Three-Dimensional Neutronics Analysis for the Final Optics of the Laser Fusion Power Reactor SIRIUS-P

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UWFDM-987

Presented at the 16th IEEE/NPSS Symposium on Fusion Engineering, 1–5 October 1995, Champaign IL.

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ABSTRACT

A three-dimensional neutronics calculation has been performed for the final optics of the laser driven reactor SIRIUS-P. The reactor utilizes grazing incidence metallic mirrors (GIMM) and dielectric coated final focusing (FF) mirrors placed at 25 and 40 m from the target, respectively. High aspect ratio neutron traps are attached to the outer reactor containment building. The GIMM can have a lifetime of 14 FPY assuming 80% recovery with annealing for a fluence limit of 10^{21} n/cm^2. For a trap with an aspect ratio of 3, the flux at the FF mirror is reduced by about two orders of magnitude. The lifetime for the FF mirror will be 0.6 FPY for a fluence limit of 10^{18} n/cm^2.

I. INTRODUCTION

The SIRIUS-P conceptual design study is of a 1000 MWe KrF laser driven inertial confinement fusion power reactor utilizing near symmetric illumination of direct drive targets [1]. Sixty beams providing 3.2 MJ of energy are used at a repetition rate of 6.7 Hz and a target gain of 114. The chamber has an inner radius of 6.5 m and consists of a first wall (FW) fabricated from a carbon/carbon (c/c) composite and a blanket made of SiC. The chamber is cooled by flowing granular beds of TiO_2 for the FW and Li_2O for the blanket. The overall tritium breeding ratio (TBR) is 1.09 and the overall energy multiplication factor is 1.08. The FW and blanket are expected to have a lifetime of ~3 full power years (FPY).

The reactor chamber is housed within a cylindrical containment building with a radius of 42 m and a height of 8.6 m. Figure 1 shows a cross section of the reactor building. The chamber is surrounded by an internal concrete wall at a radius of 10 m. The 60 laser beams, after entering the building, travel vertically and are incident onto FF mirrors located at 40 m from the target. They are then directed onto GIMM located at 25 m from the target which deflect the beams by 10 degrees and direct them into the internal reactor enclosure through ports in the walls.

The use of GIMM was first proposed by Bieri and Guinan [2] in 1991 as a solution to the problem of protecting the FF mirrors from neutron damage. The FF mirrors are placed out of the direct line-of-sight of the source neutrons. However, secondary neutrons resulting from the interaction of the streaming source neutrons with the containment building can

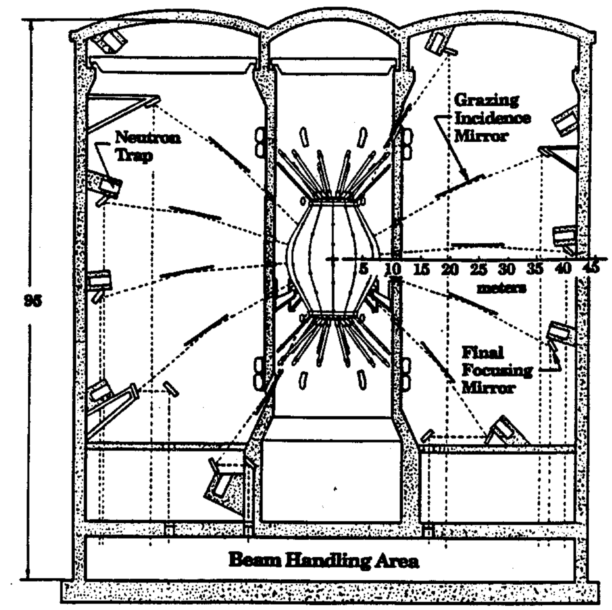

Fig. 1. Cross section of the SIRIUS-P reactor building.

cause significant damage to the coating. To reduce the secondary neutron flux and increase the lifetime of the mirrors, neutron traps are attached to the outer reactor containment building. The lifetime of the final optics depends on the neutron fluence limit for the dielectric coated or metallic mirrors, the solid angle fraction subtended by the beam ports ($\Delta\Omega/4\pi$), damage recovery with annealing and the location of the mirror relative to the target. The solid angle fraction subtended by the 60 beam ports in SIRIUS-P is only 0.4%. It is essential to perform multi-dimensional calculations for accurate prediction of the lifetime of the final optics. Two-dimensional (2-D) and three-dimensional (3-D) neutronics calculations have been performed to determine the neutron flux levels at the GIMM and FF mirrors and their predicted lifetime.

