CONTROL SYSTEM FOR CRYOGENIC THD/DT LAYERING AT THE NATIONAL IGNITION FACILITY*

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Abstract

The National Ignition Facility (NIF) is the world largest and the most energetic laser system for Inertial Confinement Fusion (ICF), located at the Lawrence Livermore National Laboratory (LLNL). In 2010, NIF began ignition experiments using cryogenically cooled targets containing layers of tritium-hydrogen-deuterium (THD) or deuterium-tritium (DT) fuel. The 68 µm-thick ice layer is formed inside of a 2 mm target capsule at temperatures of approximately 18.3 Kelvin. The ICF target designs demand sub-micron smoothness of the THD/DT ice layer. Precise formation and characterization of such layers is a challenging task and still an active research area. It requires a flexible control system capable of executing evolving layering protocols. At NIF, this task is performed by the Cryogenic Target Subsystem (CTS) of the Integrated Computer Control System (ICCS). ICCS is a large-scale, distributed control system which integrates scientific instruments, control hardware and computing platforms under a common object-oriented architecture. The CTS provides precise cryogenic temperature control, advanced x-ray imaging capability, and monitoring of vacuum and gases. Equipped both with automatic software engines and an interactive development environment, the recently deployed control system has enabled first NIF cryo-layered target campaigns and supported layering research.

INTRODUCTION

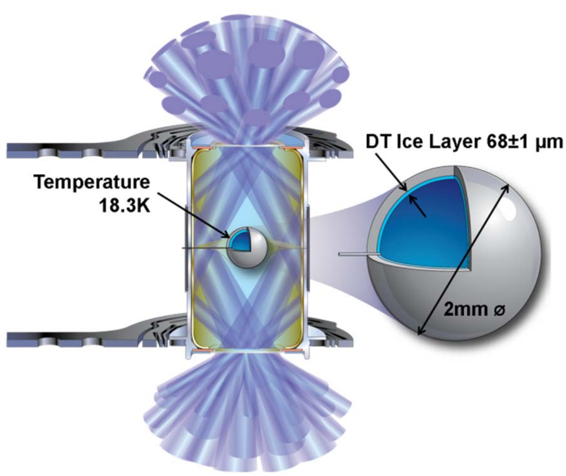

Figure 1: NIF cryogenic layered target.

The National Ignition Facility at Lawrence Livermore National Laboratory is a 192 beam, 1.8 MJ, 351 nm laser designed to conduct Inertial Confinement Fusion (ICF) experiments. Construction of NIF was completed in March of 2009. While NIF was conducting its first hohlraum energetics campaigns, the facility was also preparing for cryo-layered target experiments [1]. The key systems commissioned in the first half of 2010 included the Cryogenic Target Positioner (CryoTARPOS) with the Ignition Target Insertion Cryostat (ITIC) and the Load, Layer and Characterization Station (LLCS). Along with installation of hardware, the software for the Cryogenic Target Subsystem (CTS) of the Integrated Computer Control System (ICCS) was deployed and qualified for operations [2]. Precise cryogenic THD/DT layering was the main capability delivered with this new hardware and software.

An ignition target consists of four essential components: the hohlraum, the thermal control hardware, the capsule and the ice layer, see Fig. 1. The THD/DT ice layer is formed inside of the 2 mm target capsule at temperatures of approximately 18.3 K. In ignition experiments, the ice layer is 68 µm thick. Most of the target parts are precisely manufactured and calibrated in dedicated facilities, weeks and months before the shot. The ice layer is formed in the target mounted at the end of the target positioner, next to the NIF target chamber, just hours before the shot. Furthermore, the ice layer is cryogenic and is not accessible for direct inspection. However, the quality of the ice layer formation (or "manufacturing") is essential for the success of the ignition experiment.

THD/DT LAYER FORMATION

The THD/DT ice layer is formed by executing a cryogenic layering protocol. The layering protocols are first developed and proved in the R&D lab to accommodate a variety of target designs and fuel mixes. The protocols consist of several melting-freezing phases and last 17-24 hours. The x-ray images of the developing ice layer are periodically acquired in three imaging directions. The images provide the feedback on the layering process.

The goal of the layering protocol is to produce an ice layer which is both symmetrical and smooth. In a high-quality layer, the ice is distributed into a perfect sphere. The sphericity is measured by calculating the power spectrum of the unwrapped image in three directions. In addition, the ignition-quality layer must be free of local defects, such as boundary grooves and thermal stress cracks.

The formation of a spherical shape and elimination of local defects require application of different techniques.

* *This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.* LLNL-CONF-505491.

