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Fielding the NIF Cryogenic Ignition Target

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Abstract

The United States Department of Energy has embarked on a campaign to conduct credible fusion ignition experiments on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in 2010. The target assembly specified for this campaign requires the formation of a deuterium/tritium (DT) fuel ice layer on the inside of a 2 millimeter diameter capsule positioned at the center of a 9 millimeter long by 5 millimeter diameter cylinder, called a hohlraum. The ice layer requires micrometer level accuracy and must be formed and maintained at temperatures below 19 K. At NIF shot time, the target must be positioned at the center of the NIF 10 meter diameter target chamber, aligned to the laser beam lines and held stable to less than 7 micrometers rms. We have completed the final design and are integrating the systems necessary to create, characterize and field the cryogenic target for ignition experiments. These designs, with emphasis on the challenges of fielding a precision cryogenic positioning system will be presented.

1 Introduction

The NIF ignition target is shown in Figure 1 and is described by Atherton[1] and Klingmann[2]. In the context of this paper, fielding of the NIF ignition target begins when the target assembly is delivered to the NIF with its target base reservoir filled with DT fuel. Once at the NIF, the target assembly is mounted to the end of a cryogenic target positioner which sits just outside the NIF target chamber. All handling of the target assembly is performed using a glove box that is integral to the cryogenic target positioner. After mounting the target, the positioner vessel is pumped to vacuum and the cryogenic system begins to cool the target. The positioner, glove box, ice layer imaging, and cryogenic system designs form the integrated system called the CryoTARPOS. The CryoTARPOS design is shown in Figure 2.

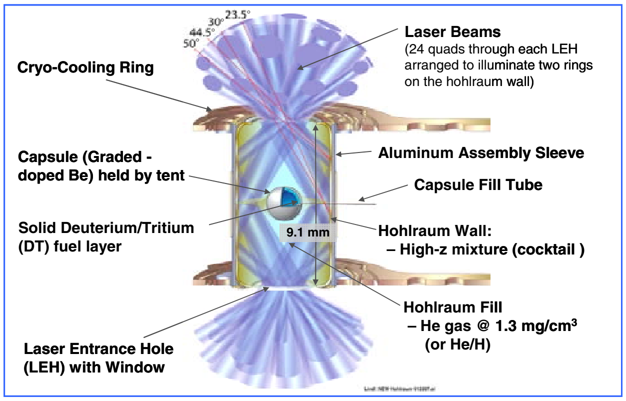

Figure 1. Schematic of the NIF cryogenic ignition target

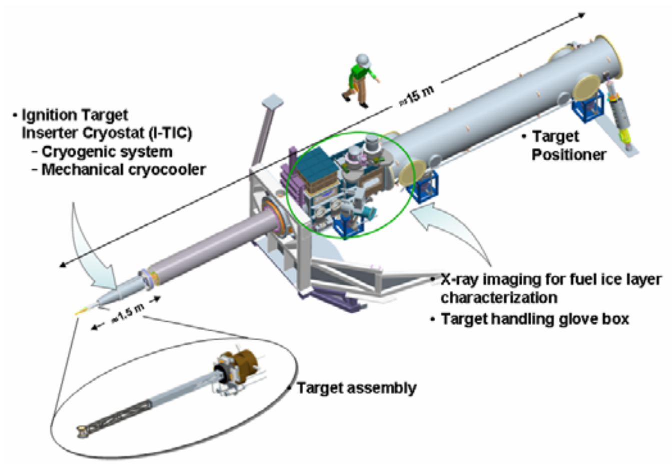

Figure 2. The CryoTARPOS provides the systems necessary to field the NIF ignition target.

During cool down, temperature differentials between the target base DT reservoir and the capsule are used to drive the DT fuel from the reservoir into the capsule. Once the capsule is filled, further cooling begins to form the fuel ice layer. The processes of fuel transfer and ice layer formation are monitored with 3 axes of x-ray imaging that is built into the CryoTARPOS vessel. The total time from target loading to creation of an acceptable fuel ice layer is estimated at between 15 and 20 hours. Throughout this time, the target remains just outside the NIF target chamber on the retracted boom of the CryoTARPOS.

After the DT ice meets specification, the CryoTARPOS uses a 7-meter long boom to extend the target to target chamber center. Near target chamber center, an optical Target Alignment System (TAS) provides feedback for positioning of the target. The TAS can also image the NIF alignment laser beams and is used to align all beams to the upper and lower hohlraum light entrance windows. The TAS is retracted out of the chamber prior to the shot. Figure 3 provides a likely timeline for completing a NIF ignition target shot cycle.

