How Accurate Laser Physics Modeling is Enabling Nuclear Fusion Ignition Experiments

ICALEPCS 2023

K.P. McCandless, R.H. Aden, A. Bhasker, R.T. Deveno, J.M. Di Nicola, M.A. Erickson, T. E. Lanier, S.A. McLaren, G.J. Mennerat, F.X. Morrissey, J. Penner, T. Petersen, B. Raymond, S.E. Schrauth, M.F. Tam, K.C. Varadan, L.J. Waxer

October 13th, 2023

LLNL-PRES-855236

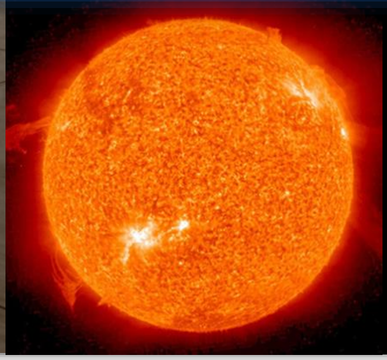
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

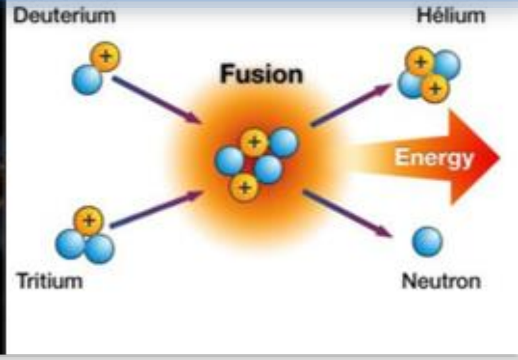
Lawrence Livermore National Laboratory

The National Ignition Facility (NIF) is the world's most energetic laser enabling the study of extreme conditions for Stockpile Stewardship

192 beams are used to drive inertial confinement fusion (ICF) processes – recreating what happens in the sun

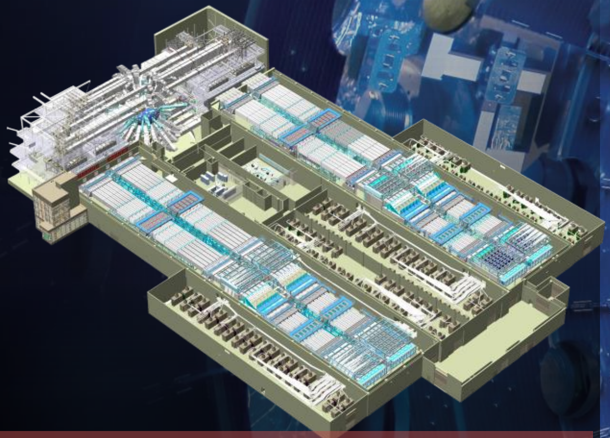
- 192 Beams
- 2.05 MJ Energy, 500 TW Power
- Thousands of Laser Diagnostics
- Hottest place in our solar system (for a few nanoseconds)





On Dec. 5, 2022, we demonstrated for the first time an igniting fusion* reaction in the laboratory

NIF Laser - 2.05 MJ UV
440 TW Peak power, ~4 ns

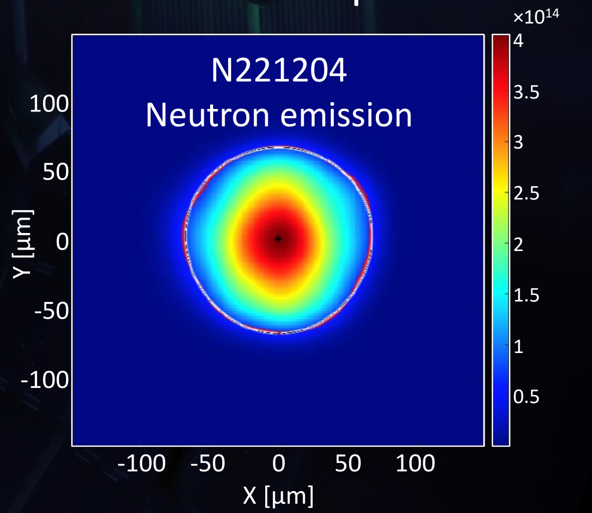


Fusion ignition is the point at which a nuclear fusion reaction becomes self-sustaining

- When the energy being given off by the reaction heats the fuel mass more rapidly than it cools
- The point at which the increasing self-heating of the nuclear fusion removes the need for external heating

Energy Output
From 12/5/2022 Experiment

>30,000 trillion watts (30 PW)
~3.15 MJ with G_{target} ~ 1.5*
for ~100 ps



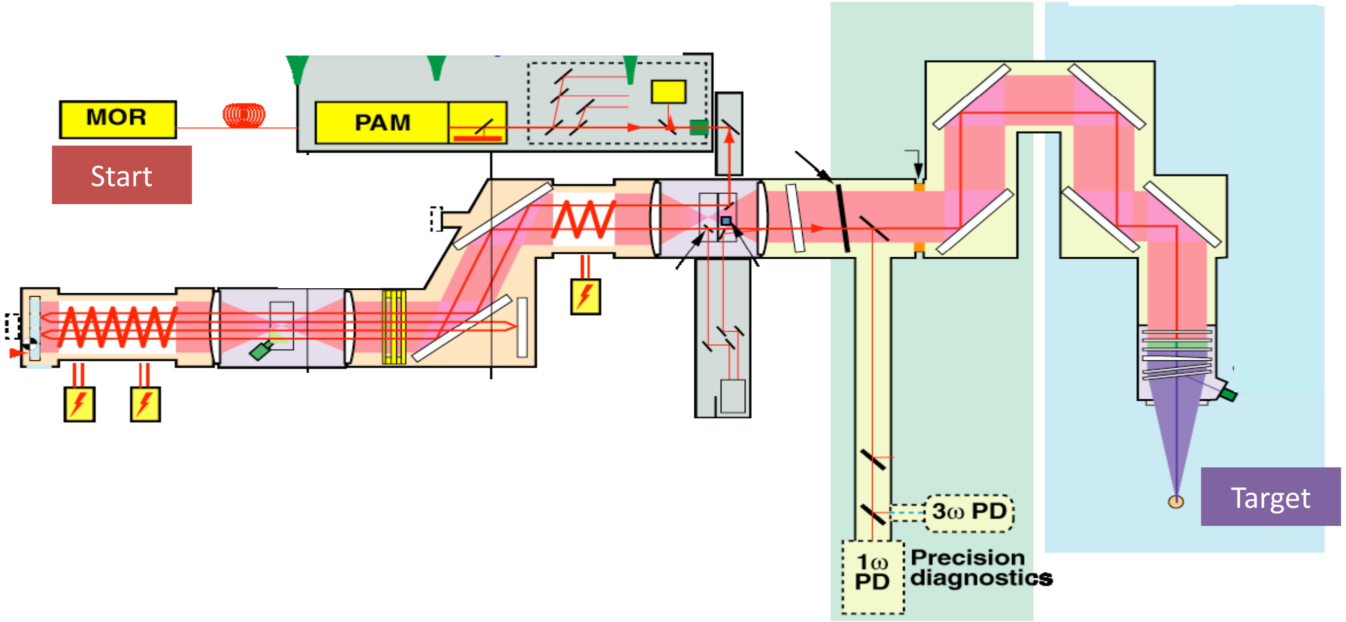
Fusion plasma ~100 µm
Temperature ~130,000,000 K

* Exceeding 1997 NAS definition of Fusion Ignition

The experiment was repeated on July 30th 2023, with a higher yield 3.88 MJ and G_{target} ~ 1.9*

LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots

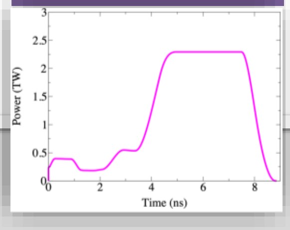
The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target



