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CHARACTERISTICS OF THE NEUTRON FLUX FROM A D-Li NEUTRON SOURCE

by

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CHARACTERISTICS OF THE NEUTRON FLUX FROM A D-Li NEUTRON SOURCE

Itacil Gomes and Dale L. Smith

ABSTRACT

A D-Li neutron source produces a high flux of neutrons which can be used for testing fusion materials. The characteristics exhibited by the neutron flux inside the test assembly volume of a D-Li neutron source irradiation facility is a function of several design options, such as deuteron energy, beam current, beam cross sectional area, and lithium target configuration, among others. The influence of each of these parameters on the overall performance of the machine, in terms of best results for irradiation of materials for fusion applications, can be inferred by scoping their impact on the uncollided neutron flux magnitude and distribution.

The first part of this paper describes an analysis performed on the uncollided neutron flux (without material inside the test assembly region) for different beam-target configurations for determining the effect of varying the elements of the configuration on the uncollided neutron flux gradient. The second section deals with the neutron energy spectrum from the D-Li reaction and a brief discussion on "fusion reactor spectrum" is also presented. In the third section results from calculations of the volume with uncollided neutron above a threshold value are presented.

1. INTRODUCTION

A D-Li neutron source produces a high flux of neutrons which can be used for testing fusion materials. The characteristics exhibited by the neutron flux inside the test assembly volume of a D-Li neutron source irradiation facility is a function of several design options, such as deuteron energy, beam current, beam cross sectional area, and lithium target configuration, among others. The influence of each of these parameters on the overall performance of the machine, in terms of best results for irradiation of materials for fusion applications, can be inferred by scoping their impact on the uncollided neutron flux magnitude and distribution.

This study was performed to analyze the implications of varying the beam-target configuration on the characteristics of the uncollided neutron distribution inside the test cell. The parameters used in this analysis to evaluate the performance of the different configurations were the neutron flux uniformity (gradients), volume with neutron flux above a specified threshold value, and engineering feasibility of the proposed option. Simple geometries such as single beam incident perpendicular to the lithium jet and two beams incident on the same jet at a defined angle between them presented very good performance when compared with a more sophisticated configuration such as a convergent beam incident on a jet curved in the direction perpendicular to the flow. These simple configurations even presented better results than a more complex configuration of two separated and perpendicular jets with a single beam on each jet.

The first part of this paper describes an analysis performed on the uncollided neutron flux (without material inside the test assembly region) for different beam-target configurations for determining the effect of varying the elements of the configuration on the uncollided neutron flux gradient. The second section deals with the neutron energy spectrum from the D-Li reaction and a brief discussion on "fusion reactor spectrum" is also presented. In the third section results from calculations of the volume with uncollided neutron above a threshold value are presented.

2. UNCOLLIDED NEUTRON FLUX INTO THE TEST CELL

The uncollided neutron flux magnitude and spatial distribution are significant parameters in comparing neutron irradiation facilities. Associated with the neutron energy spectrum it can provide, as a first approximation, a basis for comparison of the expected performance of different neutron sources. In a D-Li facility the neutron source term is directly proportional to the deuterium beam current, and, as a consequence, so is the neutron flux strength inside the test cell.

The evaluation of the uncollided neutron flux distribution inside the test cell is, to some extent, the simplest calculation that can be performed for the test cell volume, since it neglects the reflection of neutrons from the test specimens and structural materials and there is no material present to generate gamma-rays.

