# NIF Sustainment – Injection Laser

NIF User Group Meeting

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# Introduction

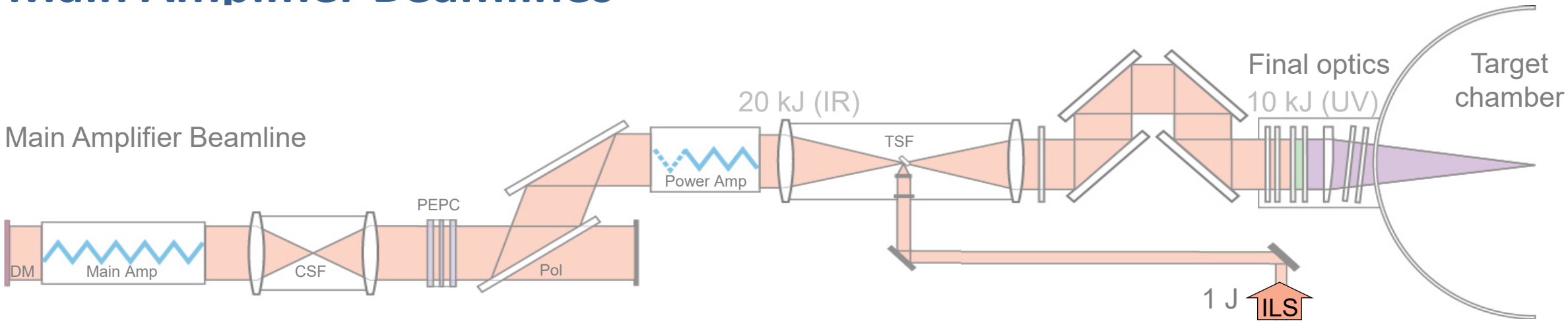
- The front ends of High Energy Laser systems like the National Ignition Facility (NIF) are often the unsung workhorses tasked with delivering near perfect pulsed beams with high precision & stability
- The front end of the NIF known as the Injection Laser System (ILS) has a 30-year history of development and phased upgrades
- The NIF-ILS continues to be modernized as part of the NIF Sustainment mitigating obsolescence and ensuring the capability to meet system performance, reliability, availability, maintainability, as well as future sustainability

*Acknowledgement: J. Heebner, "Ignition laser system architecture, upgrades, and future at the National Ignition Facility" Photonics West 2025 Invited Talk 13358-21*

# Outline

- Architecture
  - System overview
  - Requirements
  - Subsystems
- Sustainment projects
  - High-Fidelity Pulse Shaping (HiFiPS)
  - Beamline-Based Programmable Spatial Shaper (BBPSS)
  - Diode-Pumped Multi-Pass Amplifier (DPMPA)
- Summary

# The NIF ILS delivers 192x Joule-class beams to the Main Amplifier Beamlines




**Master Oscillator Room (MOR)**
Oscillators
Pulse Shaping
Distribution by transport fiber

1 nJ →

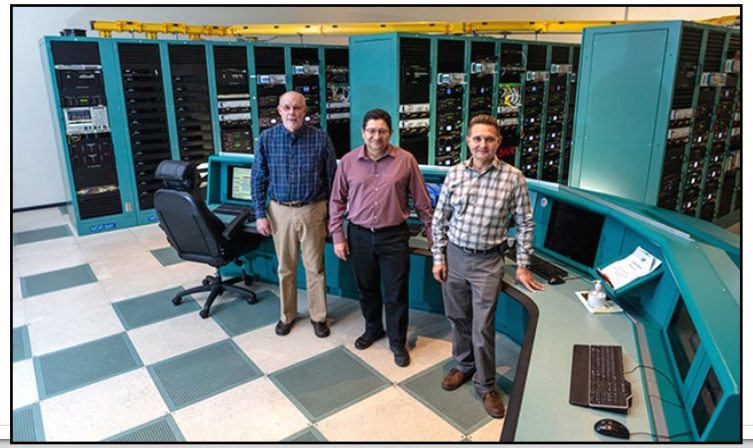
**Pre-Amplifier Modules (PAMs)**
Regens, Beam Shaping
Multi-Pass Amp (MPA)

6 J →

**Input Sensor Packages (ISPs)**
Diagnostics
Alignment aids

6 J →

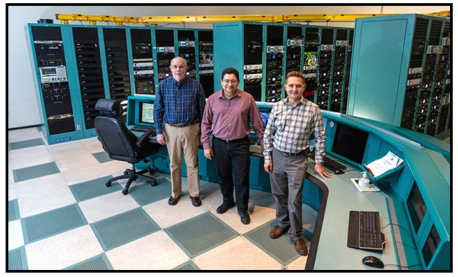
**Pre-Amplifier Beam Transport System (PABTS)**
Splits x4
Timing trombones





