Core size effects of laser fusion subcritical research reactor for fusion engineering research

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Abstract

A multi-purpose high repetition laser facility, the so-called Japan establishment for Power-laser community Harvest (J-EPoCH) is proposed as a next generation laser facility. J-EPoCH will operate at the maximum rate of 100 Hz. The omnidirectional 12 laser beams with 8 kJ would yield ~10^{13} neutrons with a Large High Aspect Ratio Target (LHART). As one of the applications of J-EPoCH, a laser fusion subcritical research reactor has been conceptually designed based on existing technologies. Moreover, a variety of fusion engineering studies: energy conversion, tritium breeding, neutron irradiation effects, etc., can be conducted. The feasibility of the subcritical research reactor is considered in terms of neutron - thermal (n-t) conversion and tritium breeding. Lead-lithium alloy ($Li_{17}Pb_{83}$) and boron carbide (B_4C) have the potential to be studied for preliminary fusion power generation. The subcritical reactor will generate 21.4 W and 20.0 W of the thermal fusion power with the $Li_{17}Pb_{83}$ and the B_4C layers of the thickness of 80 cm, respectively at 1 Hz operation. The $Li_{17}Pb_{83}$ layer of a 5 mm thickness will achieve the temperature rise of 0.203 mK per shot. The thermal fusion energy is detectable with conventional measurement techniques. The core with the $Li_{17}Pb_{83}$ layer thickness of 100 cm will yield more than one tritium from a DT fusion neutron. However, laser windows reduce the efficiency of n-t conversion and tritium yield.

Keywords: laser fusion, subcritical research reactor, J-EPoCH, fusion power, tritium breeding

1. Introduction

Fusion research has been focused on plasma physics. ITER is under construction to prove the feasibility of fusion burning. Its operation will start with hydrogen plasma in 2025 and then will change to deuterium-tritium (DT) plasma in 2035 [1]. During the phase of DT plasma experiments, tritium breeding and power generation will be partially studied. For DEMO reactors, Test Blanket Modules (TBMs) will be tested in ITER, and tritium breeding and energy conversion technologies will be developed. After that, DEMO reactors are proposed to be constructed without any integrated experiment as a fusion system. In particular, tokamak DEMO reactors are designed to generate several GW of thermal energy and to produce ~100 kg of tritium per year [2, 3]. All required technologies to realize DEMO reactors must be completed before the DEMO engineering designs.

Laser fusion is approaching the ignition and burning condition by the central ignition experiments at the National Ignition Facility (NIF). Alpha heating has been observed in the experiments [4]. On the other hand, the Fast Ignition Realization Experiment (FIREX) has also progressed due to the fast ignition scheme to achieve the ignition temperature of 5-10 keV [5]. The Inertial Fusion Energy (IFE) forum in Japan organized committees to design two reactors: the Laser

Inertial Fusion Test (LIFT) and the Koyo-Fast reactors. LIFT has been designed as an experimental reactor with three technical phases [6] and will be developed step by step. Koyo-Fast has been designed as a commercial reactor [7]. Furthermore, CANDY has been designed as a compact reactor by the group of the Graduate School for the Creation of New Photonics Industries [8]. However, no laser system with high repetition and high power exists to demonstrate required technologies. Many engineering issues still remain in order to realize the fusion reactors.

The Institute of Laser Engineering (ILE), Osaka University proposes J-EPoCH with 8 kJ omnidirectional 12 laser beams at the maximum rate of 100 Hz. To date, the Large High Aspect Ratio Target (LHART) containing gaseous DT at several 100 kPa has yielded 10^{13} neutrons with Gekko XII in ILE [9]. Under the assumption that the yield of 10^{13} neutrons is also available with J-EPoCH, a laser fusion subcritical research reactor has been designed conceptually. The ability of the laser fusion subcritical research reactor has been discussed with a fixed core size [10]. The radius of the core is assumed to be 33 cm. The subcritical reactor can convert 10^{13} neutrons per shot into the thermal energy of 14 J with a B_4C core and can yield 9.1 x 10^{11} tritium atoms per shot with a $Li_{17}Pb_{83}$ core. The subcritical reactor makes it possible to conduct a variety of fusion engineering research on energy conversion, tritium breeding, neutron irradiation effects, etc.

