# The National Ignition Facility Laser Performance Status

JM. Di Nicola, D. Kalantar, S. T. Yang, D. Alessi, S. Ammula, T. Bond, M. Bowers, B. Buckley, A. Calonico-Soto, W. Carr, L. Chang, J. Chou, S. Cohen, A. Deland, P. DeVore, G. Erbert, M. Erickson, C. Filip, J. Folta, N. Gottesman, A. Gowda, A. Handler, J. Heebner, V. Hernandez, S. Herriot, R. House, C. Kinsella, T. Lanier, B. MacGowan, K. Manes, K. McCandless, R. Muir, B. Olejniczak, M. Ordoñez, C. Orth, E. Padilla, A. Pao, L. Pelz, S. Rana, B. Raymond, S. Schrauth, S. Sommer, T. Suratwala, M. Spaeth, B. Van Wonterghem, A. Wargo, L. Wang, P. Whitman, N. Wong, P. Wegner and D. Larson

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LLNL-PROC-819559

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

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# The National Ignition Facility – Lawrence Livermore National Laboratory, Livermore California

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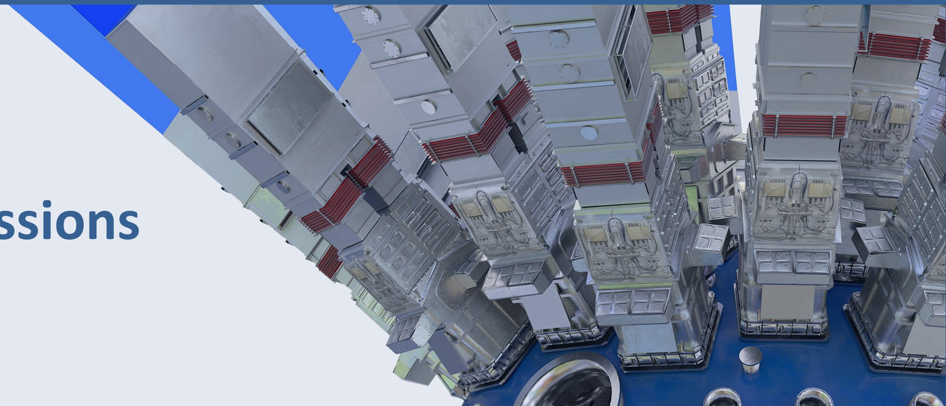
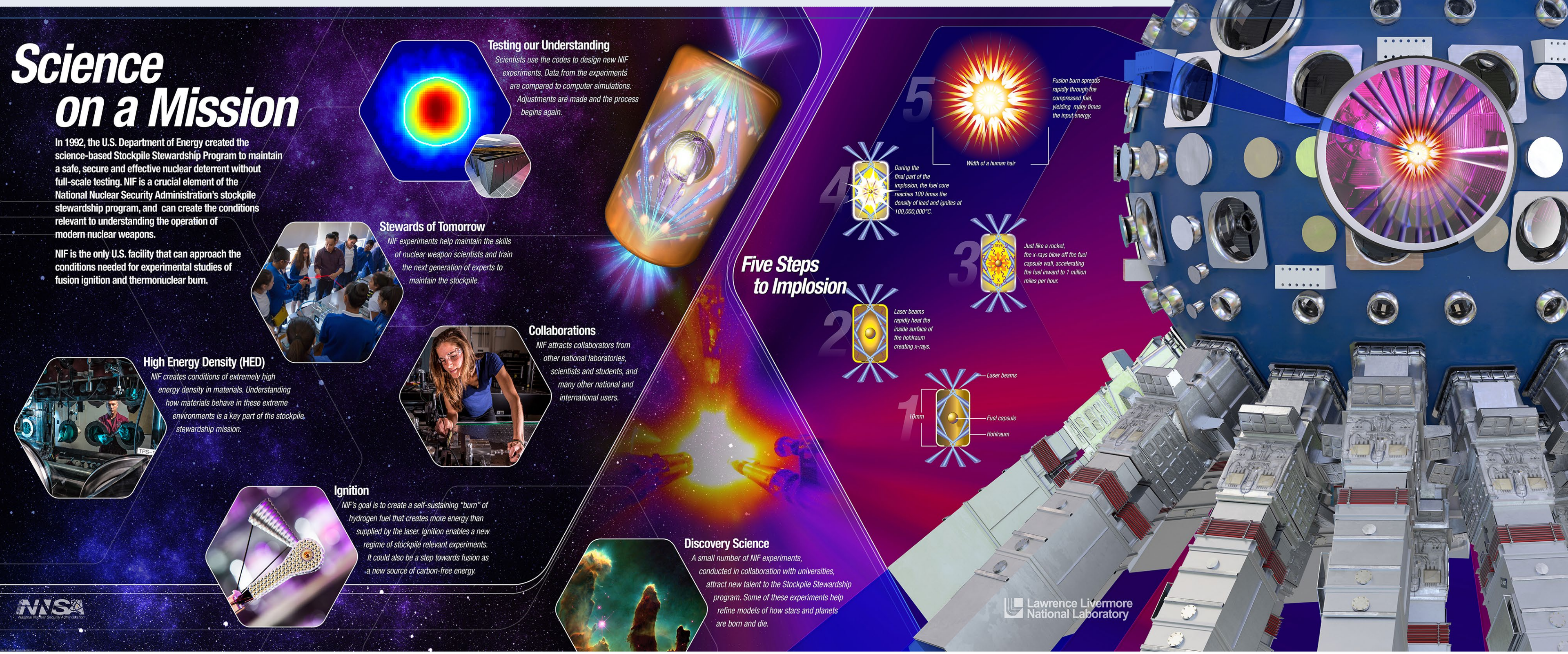
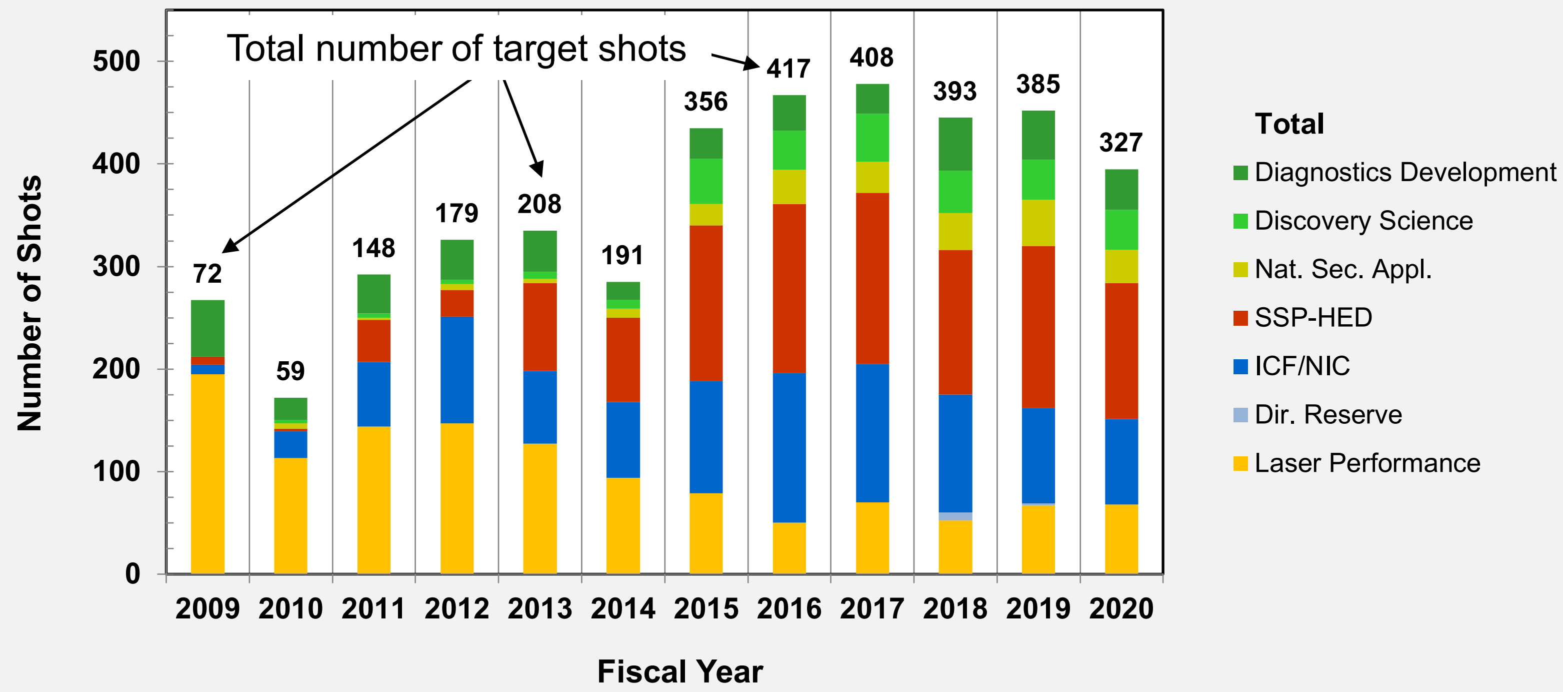
## The NIF supports a broad range of Missions





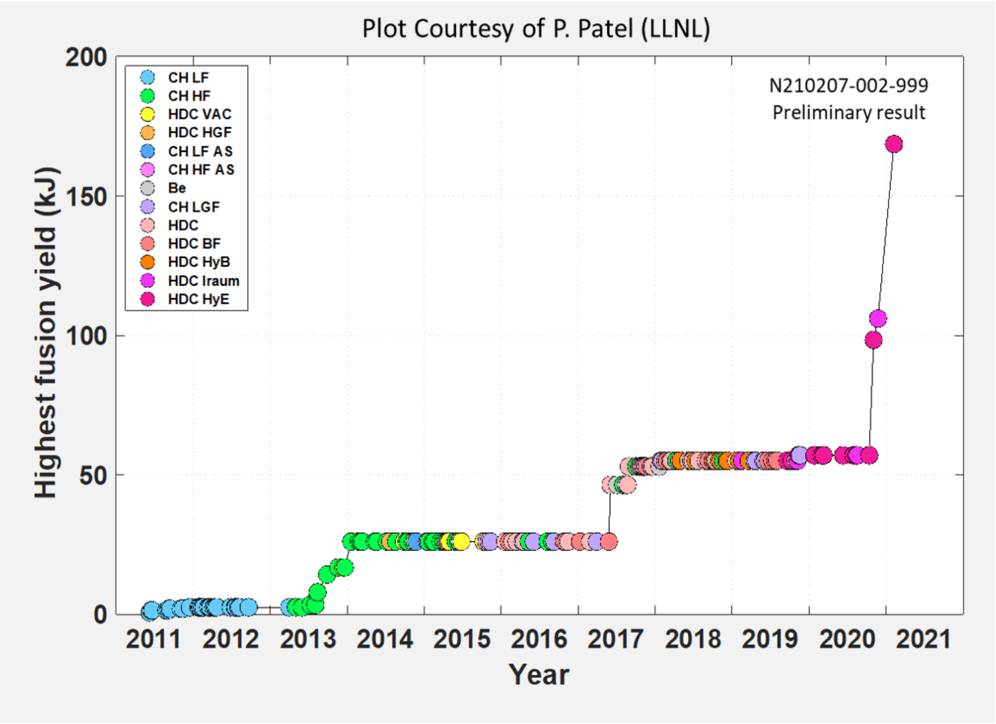
# For everybody 2020 was a challenging year. NIF made a lot of efforts to integrate new COVID protocols and minimize the impact

