SHOT AUTOMATION FOR THE NATIONAL IGNITION FACILITY*

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ABSTRACT

A shot automation framework has been developed and deployed during the past year to automate shots performed on the National Ignition Facility (NIF) using the Integrated Computer Control System This framework automates a 4-8 hour shot sequence, that includes inputting shot goals from a physics model, set up of the laser and diagnostics, automatic alignment of laser beams and verification of status. This sequence consists of set of preparatory verification shots, leading to amplified system shots using a 4-minute countdown, triggering during the last 2 seconds using a high-precision timing system, followed by post-shot analysis and archiving. The framework provides for a flexible, model-based execution driven of scriptable automation called macro steps. The framework is driven by high-level shot director software that provides a restricted set of shot life cycle state transitions to 25 collaboration supervisors that automate 8-laser beams (bundles) and a common set of shared resources. Each collaboration supervisor commands approximately 10 subsystem shot supervisors that perform automated control and status verification. Collaboration supervisors translate shot life cycle state commands from the shot director into sequences of "macro steps" to be distributed to each of its shot supervisors. Each Shot supervisor maintains order of macro steps for each subsystem and supports collaboration between macro steps. They also manage failure, restarts and rejoining into the shot cycle (if necessary) and manage auto/manual macro step execution and collaborations between other collaboration supervisors. Shot supervisors execute macro step shot functions commanded by collaboration supervisors. Each macro step has database-driven verification phases and a scripted perform phase. This provides for a highly flexible methodology for performing a variety of NIF shot types. Database tables define the order of work and dependencies (workflow) of macro steps to be performed for a shot. A graphical model editor facilitates the definition and viewing of an execution model. A change manager tool enables "de-participation" of individual devices, of entire laser segments (beams, quads, or bundles of beams) or individual diagnostics. This software has been deployed to the NIF facility and is currently being used to support NIF main laser commissioning shots and build-out of the NIF laser. This will be used to automate future target and experimental shot campaigns.

INTRODUCTION

The National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) will be a national center for the U.S. Department of Energy to study inertial confinement fusion and the physics of extreme energy densities and pressures. Construction of the building that houses the laser system was completed September 2001 and the construction of all 192 ultra-clean and precision aligned beam path enclosures was completed September 2003. In late 2002 NIF began activating its first four laser beam lines. By July 2003, NIF had delivered world-record single beam laser energy performance in the primary, second and third harmonic wavelengths (NIF's primary wavelength is 1.06 micron infrared light). By September 2004, the first four NIF beams (a "quad") were commissioned to the center of the target chamber. End to end functionality was demonstrated for all major subsystems. Semi-automated scripted software was successfully used for experimental shot campaigns for 4 beams in 2004. 4-hour shot rates and initial automation enabled efficient experimental shot campaigns using a 6000 line checklist. A variety of experiments were successfully performed using ICCS through Sept. 2004. Laser beam propagation in under-dense plasmas to study phenomena in ignition targets, hohlraum experiments were used to commission diagnostics, planar hydro experiments validated new three dimensional hydrodynamic codes and steady shocks were demonstrated. When completed in 2009, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally in the interior of stars and in nuclear weapons explosions [1].

NIF DESCRIPTION

The NIF facility consists of two laser bays, four capacitor areas, two laser switchyards, the target area, and the building core containing the control room and master laser oscillator. In addition, there is an Optics Assembly Building and a Diagnostics Support Building. The laser is configured in four clusters of 48 beams, two in each laser bay. Each cluster has six sets of eight beams called a bundle that is the fundamental beam grouping in the laser bay. In the switchyard, each bundle is split into two sets of four beams, or quads, with one quad from each bundle directed toward the top of the chamber and the other quad directed toward the bottom. The irradiation geometry for an indirect-drive ICF ignition target focuses the upper and lower groups of 24 quads through the two laser entrance holes in the target hohlraum.

