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How Accurate Laser Physics Modeling is Enabling Nuclear Fusion Ignition Experiments

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Abstract

This last year we achieved an important milestone by reaching fusion ignition at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF), a multi-decadal effort involving a large collaboration. The NIF facility contains a 192-beam 4.2 MJ neodymium-doped phosphate glass laser (around 1053 nm) that is frequency converted to 351nm light. To meet stringent laser performance required for ignition, laser modeling codes including the Virtual Beamline (VBL) and its predecessors are used as engines of the Laser Performance Operations Model (LPOM). VBL comprises an advanced nonlinear physics model that captures the response of all the NIF laser components (from IR to UV and nJ to MJ) and precisely computes the input beam power profile needed to deliver the desired UV output on target. NIF was built to access the extreme high energy density conditions needed to support the nation's nuclear stockpile and to study Inertial Confinement Fusion (ICF). The design, operation and future enhancements to this laser system are guided by the VBL physics modeling code which uses best-in-class standards to enable high-resolution simulations on the Laboratory's high-performance computing platforms. The future of repeated and optimized ignition experiments relies on the ability for the laser system to accurately model and produce desired power profiles at an expanded regime from the laser's original design criteria.

INTRODUCTION

Here at NIF we have now officially repeated the achievement of fusion ignition in a laboratory setting - once in December 2022 and this past summer in July 2023. This feat was long in coming and relies on many teams working together to push the frontiers of high energy density science, laser performance and target design. This paper will explore some of the details and challenges on the laser performance team and highlight a few cases where we have tightened up the accuracy to deliver better quality laser pulses at the target.

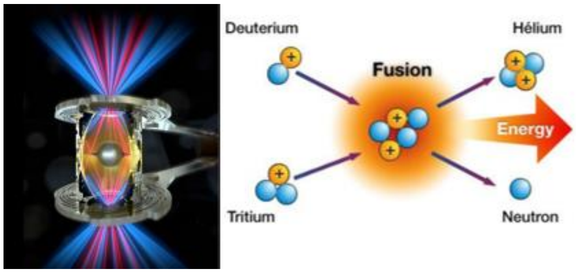

Figure 1: Artist rendition of 192 laser beams of NIF entering the target hohlraum to start heating the walls and cause an X-ray bath which begins compressing the fuel pellet (grey sphere) triggering a runaway fusion ignition process. (left) In a fusion reaction, the nuclei of hydrogen deuterium and tritium are forced together by extremes of temperature and pressure and fuse to form a helium nucleus. In the process some of the mass is converted to energy and released as neutrons (right).

BACKGROUND

At its core, fusion ignition refers to the point at which a controlled fusion reaction becomes self-sustaining, releasing an immense amount of energy through the fusion of atomic nuclei, the same process that powers the sun (see **Error! Reference source not found.**). Achieving and studying fusion ignition in a controlled environment has several key implications: providing a clean and abundant energy source, advancement in our understanding of fundamental physics, plasma behaviours and high-energy processes, and it is a key factor in avoiding a return to underground nuclear weapons testing as a stable fusion-based scientific platform is needed to assure the nuclear weapons stockpile in the United States remains safe, secure, and reliable [1].

At NIF we use a laser driven technique to achieve fusion ignition by a process termed "Inertial Confinement Fusion". ICF is a method of achieving controlled nuclear fusion by using intense pulses of energy to compress and heat a small target containing fusion fuel. In the context of ICF, the term "inertial confinement" refers to the fact that the fusion fuel is compressed and heated through the inertia of the material surrounding it, rather than by using external pressure. The energy released from the fusion reactions can potentially be harnessed for various applications including electricity generation and survivability experiments (see Fig. 1)

