ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

STATUS OF THE NATIONAL IGNITION FACILITY (NIF) INTEGRATED COMPUTER CONTROL AND INFORMATION SYSTEMS

G. Brunton, A. Barnes, J. Castro-Morales, M. Christensen, J. Dixon, M. Fedorov, M. Flegel, R. Lacuata, D. Larson, A.P. Ludwigsen, D. Mathisen, V. Miller-Kamm, M. Paul, S. Townsend, S. Weaver, R. Wilson, B. Van Wonterghem
Lawrence Livermore National Laboratory, Livermore, USA

Abstract

The National Ignition Facility (NIF) is the world's most energetic laser experimental facility with 192 beams capable of delivering 2.1 megajoules of 500-terawatt ultraviolet laser light to a target. NIF experiments facilitate the study of extreme physical conditions at temperatures exceeding 100 million K and 100 billion times atmospheric pressure allowing scientists the ability to generate conditions similar to the center of the sun and explore the physics of planetary interiors, supernovae and thermonuclear burn. This year concludes a series of optimizations and enhancements to the control & information systems to sustain the quantity of experimental target shots while developing an enhanced precision diagnostic system to optimize and increase the power and energy capabilities of the facility. In addition, many new system control and diagnostic capabilities have been commissioned to increase the understanding of target performance. This year also concludes a multi-year sustainability project to migrate the control system software to Java. This talk will report on the current status of each of these areas in support of the wide variety of experiments being conducted.

INTRODUCTION

The National Ignition Facility (NIF) [1] provides a scientific center for the study of inertial confinement fusion (ICF) and matter at extreme energy densities and pressures [2]. Each NIF experiment, or shot cycle, is managed by the Integrated Computer Control System (ICCS) [3], which uses a scalable software architecture running code on more than 2300 front end processors, embedded controllers and supervisory servers. The NIF control system operates laser and industrial controls hardware interfacing with 66,000 control points (e.g. motors, calorimeters, sensors, etc) to ensure that all NIF's 192 laser pulses arrive at a target within 30 picoseconds of each other, are aligned to a pointing accuracy of less than 50 microns, and orchestrate a host of diagnostic equipment collecting experimental data in a few billionths of a second. Every NIF automated shot cycle [4] consists of approximately 2 million sequenced operations, such as beam path alignment, pulse shaping, and diagnostic configuration and each shot is typically conducted within 4-8 hours depending on the experiment complexity.

NIF has been a 24x7 operational facility since 2009 and has supported scientific advancement in various fields of physical studies such as High Energy Density (HED) experiments for Stockpile Stewardship, Inertial Confinement Fusion (ICF), National Security Applications and Discovery Science. The facility and control systems advancement has continued since becoming operational and many significant changes have occurred to increase its capabilities and efficiency since last reporting [5]. A summarization of the most recent enhancements is detailed in the following paper.

CONTROL SYSTEM STATUS

NIF Shot Rate Sustainment

As the NIF celebrates its 10th year of full-scale operations controls priorities continue to be sustaining a high system availability for maximizing the conduct of experimentation for all associated fields of research. With the deployment of new diagnostic capabilities, we continue to further advance our scientific capabilities and understanding however increased focus has been placed on modernizing the laser, controls and infrastructure to sustain many more years of valuable operation (Fig. 1).

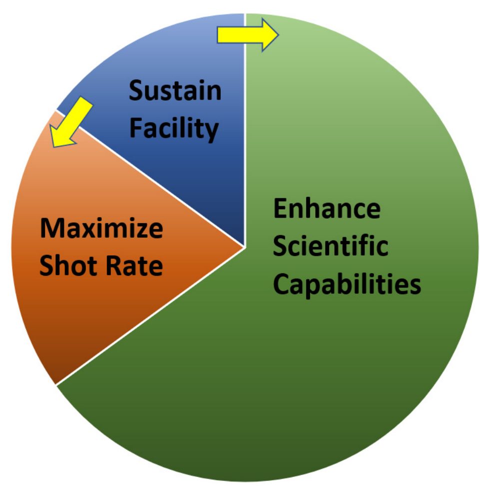

Figure 1: Balance of NIF primary priorities shifting to reduce risk to long term facility sustainment.

