional Bonner Sphere Spectrometers (BSS) in pulsed neutron fields (PNF) is limited by the fact that proportional counters, usually employed as the thermal neutron detectors, suffer from dead time losses and show severe underestimation of the neutron interaction rate, which leads to strong distortion of the calculated spectrum. In order to avoid these limitations, an innovative BSS, called BSS-LUPIN, has been developed for measuring in PNF. This paper describes the physical characteristics of the device and its working principle, together with the results of Monte Carlo simulations of its response matrix. The BSS-LUPIN has been tested in the stray neutron field at the CERN Proton Synchrotron, by comparing the spectra obtained with the new device, the conventional CERN BSS and via Monte Carlo simulations.

INTRODUCTION

The Bonner Sphere Spectrometer (BSS)⁽¹⁾ is one of the most employed instruments for neutron spectrometry in radiation protection. It shows a number of advantages compared with other methods like proton recoil telescopes⁽²⁾ and time-of-flight spectrometers⁽³⁾, such as wide energy range, isotropic response and simplicity. The technique consists in using a thermal neutron detector inserted at the centre of several moderating spheres of varying size. The neutron spectrum is derived by unfolding the counts obtained from the spheres, normalised to a reference quantity, with their response matrix. Obtaining accurate results from a BSS is related to a good estimation of the uncertainty of the experimental data and to the availability of a well-established response matrix, calculated on a consistent number of energy bins and verified in reference neutron fields. The disadvantages are the need of comparatively long exposure times due to the sequential irradiation of the spheres, and the limited energy resolution, especially in the epithermal region. Moreover, the solution spectrum is not uniquely determined, but depends on the unfolding code employed⁽⁴⁾. The CERN BSS^(5, 6) employs a spherical ³He proportional counter as thermal neutron detector and it comprises seven spheres: five made of polyethylene with outer diameters of 81, 108, 133, 178, 233 mm, complemented by other two, nicknamed ‘Ollio’ and ‘Stanlio’, where cadmium and lead inserts have been introduced in order to reduce the sensitivity to thermal neutrons and increase it at high energies, up to the GeV range.

THE UPGRADED SPECTROMETER

When measuring in pulsed neutron fields (PNF), proportional counters suffer from pulse pile-up and

space charge effects, leading to count losses, and show severe underestimations of the neutron interaction rate which result in strong limitations of their applications, especially around particle accelerators, where PNF are a common radiation environment. Count losses are typical of all systems working in pulse mode and can be compensated with correction algorithms only in case of steady-state sources of constant intensity, but not for PNF⁽⁷⁾. LUPIN is a neutron rem counter, using either a ³He or BF₃ proportional counter, conceived to overcome these limitations and work in PNF^(8, 9). Its front-end electronics is based on a current to voltage logarithmic amplifier, and the charge produced in the gas is calculated by integrating the current over a user settable time base. The total charge divided by the average charge expected by a single interaction represents the number of interactions occurring during the integration time. The CERN BSS has been upgraded in order to be employed in PNF by using the LUPIN electronics. Since this innovative working principle needs an electrostatic shielding in order to avoid noise pick up, the sphere geometry has been slightly modified to host an aluminium cylinder of 1 mm thickness surrounding the proportional counter and the connector. Figure 1 shows the geometry of the upgraded system, called BSS-LUPIN, for the 81-mm sphere.

MONTE CARLO SIMULATIONS

The response matrix of the BSS-LUPIN was calculated with the 2011.2b version of the FLUKA^(10, 11) Monte Carlo code, following the same methodology described in ref. (4). The response to neutrons of

Figure 1. 81 mm sphere of the BSS-LUPIN (please refer to the electronic file for the colour version).

