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

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Abstract

The National Ignition Facility (NIF) is the world's most energetic laser system used for Inertial Confinement Fusion (ICF) and High Energy Density Physics (HEDP) experimentation. Each laser shot delivers up to 1.9 MJ of ultraviolet light, driving target temperatures to more than 180 million K and pressures 100 billion times atmospheric, making possible direct study of conditions mimicking interiors of stars and planets, as well as our primary scientific applications: stockpile stewardship and fusion power. NIF control and diagnostic systems allow physicists to precisely manipulate, measure and image this extremely dense and hot matter. A major focus in the past two years has been adding comprehensive new diagnostic instruments to evaluate increasing energy and power of the laser drive. When COVID-19 struck, the controls team leveraged remote access technology to provide efficient operational support without stress of on-site presence. NIF continued to mitigate inevitable technology obsolescence after 20 years since construction. In this talk, we will discuss successes and challenges, including NIF progress towards ignition, achieving record neutron yields in 2021.

INTRODUCTION

The National Ignition Facility is a large (3 football fields) and complex (192 laser beams) experimental physics system (Fig. 1) [1] . It is efficiently operated 24x7 by a shift of the 12-14 Control Room operators with the help of the Integrated Computer Control System (ICCS). Over 66,000 devices with rich APIs are distributed over 2,300 front-end-processors (FEPs) and embedded controllers (ECs).

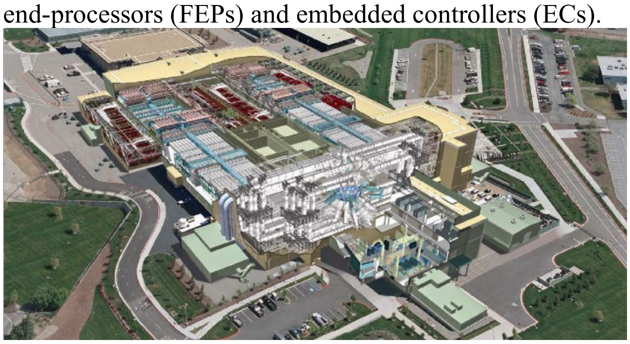

Figure 1: NIF building layout.

NIF experiments are structured around laser shots. Each shot takes 4-8 hours and involves the control system to execute over 2 million device operations.

Experiments at NIF support several programmatic missions, such as Stockpile Stewardship, Discovery Science, National Security Applications, and Inertial Confinement Fusion (ICF). For ICF, thermonuclear ignition has been the long-term goal of the facility, defined as producing more energy from the DT target fusion than the 3w laser energy on the target (for example, 1.9 MJ). The NIF was pursuing the ignition goal for almost 10 years, and it proved to be a scientific and engineering challenge. During 2011-2020, the target energy yield maxed at about 50 kJ, well below the ignition goal.

UNEXPECTED INTERRUPTION

The NIF's quest for ignition and scientific discovery was abruptly interrupted when in March of 2020 a "shelter-in-place" order was issued at our location to quench a spike of COVID-19 infections. Facility shifted to minimal safe operations, shots pauseda, and the Control Room staff reduced from 14 to 3 operators. Controls and IT teams have supported the change, assuring continuity of operations of the networks, hardware and ICCS in a non-shot, monitoring mode.

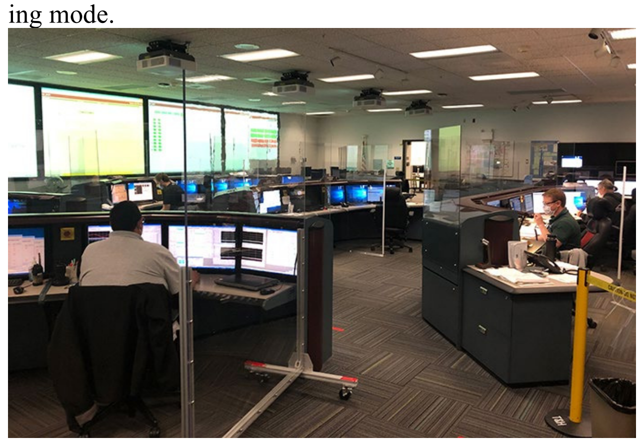

Figure 2: NIF Control with COVID-19 personnel protections: plexiglass screens, masks, traffic barriers.

