PROGRESS ON A FUSION NEUTRON SOURCE BASED BNCT IRRADIATION FACILITY DESIGN

J. Esposito

LNL, Istituto Nazionale di Fisica Nucleare, Legnaro, Padova, Italy

ABSTRACT

In the framework of Italian BNCT project a research activity on alternative, RF driven, accelerator based $^2H(d,n)^3He$ (D-D) and $^2H(t,n)^4He$ (D-T) fusion neutron generators is being carried out in collaboration with the nuclear departments of Pisa (DIMNP) and Genova (DITEC) Universities. Monte Carlo modeling of an irradiation facility, based on such an, advanced type, neutron source device is presented. The facility here proposed could represent an interesting alternative to the much more investigated Li or Be based accelerator driven neutron sources, to be used by an hospital environment. Preliminary Snyder head phantom central axis depth vs. dose distribution calculation is also presented.

Introduction

Nuclear reactors still represents the unique neutron source able provide an irradiation beam close to the BNCT requirements and the only one used in the first patient trials so far. Notwithstanding their basic role is however hard to think about a reactor based facility in an hospital environment, due mainly to safety issues and public acceptability, which strongly limits the wide use of this kind of neutron source. On the other hand, R&D efforts on different, accelerator based, neutron source concepts are being carried out with increasing interest, during the last years, mainly to provide an efficient, high yield solution aimed at an hospital based BNCT irradiation facility.

Some recent engineering solution has been focused on Li or Be target design, exploiting proton and/or deuteron ion beams as well as photoneutron reaction. Their main advantage relies on a relatively softer neutron spectrum supplied (few tens÷hundreds of keV) [1], closer to the required epithermal range (1 eV-10 keV). This implies a simplified beam shaping assembly design, a more compact facility and a low neutron leakage. The target heat power removal as well as reliability concern, while being the main engineering issues which still have to be proven, the main drawback of such a sources however mainly rely on the of 1.8÷4 MeV proton or deuteron beam requirement. Expensive accelerating facilities must be therefore employed (RFQ linacs or tandem cascade) which, moreover, can hardly achieve beam currents greater than few tens of mA [2].

On the other hand our first attempt to assess a NCT facility relied on the alternative and less investigated (D-T) fusion neutron generator [3], revealed that this solution could be taken into account. This choice is suggested by the possibility of using simpler and small size accelerator device, with relatively low energy beams (100–300 keV), although a much harder neutron spectrum has, on the other hand, to be slowed down. The other possible solution, (D-D) neutron generator, due to the relatively low neutron yield performance seems unlikely to be used at the moment, despite the less radiological problems it could provide.

Assessment of *proper* spectrum shifter materials

Neutrons emerging from D-T nuclear fusion reactions have a rather hard, quasi-monoenergetic spectrum (14.1 MeV). A proper spectrum shifter device is therefore required, in order to provide a therapeutic beam, at the irradiation position, in the desired epithermal energy range, able to fulfil the BNCT quality specifications. The widely accepted requirements used in the BNCT community, at the preliminary facility design stage, are based on the estimation of some *in-air* beam port parameters [4]. As a general rule, a good spectrum shifter material should provide for an efficient and selective slowing down from the fast towards the epithermal energy range (10 keV-1 eV), in order to get a net accumulation of neutrons in the desired group with acceptable beam intensity loss.

Within the three energy group model representation of Fermi's neutron slowing down theory, the most important parameters to be considered are the *fast slowing down macroscopic cross section*

Material	$\Sigma_{ds,fast \to epi}$ [cm^{-1}] $\times 10^{-3}$	$\Sigma_{r,fast}$ [cm^{-1}] $\times 10^{-3}$	$\Sigma_{r,epi}$ [cm^{-1}] $\times 10^{-3}$	$\Sigma_{t,fast}$ [cm^{-1}] $\times 10^{-3}$	$\frac{\Sigma_{ds,fast \to epi}}{\Sigma_{r,epi}}$	$S.I. = \frac{\Sigma_{ds,fast \to epi}}{\Sigma_{r,epi}} \cdot \frac{\Sigma_{r,fast}}{\Sigma_{t,fast}}$ $\times 10^{-3}$
PbF_4	8.28	12.02	3.53	372.35	2.35	~ 76
Al/AlF_3 $^{(*)}$	5.58	6.96	2.43	220.03	2.30	~ 73
AlF_3	8.11	9.94	3.86	299.73	2.10	~ 70
BiF_3	5.25	7.59	2.24	272.49	2.34	~ 65
PbF_2	6.50	9.87	2.75	363.48	2.36	~ 64

$^{(*)}$ AlF_3 (70 wt %) - Al (30 wt %) mixture.