II. TWO-DIMENSIONAL CALCULATION

A. *Calculational Model*

2-D neutronics calculations have been performed to determine the neutron flux levels at the GIMM and FF mirrors. The discrete ordinates code TWODANT [3] was utilized along with the ENDF/B-V cross section data. The

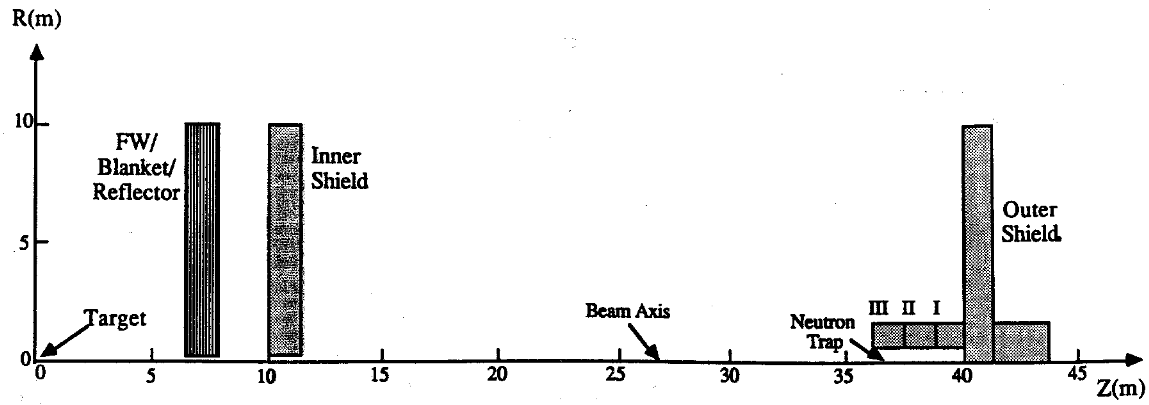

Fig. 2. 2-D model for region around a beamline.

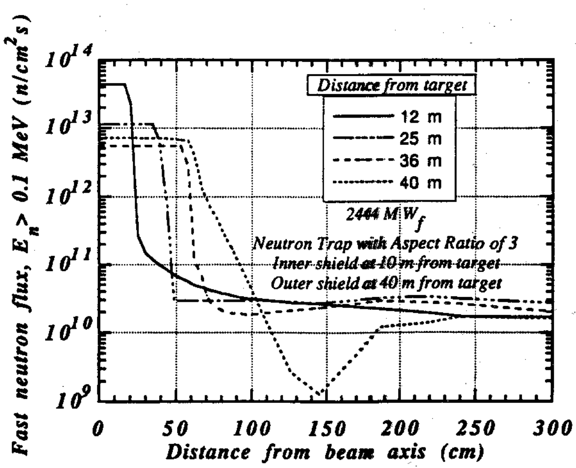

Fig. 3. Fast neutron flux in space between inner and outer shields with neutron traps having aspect ratio of 3.

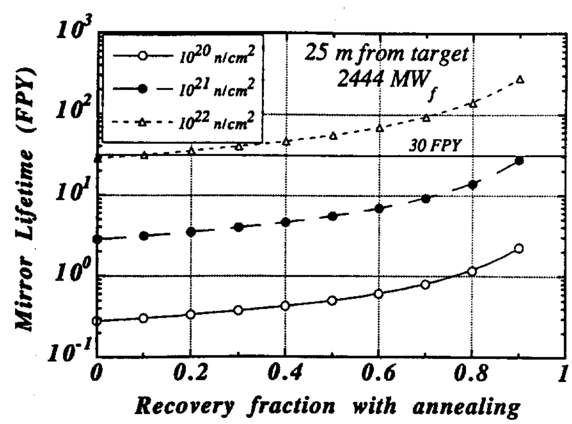

Fig. 4. Lifetime of GIMM as a function of annealing recovery and fluence limit.