LPOM (VBL)

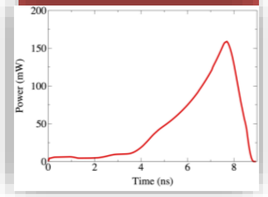
Shot Goals

3ω pulse

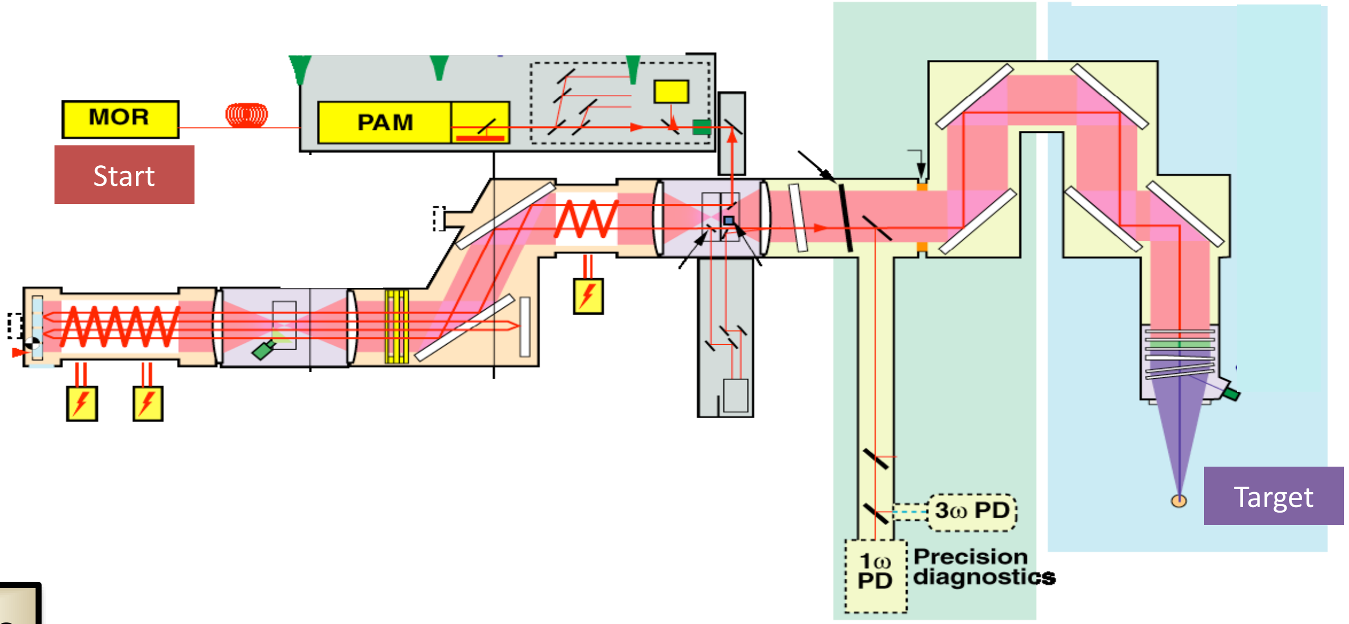


LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots

1ω pulse



The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target

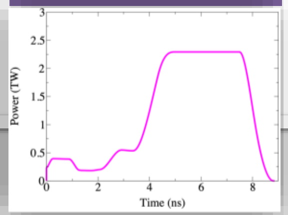


Shot Settings

LPOM (VBL)

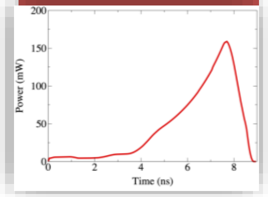
Shot Goals

3ω pulse

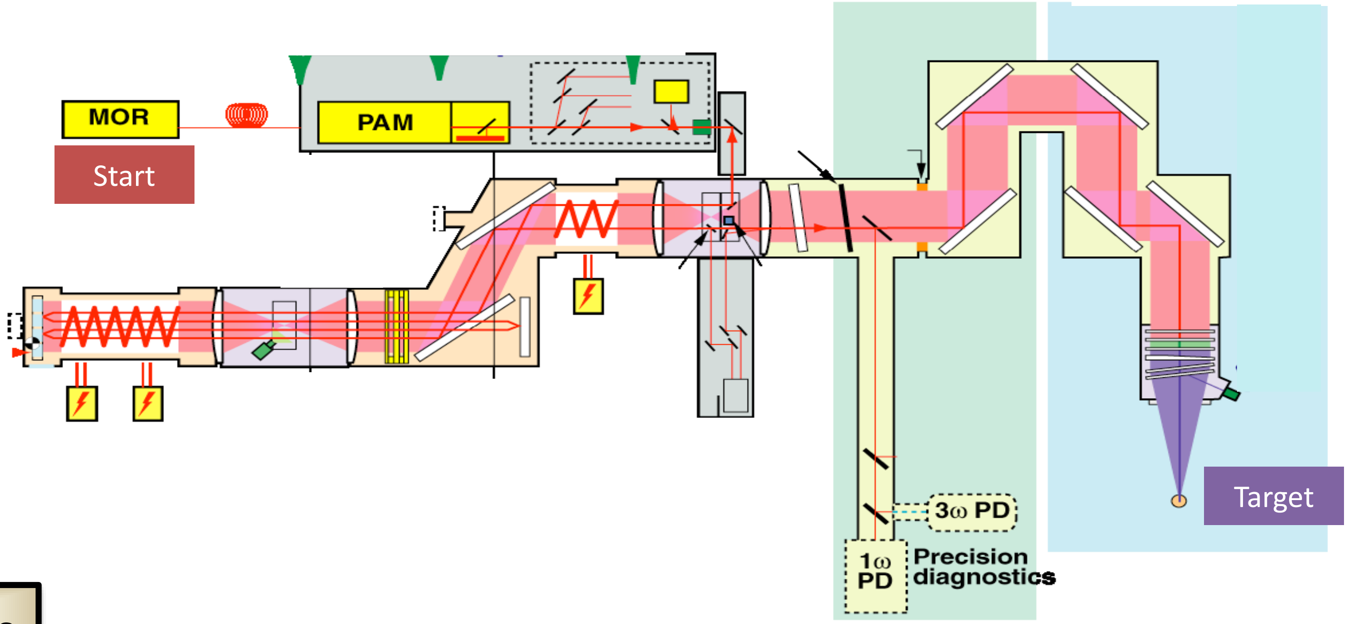


LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots

1ω pulse



The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target



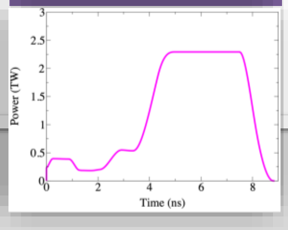
Shot Settings

LPOM (VBL)

Shot Goals

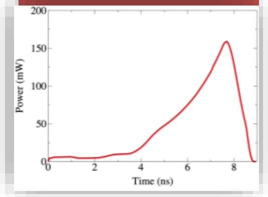
VBL is the physics engine for LPOM – modeling a single NIF beamline with Fourier split step wave propagation, amplification, frequency conversion, etc.

