# Target Detection and Shroud Pull Sequencing for Cryogenic-Target Operations on the OMEGA System

## Introduction

The long-term plan for the upgraded OMEGA laser system includes continued improvements in beam quality, beam-to-beam energy and power balance, and the incremental addition of several beam-smoothing techniques. Incorporating the capability to shoot "cryogenic" targets is also part of the plan. Integration and activation of the Cryogenic Target Handling System is in progress as of this writing. This article introduces the elements of cryogenic-target operations and details the technique that will ensure correct and safe sequencing of cryogenic shots.

### 1. Cryogenic Operations

A cryogenic target is a ~1-mm-diameter spherical shell that is processed at very low temperatures and delivered to the target chamber with the fuel frozen as a layer of "ice" approximately 100 $\mu$m thick on the inside surface of the shell. These targets can contain significantly more fuel than the normal, room-temperature, gas-filled targets. Figure 81.21 illustrates how cryogenic targets are suspended by spider's silk from a beryllium "C" mount (see description in the **Target Filling** section, p. 7, this issue).

Figure 81.22 shows the equipment installed in the OMEGA target area to allow cryogenic targets to be positioned and shot. The lower pylon, supported by the target chamber (TC), extends downward from the center of the TC and through the Target Bay floor; this lower pylon is basically a cylindrical vacuum vessel fitted with a kinematic dock inside its upper end and an isolation valve and flange at its lower end. The upper pylon extends from above the center of the TC, through a bellows joint at the top of the TC; it is supported by the bridge structure that spans the Target Bay. The linear induction motor and shroud retractor, which are housed within the upper pylon, are used to remove a thermal shroud that protects the target until shot time.

Figure 81.23 shows the elements at the center of the TC in more detail. The target is housed in a moving cryostat (MC) that is placed at the center of the TC by the lower pylon equipment. The position of the target can be checked and adjusted using the standard OMEGA Target Viewing System and the positioner built into the MC. The OMEGA system may then be charged and sequenced to shoot the target. The charging and countdown take approximately 3 min. In the last second, the shroud retractor is commanded to pull the upper shroud upward, away from the target, so that it is clear of the beams before the laser pulse arrives.

Cryogenic targets are produced by permeating deuterium or deuterium/tritium fuel into the shell at pressures of up to 2000 atm and then cooling the assembly to below 20°K. The


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Figure 81.21
Cryogenic targets utilize a "C" mount configuration that minimizes the mass in the vicinity of the target and does not obscure any of the 60 OMEGA beams.

MC maintains a cold environment around the target while it is moved from the permeation site, completes its preparation cycle, and is moved to the center of the target chamber. Figure 81.24(a) shows the base of the MC; Fig. 81.24(b) shows the components that make up the upper shroud. The inner, middle, and outer shrouds are joined to form a single upper-shroud assembly that can move in a vertical direction over the target and mate with the lower shrouds on the base. In this configuration, the target is centered in the "layering sphere," which is a metal cylinder with an internal spherical cavity that is controlled to provide the low-temperature, spatially uniform radiation environment that promotes formation of a smooth, concentric ice layer. Windows in the layering sphere, the middle shroud, and the outer shroud allow the target to be viewed along two axes by the Target Viewing System (TVS), which is used to position objects in the OMEGA target chamber.

The MC transport cart mounts all of the cooling, vacuum, and control equipment required to maintain the MC at the required low-temperature, high-vacuum condition. A major feature of the transport cart is an evacuated umbilical spool that manages the electrical and fluid lines that connect the MC to the equipment on the cart. Figure 81.25 shows the transport cart. In this view, the cryostat is located below the large gate valve near the top of the cylindrical vacuum vessel (left of center). The entire transport cart is mounted on a pneumatic bearing system that allows operators to push it from place to place within the facility. A total of five transport carts are planned.