Although previous optimizations [6] identified major opportunities to improve the shot rate on NIF, the focus on efficiency has required to be continuous in order to offset the operational cost of increasingly complex capabilities and experimental configurations that are added annually (Fig. 2). Experimental configurations, such as the Advanced Radiographic Capability (ARC) [7] Petawatt laser is used with far greater frequency and these shot cycle configuration takes significantly longer than other target experiments (~12 hours per shot). Additionally, with greater

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

target diagnostic capabilities the number of diagnostic positioner reconfigurations required has steadily been increasing over the past several years which adds to the setup duration required between each shot cycle. Although the recent optimizations are not as dramatic as the initial focused efforts, they have a significant impact in offsetting the experimental complexity increases.

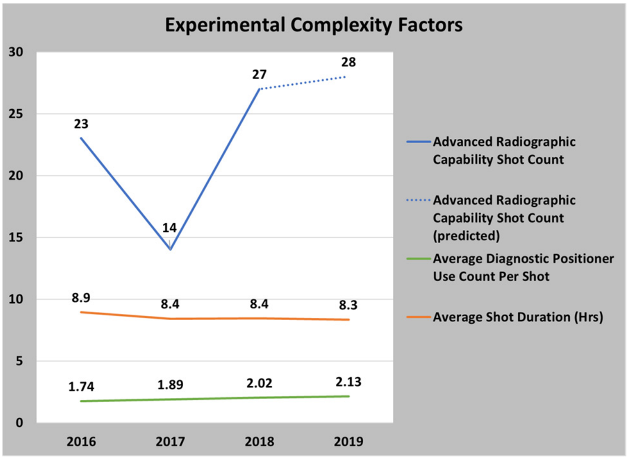

Figure 2: Shot cycle average complexity factor increase examples.

Two recent examples of these optimizations were identified as a result of our continued focus on metrics collection, analysis and visualizations [8]. The first optimization was an anomalous data pattern (Fig. 3) observed during movement of a specific laser shutter throughout each shot cycle. Although no operational problems had been identified it was determined that one specific shutter location was frequently taking longer to move to one limit switch than other locations. This shutter is moved many times during each shot cycle and the impact of this badly performing instance was evaluated at greater than 45 minutes of lost critical path time during the average week. The root cause was an unoptimized overdrive configuration and was being masked due to an automated software 'fail and retry' behavior.

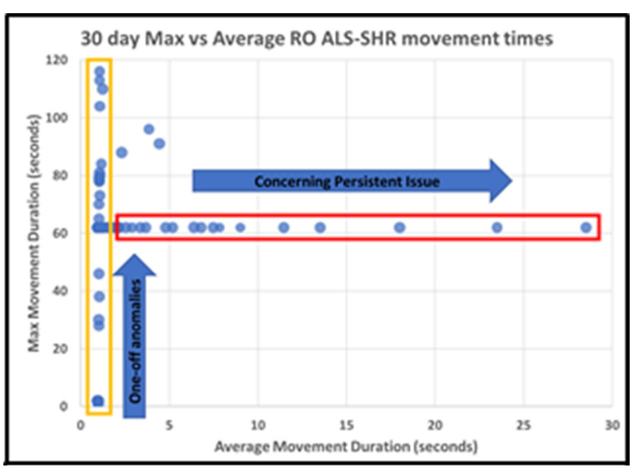

Figure 3: Anomalous maximum versus average motor movement duration patterns.

The second optimization was to the extensive number of database operations performed throughout each shot cycle. Each shot cycle was analyzed to consume approximately 22 minutes of critical path database calculation time which appeared excessive. Analysis of the PL-SQL data operations identified that due to the repetitive nature of the operations (i.e. separate queries were being executed for each NIF beamline) the query implementation would be more efficient with the use of bind variables to optimize the Oracle server execution plan construction. Several new table indexes were also added to further refine the performance. After deployment the performance was evaluated to have an average shot cycle time reduction of 88% (or ~19 minutes per shot cycle).