## Yearly Historical Shot Count by Program




We met ~80% of our target experiments goal and made exciting progress on ignition this year

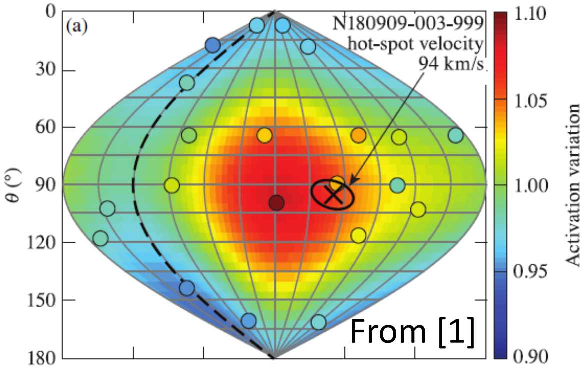
# Recent progress has closed the gap to fusion ignition on NIF

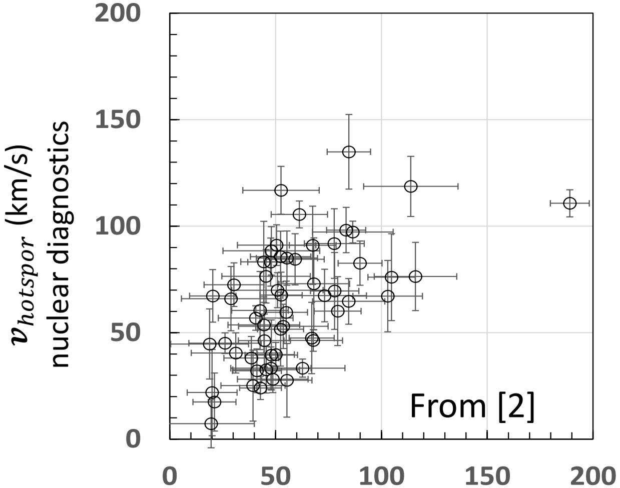



- The ignition program focus is on
  - Understanding and increasing compression of the hot spot
  - Understanding and increasing coupling of laser energy to the target capsule
  - Improving predictive capability through better simulations and theory
- Progress on all of the above have fueled the recent performance increases
- Additional laser and target physics changes identified that are expected to enable higher nuclear yield

# Inferred from neutron measurements, the hot-spot velocity provides a diagnostic of the overall (laser + target) implosion symmetry

- During implosion experiments, asymmetric convergence produces un-stagnated flows in the fuel and hot spot which limits the maximum hot-spot pressure and reduces confinement time
- Neutron diagnostic measurements provide hot-spot velocity vector. Magnitudes up to 150 km/s are observed and are overall a sign of degradation of the implosion
- The mode-1 asymmetry is calculated using a ViewFactor code and the measured imperfections from laser, hohlraum (diagnostic window) and capsule
- Mode-1 asymmetries are correlated with large hotspot velocities on NIF DT implosions




$v_{fit}$ (km/s) from Mode-1 estimate using laser and target metrology data

**Prescribed changes to the laser Power balance can be used to cancel out diagnostic windows and capsule fabrication asymmetry and ultimately minimize mode-1 asymmetry of DT implosions**

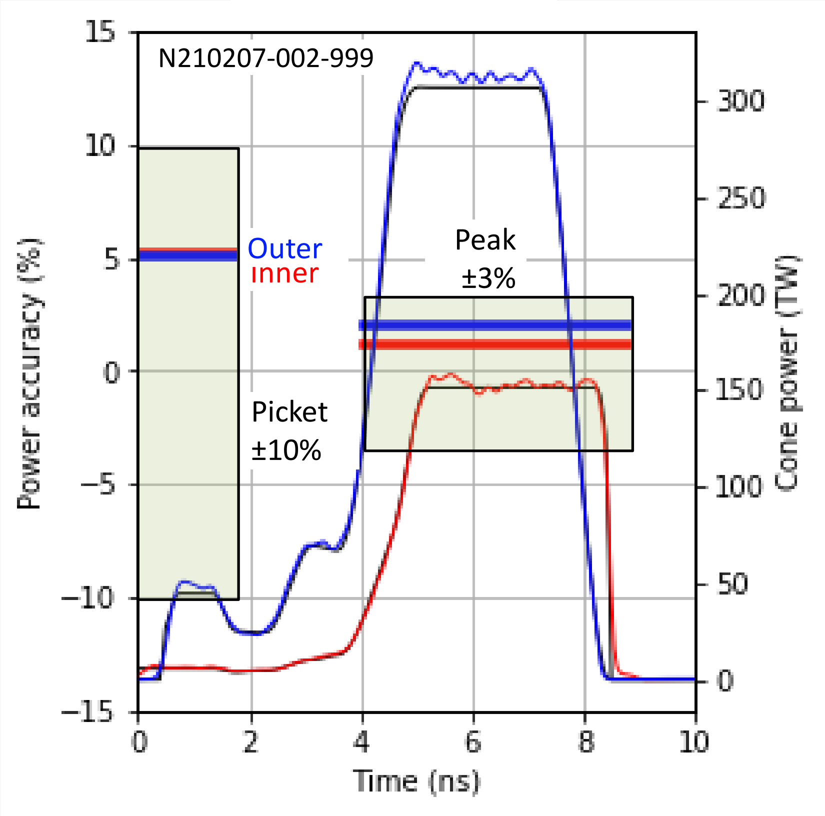


[1] H. Rinderknecht PRL **124**, 145002 (2020)
[2] B. MacGowan et al. APS (2020)

# NIF laser 3ω power performance on target has requirements for power accuracy and power balance for ICF experiments

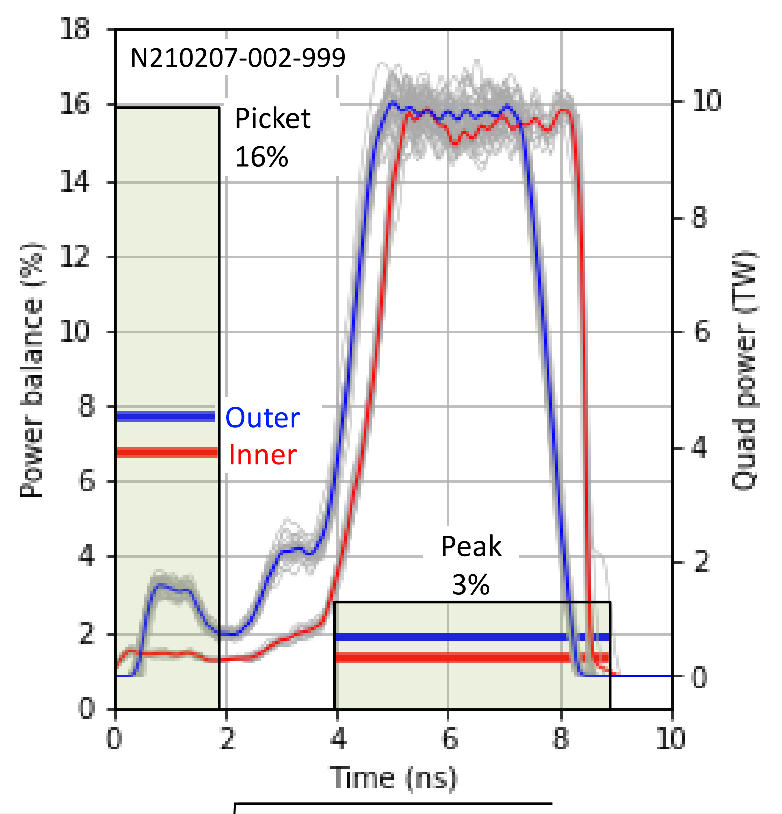
**N210207-002-999 - Record Yield shot with 1.94 MJ / 474 TW**