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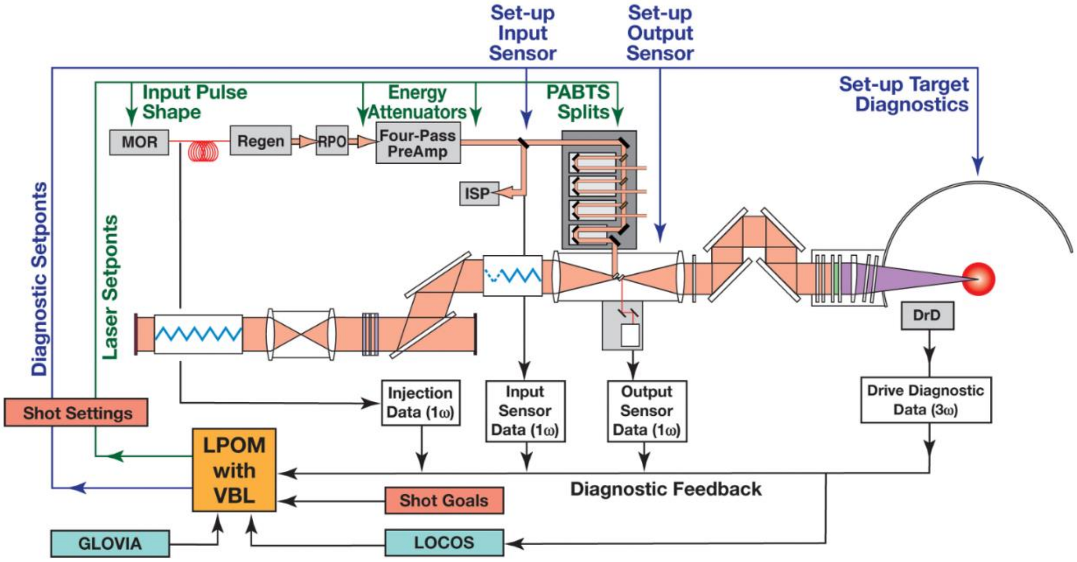


Figure 2: LPOM contains a detailed model of each beamline. Propagation calculations using the VBL model provide predicted energy and power throughout the laser, information that is used for equipment protection and to configure diagnostics via the control system. MOR is the Master Oscillator Room where the input pulse is shaped, LoCoS and Glovia are databases with the optics configuration and status.

Overall, the performance of NIF directly impacts its versatility, efficiency, effectiveness, and safety across a wide spectrum of applications – not just ignition experiments, optimizing laser performance is key to unlocking NIF's full potential. We do this by developing and maintaining a team of experts backed by the Laser Performance Operations Model (LPOM) software [2]. LPOM is a set of trending data, visualizations, and software tools capable of predicting and reporting laser performance on individual shot experiments and over time as the system ages and components are upgraded or replaced. LPOM also sits between the NIF Control System (ICCS) and the scientists by setting the laser and diagnostic set points on quad and individual lasers (see Fig. 2). The specifications by a target designer for a laser pulse shape comes as power versus time at the target chamber (see Fig. 3). To produce this desired output pulse, the power versus time coming out of the front-end of the laser must be computed and communicated to the pulse shape generator.

Figure 3: Target chamber at NIF before installation, the 192 beams enter in groups of 48 quads (seen as the capped squares on the chamber's surface above).

The VBL [3] code predicts energetics, wavefront, near- and far-field beam profiles, and damage risk with a physical optics model of propagation including Kerr effect and focusing, frequency-conversion and most critically a pulse solver that enables laser set-up by determining the input power profiles required to deliver on target experimentalist requested power profiles. LPOM provides beamline specific configuration files and spatially dependent models for amplifier gain to VBL by querying the system databases and maintaining our best guess at the actual gain profiles by taking offline laser only shots to calibrate the model. Beamline specific properties can change as the characteristics of the disposal debris shields (DDS) and other components such as the programmable spatial shapers change, or when one of the final optics is exchanged as part of operation of the optics recycle loop [4].