All fusion experimental systems focus on plasma experiments, and it may be difficult to conduct engineering research. Research and development of fusion engineering parallel with the plasma experiments is required to realize DEMO reactors, LIFT, and Koyo-Fast. Fusion power generation has never been demonstrated yet. The subcritical research reactor shows the possibility to convert neutron to thermal energies, and the thermal fusion energy may be detectable. The first fusion power demonstration in principle must be impressive, and the proof of principle experiment of fusion power should reveal remaining issues to solve before realization of fusion power plants. Furthermore, the study of tritium breeding is also available with the subcritical research reactor. However, the Tritium Breeding Ratio (TBR) remains low in the fixed core size model of the previous study [10]. The core size effects of the subcritical research reactor are assessed as functions of n-t conversion and tritium breeding materials and the thickness of the material layer.

2. Subcritical research reactor, L-Supreme

The laser fusion subcritical research reactor, the newly named Laser-fusion Subcritical Power Reactor Engineering Method (L-Supreme), is one of the applications of J-EPoCH. The combination of J-EPoCH and LHART has the potential to create a point neutron source of 10^{13} per shot. L-Supreme will make it possible to study fusion engineering research by using the neutron source. The conceptual drawing of L-Supreme is shown in figure 1. L-Supreme includes a dedicated target chamber, a target delivery system, a hollow sphere core and a vacuum system with tritium recovery. The core is replaceable for conducting various fusion engineering experiments. Each LHART is contained in a capsule. A linear motor driven system delivers the capsules to the center of the core shot by shot at the repetition of more than 1 Hz. Existing technologies will realize each system. The opportunities of neutron irradiation with fluence of ~6.6 x 10^{13} n m^{-2} per shot will be also provided at a radius of 10 cm.

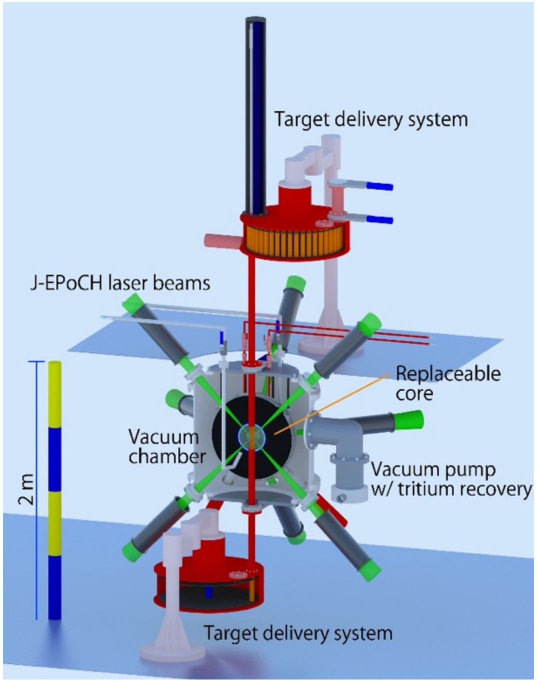

Figure 1. Conceptual drawing of L-Supreme.

3. Fusion power generation

In order to confirm fusion power generation, there may be two methods to convert thermal to electric energy. One is the Rankin cycle, and the other is utilizing thermo-electric effects. Optimum conditions should be considered for both methods. The Rankine cycle should utilize all deposited energy from thermal to mechanical power conversion, and thermal gap is required to apply thermo-electric effects. Therefore, the energy deposited and the temperature rise of the cores are discussed.