Figure 2. The BSS-LUPIN response matrix (please refer to the electronic file for the colour version).

energy E_i is defined as

$$R(E_i) = \frac{N_{\text{atom}} \cdot \sum_{E_j=0 \text{ eV}}^{E_j=\infty} \Delta x(E_j) \cdot \sigma(E_j)}{\Phi} \quad (1)$$

where N_{atom} is the ^3He atomic density (in cm^{-3}), $\Delta x(E_j)$ is the track length of the neutrons in the counter (in cm), calculated by FLUKA for each energy E_j of the neutrons entering the active volume, $\sigma(E_j)$ (in cm^2) is the cross section of the reaction $^3\text{He}(n,p)^3\text{H}$, and Φ is the fluence of neutrons impinging on a square surface of $2r \cdot 2r$ area perpendicular to the sphere (cm^{-2}): $\Phi = 0.25 \cdot r^{-2}$, where r is the sphere radius. The response has been calculated for 280 energy bins, from 0.025 eV up to 2 GeV, see Figure 2.

The insertion of the aluminium tube introduces negligible changes in the response function as compared with the CERN BSS, due to the high neutron transmission probability of aluminium, which shows nevertheless some cross section resonances below 200 keV⁽¹²⁾. Only the response of the 81 mm sphere is slightly increased for energies of few eV. Indeed in this geometry neutrons traverse the biggest relative

Table 1. Results obtained in the measurements at the CERN PS.

Sphere	CERN BSS	BSS-LUPIN
81 mm	$2.39 \pm 0.13 \times 10^{-11}$	$2.20 \pm 0.12 \times 10^{-11}$
108 mm	$1.69 \pm 0.10 \times 10^{-11}$	$2.38 \pm 0.13 \times 10^{-11}$
133 mm	$1.25 \pm 0.07 \times 10^{-11}$	$2.79 \pm 0.15 \times 10^{-11}$
178 mm	$8.91 \pm 0.55 \times 10^{-12}$	$4.23 \pm 0.31 \times 10^{-11}$
233 mm	$5.00 \pm 0.32 \times 10^{-12}$	$9.39 \pm 0.54 \times 10^{-12}$
Stanlio	$5.61 \pm 0.35 \times 10^{-12}$	$7.49 \pm 0.45 \times 10^{-12}$
Ollio	$9.38 \pm 0.76 \times 10^{-13}$	$1.96 \pm 0.40 \times 10^{-12}$

fraction of aluminium thickness before reaching the counter.

MEASUREMENTS

To compare the performance of the BSS-LUPIN and the CERN BSS, a series of measurements were performed at the entrance of the access tunnel to the beam extraction area of the CERN Proton Synchrotron (PS). In this area the duration of the losses on the electrostatic septum during extraction is 2.1 μs , with a fraction of lost beam of about 1 %, thus reproducing an ideal stray pulsed radiation field. The measurement location was at the accelerator level, just before an interlocked door. The measurements were performed by exposing each sphere for about 30 min. For the CERN BSS the counts were corrected for dead time losses. The results, given in Table 1, are expressed in number of counts normalised to the PS proton fluence, derived from TIMBER, a Java interface that allows obtaining data of CERN accelerators in terms of setting, particle fluence and beam intensity⁽¹³⁾. The uncertainty includes the statistical one, always below 1 % except for Ollio, and the uncertainty on the PS proton fluence (5 %).

The spectrum was calculated by unfolding the data with three codes: MAXimum Entropy Deconvolution⁽¹⁴⁾ (MAXED), GRAVEL⁽¹⁵⁾ and FRascati Unfolding Interactive Tool⁽¹⁶⁾ (FRUIT 6). The first two codes, available in the PTB U.M.G. package⁽¹⁷⁾, require an *a priori* estimation of the true spectrum, called guess spectrum, typically derived via Monte Carlo simulations, which should be as accurate as possible. This was taken from ref. (18), where the neutron spectrum was obtained via FLUKA simulations for a location close to the measurement position. However, since the guess spectrum was normalised to the number of lost protons whereas the measured counts were normalised to the accelerated protons, a fraction of 1 % of lost beam was estimated in order to relate the two quantities. This assumption does not introduce significant uncertainties as for the guess spectrum the main information needed is the spectral shape. FRUIT relies on a parametric approach which requires the user to provide qualitative information on the radiation environment where the measurements have

Figure 3. Solution spectra obtained from the CERN BSS (guess spectrum shown for comparison) (please refer to the electronic file for the colour version).