3ω pulse

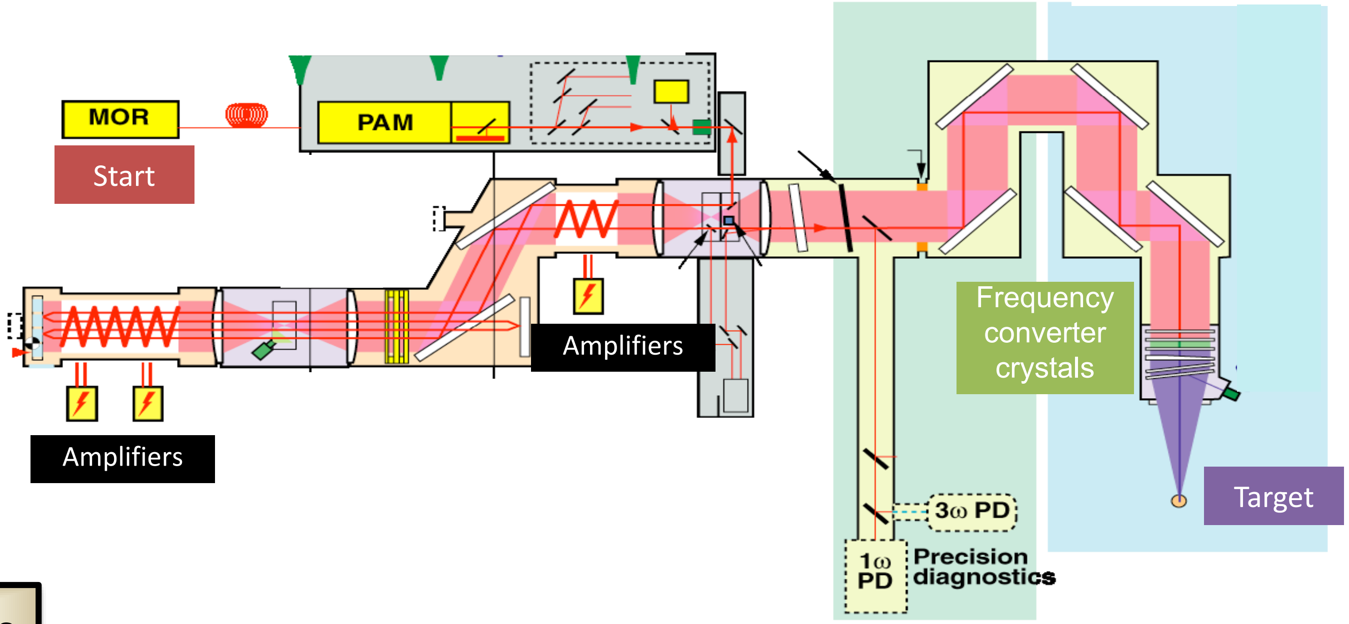


LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots

1ω pulse



The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target

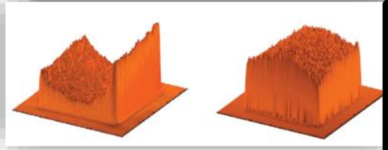


VBL is the **physics engine** for LPOM – modeling a single NIF beamline with Fourier split step wave propagation, amplification, frequency conversion, etc.

Shot Settings

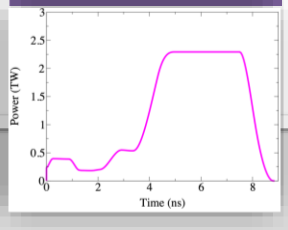
LPOM (VBL)

Shot Goals

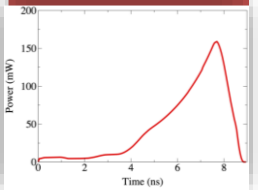


Pre-compensated spatial profile(left) produces a 'flat' beam at end of the amplification section(right)

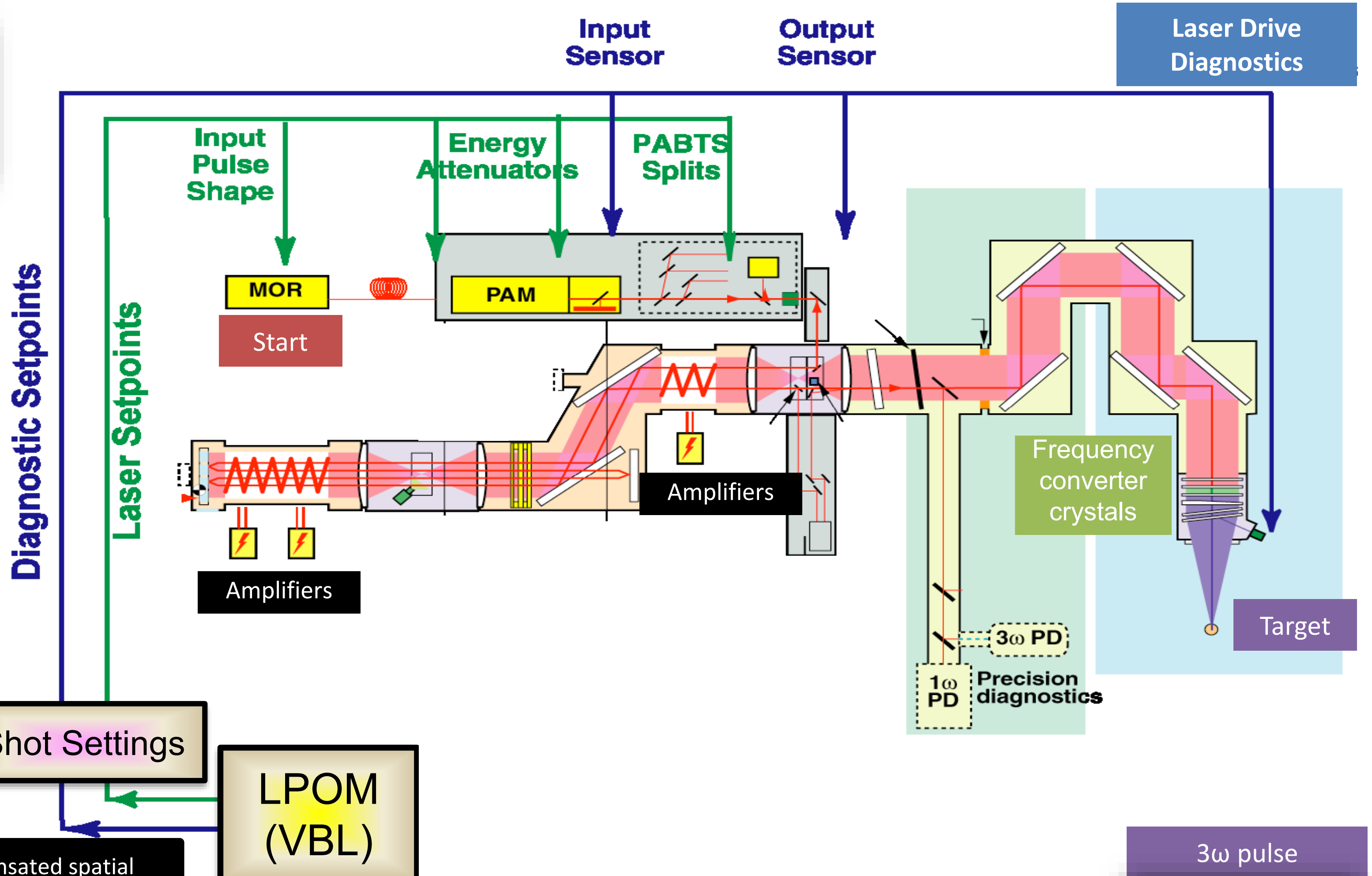
3ω pulse

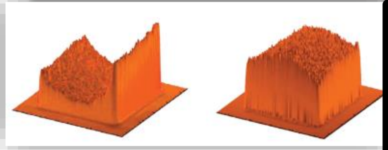


LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots



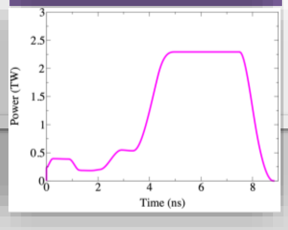
The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target





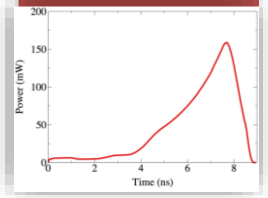
Pre-compensated spatial profile(left) produces a 'flat' beam at end of the amplification section(right)

VBL is the physics engine for LPOM – modeling a single NIF beamline with Fourier split step wave propagation, amplification, frequency conversion, etc.

