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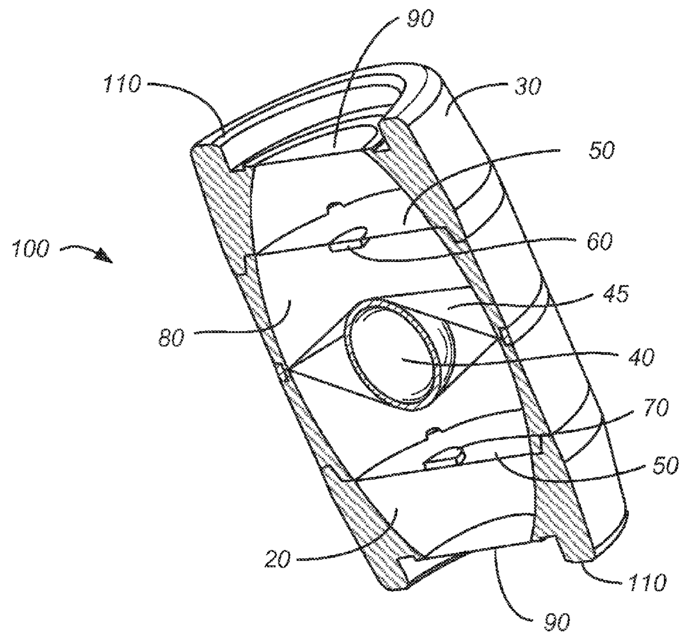

FIG. 1B

(57) Abstract: A hohlraum for an inertial confinement fusion power plant includes a generally cylindrical body having a laser entrance hole opening in opposite ends thereof to enable laser beams to reach an interior surface of the generally cylindrical body. The hohlraum also includes a first window covering the laser entrance hole in a first end of the generally cylindrical body and a first raised protrusion surrounding the first window. The first raised protrusion creates a first region of ambient gas stagnation adjacent the first window when the hohlraum is moving, to thereby reduce heat flow into the hohlraum.

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METHODS AND SYSTEMS FOR TEMPERATURE CONTROL OF FUSION TARGETS

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/736,925, filed on December 13, 2012, entitled "Carbon Membranes for Fuel Capsule Support in Fusion Targets," U.S. Provisional Patent Application No. 61/736,681, filed December 13, 2012, entitled "Controlled Interior Convection of Inertial Confinement Fusion Targets," U.S. Provisional Patent Application No. 61/736,679, filed December 13, 2012, entitled "Fusion Target Frontal Shaping for Heat Reduction," and U.S. Provisional Patent Application No. 61/736,934, filed December 13, 2012, entitled "Phase Change and Pyrolysis Protection for Fusion Targets," the disclosures of which are hereby incorporated by reference in their entirety for all purposes.

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

[0002] 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.

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 ultimately could be obtained. NIF is designed as a research instrument, one in which single laser "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] In the technology described herein, a fusion power plant is provided with a fusion chamber into which targets (i.e., hohlraums containing fuel capsules with deuterium and tritium (DT) 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.

[0006] A LIFE power plant 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. The overall fusion power plant architecture is described in International Patent Application No. PCT/US2011/059820, filed on November 8, 2011, and entitled "Inertial Confinement Fusion Power Plant which Decouples Life-limited Components from Plant Availability." The fusion chamber is described in more detail in International Patent Application No. PCT/US2011/059814, also filed on November 8, 2011, and entitled "Inertial Confinement Fusion Chamber." An embodiment of the fusion targets is described in U.S. Patent Application No. 13/290,282, filed on November 7, 2011, and entitled "Indirect Drive Targets for Fusion Power." The disclosures of these applications are hereby incorporated by reference in their entirety for all purposes.

[0007] 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 fuel capsule.

[0008] A particular challenge facing commercial implementation of a fusion-based power plant is the need to deliver the targets to the center of the fusion chamber with the DT fuel capsules at the appropriate temperature. As presently contemplated, a megawatt size ICF power plant will require on the order of 10 to 15 targets per second, thus creating extremely high temperatures within the chamber. Because it is desirable to maintain the DT fuel capsule at cryogenic temperatures, methods and systems are desired to protect the target from this heat during its injection into the chamber and its travel to the center of the chamber, a time period expected to be about 25 milliseconds.

[0009] In addition, the fuel capsule preferably has a defined position within the hohlraum at the time the hohlraum reaches the center of the fusion chamber. It is at this instant that the laser beams strike the hohlraum to irradiate the fuel capsule and initiate the fusion reaction. For this reaction to occur, the fuel capsule should be irradiated uniformly. As such, the position of the fuel capsule within the hohlraum should be reliably known and repeatable with a high precision. Thus, methods and systems to provide for fuel capsule position control are needed.

SUMMARY OF THE INVENTION

[0010] Some embodiments of this invention relate to targets used as fuel for fusion reactions, and in particular to the configuration of targets containing hydrogen fuel for inertial confinement fusion-based power plants.

[0011] We have developed a hohlraum for an inertial confinement fusion power plant that is better able to maintain a capsule containing DT fusion fuel at the desired low temperature. In an implementation, the hohlraum includes a generally cylindrical body having a laser entrance hole opening in each end thereof to enable laser beams to reach its interior surface. A window covers the laser entrance hole of at least the leading end of the hohlraum body. A raised protrusion surrounds window. The raised protrusion creates a region of ambient gas stagnation adjacent the window when the hohlraum is moving, thereby reducing heat flow into the generally cylindrical body.

[0012] In another embodiment, the hohlraum includes a film of material between the window and the fuel capsule. The film divides the interior of the hohlraum into a first region surrounding the fuel capsule and a second region adjacent the window. A recessed region in the cylindrical body of the hohlraum adjacent an edge of the film allows gases to flow between the first and second region, further facilitating maintenance of the fuel capsule at the desired temperature.

[0013] In yet another embodiment, a sublimation layer is formed on at least the window of the leading end of the target. During injection, heat from the fusion chamber causes the layer to sublimate, thereby further protecting the fuel capsule from the high temperatures of the fusion chamber. If desired further measures may be taken to maintain the fuel at the desired temperature. These measures include employing laser entrance hole windows that undergo phase change or pyrolysis of the windows in response to the elevated temperatures of the fusion chamber.

[0014] According to an embodiment of the present invention, a hohlraum for an inertial confinement fusion power plant is provided. The hohlraum includes a generally cylindrical body having a laser entrance hole opening in opposite ends thereof to enable laser beams to reach an interior surface of the generally cylindrical body. The hohlraum also includes a first window covering the laser entrance hole in a first end of the generally cylindrical body and a first raised protrusion surrounding the first window. The first raised protrusion creates a first region of ambient gas stagnation adjacent the first window when the hohlraum is moving, to thereby reduce heat flow into the hohlraum.

[0015] According to another embodiment of the present invention, a hohlraum for an inertial confinement fusion power plant is provided. The hohlraum includes a generally cylindrical body having a set of laser entrance holes in opposite ends thereof operable to enable laser beams to reach an interior surface of the generally cylindrical body. The hohlraum also includes a first window covering one of the set of laser entrance holes in a first end of the generally cylindrical body and a fuel capsule disposed at a central location in the hohlraum. The hohlraum further includes a first infrared shield disposed between the fuel capsule and the first window and a first passage in the first infrared shield allowing gas to flow through the first infrared shield.

[0016] According to a particular embodiment of the present invention, a method of reducing heat transfer to a hohlraum injected into a fusion chamber is provided. The method includes providing a window having a central portion and an edge over a laser entrance hole in the hohlraum and providing a protrusion around the edge of the window. The method also includes injecting the hohlraum into the fusion chamber with the window facing the fusion chamber so as to provide a region of ambient gas stagnation adjacent the central portion of the window.