Figure 5. Comparison of solution spectra obtained with MAXED from the CERN BSS and the BSS-LUPIN (please refer to the electronic file for the colour version).

Figure 4. Solution spectra obtained from the BSS-LUPIN (guess spectrum shown for comparison) (please refer to the electronic file for the colour version).

been performed. For these measurements the ‘high energy hadron accelerator’ environment was selected among the spectra available in the code libraries.

Figures 3 and 4 show the solution spectra for the CERN BSS and the BSS-LUPIN, respectively, expressed in fluence per unit of lethargy and normalised to the PS proton fluence. The uncertainties, not shown for clarity, were calculated for MAXED via the `IQU_FC33` program implemented in the `U.M.G.` package, which, given a solution spectrum, considers variations in the measured data and in the guess spectrum and uses standard methods to perform sensitivity analysis and uncertainty propagation. The relative uncertainties for GRAVEL were assumed to be equal to those of MAXED since the codes are based on similar algorithms. FRUIT performs the uncertainty propagation by randomly generating a large number of sets of BSS counts and by using the quadratic combination of the counting uncertainty and of the response function as the amplitude of the Gaussian perturbation.

The MAXED and GRAVEL spectra in Figure 3 are characterised by a large peak at thermal energies

and by smaller peaks in the MeV region, which is particularly jagged due to the high uncertainty of the guess spectrum, which depends on the poor statistics of the Monte Carlo simulations when the expected fluence is extremely low. The fluence integrated in the intermediate region, from 1 eV to few hundred keV, is negligible for all spectra. The intense thermal peak and the limited fluence above 1 eV are due to the fact that the stray field at the beginning of the PS tunnel, which is a 50 m long bent tunnel, is characterised by neutrons that underwent many scattering events along the concrete walls, substantially reducing their energy. Similarly, the probability of detecting high energy neutrons is very limited and thus the presence of fluence above 20 MeV is questionable. The solution spectra obtained with MAXED and GRAVEL strongly depend on the guess spectrum and the peaks at 20 and 100 MeV do not have physical meaning but derive from the guess spectrum shape. The latter was in fact calculated in a position at a few meter distance from the measurement position, where the gradient of the ambient dose equivalent, $H^*(10)$, rate is very high⁽¹⁸⁾. The uncertainties calculated for MAXED are 8 % for the thermal peak, 15–20 % for the intermediate region, 10 % around the 2 MeV peak and more than 50 % for energies higher than 5 MeV. On the other hand the FRUIT spectrum is characterised by a smoother shape, without the many resonances present in the MeV region, and it is limited to 5 MeV, being the superposition of elementary spectra described by a set of physically meaningful parameters⁽¹⁶⁾. The uncertainties given by FRUIT are 7 % for the thermal peak, 9 % in the intermediate region and 10 % around the 2 MeV peak. The fluence of the solution spectra is lower than the guess over the entire energy range, especially in the thermal region.

The spectra obtained from the same code have similar shape for both the CERN BSS and the BSS-LUPIN, whereas the absolute intensity, especially in the thermal and in the MeV region, is different. The uncertainties obtained for MAXED and FRUIT for

Table 2. Calculated $H^*(10)$, normalised to the PS proton fluence and expressed in Sv per proton.

