High Fidelity Pulse Shaping for the National Ignition Facility

ICALEPCS 2023

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*

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Lawrence Livermore National Laboratory

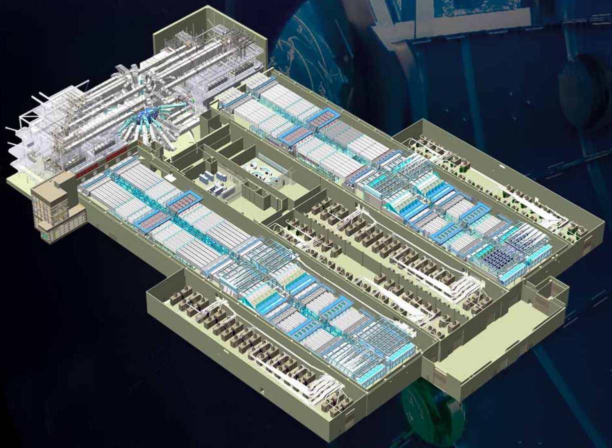
The National Ignition Facility (NIF) is the world's most energetic laser enabling the study of extreme conditions for Stockpile Stewardship

- 192 Beams, 2.05 MJ Energy, 500 TW Power
- Matter temperature >10^8 K
- Radiation temperature >3.5 x 10^6 K
- Densities >10^2 g/cm^3
- Pressures >10^{11} atm
- Number of Diagnostics >120

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

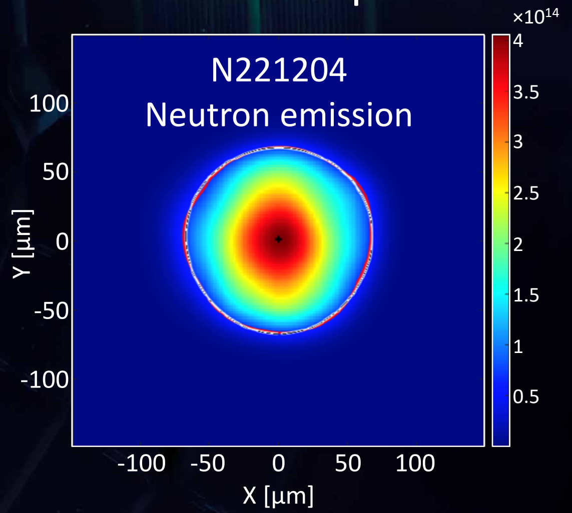
NIF Laser
on 12/5/2022

2.05 MJ UV
440 TW Peak power
for ~4 ns



Energy Output
From 12/5/2022 Experiment

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



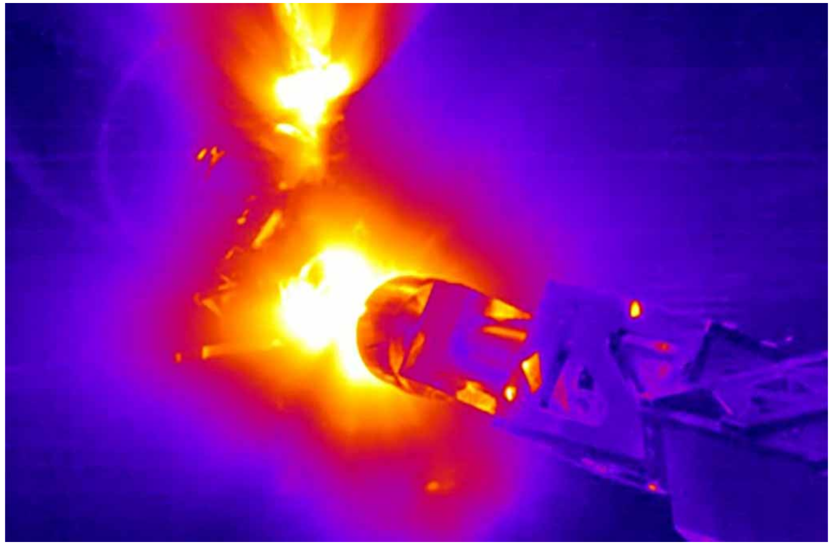
Fusion plasma ~100 μm
Temperature ~130,000,000 K

* Exceeding 1997 NAS definition of Fusion Ignition

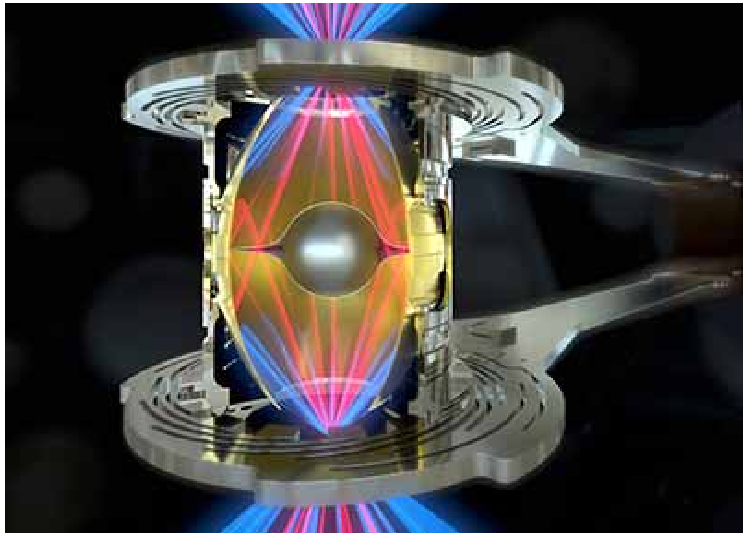
The experiment was repeated on July 30th, 2023 with a higher yield 3.88MJ and G_{target} ~ 1.9*

NIF supports a wide variety of exploratory experiments from triggering ignition fusion to emulating temperatures at the center of stars or pressures at the center of giant planets

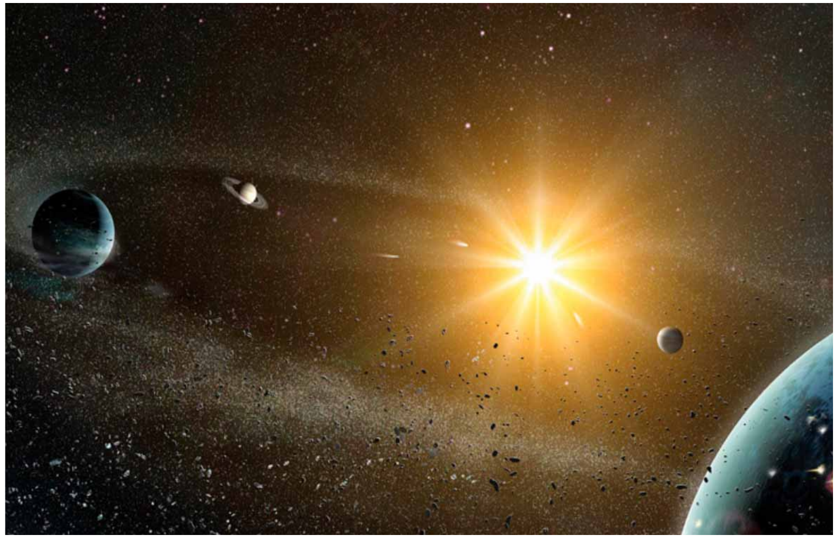
High energy density science
Studies material behavior under extreme pressure



Achieving fusion ignition
by creating a self-sustaining thermonuclear fusion reaction



Discovery Science
mimicking the mechanisms driving stars and the interiors of giant planets



The facility needs to support a variety of pulse shapes as requested by the users varying from high contrast ratio pulses to long pulses with slow but precise power ramps and simple flat-in-time

