MANAGEMENT OF EXPERIMENTS AND DATA AT THE NATIONAL IGNITION FACILITY*

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Abstract

The National Ignition Facility (NIF) consists of 192 pulsed laser beams fired simultaneously at a stationary target in a 10-m diameter vacuum chamber. During a typical 4-8 hour NIF shot cycle, culminating in a nano-second scale laser firing, thousands of adjustments are performed on the target (type, composition, shape), laser (beams used, their power profiles, pointing), and diagnostics (configuration, calibration, settings). It is imperative that we accurately define all equipment prior to the shot. Following the shot, and the data acquisition by the automatic control system, it is equally imperative that we archive, analyze and visualize the results within the required 30 minutes post-shot. Results must be securely stored, approved, web-visible and downloadable in order to facilitate subsequent publication. To-date NIF has successfully fired over 2,500 system shots, and thousands of test firings and dry-runs. We present an overview of the highly-flexible and scalable campaign setup and management systems that specify all aspects of the experimental NIF shot-cycle, from configuration of drive lasers all the way through archival and presentation of analyzed results.

EXPERIMENTS AT NIF

Experiments, or "shots", conducted at the National Ignition Facility (NIF) [1,2] are discrete events that occur over a very short time frame – up to 500 terawatts of instantaneous laser power are delivered to a target in tens of nanoseconds – separated by a few hours. The 192 beams of pulsed laser energy are directed at the mm-sized target centered in the NIF vacuum chamber. Each shot generates hundreds of gigabytes of data from over 30 diagnostics that measure optical, x-ray, and nuclear phenomena from the imploding target.

Most shots are part of a larger group, or campaign, of shots to advance a specific scientific goal in the understanding high-energy-density physics. One such campaign, the National Ignition Campaign, employs 1.8-Megajoules of 351-nm laser energy to implode a hydrogen-filled target as a demonstration of controlled nuclear fusion with gain. The campaign goal of fusion ignition and gain, the primary reaction that fuels stars, could potentially lead to a limitless clean energy source.

Often, in order to achieve efficient usage of precious target chamber time, shots from one campaign are interleaved with those of other campaigns. Each experiment can have very different needs from the facility including the laser controls and restrictions, target chamber controls, target positioning and cooling, industrial controls and safety subsystems.

Following each shot, the control system systematically stores the state of the entire system and all the raw diagnostic data for subsequent analysis. Extraction agents make them available outside the facility. These diagnostic data represent the principal scientific output of NIF, so a shot is not considered "complete" until they are safely archived in a secure database. Only then can the control system be reset and all subsystems can be quickly reconfigured to prepare for the next shot.

Careful planning and efficient execution of NIF shots is paramount to achieving a high volume of high quality science results. In this paper, we describe a set of integrated web-based enterprise tools that have been designed and fielded for NIF experiment support—from shot planning through presentation of final analyzed results. These tools, or follow-on designs, are expected to be employed for the projected 30-year experimental lifetime of NIF, during which many thousands of pulsed-laser shots will occur and many peta-bytes of data will be acquired and processed.

SHOT TIMELINE

NIF can fire only one experiment at a time—there is only one target, and a single chamber. For this reason, the control system [3] is designed around a "shot cycle" that executes all setup procedures for countdown to a shot as well as post-shot activities. Figure 1 shows a typical ignition shot timeline using an exponential time scale. The delivered 192-beam laser power has a very well-defined and repeatable pulse shape that is a few tens of nanoseconds in length. Prior and subsequent shots have the same tasks to perform, but their timelines are shifted by several hours. Therefore, many of the timeline activities occur simultaneously for dozens of shots, so coordination and communication among many teams are essential. Complicated campaigns can require months to years of planning for a few microseconds of total shot time, and the results are expected to be available for many years.

For the purposes of this paper, we can breakdown the pre-shot and post-shot tools into the six major categories shown in the figure and described in the following subsections—planning, setup, configure, archive, analyze, and visualize. The control system has been described elsewhere [3,4].

