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CRYOGENIC TARGET SYSTEM FOR Z-PINCH MACHINES

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ABSTRACT

Recent advances in the technology of fast pulsed electrical power and load design have led to growing interest in the use of z-pinch machines as x-ray sources for fusion applications.[1] To achieve high yield, z-pinch machines require the use of cryogenic targets. These targets contain a spherical polymer capsule with a layer of solid deuterium-tritium (DT) on the inside wall. This DT layer is obtained by first permeation filling the capsule with high pressure DT gas at room temperature. The filled capsule is then cooled to approximately 19 K to solidify the DT. The uniform layer is created through a process called "beta layering," which involves placing the capsule in a very uniform temperature environment and allowing the natural heating due to beta decay of the tritium to provide the thermal energy to redistribute the DT into a uniform layer. General Atomics has performed preconceptual design studies of a system designed to fill a target with DT, cool it down to cryogenic temperatures, and then insert it into a z-pinch chamber. The baseline system design uses a supercritical helium stream to cool the target. The helium is compressed by a room temperature compressor and cooled using both liquid nitrogen and liquid helium reservoirs. The cold supercritical helium then travels to the target through an umbilical tube several meters long. This umbilical allows the target to be at the center of the chamber while the cryogenic equipment is safely outside. This paper will describe the preconceptual design of a z-pinch cryogenic target system and present the supporting thermal analysis.

INTRODUCTION

The z-pinch was one of the first plasma confinement concepts to be studied in the early days of controlled fusion energy research. In such a device, a large current flows axially down a cylindrical array of wires, as shown in Fig. 1. The current creates a large circumferential magnetic field producing a Lorentz force which implodes the wire array towards the center of the cylinder. The wires vaporize from the ohmic heating into a plasma which continues to carry the current. The Lorentz force accelerates the plasma inward to the center of the wire array where it is highly compressed and heated. This, in turn, causes the plasma to emit x-rays.

In the last three years, the x-ray output energy from Sandia National Laboratory's "Z-Machine" has increased from 0.1 to almost 2.0 MJ. This is the culmination of many decades of experimenting with z-pinches and pulsed power devices. The Z-Machine now produces the world's most powerful and energetic x-rays and can be used as a driver to

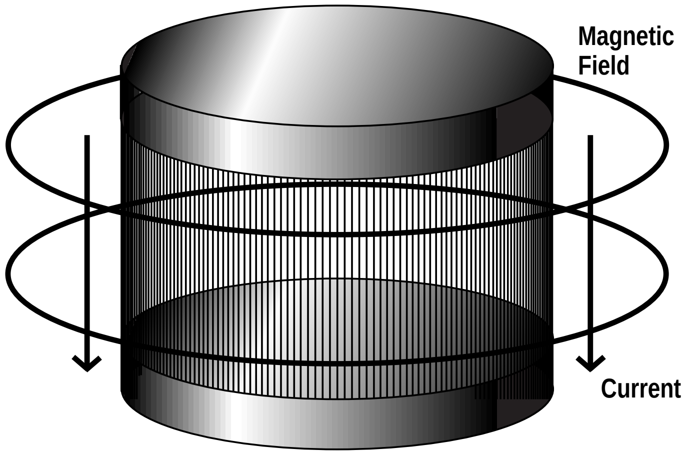

Figure 1. Sketch of z-pinch wire array showing the axial current and circumferential magnetic field.

study inertial confinement fusion (ICF). The x-rays can be used to compress capsules filled with a mixture of deuterium and tritium (DT). For an ICF device to reach ignition, the DT must be a solid (~19 K) and must form a smooth, symmetrical layer on the inside of the capsule wall.

Sandia National Laboratory has proposed two follow-on z-pinch devices for the Z-Machine. The X-1 Advanced Radiation Source is designed to have a x-ray output of 16 MJ. This is enough energy to explore ignition and even high gain fusion. The ZX machine is an intermediate step between Z and X-1 and has a design output of 7 MJ.

Z-Pinch Cryogenic Target Systems

Both X-1 and ZX require cryogenic targets to meet their design goals. General Atomics in cooperation with the University of Rochester and Los Alamos National Laboratory, has designed a cryogenic target delivery system for the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics.[2] This system has been fabricated and is in final testing in Rochester. The first laser shot of a cryogenic target is scheduled for September 1999.