VBL utilizes an iterative pulse solving scheme, which is a series of calculations from an input to output plane, (say the MOR to the input of the target chamber) of the beamline being modeled to "guess and correct" for the proper input pulse shape which will meet the desired output shape after undergoing amplification and frequency conversion in the chain. This input-pulse-solve (IPS) by VBL is logically similar to using an inverse-transfer function, though captures much more nuanced detailed through the modeling of nonlinear effects in the materials propagated through. For each beamline and quad, a series of pulse solver runs establish the expected spatial beam profiles injected into the main laser. This process is physically complex for a few reasons:

- The amplifier regions experience more gain in the central region of the spatial beam profile than on the edges, requiring spatial shaping of the beam to compensate and generate a flat spatial profile at the target (See Fig. 4).
- Differences in individual beamlines must be accounted for all 192 beams to have good power balance and arrive at the same time to the target chamber. There are nonlinear losses and defects introduced when passing through optics that accumulate over the length of the laser chain, these must be characterized and monitored for changes over time. This is accomplished by keeping detailed trending data and a live physics model (VBL) of each beamline, coordinating with the Glovia and LoCoS databases (see Fig. 2).
- The time to solution must be under 20 minutes to keep reasonable throughput in the NIF shot cycle. One key step we take is adjusting the temporal sampling of the specified pulse (see Fig. 5).
- The constraints of having 48 quads for 192 beamlines means that the energy generated in the front end of the last must be split and balanced across the four outgoing beamlines from the Preamplifier Beam Transport System (PABST) (see Fig. 6), we use the VBL physics model in conjunction with LPOM to accomplish this.

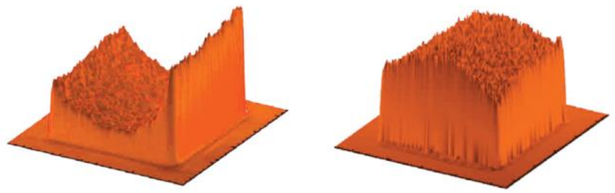


Figure 4: 1ω spatial beam shape before amplification showing a U shape to account for gain compensation (left) and after amplification the beam is 'flat' (right).

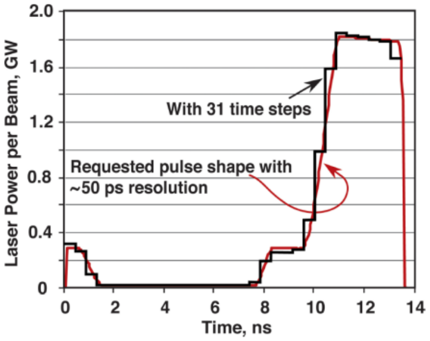


Figure 5: Example desired laser pulse shape at the target showing the request/specified (red) vs. coarser discretization used in the VBL/LPOM model (black) which saves wall-clock time while still producing accurate results.

WHY LASER PERFORMANCE MATTERS

To perform nuclear fusion experiments at NIF, all 192 laser beams are used to drive the implosion of the fuel capsule. The performance of these lasers is critical to a successful experiment and to tune them we use physics modeling and simulations to guide our laser setups and calibrations, and additionally provide extensive post shot reporting and analysis to understand how the beam-to-beam power variation performed as well as performance between shots. Both the spatial and temporal profiles of the laser beams can accrue defects as they propagate through components and air which directly affects how well the laser energy is focused. A higher-quality beam retains its focus over greater distances, leading to better performance in delivering consistently shaped beams to the target chamber.

In the next few sections, we will explore how LPOM works with the VBL physics simulation code and how we have used both LPOM and VBL to achieve more accuracy by:

1. **Real-time input pulse correction:** Correct the gain model of the laser using less energetic shots to improve the quality of the system shot by applying a multiplier/correction on the input pulse shape.
2. **Pulse solver fidelity:** Improving the fidelity of the experiment setup models to increase the pulse request accuracy for fusion ignition pulse shapes.
3. **Final optics conversion correction:** Tune the requested power profile by using a series of shots using a recently developed LPOM tool as the performance behavior here is quite nonlinear.
4. **Enhanced symmetry reporting:** Improve the symmetry reporting across all 192 laser beams to aid the target designers understanding of power balance and energy hot spot tuning in the LPOM published shot report.
5. **Power accuracy delivery:** Characterizing shaping errors, which has led to a retooling of the front-end hardware – see A. Gowda's HiFiPs talk here at ICALEPCS 2023.

