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(71) Applicant: **LAWRENCE LIVERMORE NATIONAL SECURITY, LLC** [US/US]; 2300 First Street, Suite 204, Livermore, California 94550 (US).

(72) Inventors: **ROSSO, Paul**; 2300 First Street, Suite 204, Livermore, California 94550 (US). **MILES, Robin**; 2300 First Street, Suite 204, Livermore, California 94550 (US). **SPAETH, Mary L.**; 2300 First Street, Suite 204, Livermore, California 94550 (US).

(74) Agents: **LARGENT, Craig C.** et al.; Kilpatrick Townsend & Stockton LLP, Two Embarcadero Center, 8th Floor, San Francisco, California 94111 (US).

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(54) Title: IRRADIATION SHUTTER FOR TARGET INJECTION INTO A FUSION CHAMBER

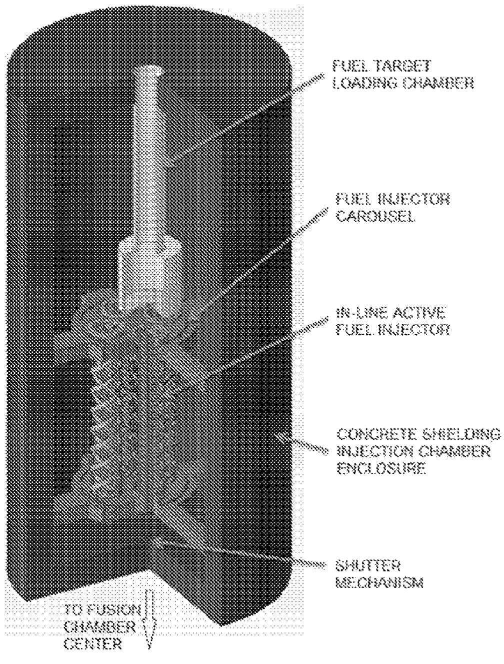

Figure 1

(57) Abstract: A shutter for an injection mechanism that injects targets into a fusion chamber includes a rotatable cylinder rotating about its axis. The cylinder includes a top opening for allowing targets to enter the shutter and a bottom opening for allowing targets to leave the shutter. A curved passage extends between the top opening and the bottom opening. Rotational velocity of the cylinder is coordinated with the velocity of an injected target to enable the injected target to pass through the curved passage without interference, and to emerge from the bottom opening to travel into the fusion chamber. The curvature of the passage is coordinated with the rotational rate of the cylinder allows the target to pass through the shutter without interference, yet protects targets waiting to be injected into the fusion chamber from being exposed to conditions in the fusion chamber.

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Irradiation Shutter for Target Injection Into a Fusion Chamber

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0001] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC for the operation of Lawrence Livermore National Laboratory.

REFERENCE TO RELATED APPLICATION

[0002] This application claims priority from earlier filed U.S. Provisional Patent Application serial number 61/719,224, filed October 26, 2012, and entitled: "Constant Rotation Irradiation Shutter for Target Injection Into a Fusion Chamber." This provisional patent application is incorporated by reference herein.

BACKGROUND OF THE INVENTION

[0003] The National Ignition Facility (NIF), the world's largest and most energetic laser system, is operational at Lawrence Livermore National Laboratory (LLNL) in Livermore, California. One goal of operation of the NIF is to demonstrate fusion ignition for the first time in the laboratory. Initial experiments are calculated to produce yields of the order of 20 MJ from an ignited, self-propagating fusion burn wave. The capability of the facility is such that yields of up to 150-200 MJ could ultimately be obtained. The NIF is designed as a research instrument, one in which single "shots" on deuterium-tritium containing targets are performed for research. A description of the NIF can be found in Moses et al, *Fusion Science and Technology*, volume 60, pp 11-16 (2011) and references therein.

[0004] There is a rapidly growing need worldwide for power, and especially for clean power. At LLNL a project known as Laser Inertial-confinement Fusion Energy, (often referred to herein as "LIFE") is working toward introduction of fusion based electric power plants into the U.S. economy before 2030, and in a pre-commercial plant format before that. LIFE technology offers a pathway for the expansion of carbon-free power around the world.