Soon after the U.S. Center for Disease Control (CDC) recommendations became available, the NIF started to reorganize facility operations. Ventilation flows were adjusted, plexiglass screens between the consoles were installed and personnel traffic was directed with barriers to assure social distancing of at least 7.5ft (Fig. 2,3). Our teams have supported gradual restoration of normal shot operations, by May 2020. Quick restart of experiments was welcomed by the U.S. National Nuclear Security Administration [2,3].

While initially the restarted operations progressed slowly and deliberately, soon the shot rate had ramped up to normal, and control teams had to address the need for support and maintenance activities such as ICCS releases. Traditionally, for major software releases as well as testing and troubleshooting, ICCS software engineers were

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present in the NIF Control Room (Fig. 4). Now, with the Control Room access limited to operator shift only, and most of the software groups and IT teams working remotely from their homes, we had to come up with new processes and tools.

Figure 3: Access to the Control Room is restricted.

Control software engineers, in collaboration with IT, have enthusiastically explored remote access and collaboration tools available on our enterprise networks.

Figure 4: Before COVID-19, ICCS software engineers can often be seen joining operators in the Control Room.

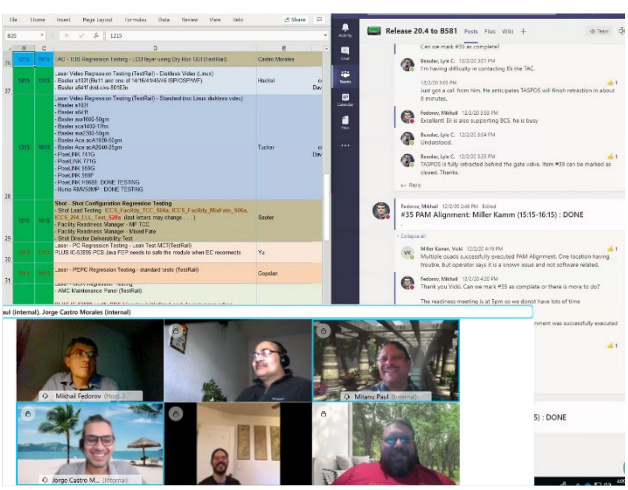

Figure 5: New all-remote software release process.

Our team has settled on Cisco WebEx for remote teleconferencing (similar to Zoom), Microsoft Teams for persistent group chat (similar to Slack) and Microsoft Office 365 for distributed "cloud" collaboration (similar to Google Docs). Both software release coordination and off-hours support have moved to these platforms (Fig. 5) [4].

EXPANDING LASER AND DIAGNOSTICS CONTROLS CAPABILITIES

With COVID-19 concerns addressed and mitigated, the control teams have returned to their primary mission of expanding and maintaining capabilities to the benefit of the NIF programmatic missions.

Target Diagnostics Controls

The NIF is well equipped with target diagnostic instruments to capture laser-target interactions in time and space using various bands of electromagnetic spectrum and particles. Over 87 of the active target diagnostics are controlled by ICCS software control system, combining over 600 rich API devices of 55 types (cameras, oscilloscopes, alignment, etc.).