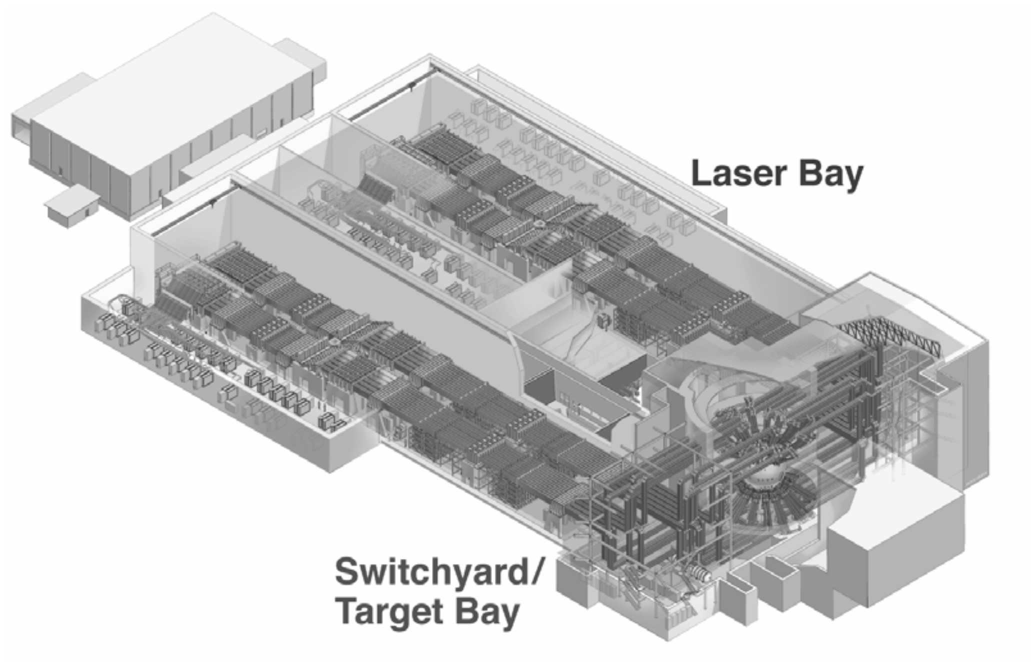

Figure 1. Layout of the National Ignition Facility.

A NIF laser beam begins with a 1-nJ infrared pulse from a master oscillator system that can provide a variety of flat to high-contrast pulse shapes. The pulse travels over fiber-optics to preamplifier modules (PAMs) for amplification and spatial beam shaping. Each of the 48 PAMs boosts the pulse to a maximum of 10-J. From the PAM the laser beam is split four-ways and enters the main laser system, which provides 99.9% of NIF's power and energy. Flashlamps that pump neodymium-doped glass slabs in the main amplifiers receive their power from the Power Conditioning System, which consists of the highest energy array (delivering up to ~400 MJ) of electrical capacitors ever assembled. An optical switch in each beam line called the plasma-electrode Pockels cell (PEPC) allows 4 passes through the main amplifier to increase the laser efficiency. After amplification the beam leaves the laser bay to travel through the switchyard, where it is redirected through the final optics assembly (FOA) and focused on target. A harmonic converter in the FOA converts the beam to the ultraviolet third harmonic (3ω). Upper and lower groups of 24 quads are focused onto a target located at or near the center of the 10 meter diameter target chamber.

NIF is controlled by a large-scale distributed integrated computer control system (ICCS). The ICCS is a layered architecture of 700 front-end processors (FEP) coordinated by supervisor subsystems including automatic beam alignment and wavefront control, laser and target diagnostics, pulse power, and shot control timed as required to 30ps. Software is based on an object-oriented framework using CORBA that incorporates services for archiving, machine configuration, graphical user interface, monitoring, event logging, scripting, alert management, and access control. Software coding in a mixed language environment of Ada95 and Java is 80% complete at over one million source lines. A more detailed description of the overall status and architecture can be found in [2,3].

SHOT DESCRIPTION

ICCS's primary requirement is to fire and diagnose each laser shot within 4-8 hours. This requirement includes shot setup preparations and a countdown sequence; performing automatic alignment, laser beam diagnosis, and control of power conditioning and electro-optic subsystems; monitoring the status of all subsystems and components; and providing operators with graphical interfaces to display those data. ICCS also must maintain records of system performance and archive the experimental data recorded by NIF's advanced diagnostic instruments.