Using the experience gained on the OMEGA system, we have produced design concepts for the proposed z-pinch machines. One major difference between OMEGA and the proposed z-pinch machines is the amount of damage caused by the shot. For OMEGA, everything within about one centimeter of the target is vaporized or severely damaged. For X-1, this radius will be about 50 cm. All components inside this spherical volume must be replaced after each shot. In addition, all unshielded regions inside the experiment chamber will be subject to shrapnel damage. This requirement forces all non-expendable equipment to be located safely outside of the chamber.

Z-PINCH CRYOGENIC TARGET SYSTEM

A pre-conceptual point design for a z-pinch cryogenic target system has been produced, as shown in Fig. 2. The system consists of the z-pinch target, the target cooling cryostat, the fill station, the insertion robot, and the auxiliary cooler.

Z-Pinch Target Design

Target designers working at Sandia and Lawrence Livermore National Laboratories have developed several z-pinch target designs.[3] A one-sided dynamic hohlraum design is shown in Fig. 3. The dynamic hohlraum design has the target centered inside of the wire array. During the shot, the high atomic number plasma is accelerated inward forming, in effect, a dynamic hohlraum wall. This wall implodes and stagnates on the foam cylinder emitting x-rays onto the capsule for its implosion.

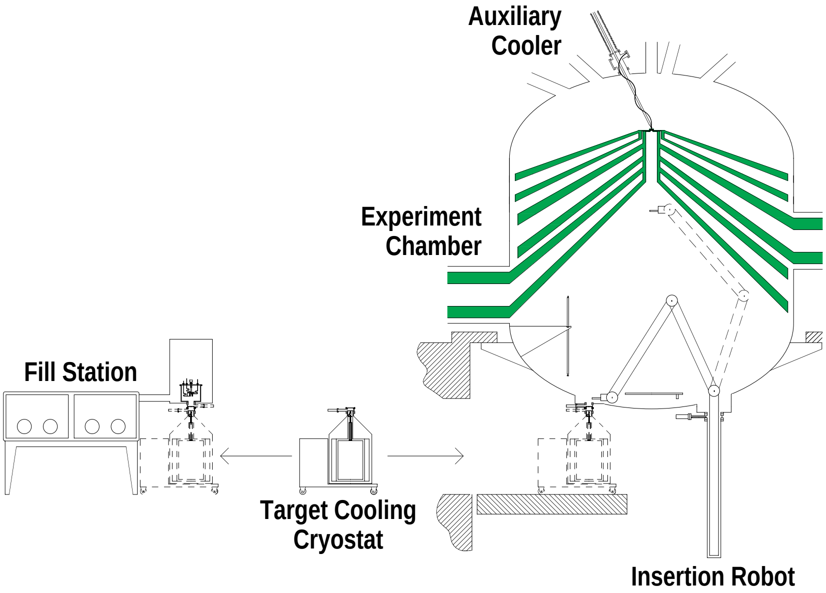

Figure 2. The z-pinch cryogenic target system includes a DT fill station, a target cooling cryostat, an experiment chamber, an insertion robot, and an auxiliary cooler.

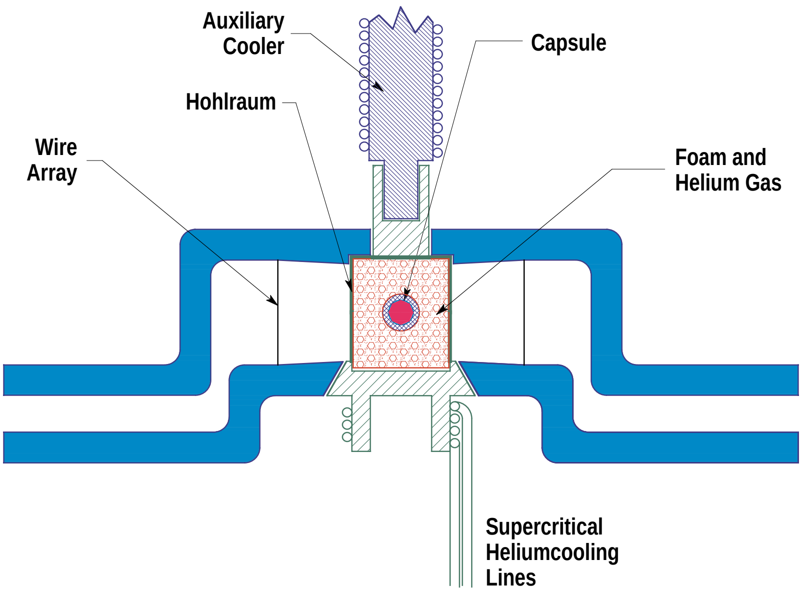

Figure 3. One-Sided dynamic hohlraum design.

