A sub-critical neutron irradiator driven by an electron accelerator

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Abstract

Spallation neutron sources, though very effective in neutron production, are large, expensive and presently would involve certain difficulties in their operation (e.g., beam trips). Contrary, an electron driver, although much less effective in neutron production, is rather cheap and compact machine that might also bring advantages in terms of reliability. In this paper we investigate the use of an external neutron source (irradiator) driven by an electron accelerator. The system is based on a compact spherical geometry with electron beam interacting with an inner surface of the target-envelope made of enriched uranium. Neutron balance is improved by using different reflecting materials. We show that with an incident electron beam of the order of 6 MW neutron fluxes up to a few $10^{14}\ \frac{n}{cm^2 s}$ could be reached in the sample irradiation zone.

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1 Introduction

Recently, a world-wide interest in photonuclear processes is experienced, what is motivated by a number of different applications such as shielding problems of medical or fundamental research accelerators, the need of new cost effective neutron sources, transmutation of nuclear waste either directly by photons [1] or by neutrons created from photonuclear reactions [2], radioactive nuclear beam factories based on photofission process [3], etc. For a long time photonuclear processes were neglected by particle transport codes mainly due to the lack of the evaluated photonuclear data files. In 1996, in order to make up this backlog, IAEA started a coordinated research programme for compilation and evaluation of photonuclear data for applications. As a result of this effort, a photonuclear data file in ENDF format for 164 isotopes became available in 2000 [4]. One of the first attempts to benchmark these new data files have been performed recently with well known Monte Carlo codes as MCNPX [5] and MCNP [6], enhanced with a photonuclear capability independently by LANL (US) [7] and KFKI (Hungary) [8].

In this paper an unusual system to produce neutrons for irradiation purposes is described eliminating most of the problems encountered in conventional ADS. The accelerator is an electron machine, being cheaper, more reliable and more compact than high energy high power proton linac. Neutron are produced in an enriched uranium target by photonuclear rather than spallation process. A schematic layout and design of a compact neutron irradiator is proposed with its neutronics and safety being analyzed and discussed in detail. In all calculations we employ already benchmarked MCNP code enhanced with photonuclear capability [8] together with the recommended IAEA photonuclear data files [4].

2 Neutron yield and cost

Photonuclear reactions as (γ,n) and (γ,2n) can be induced in any material by specific gamma rays exciting the Giant Dipole Resonance (GDR) of the nuclei, while (γ,fiss) may occur only in the case of actinides. For example, a maximum fission probability of 160 mb can be obtained for photons having energy around 15 MeV. Unfortunately, the most common way for producing high gamma fluxes in the GDR region is the bremsstrahlung process resulting from electrons passing through the matter. This process has a cross section linear with energy above 20 MeV. The resulting bremsstrahlung spectrum is widely spread in the energy range from zero to the incident energy of electron, and only a small fraction of these photons are "useful" photons, i.e. lying in the GDR range of 15$\pm$5 MeV. Therefore, the overall efficiency of neutron production is much lower than one might expect by having in mind the direct photonuclear process.

Let us take an example. The number of fissions per incident electron impinging on an infinite natural uranium target approximately follows a linear law with a threshold energy about 8.5 MeV [2]:

$$(fiss/e) = 1.9 \cdot 10^{-4}(E_{in\,MeV} - 8.5).$$

In other words, an electron having an energy of 100 MeV will induce 0.017 fissions. The neutron flux can then be estimated taking into account that each fission will release about ν=3.4 prompt neutrons in addition to the contribution of other photonuclear reactions as (γ,n) and (γ,2n), which contribute nearly the same number of neutrons as the photofission process [2]. The total number of neutrons produced for a 100 MeV electron is then (n/e)=0.11. In this case the neutron cost is about 900 MeV. This is much larger than the neutron produced by the spallation process (e.g., a 1 GeV proton on lead target), where each proton can create about 30 neutrons. Here the neutron cost is around 30 MeV, i.e. $\sim$30 times cheaper than the photonuclear one. On the other hand, even the neutron cost is higher, the accelerator cost is much lower in the case of electron machine. Therefore, for the same neutron flux required, a higher electron intensity (and beam power) will be needed due to the lower efficiency. Thus, above a given neutron flux, the spallation will be preferred while for the lower fluxes, the photonuclear process will tend to be cheaper. This is illustrated in Fig. 1, where for a given neutron flux, both an electron machine as