REAL-TIME PULSE CORRECTION

When calibrating a laser model to match a given pulse shape, the ability to tune the machine to appropriately deliver a given feature in the pulse is highly dependent on nonlinear physics and it can be exquisitely challenging to capture all features with similar accuracy. Before software automation in LPOM and VBL, laser scientists had to manually tweak the results from the pulse solver in VBL/LPOM to improve overall and feature specific accuracy.

The team has now automated this process for high-contrast ratio ignition type pulse shapes. Upon request, we perform a specialized time-dependent pulse correction by setting up the laser first to run shots without energizing the flash lamps and triggering gain amplification using LPOM/VBL calculated pulse shapes. A sequence of these shots is performed only propagating to the image plane just before the main amplifiers. The average deviation over the sequence of low energy shots of the achieved pulse shape relative to the specified/requested is used to define a time-dependent correction for the front-end pulse shape. This correction is then applied in the front-end MOR when setting up for the final shot to the target chamber.

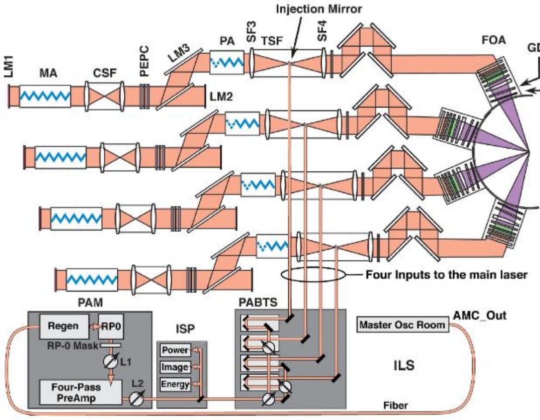


Figure 6: NIF has a single front-end per quad (4 beamlines) and uses LPOM to decide the splits of beam from 48 to 192 before reaching the amplification sections of the laser chain. This shows the start of the initial laser pulse at 1053 nm (or 1ω light), the amplification and spatial filtering section comprising the main 1ω laser and the frequency conversion section which converts to a brighter 351 nm (or 3ω light) in the Final Optics Assembly before all 192 head to the target chamber.

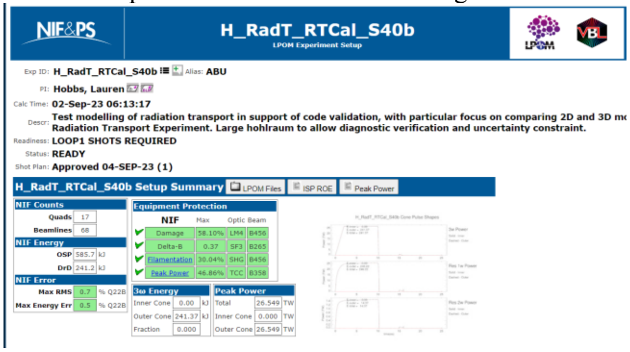
HIGHER FIDELITY PHYSICS MODEL

Before an experiment is shot on NIF, the setup calculation using VBL is completed, and a report is generated so that the scientists clearly see the approvals and successful calculation of the desired output pulse given the current laser configuration (see Fig. 7). LPOM uses the VBL pulse solver code to determine the input pulse shape (with or without the real-time loop1 correction) that should be injected at the front end of the laser. To do this, the pulse solve calculation in VBL first creates an estimate of the input power profile $P_{in}(t)$ at the first component at the injected location for the run by using a simplified model of the amplifiers. Starting at that point, it then does a full-chain simulation up to the last component defined to derive the resulting power profile $P_{out}(t)$. VBL then compares that calculated output to the requested result and uses the comparison to refine the estimated input; it resets the beamline to its initial state and iterates until the comparison of the calculation is within a predetermined error ~0.5%.