*M. L. Spaeth, et al., "Description of the NIF Laser," Fusion Science and Technology 69, 25-145 (2016).*
*M. Bowers, et al., "The injection laser system on the National Ignition Facility," Proc. SPIE 6451, 64511M (2007).*

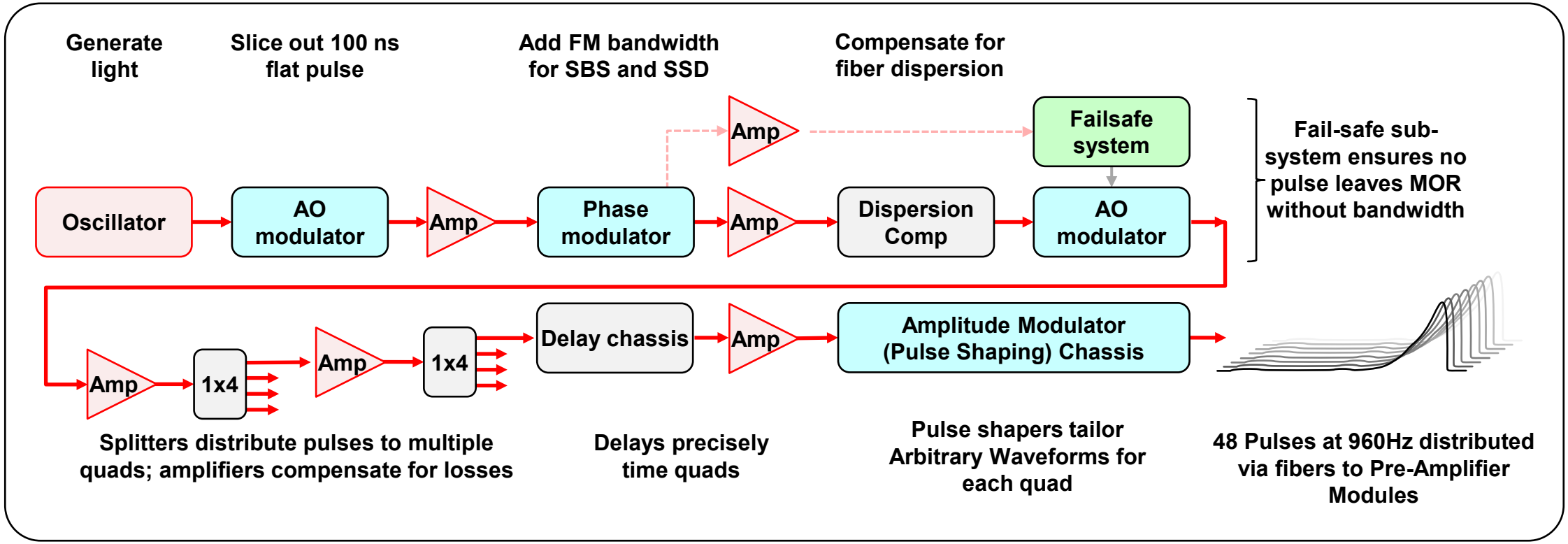
# The ILS met requirements with a baseline design then has been continuously upgraded to ensure optimal performance



| | Requirement | Baseline | Upgrade |
|---|---|---|---|
| MOR | Wavelength control | Tunable oscillator | 4X tunable oscillators |
| | Bandwidth control | Frequency modulators for SBS & SSD | FM-AM mitigation |
| | Pulse shaping | Amplitude modulators | High Fidelity Pulse Shaping (HiFiPS) *deployed at end of CY2023* |
| PAM | Beam shaping | | Programmable Spatial Shaper (PSS) *2nd generation under development (BBPSS)* |
| | Gain to multi-J level | PA | Diode-Pumped MPA (DPMPA) *under development* |
| ISP & PABTS | Precision verification | Energy, pulse shape, timing, NF, FF | AMT/SHIELD diagnostic |
| | Beam energy & timing | Motorized waveplates & trombones | Refinements for stability and repeatability |
| | Alignment stability | Automatic alignment system(s) | |

Talk will focus on these 3 Sustainment Injection Laser projects in the following slides

