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Fission–fusion neutron source

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ABSTRACT

In order to meet the requirements of fusion power reactors and nuclear waste treatment, a concept of fission–fusion neutron source is proposed, which consists of a LiD assembly located in the heavy water region of the China Advanced Research Reactor. This assembly of LiD fuel rods will be irradiated with slow neutrons and will produce fusion neutrons in the central hole via the reaction ^{6}Li(n,α). More precisely, tritium ions with a high energy of 2.739 MeV will be produced in LiD by the impinging slow neutrons. The tritium ions will in turn bombard the deuterium ions present in the LiD assembly, which will induce fusion reaction and then the production of 14 MeV neutrons. The fusion reaction rate will increase with the accumulation of tritium in LiD by the reaction between tritium and deuteron recoils produced by the 14 MeV neutrons. When the concentration of tritium reaches $0.5 \cdot 10^{22}$ and the fraction of fusion reactions between tritium and deuteron recoils approaches 1, the 14 MeV neutron flux is doubled and redoubled, an so forth, approaching saturation in which the tritium produced at a time t is exhausted by the fusion reactions to keep constant the tritium concentration in LiD.

1. Introduction

A key issue in the development of fusion power reactors with a high thermal efficiency is the availability of adequate high-temperature materials. In fusion power reactors, the materials will be exposed to plasma particles and electromagnetic radiation and will suffer from irradiation by an intense flux of 14 MeV neutrons, which will engender a strong degradation of the material properties. There is a fundamental need to build an intense high energy neutron source to serve as a tool for (1) calibrating and validating the data generated using fission reactors and particle accelerators, and (2) qualifying materials up to about full lifetime of anticipated use in a DEMO-type reactor. The primary mission of the International Fusion Material Irradiation Facility (IFMIF) is to generate a materials database to be used for the design and construction of various components, and for the licensing and the assessment of the safe operation of a DEMO-type reactor.

IFMIF will be a deuteron accelerator-based high energy neutron source, and the specimens to be irradiated will be located just behind the lithium target. Due to engineering and economic considerations the volume of the high flux test module in IFMIF will be only half a liter in the high flux position (20–50 dpa/fpy). This volume should be sufficient to achieve within five years for a few materials a 80 dpa database needed for DEMO-predesign and for a variety of materials a 150 dpa database within about 20 years [1]. The cost is 2620.9 MICF (including construction, 20 years operation, and decommissioning) [2].

A fusion neutron source can also be obtained by slow neutrons irradiating a LiD assembly. Assuming an assembly of LiD fuel rods (ϕ 10 mm) with a center hole (ϕ 50 mm), located in the heavy water region of the CARR (China Advanced Research Reactor), a density of LiD equal to 90% of the theoretical density, with 90% enrichment of ^{6}Li and 10.5% tritium pre-implantation, the flux of 14 MeV in the ϕ 50 mm centre hole will reach $4.3 \cdot 10^{13}$ n/cm^2 s.

According to the principle of the fission–fusion neutron source, the high flux reactor will be composed of two regions: a high flux fission region in the center and a LiD fusion region surrounding the central fission region. The fission–fusion reactor will have the advantage to use nuclear fuel and to burn-up actinide elements in the central fission region to decrease the quantity of highly radioactive waste. Therefore, the research on the fission–fusion neutron source in the heavy water region of the CARR is of strong interest for potential application of nuclear energy.

2. Principle of the fission–fusion source

2.1. Fusion reaction rate inside LiD in the presence of a fission neutron field

When LiD is located in a fission neutron field, the nuclear reaction ^{6}Li(n,α) occurs as

$$^6\mathrm{Li} + \mathrm{n} \rightarrow {}^3\mathrm{T} + {}^4\mathrm{He} + 4.794\,\mathrm{MeV} \quad (1)$$

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When the neutron energy is less than 0.625 eV, the cross section σ_f of ^{6}Li(n,α) reaches $9.5 \cdot 10^2$ barns and the reaction heat Q reaches 4.794 MeV [3]. According to the conservation of energy and momentum, the energy of the α particles and the tritium ions are 2.055 and 2.739 MeV, respectively. The tritium ions with a high energy between 0.1 and 2.739 MeV bombard the deuterons, producing D–T fusion reactions:

$$\mathrm{D} + \mathrm{T} \to {}^4\mathrm{He} + n(14\,\mathrm{MeV}) + 3.43\,\mathrm{MeV} \tag{2}$$