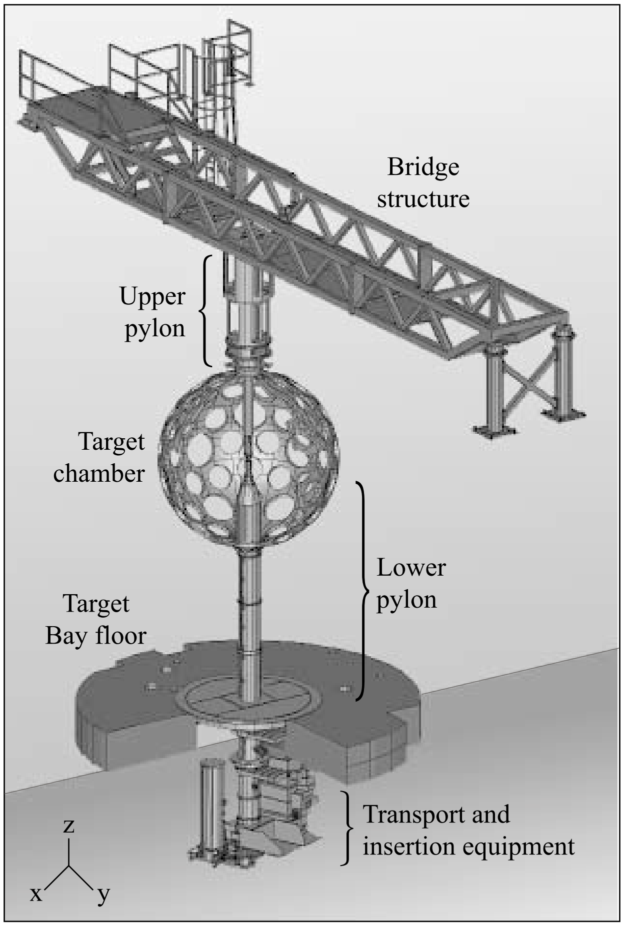

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Figure 81.22
The major equipment items recently installed in the OMEGA target area to facilitate cryogenic target shots include transport and insertion equipment beneath the target chamber, upper and lower pylons, and a structural bridge.

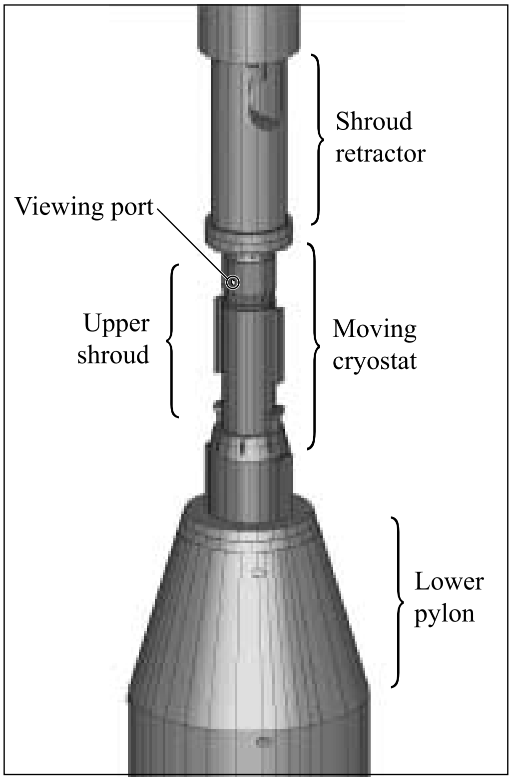

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Figure 81.23
The cryogenic target is housed in a moving cryostat (MC) that is placed at the center of the target chamber. The MC includes thermal shrouds that isolate the target from the room-temperature target chamber environment. The shroud retractor removes the upper shroud just prior to the shot.