# The NIF MOR architecture

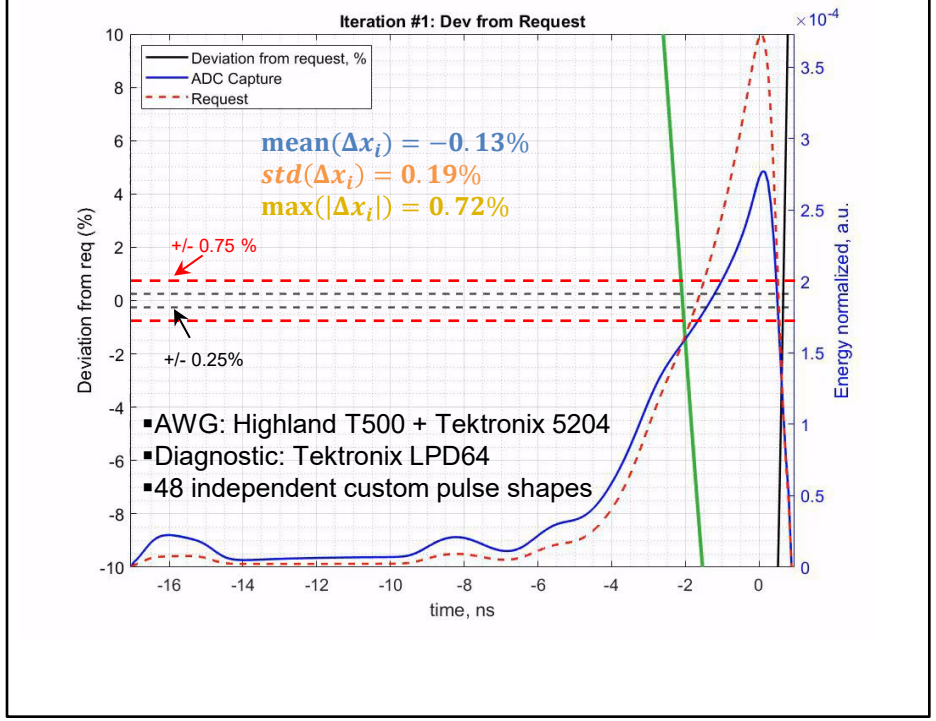



The MOR adjusts the wavelength, bandwidth, timing, & generates custom pulse shapes in support of all NIF experiments

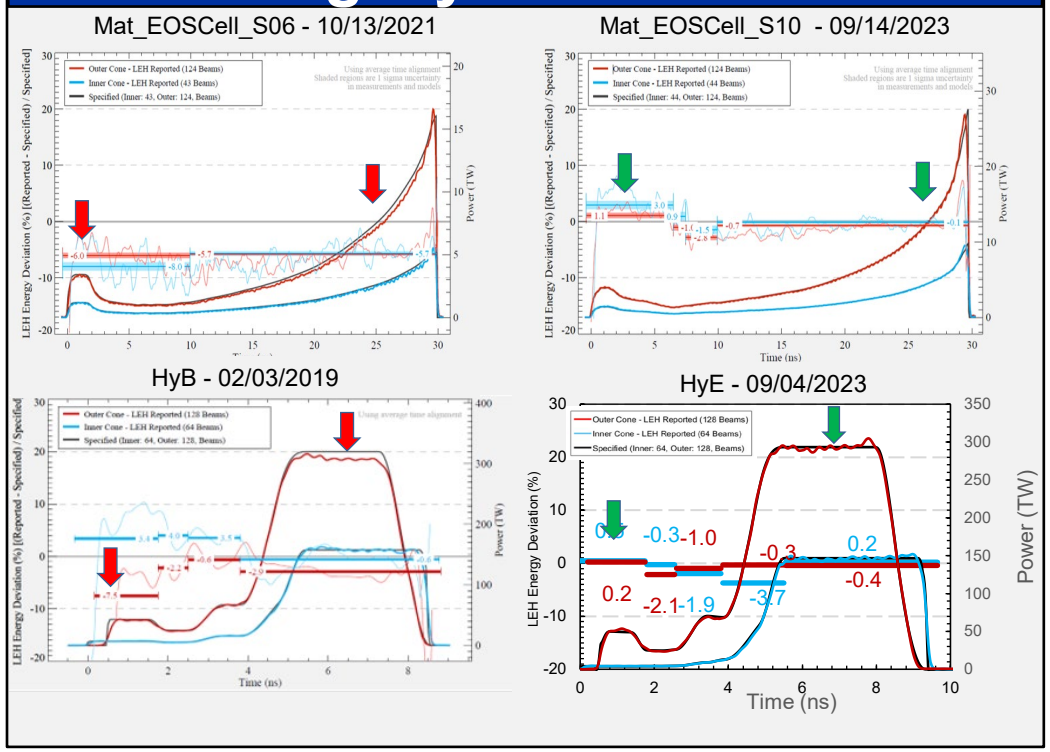
# The High-Fidelity Pulse Shaping System (HiFiPS)

