The comparison of five proton linac beams in order to set up a thermal neutron radiography installation

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Abstract. Radiography without doubt is maybe the most famous non-destructive technique with many applications in a number of scientific fields. In the present study, the performance of five photo-neutrons which delivered by proton linear accelerators with energy equal with 8, 12, 16, 20 and 24 MeV for a thermal neutron radiography unit has been designed and simulated with the help of the MCNPX 2.5.0 software which based on the Monte Carlo statistical method. The geometrical arrangement of the unit has been simulated with primary goal to provide the highest thermal neutron flux in the location of the examined item. For every energy of the proton beam all the significant parameters with the thermal neutron radiography theory like the flux of the thermals neutrons, the (collimator length)/(aperture diameter) ratio and the percentage of the thermal neutron within the neutron beam simulated for a wide series of values. Owing to the fact that there are many fast neutrons inside the beam, it is obligatory to decrease the quantity of the fast neutrons. For this reason, the addition of a single sapphire for fast neutron filtering has as a consequence a neutron beam with better quality. According to the simulations, the presence of the filter improves the % presence of the thermal neutrons with no substantial abatement in the flux of the slow neutrons.

1. Introduction
Thermal neutron radiography is a complementary method with the classical radiography method which uses γ and X-rays, and this characteristic gives new potential in Non-Destructive Evaluation (NDE) area. Neutron radiography (NR) is a very useful method with intention to study many heavy materials like copper, steel or Nickel. Additionally, it is also appropriate and for numerous light isotopes with high cross-section values like the hydrogen, the gadolinium, the lithium or the carbon. Thermal NR today has many applications in a really huge number of scientific files such as the medicine, the archaeology and almost in all engineering departments [1-6].

Research reactors are the most common neutron sources for thermal NR facilities however have significant drawbacks such as extremely high cost of construction, colossal bureaucracy to manage, and often have low public acceptability. Spallation Neutron Sources even though are powerful neutron sources require billion € for their development. Isotopic neutron sources (eg ²⁵²Cf, ²⁴¹Am/Be) suffer from low intensity [7-10]. A similar problem exists for deuterium-deuterium neutron generators which

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provide fast neutrons with energy \(\approx 2.5\) MeV but provide fluxes no more than \(10^{12}\) n s\(^{-1}\) [11-13]. Deuterium-Tritium neutron generators, even though they have harder spectrum, are capable fluxes about two orders of magnitudes higher than that of deuterium-deuterium neutron generators [14].

Proton accelerators are cheaper than power research reactors but can provide relatively high neutron fluxes and seem like an interesting compromise between neutron flux and initial cost. Beryllium and lithium are the most common material as targets for the proton beams because it provides softer spectra. Beryllium target does not require any unique design compared to lithium which has poor mechanical properties and low melting temperature [15-18].

The present article has threefold goal: First to lay out a unit appropriate for thermal NR intentions, 2) Second to simulate the designed facility and last but not least to estimate the performance of 5 proton beams with energies 8, 12, 16, 20 and 24 MeV on beryllium target which uses as a photo-neutron source. All these aims have been realized with the use of the MCNPX 2.5.0 software [19].

The needed neutrons provided when protons with energy between 8 - 24 MeV strike on a thick beryllium target. The beryllium target has a disk shape of 6 mm thickness and 16 cm diameter. Figure 1 illustrates the produced neutron spectra for five discrete energies namely 8, 12, 16, 20 and 24 MeV protons beams. These spectra were provided after experimental works by Paul et al. [20]. For proton beam current equal with 1 mA the full neutron fluxes are \(1.10\times10^{13}\), \(4.23\times10^{13}\), \(7.23\times10^{13}\), \(1.02\times10^{14}\) and \(1.42\times10^{14}\) ncm\(^{-2}\)s\(^{-1}\) for protons with energy 8, 12, 16, 20 and 24 MeV respectively. The gamma-ray spectrum received from works by Cortes-Giraldo et al. [21].

2. Materials and Methods

2.1. Thermal neutron radiography parameters

The most important factor which describes the quality of the radiographic images is the ratio of the collimator length (L) versus the inlet aperture diameter D. The neutron flux which can be measured at the collimator output given by the formula

\[
\phi_i = \left(\frac{D}{4L}\right)^2 \phi_0
\]

where \(\phi_0\) indicates the flux of the neutrons in the entrance of the collimator while the geometric unsharpness can be calculated using the formula

\[
u_g = \frac{L_f \cdot D}{L_s}
\]

where \(L_s\) is the distance between the inspected matter and the neutron source and \(L_f\) is the distance between the inspected matter and image plane (usual 0.5 cm). The beam divergence \((\theta)\) is the half-angle of the beam and gives the highest dimension of the image plane. This described mathematically by the equation [22-25]:

\[
\theta = \tan^{-1}\left(\frac{0.5 \cdot I}{L}\right)
\]