It will provide clean carbon-free energy in a safe and sustainable manner, without risk of nuclear proliferation.

[0005] One challenge with respect to LIFE, as well as any technology for generating electrical power to be distributed to large numbers of consumers, is reliability. Consumers expect to have extraordinarily high reliability in their electric power supply. The result is that utilities that provide that electrical power maintain their facilities to assure the required high reliability. Thus, among the challenges with respect to fusion power, is to provide mechanisms by which a reliable long-lived fusion chamber can be provided in which the fusion reactions occur, and with regard to which associated equipment has an appropriately long lifetime.

[0006] In the technology described herein, a fusion power plant is provided with a fusion chamber into which targets (hohlraums containing capsules with deuterium and tritium fuel) are introduced multiple times per second. As the individual fuel targets reach the center of the chamber, banks of lasers fire on the targets, heating and compressing the fuel within the capsule to create a fusion reaction.

[0007] The Laser Inertial Fusion Energy concept can operate as either a pure fusion or hybrid fusion-fission system. The LIFE fusion chamber must absorb the fusion energy, produce fusion fuel to replace that burned in previous targets, and enable both target and laser beam transport to the ignition point. One challenge with regard to the chamber is assuring that the targets injected into the chamber for each subsequent reaction, as well as the injection mechanism itself, are protected from the environment of the fusion reactions.

[0008] In the environment of the LIFE engine fusion chamber, the target capsule and hohlraum cycle in temperature from near absolute zero to thousands of degrees Kelvin and are completely ionized with each laser pulse. Each shot is introduced with a frozen film of deuterium and tritium (DT) inside the capsule. That frozen material must be protected from the heat and pressure of the fusion chamber until it is ready to be injected into the chamber. Because the targets are injected into the chamber at a rate of about nine targets per second, many targets are present in the injection system itself, and this system also must be protected from the temperatures and pressures inside the fusion chamber.

[0009] The overall fusion power plant architecture is described in "Inertial Confinement Fusion Power Plant which Decouples Life-limited Components from Plant Availability," PCT application US 11/59820, filed November 8, 2011. The fusion chamber is described in more detail in "Inertial Confinement Fusion Chamber," PCT application US

11/59814, also filed November 8, 2011. The contents of these commonly assigned patent applications are incorporated by reference herein.

SUMMARY OF THE INVENTION

[0010] In one embodiment, a shutter for an injection mechanism that injects targets into a fusion chamber includes a rotating cylinder having openings on the top and bottom of the cylinder. The top and bottom openings are connected to each other by a helical passage extending through the cylinder. Targets are injected parallel to the axis of rotation of the cylinder into the opening on the top of the cylinder. Rotation of the cylinder is coordinated with the velocity of an injected target to enable the target to pass through top opening, travel through the helical passage without interference, and then emerge from the opening on the bottom of the cylinder. After exiting the rotating cylinder, the target travels into the fusion chamber where the lasers compress and heat the fusion fuel within the capsule. The rotation of the cylinder and the helical passage assure that there is never a line of sight path between the fusion chamber and the top of the cylinder where the next target awaits injection.

[0011] In another embodiment the shutter includes a rotating cylindrical member having a curved slot there through, for example, adjacent one of the planar surfaces at the end of the cylinder. As the cylinder rotates around its axis, targets are injected into the slot perpendicular to the axis of rotation. In this embodiment, as in the first embodiment, rotation of the cylinder is coordinated with the velocity of an injected target to enable the target to pass into the slot, travel through the slot without interference, and then emerge from the opposite end of the slot. The rotation of the cylinder and the curved slot assure that there is never a line of sight path between one end of the curved slot facing the fusion chamber and the other end of the curved slot facing the injection mechanism where the next target awaits injection.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 illustrates the overall target injection system for injecting targets into a fusion chamber;

[0013] Figure 2 illustrates the architecture of a first embodiment having a helical path through which the targets pass;

[0014] Figure 3 illustrates the architecture of a second embodiment having a slot through which the targets pass;

[0015] Figure 4 is a diagram illustrating a correlation between shutter thickness and target heating.

