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HIGH FIDELITY PULSE SHAPING FOR THE NATIONAL IGNITION FACILITY

A. S. Gowda†, A. Barnes, B. Buckley, A. Calonico-Soto, E. Carr, J. Chou, P. Devore, V. Gopalan, JM. Di Nicola, J. Heebner, V. Hernandez, R. Muir, A. Pao, L. Pelz, L. Wang, A. Wargo
Lawrence Livermore National Lab, Livermore, U.S.A

Abstract

The National Ignition Facility (NIF) is the world's most energetic laser capable of delivering 2.05 MJ of energy with peak powers up to 500 terawatts on targets a few mms in diameter. This enables extreme conditions in temperature and pressure allowing a wide variety of exploratory experiments from triggering fusion ignition to emulating temperatures and pressures at the center of stars or giant planets. This capability enabled the groundbreaking results of December 5th, 2022 when scientific breakeven in fusion was demonstrated with a target gain of 1.5. A key aspect of supporting various experiments at NIF is the ability to custom shape the pulses of the 48 quads independently with high fidelity as needed by the experimentalists. For more than 20 years, the Master Oscillator Room's (MOR) pulse shaping system has served NIF well. However, a pulse shaping system that would provide better shot-to-shot stability, power balance and accuracy across the 192 beams as well as mitigate obsolescence issues is required for future NIF experiments including ignition. The pulse shapes requests vary drastically at NIF which lead to challenging requirements for the hardware, timing and closed loop shaping systems. In the past two years, a High-Fidelity Pulse Shaping System was designed, and a proof-of-concept prototype was shown to meet all requirements. This talk will discuss design challenges, solutions and how modernization of the pulse shaping hardware helped simple control algorithms meet the stringent requirements set by the experimentalists.

INTRODUCTION

The capability of imploding small capsules to study the physics and interaction of materials at high pressures, matter and radiation temperatures and densities is a valuable tool across fields, from understanding the mechanisms driving stars and the interiors of giant planets to creating a self-sustaining thermonuclear fusion reaction. While multiple technologies exist to create focused energy and power, with the demonstration of the laser in 1960, the option of focusing the energy of laser beams into a small volume was pursued by Lawrence Livermore National Labs to produce mini-fusion explosions. Decades of research and development on a practical laser system capable of delivering the power and energy required for such implosions culminated in the National Ignition Facility (NIF), the world's most energetic laser that can achieve a high-density, symmetric implosion enabling the study of extreme conditions for Stockpile Stewardship [1]. NIF focusses the energy of 192 beams into a cylindrical capsule a few mms in size to create matter temperatures $> 10^8\,K$, radiation temperatures $> 3.5 \times 10^6\,K$, densities $> 10^2\,g/cm^3$ and pressures $> 10^{11}\,atm$ [2]. The 192 beams combined deliver about 2.05 MJ energy [2]. With this capability, on December 5th, 2022, a self-sustaining fusion reaction that generated 3.15 MJ from 2.05 MJ of laser energy, a target gain of 1.5, was demonstrated for the first time [2, 3]. Recently, this achievement was repeated on July 30th, 2023 with even higher energy out 3.88 MJ with 2.04 MJ laser energy, a target gain of 1.9.

The facility is a powerful tool for experiments in fields spanning high energy density to discovery science. An important feature of the facility that supports the vast breadth of experiments is flexibility of shaping 48 independent shapes with custom delays. Figure 1 illustrates the breadth of pulses that users request at Target Chamber Center (TCC), from high contrast ratio (defined as the ratio of the power at the peak divided by the lowest power in the foot) pulses for ignition experiments to long, slow but precise power ramps for high energy density science experiments.

This paper describes the legacy pulse shaping system used at NIF and a recent upgrade that was deployed to improve performance of the shaping system as well as address obsolescence issues. The paper is broken up into three main sections, the first section describes how pulse shaping is accomplished at NIF and the more stringent performance requirements needed for future experiments, the second section describes the upgrade that was designed for higher fidelity and NIF sustainment and the third section outlines the performance of the upgrade. The conclusions are outlined in the final section.