Every NIF experimental shot is a complex computerized coordination of laser equipment and the efforts of system operators that requires reliable monitoring and controlling of 60,000 control points comprised of electronic, optical, and mechanical devices, such as motorized mirrors and lenses, energy and power sensors, video cameras, laser amplifiers, pulse power, and diagnostic instruments. Each shot begins with using LPOM to derive laser settings based on overall shot goals. During a shot, laser diagnostics instruments such as calorimeters are set up to measure laser energy at the output of the main laser. Automatic alignment is a significant part of every shot preparation, which controls mirrors and uses alignment images to direct laser beams toward the target. Laser light is precisely aligned to a target, a NIF target is positioned at the center of the target chamber and laser light is aligned to the target and experimental diagnostics are setup. This leads to a 4-minute countdown which consists of an automated sequence of final settings and verifications. This includes performing final laser and diagnostic settings, pulsing the PEPC system, verifying that critical devices are in shot position, and charging the preamplifiers before turning control over to the integrated timing system, which orchestrates laser firing and triggering of diagnostics. One or more preparatory rod shots are used to verify shot settings and performance, leading to a shot which uses the main amplifiers using the power conditioning system. Data archiving and processing is performed after a shot. A Laser Performance Operations Model (LPOM) is then used to make setting adjusts based upon monitored shot performance.

A basic strategy during the past year was to convert to a bundle-based control system and to provide more flexible automation. A bundle-based architecture could be achieved since most collaboration between subsystems was intra-bundle. Additionally, there was a need to extend the control system to be able to support a variety of experimental shots. During the past year, most controls and diagnostic hardware were converted to bundle-based at a moderate cost. Common services such as timing, industrial controls and target chamber would be shared. Independent bundle controls essentially eliminated the need for 50 times scaling in laser controls performance and limited the impact of control system failure. Over the next few years, as laser "bundles" of eight beams - the basic modular unit of NIF - are completed, computers and software that were fielded for the first bundle will be replicated to commission new bundles. NIF's natural partitioning according to the independent bundle architecture greatly simplifies the task of controlling the laser because each bundle is operated asynchronously from the others until the final countdown. The bundles are synchronized together just before shot time.

Daily operation of NIF is managed by a Lead Operator, whose role is to conduct shot experiments and oversee control room activities that operate the laser and target systems. The ICCS team developed shot supervisory software that assists the control room staff to prepare and fire each shot by automatically sequencing the many functions of the computer control system. The Lead Operator interacts with the top layer of this software to ensure that every experiment runs successfully.

Given the overall scale, timeline and commissioning approach, high-level requirements for shot automation include:

- Ability to scale to the full 24 bundles
- Support automation of dissimilar bundles
- Model-driven activity sequences
- Data-driven verification of laser component states
- Factor common activities for re-use
- Subsystem interactions and collaborations
- Localized error recovery
- Execution of activities based on calculated participation
- Automatic derivation of laser/target component settings based on experiment goals

SHOT AUTOMATION FRAMEWORK

A shot automation framework has been developed and deployed during the past year to automate shots. This framework automates a 4-8 hour shot sequence that includes inputting shot goals from a physics model, set up of the laser and diagnostics, automatic alignment of laser beams and verification of status. The framework consists of a state machine and inter-communicating dynamic workflow engines that coordinate the 24 bundles through a Shot Lifecycle of 10 well-defined Shot Life Cycle states. The workflow engine or Collaboration Supervisor organizes the collaborative work of the subsystem shot supervisors within a bundle. The state machine contained in the Shot Director program coordinates all Collaboration Supervisor transitions between Shot Lifecycle States. This provides the flexibility to autonomously operate 24 independent bundles with a minimal operations staff.

The shot automation framework is composed of the Shot Director Layer, Collaboration Management Layer, Subsystem Shot Management Layer and FEP layer (Figure 2). Each of these layers consists of one or more distributed processes and CORBA is used for communication between layers. Tasking is used extensively by these different layers to accomplish parallelism and decouple work execution from command and status messages. Interface decoupling is an important design characteristic of robust and efficient distributed systems.