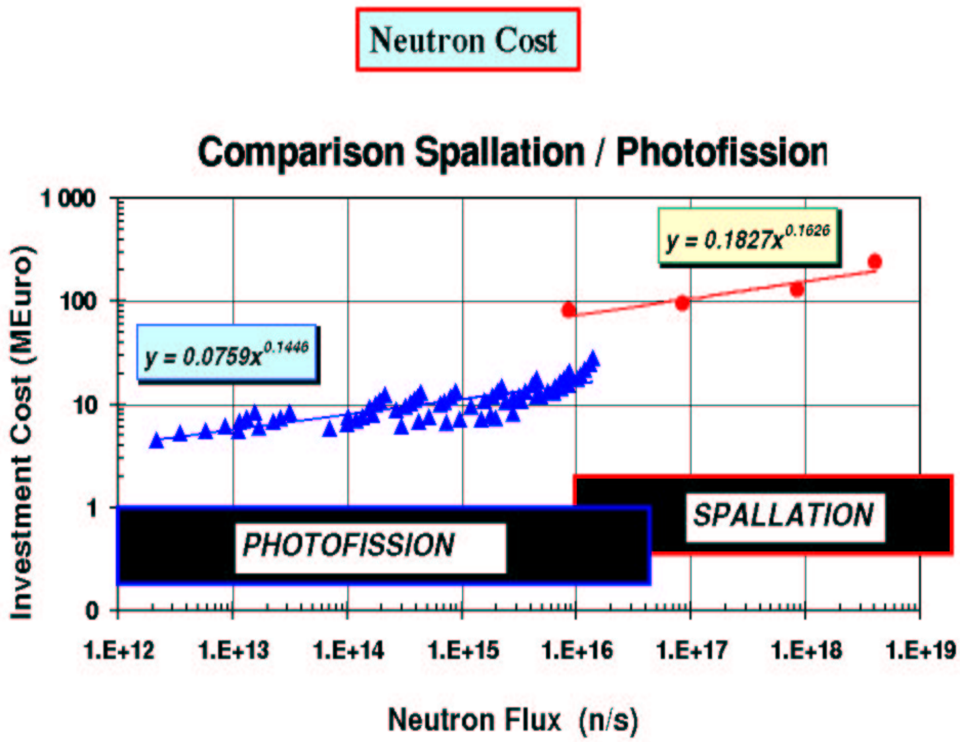

Figure 1: Spallation versus photonuclear process for neutron production [2].

well as a proton accelerator has been cost effectively estimated. Note that this is only machine cost, which does not include manpower or buildings (which again are certainly cheaper for the electron machine). In brief, for neutron source intensity higher than 10^{17} n/s, the spallation process will start to appear more effective, while below this value the photonuclear process is favoured.

3 Modelling procedure and geometry considerations

A simplified model of the neutron irradiator has been created using MCNP [6] geometry setup in 3D as shown in Fig. 2. MCNP was also used to obtain the k_{eff} eigenvalues and neutron fluxes. Neutron production with electrons was modelled by the same MCNP code enhanced with photonuclear capability [8]. In all cases the recommended IAEA photonuclear data files have been used [4]. Both (γ,n), (γ,2n) and (γ,fiss) reactions were taken into account explicitly for all materials used in the problem and with a corresponding full secondary neutron transport [8].