***Developed to improve power balance and accuracy; deployed at end of CY2023***

## Hi-Fidelity Pulse Shaping System




## NIF Power Accuracy at 3ω: Legacy vs. HiFiPS

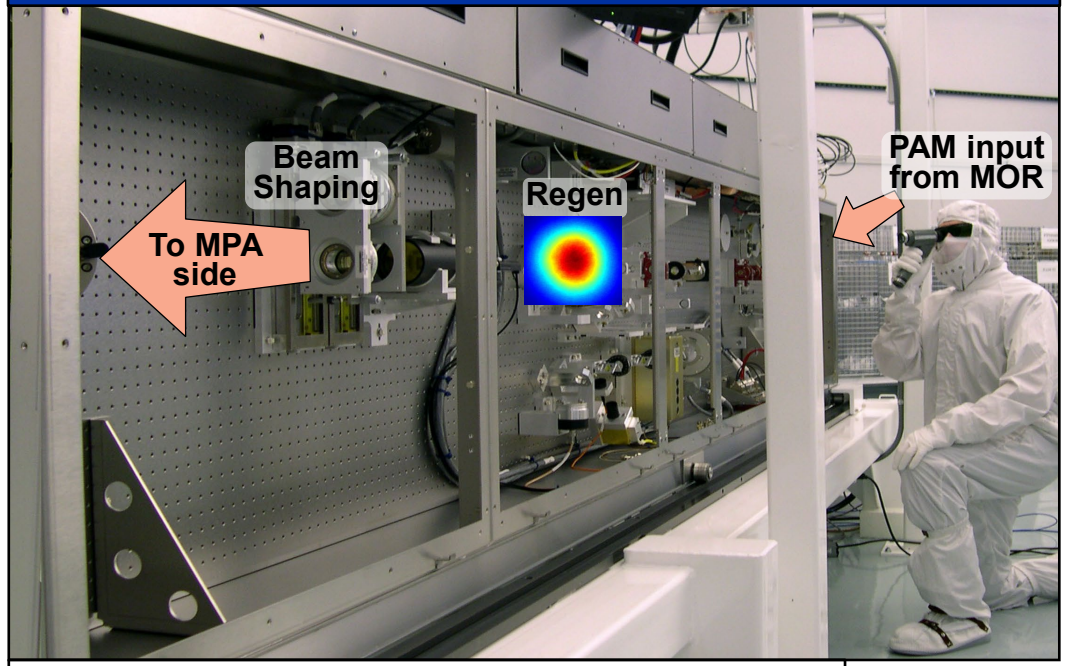



HiFiPS leverages high-speed instrumentation to modernize the NIF pulse shaping system

