The Measurement of Neutron Energy Spectra in the High Neutron Flux Environments of Medical Accelerators Using the Nested Neutron Spectrometer

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Introduction

Various types of particle accelerators find applications in medicine. Linear electron accelerators (Linac) are used for the treatment of patients while cyclotrons are used for the production of short-lived radionuclides for PET and SPECT imaging. In addition, research is currently ongoing on the use of higher energy cyclotrons and high output Linac for the production of ^{99m}Tc.

In order to assess if the radiation shielding is sufficient to protect the accelerator operators and for licensing purposes, the measurement of the neutron energy spectra in the treatment zone of a Linac or the target room of a cyclotron may be required. However, neutron flux as high as 10^8 n cm^{-2} s^{-1} can be found at 1 m from a ^{100}Mo target exposed to 24 MeV protons due to the ^{100}Mo(p,2n)^{99m}Tc reaction. We report results of a new instrument able to provide the neutron energy spectra in such high flux environments.

The Nested Neutron Spectrometer

The Nested Neutron Spectrometer (NNS) consists of a ^{3}He counter and a set of nested high density polyethylene (HDPE) cylinders, as shown in Fig. 1. The ^{3}He counter detects thermal neutrons through the ^{3}He(n,p)^{3}H reaction. The nested HPDE cylinders provide a simple means of changing the amount of moderator around the ^{3}He counter.

Figure 1: NNS fully disassembled (left) and ready for use on a tripod (right). The small cylindrical ^{3}He counter is shown.

This assembly exhibits a particular energy response curve which depends on the amount of moderator. Thus, by combining different number of cylinders, one has a system that has energy discrimination capabilities as shown by the response functions in Fig. 2.

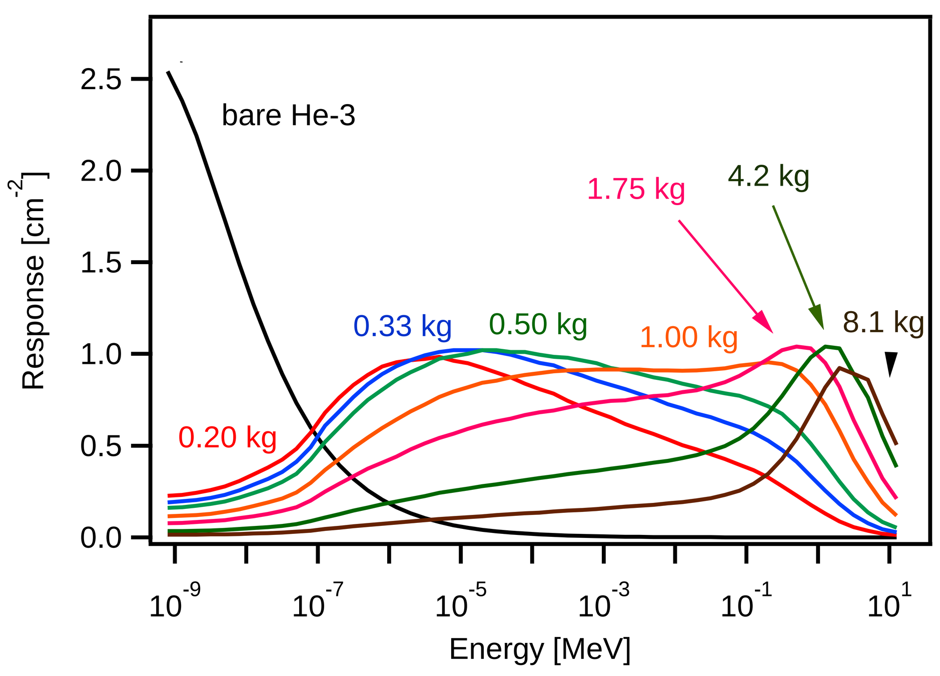

Figure 2: Response functions, or detection efficiency curves, of the NNS as a function of energy for the different masses of HPDE moderator.

NNS measurement principles

The neutron energy spectrum is obtained by performing 8 neutron detection rate measurements for the 8 configurations of the HDPE (bare ^{3}He counter to full assembly of 7 cylinders). The neutron detection rate can either be obtained by counting pulses, or by measuring the induced current.

- The pulse counting method is used for incident neutron flux below 10^4 cm^{-2} s^{-1}. The measurement is performed using nuclear counting electronics.
- The current method is used for incident neutron flux > 10^4 cm^{-2} s^{-1} such as those found near medical accelerators. The current is measured using an electrometer.