Thermal neutron content (TNC) express the percentage (%) of the thermal neutrons within the neutron beam. Finally, the ratio of the neutron flux vs. to the \(\gamma\) component (n/\(\gamma\) ratio), indicates a parameter which produces noise in the radiographies. The suggested value for this ratio is \(> 10^5\) n/(cm\(^2\)mSv\(^{-1}\)) [26].
2.2. Design of the facility

The design of the simulated geometry is depicted in figure 2. The main goal for this design was to maximize the thermal neutron flux ($f_{\text{th}}$) at the position of the investigated matter. In accordance with the spectra from figure 1, it is obvious that all the proton beams provide hard spectra for radiography which needs thermal neutrons hence is crucial to moderate these spectra using a moderator material. Based on the data from previous work by Fantidis et al. [15] the high density polyethylene (HD-PE) is the most suitable material in order to minimize the neutron energy offering the maximum $f_{\text{th}}$. In figure 2 a is the distance connecting to the beryllium target and the convergent collimator. This distance according to the simulated results is 2.5 cm in the case of 8 MeV proton beam and 2.7 cm for all the others cases. Convergent collimator has a conical shape with big radius 5 cm and small equal to 1 cm. The length $b$ of this collimator is 9 cm in the cases of 8, 12 and 16 MeV protons beam, 11 cm in the case of 20 MeV proton beam and 12 cm using the 24 MeV proton beam. This collimator in the first set up was void, and in order to enhance the values of the TNC ratio in the second configuration was filled from with a single sapphire which is the best fast neutron filter [26]. Close to this collimator is a second collimator with changeable length ($L = 100–300$ cm) and inlet aperture ($D$) equal to 2 cm. The divergent collimator has boral as lining material and two layers one from borated polyethylene (PE-B) and one other from bismuth (bi). The thicknesses of these materials three were 0.8, 3.2 and 1 cm, correspondingly. The exit aperture ($D_0$) has a dimension from 14 up to 18 cm. In order to minimize the unwanted (scattered) $\gamma$ rays and neutrons to exit from the divergent collimator were used bi and Boral with thicknesses of 1.2 and 0.8 cm respectively.

Figure 1. The provided neutron spectra for proton beams with current equal to 1mA.
3. Results and discussion

All the beams were simulated for an extensive set of simulations for the most crucial parameter of every thermal NR unit the L/D ratio. The L/D has 3 values (50, 100 and 150) whilst the θ fluctuates from 0.86–2° and u_g has values from 3.33×10⁻³ to 1×10⁻². In this article the simulation of the n/γ ratio do not presented because have values significantly higher from the suggested limits. Both f_th and TNC were estimated for every source using the F2 tally cards (which calculates surface flux). The thermal neutron energy band was 0.01–0.3 eV. The results are given in Table 1 and indicates that the 24 MeV proton beam offers both the maximum f_th values and the minimum TNC. In contrast, protons with energy 8 MeV provides both the minimum values for the f_th and the maximum for the TNC.

According to the results from the Table 1 in every simulation the TNC has rather poor values. In order to enhance these values the presence of the single sapphire as fast neutron filter is really useful. Table 2 demonstrates that using the single sapphire inside of the convergent collimator in the case of the 8 MeV proton beams improves drastically the TNC values from about 2% to 16% with only an insignificant reduction to f_th. Similar results occur and for the 12 MeV proton beams as shown in the same table, with TNC around to 8%. In accordance with the data analogous is the trend of the TNC values and for the other neutron beams which produced from protons with energy 16, 20 and 24 MeV. The TNC values in these cases were between 3.5 and 4% approximately. Again the reduction of the f_th in each source is not considerably.

![Figure 2. Configuration of the unit (dimensions are not in scale).](image)

| Table 1. The simulated values for three different L/D ratio values |
|---|
| L/D | L (cm) | D0 (cm) | θ (deg) | U_g (cm) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) |
|---|
| 50 | 100 | 14 | 2.00 | 1.00E-2 | 1.12E+6 | 2.06 | 3.07E+6 | 1.44 | 4.23E+6 | 1.08 | 5.62E+6 | 1.05 | 7.55E+6 | 1.02 |
| 100 | 200 | 16 | 1.14 | 5.00E-3 | 2.76E+5 | 1.92 | 7.51E+5 | 1.33 | 1.01E+6 | 0.99 | 1.26E+6 | 0.87 | 1.87E+6 | 0.94 |
| 150 | 300 | 18 | 0.86 | 3.33E-3 | 1.26E+5 | 1.95 | 3.33E+5 | 1.30 | 4.43E+5 | 0.96 | 5.62E+5 | 0.86 | 8.51E+5 | 0.94 |