Such fusion reactions produce 14 MeV neutrons and α particles with an energy of 3.43 MeV, the cross section of fusion reactions reaching 4.95 barns. The tritium ions with an energy of 2.739 MeV and α particles with an energy of 2.055 or 3.43 MeV can ionize LiD, so creating adequate conditions for fusion reactions. At the same time, these particles, especially the 14 MeV neutrons, can produce a recoil flux of deuterons in LiD, these energetic deuterons bombarding in turn the residual tritium to produce fusion reactions. The process is illustrated in Fig. 1. When a slow neutron interacts with ^{6}Li in LiD to induce the nuclear reaction ^{6}Li(n,α), producing a tritium ion (T) and an α particle (He), the tritium ion then interacts with a deuteron on its path in LiD to produce a fusion reaction. The fusion neutron collides with a deuteron in LiD to produce a recoil flux of deuterons (D) with energies in the range of 0.01–12.444 MeV. These deuterium ions interact in turn with residual tritium to produce fusion reactions and therefore fusion neutrons and α particles. These fusion neutrons produce further recoil fluxes and therefore more fusion neutrons, like in an in-chain reaction.

Therefore, the fusion reaction rate may be expressed as the following:

$$\dot{F}_{fu} = \dot{F}\mu_T\sigma_{fu}N_D + N_T\int \phi(E_r)\sigma_{fu}(E_r)dE_r, \tag{3}$$

where $\dot{F}$ is the reaction rate of ^{6}Li(n,α), μ_T is the range of tritium ions with an energy of 2.739 MeV; σ_{fu} is the cross section of fusion reactions, N_D and N_T are the deuteron and triton number in LiD, respectively, $\phi(E_r)dE_r$ is the recoil flux of deuterons with an energy in the range [E_r, dE_r]. The fusion cross section between deuterium ions of energy E_r and tritium ions, $\sigma_{fu}(E_r)$, is given by [4]:

$$\sigma_{fu}(E_r) = \frac{6\times10^4}{E_r}\exp[-47.40/\sqrt{E_r}], \tag{4}$$

σ_{fu} and E_r being expressed in barns and in keV, respectively. When E_r is above 100 keV, σ_{fu} is equal to 4.95 barns. According to formula (4), the average value of σ_{fu} is larger than 5 barns in the range of 0.1–10 MeV. Considering the deuteron recoil flux produced by the fusion neutrons, the second term of formula (3) is proportional to the fusion neutron production rate $\dot{F}_{fu}$, and we define,

$$v = \frac{\int_{E_r}^{\Lambda E_n^{\max}} \phi(E_r)\sigma_{fu}(E_r)dE_r}{\dot{F}_{fu}} \tag{5}$$

The fusion reaction rate from the formula (3) can be then written as,

$$\dot{F}_{fu} = \frac{\dot{F}\mu_T\sigma_{fu}N_D}{1 - vN_T} \tag{3'}$$

When $vN_T = 0.5$, one obtains $\dot{F}_{fu} = 2\dot{F}\mu_T\sigma_{fu}N_D$. When vN_T approaches $1-\mu_T\sigma_{fu}N_D$, $\dot{F}_{fu}$ reaches the saturation value $\dot{F}$, i.e., the fusion reaction rate is equal to the tritium production rate at a time t and the tritium concentration remains constant.

2.2. Tritium concentration in LiD

The change rate of tritium concentration is equal to the tritium production rate minus the consumption rate. The nuclear reaction rate of ^{6}Li(n,α), $\dot{F}$, is given by:

$$\begin{aligned}\dot{F} &= \phi\sigma_f{}^6N_0\exp(-\sigma_f\phi t) \approx \phi\sigma_f{}^6N_0(1-\phi\sigma_f t)\\ &= \dot{F}_0(1-\phi\sigma_f t), \quad \text{when} \quad \phi\sigma_f t\langle 0.2\end{aligned} \tag{6}$$

where ^{6}N and ^{6}N$_0$ are the concentration at a time t and the initial concentration of ^{6}Li in LiD, respectively, while ϕ, σ_f and t are the neutron flux in the neutron field, the cross section of the ^{6}Li(n,α) reaction, and the irradiation time, respectively. $\dot{F}_0$ is the initial nuclear reaction rate of ^{6}Li(n,α). Therefore, the change rate of tritium concentration in LiD can be written as:

$$\frac{dN_T}{dt} = \dot{F} - (\dot{F}\mu_T\sigma_{fu}N_D + N_T\int \phi(E_r)\sigma_{fu}(E_r)dE_r) \tag{7}$$