NNS measurement setup and analysis

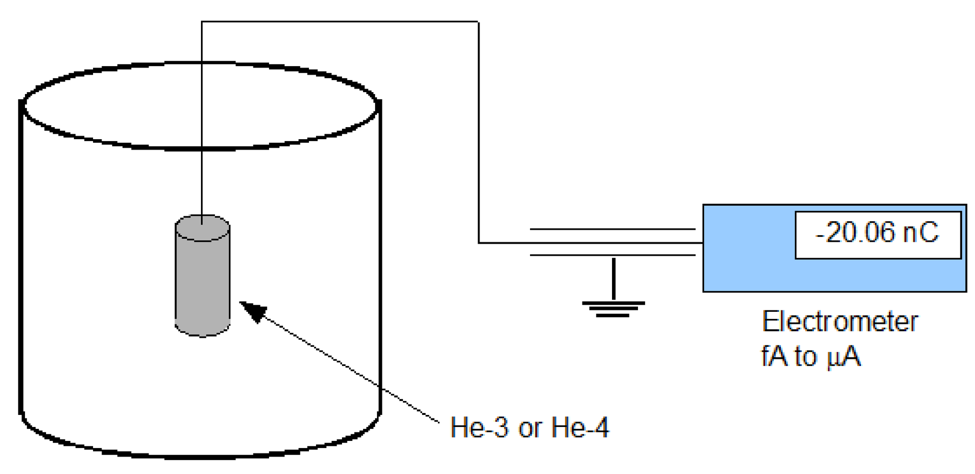

Figure 3: In current mode, the ^{3}He counter is operated at unity gain as an ion chamber. A neutron-insensitive ^{4}He ion chamber may also be used for the subtraction of the gamma-ray contribution to the current.

From the 8 measurements, an unfolding process creates an energy distribution over 52 energy bins using a specially designed software tool (Fig. 4).

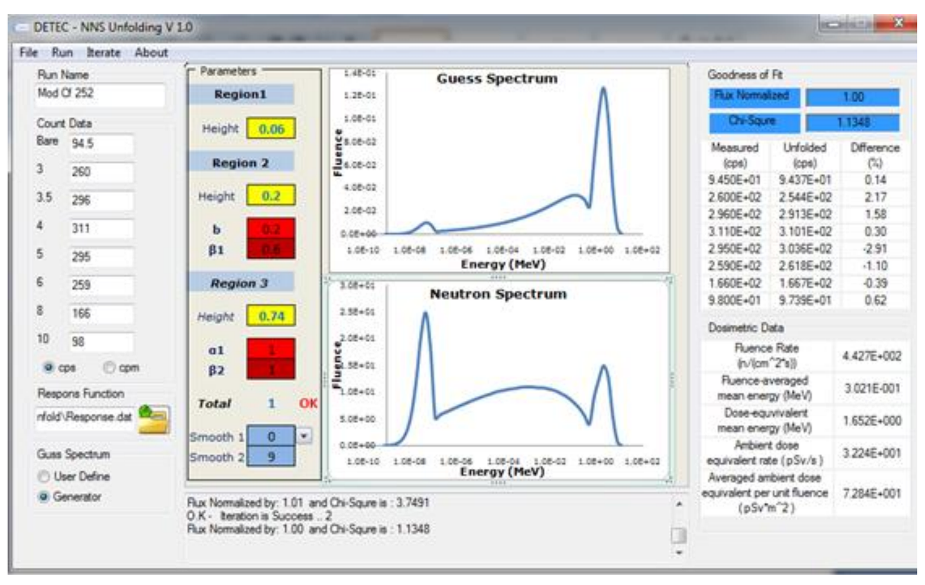

Figure 4: Screen shot of the graphical user interface of the unfolding Software. It requires a guess solution provided by the user and uses an mean square minimization algorithm.

Measurements near a ^{100}Mo target of a TR-24 cyclotron

A 423 µm thick ^{100}Mo target, on an Aluminium holder, was mounted at the end of the beam line of an ACSI (Advanced Cyclotron Systems, Richmond, BC) TR24 cyclotron at the Centre Hospitalier Universitaire de Sherbrooke and bombarded with 24 MeV protons. The resulting neutron spectrum consisted of the neutrons from the ^{100}Mo and those from the interaction of the protons, of 17.8 MeV residual energy, with the Al target holder. A second measurement was performed with 17.8 MeV protons directly on Al. The beam current was 2.5 µA, i.e. 1/200 of its operating current during ^{99m}Tc production. The distance between the NNS and the target was about 1.3 m. The resulting spectra are shown in Fig. 5.