P_3-S_8 approximation was used in the calculations. The region around a beam penetration was modeled in r-z geometry with the target represented by an isotropic point source on the z-axis. The two-dimensional model is shown in Fig. 2. The detailed radial build of the FW, blanket and reflector is included in the model. The penetration in the chamber wall has a radius of 15 cm. The inner shield is 1.5 m thick and has a penetration with 18 cm radius. The outer shield located at 40 m from the target is 1.2 m thick except behind the neutron traps where the thickness is increased to 3.3 m. The cases without traps and with traps having different aspect ratios (depth to diameter ratio) were considered. The cylindrical trap has an inner radius of 65 cm and is 1 m thick. Aspect ratios of 1, 2, and 3 were considered. The model is surrounded by a reflecting cylindrical boundary. An inherent problem associated with multi-dimensional discrete ordinates calculations with localized sources is referred to as the "ray effect." This effect has been fully mitigated by use of the first collision method [4]. In this method, the uncollided flux is determined analytically and the volumetrically distributed first collision source is used in the calculations.

B. *Results*

Fig. 3 shows the fast neutron flux (E_n > 0.1 MeV) in the space between the inner and outer shields for neutron traps having an aspect ratio of 3. The variation of flux with distance from beam axis is given at the outer surface of the inner shield, location of GIMM, front of trap, and the inner surface of the outer shield. The flux along the beam axis is dominated by the direct source neutrons and is not affected by the neutron trap. The fast neutron flux (E_n > 0.1 MeV) level at the GIMM has been determined to be 1.14×10^{13} n/cm^{2}s. Fig. 4 gives the lifetime for these mirrors as a function of the fast neutron fluence limit and the recovery fraction with annealing. A minimum time of one month between anneals is assumed. It can be seen that, for a limit of 10^{21} n/cm^2, the GIMM can have a lifetime of 14 FPY assuming 80% recovery and 28 FPY for 90% recovery. If the limit is 10^{22} n/cm^2, it can have a lifetime of 28 FPY with no annealing.

Fig. 5 gives the lifetime of the dielectric coated FF mirrors as a function of location along the outer surface of the trap for

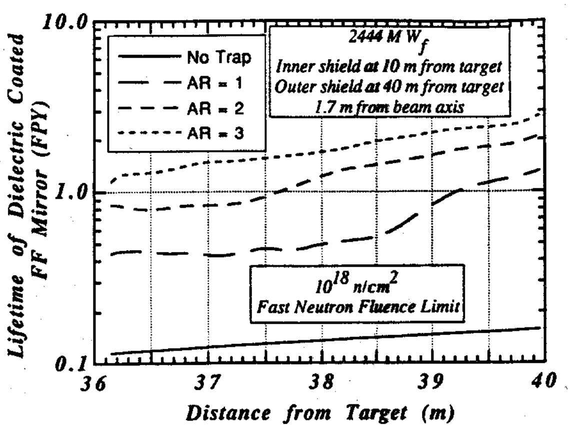

Fig. 5. Lifetime of dielectric coated FF mirrors for a fast neutron fluence limit of 10^{18} n/cm^2.

traps with different aspect ratios and a fast neutron fluence limit of 10^{18} n/cm^2. The lifetime is highest if the mirror is located as close as possible to the inner surface of the outer shield. For a trap with an aspect ratio of 3, the lifetime for the FF mirror located at 40 m from the target will be 2.8 FPY for a fluence limit of 10^{18} n/cm^2. The lifetime will reach 28 FPY if the fluence limit can be increased to 10^{19} n/cm^2. Increasing the trap aspect ratio beyond 3 is expected to lead to only a slight increase in mirror lifetime.

III. THREE-DIMENSIONAL ANALYSIS

Due to limitations on 2-D modeling of the geometry, the GIMM located along the direct line-of-sight of source neutrons were not included. Interactions between the streaming source neutrons and the GIMM result in scattered secondary neutrons that increase the neutron flux level at the FF mirrors yielding a lower lifetime compared to that predicted by the 2-D calculations. In order to quantify this effect, 3-D neutronics analysis has been performed.

