In the Midst of Fusion Ignition: A Look at the State of the National Ignition Facility's Control and Information Systems

19th International Conference on Accelerator & Large Experimental Physics Control Systems (ICALEPCS)

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NIF Integrated Computer Control System (ICCS)

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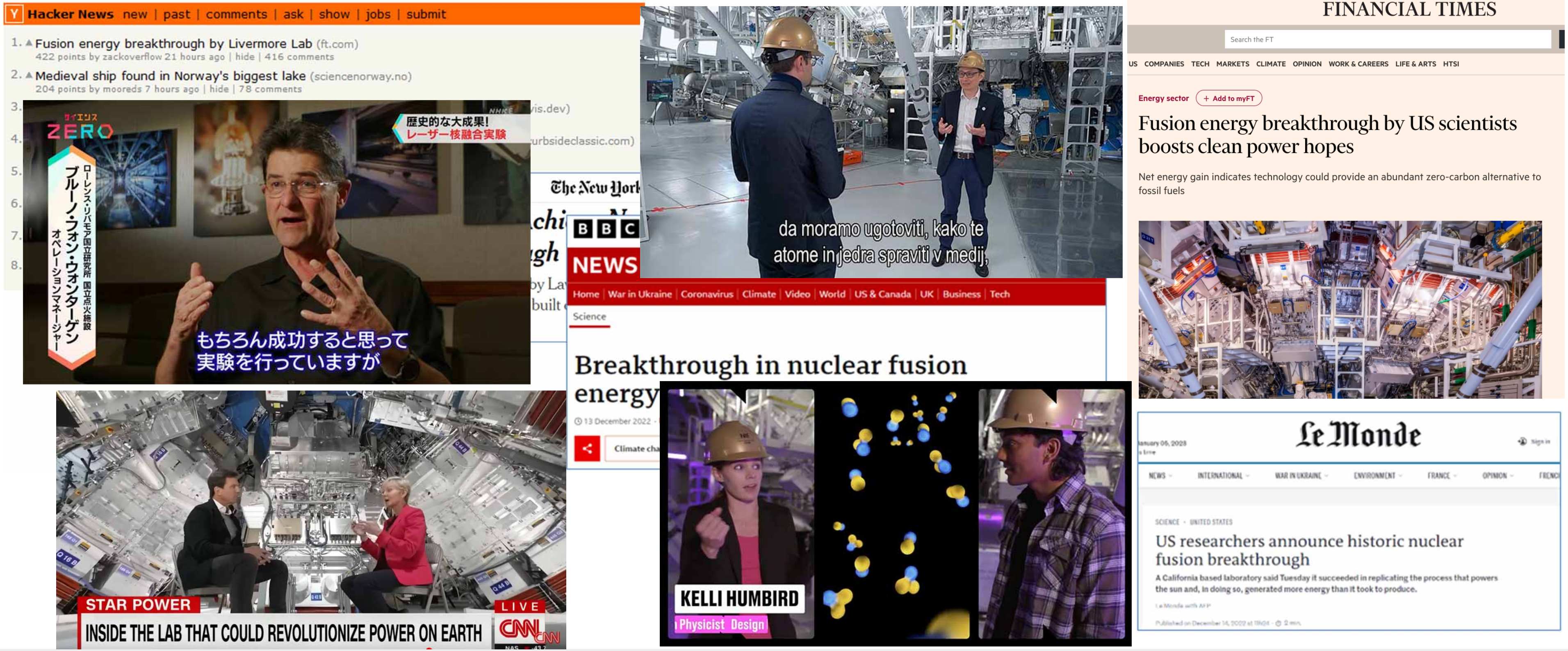
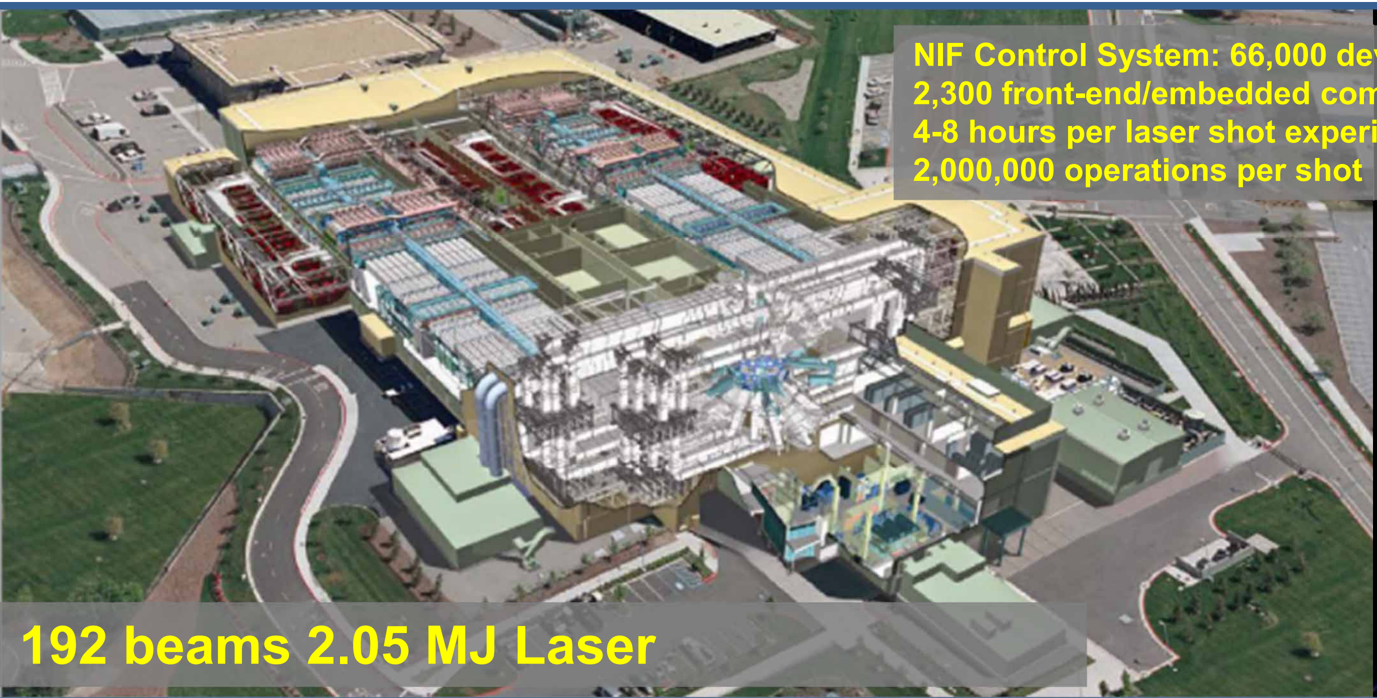
NIF in 2021-2023: Successes, Challenges and Sustainment