Pulse shape error is now ~0.5% at 200:1 contrast ratio

# The Pre-Amplifier Module (PAM)

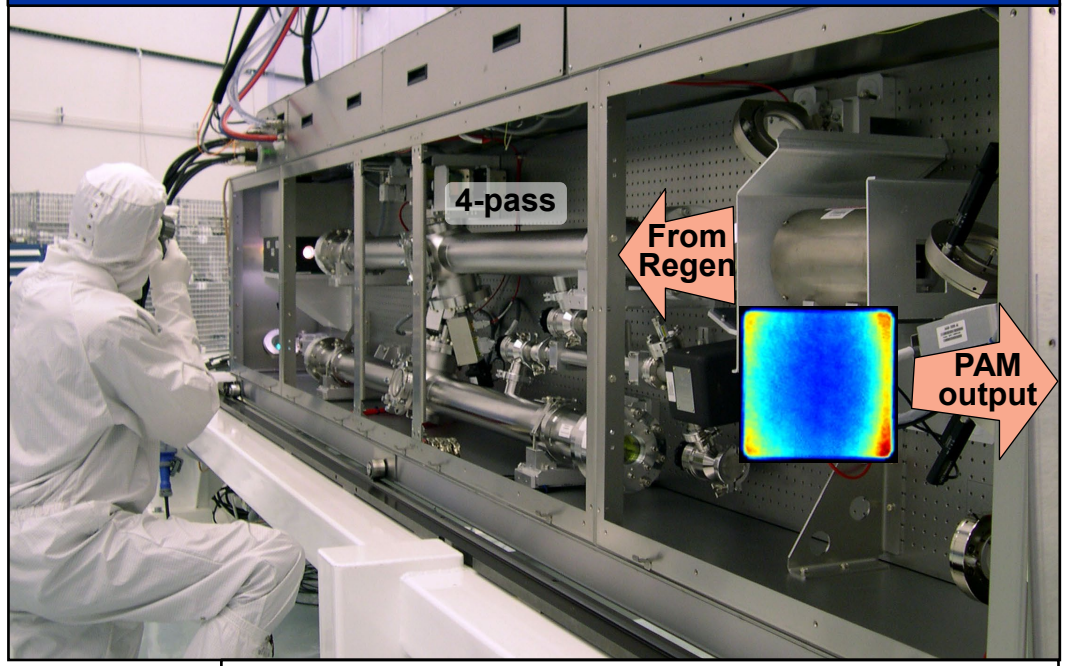
## Side 1: Regenerative amplifier




- Regenerative amp (Q-switched/dumped)
- Diode-Pumped Nd:glass rod
- Net gain = $10^8$ (nJ to 10mJ)
- Followed by beam shaping module

*J. Crane, et al., "High-gain, Nd-doped-glass preamplifier for the National Ignition Facility (NIF) laser system," CLEO (1997)*

## Side 2: Multi-Pass Amplifier (MPA)




- Four-pass imaging amplifier
- Flashlamp-pumped Nd:glass rod
- Net gain = $10^4$ (mJ to 10J)
- Smoothing by Spectral Dispersion (SSD)

The PAMs are the high-performance, high-reliability heart of the Injection Laser System

# The Programmable Spatial Shaper (PSS)

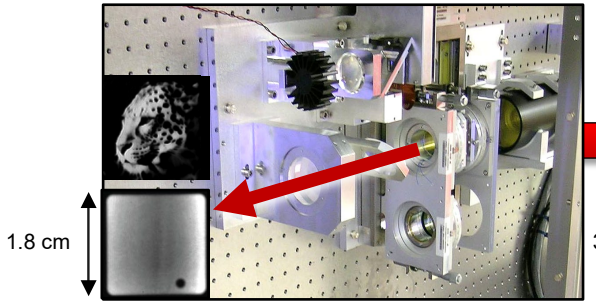
## *Developed to mitigate optic flaw growth & hotspots; deployed in 2010*

'12 R&D 100

*John Heebner, et al., "Programmable beam spatial shaping system for the National Ignition Facility", SPIE LASE (SPIE, 2011), Vol. 7916.*

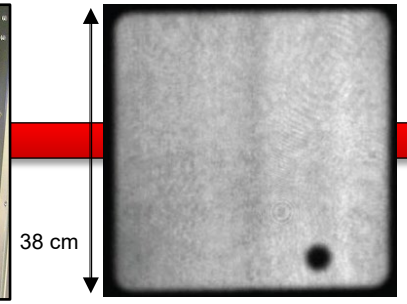
*J.M. Di Nicola, et al., "The National Ignition Facility: laser performance status and performance quad results at elevated energy," Nucl. Fusion 59 (2019) 032004*