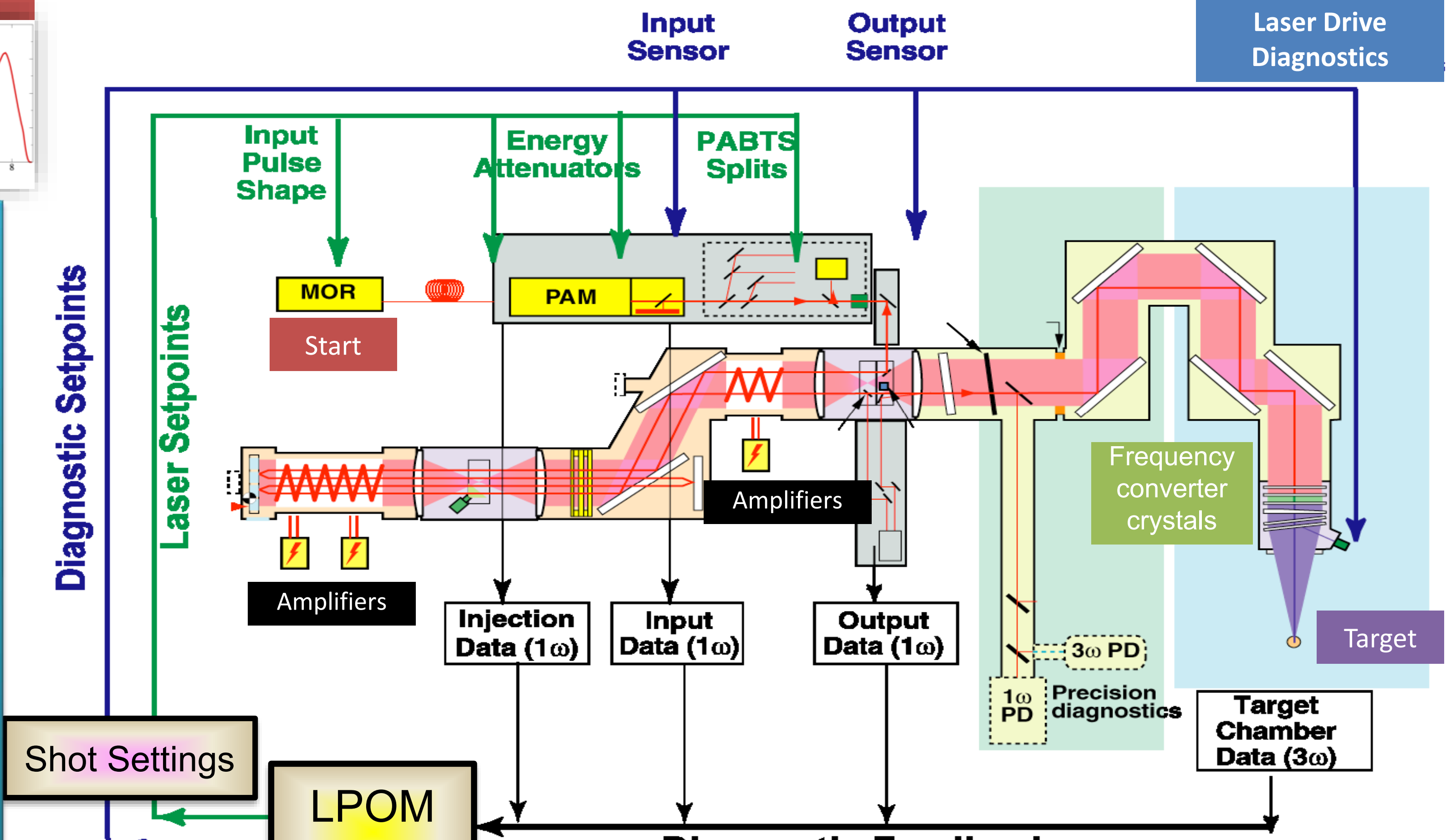


LPOM is used by the Control System (ICCS) to setup NIF and results are fed back into the models to improve future shots

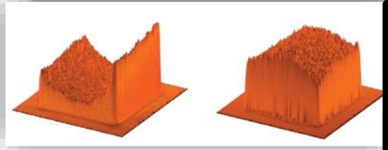
1ω pulse



The **Laser Performance Operations Model (LPOM) drives the Virtual Beamline (VBL) code** to predict the NIF's 192 beam laser performance, setup the laser and diagnostics, and deliver the desired pulse shape on target

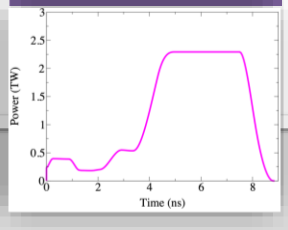


VBL is the physics engine for LPOM – modeling a single NIF beamline with Fourier split step wave propagation, amplification, frequency conversion, etc.