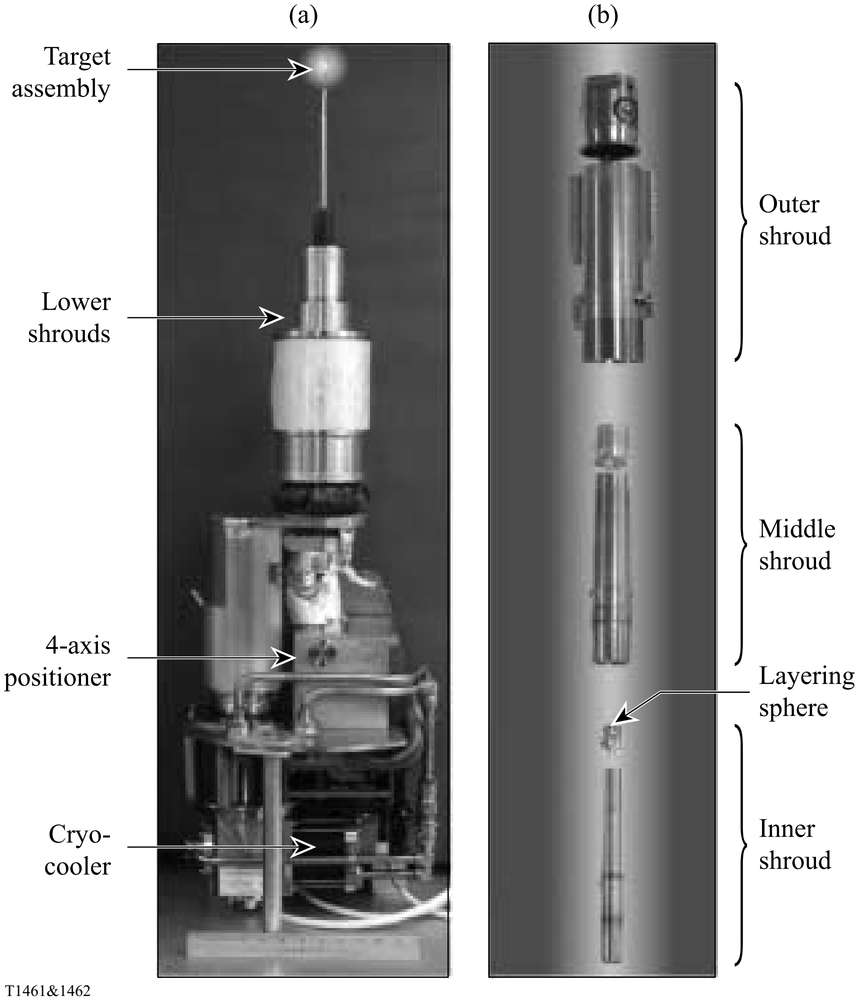


Figure 81.24
Parts of the moving cryostat: (a) The base includes a target positioner, a cooler, and the lower protective shrouds; (b) the upper shroud is a three-layer assembly. The layering-sphere element that immediately surrounds the target provides a spatially uniform radiation environment that determines the properties of the ice.

Figure 81.25
The moving cryostat transport cart carries the moving cryostat and its cooling, vacuum, and control equipment. It is moved around the facility on a pneumatic bearing system.

Figure 81.26 shows the lower pylon, in the room below the target chamber, with the transport cart docked to it. The vertical cylinder in the foreground is an evacuated "chain locker." When the system is ready, the isolation gate valves are opened, and the MC is driven to the center of the target chamber by the action of the chain being driven out of the locker and along guide rails inside the transport cart and lower pylon vacuum vessels. When it arrives at the center of the target chamber, the MC mates with the kinematic dock built into the lower surface of the top of the lower pylon and is clamped into place. This places the layering sphere and target within approximately 100 $\mu$m at the convergence of the laser beams.

The linear induction motor (LIM) in the upper pylon can then be operated to lower the shroud retractor from above to engage the upper shroud and prepare it for removal (this configuration is shown in Fig. 81.23). The shooting sequence includes commanding the removal of the upper shroud so that it is clear of the beams before the pulse arrives, assuring that the target is intact and in place, and preventing the laser pulse from propagating if a problem is detected. The details of this final sequencing, detection, and shot authorization process are performed by the cryogenic target detection equipment described in this article.

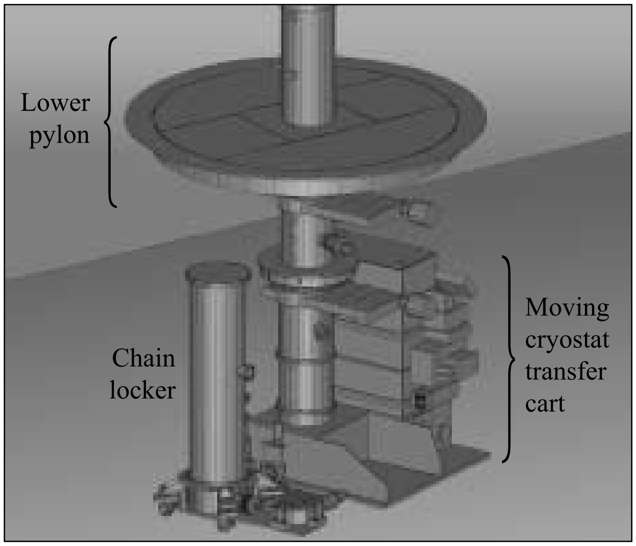


Figure 81.26
For an OMEGA shot, the transport cart is positioned under the lower pylon and connected to it. A compression chain system is used to drive the moving cryostat upward into the target chamber.

2. Cryogenic Target Detector

Because the beam ports on OMEGA's target chamber are arranged in opposing pairs, energy propagated forward in one beamline can pass through the chamber and propagate in the backward direction on the opposing beam train. This feature is exploited routinely in alignment procedures that use low-energy laser beams. High-value optics can be seriously damaged, however, if even a fraction of the high-energy shot pulse is allowed to pass the target and enter the opposing focus lens. "Target existence detectors" have been put into place to help prevent this from happening. The automatic imaging target existence detector (AITED)—a system used on noncryogenic target shots—protects against the situation where a properly aligned target moves or falls out of position late in the shot cycle. The cryogenic target detector (CTD) performs the same functions in the altered circumstances dictated by cryogenic-target operations. (The Target Viewing System cannot be used for target detection in either case because its lenses extend well into the target chamber and are protected from flash and debris by rugged shutters. Because these shutters require approximately 10 s to close, they are closed and verified prior to charging the laser system.)