3.1 Core for n-t conversion study

Graphite (C), B_4C, lithium (Li), and $Li_{17}Pb_{83}$ are selected as n-t conversion materials. Each material can compose a core as an engineering product. Figure 2 shows the cross section of a concentric core. At the center of the core, point sources of a neutron and an alpha particle with 14.1 MeV and 3.5 MeV monotonic energies, respectively, are placed. The core is placed in vacuum. Laser windows are ignored. The layer thickness of the n-t conversion material is varied to calculate the thermal fusion energy and is changed from 0.5 cm to 80 cm. The ability of the inner shield to protect against debris and wasted laser power has already been reported in reference 10. The radioactivation of the lining of the inner shield might be an issue. Minimizing the radioactivation will be addressed in the future. The Particle and Heavy Ion Transport code System (PHITS) [11] is used to calculate the energy deposited in the cores. Natural isotope ratios are assumed for all materials. Operation temperature is assumed to be ~293 K.

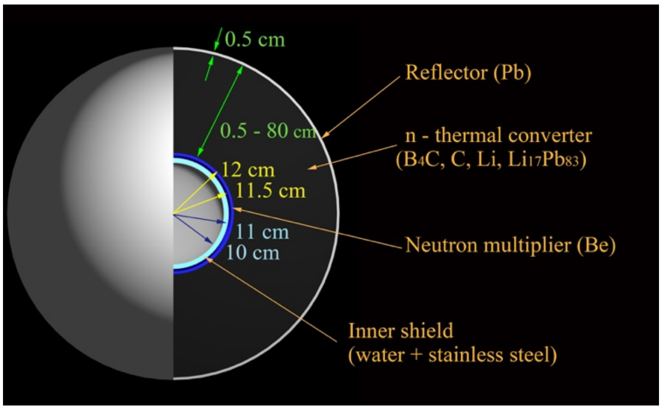

Figure 2. Core model for n-t conversion study.

3.2 Total energy deposited to cores

It is assumed that a DT fusion reaction creates a neutron and an alpha particle with 14.1 MeV and 3.5 MeV monotonic energies, respectively. Figure 3 represents the fluxes of the neutron, alpha, and all radioactive rays in the core with the 5 mm B_4C layer thickness. In the core model, the alpha particle is stopped on the surface of the inner shield and does not reach to the n-t conversion layer. The neutron can pass through the inner shield. The core with the inner shield allows us to study the energy conversion from DT neutrons with L-Supreme.

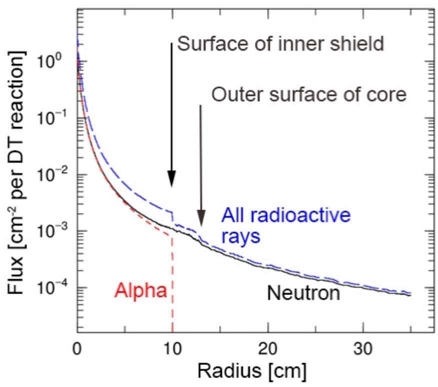

Figure 3. Fluxes in the core with the 5 mm B_4C layer thickness.

The energy deposited in the n-t conversion layers from a DT fusion reaction is calculated as shown in figure 4. As the n-t conversion layer becomes thick, the energy deposited monotonically increases. Table 1 summarizes the energy deposited in the n-t conversion materials. The DT fusion neutron energy is efficiently converted by $Li_{17}Pb_{83}$ and B_4C, and the core with an 80 cm thickness will utilize more than 89 % of the neutron energy as the thermal fusion energy. The thermal fusion power of 21.4 W and 20.0 W will be generated in the $Li_{17}Pb_{83}$ and the B_4C cores at 1 Hz laser operation. The n-t conversion material of B_4C allows us to design a compact core because the B_4C layer with a 40 cm thickness can convert 84 % of neutron energy to thermal energy. The $Li_{17}Pb_{83}$ core will yield tritium, too. Therefore, simultaneous experiments of tritium breeding might be possible.