PULSE SHAPING AT NIF

Figure 2 illustrates the physical and control path of an individual beamline [1]. The pulse starts in the Master Oscillator Room (MOR) as a nominally Flat-in-Time (FIT) pulse near ~1053 nm wavelength. The pulse is shaped in the MOR and passed through the rest of the optics which amplifies 10^{15} times and frequency converts twice from $1\omega \rightarrow 2\omega \rightarrow 3\omega$. The MOR is the only point in the beamline that has active feedback control of the pulse and can correct for the distortions to the pulse shape from the amplification and frequency conversion process. A typical shot starts with the user inputting the required pulse shape at Target Chamber Center (TCC) into the Laser Performance and Operations Model (LPOM). LPOM with the Virtual Beamline engine back propagates the pulse from

* Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-PROC-855426
† gowda1@llnl.gov

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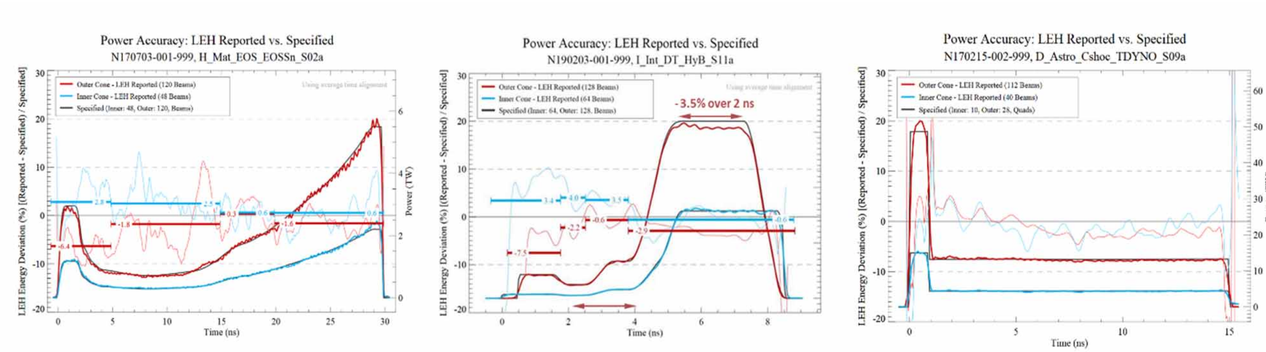

Figure 1: Pulse shapes for various experiments at the National Ignition Facility. From left to right, slow precise ramps for high energy density science experiments, high contrast ratio pulses with pickets and a main pulse for ignition experiments and a burst of energy followed by constant power for discovery science experiments.

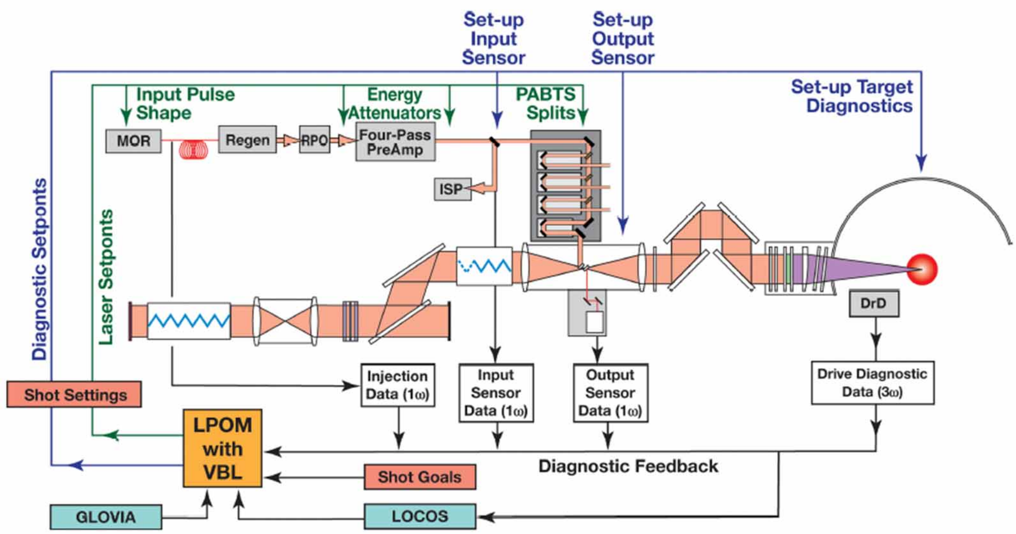

Figure 2: Block diagram of the NIF Beamline with diagnostic and control paths. The experimentalist inputs the required pulse shape for a beamline into the Laser Performance and Operations Model (LPOM). LPOM with Virtual Beamline engine (VBL) flows back to the Master Oscillator Room (MOR) where the pulse shaping system is tasked with carving the shape with tight tolerances [1].

TCC to the MOR using models of the amplification and frequency conversion process to get a best estimate of the required pulse shape at MOR. Figure 3 shows a typical change in pulse shape for ignition experiments from the TCC (blue), the output of the main laser (dark red) to the injection of the main laser (light red). A major source of distortion comes from saturation in the amplifiers of the NIF beamline, a 20:1 contrast ratio pulse in the MOR results in a 5:1 pulse at TCC. Thus, the pulse shaping system in the MOR must be capable of a high dynamic range, i.e., shaping very small features with minimal added noise.