AITED is designed to deal with targets of any shape (planar or spherical) positioned at any location near the target chamber's center. It features a single video camera to view a backlighted image of the target using an arrangement of lenses mounted outside the target chamber. Since it functions by processing video frames at 30 Hz, AITED is useful until about 30 ms prior to the shot. After the last pre-shot frame has been acquired, a fast shutter closes to protect the camera from the flash of the target event. The presence of the shroud and the sub-frame-rate timing of events prevent the use of AITED for cryogenic shots.

The CTD uses a pair of apertured photodiodes to analyze the intensity of signals provided by dedicated laser illuminators. This technique can provide detection arbitrarily close to the shot, but it is limited to spherical targets positioned at the center of the target chamber. As the design concept for the CTD developed, it was extended to include the precision timing of the shroud-retraction (or pulling) event.

Both target detectors prevent the high-energy pulse from propagating by interrupting the 5-Hz signal that triggers the power conditioning units for the regenerative amplifiers at the beginning of the laser system. The pulse that then propagates to the power amplifier stages is too low in energy to be amplified to normal levels in the remainder of the system. As a result, essentially no energy reaches the target, and damage due to energy passing through the center of the target chamber is prevented.

## Discussion

The Cryogenic Target Detection (CTD) System has been designed to meet the following requirements:

a. Synchronize the pulling of the shroud to the laser shot.
  - Ensure that the shroud is clear of all the beams before the energy arrives at the center of the target chamber.
  - Minimize the time that the target is exposed to the target chamber's thermal radiation environment (goal: 50 ms, max).
  - Ensure that the shot occurs before the vibration caused by stopping the shroud at the top of its travel can disturb the target.

b. Prevent propagation of the high-energy pulse if the target is not in place at the center of the target chamber.
  - Initiate detection when the shroud has cleared the target.
  - Continue to monitor as close as possible to shot time.

c. Prevent propagation of the high-energy pulse if the target is displaced or if shroud retraction deviates from nominal.
  - Accommodate 700- to 1100-$\mu$m-diam spherical targets at the center of the target chamber.
  - Detect displacement of the target from the center of the target chamber.
  - Detect early or late exposure of the target.
  - Detect failure of the shroud to clear the beams.

d. Provide operability and testability features compatible with OMEGA operations.
  - Provide consistent user interface look and feel.
  - Allow operator input of setup parameters.
  - Detect and display errors.
  - Implement correct responses to shot-cycle system states including "stand-down" and "abort."
  - Include test modes and signal outputs to facilitate installation, readiness checks, and trouble shooting.
  - Provide reduced functionality with one axis inoperative.

e. Fail to the "safe" triggers-are-interrupted mode.

The major elements of the CTD include a set of detectors installed on the target chamber; a rate interrupt module (RIM), which is located in the Driver Electronics Room (DER) below the Laser Bay; and user interface software, which creates a display in the Control Room. These are shown schematically in Fig. 81.27. The CTD uses two orthogonal optical detectors that are similar to the TVS. These elements are co-located with the corresponding TVS equipment on the target chamber but view along slightly different axes and operate independently. Because the CTD viewing axes are blocked by the edge of the viewing port in the outer shroud of the MC, target detection is not possible until the shroud has been pulled clear of the target late in the shot sequence.

The RIM is a package of electronics that is mounted in the same rack as the primary driver-timing equipment. A dedicated RS-485 serial link relays signals between the detector packages and the rate interrupt module (RIM). In addition to those associated with the detectors and illuminators these include the three shown connecting to the upper pylon controls in Fig. 81.27. The RIM also receives the T–10 and T–0 timing marks and the three 5-Hz rates that it controls from the Hardware Timing System equipment in the DER. The RIM communicates, via a standard RS-232 serial link, with a Sun workstation that contains the video frame grabber used by AITED. CTD operator interface software running on that computer provides the Graphical User Interface that is displayed on the laser drivers workstation in the Control Room.

### 1. CTD Illuminators

Each CTD illuminator consists of a small diode laser with a collimating optical system and a fast-acting shutter. The lasers are turned on and off by a general-purpose control software item that allows the lasers to be operated manually, as needed for checkout, and automatically cued by shot-cycle software messages. The fast shutter is controlled (like the AITED camera shutter) by the hardware timing system and a dedicated controller. It closes 1 to 5 ms before every shot to prevent the flash from damaging the illuminator laser optics and re-opens automatically after the shot. A photodiode mounted in the illuminator optics provides a signal to the RIM to indicate when the laser is on, regardless of the position of the shutter.

### 2. Detector Packages

The CTD optics focus the illuminator laser beam into the detector package, through a manually adjustable aperture, and onto a photodiode mounted within the TVS enclosure on the opposite side of the target chamber. This system is set up so that three distinct levels of illumination can be detected:

(a) No light means that the illuminator is either not on or is shuttered or that the MC shroud is blocking the line of sight.