At the center of the target is a spherical capsule holding the DT fuel. The target assembly is designed to cool the capsule to just below the triple point of DT (~19 K) in an isothermal environment (±0.1 K). Under these conditions, the DT will form a very symmetrical solid layer inside the capsule by a process called beta layering.[4] Heat energy from the beta decay of the tritium results in a redistribution of the DT into a uniform layer. This occurs due to the high vapor pressure of solid DT near its triple point. Non-uniformities in layer thickness cause local temperature variations, which translate into differences in local saturated vapor pressures. This results in net material movement from warm to cold spots until a smooth isothermal surface is created.

Immediately outside the capsule are two layers of foam of densities between 3 and 50 mg/cc. The first layer is spherical in shape while the second layer is cylindrical. These open cell foams serve to stagnate the wire plasma implosion and must include some helium gas to conduct the beta decay heat away from the capsule.

Surrounding the cylindrical foam is the cylindrical hohlraum wall. This wall is made of gold and is 2 to 4 µm thick. From a cryogenic point of view, the hohlraum wall acts like a thermal shield to keep the capsule cold and to conduct away heat. Windows may be placed in the hohlraum wall to allow access to the capsule for characterization.

Cooling tubes are attached to the bottom of the hohlraum wall to provide cooling. Supercritical helium at a pressure of approximately 15 atm and a temperature of about 13 K flows through the tubes. The helium is cooled to cryogenic temperatures in the target cooling cryostat as described in the following section. An auxiliary cooler is attached to the top of the target to provide more uniform cooling.

The target is designed to be inserted into the wire array from the bottom. To prevent a thermal short, the target is spaced away from the surrounding structure by a nominal 0.5 mm gap. A low thermal conductivity locking mechanism accurately positions the target assembly.

The pre-conceptual design of a cryogenic two-sided static hohlraum is shown in Fig. 4. The static hohlraum design has two sets of wire arrays located above and below the hohlraum and its capsule. The two wire arrays are connected in parallel to one power feed. During the shot, the wires are accelerated inward onto the foam cylinders heating them to ~100 eV. The x-ray radiation produced by the heating of this static cylinder then flows axially into the hohlraum and capsule.

The cryogenic design is similar to the dynamic hohlraum except that the axial length has been greatly increased. The interior spaces of the hohlraum are filled with CH foam and/or helium gas. The long aspect ratio of this target makes cooling this target more challenging than the dynamic hohlraum.

Z-Pinch Target Thermal Analysis

A finite-element thermal analysis has been performed on the one-sided dynamic hohlraum design shown in Fig. 3. There are two major thermal issues that must be addressed in the design of a z-pinch target. One is how the heat from radioactive beta decay of tritium inside the capsule is removed. The second issue is how to provide a sufficiently uniform thermal environment (±0.1 K) around the capsule to produce a uniform solid DT layer.

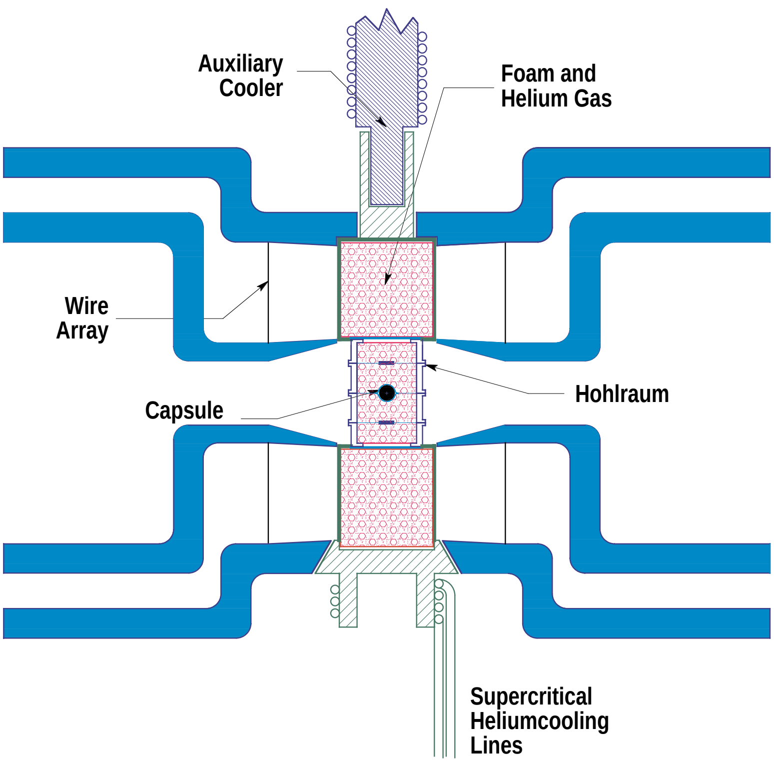

Figure 4. Two-sided static hohlraum design.