The Legacy Pulse Shaping System at NIF uses Field Effect Transistors (FETs) to carve arbitrary pulses onto a FIT optical pulse. A set of 140 FETs with 300ps wide impulse responses spaced 250 ps apart are summed together with independently controlled amplitude settings are summed to form an arbitrary waveform 35 ns long as shown in Fig. 4 [4]. While the 20-year-old pulse shaping system has served well, obsolescence issues and performance demands for future experiments were identified which warranted an upgrade for NIF sustainment. Some examples include, the FETs needing calibration in time and amplitude for better fidelity and to avoid ripples, limited fidelity due to the shaping diagnostic using RF amplifiers and stitching to achieve high contrast ratios. A pulse shaping system that would provide higher shot-to-shot stability, better power balance and accuracy across the beams was necessary for future NIF experiments including ignition.

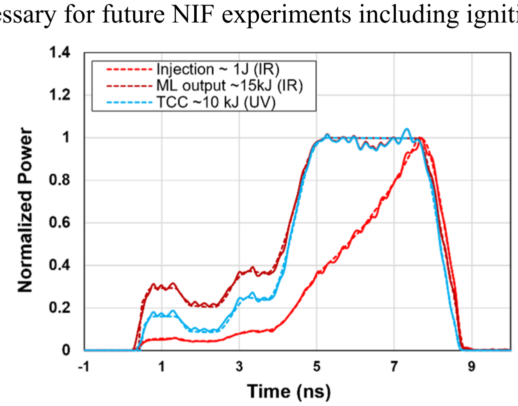

Figure 3. Pulse Shape evolution along beam B111 (outer cone) during N210808 ignition experiment.

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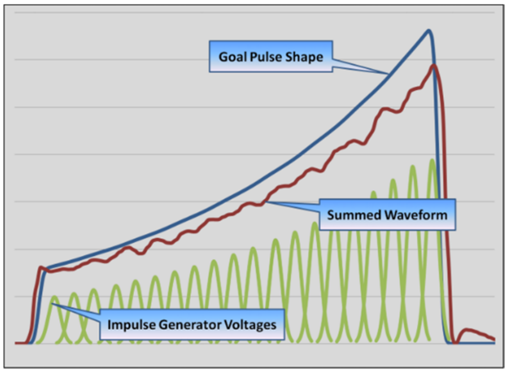

Figure 4. Legacy pulse shaping via summing of individually amplitude and time-controlled Field Effect Transistors [4].

HIGH FIDELITY PULSE SHAPER

The upgrade to the pulse shaping system in the MOR aimed to provide high fidelity shaping as well as modernize the technology used. The High-Fidelity Pulse Shaping system (HiFiPS) design combines high performance commercial off-the-shelf hardware with customizations to meet stringent performance requirements. Figure 5 depicts the high-level block diagram for HiFiPS. The carving of the pulse shape is done using a digital-to-analog converter in the Tektronix AWG5200 series Arbitrary Waveform Generator (AWG) [5]. This uses rising and falling edges of clocks for precise timing of pixels on the optical pulse and digital bits to control the amplitude of each pixel. The optical pulse is sent through a dual-stage Electro-Optic Modulator (EOM) driven by the AWG, thus imparting the shape on to the optical pulse. As shown in the block diagram, one stage is driven by the AWG and the other is driven by a gating pulse with fast rising and falling edges. The gating pulse, or "slicer", is used to sharpen the edges of the carved pulse. An additional capability is the ability to switch between a pulse shape and a short impulse of <90 ps Full-Width Half Maximum (FWHM) using a programmable switch. The impulse generator, slicer generator, summing circuitry, modulator bias control and other supporting circuitry is performed using a Highland Technology T500 Modulator Chassis, shown in Fig. 5.

The shaping in the MOR is a closed loop shaping system, i.e. a best guess of the target shape is carved into the optical pulse and the result is recorded on a shaping diagnostic which compares the optical pulse to the target shape. The AWG waveform is updated using the calculated error and the next iteration continued till the shape error w.r.t the target is below a pre-determined tolerance. To achieve the extremely low error tolerances in the shape, a high-fidelity shaping diagnostic that can measure the shape to higher precision than the tolerances was required. The design used a Tektronix LPD64 Analog-to-Digital Converter (ADC) [6] with customizations to include dithering and averaging [7]. The customizations were necessary to meet the stringent tolerance requirements. The shape also needed to meet tight timing requirements, which required careful design of the system clock and triggers. The next few subsections outline the design and specifications of the three sub-systems namely: the High Dynamic Range Shaper which includes the AWG, T500 Modulator Chassis, and the EOM; the Shaping Diagnostic and the Shaping Algorithm.