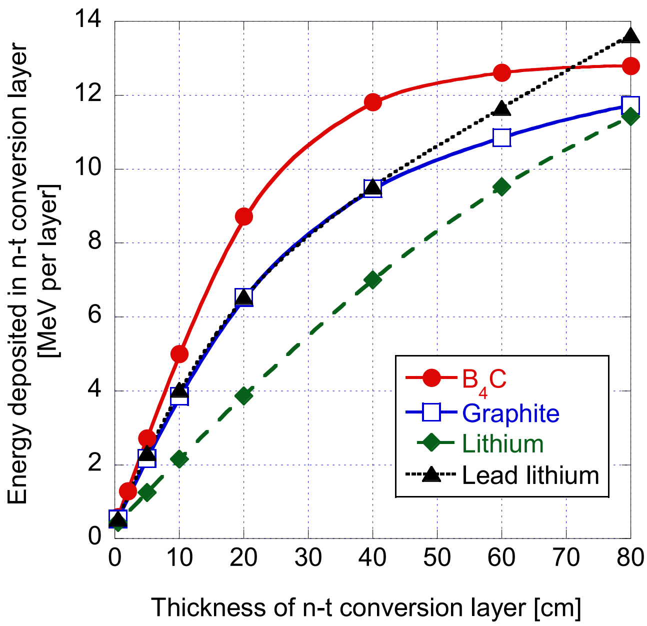

Figure 4. Energy deposited in the n-t conversion layers from a DT fusion reaction.

Table 1. Thermal fusion energy converted with an 80 cm layer thickness.

n-t conversion material	Thermal fusion energy [MeV per neutron]
B_4C	12.5
Graphite	11.4
Li	11.1
$Li_{17}Pb_{83}$	13.4