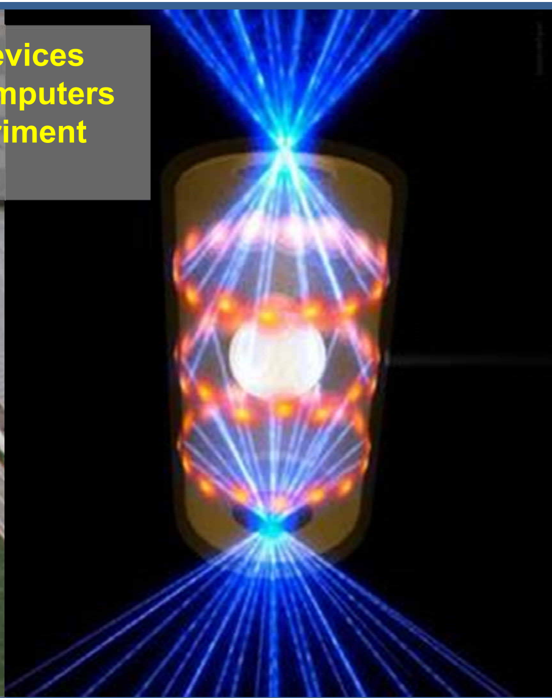
- **Fusion Ignition: on December 5, 2022, a NIF experiment produced 3.15 MJ of fusion energy, more than the laser driver energy of 2.05 MJ**
- **Precise and robust CONTROL of the laser is a key to this success**
- **Entering new experimental regime with high neutron yields: new challenges**
- **At 20 years of age, many hardware and software control system components require focused refurbishment effort**