High Dynamic Range Shaper

The AWG used in HiFiPS was required to shape a 200:1 contrast pulse with < 0.25% accuracy across the pulse. Accuracy is defined by Equation 1.

$$\Delta x_i(\%) = \frac{(x_i - r_i)}{r_i} \times 100 \tag{1}$$

where x_i is the i^{th} sample of the shape measured on the shaping diagnostic and r_i is the i^{th} sample of the target shape.

The accuracy requirement set the vertical resolution requirement of the AWG. Through simulations it was determined that >14 bits of the resolution were needed to shape to 0.25% accuracy at 200:1 contrast as shown in Fig. 6.

Additionally, the shot-to-shot noise added by HiFiPS had to be < 2.3% at 200:1 contrast. This set the Signal-to-Noise Ratio (SNR) requirement for the AWG+EOM driver. The Tektronix AWG5200 series specifications (shown in Table 1) met both the resolution and noise required to shape down to 0.25% accuracy at 200:1 contrast. The AWG driver amplification in the T500 chassis was designed for minimal degradation of the AWG SNR while filling 80-90% of the EOM's V_π (voltage inducing π phase change). Equation 2 forward propagates AWG driver noise at the RF input of an EOM to the EOM output optical pulse. Compression from the sine-square response of the EOM reduces noise at the peak but exaggerates the noise at the trough. Figure 7 shows the shot-to-shot noise of the AWG5200 forward propagated to the output of the EOM using Eq. (2). As shown the noise is well below the 2.3% requirement at 200:1 contrast.

$$SNR_{Opt} = SNR_{RF} \frac{sin\left(\frac{\pi}{2}r\right)}{\pi r} \frac{1}{\sqrt{CR - sin^2\left(\frac{\pi}{2}r\right)}} \tag{2}$$

where SNR_{Opt} is the SNR of the optical pulse at the output of the EOM, SNR_{RF} is the SNR of the AWG driver into the EOM carving the pulse, r is the ratio of the peak voltage of the AWG driver to the EOM's V_π and CR is the pulse contrast.

Table 1: Tektronix AWG5200 Specifications [5]

Parameter	Value
Vertical Resolution	16
ENOB	>9 bits at 2 GHz
Sample Rate	> 5 Gsps
Impulse Response	240 ps (optical)

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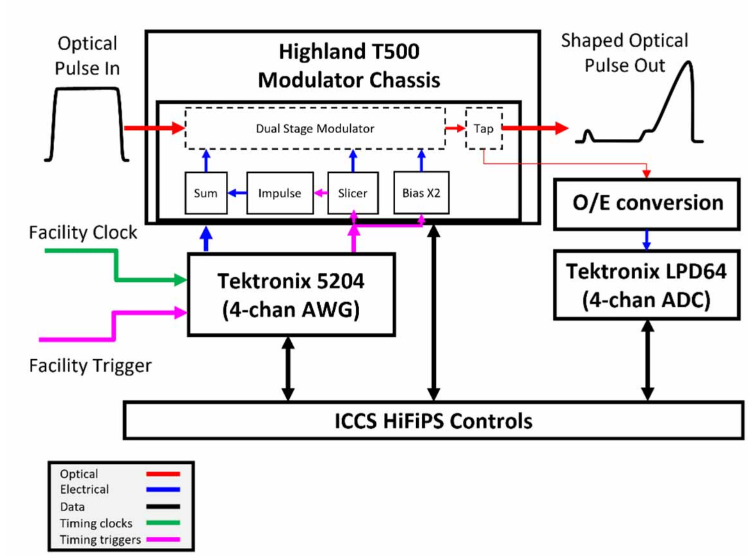

Figure 5: Block diagram of the High-Fidelity Pulse Shaping System.

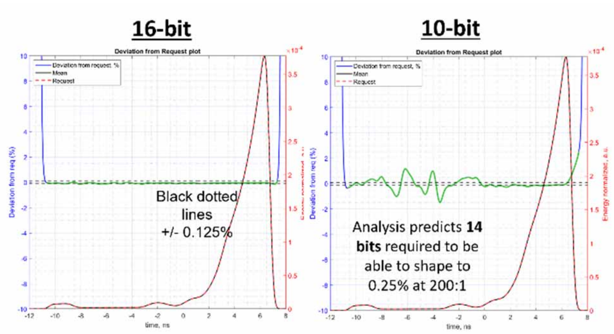

Figure 6. Simulations showing >14-bit AWG resolution required to meet <0.25% accuracy at 200:1 contrast. Left: shape error with 16 bits. Right: shape error with 14 bits.