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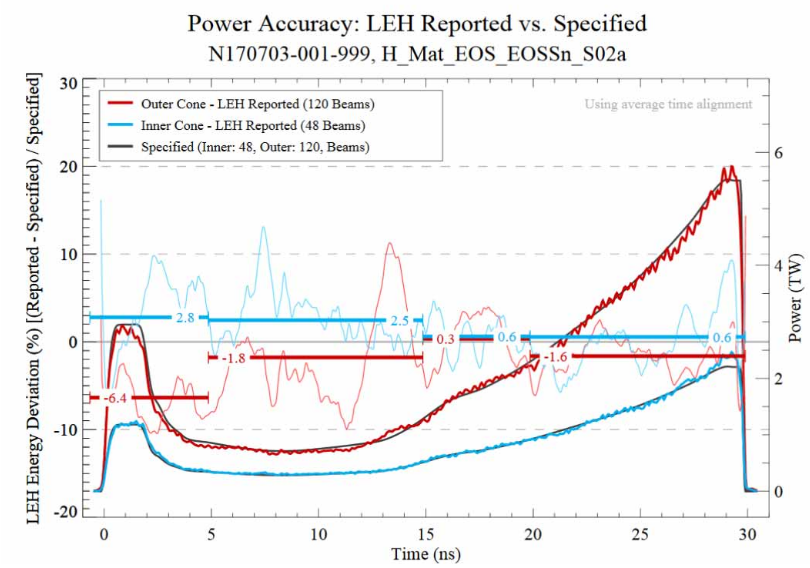

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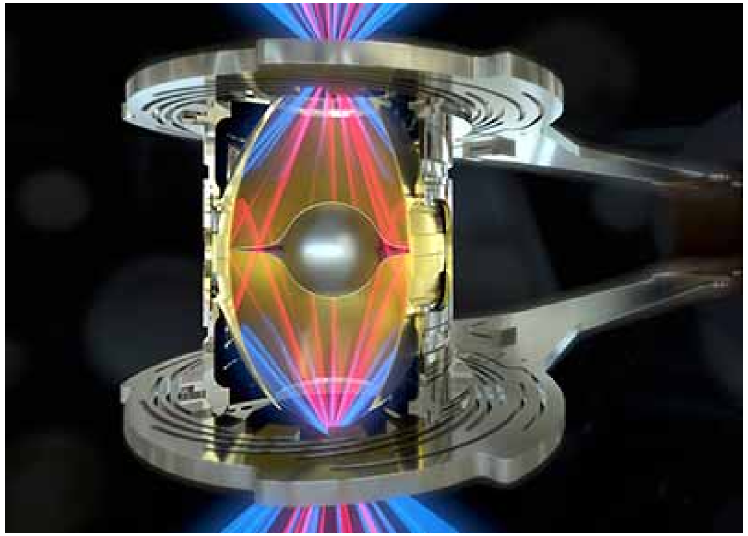

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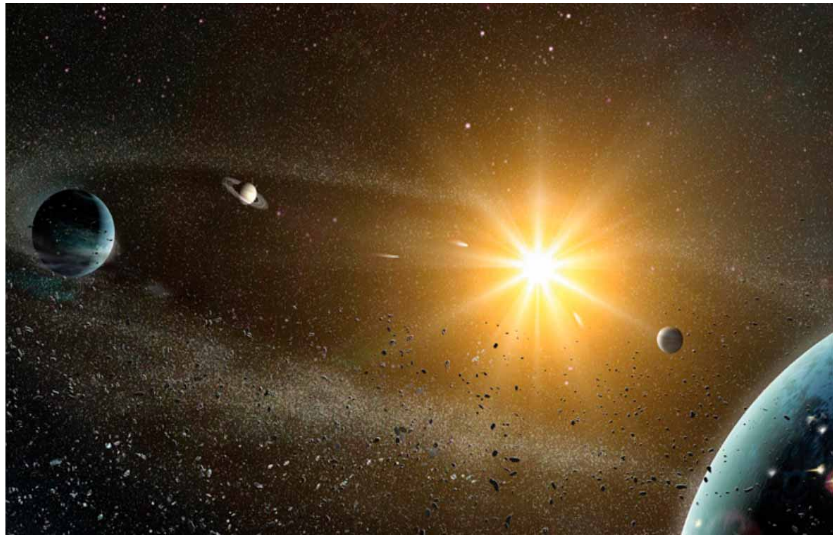

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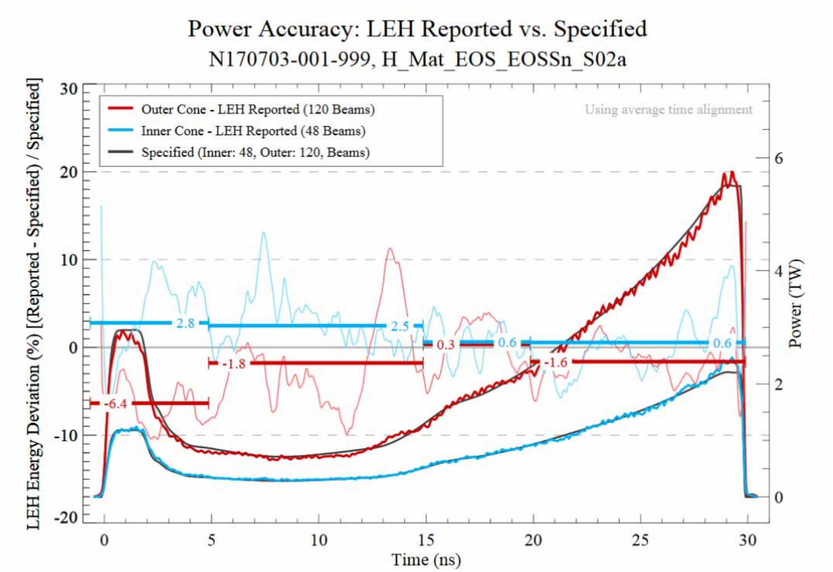

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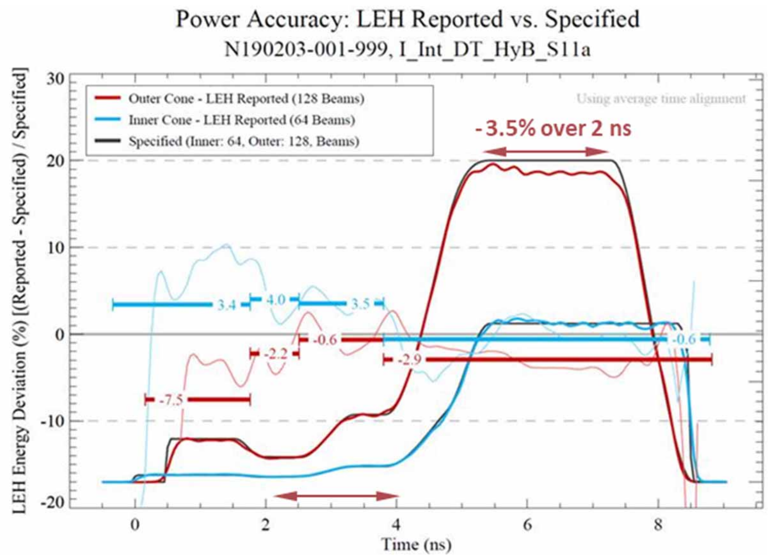

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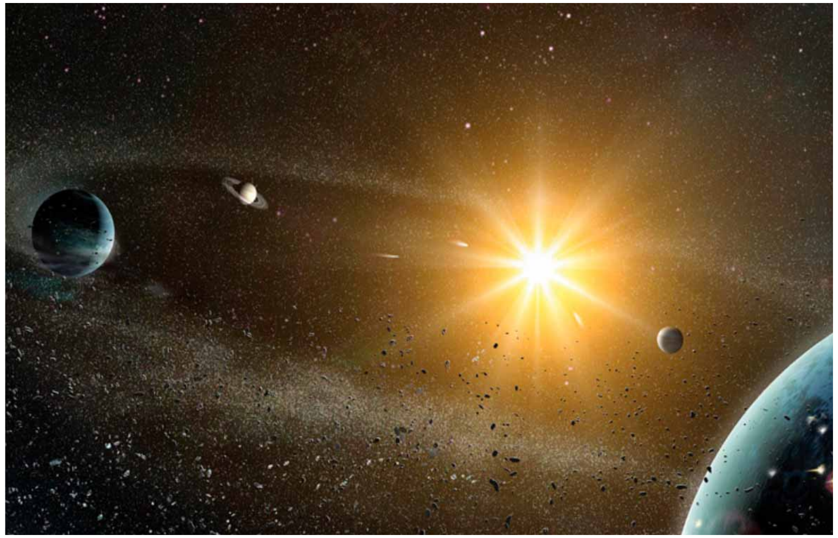