**48 PSS at Relay Plane zero (RP0)**



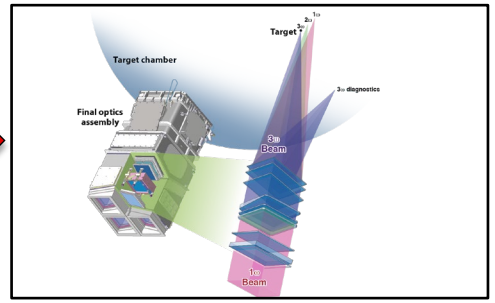

**Beam shape Pre-correction**

**Spot blocker introduction**




**Flattened beam with shadow**

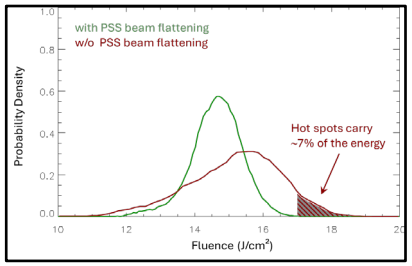
**192 Final Optics Assemblies (FOAs)**



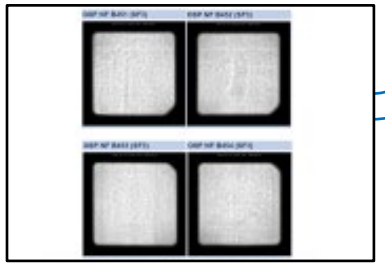

**Post-shot Inspection**

*Registration, Inspection and Blocker introduction are fully automated*

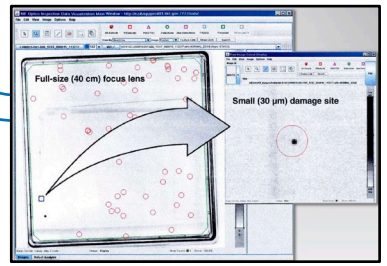
**Flattening hotspots**



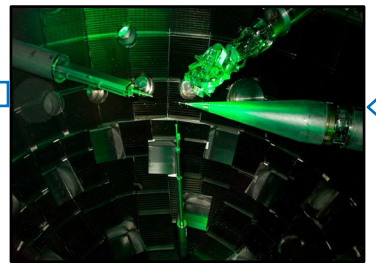

**Laser Performance Operations Model (LPOM)**



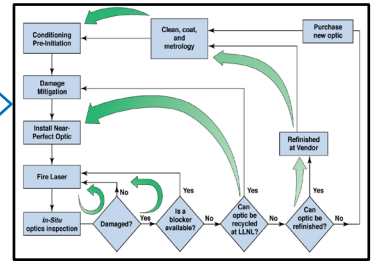
**Optics Inspection (OI) Identifies flaws**




**Final Optics Damage Inspection (FODI) camera**

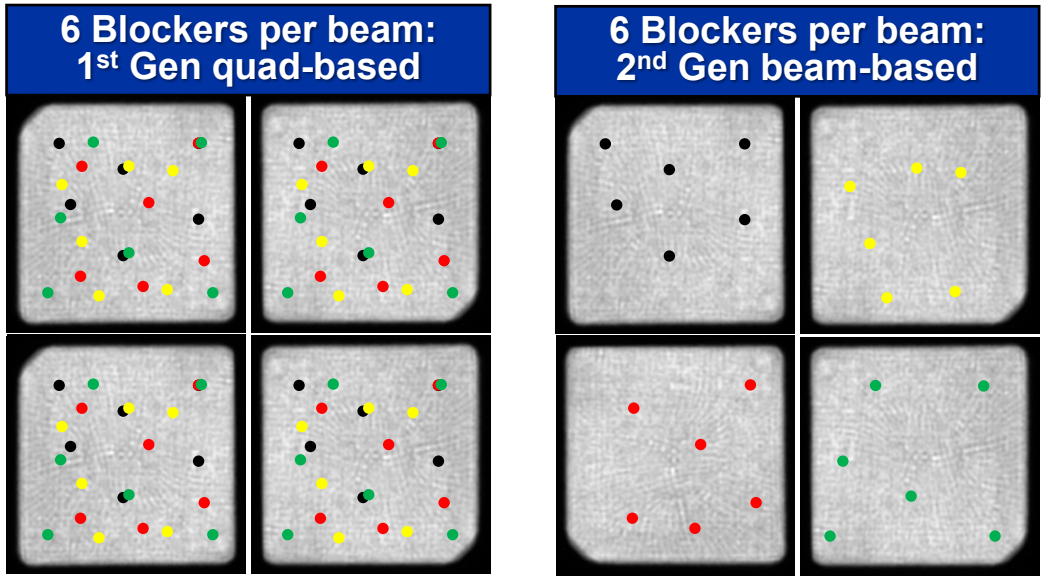


**Optics Recycle Loop**




This system upgrade enabled NIF to operate optimally and continuously allowing the scheduling of optics recycle loop maintenance activities when favorable