NIF Ignition Achievement Covered Worldwide



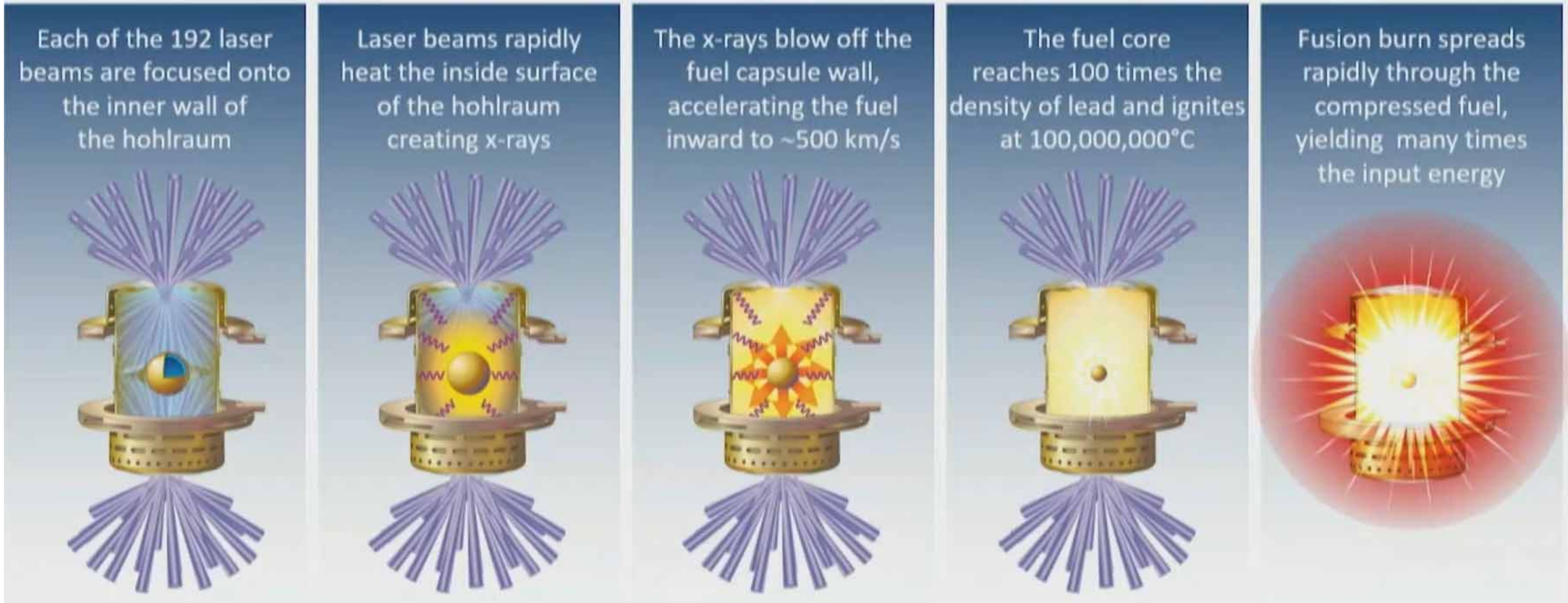
National Ignition Facility and Ignition Target





NIF, the world's largest and most energetic laser, is pursuing scientific understanding of Fusion Ignition, when DT target produces more energy from fusion than laser drive input

Indirect Drive Inertial Confinement Fusion (ICF) Process at NIF

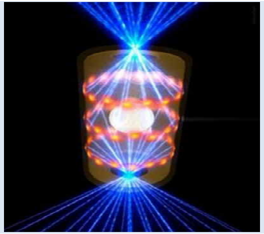


Every step of the process requires precise delivery of laser energy at proper place, time, intensity and wavelength