The Shot Director is the topmost application in ICCS Shot Control. The Shot Director manages a shot through its lifecycle. Using the Shot Director software, the Lead Operator selects a pre-approved Experiment definition using the GUI to begin the Shot Lifecycle. The Experiment definition describes the goals of the shot (e.g., desired laser performance) in terms understood by software. These goals are read from a database and used to derive specific settings used within the Shot Lifecycle by the various subsystems. The settings are represented by Shot Setpoints. A “setpoint” is a named position/state of a software object in ICCS. A named position/state of an ICCS software object typically corresponds directly to the state of a physical device or collection of devices. Setpoints are used extensively by ICCS application software to encapsulate the details of position or state. The meaning of position/state varies with the type of setpoint. For example, position for a timing channel has substantially different composition and meaning than position for a beam shutter. Client application software can refer to a position/state by name rather than having to know the detailed attributes and settings to arrive at a particular position or state. The Shot Automation Framework makes extensive use of setpoints to configure the system for shots. The Shot Director software orchestrates all participants at the Collaboration Management layer in their transitions between well-defined Shot Lifecycle states representing high-level conceptual activities such as reading goals, configuring for a preparatory shot, shot countdown, updating settings, etc. All participating Collaboration Supervisors are commanded to execute a Shot Lifecycle state in unison. The Shot Director’s state machine limits the actions available to the Lead Operator within that state. Transition events are generally triggered by Lead Operator action.

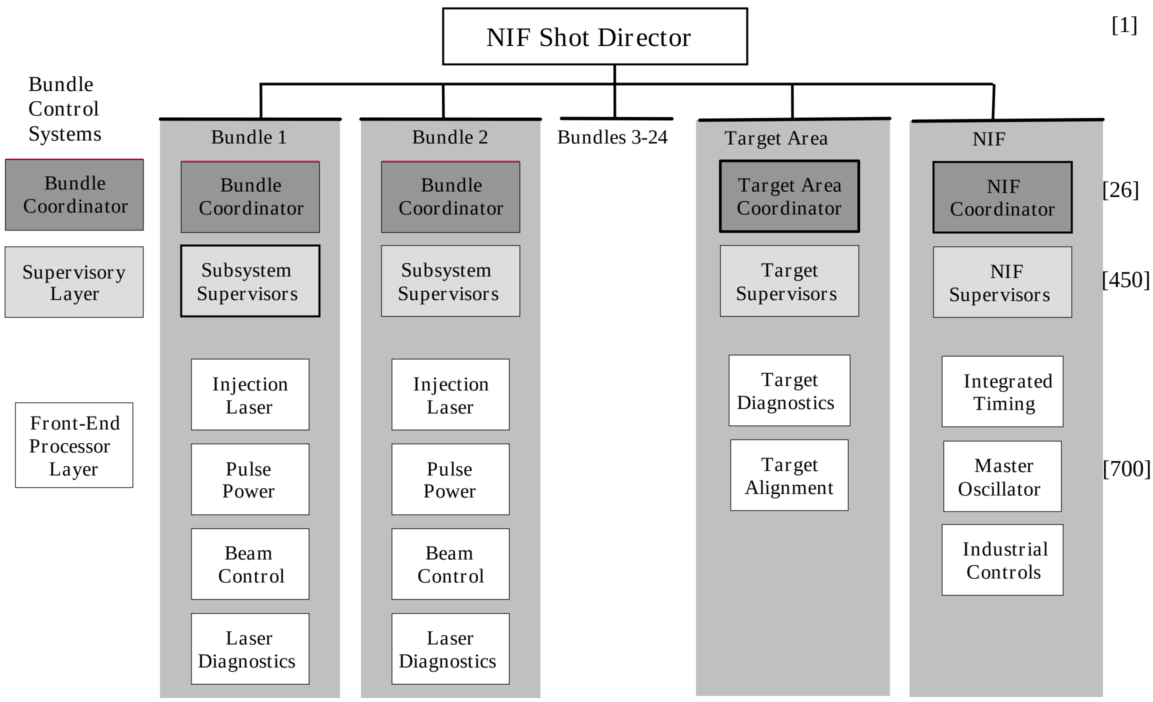

Figure 2: Shot Management Layers

The Collaboration Management layer consists of Collaboration Supervisor processes, one per bundle plus two non bundle-based systems. Each Collaboration Supervisor process accepts commands and reports status with the Shot Director via CORBA messages. When a Collaboration Supervisor is commanded to execute a Shot Lifecycle state, it reads a workflow model from the database representing the sub-functions, their order, and the inter-relationships specific to that collaboration space and state. These sub-functions are referred to as Macro Steps. A Macro Step is defined as a collection of autonomous steps, which when executed in a specific order perform a task associated with a NIF shot. The role of the Collaboration Supervisor is to coordinate the parallel, ordered execution of Macro Steps by the collection of Subsystem Shot Supervisors. The workflow graph for a specific bundle and shot lifecycle state includes a line of execution for each Subsystem Shot Supervisor belonging to that bundle, with interconnecting lines representing order dependencies between Macro Steps in different Shot Supervisors' lines of execution. Separate tasks communicate with each Subsystem Shot Supervisor.