A. *Calculational Method*

3-D neutronics calculations have been performed using the continuous energy coupled neutron-gamma Monte Carlo code MCNP [5] with ENDF/B-V cross section data. Several variance reduction techniques were utilized to improve the accuracy of the calculation. These included angular source biasing and geometry splitting with Russian Roulette. Only one of the 60 beam penetrations was modeled with the associated final mirrors, blanket and shield. A reflecting conical boundary with a half angle of 15° was used. A point neutron source was used at the origin emitting neutrons isotropically with the SIRIUS-P target energy spectrum.

The 3-D model is shown in Fig. 6. Horizontal and vertical cross sections through a beam penetration at the reactor midplane are shown. The detailed radial build of the

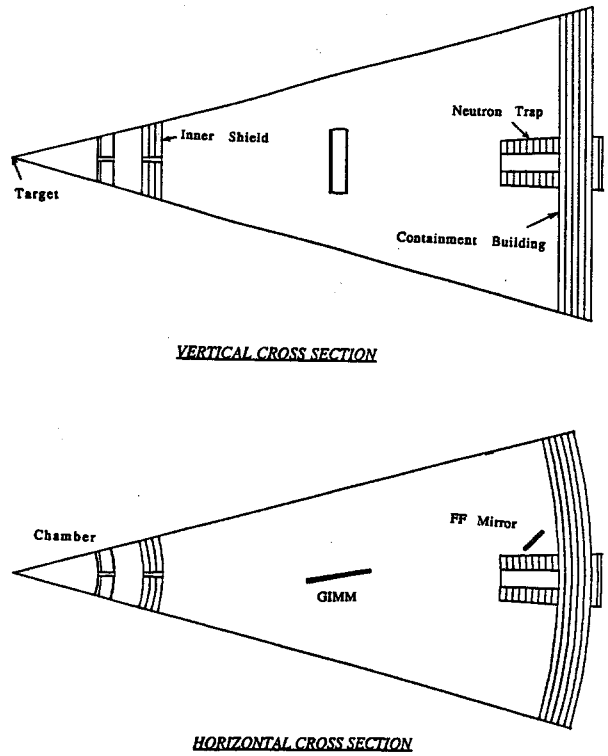

Fig. 6. Vertical and horizontal cross sections of the model used in the three-dimensional calculation.

FW, blanket and reflector at the reactor midplane is included in the model. The FW consists of a 1 cm thick c/c composite zone followed by a 5 cm thick zone that includes 20.71% c/c composite and 32.17% TiO_2 granules. The blanket is separated from the FW by a 25 cm gap and consists of 5% SiC and 95% Li_2O at a packing fraction of 60%. The blanket is followed by a 10 cm thick SiC reflector. The 1.5 m thick cylindrical inner shield and the reactor containment building are included in the model. The neutron traps with an aspect ratio of 3 are also included in the model. The inner shield, outer shield and neutron trap walls are composed of 70% concrete, 20% carbon steel (C-1020) and 10% helium coolant. A FF mirror at 40 m from the target and a GIMM at 25 m from the target are included in the model.

For f/32 final optics, the beam focusing onto the target has a conical half angle of 0.9°. The inner surfaces of the beam penetrations in the chamber, inner shield and neutron trap are considered to have a conical shape with a conical half angle of 1° that allows for clearance between the beam and duct wall. The mirrors consist of two front and rear plates cooled by water circulating through square grooves and connected by a honeycomb structure. The front and rear plates are 2 cm thick with 25% water cooling. The total mirror thickness is 24 cm. The aluminum alloy Al6061 was used for the mirror structural material. The density for the aluminum honeycomb structure is 0.0833 g/cm^3. The thin coating layers at the front surfaces of the mirrors are not included in the model as they have negligible impact on neutron transport. Based on the final optics f#, the radii of the GIMM and FF mirrors are determined to be 2.5 and 1 m, respectively. The center of the FF mirror is located at 3 m from the direct line-of-sight of the source neutrons.