2.1 Monte Carlo Model Used for Calculating the Neutron Flux Distribution

A source routine for the MCNP code [1] was written based on probability density distributions described elsewhere [2]. The test cell region, lithium jet, and back plate were modeled using standard MCNP procedures. The uncollided neutron flux was calculated for two different incident deuteron energies (35 and 40 MeV). The geometric configuration used was a 1.90 cm thick lithium target, a 0.16 cm stainless steel back plate and a 50x100x100 cm³ test cell, the 50 cm being the dimension along the beam direction. The only materials included in this configuration were the lithium (natural abundance) of the lithium jet and the back plate material (SS-316). To estimate the neutron flux 22 surfaces were placed inside the test cell parallel to the lithium jet. The subroutine Tallyx of the MCNP code was written to allow boundary crossing estimation into small segments of each surface. Each surface was divided into 256 segments of area in the first quadrant and the symmetry of the neutron flux to the "xz" and "xy" planes was used to perform the estimation to the 256 surface bins. The area of each surface bin was a function of the beam cross sectional area and of the position of the bin relative to the region of incidence of the beam. The total number of surface bins, for which the neutron flux was estimated, inside the 50x100x100 test cell volume was 22,528. Fifty neutron energy bins and 21 gamma-rays energy bins were used during the calculations. The fractional standard deviation of the results was considered very good, with an average value of about 2% within the energy groups, and below 0.5% for the totals over the energy for any of the 22,528 cells.

Figure 1 shows a 3D view of the uncollided neutron flux distribution inside the test cell for a 3x1 cm beam cross sectional area with 0.25A and 35 MeV deuterons. The axis labeled as y-direction represents the direction along the 3 cm dimension of the beam. Figure 2 shows a 2D view of the neutron flux profile along the beam axis direction for the same beam as Figure 1 (note that $x = 0$ represents the beginning of the test assembly region). Figure 3 displays a 2D view of the same distribution in the direction normal to the beam. As can be noticed in these figures, the value of the uncollided neutron flux has, for a 3x1 cm beam size, a very large variation along both directions, parallel and perpendicular to the beam.

2.2 Comparison of Some Possible Beam-Target Configurations

Several beam-target configurations were considered in this work with the aim at minimizing the neutron flux gradient and, at the same time, increasing the available volume with neutron flux and/or nuclear responses above a specified threshold value. In this subsection a brief description of the configurations considered is presented.

The first configuration considered is a single collimated beam incident perpendicularly to the lithium target. Another configuration consists of two beams perpendicular to each other incident in two separate lithium jets. A third configuration uses a beam convergent on a curved jet in such a way that at each point of the surface of the jet the deuterons would be incident perpendicularly to the tangent of the lithium jet. A fourth configuration has two deuteron beams incident on the lithium jet at a defined angle from each other in such a way that they would compose a single spot area on the lithium target. Following is brief discussion of each of these configurations.

2.2.1 One single beam configuration

This is the simplest configuration of all those presented here. This configuration with a 3x1 cm² beam cross sectional area, 100 mA beam current and 35 MeV deuteron energy was the beam-target configuration adopted for the FMIT [3] design. The configuration analyzed in this work has a single beam with uniform deuteron density distribution over the beam cross sectional area impinging on a fast flowing lithium jet. The direction of the beam is perpendicular to the lithium jet. The main concern in this configuration is to maintain the stability of the jet through an appropriate jet velocity to avoid excessive heating. The lithium jet constraints relative to the maximum energy deposition on the bulk of the jet per cubic centimeter can be accommodated through the enlargement of the beam cross sectional area and/or increasing jet velocities. The enlargement of the beam cross sectional area is also envisaged as one way to reduce the neutron flux gradient inside the test cell. Figure 4 displays the gradient of the uncollided neutron

Figure 1. 3D view of the uncollided neutron flux distribution inside the test assembly volume for a deuteron beam with $3 \times 1 \text{ cm}^2$ cross sectional area, 250 mA of current, and 35 MeV of incident deuteron energy.

Figure 2. Neutron flux distribution along the beam direction for a deuteron beam with $3 \times 1 \text{ cm}^2$ cross sectional area, 250 mA of current and 35 MeV of incident deuteron energy.

Figure 3. Uncollided neutron flux distribution in the direction perpendicular to the beam for a deuteron beam with 3x1 cm² cross sectional area, 250 mA of current, and 35 MeV of incident deuteron energy.

Figure 4. Uncollided neutron flux gradient in percentile per millimeter for six different beam cross sectional areas with the same 250 mA current, and same 35 MeV incident deuteron energy.

flux in percentile per millimeter inside the test cell for six different beam cross sectional areas. It can be seen that the larger the beam cross sectional area the lower the gradient inside the test cell.