As $\int\phi(E_r)\sigma_{fu}(E_r)dE_r$ is proportional to $\dot{F}_{fu}$, ν is independent of t. The Eq. (7) can be then written as:

$$\frac{dN_T}{dt} + v\dot{F}_{fu}N_T = \dot{F}_0(1-\mu_T\sigma_{fu}N_D) - \dot{F}_0(1-\mu_T\sigma_{fu}N_D)\phi\sigma_f t \tag{8}$$

The solution of the above equation is given by:

$$N_T = e^{-v\int\dot{F}_{fu}dt}[\int[\dot{F}'_0 - \dot{F}'_0\phi\sigma_f t]e^{v\int\dot{F}_{fu}dt}dt + C],$$

where

$$\dot{F}'_0 = \dot{F}_0(1-\mu_T\sigma_{fu}N_D)$$

As $\mu_T\sigma_{fu}N_D \sim 1.913\cdot10^{-3} \ll 1$, one gets $\dot{F}'_0 \sim \dot{F}_0$. At the beginning of the irradiation, the fusion reaction rate is equal to:

$$\dot{F}_{fu} \approx \dot{F}_{fu1} = \dot{F}_0\mu_T\sigma_{fu}N_D(1-\phi\sigma_f t)$$

We define

$$\dot{F}_{fu0} = \dot{F}_0\mu_T\sigma_{fu}N_D = \phi\sigma_f{}^6N_0\mu_T\sigma_{fu}N_D$$

Therefore, the tritium concentration at a time t is given by:

$$N_T = e^{-(v\dot{F}_{fu0}t - \frac{1}{2}\dot{F}_{fu0}v\phi\sigma_f t^2)}[\int[\dot{F}'_0 - \dot{F}'_0\phi\sigma_f t]e^{v\dot{F}_{fu0}t-\frac{1}{2}\dot{F}_{fu0}v\phi\sigma_f t^2}dt + C]$$

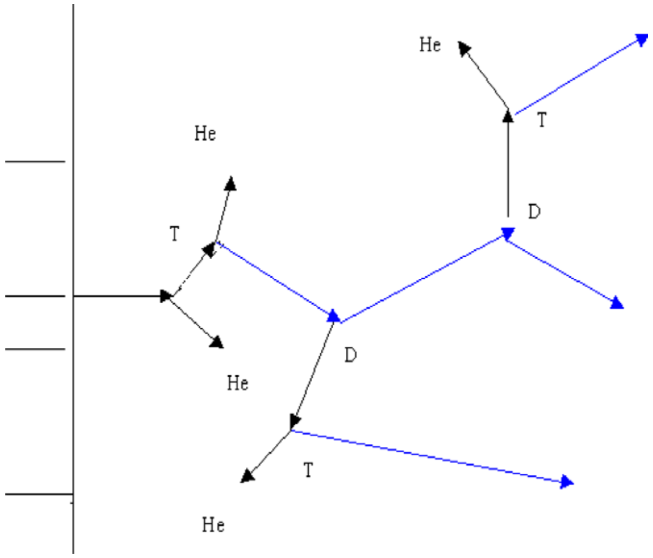

Fig. 1. Process of production of fusion neutrons by slow neutrons in LiD. Each cross point refers to a collision point and a given nuclear reaction. The first cross point refers to the ^{6}Li(n,α) reaction that produces a tritium ion (T) and an α particle (He). The second cross point refers to the fusion reaction between the tritium ion and a deuteron (D) in LiD. The blue lines represent fusion neutrons that bombard deuterons in LiD to produce a D recoil flux. D recoils interact with the deposited tritium to produce fusion neutrons and α particles. These fusion neutrons further produce more recoils that produce more fusion neutrons.