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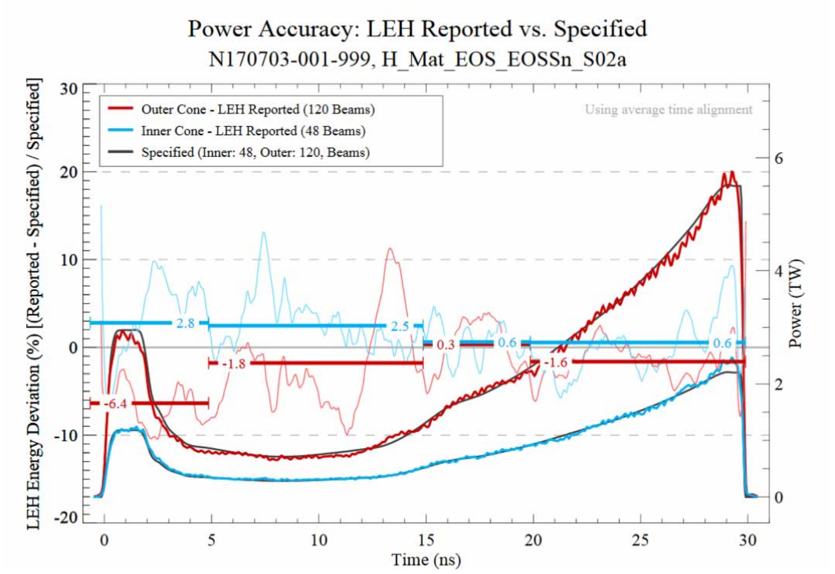

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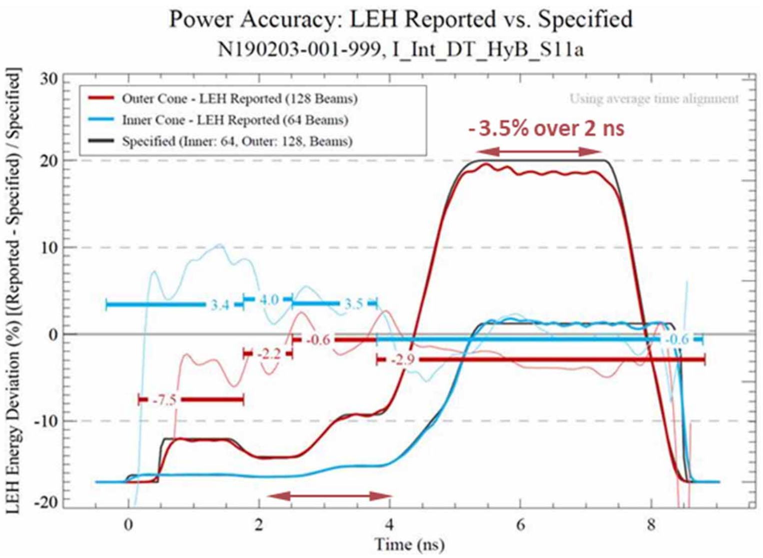

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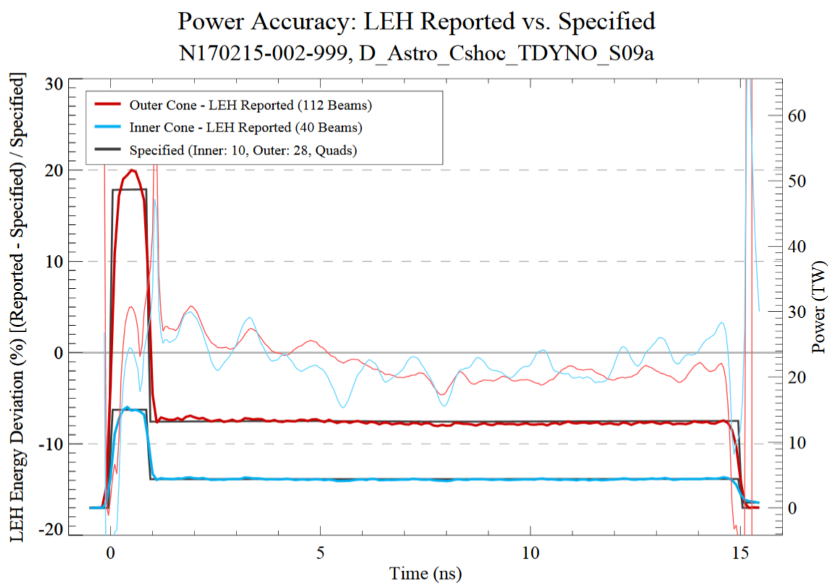
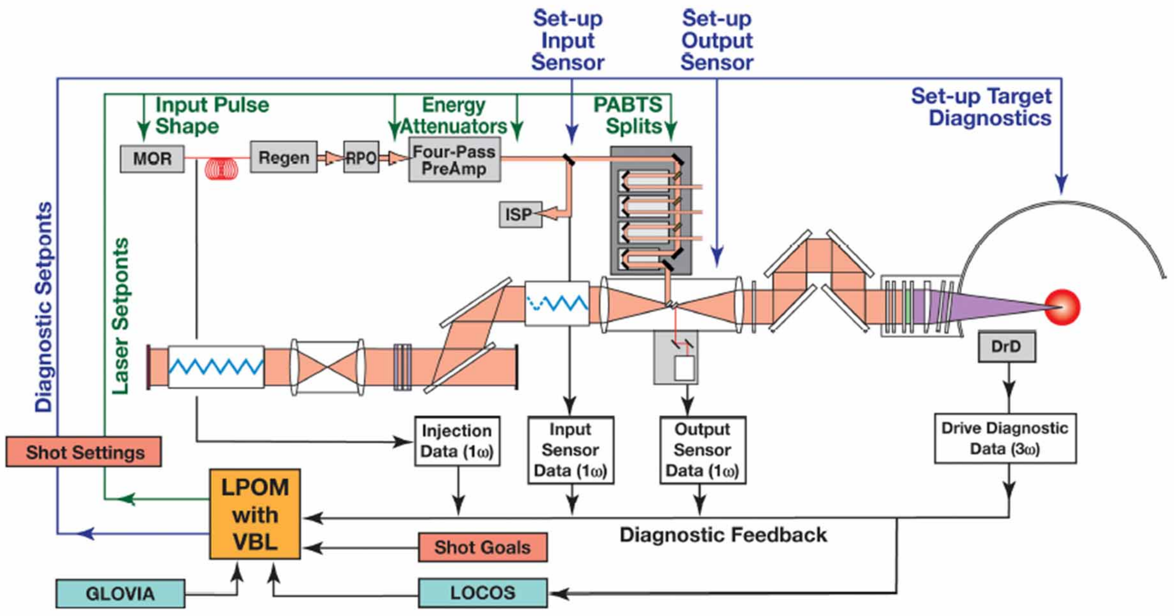
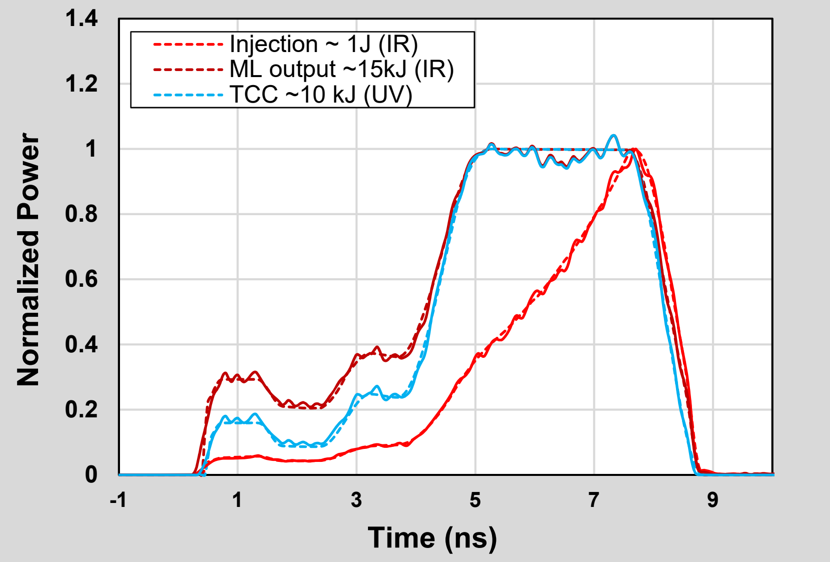


The facility needs to support a variety of pulse shapes as requested by the users varying from high contrast ratio pulses to long pulses with slow but precise power ramps and simple flat-in-time

The Master Oscillator Room (MOR) is tasked with shaping the user requested pulse profiles and delays



Contrast Ratios are much larger at the output of the MOR than at the Target Chamber Center (TCC).