[0017] According to another embodiment of the present invention, a hohlraum for an inertial confinement fusion power plant is provided. The hohlraum includes a generally cylindrical body having a laser entrance hole opening in opposite ends thereof to enable laser beams to reach an interior surface of the generally cylindrical body. The hohlraum also includes a first window covering the laser entrance hole in a first end of the generally cylindrical body and a second window covering the laser entrance hole in a second end of the generally cylindrical body. The hohlraum further includes a first raised protrusion surrounding the first window to create a first region of ambient gas stagnation adjacent the first window when the hohlraum is moving, to thereby reduce heat flow into the hohlraum. The first window is formed from a material which undergoes pyrolysis at elevated temperatures and a sublimation layer is disposed across the first window.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. 1A is a simplified side view of a fusion target with a hohlraum and fuel capsule according to an embodiment of the present invention.

[0019] FIG. 1B is a perspective view of a fusion target according to an embodiment of the present invention.

[0020] FIGS. 2A - 2C illustrate simplified side views of alternative geometries for a fusion target according to various embodiments of the present invention.

[0021] FIG. 3 is a simplified perspective view of a portion of a hohlraum illustrating a passage in the target through which gas (e.g., helium) can flow according to an embodiment of the present invention.

[0022] FIG. 4 is a cutaway diagram illustrating a quarter section of a hohlraum according to an embodiment of the present invention.

[0023] FIG. 5 is a cutaway diagram illustrating temperature contours in a hohlraum according to an embodiment of the present invention.

[0024] FIG. 6 is a diagram of an alternative embodiment of the leading edge of a fusion target.

[0025] FIG. 7 is a simplified heat flow diagram illustrating flows for a fusion target according to an embodiment of the present invention.

[0026] FIG. 8 is a simplified flowchart illustrating a method of reducing heat transfer to a hohlraum injected into a fusion chamber according to an embodiment of the present invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0027] Laser fusion targets experience very high heating in transit to the use point at the center of the fusion chamber. The targets will generally not function if heating of the target fuel exceeds approximately 100 milliKelvin or if the fuel capsule is significantly displaced from its expected location at the center of the hohlraum. Indirect drive fusion targets require stiff support and thermal isolation from mechanical and thermal environments during fabrication, transport and flight toward their use point. Carbon membranes can hold the deuterium-tritium fuel capsule with minimal displacement while simultaneously providing isolation from both infrared radiant heating and hot noble gas convective heating.

[0028] In commercial fusion plants, IFE targets are to be injected into fusion chambers at rates of about 5-20 per second and at speeds of 5-500 meters per second. Membranes are required for at least two key functions within the hohlraum. First, the fuel capsule must be supported with minimal displacement during acceleration from rest to top speed as it enters the fusion chamber. Second, the DT layer within the fuel capsule must be thermally isolated during acceleration and flight through hot fusion chamber gas. Thermal isolation can take the form of inhibiting the flow of heated gas from reaching the fuel capsule and DT layer, and it can take the form of blocking infrared radiation from reaching the surface of the fuel capsule and DT layer. Carbon membranes, either graphene bonded or diamond-like carbon (DLC) bonded can serve both these functions because of their high strength at the relevant temperatures, low transmittance at the relevant wavelengths and temperatures, and robust thermal stability.

[0029] Embodiments of the present invention utilize the thermal inertia of a lead housing and the high temperature durability of graphene or DLC windows and infrared (IR) shields.

The thermal inertia of the lead housing effectively eliminates flow of heat from the xenon toward the DT capsule via the hohlraum walls. The high temperature properties of the carbon or other material windows (at each end of the hohlraum) allow the laser entrance hole (LEH) windows to survive the high flight-dependent heat fluxes (particularly at the stagnation point, which is the center of the front window). At the same time they also transmit much of the heat from the Xe gas to the helium gas fill within the hohlraum between the windows and the IR shields. In addition, the windows can include polyimide materials as an alternative to or in combination with DLC materials.

[0030] FIG. 1A is a simplified side view of a fusion target with a hohlraum and fuel capsule according to an embodiment of the present invention. The hohlraum design is a component of the strategy for thermal protection including limiting the exposure time and providing thermal barriers against the incident heat flux. In some embodiments, the DT layer is protected by keeping the temperature rise of the DT-ice/DT-gas interface to less than 0.1K. The hohlraum 100 includes LEH windows 90 at the front and rear of the hohlraum that keep helium in the hohlraum and prevent the hot xenon from entering. Four helium compartments 112, 114, 116, and 118 isolate the DT in the fuel capsule 40 from the incoming heat loads as described herein. IR reflectors (also referred to as IR shields) 50 protect against incident radiation from the chamber wall and prevent the flow of heated helium toward the fuel capsule 40. Additional description related to the hohlraum is provided in relation to FIG. 1B below.

[0031] During the 25 millisecond flight of the target through the 6000 K Xenon chamber atmosphere, the four helium compartments 112, 114, 116, and 118 of the hohlraum develop heat distributing convection currents. In the front and rear helium compartments 112 and 118, i.e. the compartment just inside the LEH windows 90, the currents pull heat away from the LEH windows' interior surfaces and deposit the majority of this heat on the cool lead interior side walls 30. Because they are partially driven by fluid density gradients, these flows resemble free convection cells present in hot water tanks and other fluid enclosures. Target rotation, imparted by the injection mechanism at the time the targets are accelerated to be injected into the fusion chamber, enhances the buoyant effects. Similar, though less vigorous processes, occur in the two helium gas filled chambers 114 and 116 between the IR shields 50 and the capsule. The IR reflectors 50 are also heated by the He gas in the compartment between it and the LEH window. This then heats the He gas between the IR shield and the fuel capsule 40. This gas forms a convection cell driven by density differences and rotation rate which leads to small heating of the cold lead side wall and miniscule heating of the capsule surface. The heating of the rear facing LEH window is significantly weaker than the front facing window heating. Thus the back half heat transport processes are much weaker, and thus less threatening, to the fuel capsule.

[0032] FIG. 1B is a perspective view of a fusion target according to an embodiment of the present invention. The fuel capsule 40 (also referred to as a capsule) containing the fusion fuel is about a 4 mm diameter, hollow, spherical capsule 40, which may be made of high-density carbon. In an embodiment, the capsule has a chemical vapor deposition deposited diamond ablator wall, with a thickness less than about 100 μm. Nanoporous foam, e.g., CH1.2, lines the interior wall of the capsule. The inner deuterium-tritium (DT) fuel layer is about 150 μm thick. When in use the capsule and hohlraum are cooled to a low temperature on the order of less than 20K.

[0033] The hohlraum 100 is made generally of lead, about 1 cm in diameter by about 2 cm long, with an insulating wall 30. An approximately 20 μm thick layer of high-Z material 20, e.g., plated lead, on the inside hohlraum wall provides for more efficient x-ray production. The hohlraum has a rugby ball-shaped interior 80 for better coupling of the expected approximately 2.2 megajoule (MJ) laser energy to the capsule 40. The shape of the interior surface is a circular arc with the origin vertically offset to satisfy the prescribed dimensions of the hohlraum, e.g., maximum and minimum inner radii, and length.