Role of the Control Systems

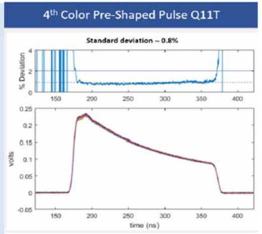
Alignment and Pointing

Patel, et al MO3AO05



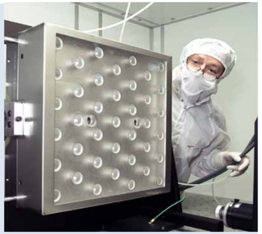
Temporal Shape of Laser Pulse

Gowda, et al WE3AO02
Burgoyne, et al TUPDP120



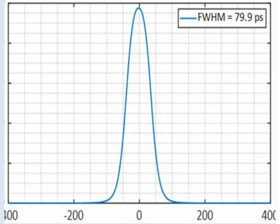
Wavefront Quality Adaptive Optics

Brunton ICALEPCS'13

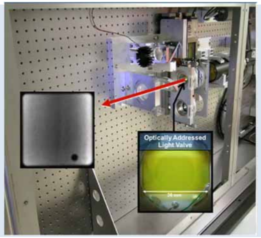


Timing

Brunton ICALEPCS'17

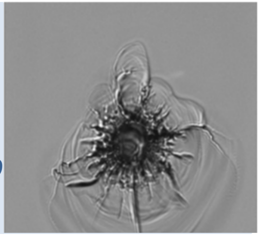


Spatial Shaping of Laser Beam



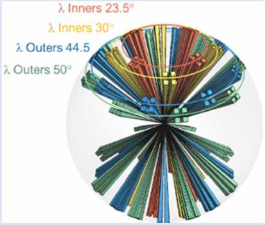
Optics Quality

Clark, et al WE3BCO03
Kegelmeyer, ICALEPCS'19



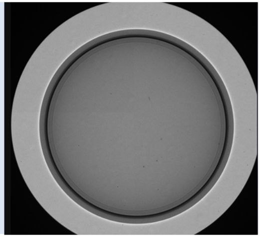
Energy Balance over 192 Beams

Spectral "Colors" of Laser Beams



Target Quality

Fedorov ICALEPCS'11



NIF control systems both regulate and monitor thousands of parameters critical for experiment success

Control of Laser Pulse Temporal Shape: new High Fidelity Pulse Shaping System (HiFiPS)

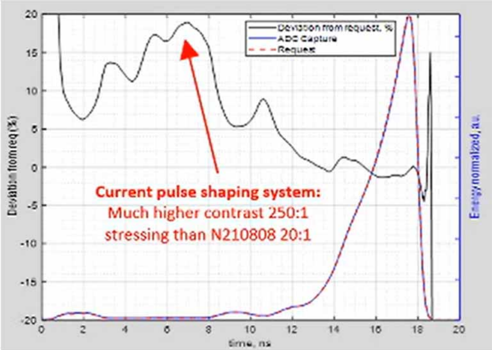
Modern high-speed analog/digital hardware and optical modulators

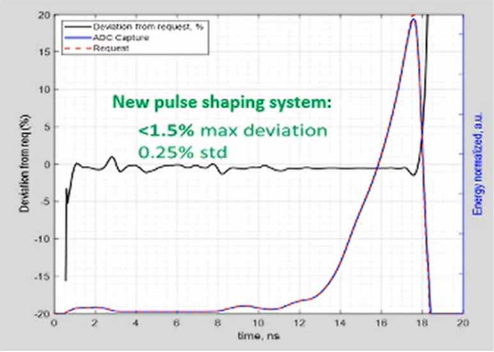
Closed loop control room compensates for non-linearity and drift

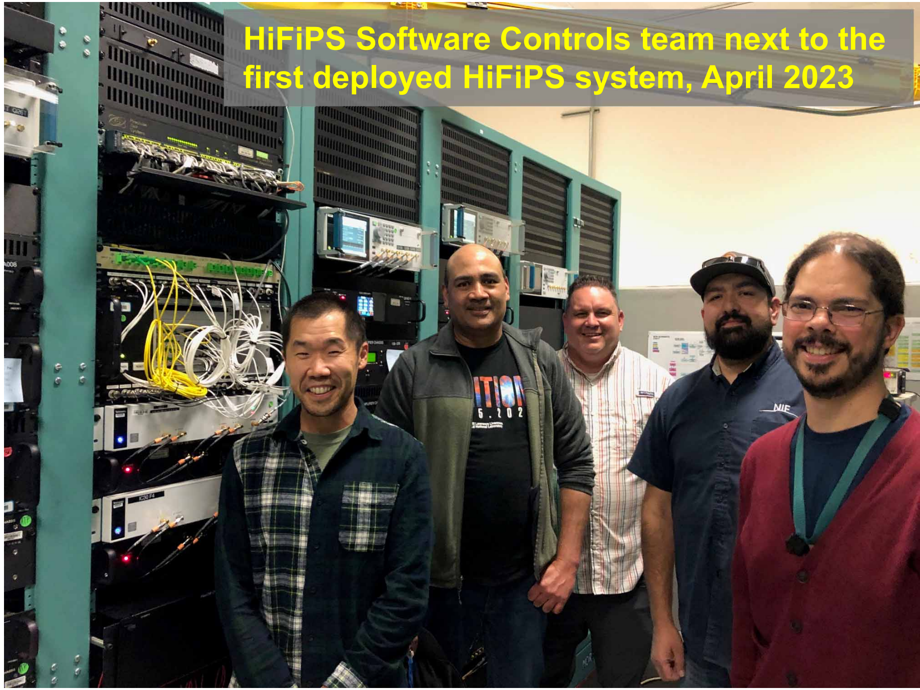
Short-term stability for 200:1 contrast pulse is better than 2%