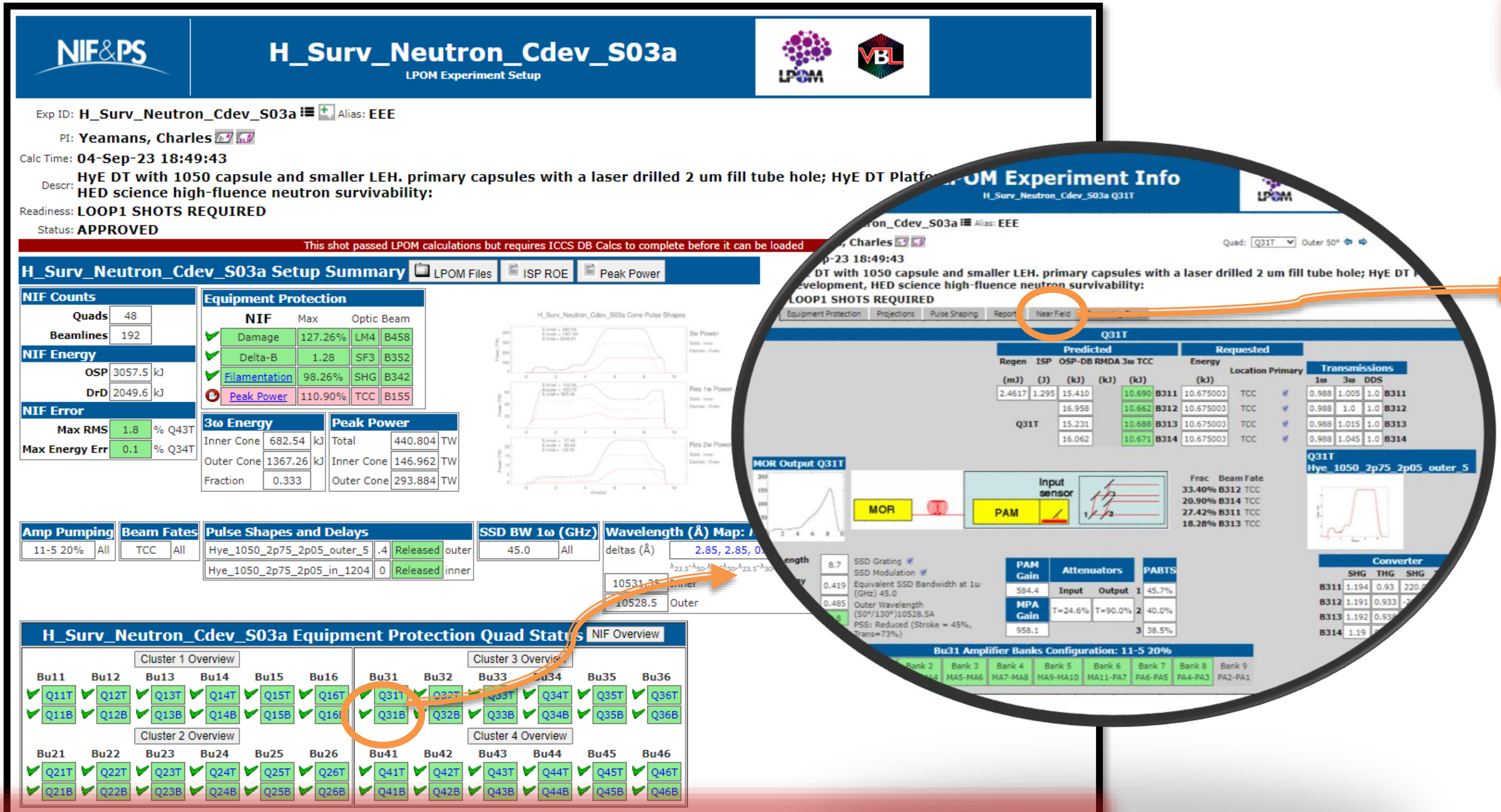


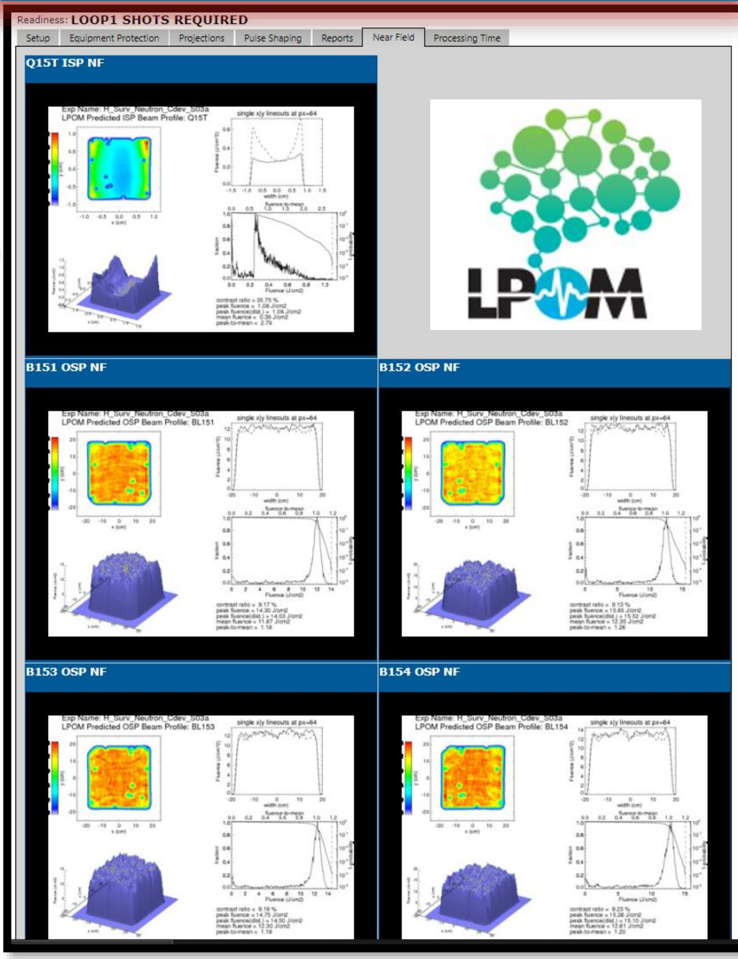
Pre-compensated spatial profile(left) produces a 'flat' beam at end of the amplification section(right)

3ω pulse



Before an experiment can be shot on NIF, LPOM runs a series of VBL calculations to predict performance



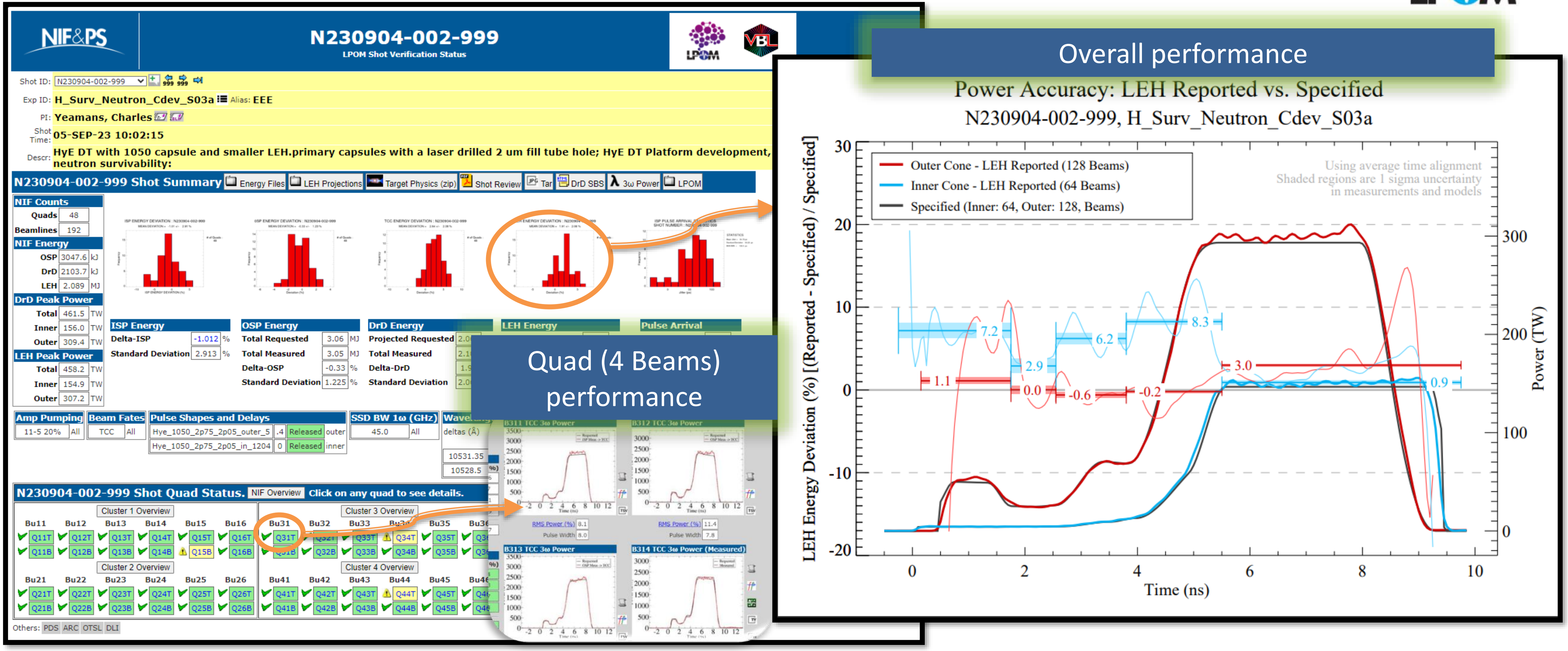


Quad Setup Report

Overall Experiment Setup Report

Achieving the conditions for ignition demands precise control of lasers that can only be achieved with the use of laser physics codes like the Virtual Beamline (VBL) driven by performance and operations modeling software tool suites like LPOM

After a shot on NIF is fired, LPOM generates a shot report to evaluate the laser performance



The accuracy and timing of the delivered pulses onto the target
directly affect the symmetry of the implosion critical to achieve fusion ignition

LPOM/VBL work together to achieve more accuracy for the fusion ignition platform at NIF

- Automating real-time input pulse corrections (Loop1)
- Enhancing pulse solver physics fidelity
- Mining data for final optics conversion correction (Loop3)
- Enhancing symmetry reporting to understand implosion dynamics
- Diagnosing and understanding performance losses and artifacts

Automated performance correction to each quad's input pulse calculated and applied during the shot cycle (Loop1)