[0034] Infrared reflectors 50 (also referred to as IR shields), typically a low-Z membrane material such as carbon or polyimide coated with a thin reflective metal layer, e.g. a 30 nm layer of aluminum, helps protect the capsule from radiant heat in the fusion chamber. "P2" shields 60 and 70, typically manufactured from the same material as the hohlraum, and deposited onto the polyimide membrane, provide symmetry and enhancement of the x-ray bath around the capsule 40. An additional low-Z membrane 45 is used to support the capsule 40 within the hohlraum 100. The hohlraum is filled with helium gas that tamps the degree of the hohlraum wall expansion to provide greater symmetry control. The LEH windows 90 over the laser entrance holes at opposite ends of the hohlraum seal in the gas. The exterior surface of the hohlraum 100 has cylindrical sides to enable guidance by a target injection system used to introduce the targets into the fusion chamber.

[0035] As illustrated in FIG. 1B, the hohlraum, which is suitable for use in an inertial confinement fusion power plant, includes a generally cylindrical body having a laser entrance hole opening in each end thereof to enable laser beams to reach an interior surface. The laser entrance holes are covered by one or more LEH windows 50 in at least one end of the generally cylindrical body. Additionally, at least one carbon based membrane 45 is disposed across a central region of the hohlraum and configured to support the fusion fuel capsule 40. In some embodiments, the carbon based membrane 45 comprises a graphene bonded or DLC bonded membrane.

[0036] The target illustrated in FIG. 1B uses windows over the laser entrance holes to keep helium inside the hohlraum, while also keeping hot xenon inside the fusion chamber away from the capsule 40. The windows also transfer heat to the sidewalls of the hohlraum. The infrared reflectors 50 protect against incident thermal radiation from the fusion chamber wall and prevent the heated helium in the portion of the hohlraum furthest from the capsule from contacting the capsule. While the highest heat flux from the xenon gas in the chamber is at the front window, the side heat fluxes from the xenon gas, estimated to be about 70% of those on the front, are applied to the hohlraum, which is preferably lead. The thermal inertia of the lead absorbs most of that heat during the 25millisecond flight through the fusion chamber.

[0037] An important feature of the target of FIG. 1B is the protrusion 110 around the LEH windows 90. This creates an ambient gas stagnation zone at the front of the hohlraum as it is injected into the fusion chamber, reducing heat transfer to the LEH window 90 and the helium contained behind the window. Tapering the opening to be wider at the front of the hohlraum but narrower at the window location allows a wider field for entrance of the laser light, and enlarges the stagnation zone of the low-pressure xenon filling the fusion chamber.

[0038] FIGS. 2A - 2C illustrate simplified side views of alternative geometries for a fusion target according to various embodiments of the present invention. In FIG. 2A, a web configuration is utilized in which carbon nanotubes are utilized to support the fuel capsule. In FIG. 2B, rods supported on the P2 shields are utilized to support the fuel capsule. Embodiments of the present invention can utilize a variety of materials, including polyimides (strength at 25 °C of 90 MPa), CNT (strength at 25 °C of 3.6 GPa), graphene (strength at 25 °C of 130 GPa), kevlar (strength at 25 °C of 2.7 GPa), or the like. One of ordinary skill in the art would recognize many variations, modifications, and alternatives. In FIG. 2C, a sublimation layer is illustrated.

[0039] Fusion targets, such as those illustrated in FIG. 1A and FIG. 1B, will experience major heat fluxes during their transit between the injector muzzle and the fusion chamber center, where lasers implode the DT in the target capsule. Gases in the chamber are expected to reach temperatures of about 6000K. The approximately 500 nm thick membranes that cover the laser entrance holes of the target can quickly heat to temperatures of about 1200K. The fill gas within the hohlraum (typically helium) circulates within the various chambers in the target due to heating and target rotation. This circulating helium transfers heat from the LEH windows to the lead sidewalls and to more interior locations, i.e. the inner shields, and ultimately to the DT fuel.

[0040] Shaping the P2 shield, the several helium chambers and passages which connect the chambers can optimize the transfer of heat to the hohlraum shell and the P2 shield, and minimize the transfer to the DT. The fill gas within the target (for example, helium) circulates due to heating and target rotation. This circulating helium transfers heat from the LEH windows to the lead sidewalls and to more interior locations, i.e. the inner shields and ultimately to the DT fuel.

[0041] FIG. 3 is a simplified perspective view of a portion of a hohlraum illustrating a passage in the target through which helium can flow according to an embodiment of the present invention. In the close-up view of the interior of the hohlraum illustrated in FIG. 3, passage 120 allows for circulation of helium from within one chamber 310 inside the hohlraum to another chamber 320 inside the hohlraum. For reference, chambers 310 and 320 correspond to compartments 112 and 114 in FIG. 1A. The chamber 310illustrated is defined by the window 90 (membrane) covering the laser entrance hole at the top of the figure, and another membrane 50 upon which a P2 shield 60 is deposited. In the illustration, the passage 120 is made possible by a recess in the interior wall of the hohlraum. In other embodiments of the invention, however, a small opening can be provided in the membrane to allow gas to move from one chamber to an adjoining chamber. In addition to enabling the flow of gas, and therefore heat, from one chamber to another, these passages 120 also allow equalization of pressure among all of the chambers within the hohlraum. This prevents a high-pressure zone, for example in the chamber adjacent the leading edge of the hohlraum as it is injected into the fusion chamber, from becoming so pressurized from heat as to deform the membranes, or even rupture them.

[0042] FIG. 4 is a cutaway diagram illustrating a quarter section of a hohlraum according to an embodiment of the present invention. FIG. 5 is a cutaway diagram illustrating temperature contours in the hohlraum according to an embodiment of the present invention. In the quarter section of the hohlraum illustrated in FIG. 4, the fuel capsule 40 is illustrated in the center of the hohlraum along with membranes 410 and 412 supporting the fuel capsule and membranes 420 and 422 supporting the P2 shields 60. FIG. 5 illustrates the results of a computation showing the temperature profile across the various portions of the hohlraum as it is injected into the chamber. In FIG. 5, the top of the diagram is the face of the hohlraum that serves as the leading edge of the hohlraum during injection. This is the region which reaches the highest temperatures during travel from the injector to the center of the chamber.

[0043] Thus, embodiments of the present invention provide a hohlraum that is suitable for use with an inertial confinement fusion power plant and includes a generally cylindrical body having a laser entrance hole opening in each end thereof to enable laser beams to reach an interior surface within the inside of the generally cylindrical body. A window covers the laser entrance hole in at least one end of the generally cylindrical body. The hohlraum also includes at least two membranes within the generally cylindrical body dividing the inside of the generally cylindrical body into at least first and second regions. Additionally, there is at least one passage between the first and second regions to enable gas in one of the first and second regions to flow to the other of the first and second regions.

[0044] As alluded to above, as the fusion targets are injected into the fusion chamber and travel through the chamber toward its center, the targets enter an environment of high temperature created by a fusion reaction of the immediately preceding target. Because the preceding target was imploded only a fraction of a second earlier, the residual heat in the fusion chamber could heat the next arriving DT fuel capsule above the desired cryogenic temperature. This problem is particularly acute on the frontal surfaces of each target as it travels through the chamber. Embodiments of the present invention address shaping of the target to assist in maintaining the DT fusion fuel within the capsule/hohlraum target at the desired the cryogenic temperature until the lasers focused on the target implode it.

Additionally, embodiments include techniques such as sublimation and pyrolysis to assist in maintaining the desired low temperature of the fuel capsule.

