IL NUOVO CIMENTO **38 C** (2015) 180
DOI 10.1393/ncc/i2015-15180-4

COLLOQUIA: UCANS-V

Neutron sources based on medical Linac

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received 22 February 2016

Summary. — The paper proposes the study of a novel photo-neutron source based on a medical high-energy electron Linac. Previous studies by the authors already demonstrated the possibility to obtain with this technique a thermal neutron flux of the order of $10^7\,\text{cm}^{-2}\,\text{s}^{-1}$. This paper shows possible Linac's setup and a new photo-converter design to reach a thermal neutron flux around $6 \times 10^7\,\text{cm}^{-2}\,\text{s}^{-1}$, keeping a reasonable high quality of the beam with respect to fast neutron and gamma contaminations.

PACS 25.20.Lj – Photoproduction reactions.
PACS 28.20.Gd – Neutron transport: diffusion and moderation.

1. – Introduction

Since 2007, projects funded by the Istituto Nazionale di Fisica Nucleare (INFN) and the Italian Ministry of Education, University and Research (MIUR), have investigated the possibility of thermal and epithermal neutron sources based on the photo-disintegration process (γ,n). The bremsstrahlung photon beam, coming out from a high-energy medical e-Linac (18–25 MV) hits a suitable self-shielded photo-converter and neutrons with energy mostly in the range 100 keV – few MeV can be produced via Giant Dipole Resonance (GDR) reaction. Then, using low-Z materials, such as D_2O and C_2H_4 primary neutrons can be moderated to lower energy. The present paper is devoted to the design of a novel thermal neutron source with a flux increased by almost a factor 6 with respect to previous works.

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2. – Material and methods

2·1. *Monte Carlo simulations.* – The photo-converter simulation studies have been carried out mainly using MCNP4B-GN (NEA-1733) [1] that can take into account the (γ,n) processes in high-Z and low-Z elements for photons up to 30 MeV. A complete simulation of an ELEKTA Precise 18 MeV Linac has also been included. The employed photo-reaction model assumes that the dominant neutron emission mechanism is evaporation, with a Maxwellian neutron energy distribution and an isotropic angular distribution. A small (10%) prompt neutron emission component, with resulting $E_n > 2\,\text{MeV}$, is also considered [2, 3]. In the Monte Carlo the photo-neutron production is simulated referring to the accelerator electron beam current. The size of each run has been dimensioned in order to have a statistical uncertainty below 5% (that represents one standard deviation). To deal with the low GDR photo-neutron production cross section with respect to the total one (about two orders of magnitude), specific variance reduction techniques have been employed.

2·2. *The photo-converter design.* – The role of the photo-converter is to produce neutrons by (γ,n) reaction and to moderate them down to thermal energy range minimizing gamma and fast neutron contamination. In particular, the gamma background is due both to primary unconverted photons (at low energy) and to those coming from neutron capture processes in the moderator. A prototype, namely "Phones Bianco", has been manufactured with a simple geometry shown in fig. 1(left): it contains mainly 10 cm thick lead neutron target followed by heavy water moderator and surrounded by graphite reflector blocks. The entire apparatus is covered by a 1 cm thick lithiated polyethylene layer to shield the cavity. Lead photo-neutron cross section shows a GDR peak of 600 mbarn around 13.5 MeV. The convolution of this peak with the bremsstrahlung spectrum gives the theoretical amount of convertible photons. Emitted neutrons have an energy spectrum characterized by a mean energy around 1 MeV and they can be thermalized mainly through elastic scattering in moderator materials. Heavy water has been chosen for its high moderation power combined with its low neutron capture cross section. A cavity of $20\,\text{cm} \times 20\,\text{cm} \times 5\,\text{cm}$, suitable to host samples to be irradiated, is placed in the inner part of the photo-converter. In order to increase the "hyperthermal" ($E_n < 10\,\text{keV}$) neutron flux inside the cavity a closed configuration has been chosen. The structure closing the cavity is made of heavy water and polyethylene in order to scatter neutrons back to the cavity. New geometries have also been investigated to optimize the neutron production and to reduce the capture loss. Figure 1(right) shows, as an example, a cross section of the Montezuma photo-converter scheme. It has a core made out of a pyramidal lead block structure interleaved with low-Z material layers. This design offers a larger impact surface to the photon beam at the production target, which contributes to increase the neutron flux without loosing moderation efficiency.

2·3. *The Elekta Precise 18 MV Linac.* – Since the final neutron beam is strictly related to the photon spectrum impinging on the photo-converter, the main components of an Elekta Precise 18 MV e-Linac have been included in the MCNP4B-GN input file. In order to enhance the neutron flux, several simulations have been carried out considering, in agreement with the Elekta technical division, possible modifications in the structure of the accelerator head and in its working parameters. Three actions have been implemented:

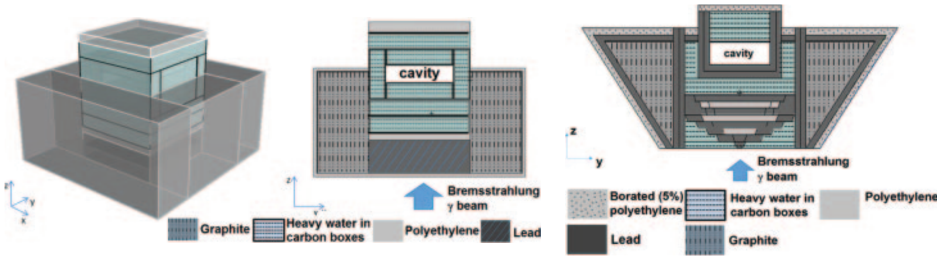

Fig. 1. – Phones Bianco (left) and the novel "Montezuma" (right) photo-converters assembly (bremsstrahlung photons are along the z-axis).