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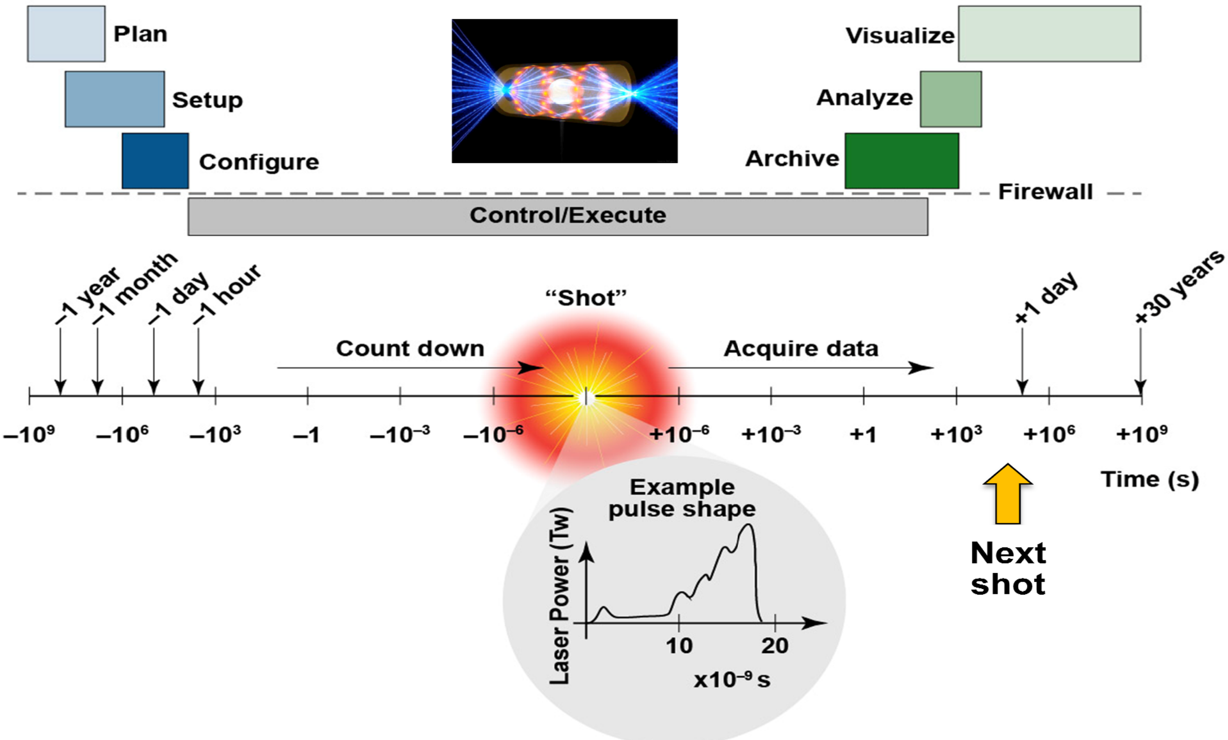

Figure 1: Shown on an exponential timeline, active control and execution of each NIF shot spans a few hours of facility time. To maximize facility usage, NIF must be rapidly reconfigured for the next shot a few hours later. Web-based tools have been developed for planning, setup, configuration, archiving, analysis and visualization of shot data.

Planning Tools

Campaign and shot planning tools provide a high-level view of upcoming experiments and facility schedules, as well as informing production and procurements. Where formerly a large shared spreadsheet was used to manage the complex decisions that dictate when and which shots will be fired, the new Shot Planning and Analysis Tool is now an on-line suite of applications that allow NIF Operations for making informed shot planning decisions based on:

- Shot dependencies, such as laser energy needed, target availability, and diagnostics required,
- Facility availability, for example, around scheduled maintenance periods or installation of new equipment,
- Predicted demand on optics, which have an expected lifetime based on cumulative laser fluence they experience, and
- Potential radiological hazards and delays caused by exposure of the facility to fusion by-products (gammas, neutrons).

Committees of NIF stakeholders use these decision support tools to evaluate the proposed shot plans, approve them and communicate that plan to the NIF community. Off-site warehouses and factories that supply the needed equipment receive advanced notice of what is needed and when. These tools help ensure that the necessary targets and diagnostics are available when needed.

The tools also enable the optimization of expensive optical consumables (lenses, mirrors, wavelength conversion crystals, etc.). NIF has an extensive optics inspection, repair and recycling program that detects and tracks micron-sized laser-induced damage sites on optics well before they can grow to impact laser performance. A rules engine is employed to predict when an optic will need replacement based on the laser energies of upcoming shots. On a single beam line, operators can intentionally block a few percent of the cross-sectional pre-amplified beam area to protect those sites, or the optic can be exchanged. In this way, the planning tools help minimize the cost of experiments by maximizing the life cycle of the optics.