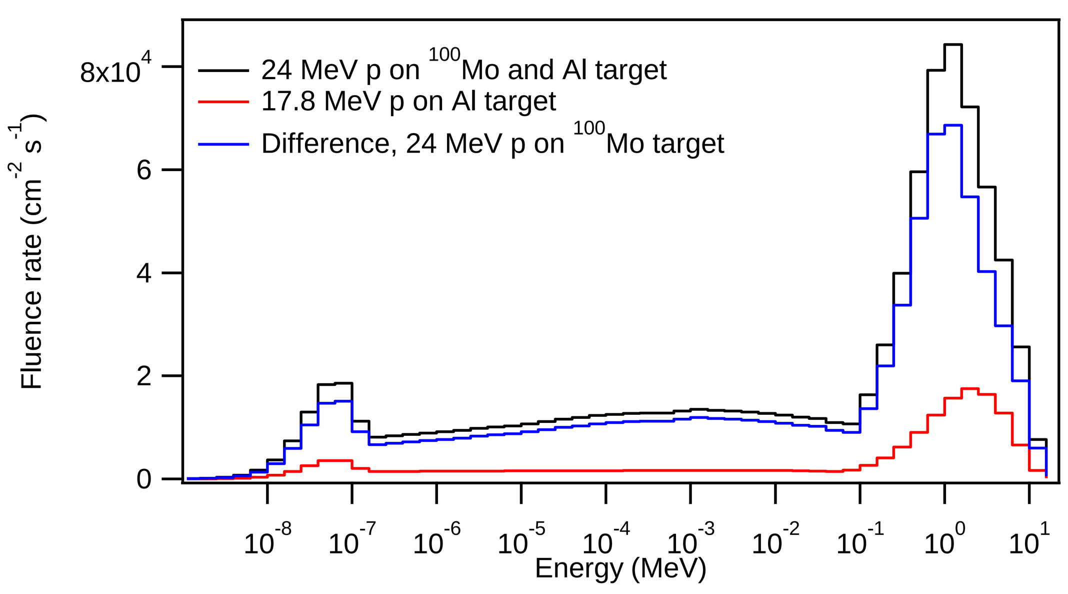

Figure 5: Neutron energy spectrum measured at 1.3 m from the target of the TR24 cyclotron. Separate measurements were performed for 24 MeV protons incident on ^{100}Mo and 17.8 MeV protons incident on the Al target holder. The difference, due to the ^{100}Mo(p,2n)^{99m}Tc, is shown.

The results in Table 1 are for the low operating current of 2.5 µA and they include low energy neutrons due to room scatter.

Table 1: Characteristics of the neutron fields produced in a ^{100}Mo target and a target holder.

Quantity	Targets		
	Mo on Al 24 MeV p$^+$	Al 17.8 MeV p$^+$	Net Mo
Fluence rate [cm^{-2} s^{-1}]	9.31 x 10^5	1.65 x 10^5	7.66 x 10^5
H*(10) rate [mSv h^{-1}]	662.4	141.8	520.6
Average energy [MeV]	0.93	1.27	0.86

Measurements near a 18 MV medical Linac

The NNS was used to measure the neutron fields at various distances from the head of a Varian 18 MV treatment Linac (Fig. 6 and Fig. 7), at the McGill University Health Centre (MUHC). The closest distance was 1.4 m from the isocentre, outside the patient plane. The variation of the neutron energy distribution, with increasing distance from the Linac, is shown in Fig. 8.

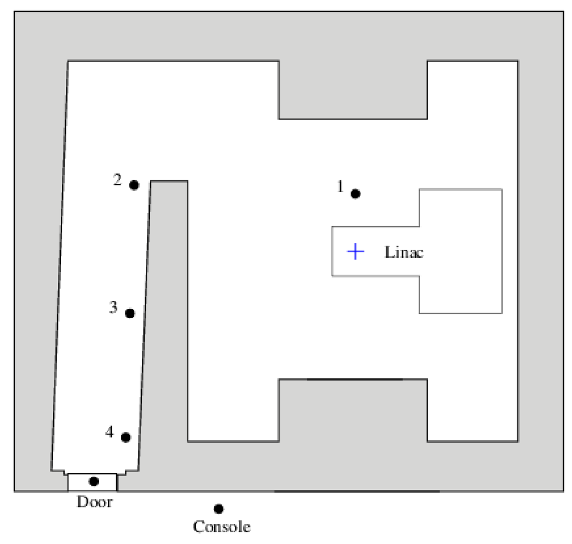

Figure 6: Schematic of the Linac room and approximate measurement locations.