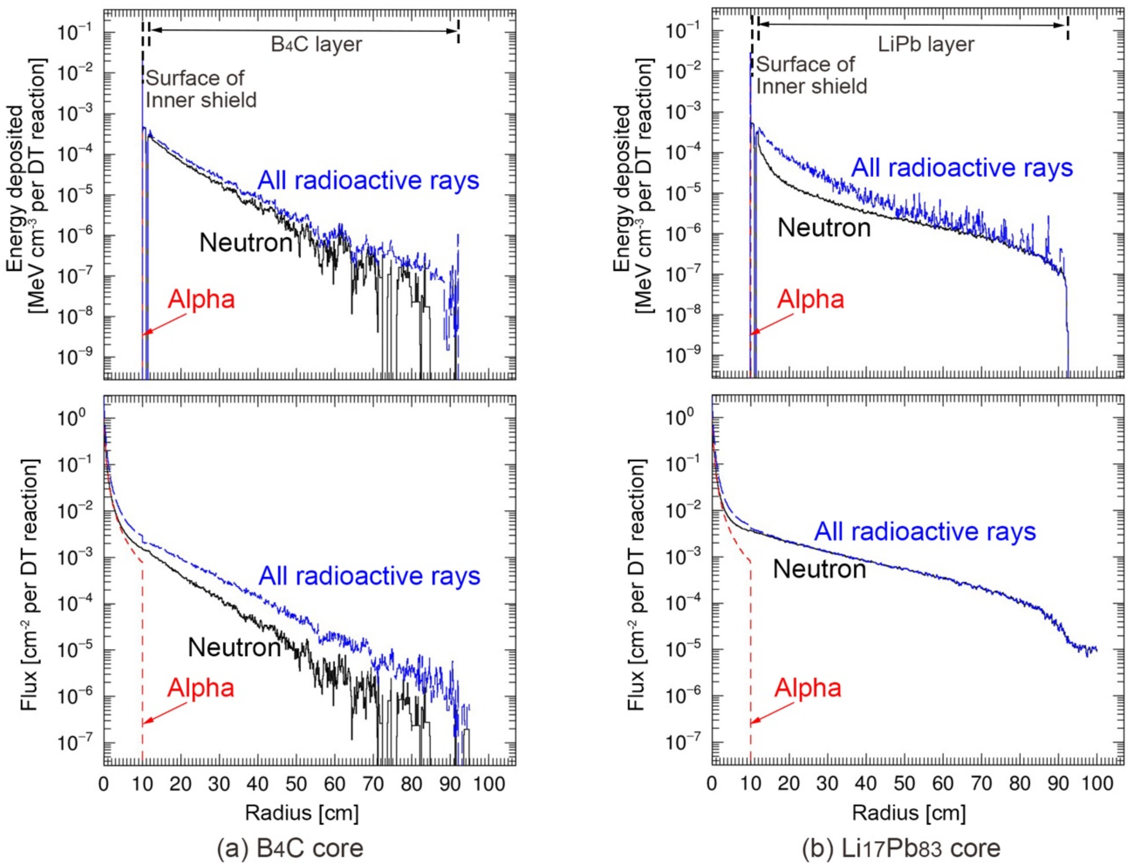

Figure 5 (a) and (b). Energy deposited and fluxes in n-t conversion layer from a DT fusion reaction.

The energy deposited and fluxes of neutron, alpha and all radioactive rays in the B_4C and the $Li_{17}Pb_{83}$ cores are shown in Figure 5 (a) and (b), respectively. The thickness of the B_4C and the $Li_{17}Pb_{83}$ layers is 80 cm. Lead (Pb) in the $Li_{17}Pb_{83}$ layer works as a neutron multiplier [12,13], and therefore, the neutron flux in the $Li_{17}Pb_{83}$ layer is higher than that in the B_4C layer. At the inner part of the n-t conversion layer, the B_4C core can convert neutron to thermal energy more than the $Li_{17}Pb_{83}$ core. The outer part of the LiPb core compensates for the low n-t conversion rate at the inner part.

3.3 Temperature rise of cores

Specific heat and density of the n-t conversion materials are shown in Table 2 [14-17]. Average temperature rises of the n-t conversion layers are calculated from the properties and the total energy deposited. Figure 6 shows the temperature rise of each conversion layer. The thinner layer reaches a higher temperature. Not only the total energy deposited but also the heat capacity affect the temperature rise. The neutron flux depends on the distance from the point neutron source in the concentric core model. Therefore, the density of heat generation in the thin layer becomes high. Table 3 summarizes the temperature rise per shot of each core with the 5 mm n-t conversion layer. The temperature rise of 0.203 mK per shot will be achieved with the $Li_{17}Pb_{83}$ layer. It is possible to measure the temperature rise by conventional measurement techniques. Ten thousand shots will realize the temperature rise of 2.03 K and require 2.8 hours at 1 Hz operation. The temperature difference of 2.03 K between the outer surface of the core and the inner surface of the vacuum chamber results in a few W of the radiation loss. An outer thermal shield should be installed in order to minimize the radiation loss.

Table 2. Specific heat and density at 293 K.

n-t conversion material	Specific heat [J g^{-1} K^{-1}]	Density [g cm^{-3}]
B_4C	0.95	2.38
Graphite	0.710	2.25
Li	3.41	0.534
$Li_{17}Pb_{83}$	0.149	10.21