Setup Tools

Once a shot or campaign is scheduled into the planning tools, a Campaign Management Tool suite (CMT) allows the experiment principle investigator (PI) to define all the necessary setup parameters for the control system to conduct the shot. This suite consists of fourteen integrated software applications that manage the preparation, validation, review, approval and configuration readiness for NIF experiments. The CMT suite manages all shot details (laser, target, diagnostics, facility), enforces the operating envelope of the laser to ensure facility safety, and provides shot setup reports and installation orders. It compares the requested facility setup to the current actual NIF configuration and notifies the PI of changes needed.

Over 15,000 setup items and over 100,000 serialized parts are monitored and controlled. The primary output of CMT is the full set of controls documentation with detailed experiment definitions to successfully perform a shot. If the entire setup documentation were to be printed as a report, it would be well over 200 pages for each shot.

Configuration Tools

When an approved shot is ready to be performed, an integrated configuration and work control suite of tools helps the on-site team ensure that NIF is ready to execute it. The tools support shot operations and data analysis by helping to enforce policies and procedures while providing a data repository to characterize the facility configuration over time. Web-based integrated applications serve to define, build, operate, maintain, and configuration-manage all components and assemblies in NIF. A transactional database monitors all installation and removal orders, while a content management database called the Location, Component and State tracking system (LoCoS) maintains the historical record of the millions of parts installed in NIF at any time.

Calibration information is also maintained in LoCoS for parts that are important to the data analysis (filters, attenuators, detectors, cameras, oscilloscopes, etc.). Re-calibration and maintenance plans are included in scheduling software. As parts are exposed to laser fluence or neutron radiation, operations personnel are notified to plan for replacement or retrofit. Work orders for part installation and removal can be automatically generated.

A NIF "Seating Chart" shows the current state of the laser, target and diagnostics on a web page that allows drill-down to every installed part and its component drawings. All drawings are under strict document control. The Shot Director will not initiate the shot cycle control system without a "green light" from the configuration tools indicating that state of the facility matches the setup request.

NIF Shot Archive

Immediately after the shot, any data potentially used in the analysis of scientific results are collected and stored in the NIF Shot Archive. This archive includes raw data and metadata, shot configuration, device calibrations and analysis parameters. In addition, the archive is also the permanent repository for experimental results produced by shots. It is meant to be the authoritative, consolidated resource for studying science at NIF. [5]

Requirements for this archive are that the data and automated results must be web-visible within a few minutes post-shot, reviewable by the scientific team for release, downloadable to authorized personnel, and secure for 30 years.

Archived data are stored in a relational Oracle Real Application Cluster (RAC) database with a software interface layer written on top of a content management framework that performs transparent object-relational mapping. This data architecture provides a powerful and flexible way that data is accessed and presented using a combination for object-relational queries or standard relational queries using SQL. Arrays of data such as waveforms and images are stored in a common Hierarchical Data Format (HDF), and are downloadable in other formats.

One key aspect to the archival of scientific data is to maintain data "pedigree" or traceability throughout all processing steps. The archive was designed to carefully maintain and validate the chain-of-custody that starts with raw data through each step of the analysis including the routines used. Pedigree is a form of metadata and is archived whenever data is refined at each step of analysis.

Analysis Tools

The Shot Analysis and Visualization (SAVI) System is an integrated set of tools for the analysis, validation and approval of science results from NIF shots. An analysis framework initiates messages to a workflow engine that launches a predefined set of analysis steps based on diagnostic type [6]. The analysis is initiated by the data as it arrives, and is performed by a highly-parallel distributed set of software components on a Linux cluster. Robust signal processing analysis tools, under version control, are customized to accommodate unique properties the each diagnostic signal or image. Results are placed back in the Shot Archive with new pedigree.

Not all analysis steps can be automated into SAVI for all diagnostics. Some, like film or trace-gas sampling, require off-line processing. Other types of new or more exotic high-speed digital systems may require specialized non-routine processing that necessitates user interaction. Also, "what-if" analysis scenarios that involve analyzing data with new, minimally-tested algorithms do not fit into the automation paradigm. In any of these cases, an alternative desktop analysis interface has been developed. Analysts can download relevant input data and pedigree, compute results using a desktop analysis code, and finally upload the results to the archive with annotations regarding their source. When both automated and desktop results appear for a particular experiment, the SAVI system provides tools to select the "authorized" results.