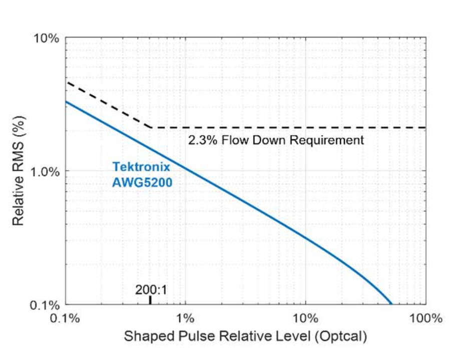

Figure 7. Analytical derivations showing >9 ENOB Arbitrary Waveform Generator can meet <2.3% rms noise at 200:1 contrast.

The dual stage EOM is housed inside the Highland T500 Modulator chassis in a temperature-controlled oven which stabilizes the bias of the EOM. In addition, a bias controller applies a voltage to the EOM such that without a signal from the AWG, no light passes through the EOM. The T500 takes the AWG output and combines it with an impulse generator capable of delivering a <90 ps FWHM pulse that can be used if requested via a programmable switch. The T500 chassis also includes a gating pulse (see Slicer in Fig. 5) with <100 ps rising and falling edges input into the second stage of the EOM and is used to sharpen the edges of the shaped pulse and define the start of the pulse. The chassis was custom built to meet the stringent rising and falling edge gating pulse requirements, low noise driver requirements and the impulse FWHM requirements.

Shaping Diagnostic

To shape to high-fidelity, a diagnostic capable of recording the pulse shape with less than the required tolerance was designed. A tap at the optical output (shown in Fig 5) was sent to an Optical-to-Electrical converter (O/E converter) and the electrical signal recorded using a high-performance oscilloscope. The performance of commercial-off-the shelf (COTs) oscilloscopes needed to be improved in both noise and linearity to meet HiFiPS requirements. The noise of an oscilloscope can be modelled as additive white gaussian noise that is uncorrelated across multiple acquisitions. By averaging these multiple acquisitions, the uncorrelated noise can be reduced by $\sqrt{N}$, where N is the number of acquisitions. Another practical limitation is the Integral Non-Linearity of the ADC, a measure of the deviation between the ideal input quantization level vs measured quantization level. At large contrast ratios, a small deviation from the ideal quantization level in the diagnostic can result in a large measurement error in the pulse shape. Randomizing the error across different quantization levels can smooth out the nonlinear error. This can be achieved by capturing the acquisitions at multiple dc offsets prior to averaging, i.e., implementing a dither in amplitude [7].

Both performance enhancements described above were provided on the Tektronix 6 series LPD64 through customizations. The specifications for the Tektronix LPD64 are in Table 2. Heavy floating-point averaging of 5120 acquisitions reduces the rms noise at 200:1 to <0.25% (as shown in Fig. 8). The custom fast-averaging feature from

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Tektronix reduced the averaging time to ~8secs for 5120 averages while maintaining high precision.

Table 2: Tektronix LPD64 Specifications [6]

Parameter	Value
Resolution	12
ENOB	>7.25 bits at 4 GHz
Sample Rate	> 12.5 Gsps
Bandwidth	4 GHz

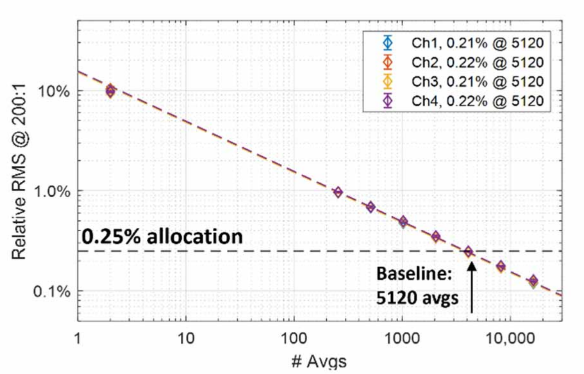

Figure 8: Measurements showing the $\sqrt{N}$ reduction in relative rms noise @ 200:1 contrast with the number of averages using the Tektronix LPD64.

Figure 9 (left) shows the inherent non-linearity of the oscilloscope leads to distortion of >1% at the trough of a typical ignition pulse (200:1 contrast). The custom feature fast-averaging feature included dithering the DC voltage offset during averaging which smooths the non-linear transfer function, reducing relative deviations to < 1% as shown in Fig. 9 (right). Thus with the designed customization worked out in collaboration with Tektronix [7] was able to enhance the COTs oscilloscope to meet the accuracy requirements.

Shaping Algorithm

To close the shaping loop, the measured pulse on the shaping diagnostic is compared to the target, deviation from the target calculated and applied as a damped correction to the AWG waveform. Below the steps involved in an iteration of the shaping loop is described:

Initialization: Smooth target shape to remove fast features, apply shaping diagnostic response and energy normalize.