Users input requested pulse shape at 3w with up to 48 independent shapes and delays

The pulses needed at the MOR are flowed back using Laser Performance and Operations Model (LPOM) using the Virtual Beamline (VBL) engine

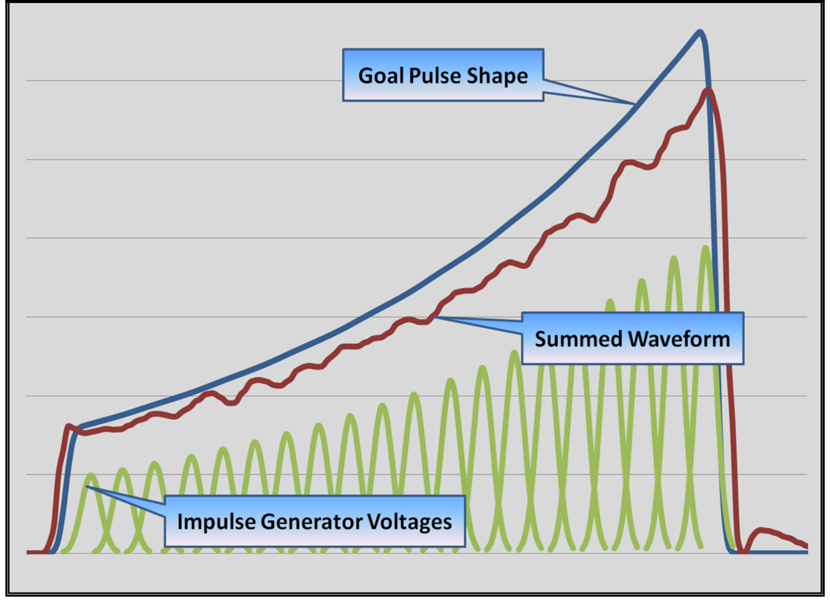
The MOR is tasked with shaping the requested pulse shape and setting delays.

The flowback of TCC request to the MOR leads to challenging shape tolerance and timing precision requirements for the hardware. Small fluctuations especially at the picket can have a larger impact (2x) at target chamber center when the laser response is not saturated.

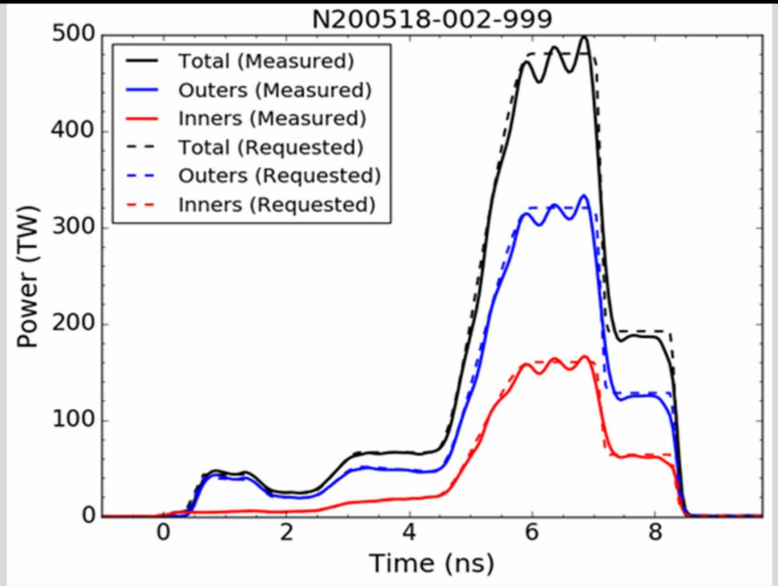
*Spaeth et.al. (2016) Description of the NIF Laser, Fusion Science and Technology, 69:1, 25-145, DOI: 10.13182/FST15-144
For more details see: FR2AO01, K. McCandless, How Accurate Laser Physics Modeling is Enabling Nuclear Fusion Ignition Experiments*

The legacy pulse shaping system has served well, but relies on 20-year-old technology

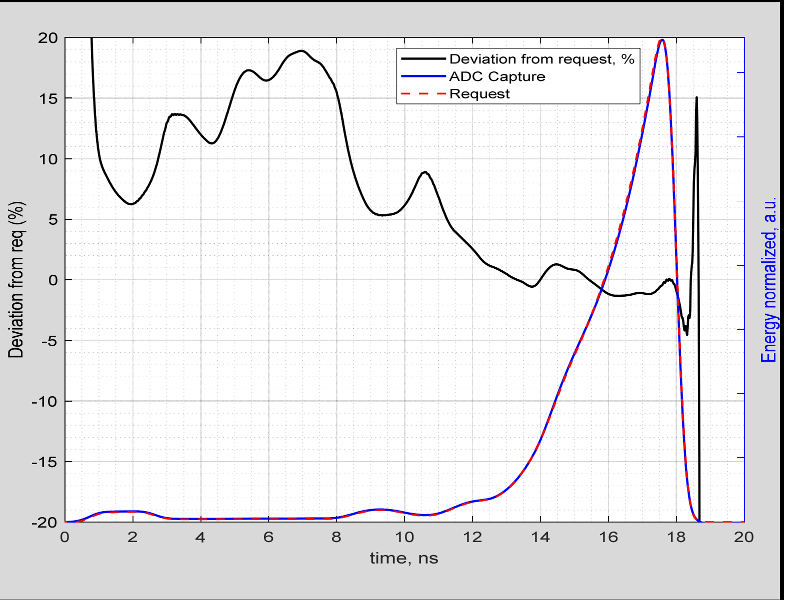
Works well for low to medium contrast ratios, but for high contrast shapes, the fidelity degrades to beyond a few %



The Field Effect Transistors need to be calibrated in time and amplitude for better fidelity and to avoid ripples



The shaping diagnostic used rf amps and stitching to achieve high contrast shaping at the expense of fidelity



Obsolescence and more stringent performance demands, such as higher shot-to-shot stability, better power balance and accuracy, prompted the development of a higher-performing and more modernized shaping system.

*Gordon Brunton, et.al., The shaping of a national ignition campaign pulsed waveform, Fusion Engineering and Design, https://doi.org/10.1016/j.fusengdes.2012.09.019

A new High-Fidelity Pulse Shaping (HiFiPS) system in the MOR will enhance the shot-to-shot reproducibility of high-contrast pulses on target

Shape error requirement: **≤ 3% at 200:1 contrast with 500ps smoothing**

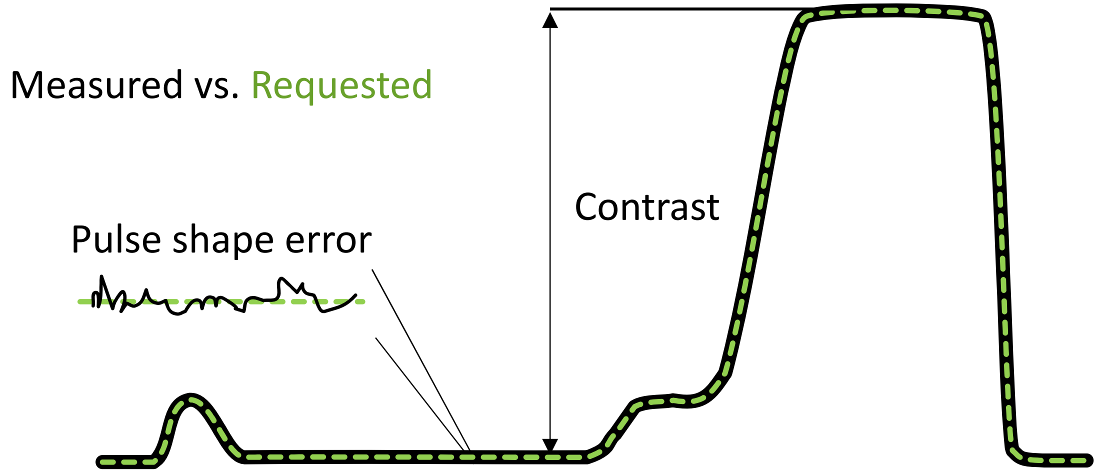
Pulse shape error contributions include:

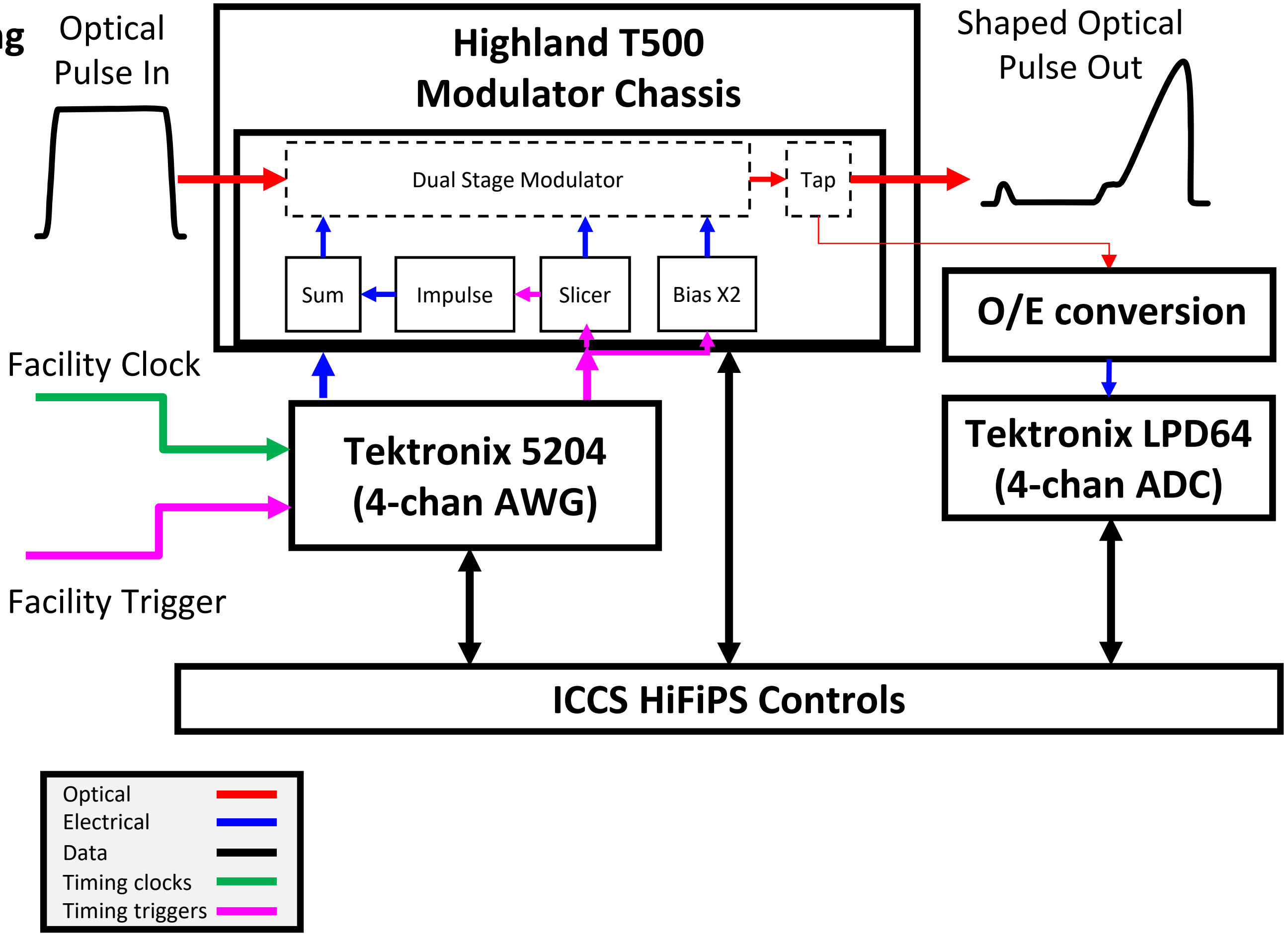
a) **Deviation from request** (averaged over 5s, deterministic, correctable)

b) **Drift** reported over 8hrs (averaged over 5s, deterministic, correctable)

c) **Shot-to-shot noise** (stochastic)

d) **Diagnostic Distortion** (nonlinearities of Photodiode and ADC)



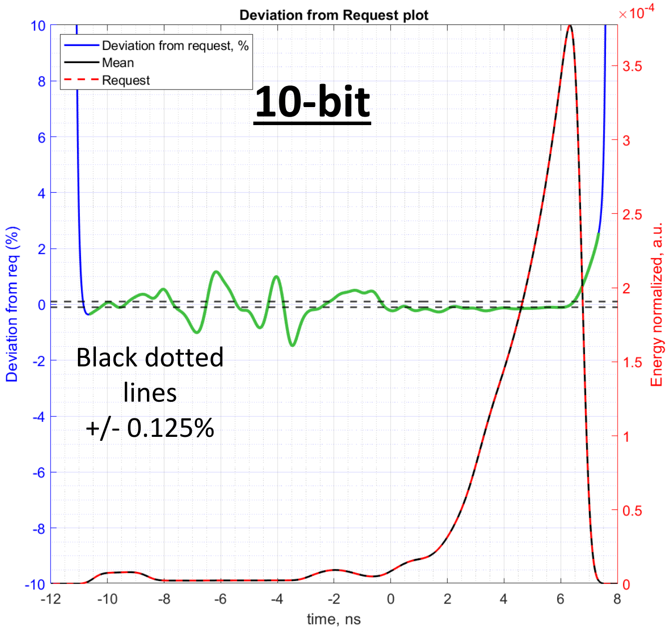


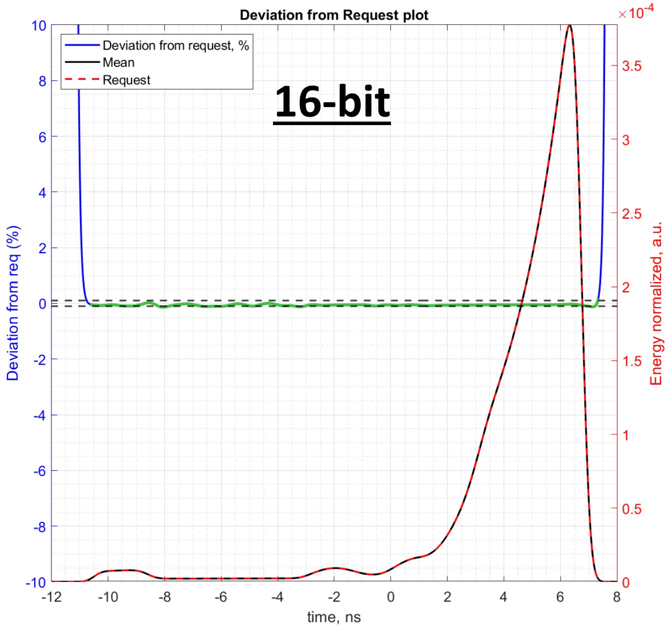
HiFiPS design combines advancements in RF electronics, fiber optics, and digital processing since NIF was commissioned with customizations to meet stringent performance requirements