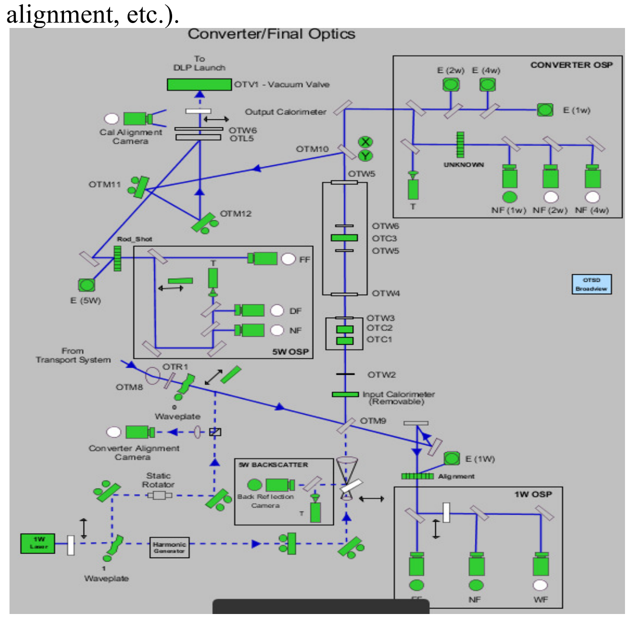

Figure 6: One of user interface panels developed for new Optical Thomson Scattering (OTS) Laser and Diagnostic.

Several new diagnostic instruments, of varying complexity, are being added to ICCS every quarter. One of the most sophisticated, the Optical Thomson Scattering (OTS), combines a high-power 5w deep ultraviolet (UV) 210 nm laser with a set of spectrometers to serve as a "plasma laser probe" (Fig. 6, 7)

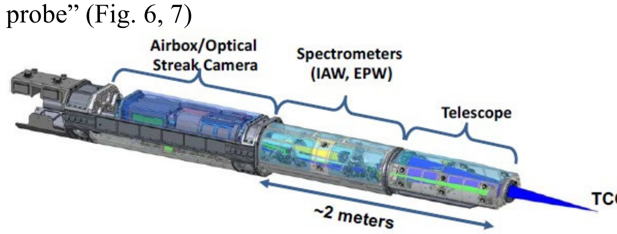

Figure 7: OTS instrument.

The design of the OTS control system and its alignment algorithms are covered by separate presentations at this conference [5,6].

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Laser Diagnostics Controls

While ICCS Target Diagnostics capture a variety of data about behaviors of the targets, it is equally important to precisely characterize the "driver", the 3w laser light which compresses NIF targets. Due to the design of Final Optics Assemblies (FOAs), the conversion of light from infrared 1w to ultraviolet 3w happens right at the vacuum windows where beams enter the target chamber. While a fraction of the converted 3w light is split off and delivered to ICCS diagnostics, it was a long-standing question how precisely these measurements correspond to energy of light on the target.

New Target Chamber Calorimeter (TC-CAL) was designed to obtain the energy measurements by placing a set of NIST-calibrated calorimeters into the target chamber, with a pinhole to separate 3w from unconverted 1w and 2w light (Fig. 8).

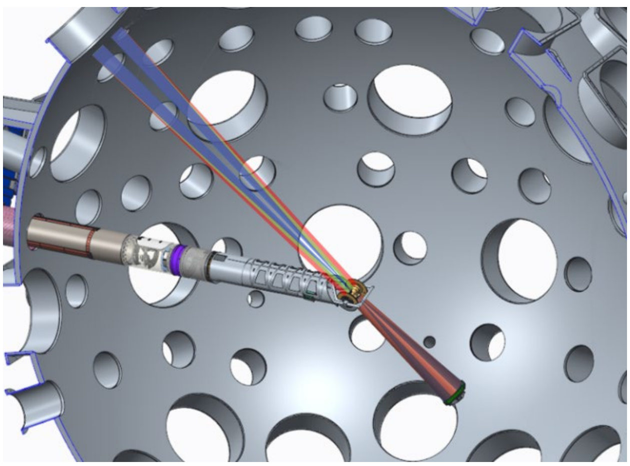

Figure 8: Target Chamber Calorimeter.

TC-CAL is a large (4.5 m+) and heavy (350 kg) mechanical device. ICCS developed a precise motion control and alignment system based on ATLAS [7], achieving excellent alignment of beams on the calorimeters, confirmed by a built-in alignment video camera.