1. Acquire averaged pulse shape from shaping diagnostic, smooth to remove fast features and energy normalize.
2. Re-interpolate to common time base.
3. Calculate deviation from request per Eq. (1)
4. If standard deviation of deviation from request over main part of the pulse is greater than specified tolerance, calculate the correction per Eq. (3)

$$\delta z = \left(\frac{target\ shape}{current\ shape}\right) \tag{3}$$

5. Update AWG pixels by multiplying damped correction factor per Eq. (4)

$$z_{i+1} = z_i \left(\frac{target\ shape}{current\ shape}\right)^{\alpha} \tag{4}$$

where $\alpha \epsilon [0, 0.5]$ is the damping factor.

6. Repeat from Step 1.

If standard deviation of deviation from request over main part of the pulse is less than specified tolerance, the shaping is complete. Figure 10a shows that the shaping loop using the hardware designed for HiFiPS as described in the previous sections was able to shape down to 0.25% accuracy at 200:1 contrast.

PERFORMANCE RESULTS

A full system prototype was built on a benchtop using the COTs Tektronix AWG5204, Tektronix LPD64 and a prototype Highland T500 chassis. The prototype was characterized for the following main performance criteria:

1. Average deviation from target over 8 hours
2. Standard deviation from mean over 8 hours
3. Shot-to-shot noise
4. Short-term timing jitter over 5.5 seconds
5. Long-term timing drift over 8 hours.

The prototype was set up with a stitched diagnostic to measure the shot-to-shot noise at high contrast (Criterion #3). An averaging diagnostic was used to measure standard deviation from mean over 8 hours (Criterion #2) and average deviation from target over 8 hours (Criterion #1). For the timing measurement, fast-frame mode on the averaging diagnostic was used to capture pulses every ~1 ms for ~5.5 seconds and the timing offset of each acquisition relative to the first capture was calculated using cross-correlation. The standard deviation of the timing offset over 5.5 seconds represents the timing jitter in Criterion #4. For timing drift, an averaged capture of 5120 acquisitions was taken every 5.5 seconds over 8 hours and the timing offset relative to the first acquisition was calculated using cross-correlation. The standard deviation over 8 hours represents the timing drift in Criterion #5.

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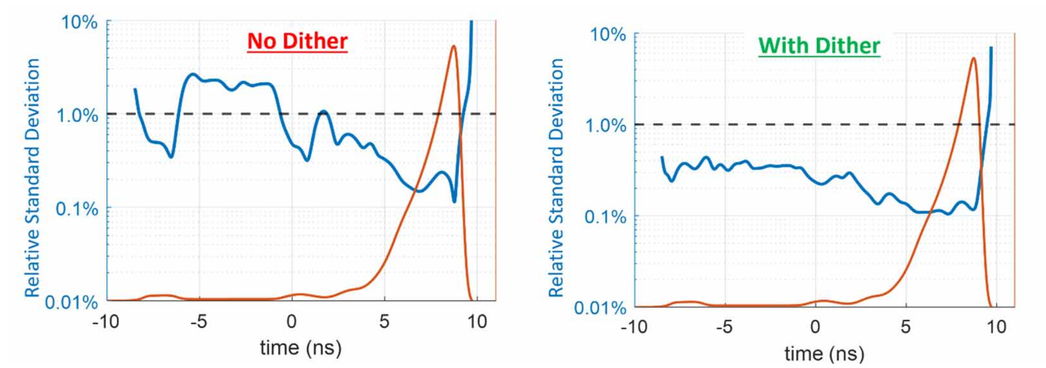

Figure 9: Inherent non-linearity of the oscilloscope leads to >1% error at trough (left). Dithering the DC voltage offset during averaging smooths the non-linear transfer function, reducing relative deviations to < 1% (right).