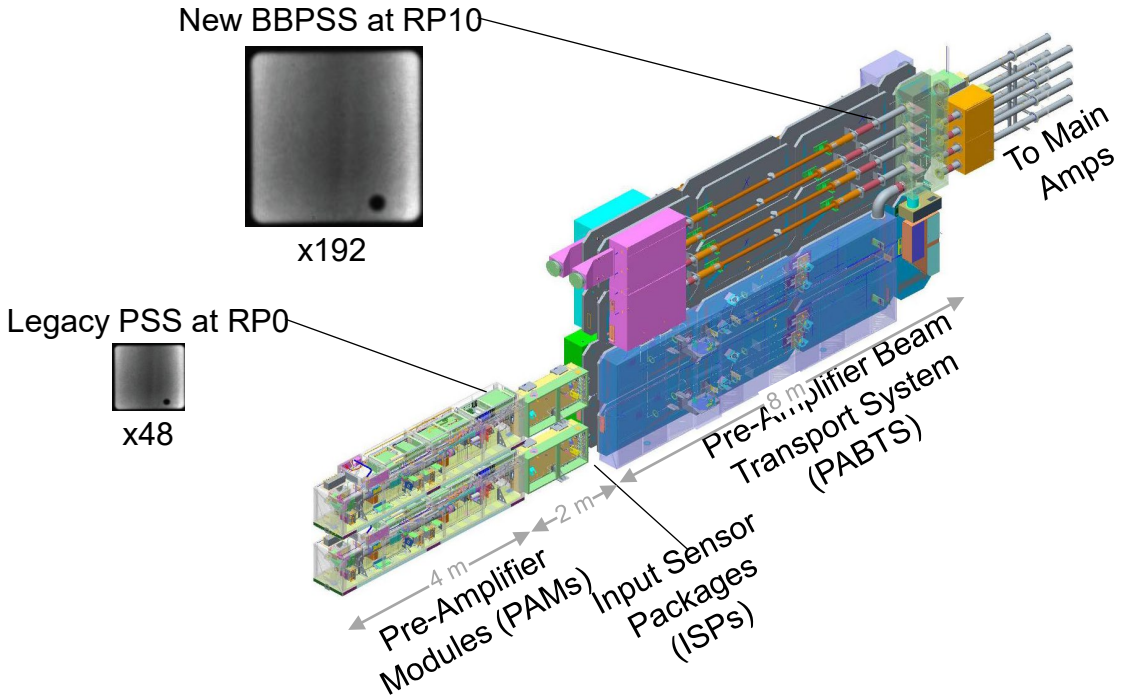
# The Beamline-Based PSS (BBPSS) being developed as part of NIF Sustainment will mimic the legacy PSS but with the ability to independently pattern each beamline




*Courtesy of Marcus Monticelli*

**Switching to beam-based blockers** would increase the number of available blockers on NIF by 4x for the same total obscuration

## Locations of legacy vs new PSS




This capability will enable the NIF laser system to be operated with lower recycle loop costs and be optimized for higher performance

# The Beamline-Based PSS requires an OALV with larger aperture and higher fluence handling capability

**Comparison of legacy vs new PSS**

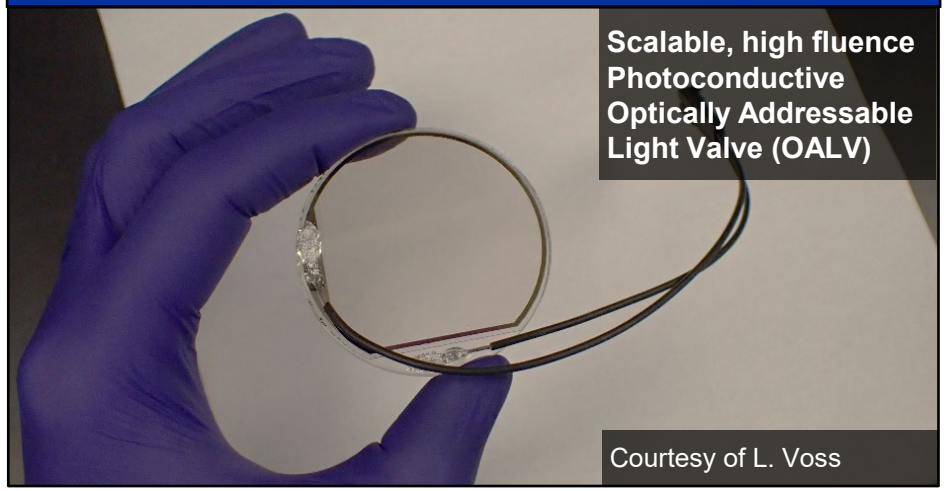
| | Legacy PSS (quad-based) | New BBPSS (beam-based) |
|---|---|---|
| Location | RP0 in PAM | RP10 in PABTS |
| Beam size (mm) | 18 x 18 | 45 x 45 |
| Energy (J) | ≤ 0.002 | ≤ 6 |
| Fluence ($J/cm^2$) | ≤ 0.001 | ≤ 0.6* |
| Quantity | 48 | 192 |

*Forward going beam not including amplified back-reflections

**2nd Generation <u>beam-based system</u> requires:**

- Larger aperture 2cm → 5cm
- Higher fluence handling $1mJ/cm^2$ → $1J/cm^2$
- 4x the number of devices

**2nd Gen beam-based PSS under development**




*B. Buckley, "Beam-based programmable spatial shaper for reducing optics exchange in the National Ignition Facility" 13343-13 Photonics West 2025*

The new, beamline-based capability is significantly more challenging to implement but a prototype demonstration is in progress implementing next generation OALVs