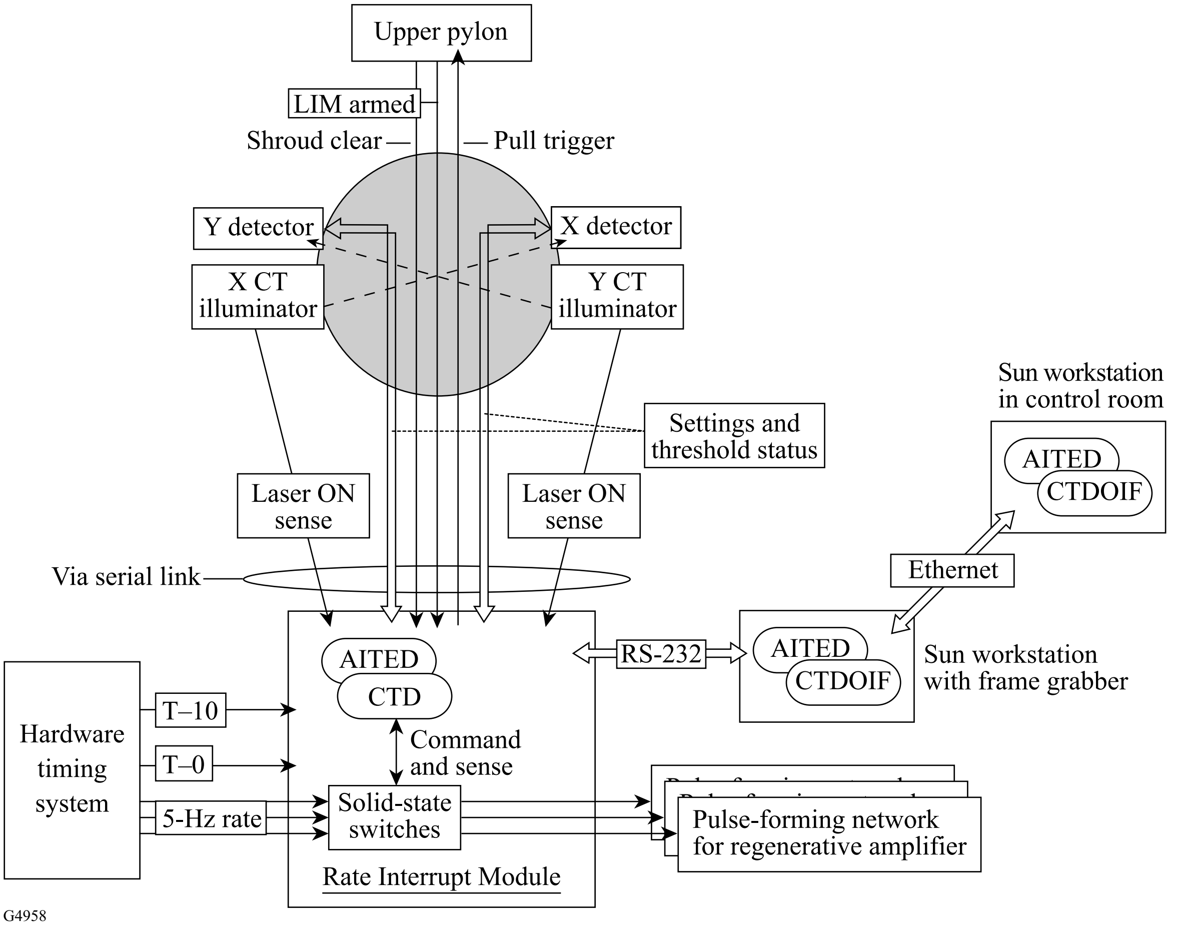


Figure 81.27
The rate interrupt module (RIM) is the heart of the Cryogenic Target Detection (CTD) System. It receives signals from detectors in the target chamber, controls the triggers to the driver preamplifiers, and communicates with the Control Room operators.

(b) A medium level means that the shroud is clear of the target and the target is in place.

(c) A higher level means that the shroud is clear but the target is out of place.

The "low" and "high" threshold settings that make this discrimination are set by the operator and passed to the detectors for implementation. Each detector uses a Microchip PICMicro 8-bit RISC microcontroller running at 16 MHz. This microcontroller includes on-board 8-bit analog-to-digital converters that transduce the photodiode signal. I/O bits on the PICMicro's are used to sense the illuminator status and handle the signals to and from the upper pylon. The detector packages also include RS-485 transceivers. The RS-485 standard uses differential signals that allow greater noise immunity, higher speed, and greater cable lengths than the RS-232 standard wire.