SAVI uses the archive to proactively validate the pedigree chain of all results in near real-time. Many different scenarios can result in a "bad" pedigree chain. For example, an improved or corrected calibration can be applied retroactively, a configuration error (e.g., wrong serial number) may have been recorded at the time of the shot, or a prior calculation step may have been re-executed whereas the final result relied on the earlier version. Any change to the quality of data inputs impact the entire pedigree chain from that point forward. Within seconds of these occurrences, the archive flags the appropriate chain of data as having bad pedigree quality, and that flag is displayed through the visualization tools. If desired, the user can then reprocess the analysis workflow with the most up-to-date inputs. Any new results created this way are stored as new versions; i.e., prior results are not overwritten.

Visualization Tools

Visualization of experimental data and results must provide a "quick look" summary of results, cross-shot analysis and trending, and collaboration tools for scientists. The web-based Archive Viewer employs rapid queries and displays to access the data in numerous ways. Additionally, collections of data can be viewed in tabular or grid formats. Hierarchical data can be traversed via hyperlinks along data relationships including between dependent results using pedigree. Scientists may download data and perform off-line desktop analysis. The application also provides an upload feature where scientists can archive desktop results to become part of the official shot record.

In 2010, the Viewer has been enhanced to include rapidly-deployable web "widgets" onto summary dashboards. Example dashboards are shown in Figures 2 and 3. Each widget loads in a separate browser thread using calls to data services hosted by visualization servers for responsive displays. Widgets in the dashboard act as windows that can be dragged, minimized, or maximized. Each widget hosts a menu of options such as data export features or actions that can performed on the data. Many of the dashboard widgets include powerful interactive data plots. Using this technique, any combination of data from the archive can be very quickly assembled into a dashboard. This method provides a current view of the data not possible with off-line tools.

The dashboard provides a collaborative environment for scientific working groups focusing on various areas of physics. Scientists view their results live (often via videoconference) from various perspective, compare results across many shots or campaigns, contrast them with simulated expectations, and select "authorized" values to be published externally.

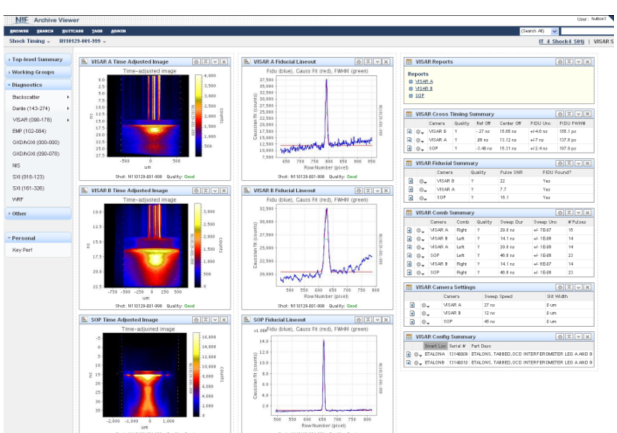

Figure 2: An example of dashboard page providing a single-shot perspective of the VISAR diagnostic.

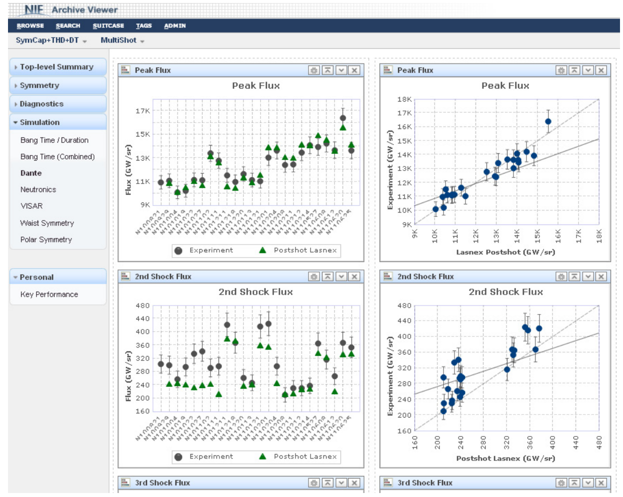

Figure 3: An example of a multi-shot dashboard containing simulation vs. experimental data. Interactive plots allow each data series to be toggled on or off.

SUMMARY

Since the start of NIF shot operations in 2009, many hundreds of shots per year have been successfully fired. To optimize the usage of precious target chamber time, shot-based operations need flexible, high-performance tools to plan and analyze experiments. We now have over 40 integrated collaborative tools that routinely support dynamic, data-driven, high-quality shots on NIF. They also provide secure and transparent access to data, analysis and results. Shots are now being planned by many international partners, who are using these tools, for 2015 and beyond. Our future goals, as NIF transitions into a user facility in 2013, include improving the efficiency and availability of the facility. We plan to use the latest application support software to enhance the intuitive user experience, as well as to include mobile applications.

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