Prior to achieving ignition, the logic in the VBL pulse solver was optimized to favor quicker turnaround times at the sacrifice of about 0.5-1% accuracy. This allowed more experiment setups to be calculated and recalculated as configuration of the laser was changed. In a very real sense, the energetics were the target of the pulse solver and the nuanced features in the pulse were not known to be quite as sensitive. In the summer of 2022, we reexamined this tradeoff as the interest of the ignition pulse designers added more scrutiny to the achieved laser performance pulse shapes – with the understanding that performance of all features in the pulse shape were critical to the shock timing results on target. To meet the request for tighter accuracy we had to do more modeling studies exploring tradeoffs between speed (wall-clock-time) and physics fidelity during the pulse solving phases. We settled on increased accuracy from two main sources:

1. An increase in spatial resolution during the pulse solver phases. Previously we had allowed quicker solves using half the spatial points early in the iteration process and during the amplification phase as the initial goal was basic energetics agreement.
2. More physics during the pulse solve phases. As a wall-clock optimization, several phases of the pulse solve calculation did not turn on diffraction effects which then limited the impact of spatial filtering and phase aberration applications.

These two trade-offs do come at the expense of a longer time to solution by about 30%, however – the accuracy needed for fusion ignition experiments demands it. A few weeks after making and deploying these changes to the VBL code pulse solver – we achieved ignition on NIF.



H_RadT_RTCal_S40b

LPOM Experiment Setup

Exp ID: H_RadT_RTCal_S40b Alias: ABU
PI: Hobbs, Lauren
Calc Time: 02-Sep-23 06:13:17
Descr: Test modelling of radiation transport in support of code validation, with particular focus on comparing 2D and 3D mo Radiation Transport Experiment. Large hohlraum to allow diagnostic verification and uncertainty constraint.
Readiness: LOOP1 SHOTS REQUIRED
Status: READY
Shot Plan: Approved 04-SEP-23 (1)

H_RadT_RTCal_S40b Setup Summary

NIF Counts	
Quads	17
Beamlines	68

NIF Energy		
OSP	585.7	kJ
DrD	241.2	kJ

NIF Error		
Max RMS	0.7	% Q22B
Max Energy Err	0.5	% Q22B

Equipment Protection				
	NIF	Max	Optic	Beam
✓	Damage	58.10%	LM4	B456
✓	Delta-B	0.37	SF3	B265
✓	Filamentation	30.04%	SHG	B456
✓	Peak Power	46.86%	TCC	B358

3ω Energy		
Inner Cone	0.00	kJ
Outer Cone	241.37	kJ
Fraction	0.000	

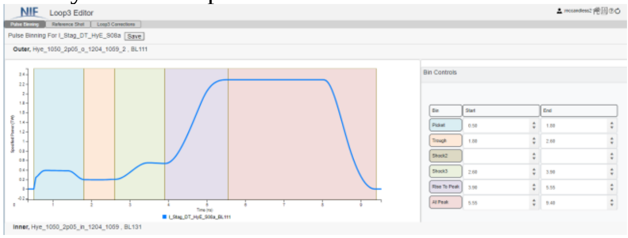
Peak Power		
Total	26.549	TW
Inner Cone	0.000	TW
Outer Cone	26.549	TW

Figure 7: Example LPOM experiment setup report, green highlighted boxes demonstrate to both the shot lead and the laser scientists that NIF can handle this experiment. VBL is the physics engine whose outputs drive the data in this report.

OUTPUT PULSE TUNING (LOOP3)

Despite model enhancements through increased VBL simulation precision, for some pulse shapes there is still a gap in performance experienced between the requested pulse shape on target and what gets ultimately measured. To compensate for this discrepancy, LPOM developed the Loop3 Editor software tool which allows laser scientists working with the target designers to propose a correction to the requested pulse shape as well – which translates to a more successful experiment (see Fig. 8).