Neither of these optimizations were particularly complex or costly to analyze nor implement but are clear examples that focusing analysis on small repetitive system actions can have significant payback. Many of the data analyses implemented during the past several years have now laid the foundations for continued application in a predictive manner using machine learning which is a growing area of research to further improve operational efficiency and availability.

With the continuous full-scale facility use now spanning several years, weaknesses in auxiliary support facility operations and processes rapidly came to light. The first was in the optic supply chain for NIF. Due to the high power and energy levels that NIF operates at a comprehensive optics management process is required to inspect, repair and replace the thousands of optics involved in routine operations. With the continuous NIF use these facilities began to struggle to sustain the optic throughput demand required. Various process and software optimizations were evaluated throughout all phases of the optic loop and it was identified that significant efficiency gains could made through application of machine learning strategies in the areas of initial inspection defect classification [9] and optic defect mitigation qualifications (Fig. 4) [10].

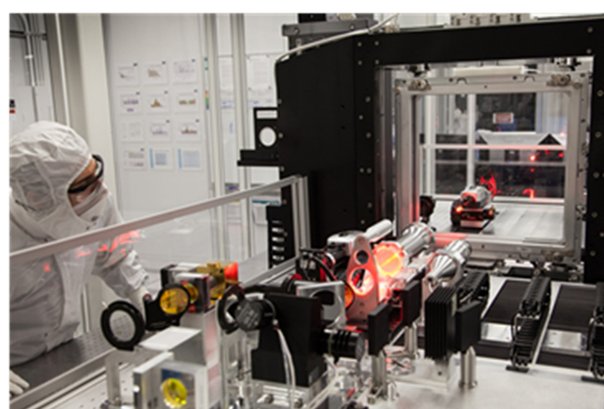

Figure 4: Automated optics processing station.

With these optimizations in place the optic facilities have now not only kept up with the demands of NIF experimentation, they have also significantly reduced the operational

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

oversight required in these areas due to many parts of the process improvements being largely autonomous.

As NIF operates, 24x7 experiments are conducted at all times of day and night. Throughout the shot cycle there are often several critical junctures that require the approval from an experimenter to proceed. Delays can often arise due to unavailability of the key personnel or inefficient methods of provisioning the necessary evaluation data required in obtaining approvals. In assessment of these potential issues it was identified that if a remote viewing mechanism was implemented this would significantly reduce the probability of incurring these delays. With the assistance of the IT team, using low cost COTS products (AV.io video media converter [11] and Net Support and WebEx technologies), a guaranteed read-only data link was implemented to facilitate remote viewing of any operational console at the request of a user (Fig. 5). The implementation provided secondary benefits to other groups such as control system and alignment support personnel to gain greater insights into operational issues through direct visualization of issues.

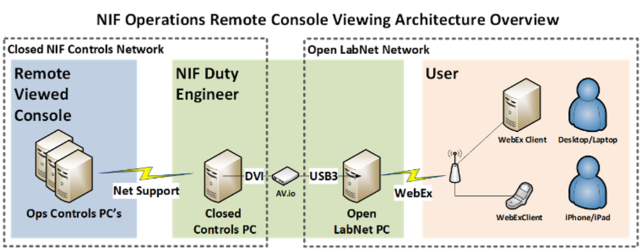

Figure 5: Secure operational remote on-demand viewing architecture.

With all optimizations implemented and shot rates tallied (Fig. 6) the results continue to show not only that NIF continues to maintain a high shot rate but that the continuous focus on optimizations have been required in order to do so. As of September 2019, the facility is also on track for maintaining approximately 400 target shots (estimated 391). Optimizations will remain a constant priority and in doing so we believe that the capacity to conduct a level annual target shot rate is sustainable.