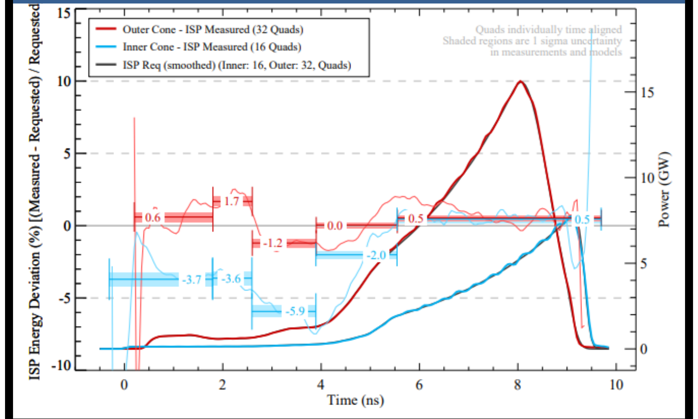
- Calculating accurate request pulse shapes at the injection of the NIF laser is complicated by several factors
  - High contrast and variability in specified shaped pulses
  - Drift over time of the MPA amplifier performance
  - Non-linear nature of gain amplification (saturation, etc.)
- To combat this the NIF uses results from low power shots early in the shot cycle to calculate corrections to the VBL model generated input request pulse shape
- This process was originally carried out by hand using data from additional shot cycles completed before the main shot
  - This was error prone and human time consuming
- Automating Loop1s as a function of the LPOM application allows this process to be essentially "free"
  - The low power shots are being taken anyway
  - The automated processing does not add human time or critical path time to the NIF shot cycle

Loop1s Correct the 1ω pulse shape at the start of high-power amplification

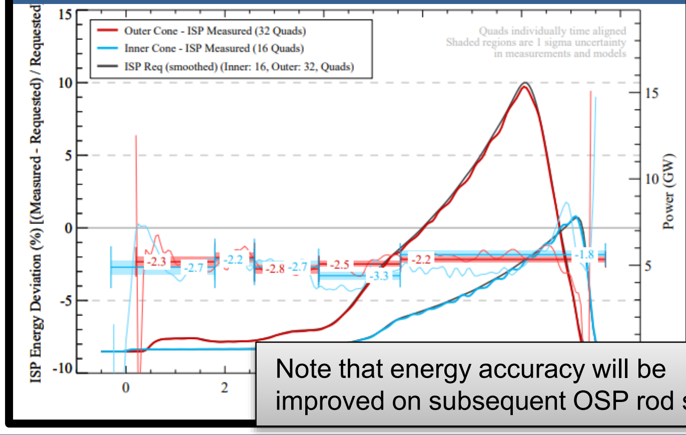
In this example, power accuracy was greatly improved after the Loop1 process was applied.

Especially on the extremely low power portions at the beginning of the Inner cone pulse shape

Pre-Loop1 Power Accuracy



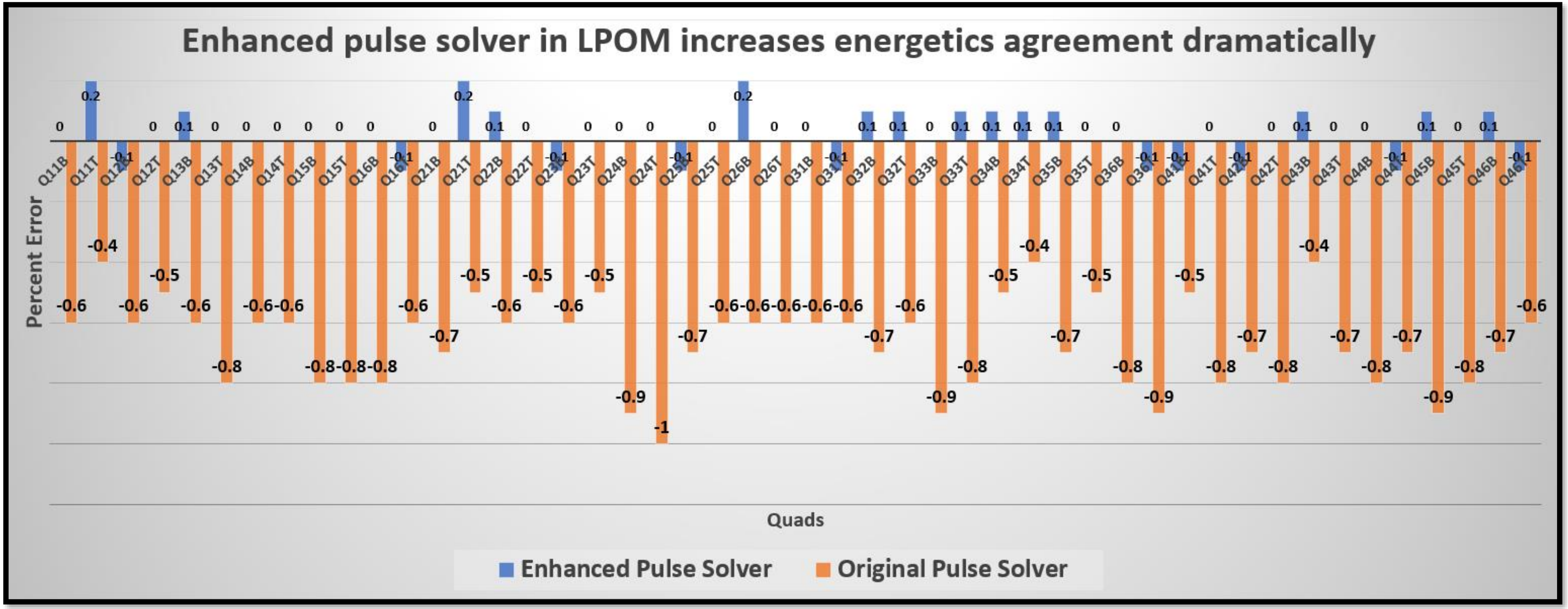
Post-System Shot Power Accuracy



Note that energy accuracy will be improved on subsequent OSP rod shots

Automated loop1 corrections improve performance without requiring time consuming manual work by the laser physicists

In the month prior to our first ignition shot, we increased the pulse solver accuracy

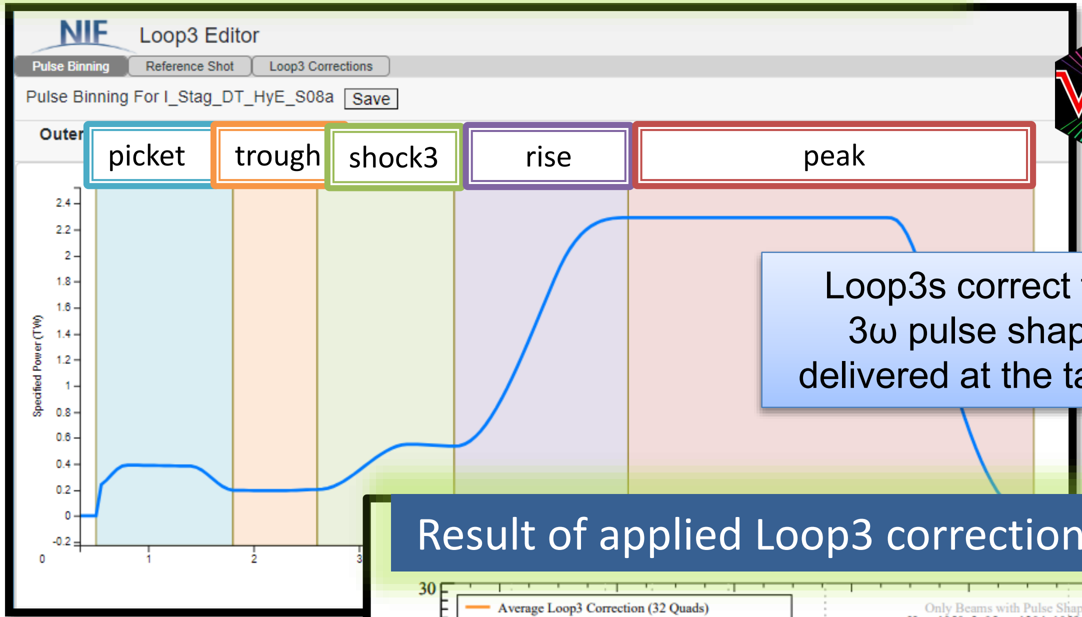


We increased the spatial resolution and added more physics in earlier phases of the pulse solver
More accuracy means more memory usage (RAM) and increased time to solution (wallclock)