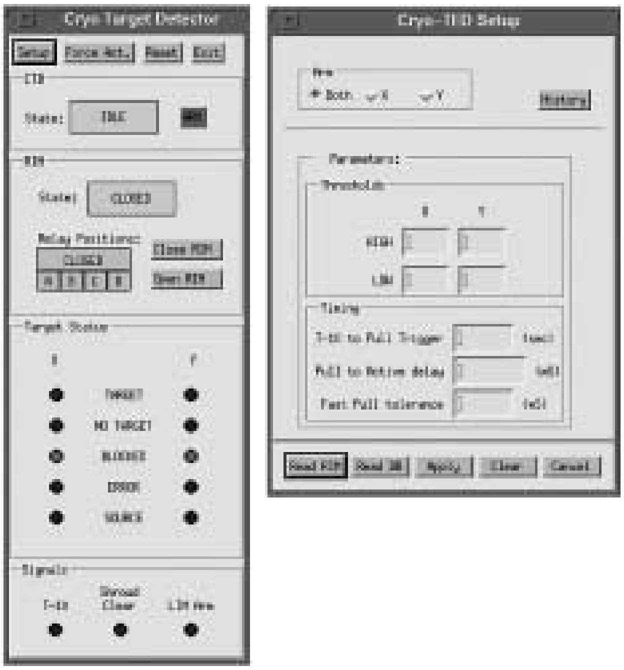
3. Rate Interrupt Module (RIM)

The RIM developed for cryogenic operations replaces the unit that was installed for AITED and is also built around the PICMicro microcontroller. The firmware running on this chip has separate AITED and CTD operating modes. The mode is determined by whether the AITED or the CTD software is running on the Sun computer. In the AITED mode, the RIM functions the same as previous versions of the RIM. In the CTD mode, the RIM implements the cryogenic target requirements. In both modes the code coordinates the activities of the RIM, including communication with the Sun, and control of the 5-Hz flashlamp triggers. Final control of the flashlamp triggers is provided by opto-isolators rather than the relays used in the previous versions of the RIM. This approach provides improved reliability and switching speed. The closed-to-open signal switching time of the rate interrupt opto-isolators has been measured as approximately 500 ns.

The overall shroud-retraction sequence must be repeatable within ±1 ms. This allocation includes the "pull trigger" signal that originates in the RIM and is relayed over the RS-485 to the Y detector package, where it is output as a voltage level to the LIM controller in the upper pylon. The performance of the CTD elements was assessed in LLE's Electronics Shop using the actual components connected by cables of representative lengths. The result of 20 trials is that the "pull trigger" can be timed and generated in the RIM, transmitted to the detector package, and output with an average latency of 128.8 $\mu$s and a rms ("jitter") of 2.6 $\mu$s—well within the required limits.

### 4. CTD Operator Interface (CTDOIF)

The CTD operator interface software was developed using X/Motif Designer 5 and is designed to run under Solaris on the AITED Sun workstation to make use of the dedicated serial link to the RIM. The Graphical User Interface is displayed on the laser drivers workstation in the Control Room. Figure 81.28 illustrates the windows that are presented to the operator. The main window provides the functions for normal shot-to-shot operation of the CTD, which includes monitoring the status of the RIM and arming the system for a shot. In particular, the status of the illuminators and the resulting signal levels at the detectors are portrayed. The setup window allows the operator to review and change the selection of axes that will be armed and the values of the RIM parameters. When revised values are applied to the RIM, they are automatically saved to the OMEGA database. The selection of one axis or both will depend on the status of the CTD hardware. Variations in target size or opacity may necessitate adjustment of the threshold values. The timing parameters will be a function of the acceleration profile that the LIM/shroud puller is commanded to follow. It is expected that once the correct set-up values have been established, they will seldom be changed.



(a) Main window (b) Setup window

State: IDLE

State: CLOSED

Relay Positions: CLOSED

Figure 81.28
The CTD operator interface windows (a) arm the system, enable/disable the solid-state relays, and monitor status; (b) choose axes to be armed and set detection thresholds and timing values.

The communication link between the Rate Interrupt Module and the Operator Interface is monitored by both elements. If communication is lost after the system has been armed for a shot, the RIM will interrupt the driver triggers. It will also abort the shroud pull if it is not too late. The OIF supports the executive-level intercommunication protocol that is used to coordinate shots. This ensures that the CTD is operated when necessary and that the operators are aware of any problems. It also allows the CTD to participate correctly in system-wide aborts or stand-downs.