[0045] The high heat fluxes described above to the frontal surfaces of fusion targets complicate the design and jeopardize survival of the fusion fuel. Shaping the front target surface reduces the heating level and enables a wider selection of material choices for the hohlraum. Heat fluxes to the exterior of laser fusion targets during travel to the center point of the chamber are expected to be in excess of 800,000 watts per meter squared in some places. The target front is particularly vulnerable as this is the side of the hohlraum that faces into the fusion chamber environment during travel from an injection mechanism to the center of the fusion chamber. Laser entrance windows are utilized as described herein at either or both of the front and rear of indirect drive fusion targets. Appropriate shaping of the front or front and rear of the target achieve reduction of heating, and subsequent lower maximum window temperature. This shaping can create an enlarged stagnation zone around the window of the laser entrance hole. Our analysis estimates that heating can be half as large with a cupped shape target front, in contrast to a flat target front. For comparison, a target having a flat frontal surface around its laser entrance holes is illustrated in FIG. 2 of U.S. Patent Application No. 13/290,282 referenced above.

[0046] Gasses in the fusion chamber are expected to reach temperatures of about 6000K. The 500 nm thick membranes that cover the laser entrance holes of the target can quickly heat to temperatures of about 1200K if unprotected from the hot chamber gases. High temperature, but brittle materials such as graphene, also may be used for the laser entrance hole (LEH) windows. In an embodiment, the material for the LEH window is polyimide, which is better able to withstand the differential pressure across the LEH window due to the helium gas pressure on the inside of the target and the near vacuum conditions of the chamber. Polyimide windows are also likely to be less expensive and more easily manufactured than alternative LEH windows.

[0047] To permit the use of polyimide LEH windows, however, the temperature of the window must be limited to that which can be sustained by the material, ~700K. The heat flux to the window must be reduced or minimized to achieve these lower temperatures. A method for reducing the heat flux to acceptable levels is to create a stagnation region in the front of the target to minimize the flow of hot gasses to the window. The cup design shown in FIG. 3 provides this benefit.

[0048] FIG. 6 is an expanded view of the leading edge of a hohlraum in which a small protrusion 120 overhangs the laser entrance hole window 90. Use of well-known simulation software has verified the presence of a stagnation zone in front of the window 90. For the implementation shown in FIG. 2, these simulations show heat fluxes of:

1.99×10^5 watts per square meter at the front surface of the hohlraum

1.88×10^5 watts per square meter at the leading edge ring protrusion

$5.88 \times 10e^4$ watts per square meter at the window surface

These simulation show that with xenon in the fusion chamber at on the order of 6000K, the temperature at the front of the window surface will be less than half of 6000K.

[0049] Referring once again to FIG. 3, the addition of small passage 120 around the edge of the infrared reflector 50 allows the helium within the hohlraum to be cooled by flow against the lead of the hohlraum. This results in lower pressures and temperatures in compartment 310 between the LEH window 90 and the IR reflector membrane 50, assisting in assuring integrity of the windows and infrared reflectors.

[0050] Referring to FIG. 2C, if further reductions in temperature are needed, a sacrificial sublimation layer 230 can be deposited across at least the leading window of the hohlraum. This layer sublimates as the hohlraum is injected into the fusion chamber, thereby helping to maintain a lower temperature behind the window. One material suitable for use as a sublimation layer is a frozen layer of an alkane, such as methane, pentane, or the like, xenon, or other inert gas, or other suitable materials. The placement of the sublimation layer does not have to be as illustrated in FIG. 2C and the other hohlraum designs illustrated and discussed herein can be modified to include one or more sublimation layers as appropriate to the particular application. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0051] For further reductions in temperature of the fuel capsule, phase change and pyrolysis can help protect the windows and the fusion fuel. By manufacturing the laser entrance hole windows with polyimide, pyrolysis of the polyimide as the target passes through the chamber will occur. Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen. This chemical reaction will assist in maintaining the internal temperature of the hohlraum at the low value desired, thereby also protecting the DT fuel capsule form being heated to the point of preventing the fusion reaction with the laser beam energies available. Of course materials other than polyimide which also undergo pyrolysis also can be used.

[0052] FIG. 7 shows the energy flows with respect to the laser entrance hole window. As illustrated for the implementation having a sublimation layer, there are six major components of heat flow. Tending to heat the target are heat convection from the chamber xenon gas, as well as heat radiated from surfaces in the fusion chamber. In response the laser entrance hole will radiate heat outward toward the chamber, as well as heat from sublimation, if a sublimation layer is used. Transferring heat toward the DT capsule are helium convection and radiation heating from the entrance hole window.

[0053] FIG. 8 is a simplified flowchart illustrating a method of reducing heat transfer to a hohlraum injected into a fusion chamber according to an embodiment of the present invention. The method includes providing a window having a central portion and an edge over a laser entrance hole in the hohlraum (810) and providing a protrusion around the edge of the window (812). In some embodiments, the protrusion does not overhang the window. In other embodiments, the protrusion includes a lip that overhangs the window.

[0054] The method also includes injecting the hohlraum into the fusion chamber with the window facing the fusion chamber so as to provide a region of ambient gas stagnation adjacent the central portion of the window (814).

[0055] In some embodiments, the hohlraum is characterized by a generally cylindrical shape about an axis. Injecting the hohlraum comprises injecting the hohlraum with its axis aligned with the direction of flight. As described herein, the hohlraum can also include a fuel capsule separated from the window by an intervening membrane. In these implementations, the method further comprises providing a passage around an edge of the intervening membrane to enable gas flow around the edge of the intervening membrane. In some embodiments, the method includes providing a sublimation layer over the window. Additionally, the window can include a polyimide material such that the window is pyrolized after injection of the hohlraum into the fusion chamber.

[0056] 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.

WHAT IS CLAIMED IS:

1. A hohlraum for an inertial confinement fusion power plant, the hohlraum comprising:

a generally cylindrical body having a laser entrance hole opening in opposite ends thereof to enable laser beams to reach an interior surface of the generally cylindrical body;

a first window covering the laser entrance hole in a first end of the generally cylindrical body; and

a first raised protrusion surrounding the first window, wherein the first raised protrusion creates a first region of ambient gas stagnation adjacent the first window when the hohlraum is moving, to thereby reduce heat flow into the hohlraum.

2. The hohlraum of claim 1 further comprising a second window covering the laser entrance hole in a second end of the generally cylindrical body.

3. The hohlraum of claim 2 further comprising:

a fuel capsule disposed at a central location in the hohlraum; and

a first infrared shield disposed between the fuel capsule and the first window; and

a second infrared shield disposed between the fuel capsule and the second window.

4. The hohlraum of claim 3 further comprising a first passage in the hohlraum allowing gas to flow around an edge of the first infrared shield.

5. The hohlraum of claim 4 further comprising a second passage in the hohlraum allowing gas to flow around an edge of the second infrared shield.

6. The hohlraum of claim 2 further comprising a second raised protrusion surrounding the second window.

7. The hohlraum of claim 1 wherein the first raised protrusion includes a first lip extending from the first protrusion so as to overhang the first window.

8. The hohlraum of claim 1 further comprising a sublimation layer disposed across the first window.

9. The hohlraum of claim 8 wherein the sublimation layer comprises a frozen alkane.

10. The hohlraum of claim 1 wherein the first window comprises a material that undergoes pyrolysis at elevated temperatures.

11. The hohlraum of claim 10 wherein the first window comprises polyimide.

12. A hohlraum for an inertial confinement fusion power plant, the hohlraum comprising:

a generally cylindrical body having a set of laser entrance holes in opposite ends thereof operable to enable laser beams to reach an interior surface of the generally cylindrical body;

a first window covering one of the set of laser entrance holes in a first end of the generally cylindrical body;

a fuel capsule disposed at a central location in the hohlraum;

a first infrared shield disposed between the fuel capsule and the first window; and

a first passage in the first infrared shield allowing gas to flow through the first infrared shield.