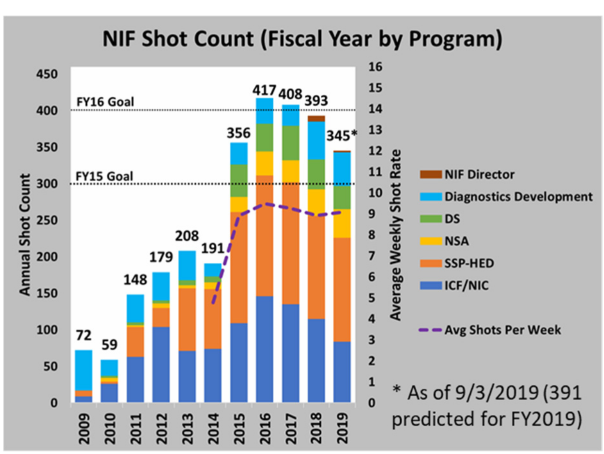

Figure 6: NIF target shot count and rates by major program.

Refreshing Laser Precision Diagnostic System

During the original NIF design phase a comprehensive laser diagnostic suite (approximately 350 active control points), the Precision Diagnostic System (PDS), was constructed to evaluate both the overall laser performance and to provide a testbed to qualify the design of the Integrated Optics Module (IOM) which is the final beamline optical package responsible for conversion of the laser wavelength from 1w (1053nm) to 3w (351nm) and focusing each beam on to the target. Once the NIF had been constructed, over ten years ago, the PDS was abandoned in place. In the past year there has been renewed interest in increasing the overall power and energy level and accuracy of the NIF. To facilitate this ongoing research the PDS system is being recommissioned (Fig. 7) and enhanced to increase understanding of laser and optical effects that limit the deliverable power and energy. Given the technology advancements made since the system was last used this has also been the ideal time to upgrade the diagnostic capabilities of PDS.

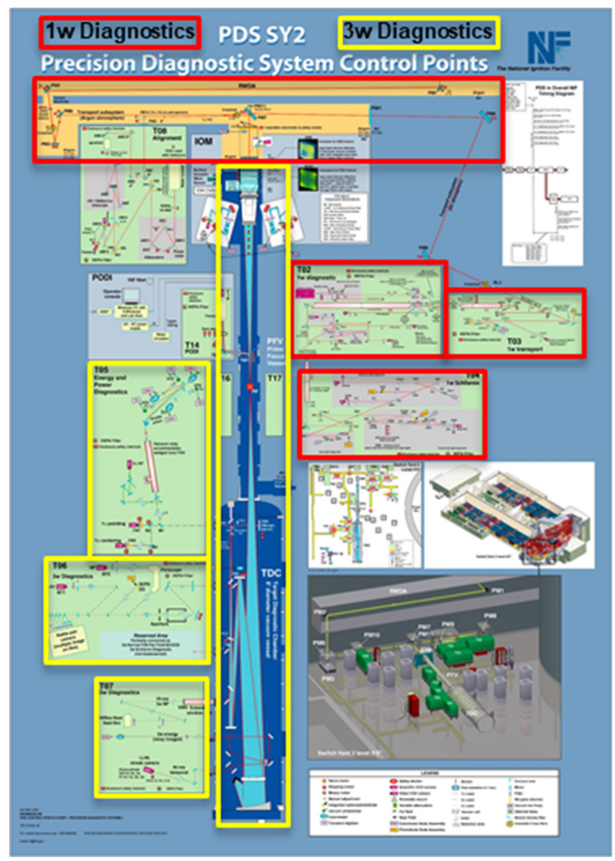

Figure 7: The control points overview summary for the NIF Precision Diagnostic System (PDS).

The PDS operates by diverting a NIF beam into two distinct diagnostic areas; one for diagnosing overall 1w laser performance and the other, after frequency conversion to 3w, to evaluate the frequency conversion design and performance of the IOM. The design enhancement also upgraded the ability to choose 1 of 4 NIF beams to redirect to the PDS (previously only a single fixed beam could be diverted).