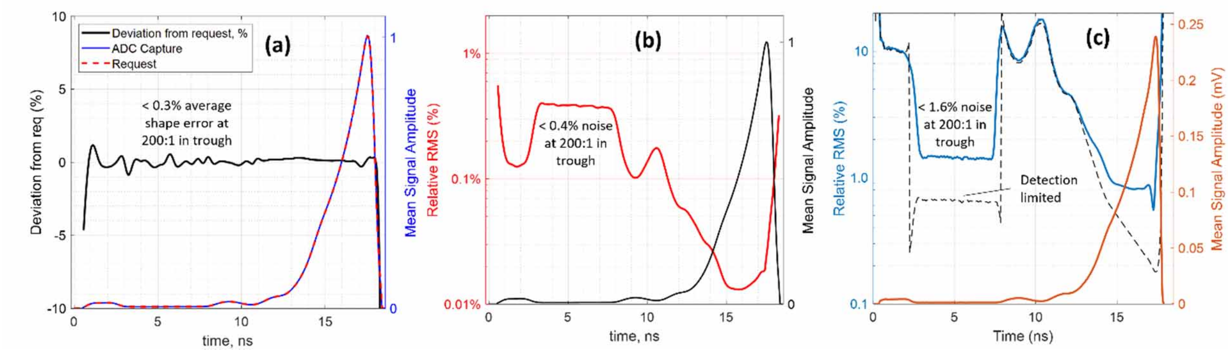

Figure 10: Performance results for (from left to right), (a) average deviation from target (criterion #1), (b) deviation from mean over 8 hours (criterion #2) and (c) shot-to-shot noise (criterion #3).

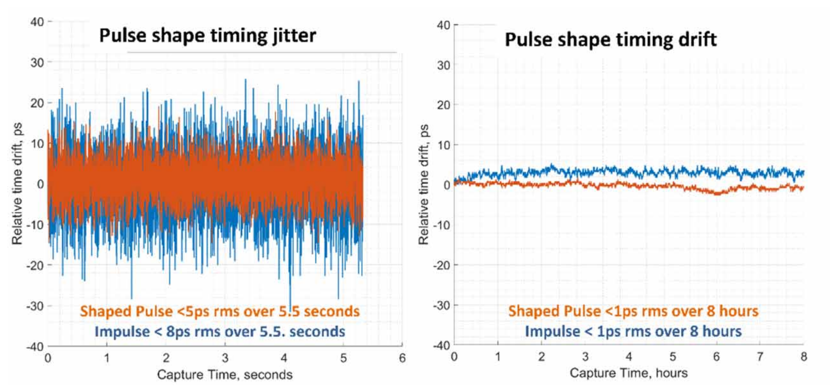

Figure 11: Performance results for (from left to right), timing jitter over 5.5 seconds (Criterion #4) and timing drift over 8 hours (Criterion #5).

The stitching diagnostic consisted of two channels of a Keysight DSOS804A stitched together in post-processing. One channel was a saturated photodiode that zoomed in on the trough to minimize added diagnostic noise, and the other was a photodiode operating in the linear regime that captured the full pulse. Contiguous captures of the pulse were taken every ~1ms and stitched together to improve the dynamic range of the measurement. The full pulse was used to estimate contrast ratio and the zoomed in trough measurement was used to measure the shot-to-shot noise (Criterion #3). The averaging diagnostic was the Tektronix LPD64 using a photodiode in linear region.

Table 3 summarizes the performance results and Figs. 10 and 11 show the measured accuracy and timing data respectively. As shown the prototype was able to achieve < 1.3% shot-to-shot noise @ 200:1 contrast with < 5 ps timing jitter. Over 8 hours, the prototype was able to keep the shape stable with < 0.5% deviation in the trough level @200:1 contrast. Additionally, the shaping loop was able to shape to < 0.3% error relative to the target. These results demonstrated a 2-4x improvement over the legacy pulse shaping system.

The new HiFiPS pulse shaping system was deployed in phases starting early 2023 and completed on all 48 quads in August 2023. Initial shots analysis at TCC since deployment is showing improved power accuracy compared to the legacy system, as shown in Fig. 12. The analysis aggregates improvements from HiFiPS as well as a recent effort to improve the pre-shaped pulse in the MOR. Figure 12 shows the power accuracy for two shapes, a slow ramp (top

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row) and a typical ignition pulse. As can be seen, the accuracy of the pulse shape at the peak has been drastically improved and the noise on the trough has been reduced by ~2x.

Table 3: HiFiPS Prototype Measured Performance

Parameter	Value
Average Deviation from target over 8 hours at 200:1	<0.3%
Standard deviation from mean over 8 hours at 200:1	<0.4%
Shot-to-shot noise	<1.3%
Timing jitter over 5.5 seconds	< 5ps
Timing drift over 8 hours	< 1ps

CONCLUSIONS

The paper outlined the recent upgrade at NIF to address obsolescence and high-fidelity shape demands for future NIF experiments. Prototype results have shown expected improvements, i.e. short-term pulse shape stability at 200:1 contrast <2%, a 4x improvement over legacy and closed-loop pulse shaping and deviation from request <0.5%. Key features such as power accuracy at TCC are expected to improve by 3-5x compared to the legacy system. While statistical data will be collected over the next year to better quantify the performance improvements in the facility, the data in this paper shows early indication of the performance enhancement available to users at NIF for future experiments.