DESCRIPTION OF THE INVENTION

[0016] As presently contemplated, a megawatt size LIFE power plant will require on the order of nine fusion targets per second. As these targets reach the center of the fusion chamber, lasers heat and compress the fusion fuel to cause the fusion reaction. Heat from the reaction can be then used to generate electrical power. Thus, inertial confinement fusion target designers must consider many engineering requirements in addition to the physics requirements for a successful target implosion. Among these considerations is protection of the targets awaiting injection to the center of the chamber. For the fuel to implode and create a fusion reaction, the fuel capsule must arrive at the chamber center in substantially its original condition where it can be irradiated evenly with energy to ablate the capsule surface to compress and heat the DT fuel. An embodiment of an injection system for injecting the fusion targets is described in our commonly assigned PCT Patent Application "Fusion Target Injection and Tracking," filed November 8, 2011, as serial number PCT/US2011/059791. The contents of that application are incorporated herein by reference.

[0017] In such a system, the multiple fusion reactions per second in the chamber create intense heat, pressure, and radiation that can damage not only the targets immediately outside the chamber in the injection mechanism waiting to be injected, but also the injection system itself. Herein we describe embodiments of a shutter to protect the targets and the target injection system from damage from the fusion reactions. The shutter described herein blocks heat, pressure, and radiation from the fusion reaction, preventing it from reaching targets outside the chamber, as well as preventing it from reaching the injection system.

[0018] Figure 1 is a perspective diagram of one implementation of the injection system by which targets are injected into the fusion chamber. As illustrated there, concrete shielding protects the injection chamber from influences of the fusion chamber. A fuel target loading chamber enables the injection mechanism to be loaded with fusion targets (hohlraums with DT capsules) that have been prepared for injection into the fusion chamber. The targets are placed in cassettes which rotate into position via a fuel injector carousel. Once the appropriate portion of the carousel is in position, targets stored in that portion of the carousel are sequentially injected into the fusion chamber using the mechanism described in our above copending patent application. The shutter, which is described in more detail below, is shown near the bottom of Figure 1.

[0019] Figure 2 illustrates the architecture of our shutter in a first preferred embodiment. As illustrated there, a cylindrical shutter 10 rotating 15 about the axis 14 of the cylinder includes a helical passage 12 through the cylinder 10. The shutter 10 separates a fusion fuel target 50 that is in flight to the fusion chamber center to become the next target to be injected into the fusion chamber (not shown) where a fusion reaction 40 will occur. The dimensions of the shutter are such that its thickness C (measured along the vertical axis) is sufficient to shield fusion targets in the injection system awaiting injection, as well as the injection system itself, from the fusion reaction creating high-energy neutrons and alpha particles. The thickness C is the sum of thicknesses A and B representing the thickness of the shielding material less the "thickness" of the helical opening as measured along the vertical axis. Thus, the shutter is of a sufficient thickness such that at any position in its rotation the total solid material thickness is sufficient to shield the next fusion fuel target and the injection system from the fusion reaction.

[0020] In operation, targets 50 are injected through the upper opening 22 in the shutter 10. As the target moves downward toward the fusion chamber, the shutter rotates at a rate such that the vertical velocity of the target keeps the target always within the helical passage. The target ultimately emerges from the lower opening 24 of the helical passage and then travels toward the center of the fusion chamber, where laser beams ablate the DT capsule and create a fusion reaction.