## Power accuracy




$$Accuracy = \frac{P_{meas} - P_{specified}}{P_{specified}} \times 100[\%]$$

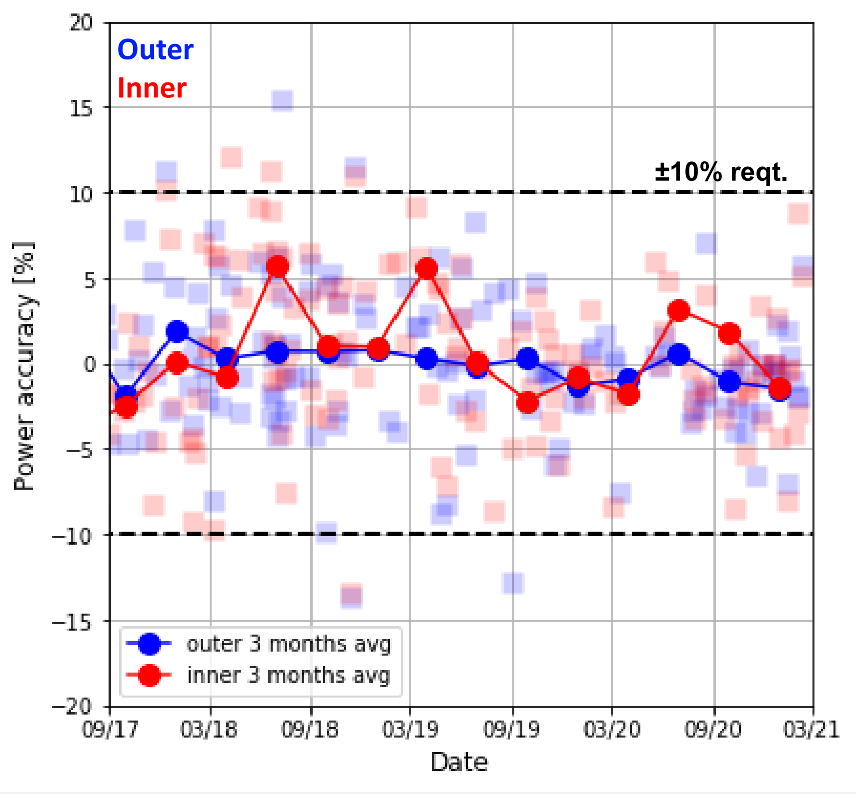
## Power balance



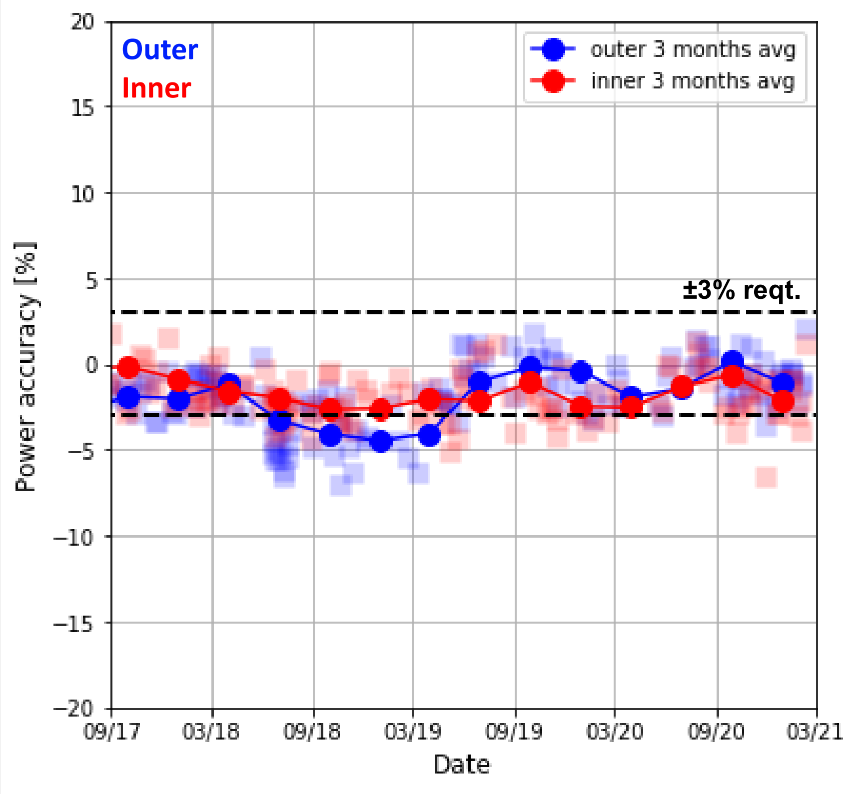

$$Balance = \sqrt{\sum_{i=1}^{n} \left( \frac{P_i - \bar{P}_{cone}}{\bar{P}_{cone}} \right)^2 / n} \times 100[\%]$$

# We have been achieving power accuracy in the picket within specified tolerance on most DT shots, less consistently in the peak

## Picket power accuracy



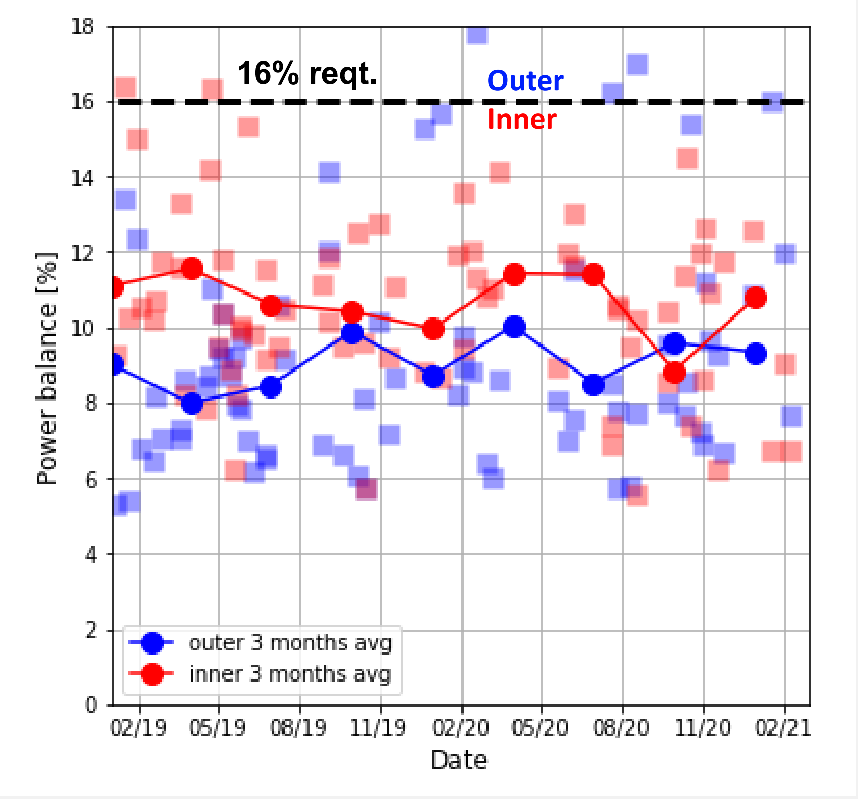

## Peak power accuracy



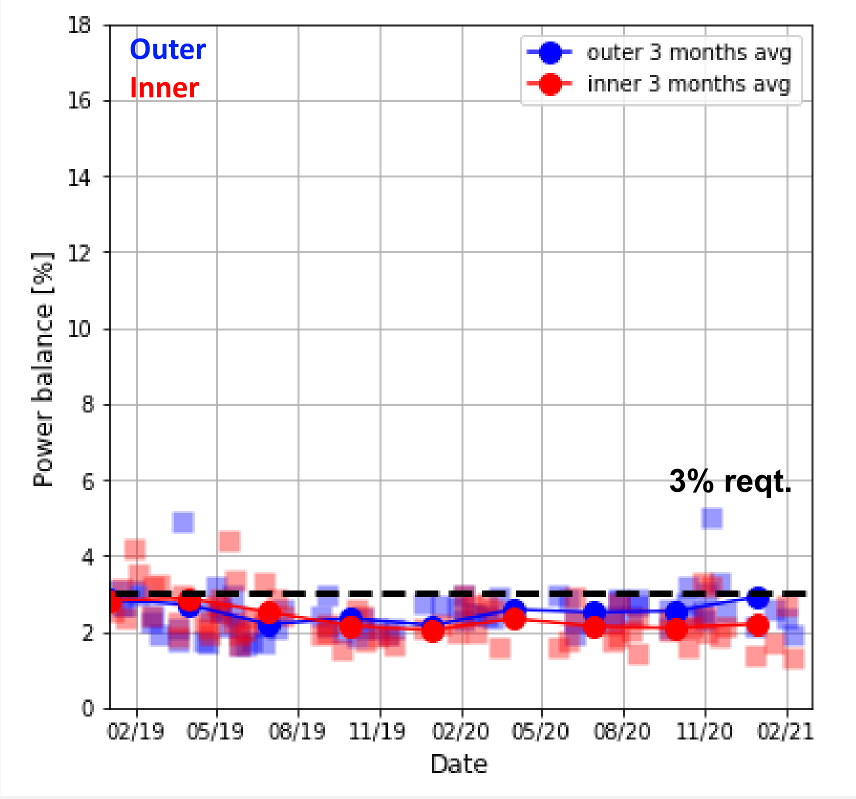

*data plotted are from ignition relevant DT shots

# Power balance specification has been met consistently in the picket while staying within tolerance in the peak is more challenging

## Picket power balance




## Peak power balance

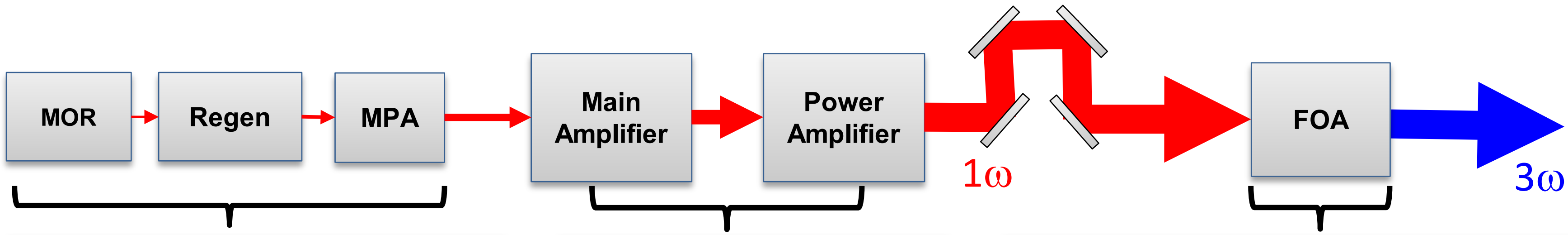



*data plotted are from ignition relevant DT shots

**Both requirements are met ~80% of the time but recent learnings call for tighter specifications**

# Based on measurements and models, we identified the main system contributors to errors in 3ω power accuracy and balance

Laser model
- Uncertainty in 1ω and 3ω model
- Uncertainty in loop3 correction




Injection Laser
- MOR pulse shape fluctuation
- Spatial correlation due to MOR architecture
- MPA output energy instability
- Pulse timing jitter

Main Laser amplifier
- Small signal gain fluctuation

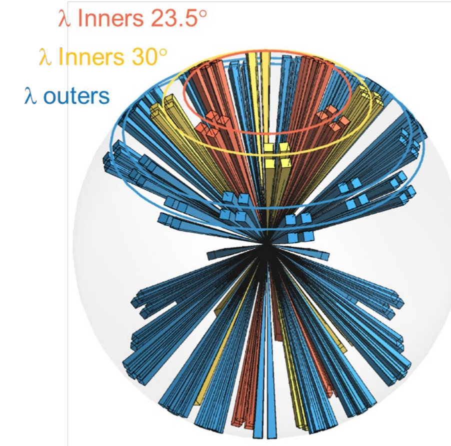
Final Optics Assembly
- Crystal angular detuning error
- Crystal temperature variation
- Optics transmission spread (contamination, scattering / absorption)
- Uncertainty in reported 3ω energy & power

- Three major factors that impact power accuracy and power balance are:
  - Injection laser stability
  - Laser model fidelity
  - Laser output energy & power reporting accuracy

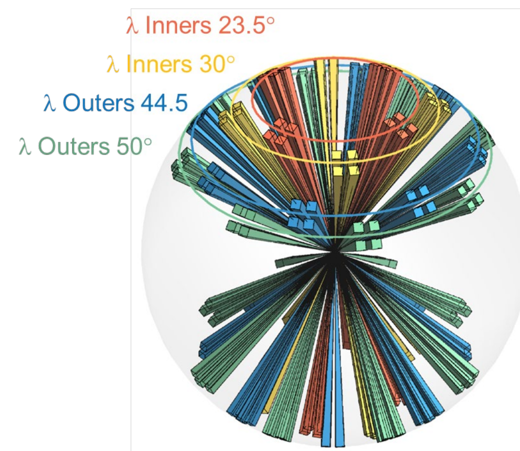
**Improving areas that impact power accuracy & balance is needed to meet current requirements with margin, and would be essential for meeting more stringent ones**