13. The hohlraum of claim 12 further comprising:

a second window covering the other of the set of laser entrance holes in the second end of the generally cylindrical body;

a second infrared shield disposed between the fuel capsule and the second window; and

a second passage in the second infrared shield allowing gas to flow through the second infrared shield.

14. The hohlraum of claim 12 further comprising a first raised protrusion surrounding the first window, wherein the first raised protrusion creates a region of ambient gas stagnation adjacent the first window when the hohlraum is moving.

15. The hohlraum of claim 14 further comprising a second raised protrusion surrounding the second window.

16. The hohlraum of claim 15 wherein the first raised protrusion includes a first lip extending from the first protrusion so as to overhang the first window and the second raised protrusion includes a second loop extending from the second protrusion so as to overhang the second window.

17. The hohlraum of claim 12 further comprising a sublimation layer disposed across the first window.

18. The hohlraum of claim 12 wherein the first window comprises polyimide.

19. A method of reducing heat transfer to a hohlraum injected into a fusion chamber, the method comprising:

providing a window having a central portion and an edge over a laser entrance hole in the hohlraum;

providing a protrusion around the edge of the window; and

injecting the hohlraum into the fusion chamber with the window facing the fusion chamber so as to provide a region of ambient gas stagnation adjacent the central portion of the window.

20. The method of claim 19 wherein the hohlraum is characterized by a generally cylindrical shape about an axis and injecting the hohlraum comprises injecting the hohlraum with its axis aligned with the direction of flight.

21. The method of claim 20 wherein the hohlraum further includes a fuel capsule separated from the window by an intervening membrane, and the method further comprises providing a passage around an edge of the intervening membrane to enable gas flow around the edge of the intervening membrane.

22. The method of claim 19 wherein the protrusion does not overhang the window.

23. The method of claim 19 wherein the protrusion includes a lip that overhangs the window.

24. The method of claim 19 further comprising providing a sublimation layer over the window.

25. The method of claim 19 wherein the window comprises polyimide, the method further comprising pyrolizing the window after injection of the hohlraum into the fusion chamber.