The thermal analysis results show that the foam surrounding the capsule must be filled with helium gas. The foam alone does not have sufficient thermal conductivity to remove the heat from the tritium beta decay and still allow the target to be at 19 K. Since theexperimental chamber must be under a high vacuum, the hohlraum walls surrounding the capsule must therefore be gas tight.

The thermal analysis also shows that cooling only from the bottom of the target cannot create the isothermal environment required for producing a uniform layer by beta layering. An auxiliary cooler has, therefore, been added to the design. This device attaches to the top of the target after the target has been placed in the center of the wire array by the insertion robot. The thermal analysis has shown that with the auxiliary cooler, a temperature uniformity of ±0.1 K can be achieved at the capsule wall.

Target Cooling Cryostat

The target cooling cryostat, shown in Fig. 5, is used during the fill, transport and insertion of z-pinch targets. It consists of three main parts: the extendible target holder, the liquid cryogen dewars and the umbilical.

The target is assembled separately at room temperature and then placed by hand on the target cooling cryostat’s extendible target holder. This device elevates the target from its storage spot inside the cryostat to an elevation above the top of the cryostat. It is used to place the target into the fill station for target filling and partially into the experiment chamber. The extendible target holder consists of a welded stainless steel bellows which is extended by pressurizing the inside with helium gas. Precision rails guide the target holder and allow only vertical motion.

Three possible target cooling techniques, shown in Fig. 6, have been examined. Conduction cooling the target from a liquid helium reservoir [Fig. 6(a)] is conceptually the simplest approach, however there are several disadvantages. The reservoir must either be designed to be replaced after each shot or it must be located far away from the target. In addition, since the target must be kept cold at all times after filling, the reservoir must be inserted into the evacuated experiment chamber at the same time as the target. The other two concepts studied use flowing supercritical helium to transfer the heat from the target to the cooling source. Supercritical helium at approximately 1.5 MPa (15 atm) is first passed through a heat exchanger submerged in liquid nitrogen to cool the gas to about 77 K. The

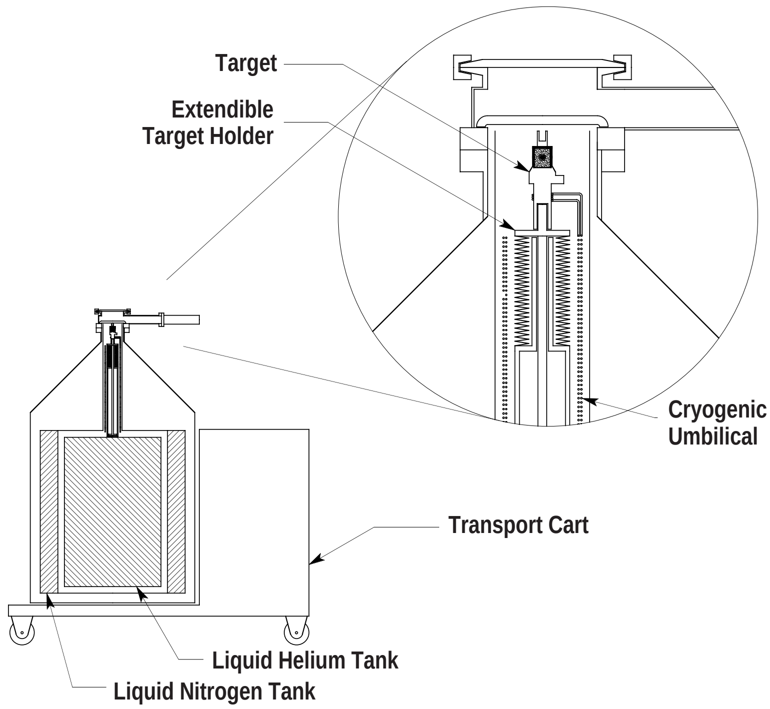

Figure 5. The target cooling cryostat moves the filled target from fill station to experiment chamber.