# The Master Oscillator Room (MOR) is being modernized to mitigate obsolescence and improve performance

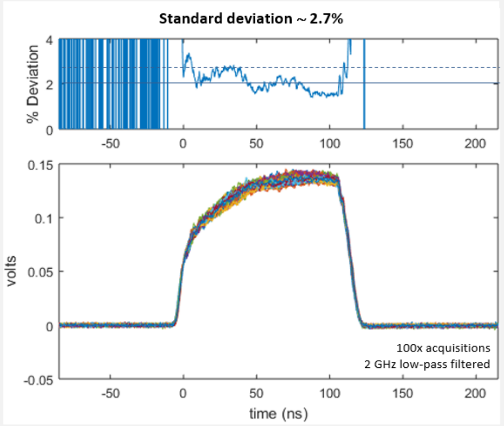
- A new MOR architecture – from the oscillator to the pulse shaping system input – was designed, tested off-line and deployed
- It mitigates obsolescence issues and leverages technological advances in fiber-based technology for the last 15-years
- It provides more flexibility for NIF with a “4th color” in the 50-degree cone for Cross-Beam Energy Transfer (CBET) mitigation and also improves shot-to-shot stability performance by ~3x
- 2/3 of the NIF quads are now upgraded with this new architecture with a final completion date in 2021




After deployment

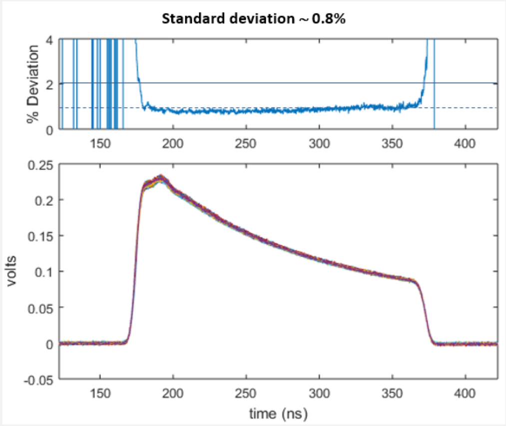


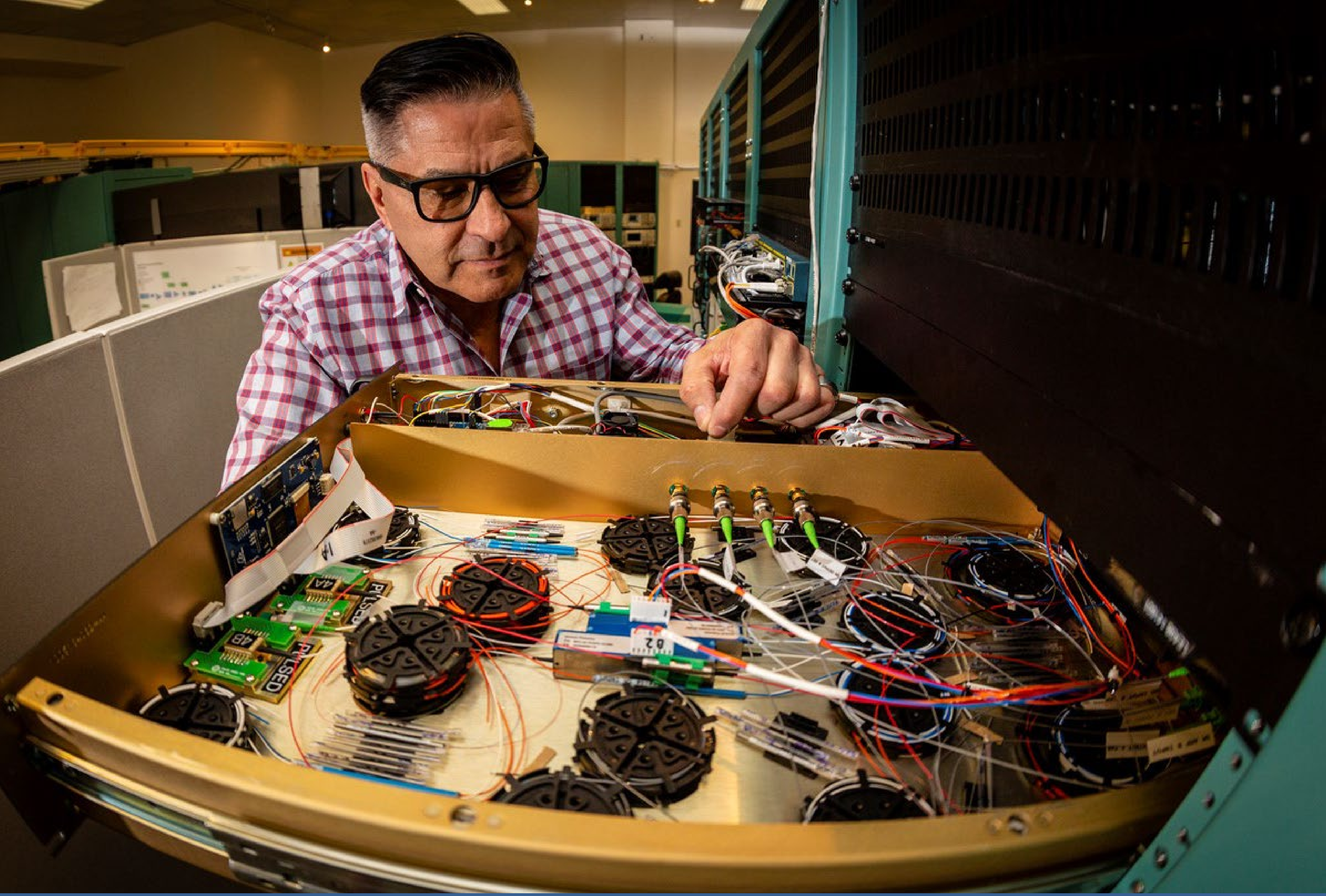

**Legacy Pre-Shaped Pulse Q11T**




After deployment

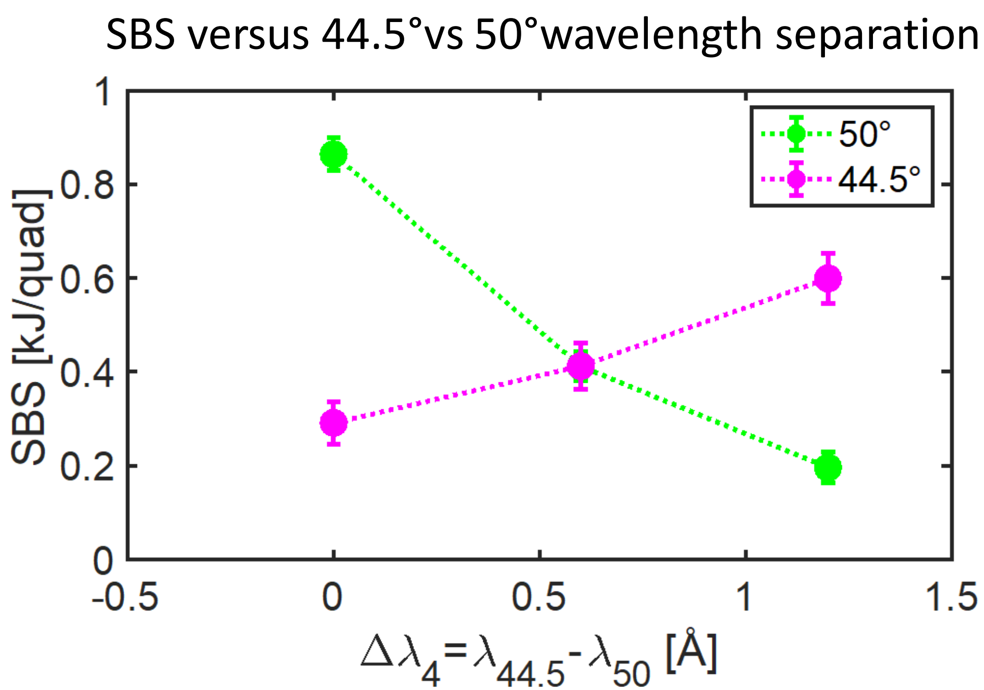
**4th Color Pre-Shaped Pulse Q11T**






Custom-design and built of the dual Yb-doped fiber amplifiers

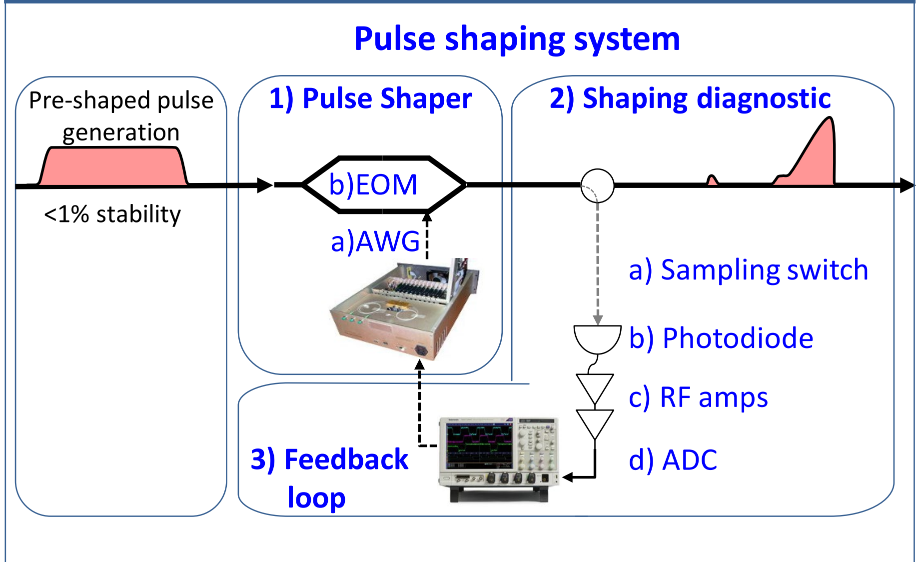
# 4th wavelength tuning capability on NIF allows balancing 44.5° and 50° beam intensities via CBET to mitigate maximum SBS threat



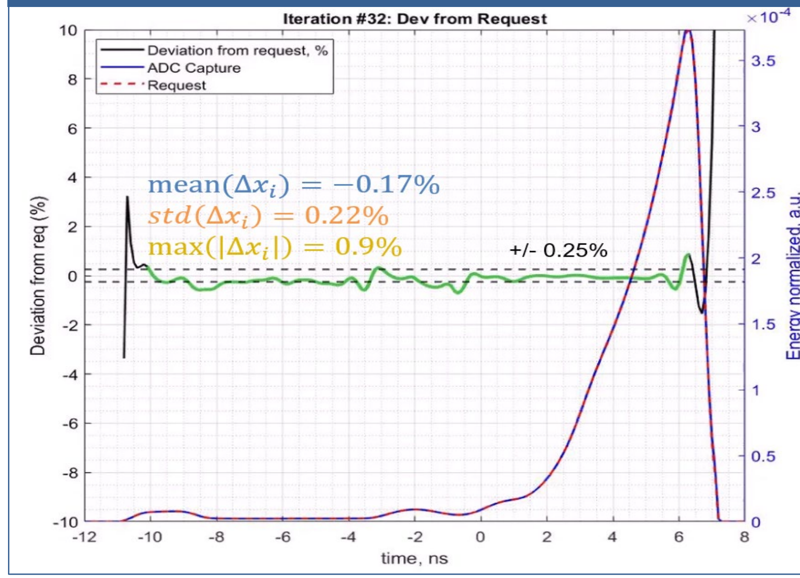

Plot courtesy of P. Michel, J. Ralph, B. MacGowan (LLNL), publication in progress