Closed loop pulse shaping deviation from request better than 0.5%

More details: Gowda, et al WE3AO02 and Burgoyne, et al TUPDP120







The HiFiPS controls are rolled out in phases on 24x7 production system: first 4 quads in December 2022, then all inner 16 quads in April 2023, and full conversion August 2023.

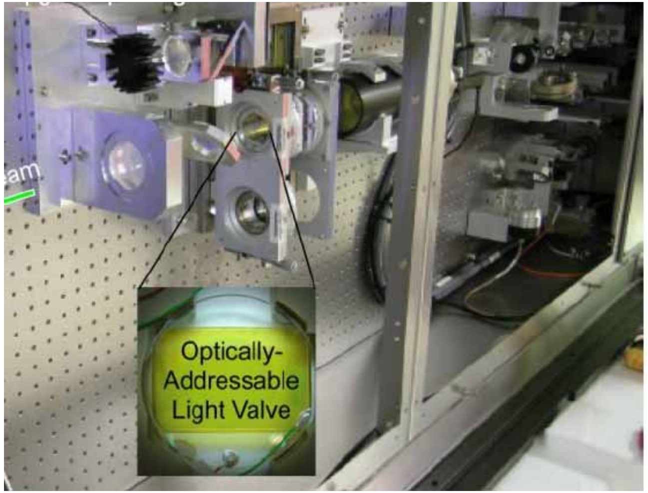
*) Di Nicola, J. M., et al. The National Ignition Facility Laser Performance Status, 2021.

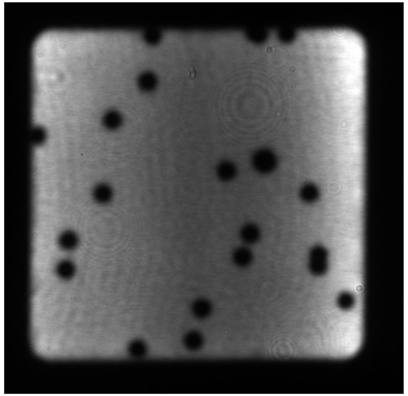
Control of Laser Pulse in Space: Programmable Beam Spatial Shaping System (PSS)

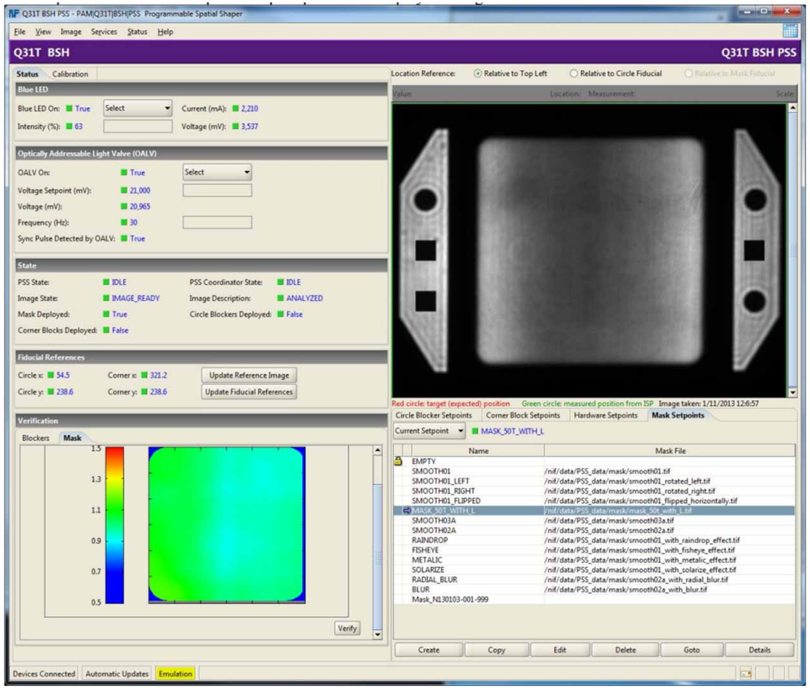
Precise tailoring of beam intensity to achieve flat laser output profile