Table 1. MCNP fast and epithermal macroscopic cross sections estimations and Spectral Indexes (S.I.) for some interesting spectrum shifter material. The fast group here considered has the upper energy limit of 20 MeV

($\Sigma_{ds,fast \to epi}$) and the *epithermal removal macroscopic cross section* ($\Sigma_{r,epi}$), joined in the $\Sigma_{ds,fast \to epi}$ /$\Sigma_{r,epi}$ ratio. The experimental as well as computational investigation results [2] have proven their effectiveness, in the spectrum shifter material selection, both for the nuclear reactor and accelerator driven Li or Be target neutron source spectra. On the other hand, when a harder neutron spectrum has to be slowed down, which is our case, the fast to epithermal spectral ratio still acts as the main spectrum shifting parameter. Nevertheless we have also found that an efficient fast neutrons removal is, in addition, crucial, in order to limit the undesired neutron component to an extent as low as possible. The parameter which takes in account this process is the $\Sigma_{r,fast}$ /$\Sigma_{t,fast}$ ratio between the *fast macroscopic removal cross section* ($\Sigma_{r,fast}$) and the *total fast macroscopic cross section* ($\Sigma_{t,fast}$). We have joined the two effects in a new, more relevant parameter, which we give the name of "*Spectral Index"* (S.I.) [5]. The S.I. therefore allows, as a whole, for a better description of the neutron slowing down process from harder down to softer neutron spectrum with respect to the former one [2].

A series of MCNP-4C runs have thus been performed, in order to simulate the neutron slowing down behavior of a set of candidate materials. In order to provide a set of data able to give an estimation of the three, broad group, weighted cross sections. Tab.1 reports a list of the most interesting compounds and mixture materials that have shown to perform the highest S.I. value [5]. Following the new parameter, we have found that other materials not previously taken into account, mainly PbF_4 [5] and, to a lesser extent, BiF3, other than PbF_2 [6], are more effective than the traditional and already proven Al-AlF_3 based mixtures, in order to provide a better epithermal picked neutron spectrum at beam port, when a D-T neutron source is employed. Furthermore Pb or Bi compounds allow avoiding the use of an additional outer gamma shield.

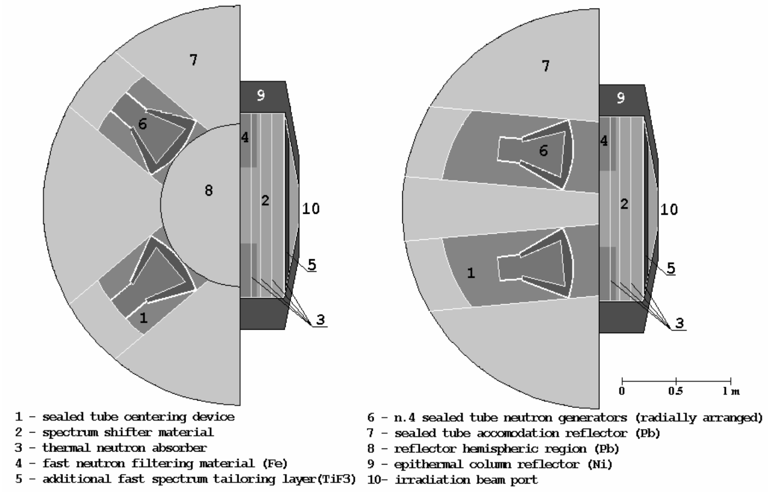

Fig.1 Cutaway view of proposed epithermal facility supplied by four, radially (left) and not radially (right) arranged, LBNL sealed tube device, D-T neutron generator.