Beta-Layering

The general spherical shape is formed using the beta-layering process [3]. The beta-decay of tritium generates volumetric heat in the THD/DT ice. Thick regions of the ice layer have higher surface temperatures. The THD/DT fuel evaporates from the thick regions which are warmer and condenses in thin areas which are cooler. Given a symmetrical capsule, a uniform thermal environment and some time, the beta-layering will produce a spherical ice layer. The time constant of this process is about 27 minutes. Unfortunately, this technique is not efficient in preventing local defects.

Single Seed Crystal Growth

It was noticed that most of the local defects are due to the boundaries between ice segments grown from multiple seeds. Thus, a technique was developed which attempts to isolate a single seed and then grow the entire spherical layer from that seed [4,5]. The procedure involves several hours of precise temperature manipulations using x-ray image analysis as feedback. First, the capsule is rapidly cooled. The resulting ice layer formed inside of the capsule has an irregular shape and many defects. Next, the temperature is gradually increased to melt most of the ice inside the capsule. The melting process is monitored with the x-ray imaging system and is stopped when almost all of the fuel is liquid again. The remaining ice speck serves as a seed for the new layer formation. The temperature is decreased slowly, and the new layer grows as a single crystal over several hours.

CRYOGENIC TARGET CONTROL SYSTEM

Temperature Control

Both the beta-layering and the single seed crystal growth techniques require a highly uniform, and precisely controlled, thermal environment. At NIF, the Ignition Target Insertion Cryostat (ITIC) provides such a controlled environment [6], see Fig. 2. The ITIC is two meters long and it is mounted at the end of the NIF target positioner, as shown in Fig. 3. The target positioner is a large mechanical structure of approximately 15 meters long. The cryogenic operations start with the positioner fully retracted from the target chamber into an isolated vacuum vessel. The vessel is equipped with a three-axis x-ray target imaging system.

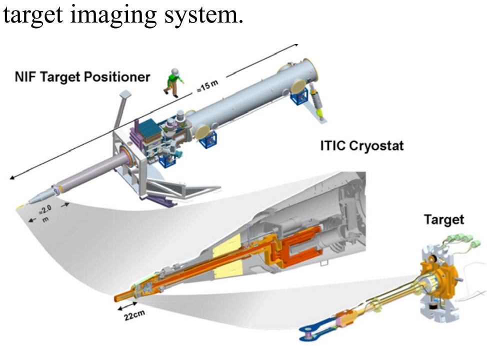

Figure 2: Ignition target cryostat system.

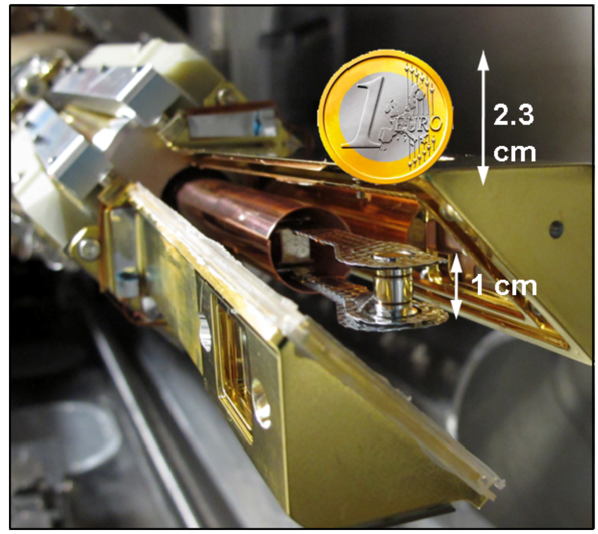

Figure 3: Front view of the ITIC shroud and the target.

Target temperatures are controlled down to 1 mK precision at multiple points. The top and bottom of the target have independent sets of controls. There are two additional shimming heaters in the middle section of the hohlraum. By adjusting these temperature control points, a highly uniform thermal environment can be created for the ice layer, even when the external environment or the target components are not perfectly symmetrical. The ice layer itself serves as a precise indicator of the temperature field. When the x-ray characterization of the layer reveals that it is asymmetric or not concentric, a calculated adjustment of the heaters is performed and beta-layering brings the layer into desired spherical shape.

The target base and the DT fuel reservoir are also precisely controlled. This is needed for filling the target with fuel. The reservoir and the target capsule are connected by a thin (10 µm OD, 5 µm ID) fill tube. The fuel is transferred by adjusting the temperature gradient between the target and the reservoir. Another important feature of the cryogenic system is the helium tank which provides thermal capacitance sufficient to maintain temperatures even when the mechanical cryogenic cooler is turned off for several minutes. This thermal capacitor capability is utilized to reduce vibration blur during the ice layer characterization.

Each experiment at NIF is conducted with a new target. There are several designs of cryogenic targets. They have different sets of control points. Each sensor comes with a unique calibration file. Therefore it is essential for the control system to be data-driven and support different control topologies.