Figure 3 shows a shot model diagram for the Implement Plan Shot Lifecycle state. Subsystem mnemonics are organized vertically on the left and Macro Steps are identified with blocks. Interconnecting lines indicate ordering and interdependencies reading from left to right. GUIs render the NIF workflow model for the Lead Operator. Progress is indicated by colorizing Macro Step rectangles.

Figure 3: Shot Model workflow

The Subsystem Shot Management Layer is composed of a collection of Shot Supervisor applications, each accepting commands and reporting status to a specific Collaboration Supervisor. These Shot Supervisors represent specific NIF subsystems. One example is the Beam Control System. The Beam Control System (BCS) is responsible for controlling the pointing of the laser beam through the main laser system to the center of the target chamber. In general, FEPs, subsystem status/control supervisors, and their GUIs support manual operator interactions with hardware. A Beam Control Shot Supervisor for each quad (top and bottom) reports to the Collaboration Supervisor and automates the BCS shot activities by executing Macro Steps that manipulate bundle BCS devices. Macro Steps are transient software objects. The Subsystem Shot Management Layer creates a specific Macro Step object upon receiving an execute command from the Collaboration Supervisor, which is discarded upon Macro Step completion.

The Shot Supervisor Framework uses defined verification phases (Is Done, Ready, and Final Done) to validate the state of the system before and after executing a Macro Step. Primarily by checking if FEP devices are at particular setpoints, these data-driven phases determine if the Macro Step is: 1) already done; 2) if not done, ready to be run; and 3) after running, successful in its execution. Between the Ready and Final Done verifications is the Perform phase of the Macro Step which is XML script driven and contains detailed steps and sub-steps. The framework supports additional parallelism within a Subsystem Shot Supervisor using tasks that position collections of similar devices in the Perform phase. Any anomalies or error conditions are reported to subsystem shot supervisor GUIs. This allows for significant flexibility in defining and redefining automation sequences without coding additional software releases.

DATA DRIVEN WORKFLOW

The Shot Lifecycle state machine governs the general flow of a NIF shot. A set of specific macro steps and their preconditions for all Shot Lifecycle states is called a shot model. Each experiment definition is associated with a particular shot model. Shot models are defined in an Oracle database.

Different shot models give flexibility to operate NIF in different ways without modifying software. For instance, a laser-commissioning model does not include target area systems.

Upon entry to a new Shot Lifecycle state, each Collaboration Supervisor queries the database to obtain the set of macro steps it is to execute, including all order dependencies and modes of operation. Each line of execution is advanced as macro steps complete and pre-conditions are satisfied. The Collaboration Supervisor creates a separate task to support each subsystem line in the model. Each Macro Step in a line is supported by a software object known as a Response Bookkeeper (RBK). The RBK tracks the completion of those Macro Steps defined as pre-conditions to its Macro Step. When a Shot Supervisor reports completion of a Macro Step, all RBKs in the model are updated with its completion status and the task associated with that Shot Supervisor is invoked to process the completion. If it completed successfully, the next Macro Step is retrieved and its RBK governs when the Macro Step can be issued. When all pre-conditions to the Macro Step have reported successful completion, the RBK wait is released and either the Shot Supervisor is commanded to execute the Macro Step (Auto mode), or it is enabled on the GUI for the Lead Operator to manually select it for execution. Shapes and colors are used to represent Macro Step progress and status on the GUI. Failure of any Macro Step presents the Lead Operator with the ability to select any Macro Step whose pre-conditions have previously been met as a valid re-entry point. Upon re-entry, a recursive graph analysis automatically interrupts affected Shot Supervisors and restarts them at the appropriate node in the graph.