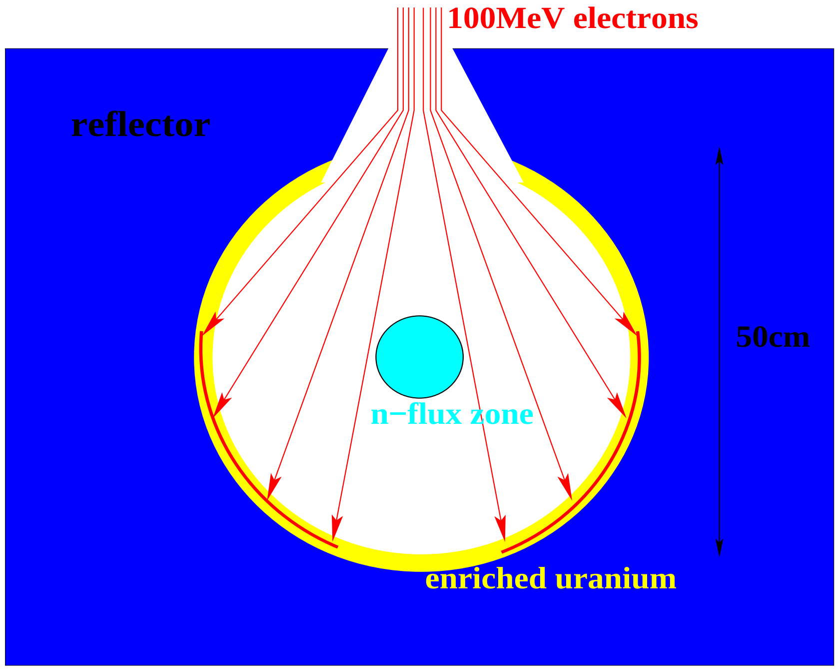

Figure 2: A simplified geometry of the neutron irradiator driven by an electron accelerator. See Table 1 for details.

Zone name	Radius (cm) R_i-R_{i+1}	Thickness (cm)	Material composition
n-flux zone	0-5	5	sample material
e-beam zone	5-25	20	void
u-blanket	25-27	2	enriched U; <20%
reflector	27-127	100	C or Pb or Be or D_2O

Table 1: Neutronics model: zone dimension and material compositions for a neutron irradiator driven by an electron accelerator. Also see Fig. 2

4 Results

A proposed electron target is 2 cm thick and made of enriched uranium (ρ=19 g/cm^3). Its total volume and mass is $\sim$17000 cm^3 and $\sim$323 kg respectively. An electron beam is dispersed at the entrance of the system, so it can interact with nearly half of the actual surface of inner uranium envelope as shown in Fig. 2. We choose 100 MeV electrons since neutron production is nearly linear as a function of the incident beam energy [2], i.e. neutron production is constant for a given beam power as discussed above. Our major observable is the neutron flux in the central sphere with its radius of 5 cm (n-flux irradiation zone in Fig. 2). The characterization of the system is done by testing different reflector-moderator materials and different enrichment of uranium target.

4.1 k_{eff} of the system

k_{eff} is an important parameter of the system for two reasons. Obviously, (a) higher k_{eff} is, higher neutron flux in the n-flux zone will be. On the other hand, (b) k_{eff} should be well below

1 even in accidental situations (e.g., break of the target wall and reflector filling the inner part of the sphere). We suppose that the system can operate safely with k_{eff} ~0.80, while k_{eff} ~0.95 is the maximum value in the case of inner wall failure. These two conditions have defined very precisely the maximum enrichment of the uranium target what is presented in Table 2 together with the corresponding k_{eff} values. In addition, the uranium enrichment below 20% we consider

Reflector material	U enriched by (%)	$k_{eff} \pm 1\sigma$
no reflector	20.0	0.261±0.001
heavy water	1.5	0.821±0.005
beryllium	2.0	0.801±0.004
natural carbon	5.0	0.816±0.004
natural lead	20.0	0.672±0.004

Table 2: Operational k_{eff} as a function of reflector materials and different uranium enrichment.

being the maximum allowed value for this type of application.

4.2 Neutronics of the system

Major neutronics parameters of the system are presented in Table 3. In addition, there is a

Reflector material	Neutrons via photonuclear (%/e)	(γ,fiss) events (%/e)	(n,fiss) events (%/e)	ϕ_{n-zone} $(\frac{n}{cm^2 e})$
no reflector	7.05	1.40	0.65	2.07e-05
heavy water	8.03	1.34	14.36	2.59e-04
beryllium	7.83	1.34	12.57	2.96e-04
natural carbon	7.11	1.35	11.84	2.57e-04
natural lead	7.69	1.43	6.57	1.90e-04

Table 3: Neutronics of the system (normalized per incident electron).

number of important points which have to be emphasized. First of all, the presence of reflector is indispensable to reduce the neutron leakage. In addition, with a help of an effective reflector the enrichment of uranium may be decreased considerably, while still giving comparable neutron flux in the irradiation zone of our interest (see column "ϕ_{n-zone}" in Table 3). Secondly, the reflector will play the role of a moderator, so one can really profit the presence of ^{235}U in the target. Finally, different reflector materials will have different moderation characteristics, what results in different thermalization level of the flux in the n-flux zone as discussed below.