Conf.	Column size		Column material	Reflector	Gamma shield	Thermal shield	ST arrangement
	D(cm)	L(cm)					
1	170	55	$Al_{(30wt\%)}\ AlF_{3\ (70wt\ \%)}$	Ni	Bi	nat. Li	rad. (75 cm)
2	170	55	Fe-PbF_4-TiF_3	Ni	-	nat Li	rad. (75 cm)
3	170	45	Fe-PbF_4-TiF_3	Ni	-	^{6}Li	rad. (75 cm)
4	170	45	Fe-[Al-AlF_3]-TiF_3	Ni	Bi	^{6}Li	rad. (75 cm)
5	170	55	Fe-PbF_4-TiF_3	Ni	-	^{6}Li	not rad. (45 cm)
6	170	55	Fe-PbF_4-TiF_3	Ni	-	^{6}Li	not rad. (25 cm)

Table 2. Some D-T facility configuration which have shown the most interesting performance

The proposed D-T irradiation facility modeling

Some beam shaping assembly geometrical configurations have been tested and neutron and gamma beam data, at beam port, have been computed aiming at the improving of spectrum shape in the desired energy range. The design study has taken into account irradiation facilities supplied by both single and multiple sealed tube neutron generators. The Monte Carlo modeling of the proposed neutron source facility based on two different layout approaches of a set of advanced type, D-T fusion neutron source device [7], is reported in Fig. 1. It represents an upgrade of the preliminary layout version accommodating ten generators [5] [8]. Another simplified, more compact and lower cost solution, both relying only on one D-T and D-D generator was also assessed [5] [8]. According to the most recent BNCT in air FOM parameters, some interesting beam shaping assembly material configurations, as well as related performance results are enlisted in Tab. 2 and Tab. 3.

Nevertheless a more realistic and reliable way of estimating the therapeutic effects of such a beam inside a multi shell, analytic ellipsoidal representation of a modified Snyder head phantom (SHP) model [4] has moreover been performed. At last preliminary central axis depth vs. dose computational investigation results in brain, bone and scalp material regions, taking into account the different contribution arising from both incoming and induced photons are also reported in Fig. 2 and Tab. 4 [9]. The phantom dose parameters suggest the facility here proposed could provide a performance comparable with the traditional reactor-based irradiation facility.

Conf.	ϕ_{epi} [$\times 10^9$ n /cm^{2}s]	ϕ_{epi} / ϕ_{fast}	ϕ_{epi} / ϕ_{th}	$\dot{D}_{fast} / \phi_{epi}$ [10^{-13} Gycm^{2}n^{-1}]	$\dot{D}_{\gamma} / \phi_{epi}$ [10^{-13} Gycm^{2}n^{-1}]	J / ϕ
1	2.730 ± 0.005	16.88	58.64	2.89	0.51	0.56
2	0.673 ± 0.005	234.00	16.50	0.26	1.64	0.57
3	1.067 ± 0.005	75.55	34.64	0.78	0.99	0.57
4	2.670 ± 0.014	20.69	233.44	2.84	0.61	0.57
5	0.832 ± 0.006	154.60	19.02	0.42	1.15	0.57
6	1.500 ± 0.003	86.07	35.27	1.13	1.24	0.57

Table 3. Beam port main parameter results related to the configurations enlisted in Tab. 2. The epithermal flux, at the exit end, takes as reference an overall primary neutron source output of $4 \cdot 10^{14}$ n/s.

Conf.	A.D. (cm)	A.R. (A.D.)	A.D.D.R. (RBE-Gy/min)	D_{skin} (RBE-Gy/min)	skin tissue $t_{s\ lim\ (min)}$ [<8 RBE-Gy]	normal tissue $t_{n.\ lim\ (min)}$ [<12.5 RBE-Gy]	A.D.D.R. x $t_{n\ lim}$ (RBE-Gy)
1	10	4.30	0.247	0.437	18	51	4.54
3	9.8	4.51	0.131	0.186	43	95	5.60
5	10	4.15	0.125	0.181	44	100	5.50
6	9.6	4.31	0.197	0.292	27	63	5.39

Table 4. In Phantom figures of merit to assess beam performance related to facility configurations enlisted in Table 2