[0021] In a typical implementation the shutter cylinder 10 is supported along its axis of rotation between plates 20 and 30 and is coupled to a motor (not shown) to cause it to spin at the desired rate of rotation. As mentioned above, when target 50 is first injected, it enters through an opening in the supporting structure 20. As the target 50 travels downward, its vertical velocity and the rotation of the shutter cylinder 10 are coordinated so that the vertical velocity of the target corresponds to an open portion of the helical slot 12. For example, if the rotating cylinder is 1000 mm thick and opening 22 in the top of the shutter is aligned directly over opening 24 in the bottom of the cylinder 10, and the two openings are connected by a slot of constant slope, then if the target velocity is such that it traverses the 1000 mm in the time it takes for the cylinder to make one rotation, the target will pass through the slot without interference from the interior surface of the slot. Yet while the target traverses the slot, the shutter cylinder 10 will never present a straight-line opening between its lower surface and its upper surface such that heat or radiation can pass from the fusion chamber to the targets awaiting injection above the shutter.

[0022] Plates 20 and 30 may also perform the function of sealing the shutter top and bottom openings, 22 and 24, during shutter rotation while the openings are in rotational positions not concurrent with the target trajectory. The addition of passageway opening sealing prevents the transfer of environmental gases and debris through the shutter mechanism. Additionally, environmental control systems can interface with the shutter passageway during these sealed rotational position states for debris clearing and/or environmental gas exchange. Other means of sealing or obstructing the passageway exist, including intermediate plates or other structures within the shutter mechanism system to be timed with shutter rotation.

[0023] Figure 3 is a diagram illustrating another embodiment of the invention. Shown there is a cylindrical shutter 60 that rotates by means of a shaft 64. The cylinder 60 includes openings 70 and 72 at opposite ends of a passage 62. In contrast to the first embodiment, in this embodiment the axis of rotation 75 of the cylinder 60 is perpendicular to the direction of travel of the fusion target 50. As shown by Figure 3a, the injection mechanism injects the target 50 into the opening 70 at the then top of the passage 62. Next as shown by Figures 3b and 3c, the curvature of the passage 62, coupled with the rotational velocity of the cylinder 60 enables the target 50 to pass through the remaining portion of passage 62, ultimately exiting from the far end 72 of passage 62. The curvature of the passage 62, rotational velocity 75 of the cylinder 60 and downward velocity of the target enable the target 50 to pass through the shutter without interference, and enter the fusion chamber. Figure 3d illustrates the next target 50 now ready for injection. In each of the two embodiments described, rotation of the shaft prevents the fusion chamber environment from ever having a direct line-of-sight impact on targets stored in the injection mechanism. As with respect to Figure 2, thickness C is sufficient such that at any position in its rotation the total solid material thickness is shields the next fusion fuel target and the injection system from the fusion reaction. Note that Figure 3 illustrates the passage as a groove in one end of the cylinder; however, the groove can be implemented as a completely enclosed curved passage through a cylinder.

[0024] Figure 4 is a diagram illustrating the relationship between shutter thickness and target heating. This diagram was prepared using simulation data. The diagram demonstrates that as the shutter thickness increases, the target heating decreases (the expected result). For example, as the shutter thickness increases from being absent (the zero thickness point) to a thickness of 66 cm, neutron heating of the next target waiting in the system for injection drops from approximately 10^{-2} watts to 10^{-7} watts. Increasing the shuttered thickness beyond 66 cm provides essentially no further reduction in target heating caused by either neutrons or photons. The data shown in Figure 4 includes factors other than shutter thickness, e.g. the surrounding structure, as well as photon production from neutron reaction in other materials.

[0025] The examples and embodiments described herein are for illustrative purposes only. Various modifications or changes in light thereof will be apparent to persons skilled in the art. These are to be included within the spirit and purview of this application, and the scope of the appended claims, which follow.

We claim:

1. A shutter for an injection mechanism that injects targets with a first velocity into a fusion chamber comprising:

a rotatable member rotating about an axis of rotation and having a top opening for allowing targets to enter the shutter, and having a bottom opening for allowing targets to leave the shutter, a curved passage extending between the top opening and the bottom opening; and

wherein rotation velocity of the rotatable member is coordinated with the first velocity of an injected target to enable the injected target to pass through the curved passage without interference and to emerge from the bottom opening to travel into the fusion chamber.

2. A shutter as in claim 1 wherein the rotatable member comprises a cylinder and the axis of rotation is the axis of the cylinder.