Considering the initial conditions ($N_T = 0$ at $t = 0$), the integral constant can be determined. Therefore, the tritium concentration N_T in LiD is found to be equal to:

$$N_T = \frac{1}{v\mu_T\sigma_{fu}N_D}\left[1 - e^{-v\dot{F}_{fu0}(t-\frac{1}{2}\phi\sigma_f t^2)}\right] \tag{9}$$

When $v\dot{F}_{fu0}t$ is small, the tritium concentration may be expressed as:

$$N_T = \dot{F}_0 t - \frac{1}{2}\dot{F}_0\phi\sigma_f t^2 \tag{9'}$$

3. Fusion reaction probability of tritium and deuteron

Tritium ion with the energy 2.739 MeV in ^{6}Li(n,α) reaction not only interacts with deuteron nucleus inducing fusion reaction, but also interacts with electrons to dissipate the energy. The collision cross section between tritium and electron could simply be estimated by the coulomb scattering cross section σ_C [4]

$$\sigma_c \approx (e^2/\mathrm{m_e v_i^2})^2$$

in which $\mathrm{v_i}$ is the initial velocity of tritium ion. The energy loss of tritium per collision is approximate to $\Delta E = \frac{\mathrm{m_e}}{M_T}E_i$, $\mathrm{E_i}$ is the initial energy of tritium ion; $\mathrm{m_e}$ and M_T are the mass of electron and tritium respectively. Therefore, the emitted tritium in ^{6}Li(n,α) reaction interacts with electron to produce energy loss rate as

$$\frac{dE}{dt} = n_e\sigma_C \mathrm{v_i}\frac{\mathrm{m_e}}{\mathrm{M_T}}\mathrm{E_i} = \mathrm{n_e}\left[\left(\frac{\mathrm{e}^2}{\mathrm{m_e v_i^2}}\right)^2\frac{\mathrm{m_e}}{\mathrm{M_T}}\right]\mathrm{v_i E_i}$$
$$= \mathrm{n_e}\left[\left(\frac{\mathrm{e}^2}{2\mathrm{E_i}}\right)^2\frac{\mathrm{M_T}}{\mathrm{m_e}}\right]\mathrm{v_i E_i} \tag{10}$$

in which n_e is the electron density, the quantity in square brackets is corresponding to the effective cross section of dissipating whole initial energy of tritium nucleus and described as σ_e. When $\mathrm{E_i} = 2.739$ MeV,

$$\sigma_e \approx \left[\left(\frac{14.4\times10^{-8}}{2\times2.739\times10^6}\right)^2\frac{3\times1.6726\times10^{-24}}{9.109\times10^{-28}}\right]$$
$$= 3.8064\times10^{-24}(\mathrm{cm}^2)$$

The cross section of fusion reaction between the tritium nucleus with energy larger than 0.1 MeV and deuteron nucleus is 4.95×10^{-24} (cm^2) which is larger than σ_e. It means that the fusion reaction play a main role in the whole process.

About the fusion reaction of deuteron recoil flux to tritium nucleus, because of the wide energy range of D recoil flux, the highest energy reaches to 12.444 MeV and σ_e is 1.8441×10^{-25} cm^2 which is much less than the cross section of fusion reaction. When the energy of deuteron nucleus is 0.1 MeV, σ_e reaches to 1.9035×10^{-21} (cm^2) and the ratio of D–T fusion reaction cross section to σ_e is 2.6004×10^{-23}. Because the deuteron recoil flux in LiD not only interact with tritium nucleus to induce fusion reaction, but also dissipates the energy by the collision with electron, therefore the fusion reaction is only a fraction of all reaction which can be described as

$$p_{fu} = \frac{\sigma_{fu}}{\lambda\sigma_e + \sigma_{fu}} \tag{11}$$

in which λ is a factor for the effect of ionization degree in LiD. If the electrons in LiD are in ionization state, although the deuteron nucleus participates to collision with electrons, the energy loss of deuteron ion is light to weaken the action of σ_e and λ becomes smaller. Considering ionization energy loss of deuteron, the fusion reaction rate induced by deuteron recoil flux is

$$N_T\int_{E_r}^{\Lambda' E_{ff}^{\max}}\phi(E_r)\sigma_{fu}(E_r)p_{fu}dE_r$$

in which the flux of deuteron recoils is [5]

$$\phi(E_r) = \frac{\dot{F}_{fu}\sigma_s\mu_n}{E_r\sigma_{D-D}(E_r)}\left[\frac{\Lambda' E_n^{\max}}{E_r} - \frac{E_r}{\Lambda' E_n^{\max}} - \frac{E_r}{\Lambda' E_n^{\max}}\ln\frac{\Lambda' E_n^{\max}}{E_r}\right]\bullet p_D$$