# Along with a more stable system for pulse generation in the MOR, we put together a conceptual design to improve the accuracy and shot-to-shot reproducibility of high-contrast pulse shapes

## Master Oscillator Room (MOR)



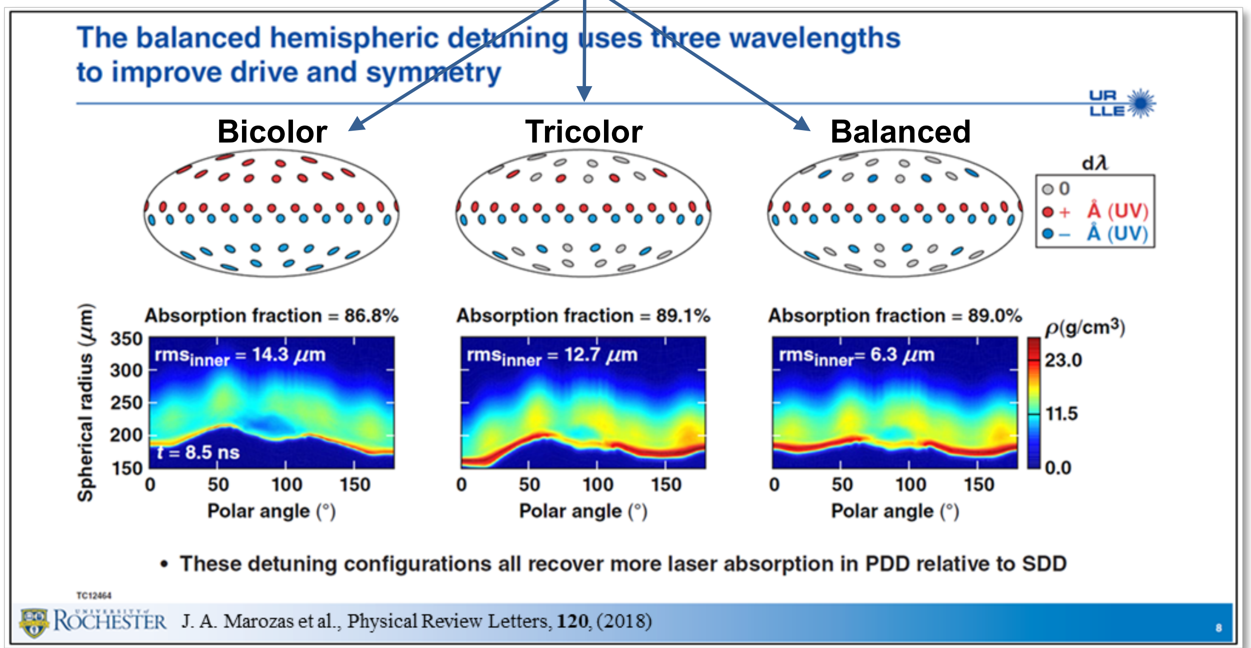

## Closed-loop shaping, deviation from request




- On key aspects, 3-5x improvements compared to the deployed system are expected
- Prototype results have shown expected improvements
  - Short-term pulse shape stability at 200:1 contrast <2% (4x improvement demonstrated)
  - Closed-loop pulse shaping and deviation from request <0.5%
- Final design review is expected later this year and deployment to follow

# In collaboration with LLE, Flexible Color to Port Mapping upgrade will provide a new NIF capability for CBET learning experiments and its mitigation for Laser Direct-Drive

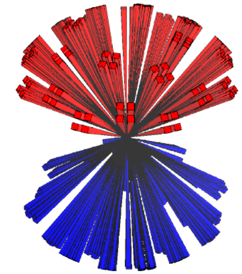
**Quad Pointing and Color Mapping onto the Capsule**



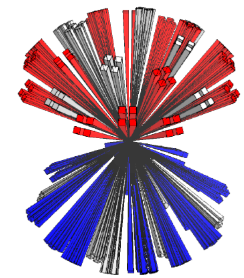

Viewgraph Courtesy of J. A. Marozas (LLE)

**Color Mapping at the NIF chamber**

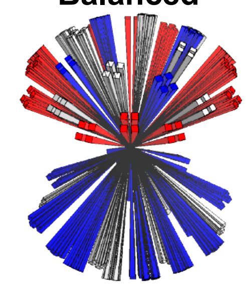
**Bicolor**



**Tricolor**



**Balanced**

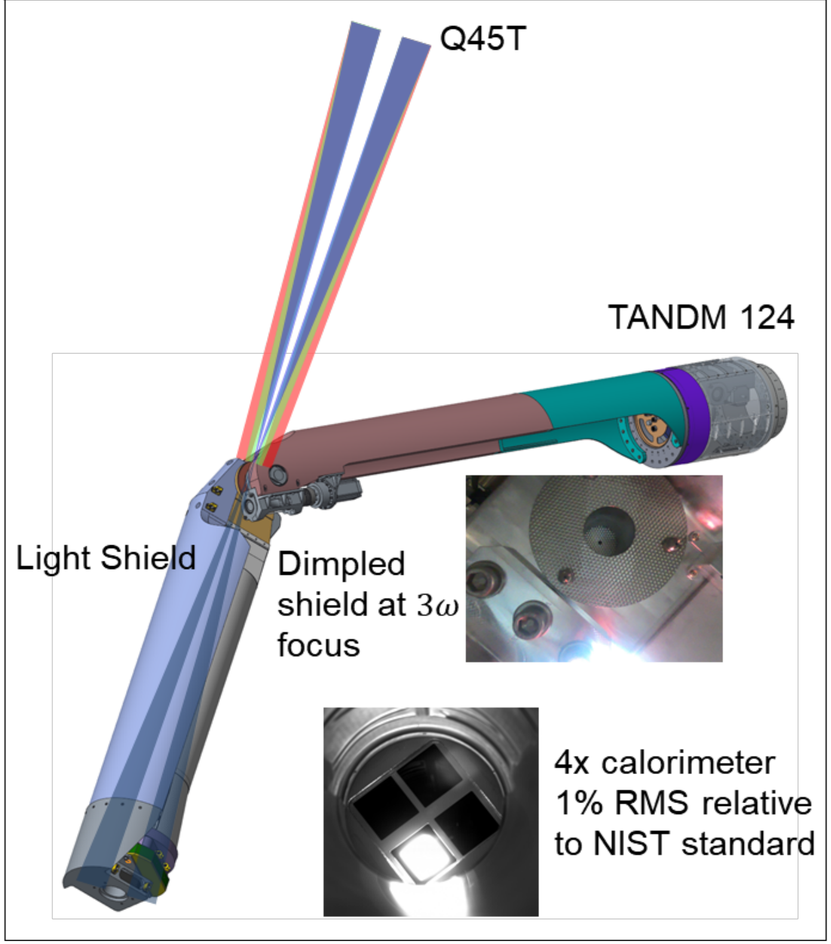


- Next year, three new color mappings will become available for CBET learning experiments for both direct and indirect drive as well as CBET mitigation for direct-drive

# The Target Chamber Calorimeter* (TC-CAL) is used to validate and potentially improve NIF 3ω energy measurement accuracy

- TC-CAL is made up of an array of 4 calorimeters mounted on an articulating boom assembly that is attached TANDM (Target and Diagnostic Manipulator)
- TC-CAL is aligned at chamber center with dimpled shield and a hole mimicking the hohlraum laser entrance hole (~3mm diameter) at 3ω focus to block residual 1ω & 2ω light
- Calorimeters are located 2m away from TCC and pointed to measure energy from all 4 beams from one quad (Q45T for now)
- Maximum energy is limited by absorbing glass damage to 500J 3ω with CPP removed from the beamline

**Target Chamber Calorimeter (TC-CAL)**

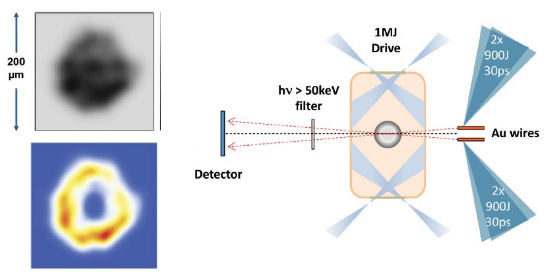



*Acknowledgements to CEA-LMJ for sharing important information with us on this topic

**Results to date indicate that TC-CAL and Final Optics 3w diagnostic measurements are consistent within <2%**

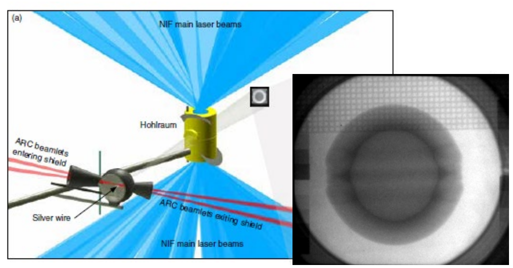
# Advanced Radiographic Capability (ARC) enables a variety of unique experiments at NIF