3. A shutter as in claim 2 wherein:

the top opening is in a first end of the cylinder;

the bottom opening is in an opposite end of the cylinder; and

the curved passage comprises a helical passage extending between the top opening and the bottom opening.

4. A shutter as in claim 3 wherein the injected target enters the helical passage through the top opening, passes through the helical passage, and emerges from the helical passage at the bottom opening to travel into the fusion chamber.

5. A shutter as in claim 4 wherein the top opening is disposed directly opposite the bottom opening.

6. A shutter as in claim 5 wherein the first velocity is x, the rotatable member has a thickness y, and the rotatable member rotates at a rate z, where z is one rotation of the rotatable member every y/x.

7. A shutter as in claim 1 wherein there is never a line of sight opening between the top opening and the bottom opening.

8. A shutter as in claim 2 wherein:

each of the top opening and the bottom opening are disposed on an exterior curved surface of the cylinder; and

the curved passage comprises a passage extending between the top opening and the bottom opening.

9. A shutter as in claim 8 wherein the curved passage is disposed adjacent an end of the cylinder.

10. A shutter as in claim 9 wherein there is never a line of sight opening between the top opening and the bottom opening.

11. A shutter as in claim 8 wherein the curved passage has a shape of an arc with respect to a plane perpendicular to the axis of rotation of the rotatable member.

12. A method of protecting targets to be injected into a fusion chamber and injection systems from conditions in the fusion chamber comprising:

providing a rotatable shutter between the fusion chamber and the injection system, the rotatable shutter having a top opening, a bottom opening, and a curved passage extending between the top opening and the bottom opening; and

rotating the rotatable shutter as targets are injected so the targets pass through the shutter without interference, but the injection system is not exposed to conditions in the fusion chamber.

13. A method as in claim 12 wherein the rotatable shutter is a cylinder and coupled to a shaft that rotates the cylinder along a central axis.

14. A method as in claim 13 wherein the rotatable shutter rotates at a rate that allows a target to pass through the first opening and emerge from the second opening within a fraction of one revolution of the shutter.

15. A method as in claim 14 wherein the top opening is in one end of the cylinder, the bottom opening is in an opposite end of the cylinder, and the curved passage is a helical

passage connecting the top opening to the bottom opening.

16. A method as in claim 14 wherein the top opening and the bottom opening are disposed on a curved surface of the cylinder.

17. A method as in claim 16 wherein the curved passage is arc shaped.

18. A method as in claim 17 wherein the curved passage is a groove extending into an end of the cylinder.

19. A method as in claim 12 wherein the top opening and the bottom opening are obstructed by stationary adjacent surfaces during rotational positions not concurrent with a time that a target is being injected.

20. A method as in claim 12 wherein at least some portion of the curved passage is sealed throughout full rotation of the shutter.