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

As of the end of FY19 NIF has successfully commissioned the new 4-beam selection mechanism in addition to completing 1w diagnostic suite upgrade. Most of the imaging diagnostics (near-field, far-field, radial shear, spectrum) have been upgraded to higher resolution Spectral Instruments SI-1000 variants, and the power diagnostic oscilloscopes have been replaced with high resolution Tektronix DPO variants. In addition to upgrading the existing equipment new time-resolved diagnostics have been added which provides significant new insight into the laser performance at variable time slices along the temporal pulse shape. The final enhancement is that all controls, except the time-resolved diagnostics, have been fully integrated with the shot automation layer to ensure PDS experimentation is performed in an efficient manner and to minimize impact to the target experimentation schedules.

Deployment and commissioning of the 3w diagnostic suite upgrades is expected to commence later this year with commissioning expected to complete early next year.

Increasing Target Performance with Improved Diagnostic Capabilities

A primary research area for the National Ignition Facility is the study of Inertial Confinement Fusion (ICF) [12], a key mission of the facility. Many of the target diagnostic capability enhancements added to NIF directly support improved understanding of the physical effects that occur during the few billionths of a second window in which a shot occurs. Most diagnostics capture data in two-dimensions whereas the physical experiment effects are in three dimensions. This can lead to a reduction in understanding of the overall characterization and symmetry of the target fuel assembly. In recent years many of the NIF diagnostic enhancements aim to fill this gap and have added multiple axes of data capture. The most recent example was commenced this year for the Neutron Imaging System (NIS) which captures imagery of the neutron symmetry and distribution. This year a third NIS diagnostic has been added on the 90-213 target chamber axis and has already provided improved understanding (Fig. 8) of the neutron emission symmetry and is helping to guide improved configurations for subsequent experiments.

In the coming year this new diagnostic will be further enhanced with the addition of a comprehensive active diagnostic system which will add primary and down-scattered neutron and gamma imaging.

Another area of ICF research being explored on NIF is the effect of plasma build-up inside each hohlraum at shot time. It is our understanding that this effect impacts the uniformity of beam energy deposition inside the hohlraum which in-turn impacts the symmetry of the implosion. Until recently no direct diagnostic measurement capabilities have been able to increase our understanding of this effect. Last year NIF embarked upon a project to resolve this gap and designed and deployed a new Optical Thomson Scattering (OTS) laser and diagnostic. This large-scale engineering and controls project required a new beamline added to NIF. The laser differs from an existing NIF beamline in that there is an additional frequency conversion to 5w (210nm) UV wavelength. This beam is used as a probe beam into the hohlraum at shot time and the plasma effect can them be measured via the beam reflection to a positioner mounted diagnostic. The 5w wavelength is used to distinguish the diagnostic signal from the other wavelengths that already exist in the NIF target chamber at shot time. The OTS system (Fig. 9) is currently deployed and going through final system commissioning and is expected to be scientifically operational early in the next year.

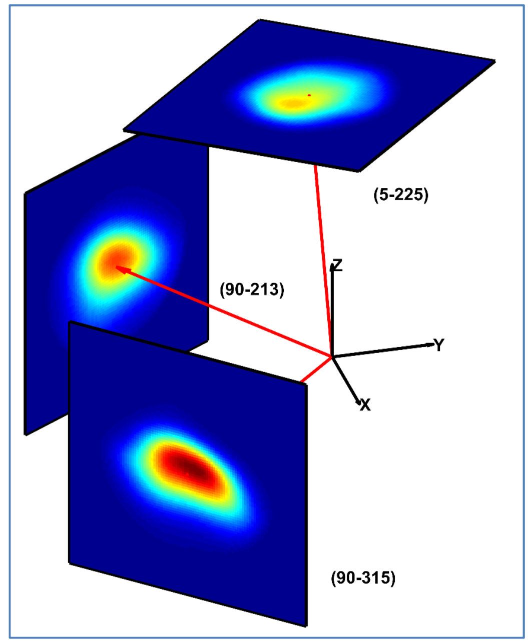

Figure 8: The third (90-213) axis of neutron imaging provides improved 3-dimensional understanding of neutron symmetry.