σ_s is the neutron scattering cross section and μ_n is the range of fusion neutron, $\sigma_s\mu_n = 0.13982\times10^2/\ N_{LiD}^D$ [5]. Λ' is the factor of mass number to be equal to $\Lambda' = \frac{4M_nM_2}{(M_n+M_2)^2}$ and M_2 is the mass of lattice atom. $E_n^{\max}$ is the maximum energy of fusion neutron. σ_{D-D} is the cross section of D–D collision. If the energy of deuteron is higher than the neutralized energy E_{neut}, the D–D collision belongs to Rutherford scattering. Assuming $E_{neut} = 1$keV and the energy of recoil $\mathrm{E_r} \geqslant 100$keV, the cross section of D-D collision is $\sigma_{D-D}(\mathrm{E_r}) = \frac{\pi e^4}{E_rE_{neut}}$. p_D is the probability of neutron–deuteron collision in LiD. If $\mathrm{E_r}$ is larger than100 keV ($\mathrm{E_r} \geqslant 100$ keV), $\sigma_{fu}(E_r)$ approaches to 4.95 barns. In simple, we use the average value of fusion reaction cross section in energy range 0.1–12 MeV instead of the value of formula (4). Therefore the fusion reaction rate induced by D recoil flux can be presented as

$$N_T\int_{E_r}^{\Lambda' E_{ff}^{\max}}\phi(E_r)\sigma_{fu}(E_r)p_{fu}dE_r$$
$$= N_T\dot{F}_{fu}\sigma_{fu}(E_r)\frac{0.1392\times10^2}{N_{LiD}^D}\frac{E_{neut}}{\pi e^4}p_D$$
$$\times\int_{E_r}^{\Lambda' E_n^{\max}}\frac{\sigma_{fu}}{\lambda\frac{e^4}{4E_r^2}\frac{M_D}{m_e}+\sigma_{fu}}\left[\frac{\Lambda' E_n^{\max}}{E_r} - \frac{\mathrm{E_r}}{\Lambda' E_n^{\max}} - \frac{E_r}{\Lambda' E_n^{\max}}\ln\frac{\Lambda' E_n^{\max}}{E_r}\right]dE_r \tag{12}$$

$$v = \sigma_{fu}(E_r)\frac{0.1392\times10^2}{N_{LiD}^D}\frac{E_{neut}}{\pi e^4}p_D\int_{E_r}^{\Lambda' E_n^{\max}}\frac{\sigma_{fu}}{\lambda\frac{e^4}{4E_r^2}\frac{M_D}{m_e}+\sigma_{fu}}$$
$$\left[\frac{\Lambda' E_n^{\max}}{E_r} - \frac{E_r}{\Lambda' E_n^{\max}} - \frac{E_r}{\Lambda' E_n^{\max}}\ln\frac{\Lambda' E_n^{\max}}{E_r}\right]dE_r$$

The integral can be presented as

$$\int_{E_r}^{\Lambda' E_n^{\max}}\frac{\sigma_{fu}}{\lambda\frac{e^4}{4E_r^2}\frac{M_D}{m_e}+\sigma_{fu}}\left[\frac{\Lambda' E_n^{\max}}{E_r} - \frac{E_r}{\Lambda' E_n^{\max}} - \frac{E_r}{\Lambda' E_n^{\max}}\ln\frac{\Lambda' E_n^{\max}}{E_r}\right]dE_r$$
$$= \int_{E_r}^{\Lambda' E_n^{\max}}\frac{a}{b+aE_r^2}\left[E_r\Lambda' E_n^{\max} - \frac{E_r^3}{\Lambda' E_n^{\max}} - \frac{E_r^3}{\Lambda' E_n^{\max}}\ln\frac{\Lambda' E_n^{\max}}{E_r}\right]dE_r$$