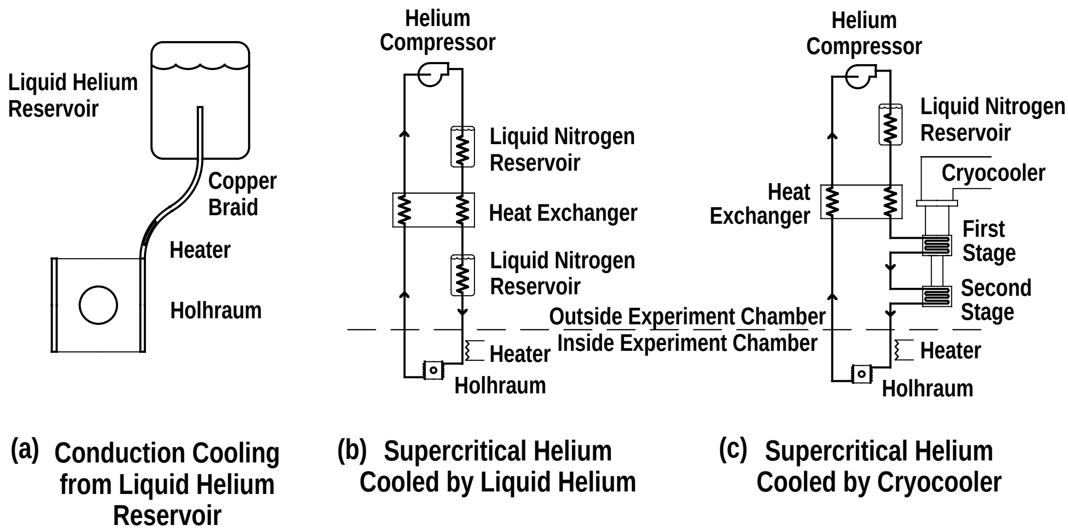

Figure 6. Several cooling schemes for target cooling were investigated.

gas is then cooled to about 13 K by either liquid helium [Fig. 6(b)] or a mechanical cryocooler [Fig. 6(c)]. Several counterflow heat exchangers can be added to precool the gas with the return stream thereby increasing the efficiency of the system. Supercritical helium is used because of its low viscosity and excellent heat transfer characteristics. In addition, the flow oscillation and excessive pressure drop problems encountered with two-phase helium flow are avoided.

The target cooling cryostat is located on a cart which moves between the fill station and the experiment chamber. The cart contains the helium compressor, support utilities, and instrumentation for the target cooling cryostat.

The baseline target cooling cryostat design presented here uses a supercritical helium stream cooled by liquid nitrogen and liquid helium as shown in Fig. 6(c). A preliminary thermal analysis predicts this system will reach steady state equilibrium in about 4 h. With a helium flow rate of 0.1 gm/s, the pressure drop through the system is about 0.4 MPa (4 atm) and the consumption rates are 0.3 L/h of liquid nitrogen and 6 L/h of liquid helium.

The umbilical carries supercritical helium between the liquid cryogen dewars and the target. This design allows the target cooling cryostat to remain safely outside the experiment chamberduring the shot. It consists of a helium supply tube, a helium return tube, and leads for temperature sensors and heaters on the hohlraum. The umbilical must extend from a span of about 0.5 m when inside the target cooling cryostat to approximately 5 m when the target is inside the wire array. This is accomplished by using a tightly coiled umbilical similar to a spring. Proof-of-concept tests were performed on 2 m long by 3.18 mm (0.125 in.) diameter tubing of various cryogenically compatible materials wound into a 9 cm (3.5 in.) diameter spiral. The sample umbilical with the best performance was made from a 304 stainless steel tube with a 0.71 mm (0.028 in.) wall. This sample umbilical showed the characteristics required for a full length umbilical: elastic deformations for small axial deflections and no kinking for large deflections.