### 5. Operating Sequence

Figure 81.29 illustrates the events in the cryogenic shot sequence. After the MC has been inserted and the target has been positioned and verified by the Experimental System operator using the Target Viewing System, the laser driver operator will verify that the CTD is set up correctly and "arm" it for the shot. In the armed state, the CTD will act in response to the events it can sense. When the CTD is not armed, the information is simply displayed to the operator.

When the entire OMEGA system is ready, the power amplifiers are charged over a period of about 2.5 min. After charging is complete, the precision timing sequence starts at T–20 s. At about T–10 s (exact timing to be determined during system activation), the pylon controller element of the Cryogenic Target Handling System initiates a "pre-pull" activity that prepares the shroud for removal. The RIM receives the "LIM armed" signal when this is complete. Meanwhile, at exactly T–10 s, the RIM computer starts a "pull timer" that counts down to the time at which the pull trigger signal must be output. Since the shroud takes about 470 ms to clear the target after it is triggered, the pull timer will run for about 9.5 s. When the pull timer expires, the RIM logic checks to ensure that it is prudent to initiate the retraction sequence. As is indicated in Fig. 81.29, the pull trigger will not be output if a system-wide abort is underway or if the pre-pull did not complete successfully (as indicated by "LIM armed") or if the CTD illuminator(s) for the axes that are armed is(are) not on at this point. (The separate function that controls the illuminators is cued by the executive-level intercommunication protocol.) In addition to inhibiting the pull trigger, these contingencies will cause the opto-isolators to be disabled, interrupting the driver pulse.

After the pull trigger has been output, the RIM logic waits until the shroud should be clear (this is timed by the "activation timer"). Figure 81.30 is a plot of the shroud trajectory that has been the baseline for the system design. The actual optimum trajectory is currently being developed on the basis of the operating performance of the LIM and its controls. The baseline features an initial constant-velocity pull that separates the upper shroud from the lower shroud. This is followed by acceleration at 2.5 g until after the time of the shot. The LIM will then decelerate the shroud to a stop at the upper end of its travel (this part of the trajectory is not shown in the plot). In Fig. 81.30, note that the shot must occur in the 4-ms window between the shroud clearing the beams (at 0.484 s) and the end of the 50-ms exposure limit (at 0.488 s). These timing values depicted in Fig. 81.30 are also reflected in Fig. 81.29. (The critical timing parameters used by the CTD can be easily adjusted to accommodate any retraction trajectory that can be executed by the LIM.)

The shroud will clear the CTD lines of sight at the point on the trajectory marked "Target is exposed…". This will allow the light from the illuminators to reach the detectors and will cause the lower thresholds to be exceeded. The activation timer will be set for the latest time that this can occur and still have a successful shot. If this "slow pull" limit is exceeded, the RIM will disable the opto-isolators to abort the driver pulse. This prevents shooting with the shroud in a position where it will intercept some of the high-energy laser beams. The "fast pull tolerance" [see Fig. 81.28(b)] will be set to represent the earliest time at which the shroud can clear the target and still allow a successful shot. If the illuminators are detected before the activation timer is below the fast pull tolerance, the driver pulse will be interrupted because the target could be exposed long enough to explode before the shot (the 50-ms exposure limit). In an extreme fast pull case, vibrations resulting from the shroud puller deceleration could reach the target and disturb it prior to the shot.