| Table 2 | The simulated values for three different L/D ratios with the use of single sapphire filter. |
|---|
| Filter depth | 9 | 9 | 9 | 11 | 12 |
| L/D | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) | f_th (n/cm²s⁻¹) | TNC (%) |
|---|
| 50 | 8.09E+6 | 16.94 | 2.21E+6 | 8.33 | 3.05E+6 | 3.76 | 3.80E+6 | 3.96 | 4.93E+6 | 3.70 |
| 100 | 1.99E+5 | 16.48 | 5.41E+5 | 8.37 | 7.30E+5 | 3.59 | 8.49E+5 | 3.45 | 1.22E+6 | 3.62 |
| 150 | 9.10E+4 | 16.51 | 2.40E+5 | 8.24 | 3.19E+5 | 3.47 | 3.80E+5 | 3.43 | 5.56E+5 | 3.64 |
4. Conclusions
In this article five proton beams which bombard a beryllium target were used as photo-neutron sources in order to set up a facility for a thermal neutron radiography purposes. Both the design and the simulations of the presented unit has been realised using the MCNPX 2.5.0 software. According to the results neutron spectrum from 8 MeV protons is capable to offer the highest values for the TNC ratio for each L/D ratio. On the other hand, owing to the smaller total neutron yield the thermal neutron fluxes are the lowest in each simulation. On the contrary, neutrons spectrum derived by the 24 MeV protons is really harder. This photo-neutron source gives the maximum neutron flux but simultaneously has the minimum values for the thermal neutron content. Last but not least the use of the single sapphire for filtering the fast neutrons ameliorates the thermal neutron content with only a non importance decrement in the flux of the thermal neutrons.

References
[1] Chen Z and Wang X 2006, Port Technol. Int, 30, pp 163-165
[2] Fantidis J G and G E Nicolaou 2011, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 648(1), pp 275-284
[3] Takahashi Y, Misawa T, Pyeon C H, Shiroya S, and Yoshikawa K, Applied Radiation and Isotopes, vol. 69 (7), pp. 1027-1032, 2011
[4] Elsheikh N, Viesti G, El Agib I, and Habbani F 2012, Applied Radiation and Isotopes, 70 (4), pp 643-649
[5] Fantidis J G and Nicolaou G E 2013, Journal of Radioanalytical and Nuclear Chemistry, 295(2), pp. 973-977
[6] Moradllo M K, Reese S R, and Weiss W J 2019, Advances in Civil Engineering Materials 8.1, pp 71-87
[7] Fantidis J G , Nicolaou G E, Tsagas N F 2010, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 618(1-3), pp 331-335
[8] Bergaoui K, Reguigui N, Gary C K, Cremer J T, Vainionpaa J H, and Piestrup M A 2014, *Journal of Radioanalytical and Nuclear Chemistry*, 299(1), pp 41-51

[9] Taylor M, Sengbusch E, Seyfert C, Moll E, Radel R 2017, *Physics Procedia*, 88, pp 175-183

[10] Lehmann E, Frei G, Nordlund A, Dahl B 2005, *IEEE transactions on nuclear science*, 52(1), pp 389-393

[11] Da Silva A X and Crispim V R 2001, *Radiation Physics and Chemistry*, 61(3-6), pp. 515-517.

[12] Fantidis J, Nicolaou G, & Tsagas N 2010, *Journal of radioanalytical and nuclear chemistry*, 284(2), pp 479-484

[13] Jafari H, & Feghhi S A H 2012, *Radiation Physics and Chemistry*, 81(5), pp 506-511

[14] Fantidis J G 2017, *Journal of Taibah University for Science*, 11(6), pp 1214-1220

[15] Fantidis J G 2018, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 908, pp 361-366

[16] Zou Y, Wen W, Guo Z, Lu Y, Peng S, Zhu K and Zhou Q 2011, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 651(1), pp 62-66

[17] Shaaban I 2017, *Indian Journal of Pure & Applied Physics (IJPAP)*, 55(2), pp 135-144

[18] Fantidis J 2012 *Journal of Radioanalytical and Nuclear Chemistry*, 293(1), pp 95-101

[19] Hendricks J S 2003 *MCNPX version 2.5. c (No. LA-UR-03-2202)*, Los Alamos National Laboratory

[20] Sabyasachi P, Sahoo G S, Tripathy S P, Sharma Ramjilal S C, Ninawe N G, Sunil C, Gupta A K, Bandyopadhyay T et al. 2014 *Review of Scientific Instruments* 85.6: 063501

[21] Cortes-Giraldo, M A, Quesada J M, Palomo F R, & Garcia-Sanchez, E 2011 *Progress in Nuclear Science and Technology*, 2, 568-575

[22] Domanus J C, 1987 *Collimators for thermal neutron radiography: An overview*, Markgraf J.F.W. (Ed.)

[23] Domanus J C and Matifield R S 1981, *Neutron Radiography Handbook*, D. Reidel Publ. Co., Dordrecht

[24] MacGillivray G M 2000 Imaging with neutrons: the other penetrating radiation. In Penetrating Radiation Systems and Applications II, *International Society for Optics and Photonics*, 4142, pp 48-58

[25] Hawkesworth M R 1977 Atomic Energy Review, 15(2), pp 169-220

[26] Mildner D F R and Lamaze G P 1998 *Journal of applied crystallography*, 31(6), pp 835-840