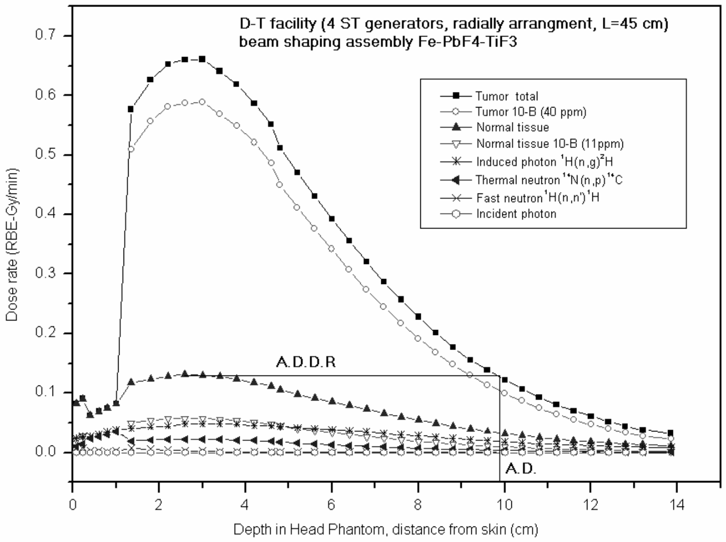

Fig.2. Depth-Dose profile for unilateral irradiation inside a modified Snyder Head Phantom model. Facility configuration n.3 reported in Table 3

Results and Conclusions

The facility here proposed, based on both the D-T neutron generator and the new PbF_4 spectrum shifter material has shown to be potentially able to provide a very good performance, concerning the neutron flux output as well as spectrum shaping tailoring. The epithermal flux limit of $\sim 1 \cdot 10^9$ n/cm^{2}s at beam port could be fulfilled when using the D-T generator yielding about 10^{14} n/s. The SHP depth-dose profile analysis points out it could be usefully employed for deep seated tumors treatment. On the contrary the D-D neutron generator based facilities investigated, although with similar depth-dose profile performance [9], require rather long patient treatment times with at present available D-D neutron generators.

Acknowledgements

Thanks are due to prof. N. Cerullo (DITEC and DIMNP) for proposing the idea, the useful discussions and for fruitful collaboration in the research activity.

References

[1] W.B. Howard, S.M. Grimes, T.N. Massey *et al.*. Measurement of the 9Be(p,n) thick target spectra for use in accelerator based neutron capture therapy, Elsevier Science Vol. 1, 511 (1997)

[2] B. Montagnini, N. Cerullo, J. Esposito, V. Giusti, F. Mattioda, R. Varone., Spectrum shaping of accelerator-based neutron beams for BNCT, Nucl. Instr. and Meth. A, 476, 90-98, (2002)

[3] N. Cerullo, J. Esposito, B. Montagnini, Feasibility of a Neutron Beam for BNCT application based on Nuclear Fusion Reactions *D-D* and *D-T*, J. Nuc. Sci. and Tech., Supp. 1, 384-388, (2000)

[4] W.S.Kiger III, S. Sakamoto, O.K.Harling, Neutronic Design of a Fission Converter-Based Epithermal Neutron Beam for Neutron Capture Therapy, J. Nucl. Sci. Engineering, 131, (1999), 1

[5] N. Cerullo, J. Esposito, G.G. Daquino, Spectrum shaping assessment of accelerator-based fusion neutron sources to be used in BNCT treatment , Nucl. Instr. and Meth. B, 213C, 641-645, (2003)

[6] Liu H.B., PbF_2 compared to Al_2O_3 and AlF_3 to produce an epithermal neutron beam for radiotherapy, Med. Phys., 23, 279-281, (1996)

[7] J. M. Verbeke, K. N. Leung, J. Vujic, Development of a sealed accelerator tube neutron generator, App.Rad. and Isot. 53, 801-809, (2000)

[8] N. Cerullo, J. Esposito, K.N. Leung., S. Custodero, An irradiation facility for boron neutron capture therapy application based on a radio frequency driven D-T neutron source and a new beam shaping assembly, Rev. Sci. Instr., 73(10), 3614-3618, (2002)

[9] J. Esposito, Studio di una sorgente neutronica da fusione per la BNCT, basata su un acceleratore compatto a bassa tensione e su originali materiali traslatori di spettro, PhD thesis in Nucl. Eng., Pisa University, a.y. 2001-2002.