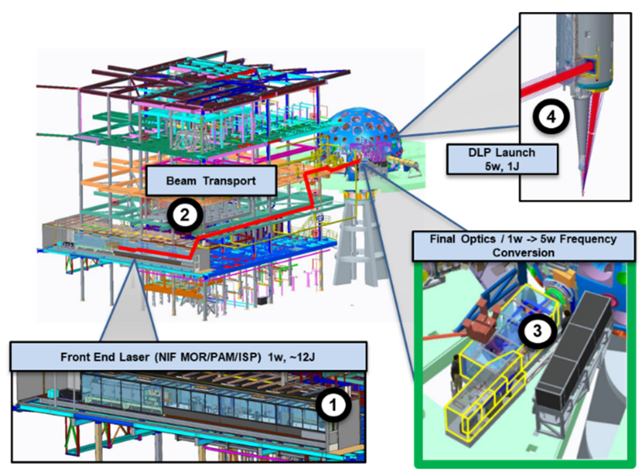

Figure 9: The Optical Thomson Scattering (OTS) diagnostic system component overview.

Multi-Year Control System Refresh Conclusion

As NIF expects to continue to provide an expanding scientific research platform for the next 20 years, sustainment of the control's software, hardware and development processes is of the utmost importance. The NIF controls architecture and infrastructure [13] was designed with this inevitable technology evolution in mind.

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

This year concludes a successful multi-year effort to migrate the 3.5 million lines of control system software from Ada95 to Java [14]. By requiring the CORBA control interfaces of each software component to remain unchanged with each migration, in conjunction with development of comprehensive unit and integration test suites to qualify old and new behaviors, the deployment and commissioning has been highly successful. In addition to maximizing the potential for successful conversion each new qualification suite provides the sustaining benefits of a) documenting the expected component behavior b) providing an efficient and extensive requalification platform on which to evaluate future modifications by existing and new staff.

All software has now been converted (Fig. 10) and the remaining few facility conversions and qualifications are expected to complete this year (Fig. 11).

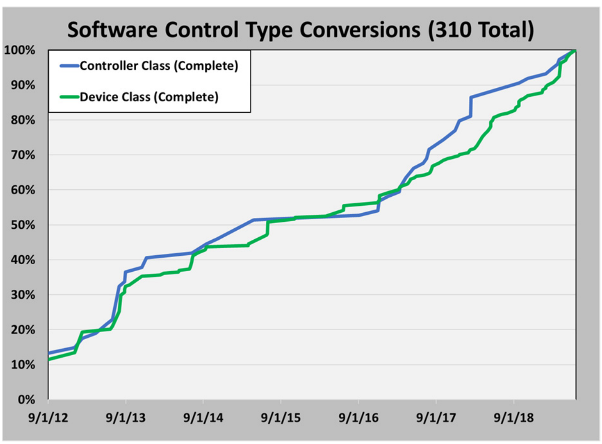

Figure 10: ICCS control component software conversion timeline.

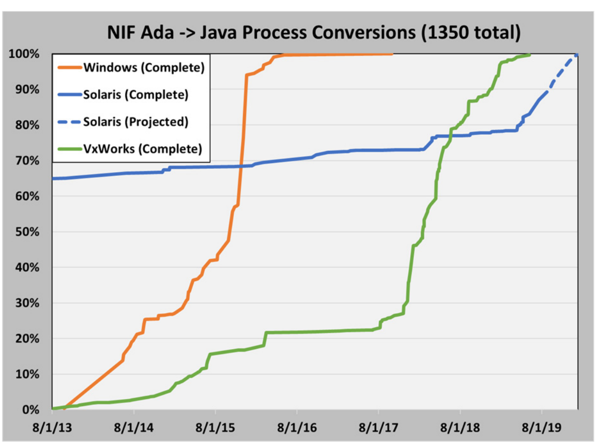

Figure 11: ICCS software process conversion timeline and status.