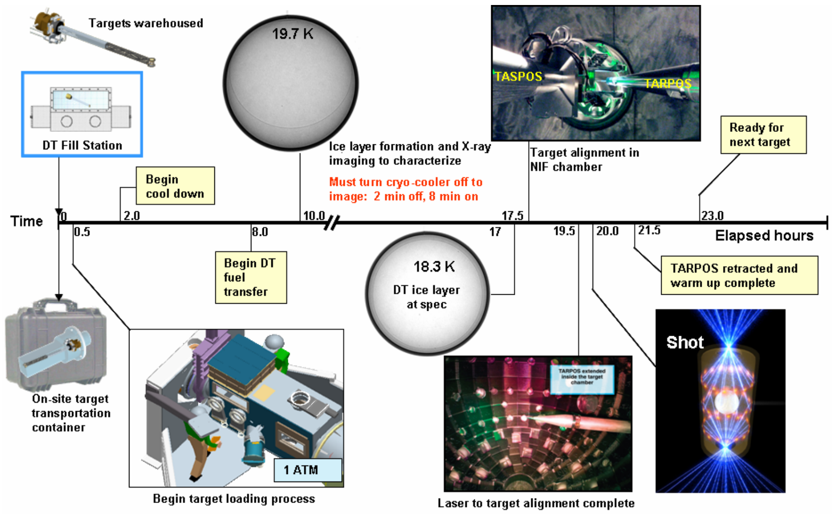

Figure 3. Process flow and possible timeline for the NIF ignition target shot cycle

2 The CryoTARPOS target positioner

Figure 4 shows the existing NIF non-cryogenic target positioner. The positioner design for the CryoTARPOS of Figure 2 is identical except that the 2 meter nose cone is replaced with a mechanical cryocooler based system (described in section 3) that cools and controls target hohlraum temperature. The CryoTARPOS positioner provides 5 degrees of freedom including three translations and two rotations of the nose cone (roll and nod). The positioner uses a 7 meter long low coefficient of thermal expansion carbon composite boom to place the target at the center of the NIF 10 meter diameter target chamber.

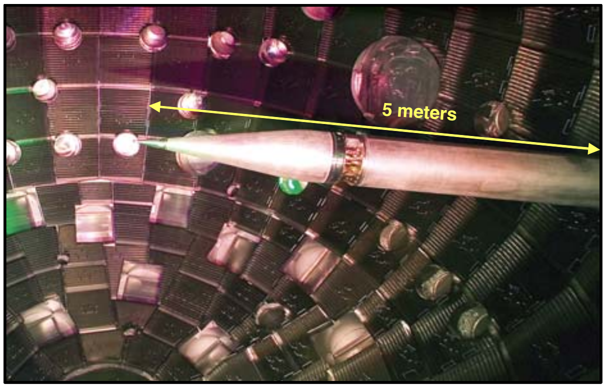

Figure 4. The existing NIF non-cryogenic target positioner inserted in the NIF chamber

The error budget for laser-on-target positioning has allocated 7 µm rms to positioning of the target. The existing non-cryogenic target positioner has demonstrated the ability to meet this requirement. A primary source of positioning error is vibration, which has been measured using accelerometers to be < 1.5 µm rms.

Target positioning with CryoTARPOS will more fully utilize the 7 µm rms budget. The design of the cryogenic system should eliminate cryocooler vibration so that the vibration component should be nearly identical to the warm target positioner. Section 2 describes how the cryogenic system has been designed to maintain target temperature while allowing all cooling functions to be turned off during periods requiring a very stable target. The remainder of the positioning error budget, approximately 5 µm, is allocated to longer term drift primarily caused by imperfect control of positioner temperature. Both environmental and internal sources contribute to this error component.

The CryoTARPOS positioner also holds the target during fuel ice layer formation. The stability required is dictated by ice layer characterization requirements and the x-ray imaging system. The stability requirement is ± 1 µm during the 6 second image frame integration time. Measurements made on the existing warm target positioner with the boom retracted as it will be during ice layer characterization are just above this requirement. To insure the CryoTARPOS design can meet this requirement, the positioner design was augmented with boom stabilizers that can be used in the retracted position. Detailed finite element analysis of the CryoTARPOS design suggests that that target vibration can be reduced to ± 1 µm. The boom stabilization system consists of rigid boom constraints that rigidly tie the boom to the CryoTARPOS vessel just behind the cryogenic nose cone. These constraints must be retracted prior to inserting the boom into the NIF target chamber.

3 Cryogenic System

The CryoTARPOS design incorporates a cryogenic system called the Ignition Target Inserter Cryostat (ITIC) to cool and control the temperature of the ignition target (Figure 5). In the CryoTARPOS, the ITIC is mounted at the end of the boom and provides a gripper for holding the target. The ITIC uses a Gifford-McHahon cryocooler to cool the target gripper and target base to 7 K and heaters to raise and control the target hohlraum temperature as specified (approximately 18 K) with 1 mK precision.