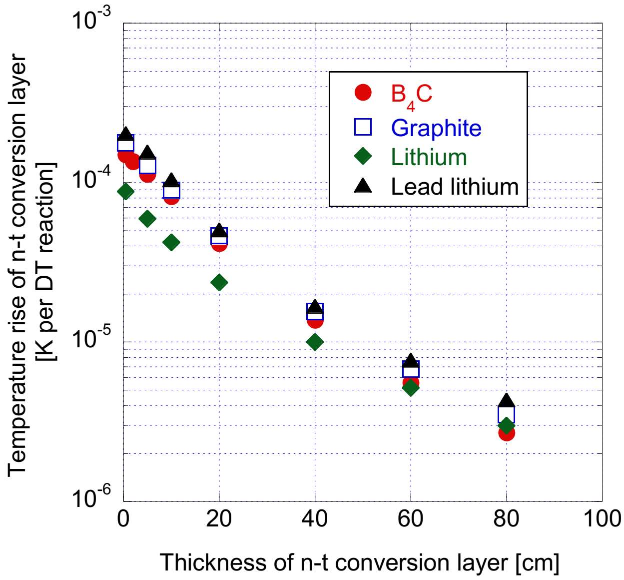

Figure 6. Average temperature rise of n-t conversion layers.

Table 3. n-t conversion and temperature rises with a 5 mm thickness.

n-t conversion material	n-t conversion [MeV per shot]	Temperature rise [mK per shot]
B_4C	0.586	0.150
Graphite	0.529	0.178
Li	0.439	0.0879
$Li_{17}Pb_{83}$	0.534	0.203

4. Tritium breeding study

In the previous study of reference 10, the ability to study the tritium yield with L-Supreme was discussed. A DT neutron will yield ~0.04 and ~0.09 of tritium in the Li and the $Li_{17}Pb_{83}$ cores, respectively, with the thickness of 20 cm. $Li_{17}Pb_{83}$ has a high tritium yield and is a candidate for the tritium breeder in the laser fusion reactor designs. Therefore, we focus on $Li_{17}Pb_{83}$ as a tritium breeding material. The effect of the thickness of the breeding material is discussed.

4.1 Core for tritium breeding study

Figure 7 shows the core model to calculate tritium yield. The thicknesses of the $Li_{17}Pb_{83}$ layer are considered in the range of 5 - 100 cm. At the center of the core, point sources of a neutron and an alpha particle with 14.1 MeV and 3.5 MeV monotonic energies, respectively, are placed. The core is placed in vacuum. Laser windows are ignored. Configuration and thicknesses of other layers are the same as those in figure 2. Natural isotope ratios are assumed for all materials. Operation temperature is assumed to be ~293 K.

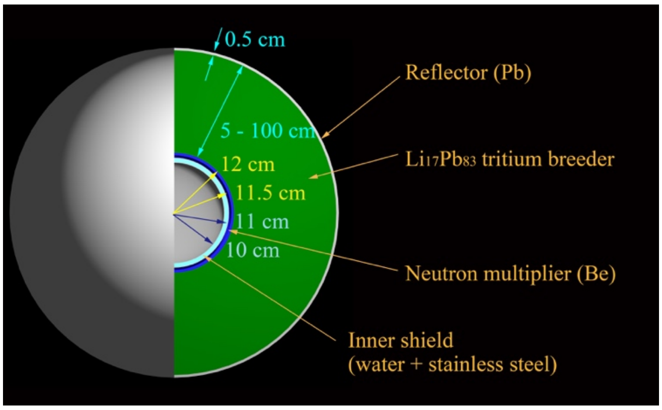

Figure 7. Core model for tritium breeding study.

4.2 Tritium yield in the $Li_{17}Pb_{83}$ core

Figure 8 shows the tritium yield from a DT reaction. The breeding rate, the number of yielded tritium from a DT reaction, monotonically increases as the $Li_{17}Pb_{83}$ layer becomes thicker. The breeding rate exceeds 1.0 when the thickness is more than 1 m. Yielded tritium of 10^{13} can be utilized for conducting tritium breeding studies by a shot.

A shot of L-Supreme requires 5.6 x 10^{16} of tritium in LHART, and neutrons of 10^{13} will be generated. Therefore, the Tritium Breeding Ratio (TBR) of L-Supreme is limited to the order of 10^{-4}. The number of wasted tritium without the fusion reaction is still more than that of the tritium bred in the core. L-Supreme should equip the vacuum system with a tritium recovery function.