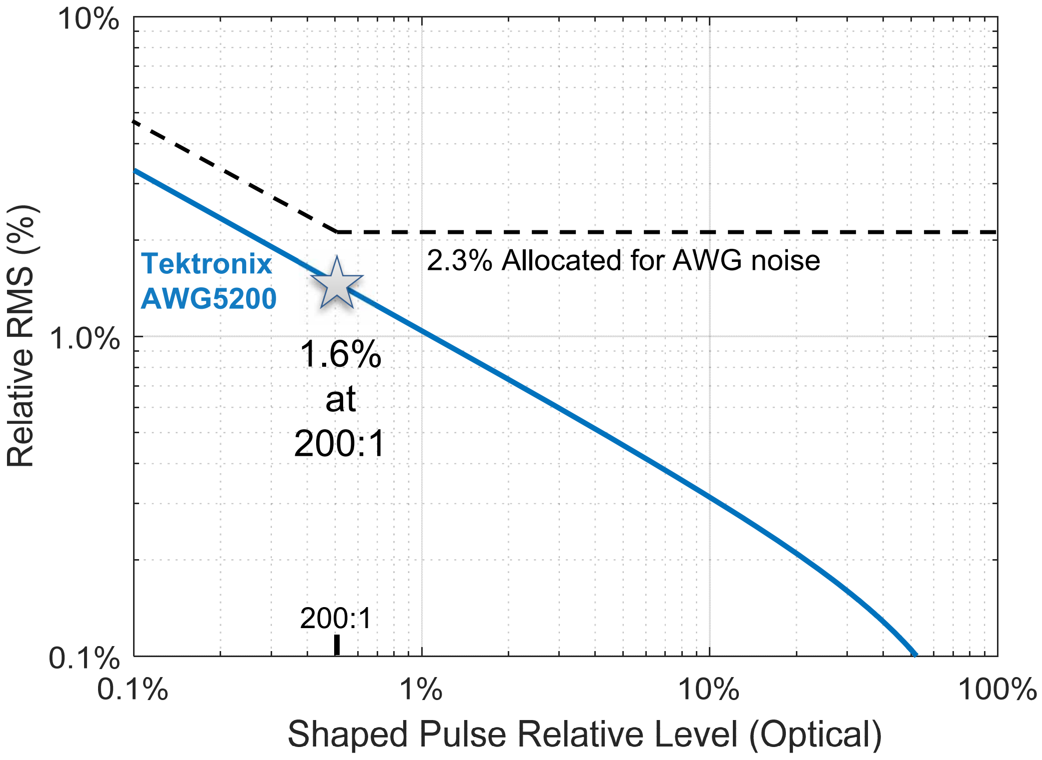
High Dynamic Range Arbitrary Waveform Generator (AWG)

Tektronix AWG5204 Specifications

- Bit depth = 16
- ENOB > 9 bits at 2 GHz
- Sample rate = 5GS/s
- Impulse response = 240ps (in optical domain)
- 4 Channels





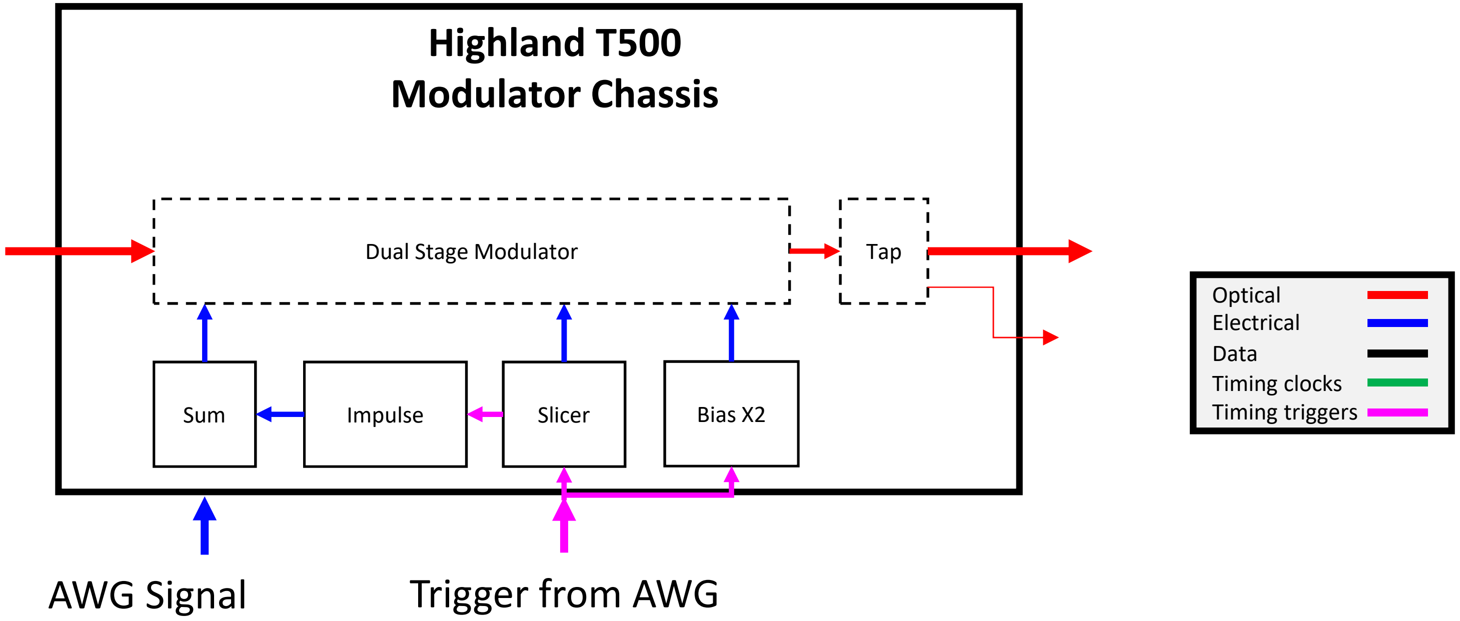


Analysis determined **14 bits** minimum was required to shape to 0.25% at 200:1

Tektronix AWG 5200 was chosen for high resolution and low noise while maintaining sufficient bandwidth

Highland T500 Amplitude Modulator Chassis

- **Functionality & features**
  - Amplifies electrical input from AWG to drive the first stage of the dual stage modulator
    - Low noise and highly linear RF amplifiers chosen by HiFiPS team.
  - Slicer with 200ps rise/fall time drives the second stage
  - Impulse generator (90ps FWHM) multiplexed with AWG signal.
  - Low duty cycle pulsed bias for EOMs
    - Bias discharge termination and AC coupling capacitor for minimizing bias drift
  - Active thermal control with optimized heatsink to further minimized drift of the Dual-Stage Modulator



The Highland T500 integrates pulse shaper components in a robust package

A high-dynamic range shaping diagnostic is critical for precisely characterizing features at high contrast

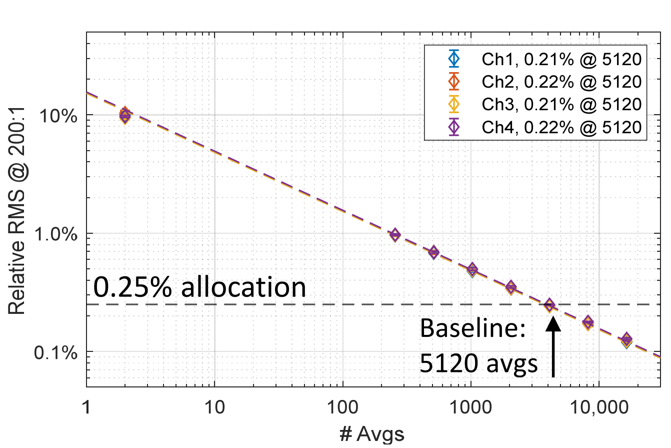
Tektronix LPD64

- Bit depth = 12
- ENOB = 7.25 bits
- Bandwidth = 4 GHz
- Sample rate = 12.5GS/s
- Custom fast averaging and dithering achieves <0.25% error at 200:1

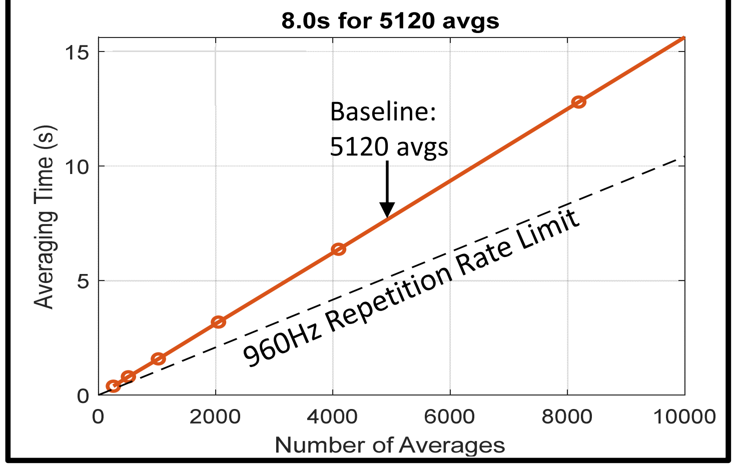
Detector Chassis

- Photodiodes chosen for highest linearity and large bandwidth so that impulse response of diagnostic is dominated by well characterized oscilloscope response.
- No external RF amplifiers required, avoiding additional sources of non-linearity.