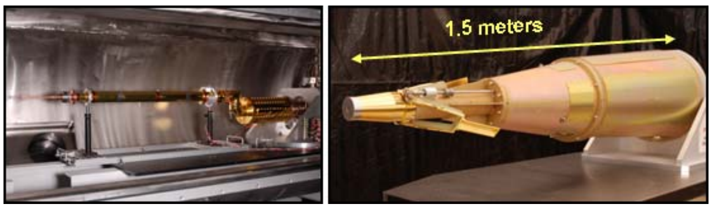

Figure 5. The cryogenic system (left) is assembled into the Ignition Target Inserter Cryostat (right) that will be used to field ignition targets.

The ITIC is designed to provide cryogenic temperature control of the target while ensuring that all structure influencing target position is maintained at 293 K. In Figure 5, the image to the left shows a prototype of the cryogenic system. It consists of the cryocooler (right edge), connected to a cylinder that is a cryogenic thermal capacitance, followed by a long cold rod system reaching to the target base(left). The inner most conductive path, called the cold rod, is connected to the 2nd stage of the cryocooler and operates near 7 K. The target gripper is attached to the end of the cold rod. Surrounding the inner cold rod is a 60 K thermal shield which limits heat transfer to the cold rod. The cold shield is connected to the 1st stage of the cryocooler. Surrounding the 60 K cold shield is a warm shield that is controlled to 293K using heaters. The cryogenic system shown in the left of Figure 5 is packaged into the ITIC structure shown to the right of Figure 5. The ITIC is mounted to the end of the target positioner boom using a large kinematic mount. Ignition targets containing DT are installed on the gripper of the ITIC by operators working through the glove box integrated into the CryoTARPOS.

A common challenge when using mechanical coolers in precision applications is the significant vibration disturbance caused by the cryocooler. The NIF cryogenic target positioner has overcome this problem by utilizing a thermal capacitance device[3] that permits the cryocooler to be turned off during periods requiring positioning stability. X-ray imaging of the ice results in the most difficult challenge. An x-ray image is constructed from a series of 20 frames, each requiring 6 seconds of CCD integration time. The cryogenic system must maintain target temperature within ±1 mK with the cryocooler off for over 2 minutes. The imaging must be repeated every few minutes to monitor the ice growth process.

Traditional engineering materials lose most of their heat capacity at temperatures below 100 K. Our cryogenic target system uses the thermal capacitance of high pressure helium at cryogenic temperatures. The helium is confined in a copper structure that minimizes the heat transfer time constant by assuring that all helium is within a few millimeters of a copper conduction path to the target. Figure 6 provides laboratory test results using the cryogenic system in Figure 5 that demonstrate better than ±1 mK hohlraum temperature control with all mechanical cooling components off for periods in excess of 4 minutes. The stability is demonstrated over a 45 hour period with a 4 minutes off and 6 minutes on duty cycle for the cryocooler.

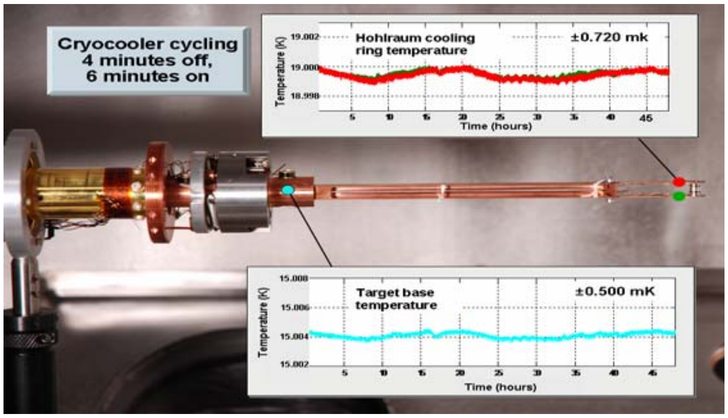

Figure 6. The required ±1mK temperature stability has been demonstrated in the lab. The surrogate target is shown with its thermal shroud removed.

4 Conclusion

We have described the designs necessary to cool the cryogenic ignition target, hold the target stable during ice layer characterization and to position the target for a NIF shot. The integrated systems are called the CryoTARPOS. A non-cryogenic positioner is operational and has demonstrated the viability of the positioner design. The cryogenic system has been prototyped and has demonstrated the necessary precision of cryogenic target temperature control. The first Ignition Target Inserter Cryostat (ITIC) has been assembled and will be fielded on the existing NIF positioner to demonstrate integrated performance of the cryogenics and the positioner. Assembly of the first complete integrated CryoTARPOS will begin later this year with installation in NIF by 2010.

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[1] Atherton, L.J., Moses, E.I., Carlisle, K., Kilkenny, J., *The Ignition Target for the National Ignition Facility*, EUSPEN Conference 2007

[2] Klingmann, et al., *Design and Fabrication of a Novel Cryogenic Laser-Driven Ignition Target*, EUSPEN Conference 2007

[3] Haid, B.J., *Helium Pot System for Maintaining Sample Termperature after Cryocooler Deactivation*, Advances in Cryogenic Engineering, V51A, 2005