Like the real-time front-end correction, the Loop3 correction is a time-dependent change directly adjusting the experiment designer's request, though in this case to the 3ω pulse shape at TCC. Before the Loop3 editor was developed, the only option was to take a non-target shot all the way to TCC and make a correction by comparing the actual (measured) 3ω result to the specified request. To avoid putting the optics at risk for non-target laser-based shots, we now use the Loop3 Editor tool to look at preexisting data for shots with similar energy and setup parameters. This continues to be an area where more data, and especially more recent data, benefits the fidelity of the Loop 3 correction.



Pulse Binning For I_Stag_DT_HyE_S08a

Outer, Hye_1050_2p05_o_1204_1059_2 , BL111

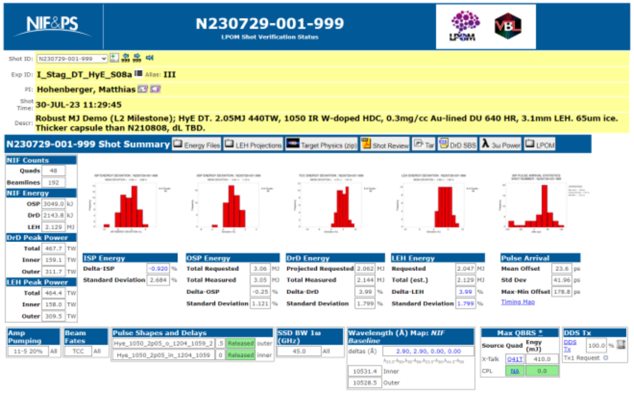
Bin	Start	End
Picket	0.50	1.80
Trough	1.80	2.60
Shock2		
Shock3	2.60	3.90
Rise To Peak	3.90	5.55
At Peak	5.55	9.40

Inner, Hye_1050_2p05_in_1204_1059 , BL131

Figure 8: Screenshot of the Loop3 Editor Tool which shows how the pulse for the latest ignition repeat shot is segmented into bins.

IMPROVED SYMMETRY REPORTING

After a shot successfully completes, the LPOM software provides detailed analysis and metrics regarding both laser performance which can in turn be used to understand how the target performed as well. The LPOM system talks to the control software and other databases with readings from various laser diagnostics and forms a similar report overall and by quad for the experiment shot report (see Fig. 9).



N230729-001-999
LPOM Shot Verification Status

Shot ID: N230729-001-999
Exp ID: I_Stag_DT_HyE_S08a Alias: III
PI: Hohenberger, Matthias
Shot Time: 30-JUL-23 11:29:45
Descr: Robust MJ Demo (L2 Milestone); HyE DT. 2.05MJ 440TW, 1050 IR W-doped HDC, 0.3mg/cc Au-lined DU 640 HR, 3.1mm LEH. 65um ice. Thicker capsule than N210808, dL TBD.

N230729-001-999 Shot Summary

NIF Counts
Quads 48
Beamlines 192

NIF Energy
OSP 3049.0 kJ
DrD 2143.8 kJ
LEH 2.129 MJ

DrD Peak Power
Total 467.7 TW
Inner 159.1 TW
Outer 311.7 TW

LEH Peak Power
Total 464.4 TW
Inner 158.0 TW
Outer 309.5 TW

ISP Energy
Delta-ISP -0.920 %
Standard Deviation 2.684 %

OSP Energy
Total Requested 3.06 MJ
Total Measured 3.05 MJ
Delta-OSP -0.25 %
Standard Deviation 1.121 %

DrD Energy
Projected Requested 2.062 MJ
Total Measured 2.144 MJ
Delta-DrD 3.99 %
Standard Deviation 1.799 %

LEH Energy
Requested 2.047 MJ
Total (est.) 2.129 MJ
Delta-LEH 3.99 %
Standard Deviation 1.799 %