System	MAXED	GRAVEL	FRUIT
CERN BSS	$6.3 \pm 1.0 \times 10^{-13}$	$6.0 \pm 0.9 \times 10^{-13}$	$6.1 \pm 0.3 \times 10^{-13}$
BSS-LUPIN	$3.8 \pm 6.4 \times 10^{-12}$	$4.7 \pm 7.8 \times 10^{-12}$	$4.2 \pm 3.5 \times 10^{-12}$

the BSS-LUPIN were slightly lower than for the CERN BSS, due to the higher measured fluence. The spectra have a thermal peak whose maximum reaches $8 \times 10^{-12} \text{ cm}^{-2}$ for the CERN BSS, consistently lower than that of the BSS-LUPIN, whose maximum is $2 \times 10^{-11} \text{ cm}^{-2}$. The intermediate region has an average value of $2 \times 10^{-13} \text{ cm}^{-2}$ for the CERN BSS and $6 \times 10^{-13} \text{ cm}^{-2}$ for the BSS-LUPIN. For the MeV region it is more difficult to define an average value, but the BSS-LUPIN spectrum shows an intensity approximately double than the CERN BSS. The same conclusion can be drawn from all codes: the fluence obtained from the CERN BSS is lower compared to the BSS-LUPIN. This confirms that the pulsed structure of the stray field leads to underestimation of the number of counts for a system using a proportional counter coupled with conventional NIM electronics. The underestimation is more significant for higher neutron interaction rates, i.e. for the spheres that show high sensitivity in the thermal or the MeV region. As a consequence the CERN BSS solution spectra underestimate the total fluence. This is better seen in Figure 5, which compares the spectra unfolded by MAXED: the fluence is substantially higher for the BSS-LUPIN in the entire energy range, except for the eV region.

The $H^*(10)$ values, normalised to the PS proton fluence, were calculated by folding the solution spectra with the ICRP fluence-to- $H^*(10)$ conversion coefficients⁽¹⁹⁾, see Table 2. The uncertainties on the $H^*(10)$ were obtained by folding the upper and the lower values of the energy bins of the final spectra with the corresponding ICRP coefficient, using the uncertainties obtained with MAXED and FRUIT. The same uncertainties were assumed for MAXED and GRAVEL, due to the similarities in the unfolding algorithms. The $H^*(10)$ values obtained with the different unfolding codes for the same system are compatible within their uncertainties. On the other hand, the CERN-BSS underestimates the $H^*(10)$ as compared with the BSS-LUPIN by a factor of seven as an average. As observed in the comparison of the solution spectra above, it is clear that the CERN-BSS heavily underestimates the neutron interaction rate, which results in underestimating the $H^*(10)$. The reliability of the $H^*(10)$ value obtained from the BSS-LUPIN solution spectra is confirmed by measurements performed with neutron rem counters in the same area⁽²⁰⁾, which showed $H^*(10)$ values in the

range 2.2 to 4.4×10^{-12} Sv per accelerated proton. Given the strong $H^*(10)$ gradient in this area as explained above, these values are in agreement with the BSS-LUPIN measurements.

CONCLUSIONS

The CERN BSS has been upgraded for its use in PNF by employing innovative electronics specifically conceived for this purpose. The upgraded system, called BSS-LUPIN, has been employed in a measurement campaign at the CERN PS in an area characterised by the presence of PNF and showed to be able to correctly estimate the neutron spectrum and the $H^*(10)$, avoiding underestimations induced by count losses. Additional measurement campaigns are planned in order to further test the performance of the upgraded system.

FUNDING

This research project has been partly supported by a Marie Curie Early Initial Training Network Fellowship of the European Community's Seventh Framework Programme under contract number PITN-GA-2011-289198-ARDENT.