Dynamic spot blocking to protect emerging optics defects

New 2022 uses of "gray" blockers to enable higher NIF laser energies







Developed in 2011, the PSS greatly enhanced uniformity of NIF laser beams and became an integral part of the NIF Optics Loop (NOL) optics defect mitigation strategy

*) Awwal, A. A., et al. *High Power Lasers for Fusion Research II* (Vol. 8602)

Control of Laser Pulse in Spectrum: “Four Colors” and Flexible Color Mapping (FlexCM)

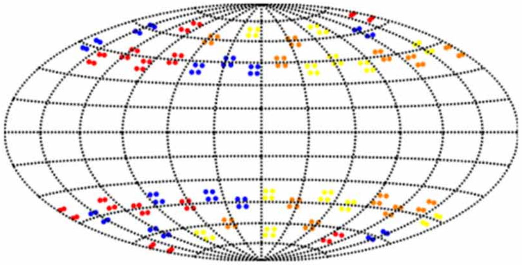
Variation in wavelength (“color”) control the Laser Plasma Interactions

Master Oscillator replicated to expand number of “color” choices to four

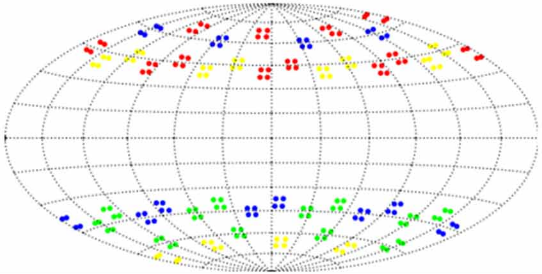
With FlexCM, the 4 colors can be mapped to desired laser beams

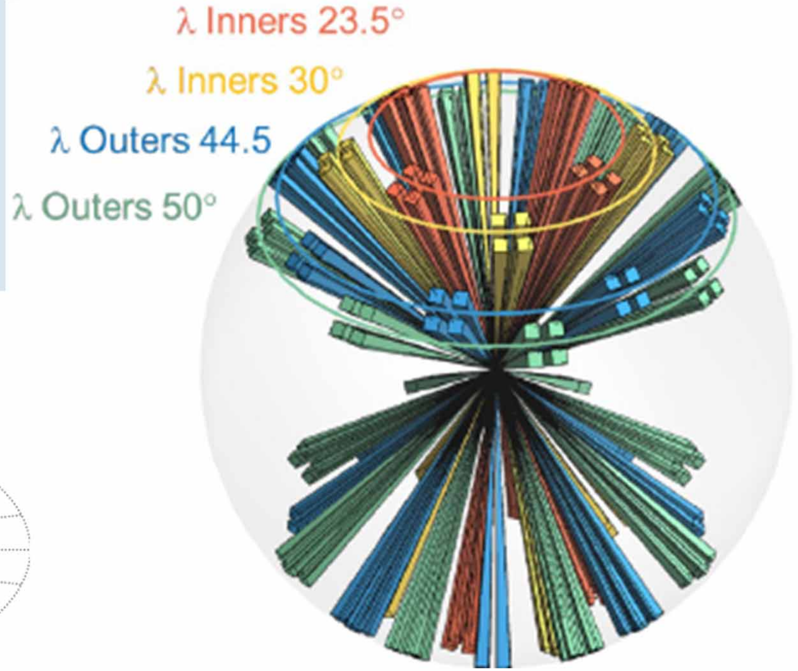
“Colors” are relatively minor adjustments to laser beam wavelength, within 1052.32 .. 1053.46 nm