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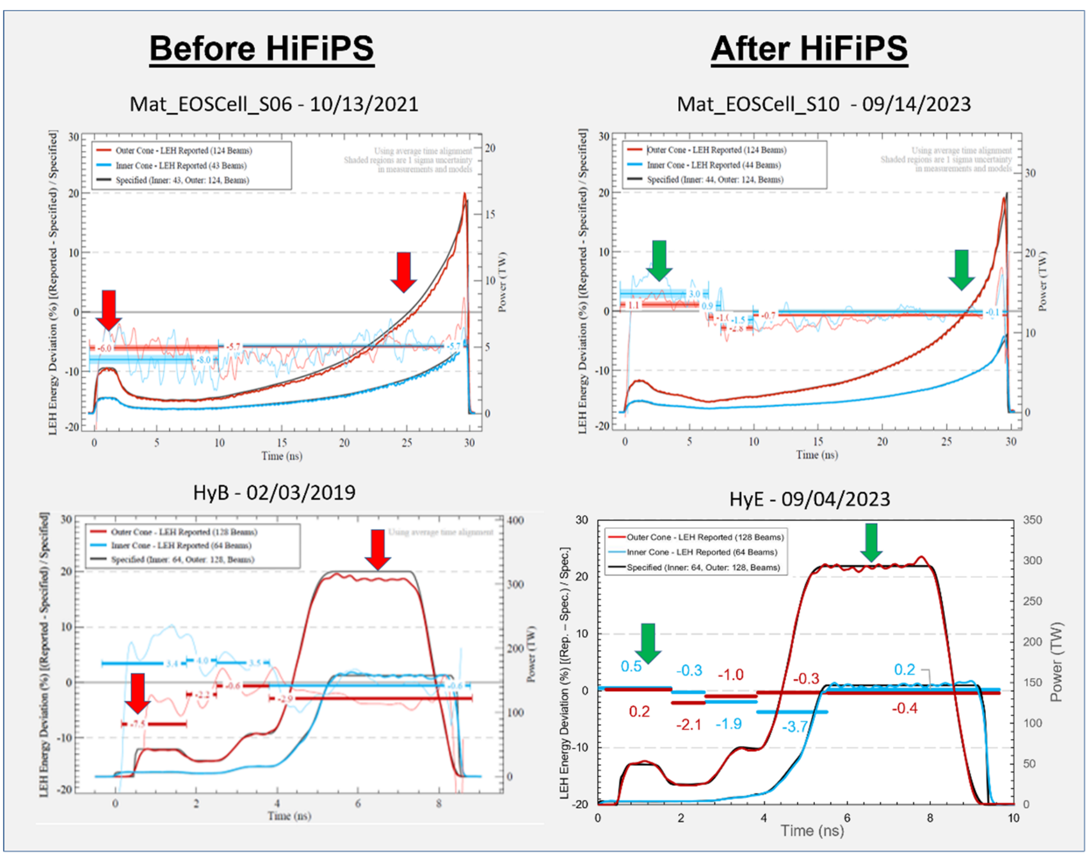

Figure 12: Initial shots analysis at Target Chamber Center since deployment is showing improved power accuracy compared to the legacy system. The accuracy of the pulse shape at the peak has been drastically improved and the noise on the trough has been reduced by ~2x.

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REFERENCES

[1] M.L. Spaeth *et al.*, "Description of the NIF Laser," *Fusion Sci. Technol.*, vol. 69, no. 1, pp. 25-145, 2016. doi:10.13182/FST15-144

[2] Jean-Michel G. Di Nicola, "First demonstration of fusion ignition by inertial confinement fusion (ICF) at the National Ignition Facility (NIF) at LLNL," in *Proc. SPIE PC12401*, High Power Lasers for Fusion Research VII, PC1240101. https://doi.org/10.1117/12.2670247

[3] A.B. Zylstra, O.A. Hurricane, D.A. Callahan, *et al.,* "Burning plasma achieved in inertial fusion," *Nature,* vol. 601, pp. 542-548, 2022. doi:10.1038/s41586-021-04281-w

[4] Gordon Brunton, Gaylen Erbert, Don Browning, Eddy Tse, "The shaping of a national ignition campaign pulsed waveform, *Fusion Eng. Des.*," vol. 87, issue 12, pp. 1940-1944, 2012. doi:10.1016/j.fusengdes.2012.09.019

[5] Tektronix AWG5200 Series Datasheet, https://www.tek.com/en/products/arbitrary-waveform-generators/awg5200

[6] Tektronix 6 Series Low Profile Digitizer Datasheet. https://www.tek.com/en/products/oscilloscopes/high-speed-digitizers/6-series-mso-low-profile

[7] Brandon Buckley *et al.*, "Discrete Offset Dithered Waveform Averaging For High-Fidelity Digitization Of Repetitive Signals," US Patent US11652494B1, 2023.