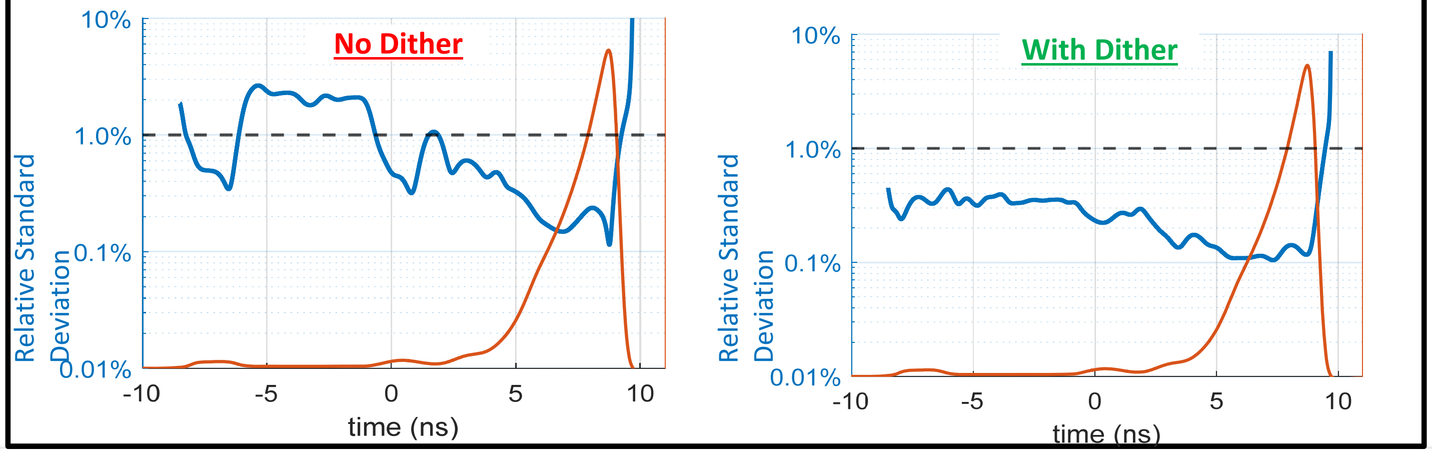
$\sqrt{N}$ noise reduction with heavy floating-point averaging



Tek Fast Averaging feature reduces acquisition time

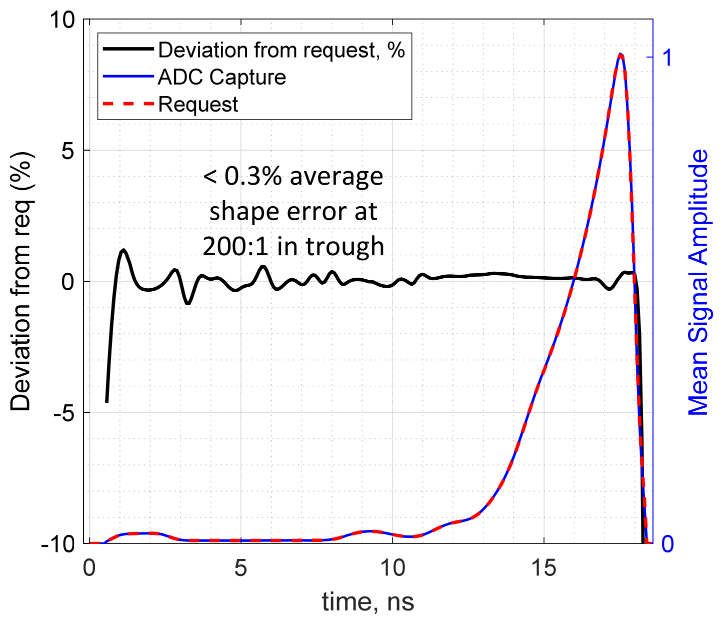


Dithering the DC voltage offset during averaging improves linearity

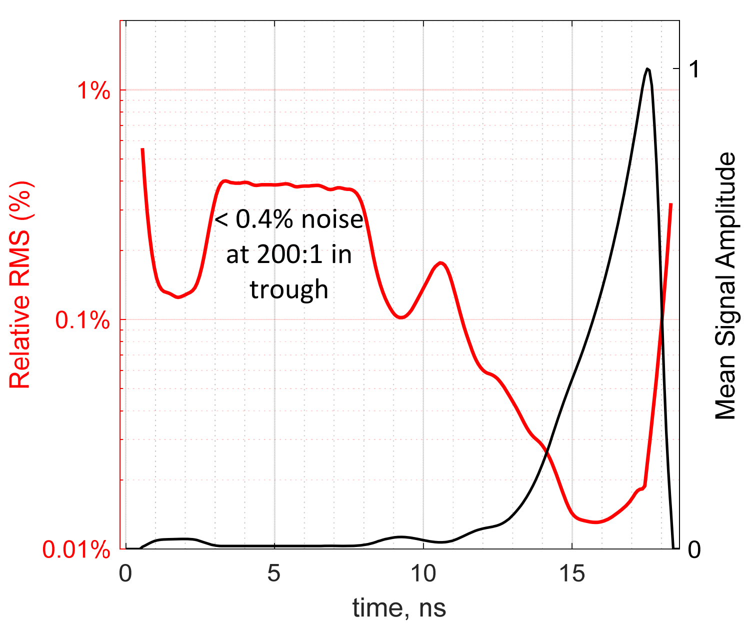


HiFiPS system was rapidly prototyped in lab environment, optimized and tested against all system requirements

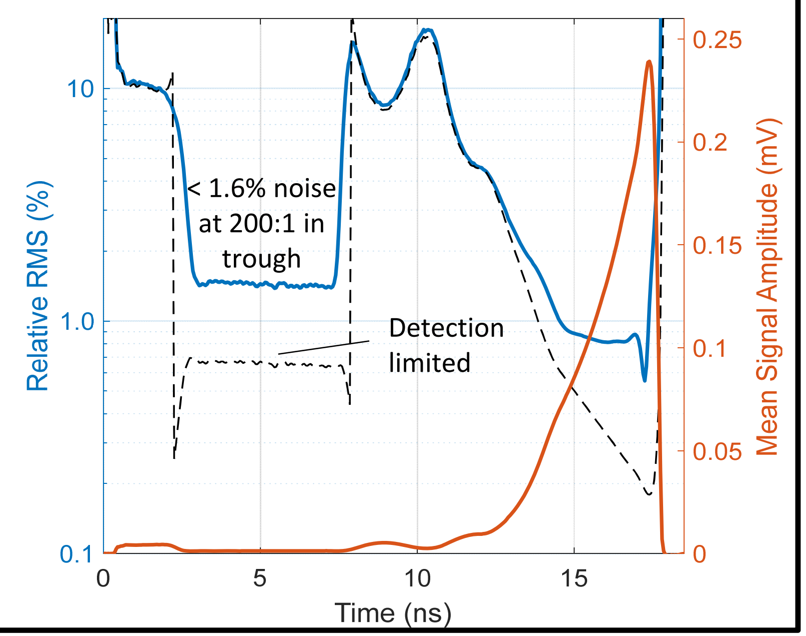
Pulse shape systematic error test
Average deviation from target over 8 hours



Pulse shape 8-hour stability drift test
Standard deviation from mean over 8 hours