Fourth Color Added



Flexible Color Mapping (FlexCM)



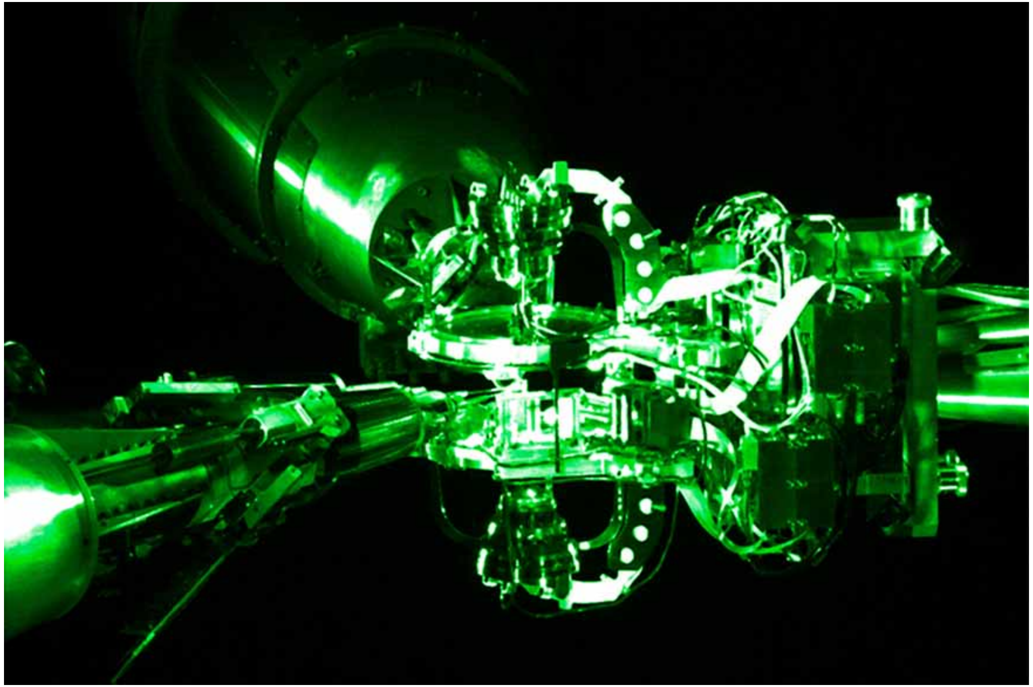


Precise tuning of the wavelength shift between the laser beams is a key technique used to achieve perfectly symmetrical implosions in NIF Ignition experiments

New High Neutron Yield Regimes – New Challenges for Controls

Many essential sophisticated sensors are located right outside of the NIF's 10-meter Target Chamber. The neutrons are damaging the electronics, requiring new mitigation strategies.

Target Alignment Sensor (TAS): Automated Calibration process



Even when retracted outside of the Target Chamber, the precise Target Alignment Sensor experiences neutron damage to its camera sensors. New automation will allow to quickly remove and reinstall TAS.

Failures of aging hardware as well as obsolescence of computing platforms call for a broad technology refresh effort

- **NIF Controls team has successfully completed several major modernization efforts: software from Ada95 to Java, platform from PowerPC VxWorks to Intel/Linux, video systems from proprietary Windows to open-source Linux - all without stopping 24x7 facility operations.**
- **In hardware controls, the ongoing efforts to replace aging power supplies, industrial, safety and access control systems.**
- **Regaining confidence in legacy embedded systems by employing automatic build and test, Continuous Integration (CI) processes.**

TU2AO05 J.Vaher Maintenance of the National Ignition Facility Controls Hardware System

MO2BCO06 V.Gopalan Embedded Controller Software Development Best Practices at the National Ignition Facility

Future Control System enhancements are part of large-scale sustainment plan to be executed over the next 5 years, necessary to extend NIF scientific discovery into the 2030s

Conclusion and Future Work

- **NIF achieved the long-standing goal of Fusion Ignition in laboratory conditions.**
- **Precise control of 192 laser beams, optics and target qualities is essential for the success of NIF experimental campaigns.**
- **High neutron yields are damaging to electronics, requiring new mitigation efforts: radiation hardening and quick turn around removal.**
- **At 20 years of age, the sustainment and continuous modernization of control systems become essential and critical activities to maintain facility operations.**