Mining data from completed shots to improve performance on upcoming shots (Loop3)

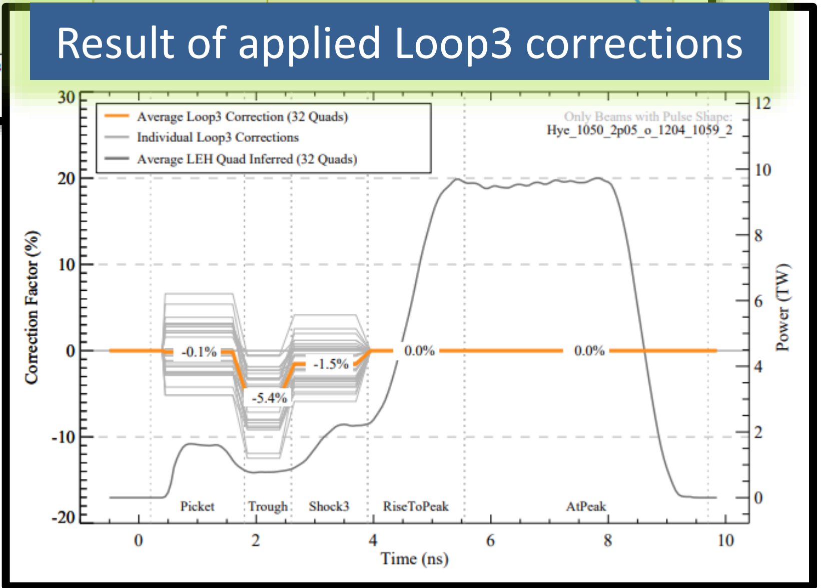
- Achieving high 3ω pulse shape power accuracy at the target is complicated by
  - The non-linear processes of gain amplification (saturation) and frequency conversion
  - High cost of 3ω calibration shots (in terms of time and optic damage)
- On the NIF we rely on VBL modeling to fit the data from a small set of calibration shots to infer machine calibrations
  - This results in high accuracy for some 3ω power levels and lower accuracy in others
- Results from prior shots with similar pulse shapes can be used to correct 3ω power accuracy performance when the calibrations aren't perfect
- The Loop3 Editor is a tool that allows a laser physicists to
  - Quickly define the regions of the pulse (picket, etc)
  - Select the closest recent representative shot
  - Apply a corrections based on the achieved power performance of the representative shot

Using the Loop3 Editor to define pulse regions



Loop3s correct the 3ω pulse shape delivered at the target

Result of applied Loop3 corrections



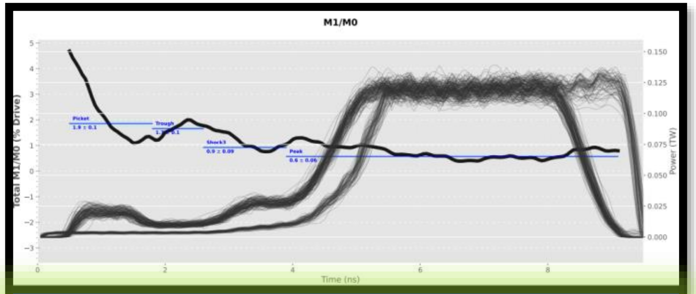
In this example, power accuracy was improved by adjusting the request in the picket, trough, and shock3 regions of the pulse, using data from a prior shot in the same campaign

Using knowledge of machine performance on past shots can improve model accuracy for future shots

New symmetry reports delivered this year are key to understanding the delivered power balance across 192 beams

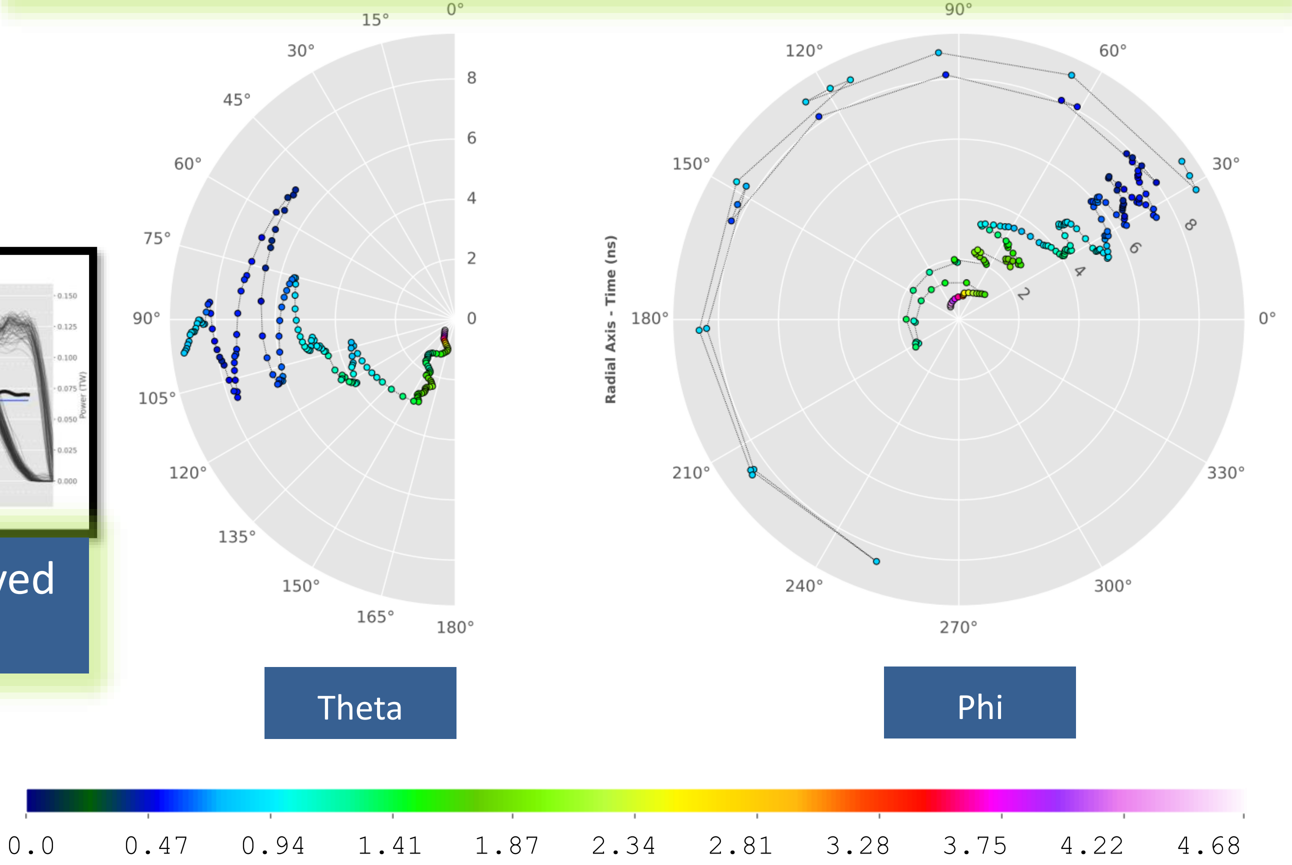
- 360° implosion symmetry is critical to achieve ignition
- To understand their results, experimentalists look at reports of the inferred hotspot movement
- These reports are driven by analysis combining all the laser beam pulses delivered to the target chamber