2.2.2 Two beams on two separated lithium jets

The two perpendicular beams configuration was proposed [4] as a way to reduce the neutron flux gradient inside the test cell and increase the available volume for testing materials. Two separated beams (each one carrying an half of the total beam current) are incident on two separate lithium jets flowing along two adjacent faces of the test assembly volume. The two lithium jets would be perpendicular to each other as well as to their associated deuteron beams. In such a configuration, the neutron flux distributions produced by the two separate beams overlap and, as a consequence, the gradient of the flux may decrease inside the test cell. One of the problems with this approach is that the possibility of reducing the gradient is limited because the compensation of the attenuation can take place only in a very restricted volume. In other words, this scheme works well in a very limited volume inside the test cell; other regions are almost not affected at all. Other possible problems are the added complexity from having two separated lithium jets, the increased radiation damage to the support equipment placed on the sides of the lithium jets, and the reduced access to the test cell volume.

Figure 5 presents the neutron flux distribution profile inside the test cell along the direction of the beam for a beam size of 3x1 cm. The curves represent the uncollided neutron flux distribution for a single beam and for two-perpendicular beam configurations. There are four curves for the two-perpendicular beam configuration each one representing a different distance from the center line of the beam to the corner of the test assembly. As can be seen, for each distance from the corner there is a small region at which the neutron flux profile is flattened, indicating that only a small part of the test cell assembly benefits from splitting the incoming deuterons into two perpendicular beams. It should also be noticed that the peak value of the flux is reduced by a factor of two using the two-perpendicular-beam configuration.

2.2.3 One beam incident on a curved jet

This option is proposed here as a way to reduce the neutron flux gradient inside the test cell. The idea is to compensate the angular divergence of the generated neutrons (that produces the so called geometric attenuation of the neutron flux) making the incoming deuterons to converge. The deuteron beam would be focused to the center of the curvature of the lithium jet and, as a consequence, each incident deuteron would enter the lithium target perpendicularly to the tangent of the jet at that point. This configuration would have the jet flowing rectilinearly vertically and the curvature would be in the direction perpendicular to the jet flow. Figure 6 presents a plan view of

the geometric model of this configuration used in the analyses. The parallel lines represent the surfaces at which the neutron flux was estimated. The problems with this configuration are basically two: first, it is not straightforward to have a stable curved jet in the direction perpendicular to the flow, and if a curved back plate is required to maintain the stability of the jet (the curvature of the back-plate to stabilize the jet has to be in the direction of the flow) it may be difficult to meet both curvature requirements. The second problem is relative to focusing the deuteron beam and the possible necessity of having magnets inside the test cell room close to the neutron source.

Figure 7 is a 3D plot of the neutron uncollided flux distribution inside the test assembly. This figure shows that a very good uniformity of the neutron flux is achieved with this configuration, mainly perpendicular to the beam direction. Figure 8 displays a plot of the neutron uncollided flux profile perpendicular to the beam direction for different distances, inside the test assembly, from the back plate. It can be noticed that up to 8.0 cm inside the test assembly the neutron flux distribution is essentially flat.

2.2.4 Two beams incident at an angle on the same lithium jet

This configuration has two basic objectives, one is to reduce the neutron flux gradient and another is to accommodate the possible need for two separated beams to deliver the 250 mA of current. The characteristic of this configuration is to have two deuteron beams incident, without overlapping, on a single lithium target in such a way that they define a beam impingement area twice as large as that of one of the beams. Each of the beams carries half of the total current (for the 250 mA-case it represents 125 mA per beam). In the case analyzed here two 10x20 cm² beams are incident on the lithium target to form a single impingement area of 400 cm² (20x20 cm). The angle between the beam-direction and the normal to the lithium jet was varied from 5° to 30° to find the optimum value.

Figure 9 displays the neutron flux distribution along the beam direction for the 4 (four) angles considered (5°, 10°, 20°, and 30°). It can be noticed that after 50 cm, the neutron flux attenuation is minimum for the 5° case and maximum for the 30° case. On the other hand, for the first 5 cm, the attenuation of the 30° case is the minimum one and of the 5° is the maximum. Figure 10 displays the neutron flux distribution in the direction perpendicular to the beam at a distance of 8 cm from the lithium jet for the 4 angles analyzed. As can be seen from Figures 9 and 10, there is no dramatic change in the flux gradient due the angle between the beams and the figures do not present conclusive evidence of one of the angles as the optimum. Further analysis of the available volume above a threshold value is required to select one of the angles.