Pulse Arrival
Mean Offset 23.6 ps
Std Dev 41.96 ps
Max-Min Offset 178.8 ps

Amp Pumping
11-5 20% All

Beam Fates
TCC All

Pulse Shapes and Delays
Hye_1050_2p05_o_1204_1059_2 .5 Released outer
Hye_1050_2p05_in_1204_1059 0 Released inner

SSD BW 1ω (GHz)
45.0 All

Wavelength (Å) Map: *NIF Baseline*
deltas (Å) 2.90, 2.90, 0.00, 0.00
10531.4 Inner
10528.5 Outer

Max QBRS
Source Quad Engy (mJ)
X-Talk Q41T 410.0
CPL NA 0.0

DDS Tx
DDS Tx 100.0 %
Tx1 Request

Figure 9: The shot report main page from a recent ignition repeat. The red histograms show energy deviations at key laser diagnostic sensors read from the ICCS databases.

In addition to general overall performance, LPOM also provides detailed time-based comparisons of the power profiles requested and delivered across all 192 laser beams. We do not have 3ω power sensors on all the laser beams, so when not available both the VBL model and some transfer functions can be used as a substitute to derive 192 beam-based metrics. In the power accuracy plot shown we can see the pulse is broken up into several bins, each of which is carefully modelled and managed to time shock waves in the pulse to properly implode the target (see Fig. 10). As mentioned earlier in the paper, the accuracy in the model had been sufficient at 1% but in more recent ignition shots we have tightened this requirement. In the red line shown below at the peak of the pulse, you will see it is a bit higher than the requested black line. That is due to relatively newly uncovered phenomena at NIF – neutron induced energetics readings – meaning the neutrons produced by the target implosion are affecting the yield recorded by the energy calorimeters at the level of a couple of percent LPOM just recently deployed neutron corrected energetics measurements, though we do not yet have the fine detail to correct the entire pulse at the peak due to this effect.

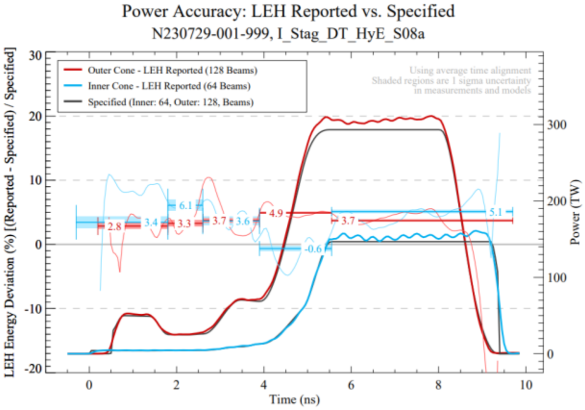


Figure 10: Binned power accuracy report on the recent successful ignition repeat shot

Another crucial aspect LPOM is used for by the target physicists is to produce metrics about how symmetric the target implosion is likely to have been. We can do so by examining the measured power profiles and energetics in the 3ω section just before the beams enter the target chamber. The display of metrics related to this symmetry work is done in the shot report symmetry tab, and now has new 360-degree projections to visualize the hotspot over time [5] (see Fig. 11).