Fig. 3 summarizes the consequences as above. As it is shown in Fig. 3 (on the left), by placing a right reflector material one may increase considerably both the absolute value of the neutron flux (by a factor of ~15) as well as the contribution of thermal neutrons (from ~0% to ~10%). A contribution of fission neutrons due to ^{235}U is easily seen from the neutron time dependence presented in the same Fig. 3 (on the right). In the time range from 1e-08 to 1e-05 s neutrons had not enough time to be thermalized. After that (on their way back from the reflector to the target) they will not only contribute to the thermal part of the total neutron flux but also will create secondary fast fission neutrons via n+^{235}U fission reaction (see the increment of neutron flux in the time range from 1e-04 to 1e-01 s). In this case source neutrons will contribute less than 10% to the total neutron flux in the n-flux zone (aslo see Table 3 for details).

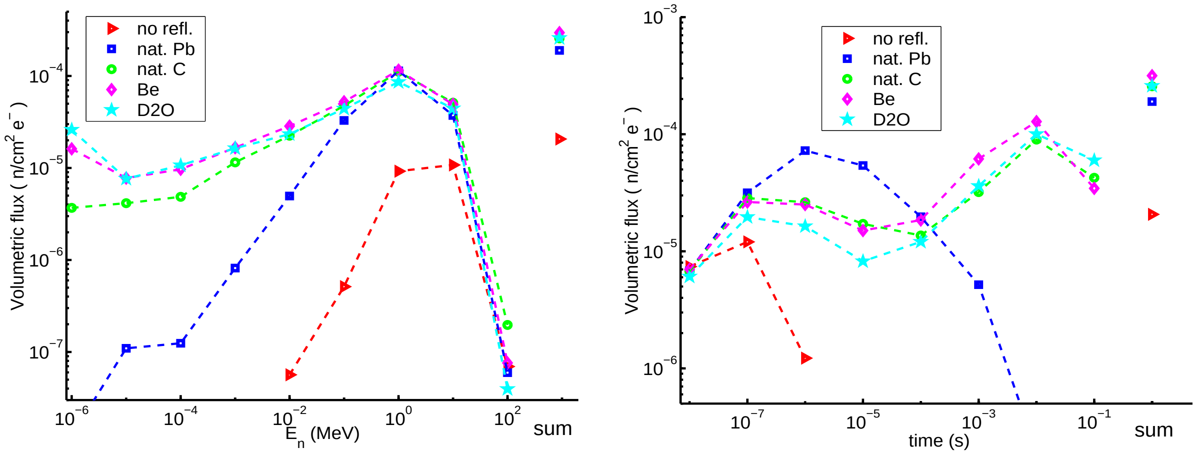

Figure 3: Neutron energy spectra (on the left) and time dependence (on the right) as a function of different reflector material. The estimated flux corresponds to the average volumetric flux in the n-flux zone (see Fig. 2).

4.3 Discussion

Let us assume that our goal is to have a neutron flux of the order of 1e+14$\frac{n}{scm^2}$ to be compatible with a typical experimental reactor installation. It is easy to estimate with a help of Table 2 that in this case one would need an incident 100 MeV electron beam (current) of the order of ∼6 MW (60 mA), i.e. as many as ∼3.7e+17pps. Working with even higher beam power might be not an easy task due to the target heat dissipation. We note that the electron target will be heated not only by the incident beam (∼6 MW) but also by a non negligible fission power being ∼1.8 MW (due to ∼5.6e+16 fiss/s), what results in the total average power density of ∼0.5 kW/cm^3 deposited in the uranium target. In our opinion, this value still could be tolerated but going much further might become difficult if not technologically impossible. In any case, it is also clear that this situation favours a liquid reflector-moderator, which could be used as a coolant at the same time. More detailed study on the target heating-cooling is definitely needed.

In addition, one should also make an estimate for how long the target could operate in normal conditions. We believe that the burnup of ^{235}U will be non negligible at these flux levels. Finally, we would like to mention that the radioprotection and non-proliferation issues should be addressed separately.

5 Conclusions

A non-conventional ADS system has been proposed to produce neutrons via photonuclear reactions. It includes an electron accelerator and a spherical enriched uranium target-blanket (2 cm thick) surrounded by a reflecting material. The system is well sub-critical (k_{eff} <0.8) and uranium enrichment is below 20%. Very encouraging preliminary calculations have been performed using the MCNP code enchanced with a photonuclear capability. It was shown that variable (from 0 to 10 % thermal) neutron fluxes of a few 10^{14} $\frac{n}{cm^2\,s}$ could be obtained for different irradiation purposes. The electron machine at ∼6 MW power and 100 MeV incident energy should be sufficient to produce external neutrons to drive the system.

More detailed calculations related to safety and heat dissipation issues are in progress and will be reported elsewhere.

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