in which a = $4\sigma_{fu}$, b = $\lambda e^4M_D/\mathrm{m_e}$. The result of integral is

$$\frac{1}{2}\Lambda' E_n^{\max}\ln\frac{\lambda e^4\frac{M_D}{m_e}+4\sigma_{fu}(\Lambda' E_n^{\max})^2}{\lambda e^4\frac{M_D}{m_e}+4\sigma_{fu}\sigma_r^2}$$
$$-\Lambda' E_n^{\max}\left[\frac{1}{2}-(\frac{E_r}{\Lambda' E_n^{\max}})^2-\frac{\lambda e^4\frac{M_D}{m_e}}{4\sigma_{fu}(\Lambda' E_n^{\max})^2}\ln\frac{\lambda e^4\frac{M_D}{m_e}+4\sigma_{fu}(\Lambda' E_n^{\max})^2}{\lambda e^4\frac{M_D}{m_e}+4\sigma_{fu}\sigma_r^2}\right]$$
$$-\frac{\Lambda' E_n^{\max}}{4}\ln\left(\frac{4\sigma_{fu}(\Lambda' E_n^{\max})^2}{\lambda e^4\frac{M_D}{m_e}x^2+4\sigma_{fu}(\Lambda' E_n^{\max})^2}\right)$$

in which $x = \frac{1}{2}\left(1+\frac{\Lambda' E_n^{\max}}{E_r}\right)$, if $\lambda = 1$, $E_n^{\max} = 14$ MeV, and $E_r = 0.1$ MeV, the factor $v = 1.75878\times10^{-22}$ which is independent to ^{6}Li enrichment and the neutron flux in reactor. If the pellet density of LiD is 90% theoretical density with 90% enrichment of ^{6}Li and $\lambda = 1$ in the heavy water region of CARR without the neutron flux depression, the concentration of tritium and fusion neutron production rate with the irradiation time from formula (9) and Eq.

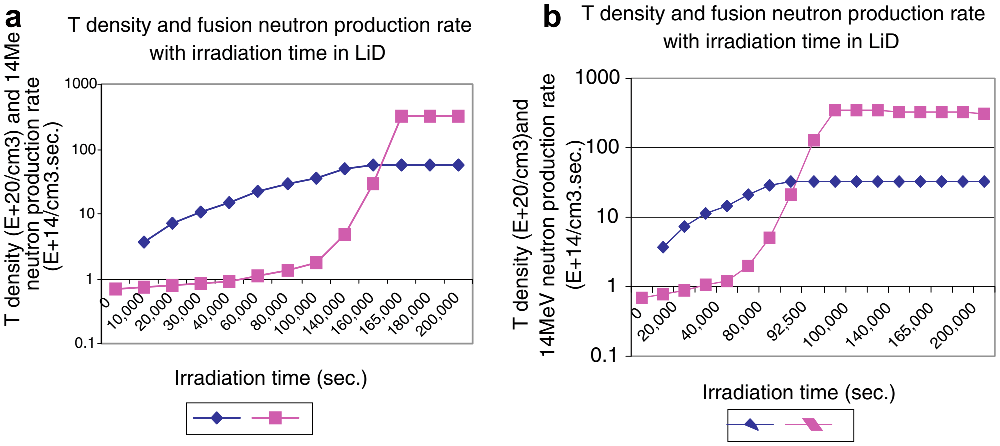

Fig. 2. Tritium concentration and fusion production rate versus irradiation times (a) $\lambda = 1$; (b) $\lambda = 0.1$, ♦ tritium concentration (10^{20} T/cm^3), ■ fusion neutron production rate (10^{14} n/cm^3· sec).

(3′) are shown in Fig. 2a. When irradiation time $t = 40.629$ h, the tritium concentration $N_T = 0.5117 \times 10^{22}$cm^{-3} and $\dot{F}_{fu} = \dot{F}_{fu1}$, if irradiation time reaches 45.459 h, (corresponding to 12.3% burn-up), the tritium concentration N_T approaches 0.5686×10^{22}cm^{-3} and the fusion reaction rate approaches to saturation, i.e. $\dot{F}_{fu} \Rightarrow \dot{F}_f = \phi\sigma_f {}^6N$. In the same condition, if $\lambda = 0.1$, the factor ν becomes 3.0099×10^{-22}, at irradiation time 26.111 h (corresponding 7.14% burn-up), the tritium concentration N_T approaches 0.3322×10^{22}cm^{-3} and fusion reaction rate reaches saturation. It means that, if there is enough tritium in LiD, the fusion reaction rate will reach saturation and the fusion neutron flux is able to meet the requirement for irradiation, such as 5×10^{13} n/cm^2 s.