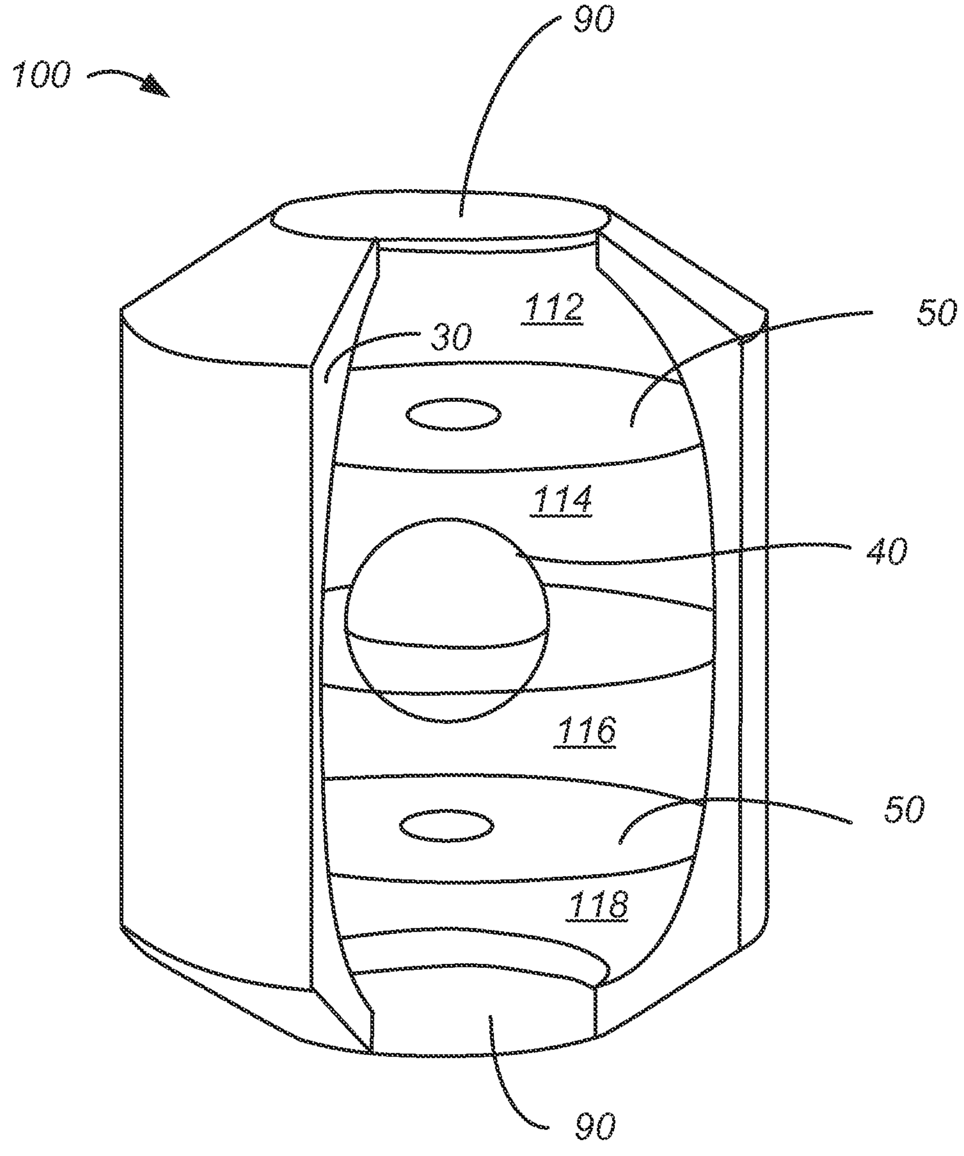

FIG. 1A

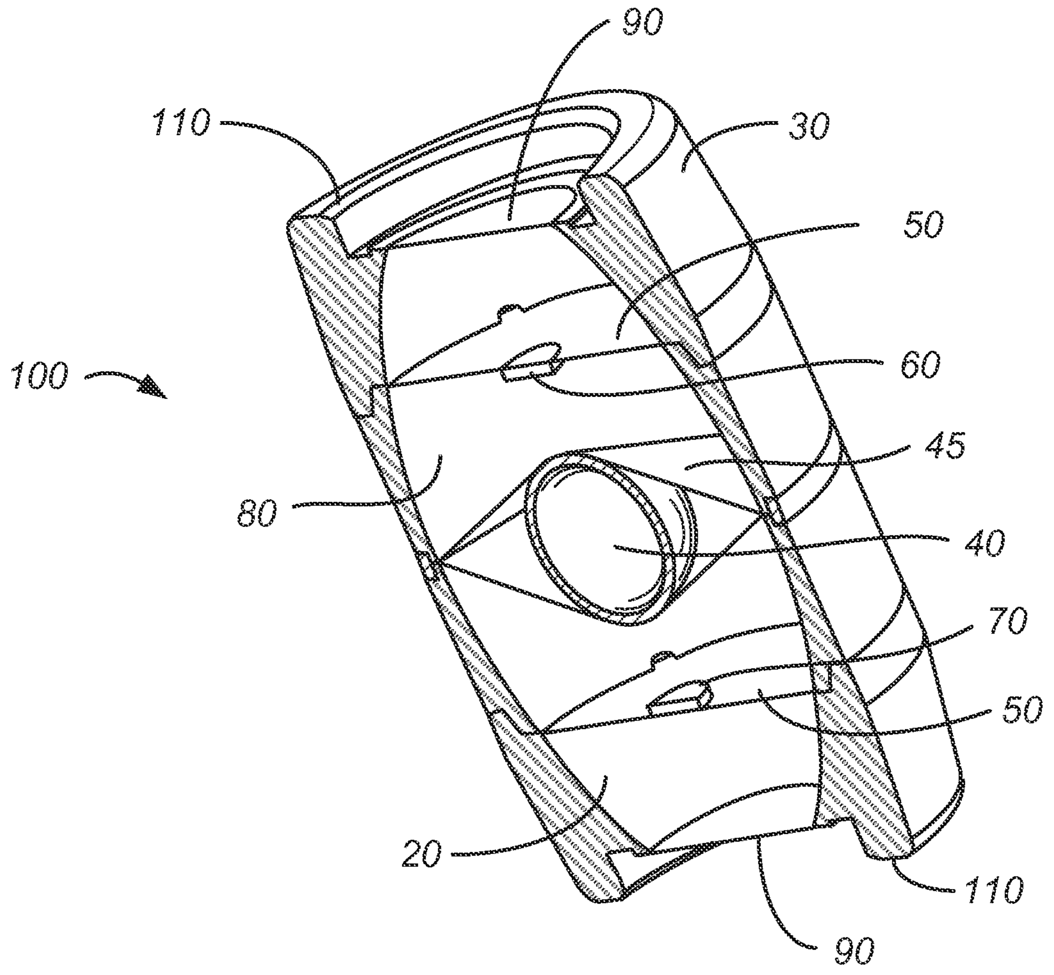

FIG. 1B

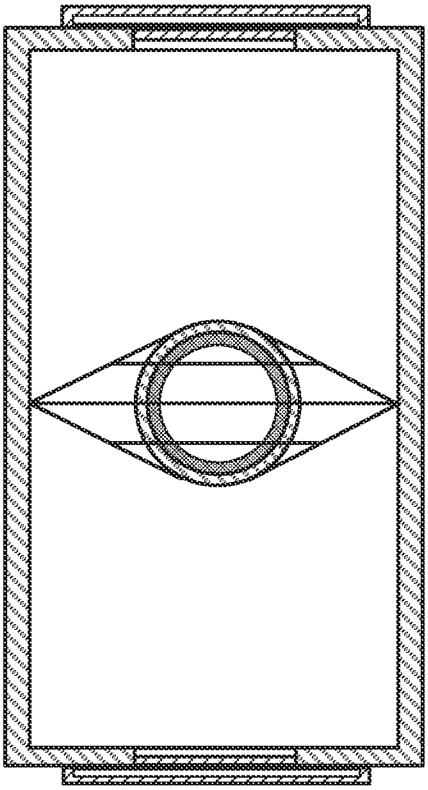

FIG. 2A

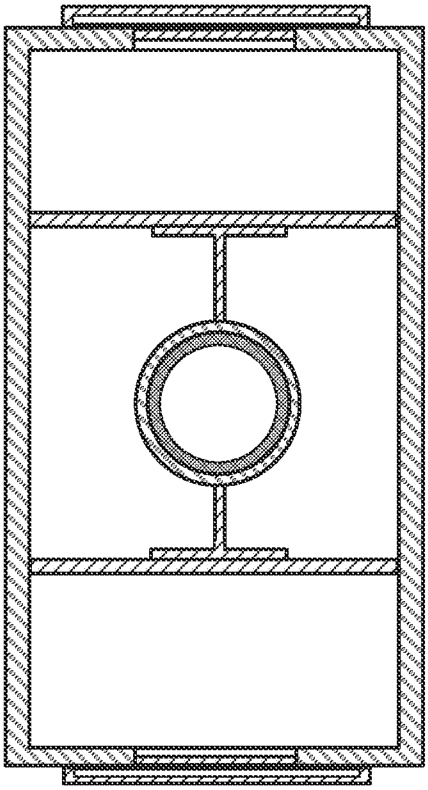

FIG. 2B

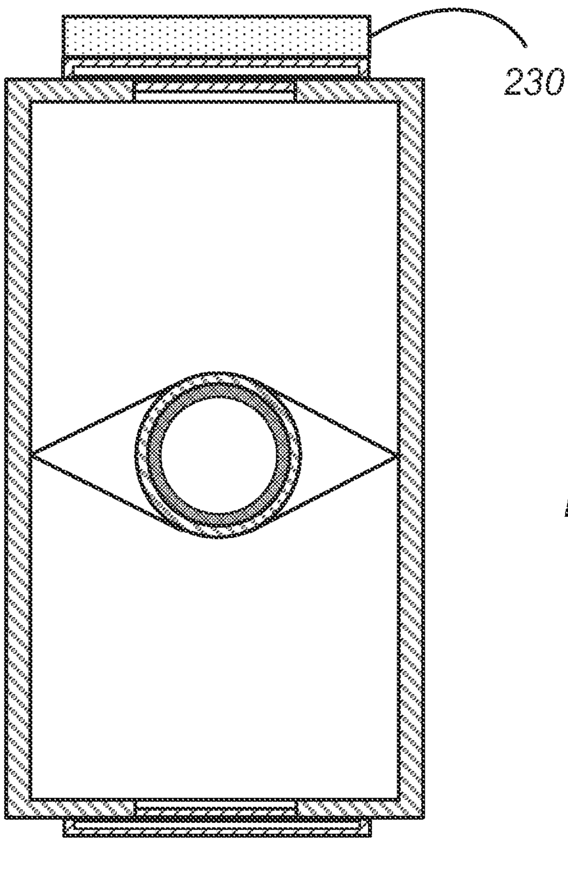

FIG. 2C