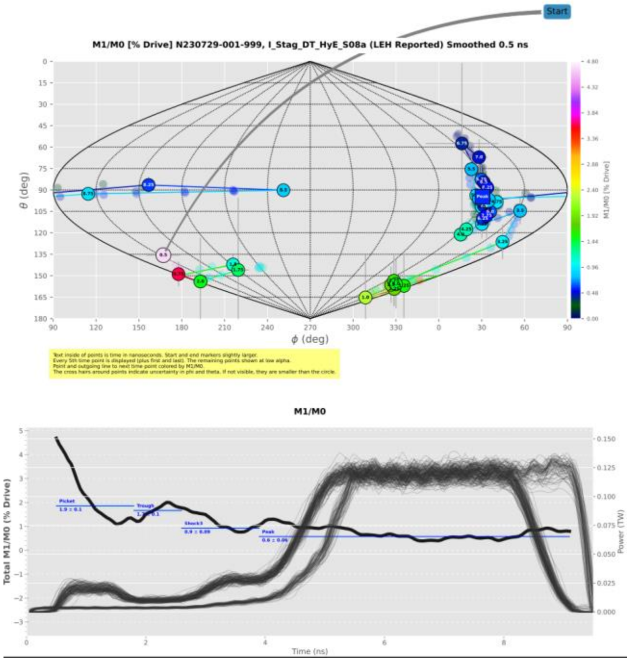


Figure 11: Several new symmetry related plots have been added to the LPOM shot report page to show the changes in the symmetry over time.

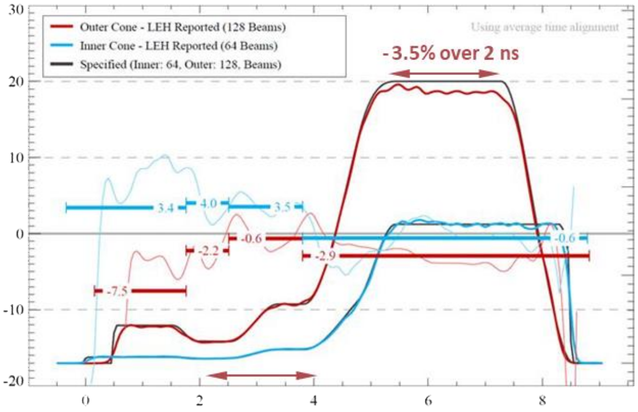


Figure 12: Example LPOM developed power accuracy report showing a ‘droop’ at the peak of the pulse resulting in poor accuracy. Thick lined traces are power (TW) vs. time (ns).

PULSE SHAPING ERRORS

A few years ago, we started noting some of the higher yield ignition type pulses would experience a ‘droop’ in the power traces (see Fig. 12) originating from the front-end. To keep gathering metrics before and after a complete retooling of the front-end was undertaken, LPOM developed a sophisticated droop detection algorithm to issue warnings to laser performance experts that such an event had occurred. This built confidence that the event was indeed mitigated by the new fiber-based MOR retooling, as shown in Fig. 13. After the front-end redesign, this shape error was fixed It has led to more studies and evaluation of future hardware improvements to get superior stability in the generated 3ω pulse on target with an advanced system called High-Fidelity Pulse Shaping (HiFiPS) system.

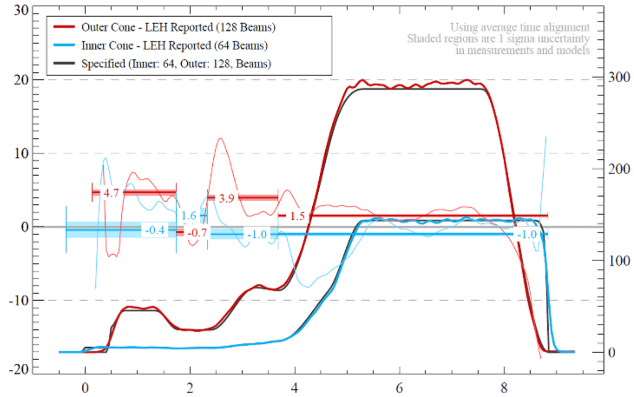


Figure 13: The pulse shaping error event has now been mitigated by the front-end redesign. Thick lined traces are power (TW) vs. time (ns).

CONCLUSION

It required a large collaboration of many teams working together to be able to stand at and cross over the threshold that is fusion ignition. The success we’ve had in this last year required fine tuning of the pulse shape by target designers, the simulation predictions by the physics modelers and the performance of the laser by the laser physics team. We tackled all these aspects while at the same time delivering on many other critical missions at NIF. This multidecadal effort began with a vision and to meet it more stringent laser performance was required and delivered which included utilizing the laser modeling VBL and the driver of that engine, the Laser Operations Performance Model software.

ACKNOWLEDGEMENTS

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