Figure 5. Uncollided neutron flux distribution along the direction of the beam for one single beam configuration and for two-perpendicular beams configuration with four different distances between the center of the beam and the corner of the test assembly. The beam cross sectional area is $3 \times 1 \text{ cm}^2$ for all cases, as well as the beam current (250 mA) and the incident deuteron energy (35 MeV).

Figure 6. View of the XY-plane of the geometric model used for calculating the curved jet configuration.

Figure 7. Neutron uncollided flux distribution for the curved jet configuration. Distribution inside the test assembly in the $Z=0$ cm plane. The beam spot area on the lithium target is 20×20 cm², the beam current 250 mA, and the deuteron energy is 35 MeV.

Figure 8. Uncollided neutron flux distribution for the curved jet configuration. Distribution inside the test assembly in the Y -direction at the plan $Z=0$ cm. The deuteron beam has 250 mA of current, deuteron energy of 35 MeV, and beam spot area on target is 20×20 cm².

Figure 9. Uncollided neutron flux distribution for the two-beams on the same target configuration considering four different angles between the beam directions and the normal to the lithium jet. Distribution along the beam direction at the center of the beam spot area.

Figure 10. Uncollided neutron flux distribution for the two-beams on the same target configuration, considering four different angle between the beam directions. The curves show the profile in the direction perpendicular to the beam (Y-direction).

2.3 General Comments About Neutron Flux Uniformity

Figure 11 displays the flux profile along the beam direction for the four types of configuration analyzed using a $20 \times 20 \text{ cm}^2$ beam cross sectional area for each beam (except the 2 beams at an angle configuration which has 2 beams of $10 \times 20 \text{ cm}^2$ each). The total beam current in each case analyzed is 250 mA. Figure 12 displays the neutron flux profile perpendicular to the beam direction of the same distributions as Figure 11.

Based on Figures 11 and 12 it is possible to draw some conclusions about the uniformity of the neutron flux distribution inside the test assembly region. As a general conclusion, the curved target presents the lowest gradient of all configurations analyzed (when considering both, parallel and perpendicular to the beam directions). The two beams at an angle configuration also decreases the flux gradient inside the test assembly region. The single beam configuration can have its performance enhanced, in terms of uniformity of the flux, by enlarging the beam cross sectional area, but for similar cases it is less uniform than the two above mentioned configurations. The two-perpendicular beam configuration does not present noticeable advantage over the other configurations, except over a very restricted volume.

3. NEUTRON ENERGY SPECTRUM INSIDE THE TEST ASSEMBLY REGION

In talking about the neutron energy spectrum of a fusion reactor there is a tendency to think of neutrons with 14 MeV as the "characteristic spectrum" of a fusion reactor. In fact, each fusion reactor design has a different neutron energy spectrum depending on the kind of blanket, coolant, shielding, and structures used in the design. Also, the location inside the reactor at which the material will be used is important in determining the neutron energy spectrum. The neutrons produced by the D-Li nuclear reaction have an energy spectrum similar but not identical to the neutron energy spectrum of a fusion reactor first wall. The neutron energy spectrum of the D-Li reaction exhibits a high-energy tail (neutron energies above 20 MeV) which is not present in a "characteristic fusion reactor neutron energy spectrum." Also, the energy spectrum of a fusion reactor at positions close to the first wall presents a well defined peak at 14 MeV which is not so visible in the D-Li neutron energy spectrum.

Figure 13 displays three curves of normalized neutron energy spectra. The ordinate in these curves is the percentage of neutrons within each 1 MeV energy interval. There are two curves for the D-Li neutrons and one for the first wall of the ITER-R design with liquid metal blanket (lithium as coolant and breeder). The curves for the D-Li neutron source correspond to two different positions in the test assembly region; one at the back plate and another 10 cm inside the test assembly. Both positions are on the axis of the deuteron beam. It can be seen that the

Figure 11. Uncollided neutron flux distribution along the beam direction for the four beam-target configurations analyzed.