B. *Results and Comments*

The fast neutron flux (E > 0.1 MeV) has been calculated at the front surface of the GIMM and FF mirrors. Five thousand histories have been used yielding statistical uncertainties less than 2% in the calculated flux values. The fast neutron flux at the GIMM is 1.15×10^{13} n/cm^{2}s. This is identical to that determined in the 2-D calculation and is contributed mostly by the direct source neutrons. The lifetime for the GIMM is similar to that estimated from the 2-D calculation. It is clear that the lifetime of the GIMM is very sensitive to the neutron fluence limit and damage recovery by annealing. Experimental data on radiation damage to metallic mirrors are essential to allow for a more accurate prediction of the GIMM lifetime.

The fast neutron flux at the front surface of the FF mirror is 5.6×10^{10} n/cm^{2}s. This is about a factor of 5 higher than that calculated using the 2-D model that does not account for direct source neutron scattering by the GIMM. The neutron flux quoted from the 2-D calculation corresponds to a location at the intersection of the outer surface of the trap wall and the inner surface of the outer shield. The flux at this location is expected to be lower than that at locations away from the neutron trap wall. In fact, the fast neutron flux obtained from the 2-D calculation at the position where the FF mirror is located in the 3-D model is 2.8×10^{10} n/cm^{2}s.

The results imply that direct source neutron interactions with the GIMM result in increasing the neutron flux at the FF mirror by a factor of ~2. This is due to the secondary scattered neutrons diverted from the straight path of source neutrons directed towards the neutron trap. Hence, the effectiveness of the neutron trap is somewhat reduced by neutron interactions with the GIMM. Although the GIMM is made of thin metallic elements, the direct source neutron will see effectively thicker materials as they travel along the beam line due to the angular configuration of the GIMM relative to the beam line. There is little or no data on neutron damage to dielectric mirrors. If we make the conservative assumption that a multilayer mirror with no color centers will have a lifetime fast neutron fluence (E > 0.1 MeV) of 10^{18} n/cm^2, the lifetime of the FF mirrors in SIRIUS-P is estimated to be about 0.6 FPY (9.6 months at 75% availability). The lifetime can be increased by proper material choice for the GIMM. It should be emphasized that using the GIMM results in significant enhancement of the lifetime of the FF mirror. Based on the 3-D calculation, the fast neutron flux at the FF mirror will be 4.8×10^{12} n/cm^{2}s if it is placed in the direct line-of-sight of source neutrons. In this case, the expected lifetime will drop to only 2.4 full power days. Again, experimental data on the impact of radiation damage on the reflectivity of the dielectric coating of the FF mirrors are required.

IV. SUMMARY AND CONCLUSIONS

SIRIUS-P utilizes GIMM with the dielectric coated FF mirrors placed out of the direct line-of-sight of source neutrons. High aspect ratio neutron traps are attached to the outer reactor containment building. 2-D neutronics calculations have been performed to determine the neutron flux levels at the GIMM and dielectric coated FF mirrors. Due to limitations on 2-D modeling of the geometry, a 3-D neutronics calculation has been performed. The model includes the beam penetrations with the associated final optics, blanket, inner shield, containment building, and neutron traps. The fast neutron flux at the GIMM is identical to that determined by the 2-D calculation. These mirrors can have a lifetime of 14 FPY assuming 80% recovery with annealing for a fluence limit of 10^{21} n/cm^2. The fast neutron flux at the dielectric coated FF mirror is about a factor of 2 higher than that calculated using the 2-D model due to neutron scattering by the GIMM. In order to reduce this effect, careful choice of materials to be used in the GIMM is essential. Materials with low density and low interaction cross sections are needed. Neutron absorbing materials such as boron will also help reduce the amount of secondary neutrons emanating from the GIMM. For a trap with an aspect ratio of 3, the flux at the FF mirror is reduced by about two orders of magnitude compared to the case without trap. The lifetime for the FF mirror will be 0.6 FPY for a fluence limit of 10^{18} n/cm^2. This work shows that 3-D analysis is essential for determining the lifetimes of the final optics in laser driven inertial fusion reactors.

ACKNOWLEDGMENT

Support for this work was provided by the U. S. Department of Energy.

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