NIF target chamber during installation



All 192 power traces overlayed onto the % drive report

M1/M0 [%Drive]* 2nd Ignition Shot July 29, 2023



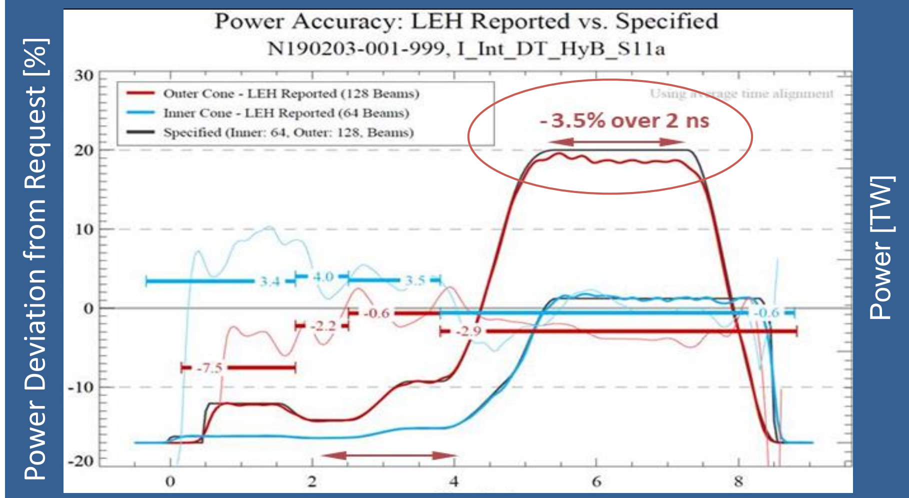
Experimentalists use this laser data to adjust their pulse shape requests and understand the initial conditions before the implosion

*B.J. MacGowan, et. al., "Trending low mode asymmetries in NIF capsule drive using a simple viewfactor metric", High Energy Density Physics, Volume 40,2021,100944,ISSN 1574-1818

LPOM detected decreasing 3ω performance used modeling to assess the situation and devise model and hardware upgrades

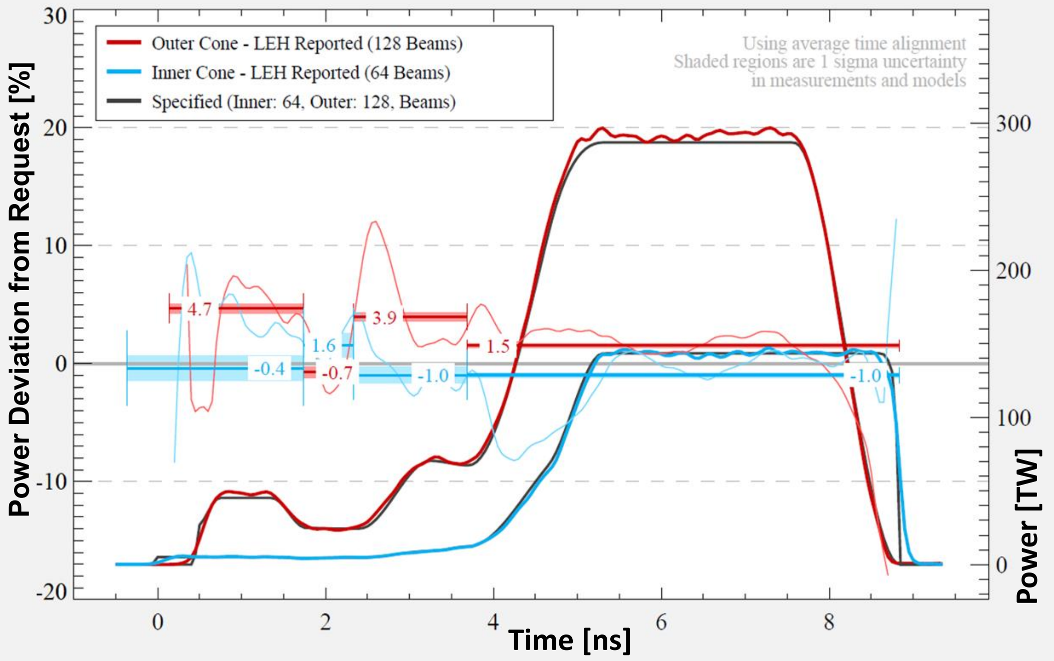
- NIF is operating at its highest sustained levels of energy and power to date by continued investments in optics and laser technology
- Fidelity of the laser models, accuracy of the laser diagnostic; beam quality, front-end performance and low-mode symmetry have been all improved

Power accuracy showing 3ω "droop"



Hardware and model upgrades

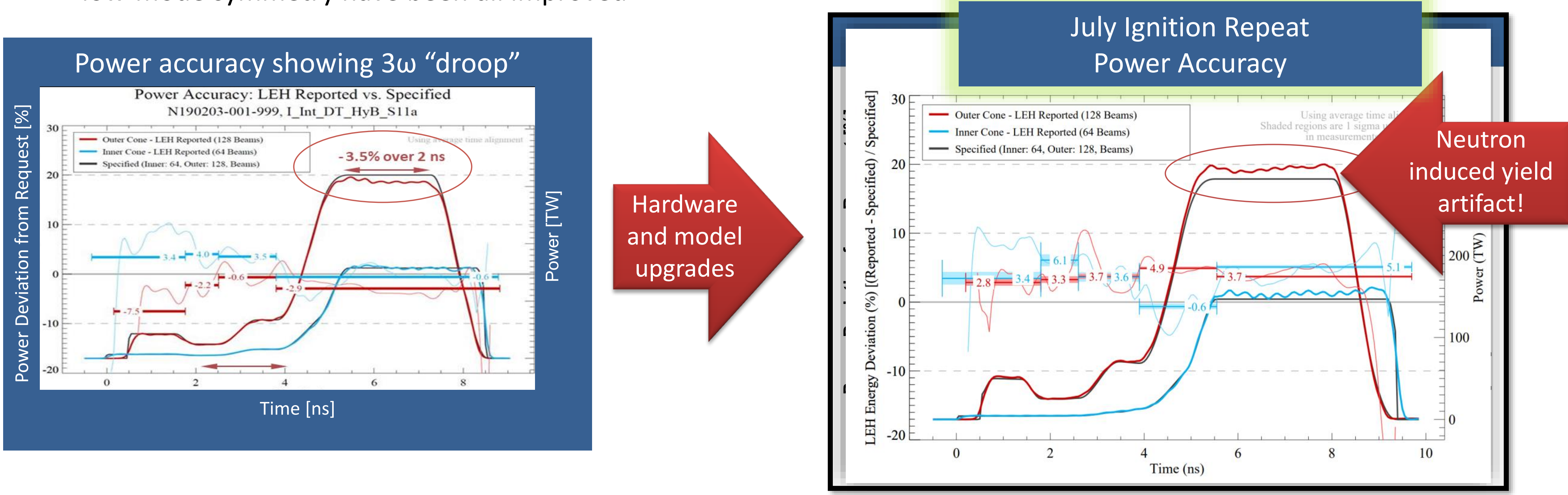
N210808 HyE Power Accuracy met all requirements



In addition to using model-based calibrations, we use laser physics modeling to determine the need to upgrade hardware (A. Gowda HiFiPs talk ICALEPCS 2023)

LPOM detected decreasing 3ω performance used modeling to assess the situation and devise model and hardware upgrades

- NIF is operating at its highest sustained levels of energy and power to date by continued investments in optics and laser technology
- Fidelity of the laser models, accuracy of the laser diagnostic; beam quality, front-end performance and low-mode symmetry have been all improved



NATIONAL IGNITION FACILITY

We are hiring! Visit **careers.llnl.gov**

Lawrence Livermore
National Laboratory