X-ray Imaging System

The distribution of DT fuel inside of a target capsule is monitored and measured using a three-axis x-ray imaging system. The phase contrast, computer enhanced imaging reliably detects boundaries of solid and liquid DT inside of the beryllium and plastic capsules.

The imaging system includes three sets of x-ray sources and x-ray cameras arranged as three perpendicular axes.

The vertical axis is aligned with the hohlraum laser entrance hole and provides an unobstructed full view of the capsule. The two side views are taken through the starburst-shaped apertures in the hohlraum walls.

The image acquisition engine controls and monitors imaging hardware, see Fig. 4. It configures hardware settings, such as x-ray source voltage and beam current.

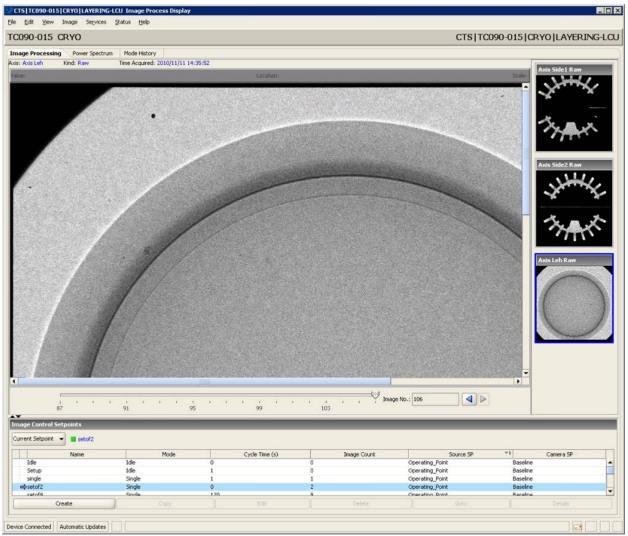

Figure 4: Control panel for x-ray imaging engine.

Because of the proximity of the target to the mechanical cryogenic cooler, the vibration blur distorts fine features of the images. To reduce blurring, the image acquisition engine times camera exposures to pauses in the cooler operations. The signal-to-noise ratio of the images is enhanced by taking multiple exposures and computing summed images. The capsule drift between the exposures is compensated by aligning images through image registration.

Interactive Layering Environment

In addition to automatic, data-driven software engines, the cryogenic controls are equipped with an interactive analysis and development environment. The environment is based on MATLAB and is implemented as a MATLAB Layering Toolbox extension. The environment enables real-time interaction with the growing ice layer, see Fig. 5.

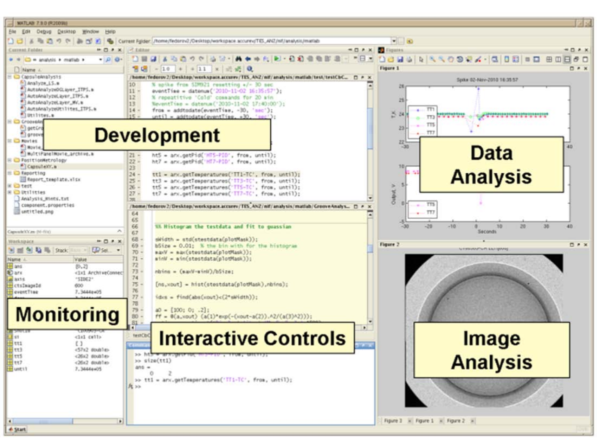

Figure 5: Interactive layering environment.

Implementation of the Layering Toolbox is based on the standard ICCS frameworks and CORBA middleware. Through this distributed control system infrastructure, the interactive environment automatically benefits in network connectivity, process concurrency and data sharing. The layering specialists at multiple workstations can monitor and support the ongoing layering process. Interactive sessions co-exist and communicate with the automatic software engines. The cryogenic process can be switched between automatic and interactive execution based on the complexity and novelty of a specific procedure.

Isolation of the interactive environment from the low-level hardware controls was one of the key design goals. The cryogenic target specialists preferred to avoid dealing with the specifics of the hardware configuration. The control system operators demanded that interactive environment actions are always entirely contained within a well-defined scope. The isolation goal was achieved by introducing the layering recipe controls abstraction. The minimalistic interface provides only a few virtual control points relevant to the physics of layering. It hides dozens of configuration settings which are managed by the core control system. The x-ray imaging is abstracted into named acquisition patterns and a flow of images. The low-level settings and sequencing of the x-ray imaging hardware are handled by the automatic software engines. The mapping of the virtual layering control points to hardware is data-driven and is managed by the core control system.