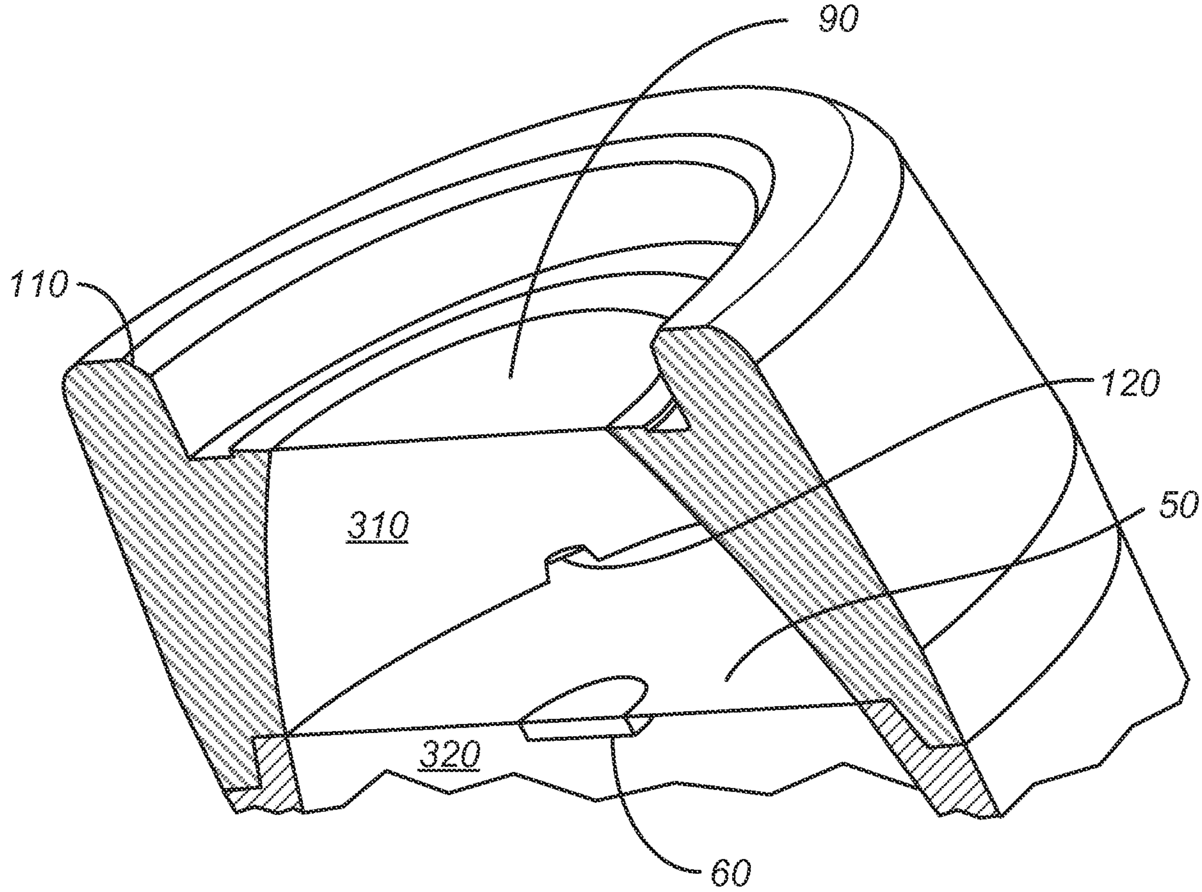

FIG. 3

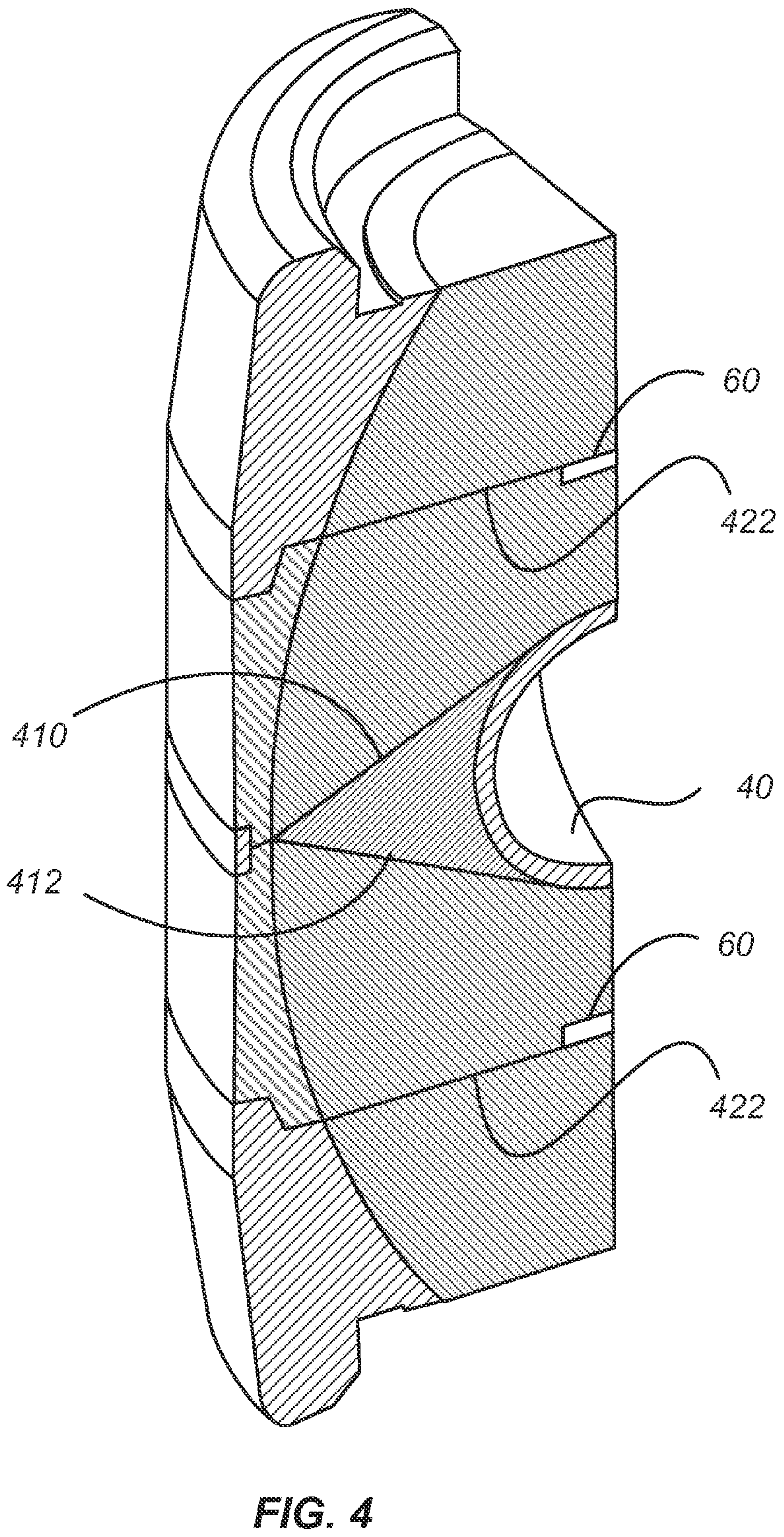

FIG. 4

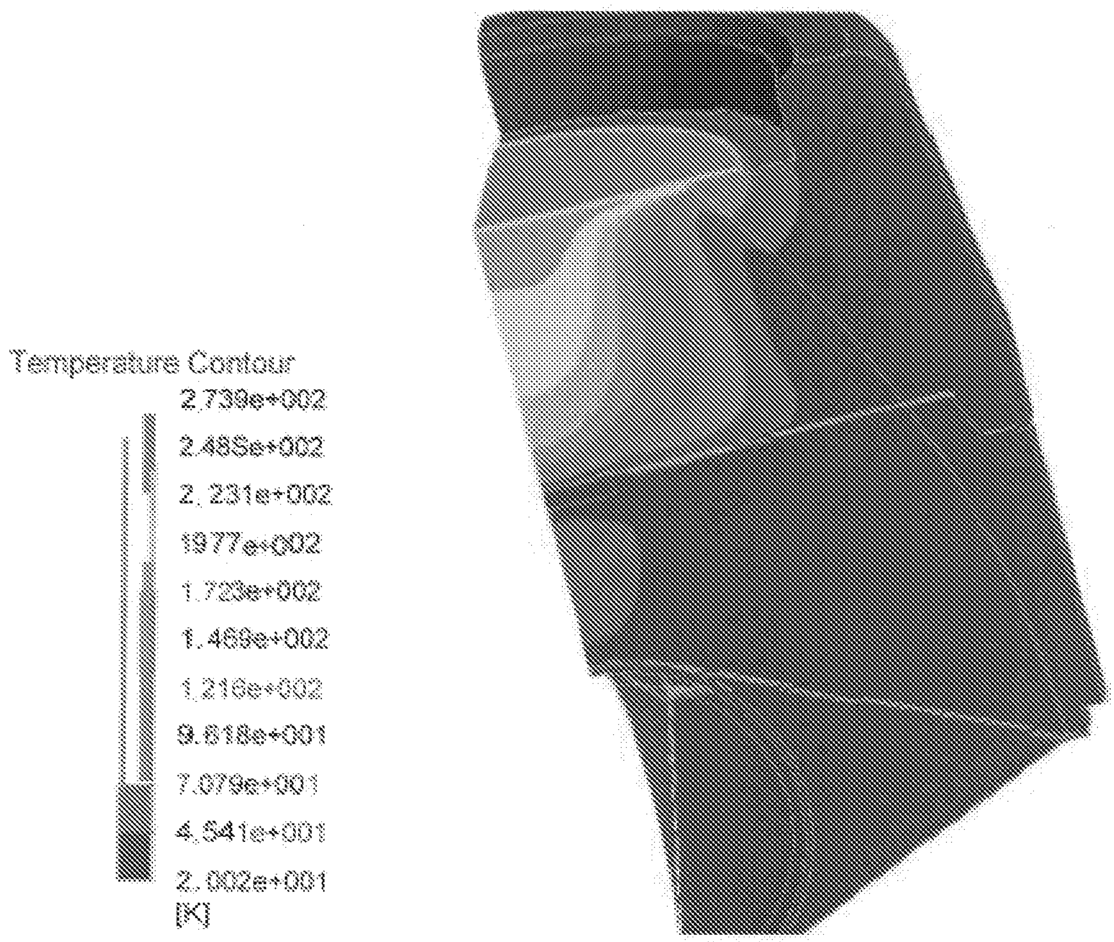
Temperature Contour
2.739e+002
2.48Se+002
2. 231e+002
1977e+002
1.723e+002
1.469e+002
1.216e+002
9.618e+001
7.079e+001
4.541e+001
2.002e+001
[K]