# A diode-pumped 10J head is being developed as a more stable & sustainable upgrade to the PAM MPA (Diode-Pumped MPA [DPMPA])

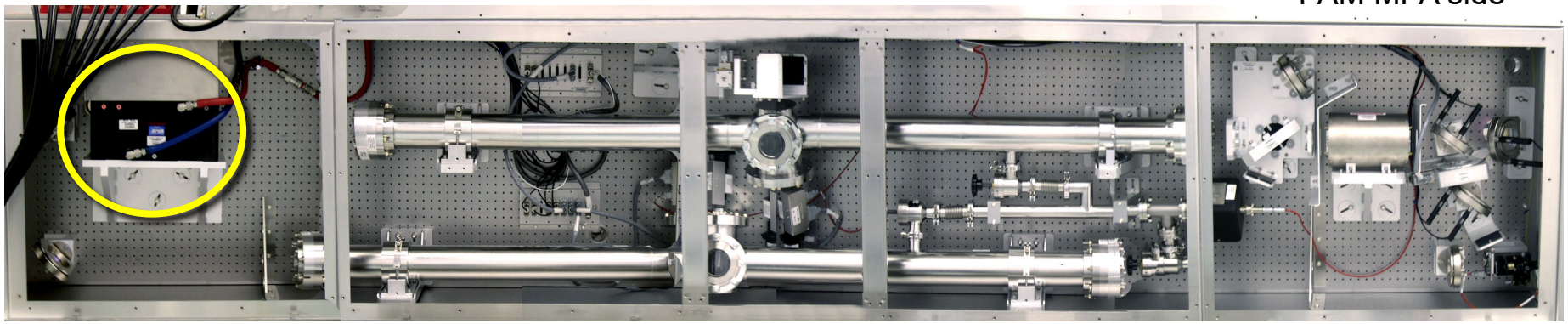
**Engineered as a "drop-in" retrofit** of the flashlamp-pumped head without modifying 4-pass architecture

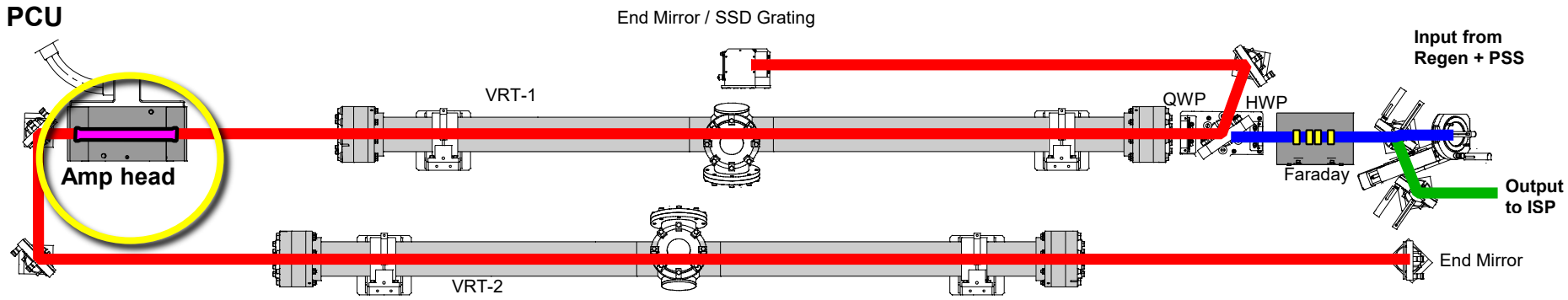
**Preserving spatial gain profile** with diode pattern is challenging

**Preserving temporal distortion** implies minor change to Fsat and extraction efficiency but modefill efficiency is paramount to lowering diode cost

*Following: J. L. Emmett, W. F. Krupke, W.R. Sooy, "The Potential of High-Average-Power Solid State Lasers," UCRL-53571 (1984).*

PAM MPA side






While far too costly to implement diode pumping on the NIF main amplifiers, it is cost effective to implement at the 10J scale x48 (making the entire ILS diode-pumped kJ-class)

# Summary

- The NIF Injection Laser System (ILS) has been a workhorse providing most of the laser gain and many of the control functionalities required for delivering precision pulsed beams to the NIF Main Amplifiers
- Multiple upgrades have supported evolving demands to ensure that NIF operations continue smoothly with high reliability, availability, and maintainability
- New upgrades under development as part of the NIF Sustainment program will further improve the long-term sustainability of the laser system
- Technologies for ICF and IFE in the future will likely both rely upon and build upon these capabilities

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