Pulse shape shot-to-shot noise test
Standard deviation from mean over 5.5s

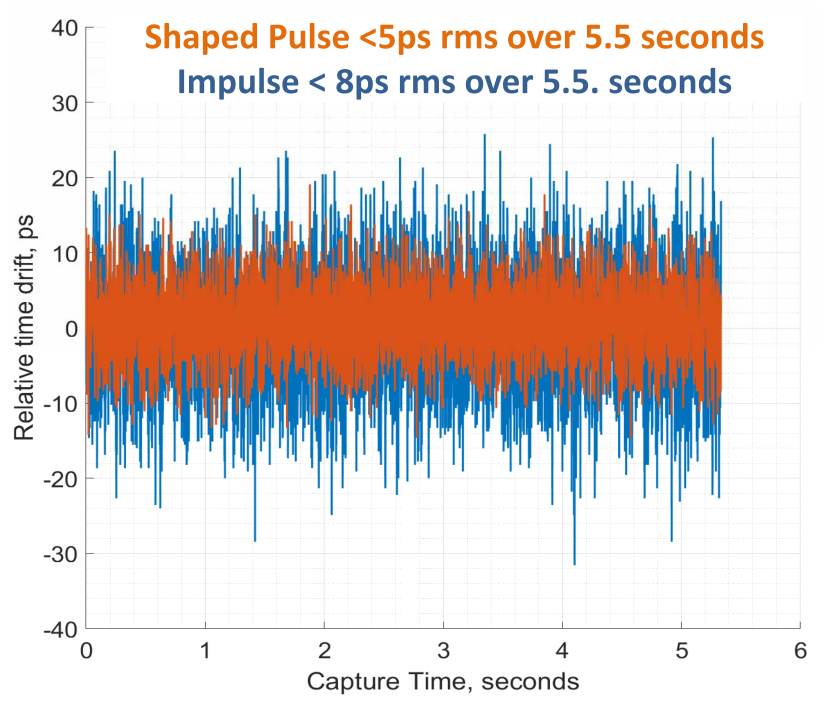


HiFiPS achieved <2% total pulse shape error at 200:1 contrast, successfully meeting the project goal of 3%

The system had to be integrated with the NIF timing system and meet stringent timing error requirements

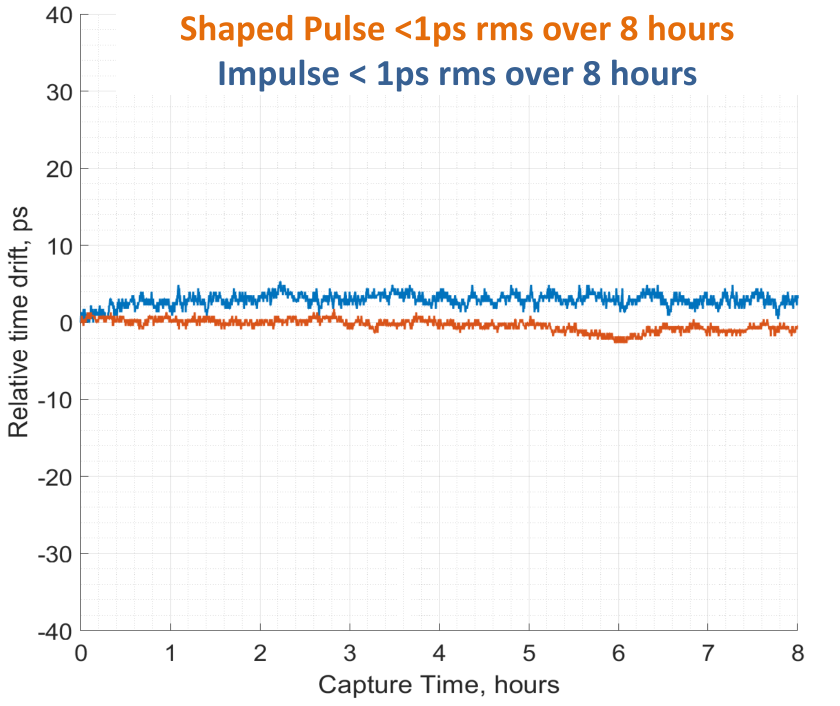
Pulse shape timing jitter test

Shot-to-shot timing offset from mean



Pulse shape timing drift test

Timing drift on a 5.5s scale

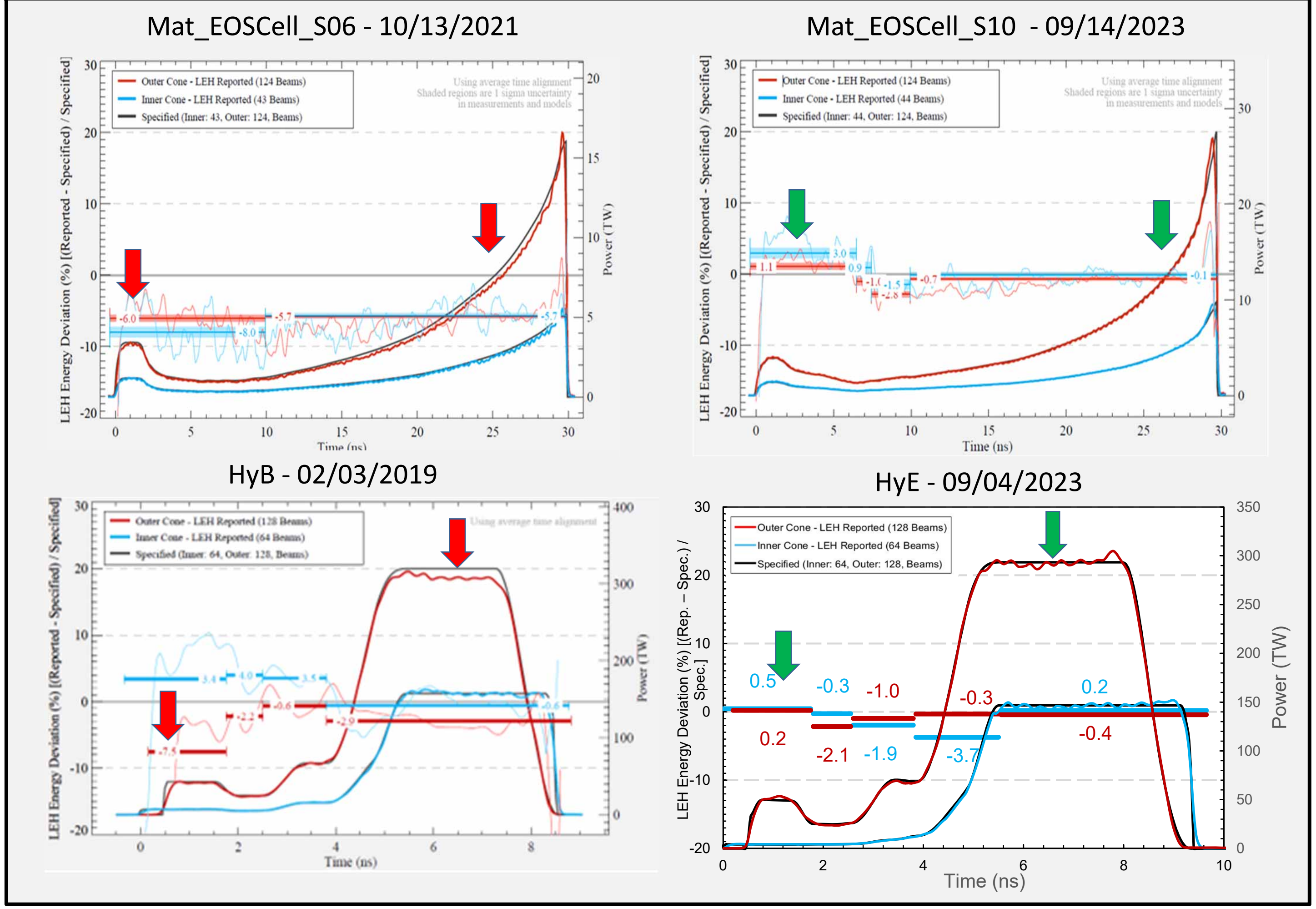


HiFiPS achieved < 10ps rms timing error, successfully meeting the project goal of 15ps

Conclusions and Outlook

- More stringent requirements and concerns over obsolescence prompted the development of a higher-performing and more modernized shaping system for NIF.
- The new High Fidelity Pulse Shaping System (HiFiPS) on NIF leveraged the progress made in the telecom industry and high-speed electronics since NIF was commissioned.
- HiFiPS successfully met all project requirements and was fully deployed in August 2023.
- 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.

Power Accuracy at 3w: Legacy vs. HiFiPS



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