Figure 12. Uncollided neutron flux profile in the direction perpendicular to the beam (Y-direction) for the four beam-target configurations analyzed.

differences in the spectra are not so dramatic that they portray completely different irradiation environments. The spectrum produced by the D-Li neutrons varies more smoothly than the ITER-Li first wall spectrum in the interval from 1 to 14 MeV. Also, the ITER-Li first wall spectrum has more neutrons into the 0-1 MeV energy interval than the D-Li neutron source. Overall, these spectra can be considered sufficiently similar for material testing purposes, since they have neutrons in all energies of interest. The D-Li high neutron energy tail has a flux magnitude small enough to be negligible (many of these conclusions will be better supported when induced nuclear responses from both types of spectra are compared.)

In the case of the D-Li neutron energy spectrum, changes in the beam cross sectional area affect the neutron energy spectrum too. Figures 14 and 15 present the normalized neutron energy spectrum of the D-Li neutron source at the same locations as Figure 13 for six different beam cross sectional areas. It can be seen that the larger the beam cross sectional area the softer is the neutron energy spectrum (i.e. more neutrons are present, proportionally, in the lower energy intervals.)

Figure 13. Comparison of the normalized neutron energy spectra from the D-Li neutron source and from the ITER (lithium blanket) first wall.

Figure 14. Normalized neutron energy spectra at the back plate for 6 different beam spot areas for 35 MeV deuterons.

Figure 15. Normalized neutron energy spectra at 10 cm in the beam direction from the back plate for six different beam spot areas for 35 MeV deuteron energy.

4. VOLUME WITH UNCOLLIDED FLUX ABOVE A GIVEN THRESHOLD

The availability of a region inside the test cell with a neutron flux or nuclear response above a given threshold is another important parameter to be considered during the design phase of a neutron source. The volume of the region with an uncollided neutron flux with magnitude above a given lower limit is a measure of the performance of a given combination of the incident energy and current of the deuteron beam and lithium target thickness. Supplementary features of a configuration under consideration such as the number of deuteron beams incident on the target, the distance and angle between the beams, the cross sectional area of the beam, and the ion density distribution over the beam cross sectional area also can be evaluated in terms of the total available volume above a given threshold value. Whereas this measure is not an absolute indicator of the performance, it is a valuable criterion combined with other key parameters, in the design development process.

Table 1 presents results of the available volume with uncollided neutron flux above an indicated threshold for a $3 \times 1 \text{ cm}^2$ beam cross sectional area for three different deuteron energies and the same 250 mA deuteron current. The configurations used in this table are: a) one single beam carrying all the 250 mA current and b) two perpendicular beams each carrying one half of the current. For the two perpendicular beams configuration 4 (four) cases were considered by varying the point of incidence of the beam relative to the corner of the test cell. It can be seen that the use of two-perpendicular beams configuration presents advantages in terms of the available volume only when the threshold considered is low enough to permit a significant interference between the two beams or when the distance from the center of the beam to the corner of the test cell is small enough to optimize the relationship between threshold value and volume for that particular threshold. In the case in which the threshold is high ($1.25 \times 10^{15} \text{ n/cm}^2 \cdot \text{sec}$) splitting the beam in two perpendicular lines results in significant reduction of the available volume.

The neutron source strength is proportional to the deuteron energy; the higher the deuteron energy the higher is the neutron generation rate (also higher volume) for the same beam current. Figure 16 displays the available volume above a specified neutron flux threshold value for 35 MeV and 40 MeV deuterons as a function of the uncollided neutron flux threshold value for a $7 \times 7 \text{ cm}$ deuteron beam with 250 mA current. As can be seen, the available volume increases considerably with an increase in deuteron energy from 35 MeV to 40 MeV. The factor of increase is about two over a large range of threshold values and increases even more as the threshold value goes over 1×10^{15} . It can be seen that in a logarithmic scale the relationship between available volume and neutron flux threshold value is basically linear up to the point where the neutron flux threshold value gets near the maximum available flux. After this point a fast drop in the available volume is observed.