## Compton Radiography of ICF Experiments



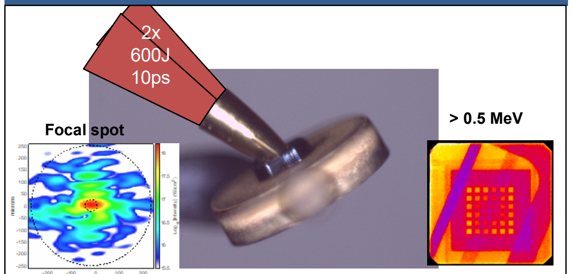

R. Tommasini et al., PRL (2020)

## X-ray Radiography of Complex Hydrodynamics



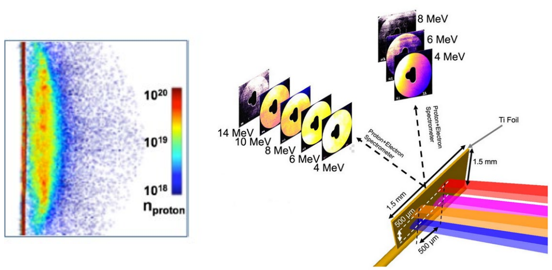

D. Martinez et al., LLNL S&T Rev. (2018)

## MeV Radiography



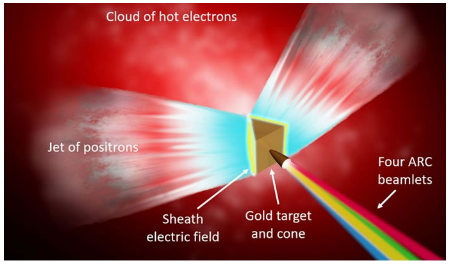

S. Kerr et al. (unpublished)

## Proton Source Development



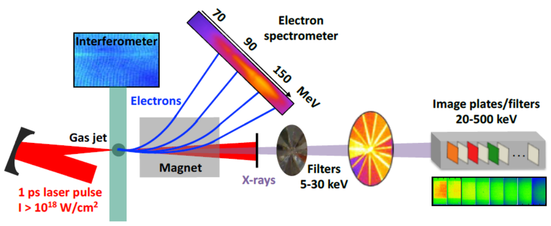

D. Mariscal et al., PoP (2019)

## Pair Plasma Creation




J. Williams et al., (submitted)

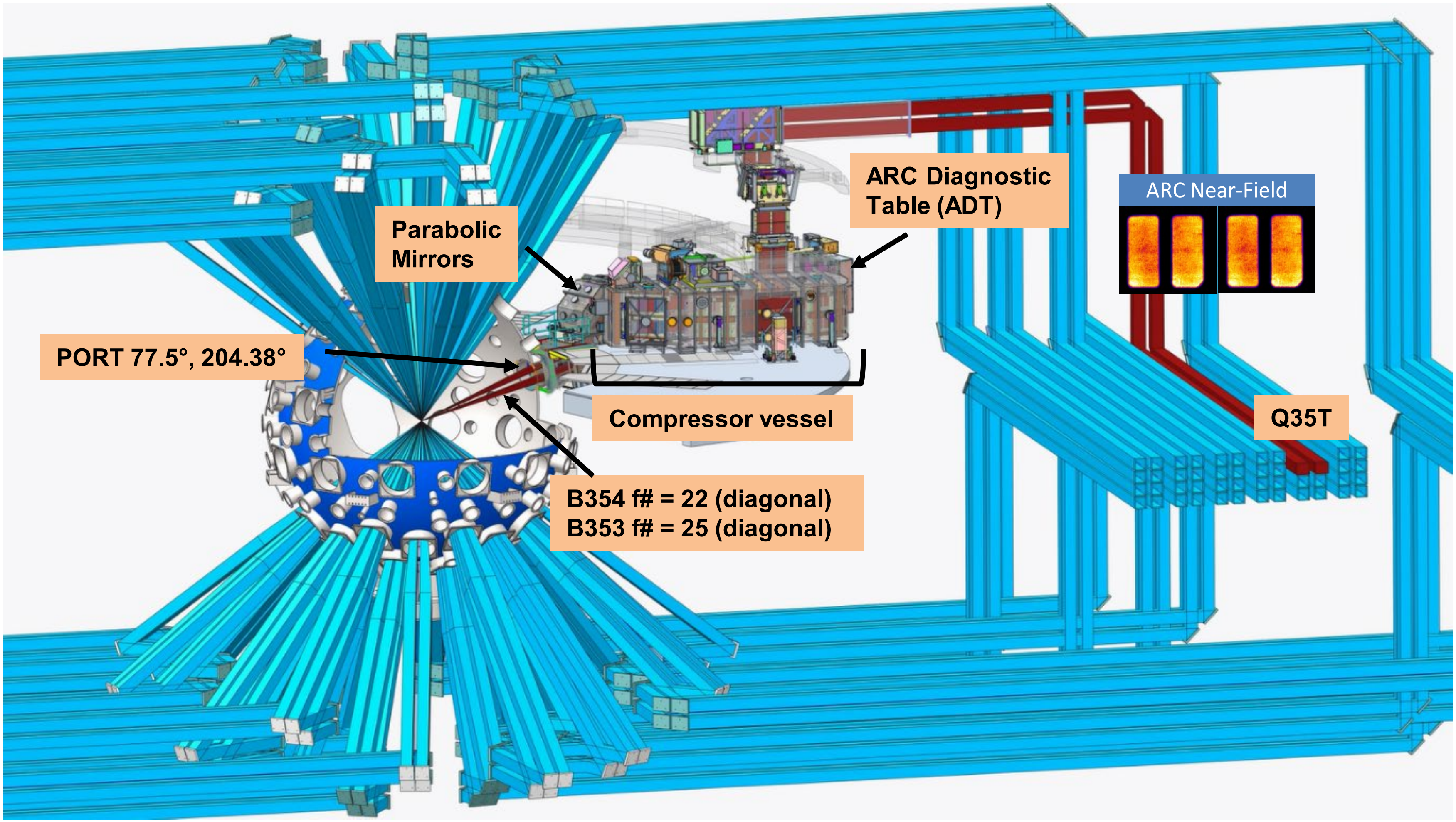
## Laser-wakefield Driven keV and MeV Source Development



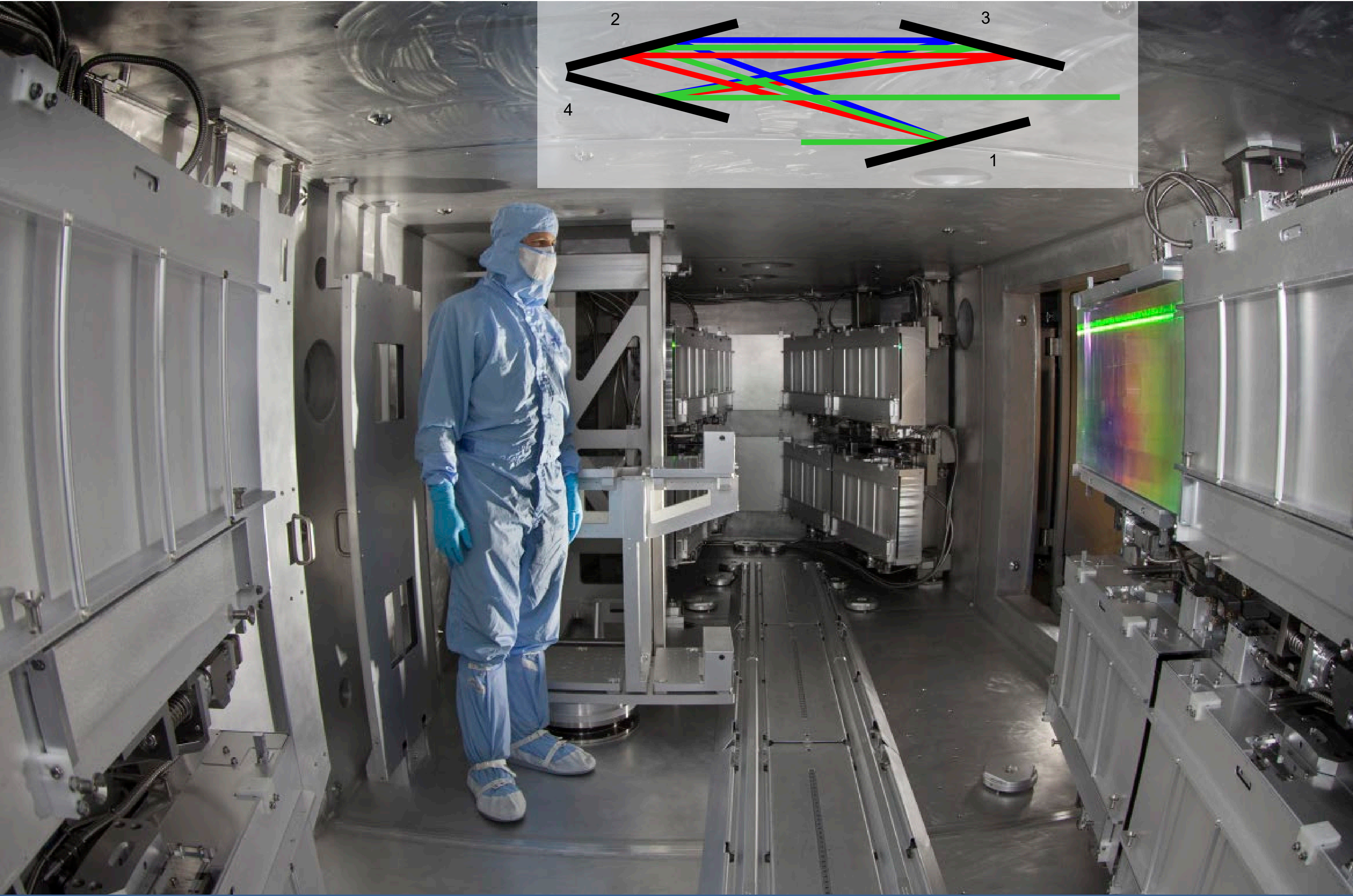

F. Albert, et al.

**This capability is in high demand and we execute ~40 experiments of this type every year**

# NIF switchyard and target area highlighting ARC beams

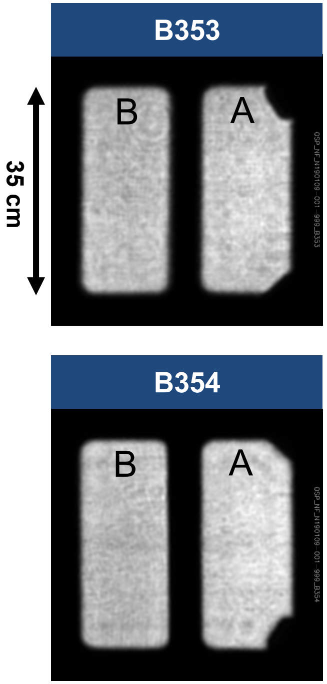



ARC operates in a unique multi-ps, high energy area of short-pulse lasers




A compact folded compressor uses 16 meter-scale gratings to compress the ARC 4 beamlets

# ARC current performance specifications are based on measurement, modeling and design



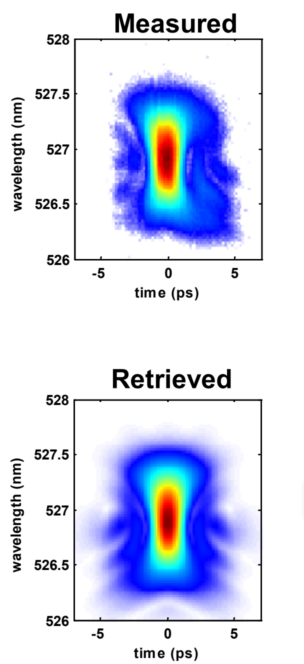

Near field images

| ARC Beamlet | Current Capabilities | | | |
|---|---|---|---|---|
| Number | 4 | | | |
| **Energy & pulse duration** | **250 J @ 1* ps** | **600 J @ 10 ps** | **900 J @ 30 ps** | **1000 J @ 38 ps** |
| Focal spot (~ 30 ps, ~ 1 kJ) | 10-30% of energy at ≥1e17 W/cm$^2$<br>≥30-50% in 150 µm spot | | | |
| Alignment accuracy rms ($X_{ARC}$,$Y_{ARC}$) | (42, 31) µm | | | |
| Pointing range from TCC (ARC) | (±50,±50,+10/-45) mm | | | |
| Beamlet-to-beamlet pointing | 1.26 mm perpendicular, 2mm along focus. | | | |
| Pre-pulse contrast for 1* ps pulse | 80 dB (t < -1.5 ns), 70 dB (t < -200 ps) | | | |
| Timing Accuracy ARC to ARC | 10 ps rms (any beamlet wrt any other beamlet) | | | |
| Timing Accuracy ARC to NIF | 30 ps rms (any beamlet wrt NIF) | | | |
| Delay relative to NIF | Up to 70 ns (any beamlet wrt NIF) | | | |
| Delay of B beamlet wrt A beamlet | Up to 30 ns (B after A) | | | |
| Delay of B354 wrt B353 | Up to 3.6 ns (B353 after B354) | | | |

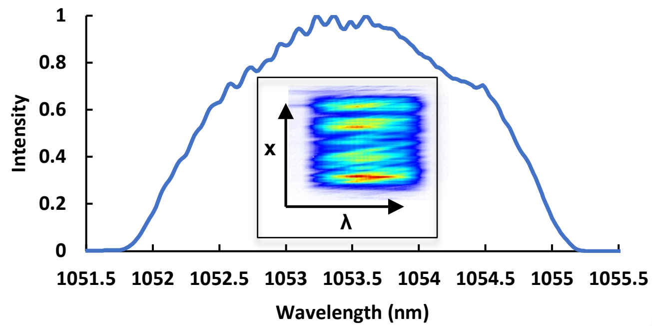
*Aberrations in NIF chain produce a ~1.5ps pulse duration on target (calculated).