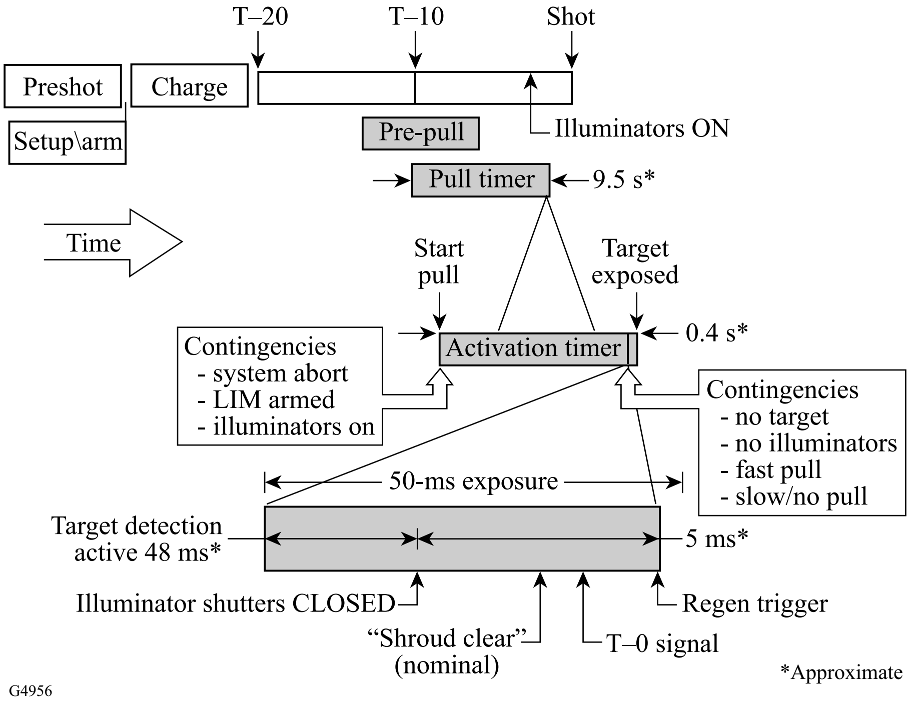


Figure 81.29
The nominal timeline for a cryogenic-target shot illustrates the increasingly precise timing of events orchestrated by the CTD system.

If the target is in place when the shroud clears the CTD lines of sight, the detector signals will be above the lower thresholds but will not exceed the upper thresholds. This is the "TARGET" situation on the operator displays and within the CTD logic. If the armed axes are in this condition, the shot and monitoring can continue until the illuminator fast shutters close a few milliseconds before T = 0. At that point, the signals will drop back below the lower threshold. The detection logic is then disabled. While the detection logic is active, the driver pulse will be aborted if the detector signals indicate that the target is not present or that the illuminators have failed.

The "shroud clear" signal is derived from a photosensor attached to the LIM structure. It indicates that the shroud is near the point at which it is out of the beam paths. This signal is monitored by the CTD to deal with the contingency that the shroud retractor slows down or stops after a successful initial retraction. A T–0 signal is provided to the RIM primarily as a means for disarming the target detector after the shot (so that an abort is not initiated when the target disappears due to the shot). This T–0 signal will be delayed by the timing system so that it occurs as close as possible prior to the arrival of the driver PFN triggers. If the "shroud clear" signal is received before the T–0 signal, the shot can continue. If "shroud clear" has not been received when T–0 arrives, the opto-isolators will be disabled.

The RIM will count the time interval between the "shroud clear" and T–0 and report it to the OIF for review by the operator. These values will also be logged to the database as an indication of the shroud puller's performance.

## Conclusion

Cryogenic target detection (CTD) is a critical part of the functional integration of the Cryogenic Target Handling System into OMEGA. The newly designed CTD is based on existing elements of the OMEGA controls and will provide the necessary sequencing and safety features. The CTD setup features sufficient flexibility for the evolution of the details of cryogenic operations and target physics research.

## ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

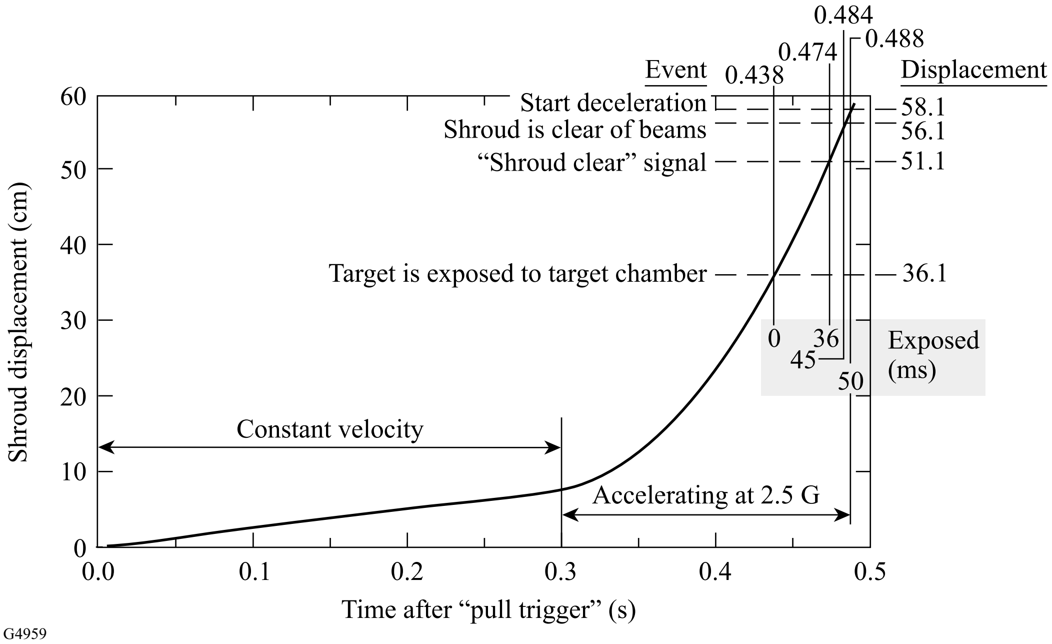


Figure 81.30
The baseline shroud-removal trajectory features constant velocity separation of the shrouds followed by constant acceleration until after the shot.