- the removal of the flattening filter, a stainless-steel cone normally used to make the photon field homogeneous in energy and space at the patient plane.
- the increase of the primary electron beam energy from 18 MeV to 20 MeV with corresponding rise of the mean energy of the photon spectrum.
- the modifications of the duty cycle parameters to rise the electron current N_e on the target from $1.05 \times 10^{14}\,\mathrm{s}^{-1}$ up to $1.75 \times 10^{14}\,\mathrm{s}^{-1}$.

An Elekta Precise 18 MV is being installed at Physics Department in Torino and it will be operational early 2016, 100% dedicated to research. The setup here proposed will be implemented and the improvements verified experimentally.

3. – Results

This section reports the main results obtained with MCNP4B-GN simulations of the Elekta Precise 18 MV Linac in different configurations, coupled with Phones Bianco and the novel Montezuma photo-converters.

Figure 2(left) shows the mean photon energy spectrum, calculated on a $(20 \times 20)\,\mathrm{cm}^2$ surface at 50 cm from the Linac target, in different machine configurations. As far as the

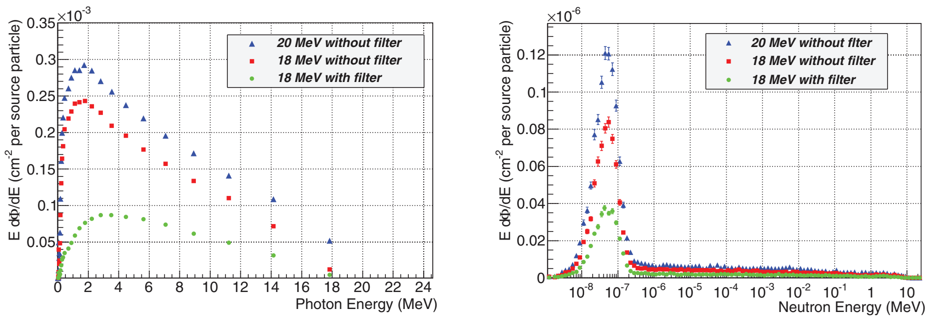

Fig. 2. – The bremsstrahlung photon and the final thermal neutron spectra calculated on a $(20 \times 20)\,\mathrm{cm}^2$ surface with MCNP4B-GN at 50 cm from the target. The lowest curve corresponds to the nominal accelerator configuration; the intermediate one is obtained removing the flattening filter from the Linac head; the highest curve is obtained removing the flattening filter and rising the electron energy up to 20 MeV.

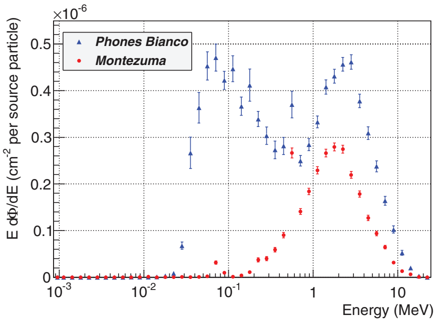

Fig. 3. – Mean photon spectra calculated with MCNP4B-GN inside the irradiation cavity. Comparison between "Phones Bianco" and "Montezuma" photo-converters with the same optimized Linac configuration.

neutron production and moderation is concerned, fig. 2(right) shows the mean neutron energy spectrum calculated in the cavity. The thermal neutron flux and its correspondent photon flux are clearly correlated. The removal of the flattening filter brings an increment of a factor 2.2, while the increase of the primary electron energy up to 20 MeV brings a further 1.44 gain factor. Both modifications will be implemented in the Linac setup under commissioning in Torino.

Concerning the neutron spectrum composition the thermal ($E < 0.4\,\text{eV}$) component accounts for 75%, while the epithermal ($0.4\,\text{eV} < E < 10\,\text{keV}$) and the fast ($E > 10\,\text{keV}$) components are of the order of 19% and 6% respectively. With the "Phones Bianco" geometry a hyperthermal neutron flux of $5.19 \times 10^7\,\text{cm}^{-2}\,\text{s}^{-1}$ is obtained. Using the "Montezuma" photo-converter scheme and the optimized e-Linac configuration two main effects have been observed inside the cavity. The hyperthermal neutron flux increases up to $(5.89 \pm 0.05)10^7\,\text{cm}^{-2}\,\text{s}^{-1}$, while the gamma contamination, shown in fig. 3, is reduced by a factor 2.5.

4. – Conclusions

This paper proposes to use a commercial medical e-Linac coupled with a dedicated self-shielded photo-converter to obtain a thermal neutron field inside a cavity whose dimensions can be chosen according to the specific application. Using appropriate photo-converter geometries and materials, and tuning the machine working parameters, a hyperthermal neutron flux as high as $(5.89 \pm 0.05)10^7\,\text{cm}^{-2}\,\text{s}^{-1}$ has been achieved. This results in an improvement of the useful neutron flux by almost a factor six with respect to previous studies [4]. The gamma contamination in the cavity has also been reduced by almost a factor 2.5 while the fast neutron contamination should be still decreased. New geometries and materials are under investigation. The use of commercial e-Linac has the advantage to be easily reproducible, robust, safe and cheap. Such a kind of facility is under construction at INFN in collaboration with the Physics Department at the University of Torino.

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