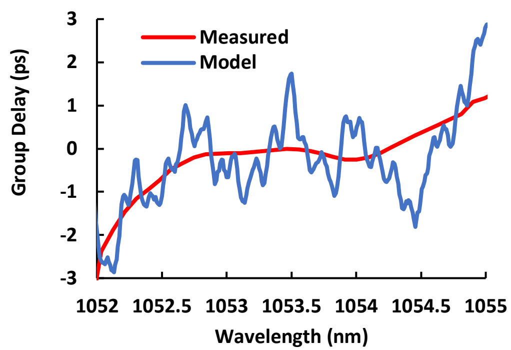
# At its shortest duration, ARC is operating at ~1ps with 250J in each beamlet

## SHG FROG traces

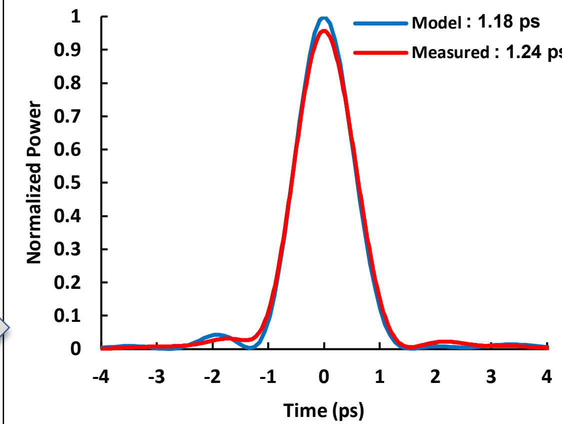



## Spectrum and Group delay



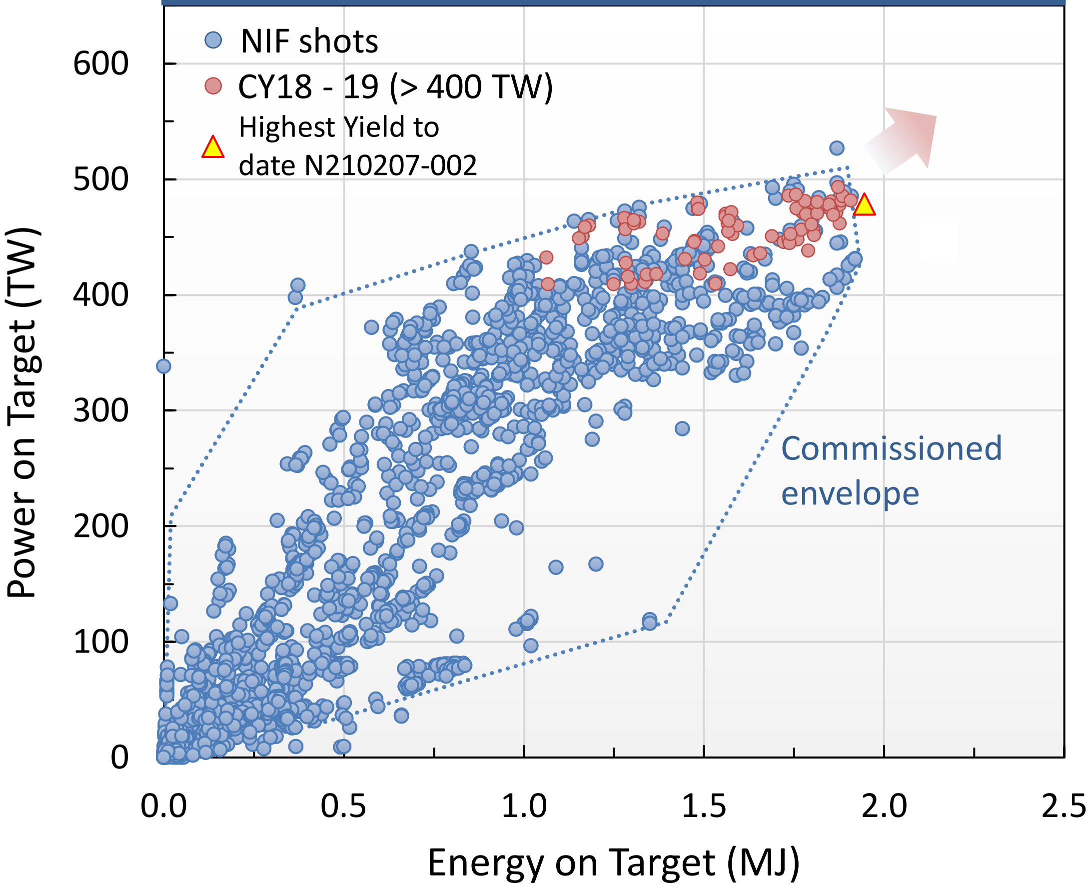

## ARC pulse at compressor exit



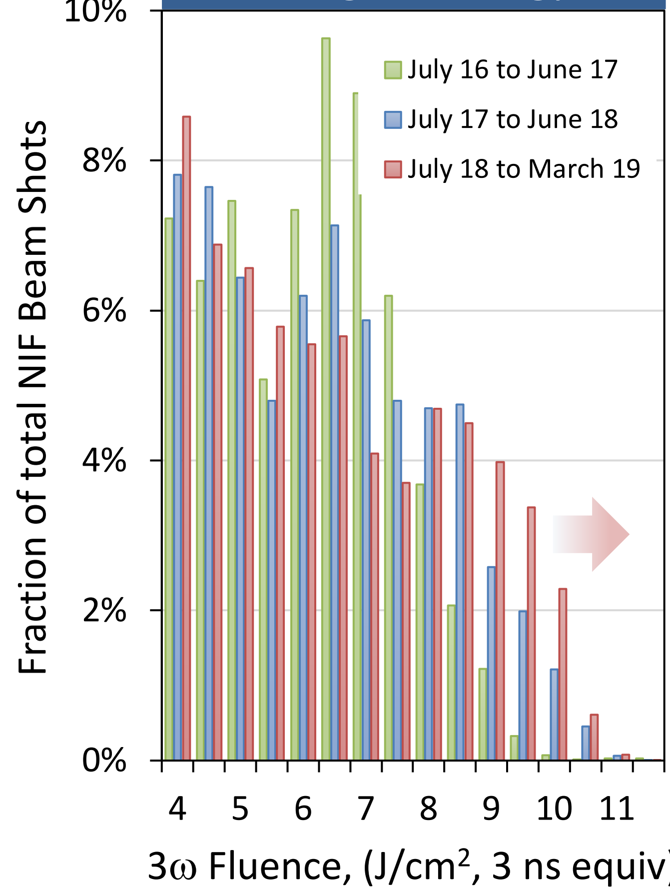

- On-shot FROG and spectrum measurements taken at the ARC diagnostics table.
- There is good agreement between measured and modeled group delay.
- Measured pulse duration is within 5% of modeled (sub-aperture)

# Understanding NIF's potential to deliver higher energy and power for core mission is of increasing interest

ICF experiments are pushing up against operational limits and looking for more




Trend is to more shots at higher energy




To better understand beam quality and performance limitations, diagnostics were resurrected/upgraded like the Precision Diagnostic System (PDS) and efforts are made to enhance our models

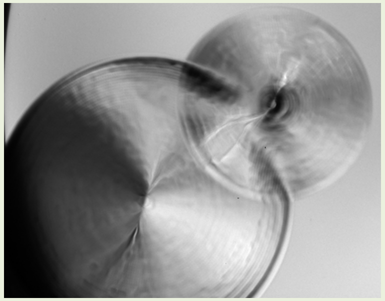
# The NIF laser has capability for higher performance

- Substantial increases in performance are possible through improvement in beam uniformity (fill factor) and reductions in passive losses alone
  - Quad-optimized beam flattening with the programmable spatial shaper system (PSS)
  - Installation of deuterated vs un-deuterated KDP polarization rotators in the final optics
  - Application of anti-reflection coating on the $3\omega$ diagnostic sampling grating in the final optics
- Continued efforts to improve UV optics quality with the goal of lowering NIF operating costs also enable higher performance
  - AMP3 quality fused silica in the final optics
  - Mitigating the damage initiated by target debris and Borofloat inclusions
- The fielding and integrated testing of these improvements has been completed on a single NIF Quad ("Performance Quad") operated up to 2.6 MJ full-NIF-equivalent:
  - Re-assess the performance limits of the laser and update laser performance models
  - Extend existing optics damage models to higher fluence to better predict cost of operation at increased energy and/or power

# Potential for higher energy and power leverages sustained investments in optics and laser technology

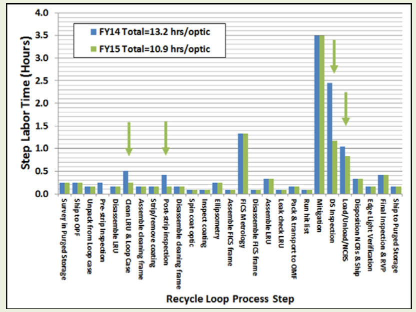
**Process Improvements**

### New Mitigation Protocols



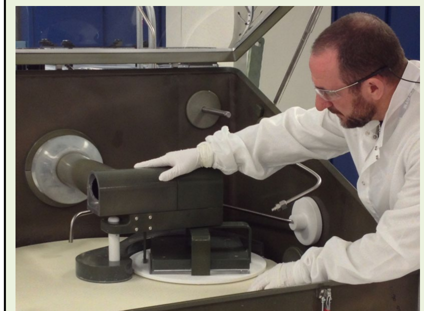
**Reduced permanent blocker rate & optic losses**