Table 1
Volume with Neutron Flux above Indicated Threshold for a 250 mA Deuteron Current

Configuration Type	Deuteron Incident Energy		
	30 MeV	35 MeV	40 MeV
Volume (cm³) with Neutron Flux Above 1.25x10¹⁵ n/cm².sec			
One single beam with 3x1 cm cross section	19	38	66
Two perpendicular beams:			
Beams placed 20 cm from the corner (3x1 beams with half of the one beam type current)	7	20	40
Beams Placed 15 cm from the corner	7	20	41
Beams Placed 10 cm from the corner	7	21	41
Beams Placed 5 cm from the corner	8	25	66
Volume (cm³) with Neutron Flux Above 1.25x10¹⁴ n/cm².sec			
One Single Beam with 3x1 cm cross section	930	1550	2400
Two perpendicular beams:			
Beams placed 20 cm from the corner (3x1 beams with half of the one beam type current)	690	1290	2370
Beams Placed 15 cm from the corner	830	1610	2650
Beams Placed 10 cm from the corner	1020	1700	--

Figure 17 displays the available volume as a function of the uncollided neutron flux threshold value for 6 beam cross sectional areas. It can be seen that the available volume is roughly independent of the beam cross sectional area when the threshold value is not close to the maximum flux for a given cross sectional area. Also, beams with square cross sections have an advantage, in terms of available volume, over beams with rectangular ones.

Figure 16. Volume with uncollided neutron flux above a specified threshold as a function of the threshold value for 35 MeV and 40 MeV deuteron energy, 7x7 beam cross sectional area and 250 mA of beam current.

Figure 17. Volume above a specified uncollided neutron flux threshold value as a function of the threshold value for six different beam cross sectional areas (35 MeV).

Figure 18 displays a comparison of the available volume for the 2 beams at an angle configuration as a function of the uncollided neutron flux threshold value. Each carries an half of the total current and is incident on the same target. Different angles of incidence relative to the normal to the free surface of the lithium jet have been considered. It can be seen that of the 4 angles analyzed the 20° angle produces the highest volume of the 4 angles analyzed (with this analysis it is possible to choose one of these angles as the optimum; it is not possible to conclude the optimum angle by only analyzing the gradient of the flux).

Figure 19 displays the available volume for the four configurations analyzed as a function of the uncollided neutron flux threshold value. The legend of the plot indicates the configuration associated with each curve, which are: 1) one single beam [1 beam]; 2) two perpendicular beams incident on two separated lithium targets [2b-90deg]; 3) two beams incident on the same lithium target at a 20° angle to the normal to the lithium target [2b-20deg]; and 4) one single convergent beam incident on a curved lithium jet [curved]. All cases in this plot have the same parameters as previously described, which are, 20x20 cm² beam cross sectional area at the jet, 250 mA current, and 35 MeV deuteron energy. It can be seen that the uniformity of the neutron flux translates itself in a larger available volume, since the two configurations which have resulted in a more uniform uncollided neutron flux distribution (2 beams incident at 20° to the normal and curved jet) are the ones which present the highest volume with uncollided neutron flux above a specified threshold value.

5. CONCLUSIONS

The D-Li neutron source provides a well-behaved neutron flux distribution inside the test assembly volume. By varying the beam-target configuration, it is possible to change some of the characteristics of the neutron flux, some considerably such as peak neutron flux and energy deposition on the target, and others less so such as neutron energy spectrum and volume with neutron flux above a threshold value.

The D-Li neutron energy spectrum provides an acceptable substitute for the fusion reactor spectrum since it contains neutrons with energies over the range of a fusion spectrum. Further analysis, presented elsewhere [5], of the helium to DPA ratio supports the above statement, by demonstrating that ratios very close to a first wall helium to DPA ratio can be achieved using the D-Li neutron source.

This analysis demonstrates that it is possible to improve the performance of the D-Li neutron source by proper selection of the design parameters.

Figure 18. Volume with uncollided neutron flux above a specified threshold as a function of the threshold value for the two beams on the same target configuration for different angles between the beam direction and the normal to the target.

Figure 19. Volume with uncollided neutron flux above a specified threshold as a function of the threshold value for the four beam-target configurations analyzed.

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