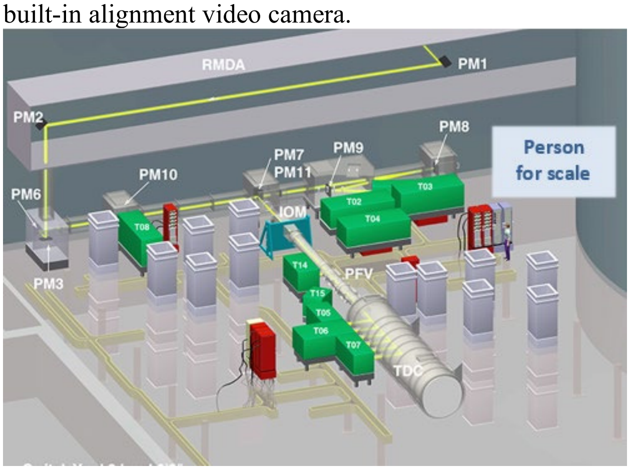

Figure 9: Layout of Precision Diagnostic System.

Another approach to study the 1w light and non-linear process of conversion to 3w is to redirect a full 40 cm x 40 cm NIF laser beam into the specialized lab, Precision Diagnostic System (PDS), (Fig. 9). PDS was recently reactivated, adding over 400 control devices. In addition, a new motorized mirror pickoff was implemented, so a selected beam is automatically routed for a detailed characterization by calorimeters, oscilloscopes, cameras, and spectrometers on multiple 1w and 3w diagnostic tables.

Expanding Laser Master Oscillator Controls

In addition to diagnostics, the laser pulse generation continued to improve as well. In ICCS architecture, the Master Oscillator Room (MOR) subsystem is responsible for the devices which generate the initial fiber laser pulse, and then shape it in time and space. For some experiments, it is desirable to have independent wavelength (or "color") control of NIF laser beam cones. In 2020, we have added a fourth master oscillator, for Outer 50 cones (Fig. 10).

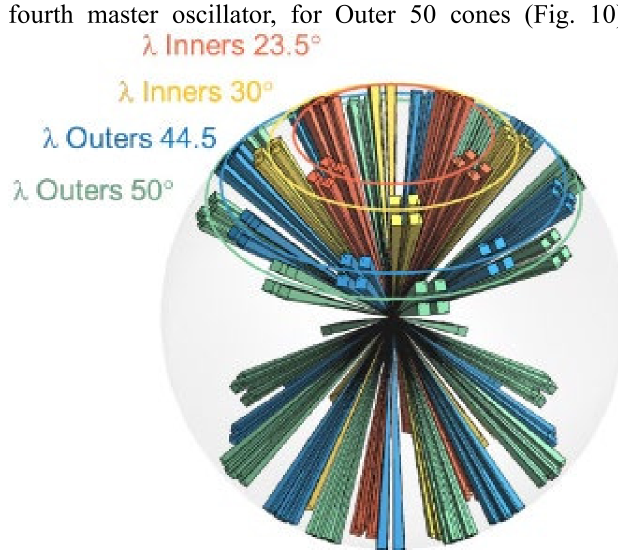

Figure 10: New dedicated laser wavelength "color" was added for Outer 50 cone of laser beams.

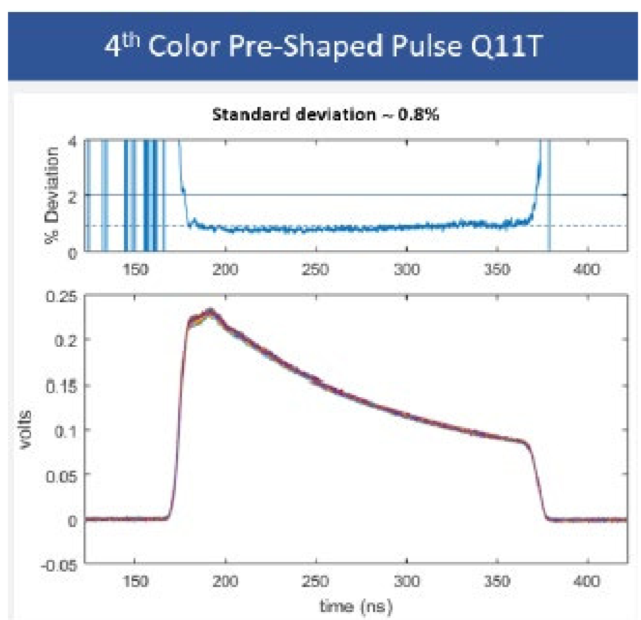

Figure 11: Laser pulse shape stability shot-to-shot improved 3X with the completion of 4th Color project.