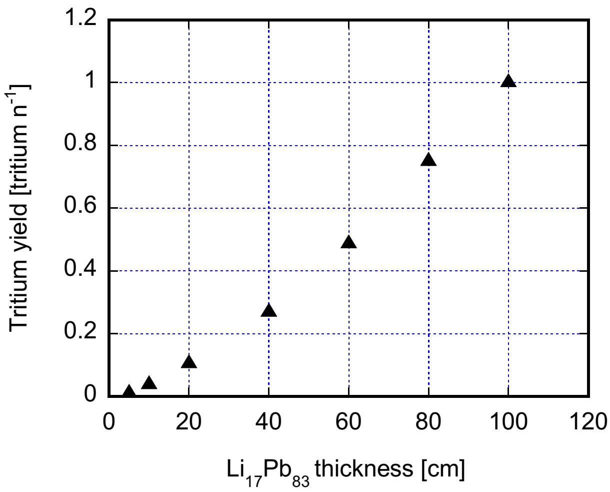

Figure 8. Tritium yield in the $Li_{17}Pb_{83}$ core from a DT neutron.

5. Effects of laser windows

In the above chapters, the cores are modelled without laser windows because the details of the J-EPoCH are under design. However, laser windows should affect the efficiencies of the n-t conversion and the tritium yield. In this chapter, omnidirectional 12 laser windows are assumed to be equipped through the core. Effects of laser windows on n-t conversion and tritium breeding are discussed.

5.1 Core with laser windows

The n-t conversion and the tritium yield are considered on the opening solid angle of the laser windows. Figure 9 shows the calculation model of the core with laser windows. The thickness of 60 cm of the n-t conversion and the tritium breeder layers is represented. The opening radius at a 200 cm distance from the center is varied from 10 cm to 25 cm at an interval of 5 cm. At the center of the core, point sources of a neutron and an alpha particle with 14.1 MeV and 3.5 MeV monotonic energies, respectively, are placed. The core is placed in vacuum. Natural isotope ratios are assumed for all materials. Operation temperature is assumed to be ~293 K.

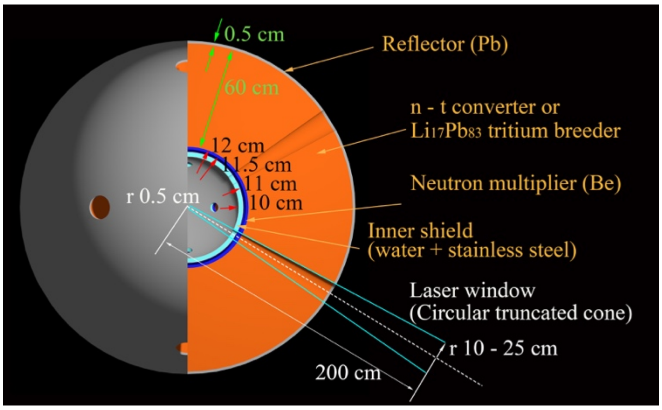

Figure 9. Core model with 12 omnidirectional laser windows. Laser windows are defined as circular truncated cones.

5.2 Effects on the size of laser window

Figure 10 shows the dependence of the energy deposited on the radius of the laser windows. The reduction rate is normalized by the energy deposited without laser windows. The reduction rates of small windows are proportional to the solid angles of the laser windows. However, larger windows will reduce the available n energy, especially for the $Li_{17}Pb_{83}$ core which has a larger dependence on the window size. The laser window of 25 cm radius results in a drop in the fusion thermal energy by 11 % in the case of the $Li_{17}Pb_{83}$ core. The reduction rate of the energy deposited is more sensitive to the radius of the laser windows in the order of $Li_{17}Pb_{83}$, graphite, Li, and B_4C. Figure 11 shows the dependence of tritium yield on the radius of laser windows in the $Li_{17}Pb_{83}$ core. The reduction rate is normalized by the tritium yield without laser windows. The reduction rate of tritium yield is more sensitive to laser windows than that of the energy deposited. The laser window of a 25 cm radius reduces tritium yield by 25 %.