The subsystem shot management layer is responsible for executing Macro Steps. The contents of a Macro Step are also defined in the database. The shot supervisor framework obtains the Macro Step details from the database to execute a particular Macro Step. This portion of the shot framework relies heavily on ICCS setpoints. The subsystem shot management layer also supports scripted Macro Step activities. Steps are defined in XML scripts that are read and executed by the framework and scripts provide some primitive language constructs. If necessary, the behavior of a macro step can be changed in XML data without modifying code.

CHANGE MANAGER/DYNAMIC PARTICIPATION

The initial experiment goals for a NIF shot specify participating beams, energies, pulse shape, diagnostics, etc. Derived goals establish settings required to accomplish the experiment goals. Because experiment approval happens sometime before the shot is scheduled, changes in the laser configuration may be required to accommodate situations arising at the time of the shot. For example, a particular beam or diagnostic may not be functioning properly. The Shot Framework allows operators to reconfigure the participation and/or derived settings. To accommodate this requirement, all shot steps and verifications must take into account the concept of participation. The shot framework maintains participation information for a predefined set of laser/diagnostic components. Macro Step execution queries participation prior to all verification and perform operations.

The participation information is generated by database calculations based on shot-specific laser beam and diagnostic use plans. A Change Manager tool provides the human interface to modify participation during the shot cycle. It enforces certain rules of engagement for change requests, approvals, and recalculation of participation that allow changes to laser settings and permits de-participation of failed components, including removal of entire beams from the shot. A shot framework participation object resides in each subsystem shot supervisor process. The participation object is updated at the beginning of the upcoming Macro Step whenever participation is recalculated.

COUNTDOWN CLOCK

Time-critical sequences are executed during a 255 second countdown implemented by the Countdown Shot Lifecycle State. This includes final checks, charging of capacitors, and verification of critical devices. A failure in any one of these activities automatically suspends the countdown. In certain critical failures the shot is aborted and transitions to Post-Countdown activities. At T-2 seconds, the Shot Director software gives control over to the Integrated Timing System, which in turn activates thousands of preset delay timers at the FEP layer that trigger firing and diagnosing the shot.

The Shot Director software executes the countdown clock. It manages the emission of ticks every second, and “shot holds” that may be requested by the subsystem shot management layer. Each Shot Supervisor contains a countdown agent that receives ticks and executes subsystem specific activities at particular times in the countdown. The countdown clock supports shot holds registered before the clock starts. These are referred to as synchronization holds and if not removed prior to their associated tick, will cause the clock to stop and send a holding message to all countdown participants. Holds can also be registered while the clock is running. These are exception holds and cause the clock to stop immediately.

ABORT/ABANDON EVENTS

One of the primary requirements of the Shot Framework is to support abort and abandon events. Aborts are specific to the countdown shot lifecycle state. The countdown is where critical device states are verified and high-energy pulse power systems are charged and fired. If problems are detected within certain critical regions of the countdown, the shot must be aborted to prevent potential equipment damage or spoiling the shot. When one subsystem shot supervisor detects a problem, it may request an abort that is propagated to all shot management layers. Subsystem operators also have access to an abort button that initiates the abort sequence.

Abandon semantics are handled by the Shot Lifecycle state machine. A shot may be abandoned when failures in hardware or software make continuing shot execution unfeasible. Shot abandon may only be requested by the Lead Operator. It causes the Shot Lifecycle state machine to go directly to the "End Shot" state. Cleanup activities for an abandoned shot must reset all shot-related components to their idle/safe state regardless of the state where the abandon was initiated. Cleanup activities are complex for some subsystems, and are being made more robust through a continuing process of refinement.

SUMMARY

A shot automation framework has been developed and deployed during the past year to automate shots performed on the NIF using the ICCS. This framework was used to perform laser commissioning shots for a bundle through the main laser during in June and July 2005. The software flexibility was demonstrated by using it to perform main laser rod and system shots as well as parasitic shots. During the last several months, a more efficient commissioning shot model was used to reduce shot times down to 3 hours. The framework will be used to support shots for Precision Diagnostics System (PDS) experiments beginning November 2005. It will then support multi-bundles in June 2006, a cluster-level of 48 beams during 2007, and eventually support target chamber and experiments during 2008-2009, leading to ignition experiments beginning in 2010. With the ability to modify the shot behavior by updating the database, the framework provides the robustness and flexibility necessary to support the scale, complexity and 30-year expected lifetime of NIF.

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