REFERENCES

1. Bramblett, R. L., Ewing, R. I. and Bonner, T. W. *A new type of neutron spectrometer*. Nucl. Instrum. Methods **9**, 1–12 (1960).
2. Sloan, D. and Robertson, J. C. *The efficiency of a recoil proton monitor*. Nucl. Instrum. Methods **198**, 365–372 (1982).
3. Elevant, T. *Fusion neutron energy spectra measured by time-of-flight spectrometers*. Nucl. Instrum. Methods A **476**, 485–489 (2002).
4. Matzke, M. *Neutron spectrometry in mixed fields: unfolding procedures*. Rad. Pro. Dos. **107**(1–3), 37–72 (2003).
5. Birattari, C., Dimovasili, E., Mitaroff, A. and Silari, M. *A Bonner sphere spectrometer with extended response matrix*. Nucl. Instrum. Methods A **620**, 260–269 (2010).
6. Agosteo, S., Bedogni, R., Caresana, M., Charitonidis, N., Chiti, M., Esposito, A., Ferrarini, M., Severino, C. and Silari, M. *Characterisation of extended range Bonner Sphere Spectrometers in the CERF high-energy broad neutron field at CERN*. Nucl. Instrum. Methods A **694**, 55–68 (2012).
7. Knoll, G. F. *Radiation Detection and Measurement*. John Wiley & Sons, Inc. (2010). ISBN 0470131489, p. 105.

8. Caresana, M., Ferrarini, M., Manessi, G. P., Silari, M. and Varoli, V. *LUPIN, a new instrument for pulsed neutron fields*. Nucl. Instrum. Methods A **712**, 15–26 (2013).
9. Caresana, M., Cassell, C., Ferrarini, M., Hohmann, E., Manessi, G. P., Mayer, S., Silari, M. and Varoli, V. *A new version of the LUPIN detector: improvements and latest experimental verification*. Rev. Sci. Instrum. **85**-065102 (2014).
10. Ferrari, A., Sala, P. R., Fasso, A. and Ranft, J. *FLUKA: a multi-particle transport code*. CERN 2005–10, INFN-TC_0511, SLAC-R-773 (2005). Available on cds.cern.ch.
11. Böhlen, T. T., Cerutti, F., Chin, M. P.W., Fasso, A., Ferrari, A., Ortega, P. G., Mairani, A., Sala, P. R., Smirnov, G. and Vlachoudis, V. *The FLUKA code: developments and challenges for high energy and medical applications*. Nuclear Data Sheets **120**, 211–214 (2014).
12. Reillo, E., Cano-Ott, V. and Martinez, T. *On the neutron transparency of various materials proposed for the AIDA enclosure*. CINEMAT Internal Report 12.05.2008 (2008). Available on cds.cern.ch.
13. Billen, R. and Roderick, C. *The LHC logging service: capturing, storing and using time-series data for the world's largest scientific instrument*. CERN Technical Note, CERN-AB-Note-2006-046 (2006).
14. Reginatto, M. and Goldhagen, P. *MAXED a computer code for maximum entropy deconvolution of multisphere neutron spectrometer data*. CERN (1999). Available on cds.cern.ch.
15. Vega-Carrillo, H. R., Miramontes de Leon, G. and McBride, L. E. *Noniterative unfolding algorithm for neutron spectrum measurements with Bonner spheres*. IEEE Trans. Nucl. Sci. **46**, 28–35 (1999).
16. Bedogni, R., Domingo, C., Esposito, A. and Fernandez, F. *FRUIT: an operational tool for multisphere neutron spectrometry in workplaces*. Nucl. Instrum. Methods A **580**, 1301–1309 (2007).
17. Reginatto, M. *The 'few-channel' unfolding program in the UMG Package: MXD_FC33, GRV_FC33 and IQU_FC33 (UMG Package, Version 3.3.)*. CERN (2004). Available on cds.cern.ch.
18. Damjanovic, S., Witorski, M. and Gilardoni, S. *Shielding studies for the Route Goward/PS crossing*. CERN-DGS-2011-065-RP-TN (2012). Available on cds.cern.ch.
19. International Commission on Radiological Protection. *Conversion coefficients for use in radiological protection against external radiation*. ICRP Publication 74 (1996). Available on cds.cern.ch.
20. Aza, E., Caresana, M., Cassell, C., Colombo, V., Damjanovic, S., Gilardoni, S., Manessi, G., Pangallo, M., Perrin, D. and Silari, M. *Comparison of the performance of different instruments in the stray neutron field around the CERN Proton Synchrotron*. Radiat. Prot. Dosim. **161**, 190–195 (2014).