With completion of all the control system software to a modern sustainable programming language, focus now shifts to the next areas of control system sustainability risk with modernization of our embedded controller platforms and elimination of the majority of Windows XP operating systems for video processors.

Future Work

Looking forward, the NIF controls will continue to support the pursuit of ignition in addition to ensuring we have a sustainable platform for many future years of operation. Symmetry of ICF experiment results is of the utmost importance and the current methods of suspending targets in their hohlraum is known to have impacts. Advancements are currently underway to reduce the impact of target engineering features, one of which is a new tetra-cage wire support system (Fig. 12). This system supports the target over a significantly reduced surface area versus the current hammock-like design. Due to fragility of this support system a machine safety 'light curtain' monitoring system is required to ensure the target remains positioned in place throughout the entire shot. The failsafe detection system detects displacement of target capsule if the energy sensor measures energy from the light source on the opposite side the target.

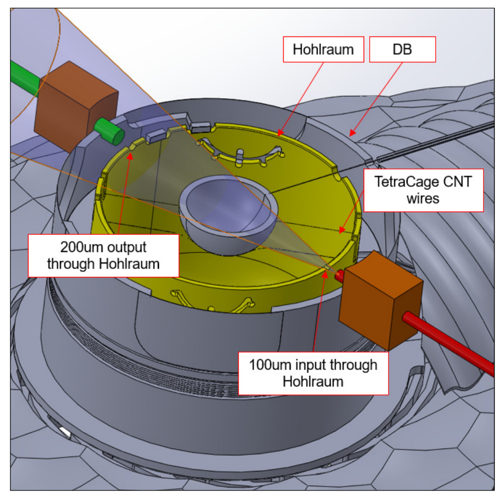

Figure 12: Light curtain monitoring system for tetra-cage target wire support system design.

Alternative strategies are also presently being researched to provide a boost to the ICF process (Fig. 13). Generating a magnetic field around the target is expected to improve the confinement of fusion alpha particles at shot time and increase the yield from ICF targets. In the past year target platforms with magnetic field generating coils have been tested with non-ICF targets yielding positive results. The platforms are being extended in the coming year to warm hohlraum targets and subsequently to ICF layered cryogenic target designs.

With the control system migration from Ada to Java now complete focus shifts to the next priorities in long term system sustainment. In the next two years the controls for all the video imaging systems (~500) will be migrated from the current Windows XP operating system configuration to a diskless Linux configuration. The goal of this migration is to improve the configuration management reliability and efficiency of these computer types and improve longer term compatibility with commodity hardware platforms. The next year will also commence the first phase of the NIF's industrial and machine and personnel safety control

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP04

servers from Rockwell RSView32 to a modern FactoryTalk platform, the largest challenge in this upgrade being the phased deployment and requalification while minimizing facility downtime.

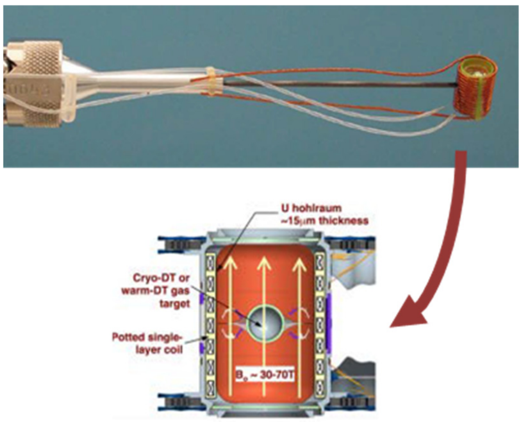

Figure 13: Extending magnetized targets to hohlraums for improved confinement of fusion alpha particles.