4. Fusion neutron flux in the central hole of the LiD assembly

As mentioned under Section 2.1, as LiD is a strong absorber for thermal neutrons, we designed an assembly with a central hole as irradiation space, as illustrated in Fig. 3.

The hexagonal assembly consists of 198 LiD fuel rods with a diameter of 10 mm (containing hollow LiD pellets) and a central hole of 50 mm. The outside and inner diameters of the hollow LiD pellets are 9 mm and 5 mm, respectively. The tritium can be implanted into LiD by filling tritium gas into fuel rods to meet the requirement of enhancing the fusion reaction rate. In order to calculate the fusion neutron flux in the central hole, it is necessary to account for the shielding effects. The shielding coefficient of the assembly, γ, can be calculated using the following equation [6]:

$$\gamma = [1 + \Sigma_a(R_2^2 - R_1^2)/(2D_M)]^{-1} \tag{13}$$

where Σ_a is the average absorbed cross section of thermal neutrons in the assembly and can be calculated using the uniform method. R_1 and R_2 are the outside and inner radius of the assembly, respectively. D_M is the diffusion coefficient of thermal neutrons in heavy water and equal to 0.85 cm. The average thermal neutron flux in the assembly is $\gamma < \phi_0 >$, where $< \phi_0 >$ is the thermal neutron flux in heavy water in the absence of the assembly.

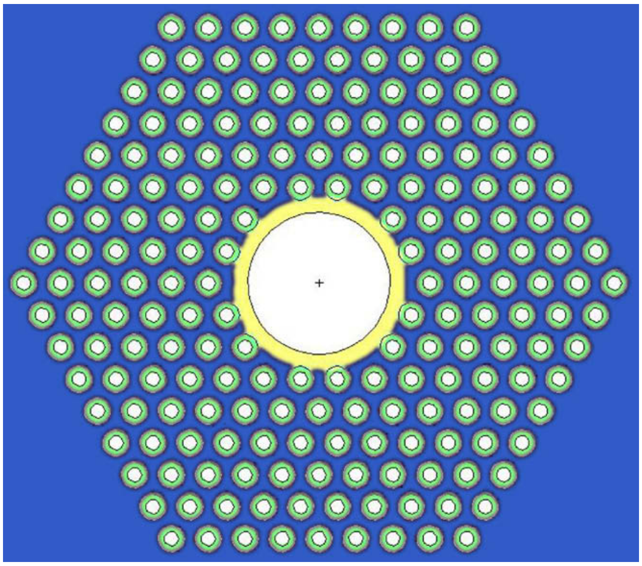

Fig. 3. Assembly of 198 LiD fuel rods with a diameter of 10 mm (containing hollow LiD pellets) and a central hole of 50 mm in diameter. The outside and inner diameters of the hollow LiD pellets are 9 and 5 mm, respectively.

For the calculation of the fusion neutron flux, the assembly is divided into two regions: the LiD region as outside region, referred to as 1, and the central hole region as inner region, referred to as 2. According to the equilibrium relation for the fusion neutron collision rate, the fusion neutron flux in the central hole, Φ_2, is given by [6]:

$$\Phi_2 = \frac{V_1 P_{12}}{V_2 \Sigma_{s2}} \dot{F}_{fu} \tag{14}$$

where V_1 and V_2 are the total volume of the LiD region and the central hole region, respectively, Σ_{s2} is the scattering macro-cross section of the central hole region, P_{12} is the probability of a fusion neutron produced in the LiD region to undergo a first collision in the central hole region. Thus, $P_{12} = P_{1s}P_{s2}$, where P_{1s} is the probability of a fusion neutron emitted from the LiD region to reach the boundary surface between the LiD region and the central region and P_{S2} is the probability of a neutron entering the region 2 to undergo a primary collision. Accounting for the scattering cross section of both regions, P_{12} can be calculated using the formula of integral transportation theory, and one gets $P_{12} = 0.0806$ [6]. On the basis of these data the fusion neutron flux in the central hole can be then calculated on the basis of the fusion reaction rate $\dot{F}_{fu}$. Fusion neutron 'feedback effects', in which fusion neutrons are slowed down to thermal neutrons in the reactor and absorbed by ^{6}Li of LiD to produce fusion neutrons, have also to be accounted for. This can do done in adding the term - $\mu_T \sigma_{fu} N_D \tilde{\beta}$ into the denominator of the right hand of Eq. (3′), where $\tilde{\beta}$ is the probability of a fusion neutron to slow down to a thermal neutron and to stay in the assembly region, which is equal to $\tilde{\beta} = 0.47$ [6].

Assuming that the density of the LiD pellets is 90% theoretical density, that they are enriched with 90% of ^{6}Li, and that 10.5% tritium is added into the LiD fuel rods (the fusion reaction rate reaching saturation), the fusion neutron flux in the central hole, accounting for the shielding effects and feedback effects, reaches 4.2624×10^{13} fusion neutrons/cm^2 s.

The initial ionization rate $\dot{F}_e/N_e$ in the heavy water region of the CARR may be written as:

$$\dot{F}_e/N_e = \frac{\phi\sigma_{\mathrm{f}}(\varepsilon_{\mathrm{p}} + \mu_{\mathrm{T}}\sigma_{\mathrm{fu}}\mathrm{N}^{\mathrm{D}}_{\mathrm{LiD}}\varepsilon_{\mathrm{He}})\mathrm{N}^{\mathrm{Li}}_{\mathrm{LiD}}}{(Z_{Li} + Z_D)\varepsilon_i N_{LiD}} \tag{15}$$

where σ_{f} is the cross section of the ^{6}Li(n,α) reaction, ε_p is the sum of T ion and α particle energies produced by the ^{6}Li(n,α) reaction, $\varepsilon_{\mathrm{He}}$ is the energy of the α particles produced by the fusion reactions, ε_i is the ionization energy of electrons in LiD, N_{LiD} is the number of LiD per unit volume, N^{Li}_{LiD} is the number of ^{6}Li per unit volume of LiD, and Z_{Li} and Z_D are the number of Li and D atoms, respectively. Assuming that ε_{i} is equal to 2 eV, the ionization rate reaches 0.142 sec^{-1}.

5. Summary

A LiD assembly has been proposed to produce fusion neutrons from thermal neutrons in the heavy water region of the CARR reactor. The reaction ^{6}Li(n,α) produces tritium ions with an energy of 2.739 MeV in LiD bombarded by thermal neutrons, and the energetic tritium ions then bombard the deuterons of LiD to produce 14 MeV neutrons via fusion reactions. The 14 MeV neutrons engender a recoils flux of deuterons in LiD, these energetic deuterons bombarding in turn the residual tritium, producing fusion reactions. These fusion neutrons produce a further recoils flux that engenders more fusion neutrons, according to an in-chain reaction. When the concentration of tritium reaches $0.5 \cdot 10^{22}$ and the fraction of fusion reactions between tritium and deuteron recoils approaches 1, the 14 MeV neutron flux is doubled and redoubled, an so forth, approaching saturation in which the tritium produced at a time *t* is exhausted by the fusion reactions to keep constant the tritium concentration in LiD.

A hexagonal assembly with a center hole as irradiation space has been designed on the basis of LiD as strong absorber for thermal neutrons and accounting for the shielding effects and feedback effects. The assembly consists of 198 LiD fuel rods with a diameter of 10 mm (containing hollow LiD pellets) and a central hole of 50 mm. The outside and inner diameters of the hollow LiD pellets are 9 mm and 5 mm, respectively. Assuming that the density of the LiD pellets is 90% the theoretical density, that they are enriched with 90% of ^{6}Li, and that 10.5% tritium is added into the LiD fuel rods (the fusion reaction rate reaching saturation), the fusion neutron flux in the central hole of the assembly in the CARR heavy water region reaches 4.2624×10^{13} fusion neutrons/cm^2 s.

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