Figure 7: NNS near the Linac at location 1.

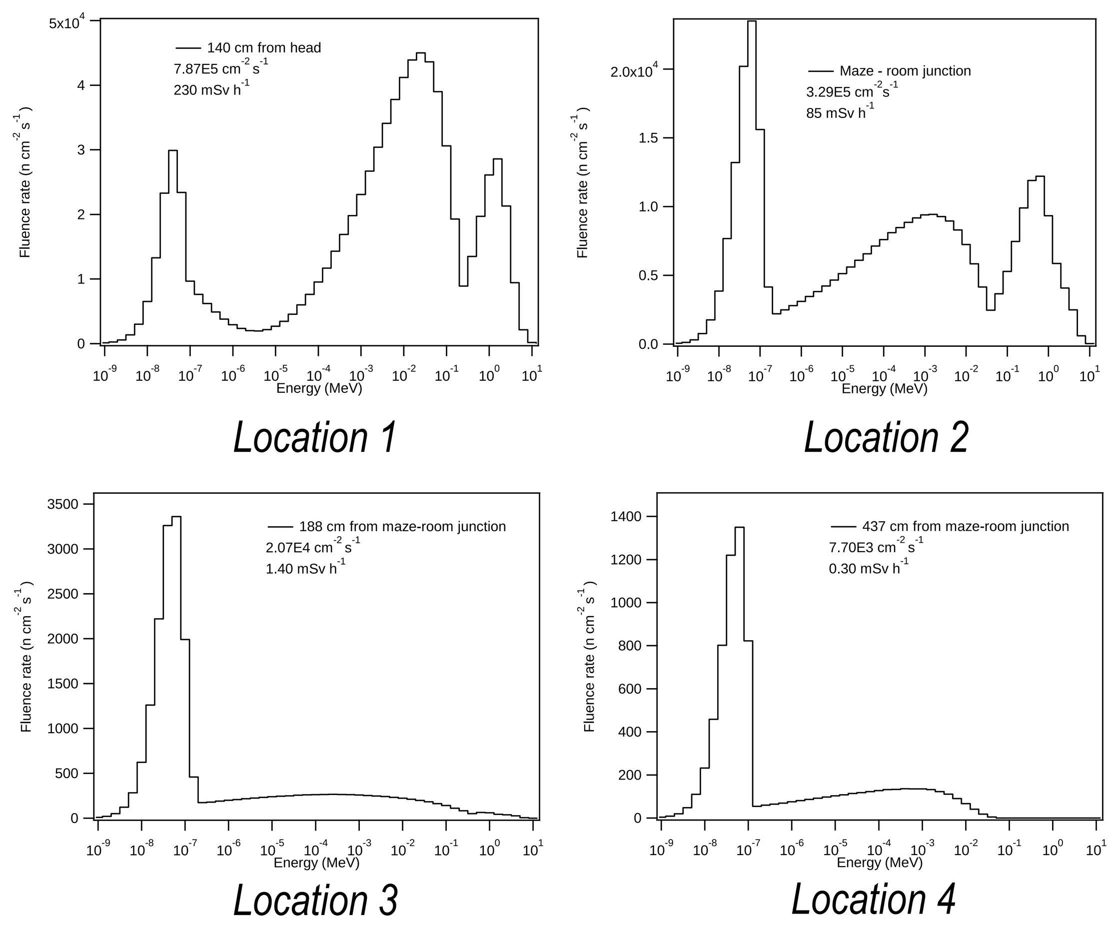

Figure 8: Neutron energy distributions measured at various locations around the MUHC18 MV Linac.

The NNS clearly showed the variation in the shape of the neutron energy distribution with distance away from the Linac. At greater distances the spectrum was dominated by thermalized neutrons. Measured fluence rates and ambient dose equivalent rates are given in Table 2.

Table 2: Characteristics of the neutron fields measured at various distances from the MUHC 18 MV Linac running at 600 MU min^{-1}, collimator closed.

Quantity	Locations			
	1	2	3	4
Fluence rate [cm^{-2} s^{-1}]	7.87 x 10^5	3.29 x 10^5	2.07 x 10^4	7.70 x 10^3
H*(10) rate [mSv h^{-1}]	230	85	1.40	0.30

Conclusion

The NNS provided, for the first time, neutron energy spectra in the high flux environments near medical accelerators. The instrument should prove of value for the characterization of the output of these types of accelerators and for the evaluation of the adequacy of radiation shielding.

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