FIG. 5

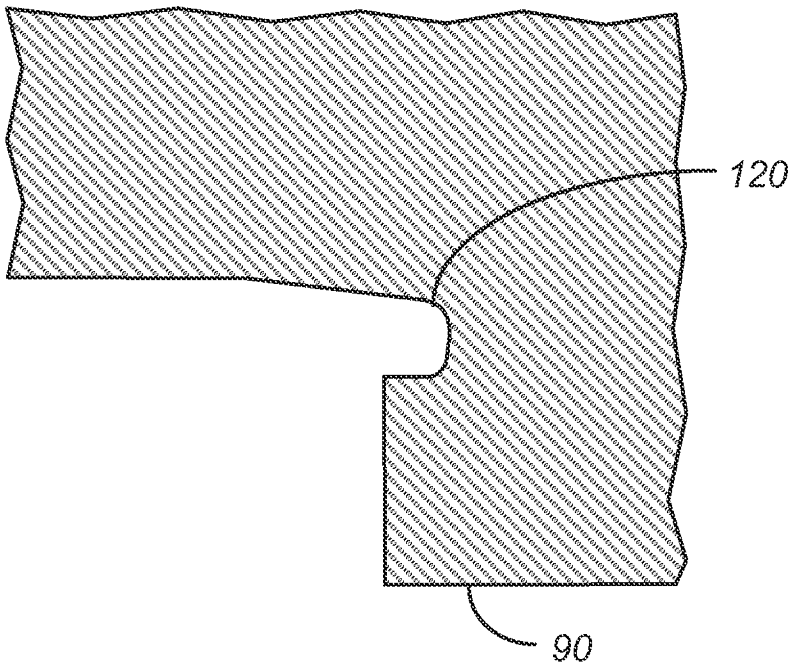

FIG. 6

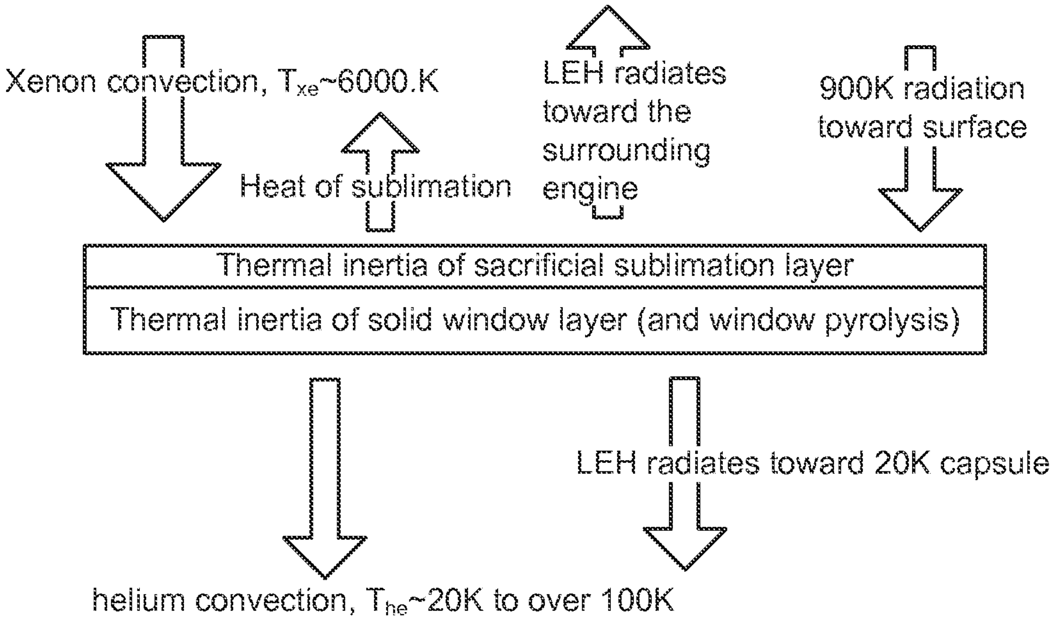
Xenon convection, T_{xe}~6000.K
Heat of sublimation
LEH radiates toward the surrounding engine
900K radiation toward surface
Thermal inertia of sacrificial sublimation layer
Thermal inertia of solid window layer (and window pyrolysis)
LEH radiates toward 20K capsule
helium convection, T_{he}~20K to over 100K

FIG. 7

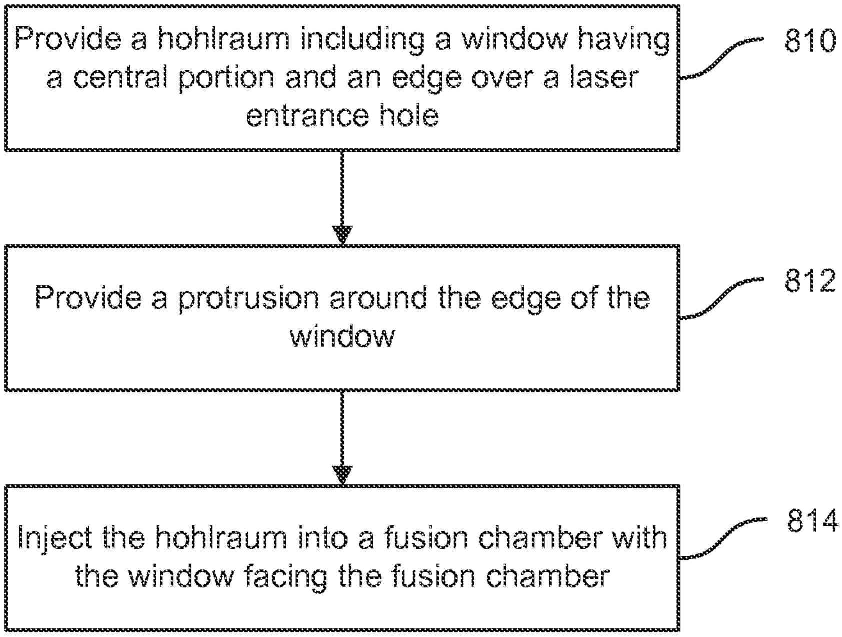
Provide a hohlraum including a window having a central portion and an edge over a laser entrance hole
810
Provide a protrusion around the edge of the window
812
Inject the hohlraum into a fusion chamber with the window facing the fusion chamber
814

FIG. 8