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Once the new hardware components and new enhanced design, the Pre-Shaped Pulse Generation (PSPG), were utilized, the effort also resulted in 3X improvement in shot-to-shot stability of the laser pulse shapes (Fig. 11) [8].

The precision of the laser pulses, their reproducibility and energy balance are critical for the quality of scientific data produced by NIF. These efforts will continue, with the next phase of the High-Fidelity Pulse Shaping (HiFiPS) effort starting in 2021-22. The software development work is already underway to develop low-level interfaces for new pulse shaping hardware, to fine-tune new shaping algorithms. The goal is to achieve 4X better short-term pulse shape stability, and better than 0.5% accuracy of actual waveform relative to the requested.

Recent Achievements

The multi-year efforts by NIF, LLNL and the broad scientific community to better understand and control ICF processes continue to pay off. The progress towards the ignition goal was remarkable this year, breaking both 100 kJ and 1 MJ fusion energy barriers.

The most recent record shot on August 8, 2021, produced over 1.3 MJ of fusion energy, putting researchers at the threshold of ignition (Fig. 12) [9].

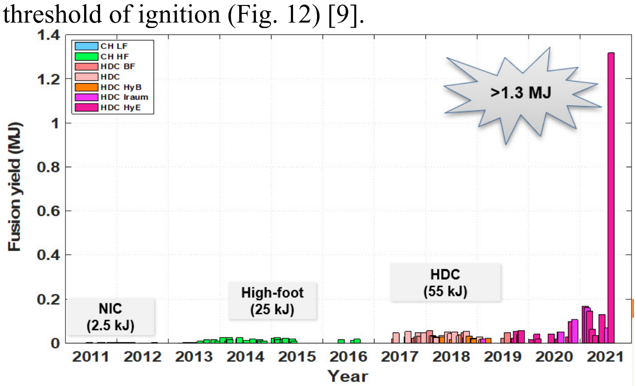

Figure 12: Recent progress toward ignition goal.

LONG-TERM SUSTAINMENT

Multiple priorities are driving control system organizations at large experimental physics facilities: assuring high 24x7 availability, continuous expansion of capabilities, and efficiency optimizations to produce even more high-quality data. And since our facilities represent significant investment of public funds and human capital, we also need to assure that facilities will continue to produce knowledge for the next 10-20 years.

Increasing uptick in failures of aging hardware, and obsolescence of computing platforms call for a broad technology refresh effort. By 2020, NIF ICCS software team has successfully completed a multi-year effort to migrate from legacy Ada 95 codebase to Java, from PowerPC VxWorks and Sun Solaris to Intel Linux – all without stopping 24x7 facility operations [10].

Our focus for 2020-2021 is to migrate hundreds of NIF video acquisition systems from proprietary Windows software to Linux, employing open-source FireWire and GigE drivers, making these systems diskless for high availability, consistency, and cyber security [11].

Looking further, we will be migrating a variety of NIF embedded controllers from aging PC104/VxWorks units to a modern, small factor platform. To support a broader range of R&D laser projects within Photon Sciences, we have proposed and continue to advance a lightweight framework for distributed LabVIEW-based control systems [12].

CONCLUSION

The NIF control systems teams: hardware, IT and software have successfully mitigated the unexpected challenge of COVID-19, adapting to "New Normal" with more health protections, social distancing, and remote work.

Broad and deep 10-year investigation of the most fundamental behaviours of laser, plasma and target interactions has started to pay off, with fusion energy outputs rising, bringing NIF to the threshold of thermonuclear ignition.

Increased neutron yields attach new urgency to already planned sustainability efforts. Some of the video camera systems in the Target Bay will need to be replaced sooner than originally planned: the Target Alignment System (TAS 2.0), Chamber Center Reference (CCRS), Final Optics Inspection (FODI).

NIF entered a new experimental regime of much higher fusion yields, requiring a new generation of time-resolved diagnostics, such as Magnetic Recoil Spectrometer (MRSt).

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