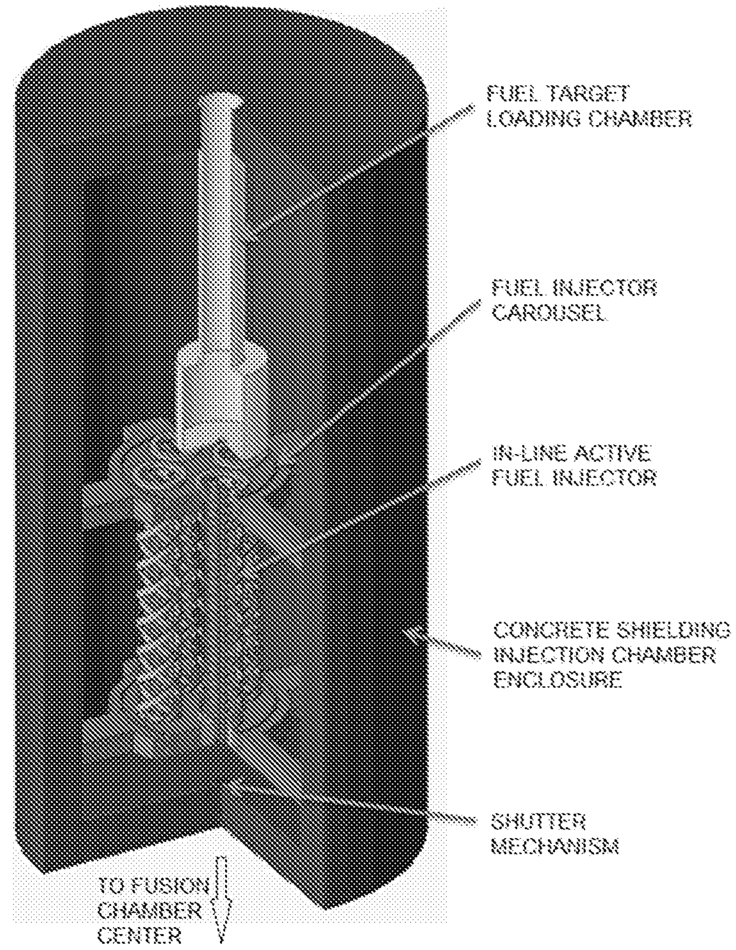
FUEL TARGET
LOADING CHAMBER
FUEL INJECTOR
CAROUSEL
IN-LINE ACTIVE
FUEL INJECTOR
CONCRETE SHIELDING
INJECTION CHAMBER
ENCLOSURE
SHUTTER
MECHANISM
TO FUSION
CHAMBER
CENTER

Figure 1

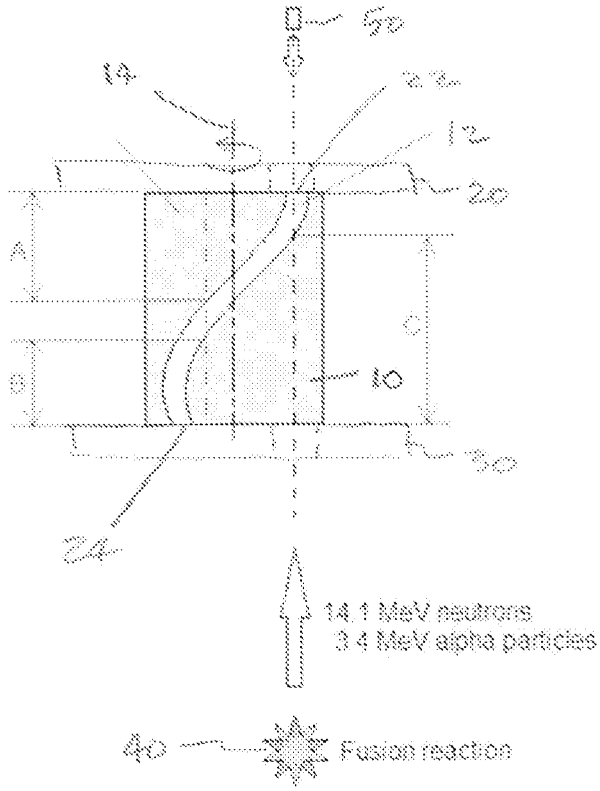
50
14
22
12
20
A
C
B
10
30
24
14.1 MeV neutrons
3.4 MeV alpha particles
40
Fusion reaction