Fill Station

The fill station includes several pieces of equipment, as shown in Fig. 7, which are designed to fill a polymer capsule by permeation of high pressure [up to 150 MPa (1500 atm)] DT gas through the capsule wall. The target cooling cryostat, with a target inside, is mated with the fill station. The extendible target holder is raised up to insert the target inside a permeation cell. The cell is then rotated 60° to engage a breech lock mechanism for containment of the high pressure DT. The cell is slowly pressurized with DT at a rate calculated to equal the rate of permeation through the capsule wall. The maximum pressure is determined by the required solid DT layer thickness. Once that pressure is reached, the permeation cell is gradually cooled to condense the DT. Both the permeation cell and

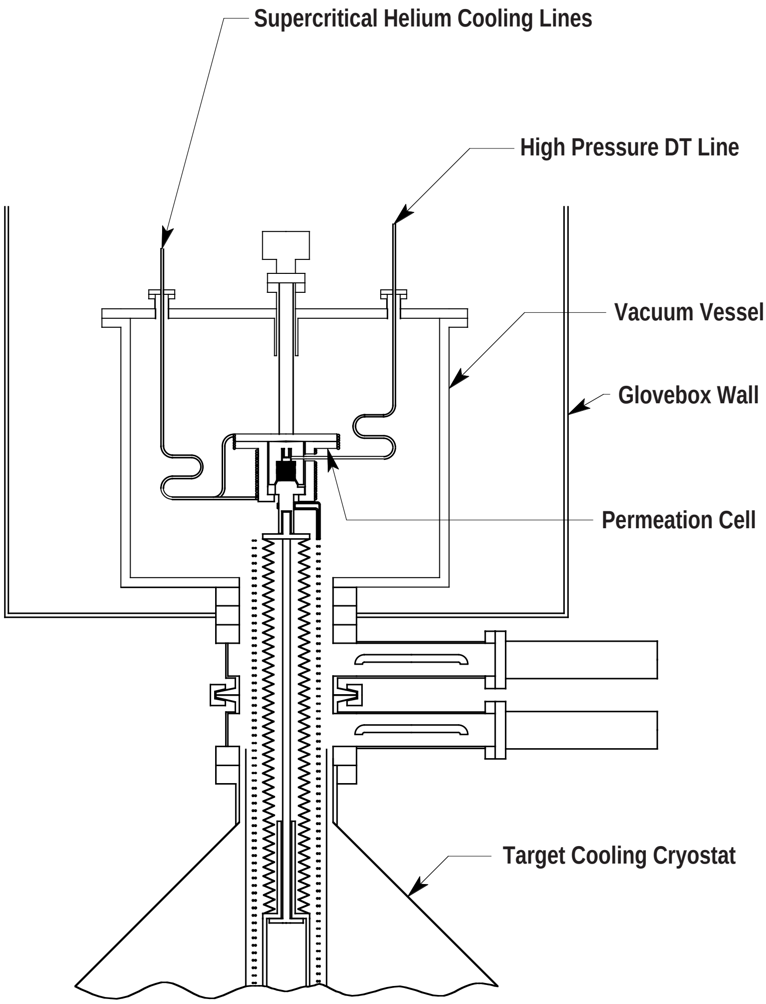

Figure 7. Target cooling cryostat extends target up into fill station for permeation filling.

target base include cooling tubes. The DT not trapped inside the capsule can now be pumped out of the cell. The breech lock mechanism is then disengaged and the target is lowered back down inside the target cooling cryostat. After the gate valve is closed, the target cooling cryostat can be disconnected from the Fill Station and transported to the experiment chamber.

Insertion Robot

The insertion robot is used to transfer targets from the target cooling cryostat to the center of the wire array, as shown in Fig. 2. Since the polymer capsule wall is not strong enough to withstand the room temperature pressure of the DT gas, the target must be kept at cryogenic temperatures until the shot. In order to maintain the cryogenic temperatures, the target must also be kept in a vacuum environment. Thus, any manipulation of the target must be done remotely.

After the target cooling cryostat is mated with the experiment chamber, the extendible target holder raises the target into the experiment chamber. The insertion robot then grasps the bottom of the target, lifts it into the experiment chamber, and places it on a long vertical end effector for placement within the wire array. The umbilical cooling lines spool out as the target is lifted, maintaining thermal contact between the target cooling cryostat and the target. The robot can also be used to position blast shields. Before the shot, the robot is removed from the experiment chamber to prevent neutron activation and damage from shrapnel.

Auxiliary Cooler

After the target is placed within the wire array, an auxiliary cooler extends from the top of the experiment chamberand makes thermal contact with the target. The arm which places the cooling tip in place is withdrawn to outside the experiment chamber. The auxiliary cooler allows both the bottom and top of the target to be actively cooled in order to create a uniform temperature environment required for beta layering the DT. In this baseline design, the cooling is provided by a supercritical helium loop similar to the one cooling the target base.

SUMMARY

The concepts described should allow the successful fielding of cryogenic targets on z-pinch machines, such as the existing z-machine or the proposed zx or x-1 facilities.

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