CONCLUSION

The NIF control system is critical for the effective and efficient continued advancement of various physical areas of study supported by the National Ignition Facility. Controls efficiency improvements continue to be required to sustain a constant NIF shot rate and offset the additional operational cost of operating new scientific operational capabilities. Many new laser and target diagnostic capabilities have been deployed and commissioned for operational use with an increased focus on supporting a power energy increase on the NIF and advancing to the goal of fusion ignition. A successfully major NIF control software modernization completes this year resulting in improved sustainability of the system. Focus is now shifting to other aging controls such as embedded controllers and imaging infrastructure and operating systems.

ACKNOWLEDGMENT

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-791805

REFERENCES

[1] E. I. Moses, "Overview of the National Ignition Facility", *Fusion Sci. Technol.*, vol. 54, no. 2, pp. 361-366, 2008. doi:10.13182/FST08-A1831

[2] J. D. Lindl *et al.*, "The US ICF Ignition Program and the Inertial Fusion Energy Program", in *Proc. 30th EPS Conference on Controlled Fusion and Plasma Physics*, St. Petersburg, Russia, Jul. 2003. Lawrence Livermore National Lab., CA, USA, Rep. UCRL-JC--152987.

[3] P. J. Van Arsdall *et al.*, "National Ignition Facility integrated computer control system", in *Proc.Third Annual International Conference on Solid State Lasers for Application (SSLA) to Inertial Confinement Fusion (ICF),* Monterey, CA, USA.,1998, pp. 538-548. doi:10.1117/12.354167

[4] L. Lagin *et al.*, "Shot automation for the National Ignition Facility", in *Proc. 10th Int. Conf. on Accelerator and Large Experimental Control Systems (ICALEPCS'05)*, Geneva, Switzerland, Oct. 2005, paper I2_002.

[5] G. Brunton *et al.*, "Status of the National Ignition Facility (NIF) integrated computer control and information systems", in *Proc. 16th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'17)*, Barcelona, Spain, Oct. 2017, pp. 14-18. doi:10.18429/JACoW-ICALEPCS2017-MOAPL03

[6] G. Brunton *et al.*, "Shot rate improvement strive for the National Ignition Facility (NIF)", in *Proc. 15th Int. Conf. on Accelerator and Large Experimental Control Systems (ICALEPCS'15)*, Melbourne, Australia, Oct. 2015, pp. 56-59. doi:10.18429/JACoW-ICALEPCS2015-MOD3003

[7] G. Brunton *et al.*, "The Advanced Radiographic Capability, a major upgrade of the computer controls for the National Ignition Facility", in *Proc. 14th Int. Conf. on Accelerator and Large Experimental Control Systems (ICALEPCS'13)*, San Francisco, CA, USA, Oct. 2013, paper MOCOBAB04, pp. 39-42.

[8] M. A. Federov *et al.*, "Leveraging Splunk for control system monitoring and management", in *Proc. 16th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'17)*, Barcelona, Spain, Oct. 2017, pp. 253-257. doi:10.18429/JACoW-ICALEPCS2017-TUCPA02

[9] L. M. Kegelmeyer, "Evolution of machine learning for NIF optics inspection", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), Brooklyn, NY, USA, Oct. 2019, paper THCPL02, this conference.

[10] S. Trummer *et al.*, "Optimizing the automated control system for repairing optics at the National Ignition Facility", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), Brooklyn, NY, USA, Oct. 2019, paper MOPHA146, this conference.

[11] epiphan video, https://www.epiphan.com/products/avio-hd/

[12] R. Betti and O. A. Hurricane, "Inertial-confinement fusion with lasers", *Nat. Phys.*, vol 12, pp. 435-448, 2016. doi:10.1038/NPHYS3736.

[13] A. Casey *et al.*, "Modernization challenges for the information technology infrastructure at the National Ignition Facility", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), Brooklyn, NY, USA, Oct. 2019, paper WEAPP02, this conference.

[14] M. Fedorov *et al.*, "In-place technology replacement of a 24x7 operational facility: Key lessons learned and success strategies from the NIF control system modernization", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), Brooklyn, NY, USA, Oct. 2019, paper WEDPL01, this conference.