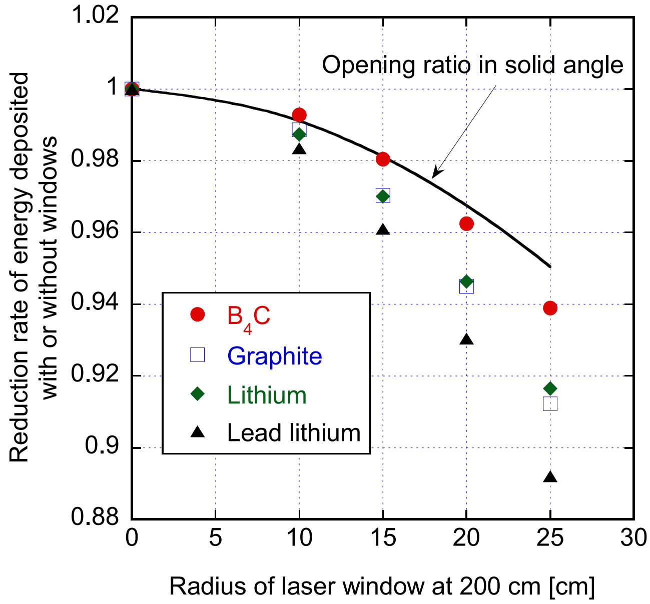

Figure 10. Reduction rates of energy deposited.

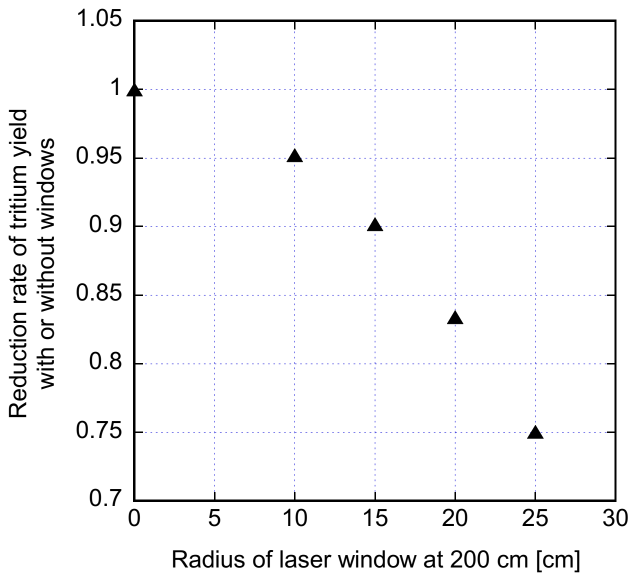

Figure 11. Reduction rate of tritium yield.

6. Summary

For the design study of L-Supreme, effects of the core size are considered regarding the n-t conversion and the tritium breeding by PHITS calculations. The n-t conversion materials of B_4C, graphite, Li, and $Li_{17}Pb_{83}$ are selected. The DT fusion neutron energy is effectively converted by $Li_{17}Pb_{83}$ and B_4C, and the cores with an 80 cm thickness can convert more than 89 % of the neutron energy into thermal energy. The thermal fusion power of 21.4 W will be generated in the $Li_{17}Pb_{83}$ core at 1 Hz operation. The $Li_{17}Pb_{83}$ layer with a 5 mm thickness will achieve the temperature rise of 0.203 mK per shot. The fusion thermal energy is detectable by conventional measurement techniques. $Li_{17}Pb_{83}$ is studied as a tritium breeding material. The core with a 100 cm thickness of the $Li_{17}Pb_{83}$ layer can yield more than one tritium from a DT fusion neutron. However, laser windows degrade the efficiency of n-t conversion and tritium yield.

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