The development of the interactive layering environment was greatly simplified by choosing a well known scientific and technical computing product (MATLAB) as a COTS platform. While the Layering Toolbox codifies our domain expertise, the COTS component supplies a user-friendly IDE for code editing, debugging and version control. Extensive selection of data visualization and image processing tools for MATLAB is readily available, both commercial and open-source.

The rich toolset and flexibility of the layering environment have simplified evaluation of the new target designs and supported layering research.

COORDINATION WITH NIF LASER SHOT

Layering Report

When the ice layer is completely formed, an extended set of image analysis routines is run to produce the Layering Report., shown in Fig. 6. The Report contains metrics and checks whether the layer meets the ignition specification. The Layering Report is a key decision point, when the scientific review board meets to decide whether to proceed with a NIF shot.

For visual inspection, the layering report contains unwrapped images of the ice layer in three dimensions. These images help evaluate the general spherical shape and severity of local defects. The power spectral density of the unwrapped ice surface is calculated for three axes and it is plotted against the ignition target specification. In the Layering Report section shown on Fig. 6, the spherical shape is within the specification for all three directions. For local defects, a cumulative metric is calculated based on the total surface area affected by the defects.

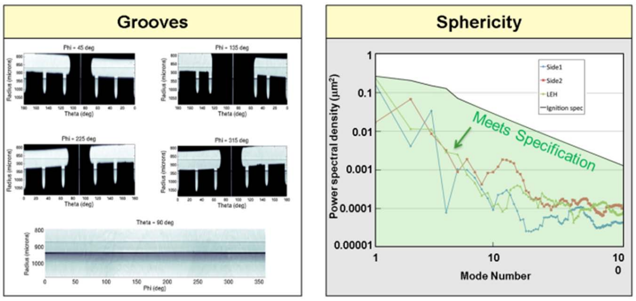

Figure 6: Section of a Layering Report.

The summary of the Layering Report includes a recommendation to proceed with the shot or to re-attempt the layering.

Cryogenic Activity and NIF Shot Sequence

Formation of the high-quality ice layers is a long process. It takes many hours, see Fig. 7. Including retries and supporting operations, it can take days. All cryogenic operations are coordinated under the Cryogenic Activity. The Cryogenic Activity is a sequence of steps similar to a NIF Shot [7]. Due to its extended duration, the Cryogenic Activity starts independently from a NIF shot. When the layer is close to completion, the NIF shot sequence starts. The Cryogenic Activity communicates to shot controls and joins the NIF Shot cycle.

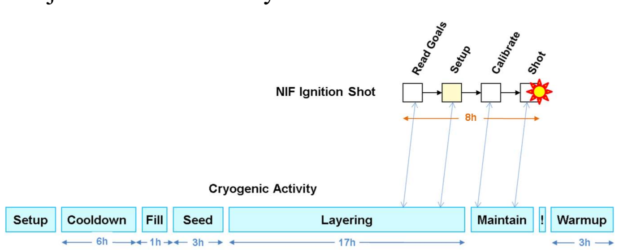

Figure 7: Timeline of Cryogenic Activity and NIF Shot.

Final Pre-shot Cryogenic Target Operations

The cryogenic target subsystem continues to monitor target temperatures during target insertion into the chamber and during target alignment. Seconds prior to the main laser shot the cryogenic controls perform final temperature adjustments and open the shroud.

Ignition target specifications require that the final target temperature is ~1.5K lower than the temperature at which the ice layer is formed and maintained [4]. At lower temperatures, the ice layer quickly develops roughness and cracks. To minimize the degradation of the ice surface, the cryogenic controls perform final temperature adjustment, called quench, only 30 seconds prior to the main laser shot (T-30). To further reduce the thermal stress, the quench is performed as a smooth linear ramp.

From the beginning of the cryogenic activity until the laser shot, the protective shroud surrounds the cryogenic target. This shroud shields the target from infrared radiation and prevents undesirable condensation on the outer surfaces of the target. The NIF shot control software commands mechanical opening of the shroud eight seconds prior to the main laser shot (T-8). The cryogenic system has adequate control authority to maintain precise temperatures for several minutes after the shroud is open. This is sufficient to handle normal and off-normal shot cases.

Normally, at T-0 the main laser shot is fired and the cryogenic target is consumed. Next, the cryogenic controls proceed to the warm-up sequence. If the laser shot is aborted during the final seconds, the cryogenic controls quickly revert the quench and return the target to temperatures at which the ice layer can be maintained safely until the next attempt.

RESULTS

Since 2010, the Cryogenic Target System supported 72 NIF experiments, including 13 with layered targets. The integrated hardware-software system provided a robust and accurate platform for cryogenic target experiments. The automatic data-driven process consistently executed complex layering protocols. Finally, the flexible interactive environment simplified evaluation of new target designs and supported layering research.

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