Figure 2

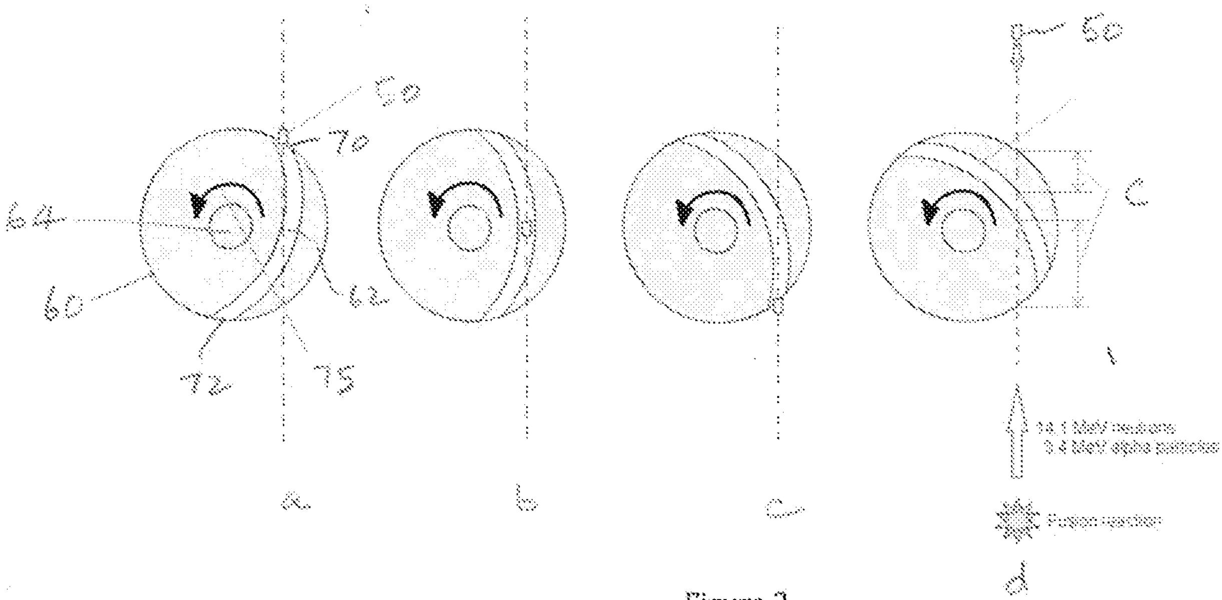

Figure 3

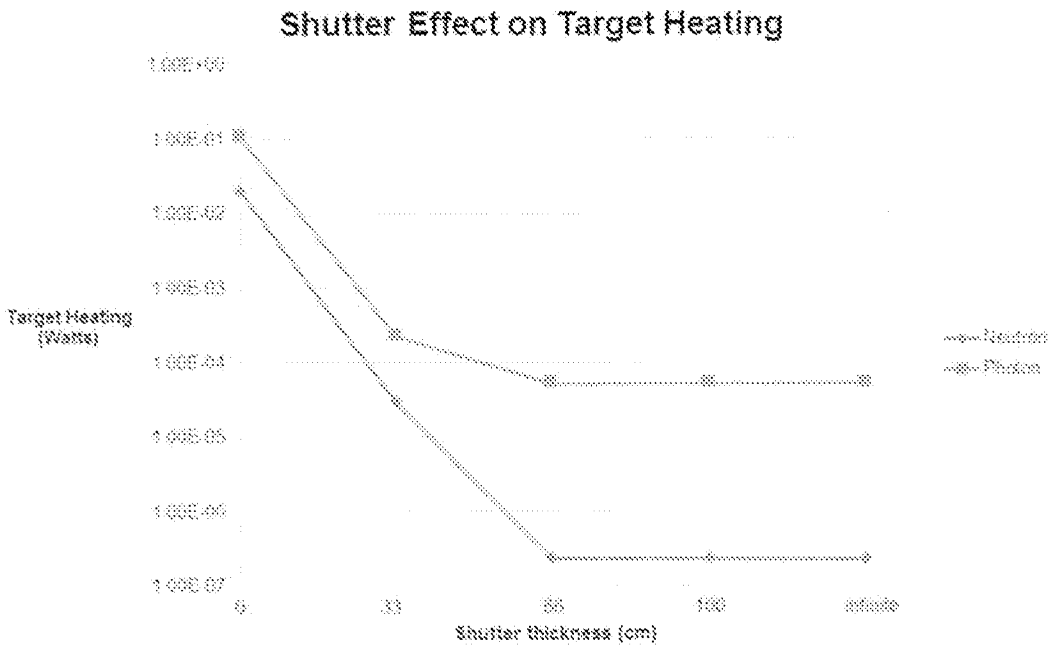

Figure 4