### Loop Efficiencies



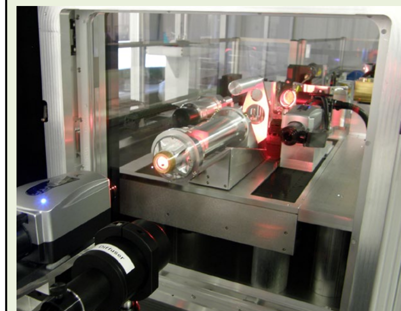

**Reduced recycle cost**

### Low cost finishing



**Reduced flat optic finishing costs**

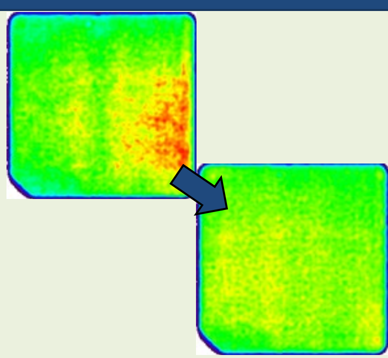
### Mitigation Automation



**Reduced recycle cost**

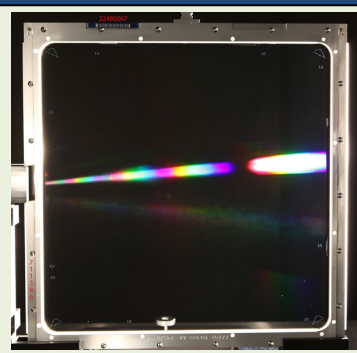
**Laser Improvements**

### Quad-Opt. Gain Mask



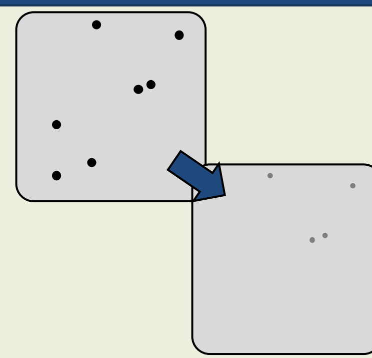
**Lower beam fluence contrast**

### AR coating on Grating



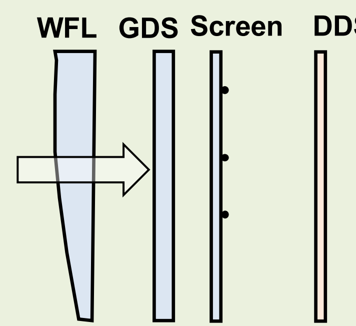
**Lower transport losses**

### Smaller, gray blockers



**Reduced optic exchange rates**

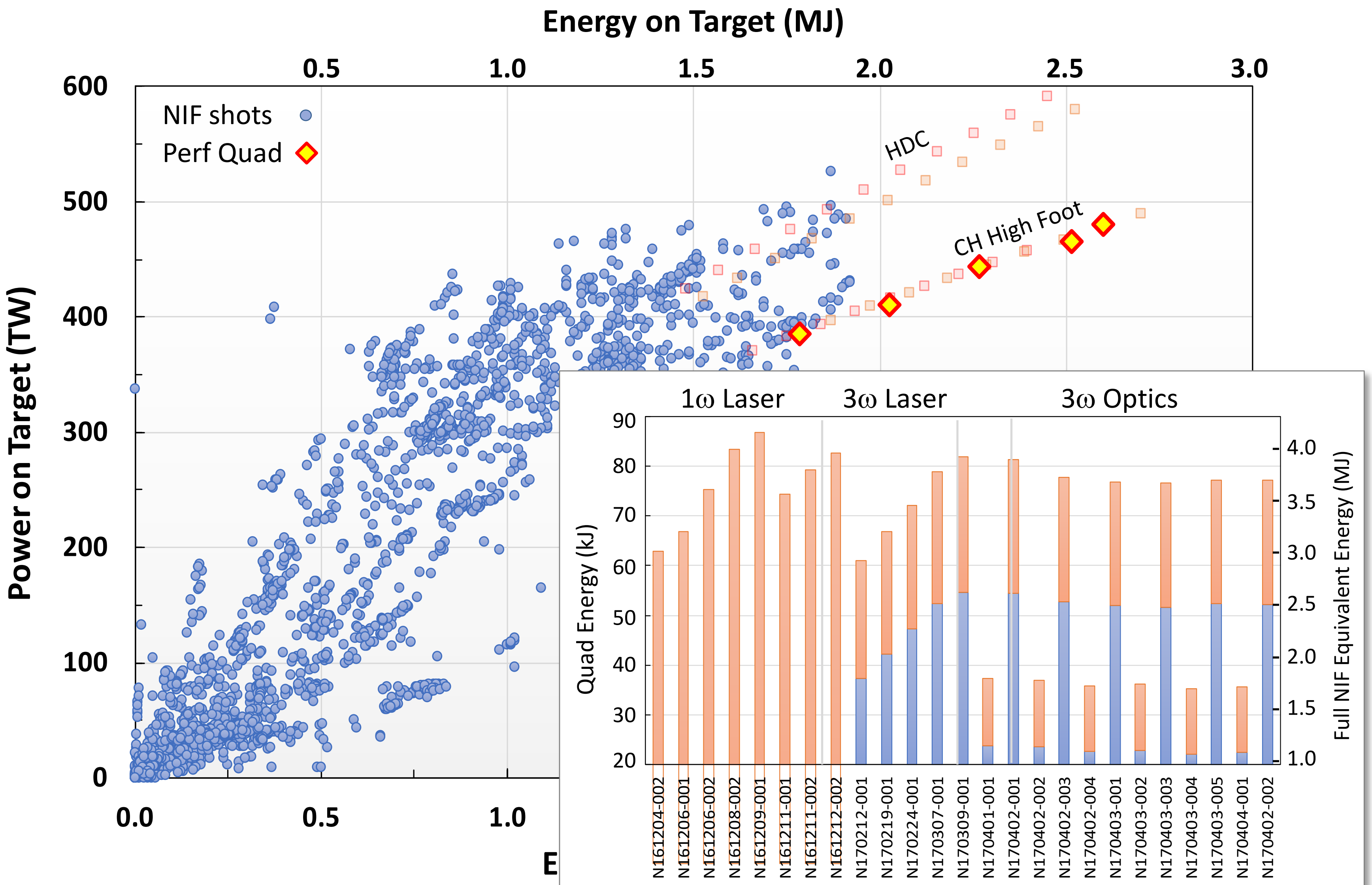
### Fused Silica Screen




**Reduced debris-induced damage**

Investments in new capabilities have enabled increases in NIF shot rate (i.e., more energy & power) for equivalent or less cost

# Performance Quad Campaign tested feasibility of supporting ignition experiments up to 2.6 MJ, 480 TW*



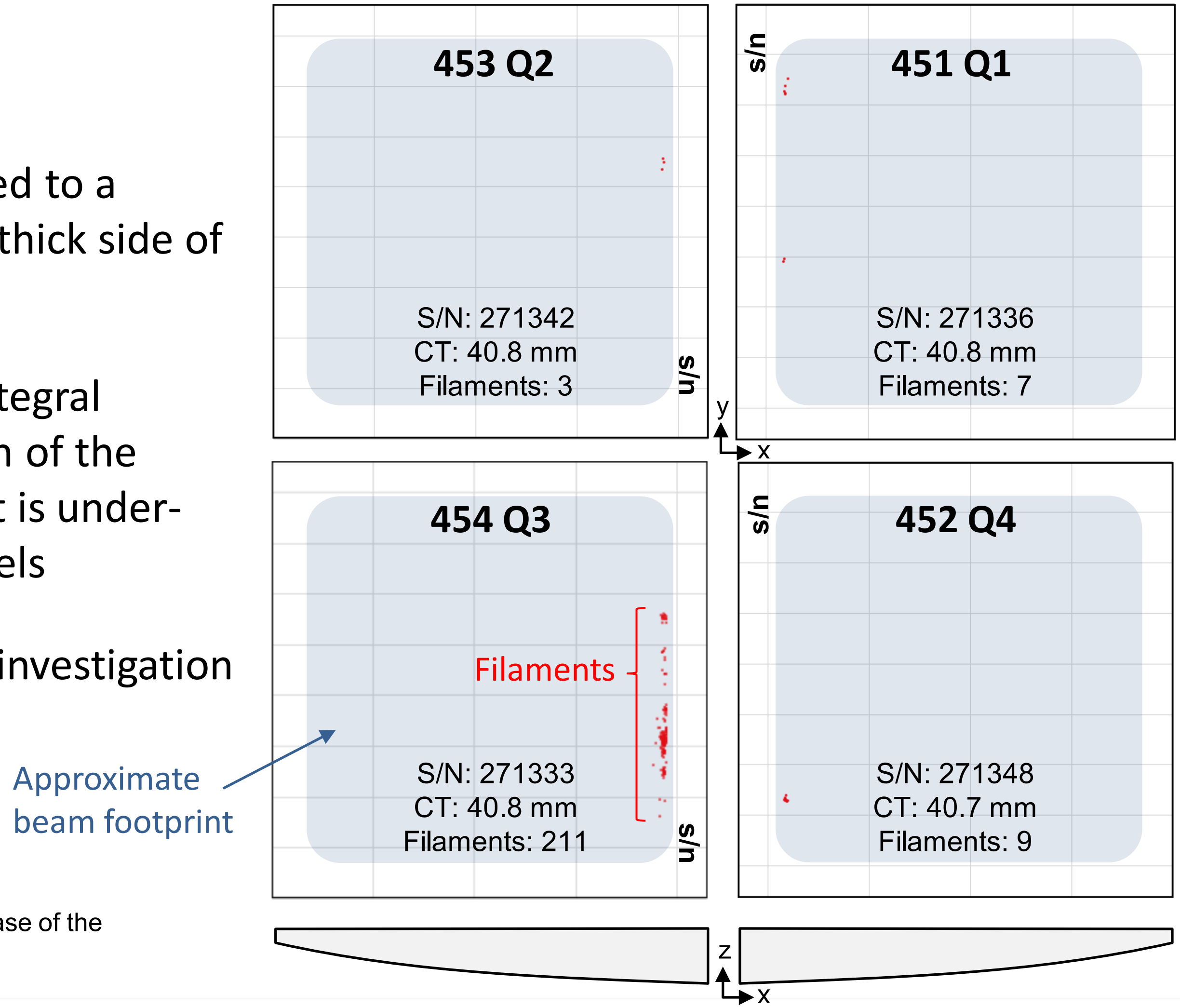



* Di Nicola *et al.*, Nuclear Fusion **59**, 12 (2019)

# Onset of filamentation was observed in the 3ω wedged focus lenses at the highest energies and powers tested - an unexpected result

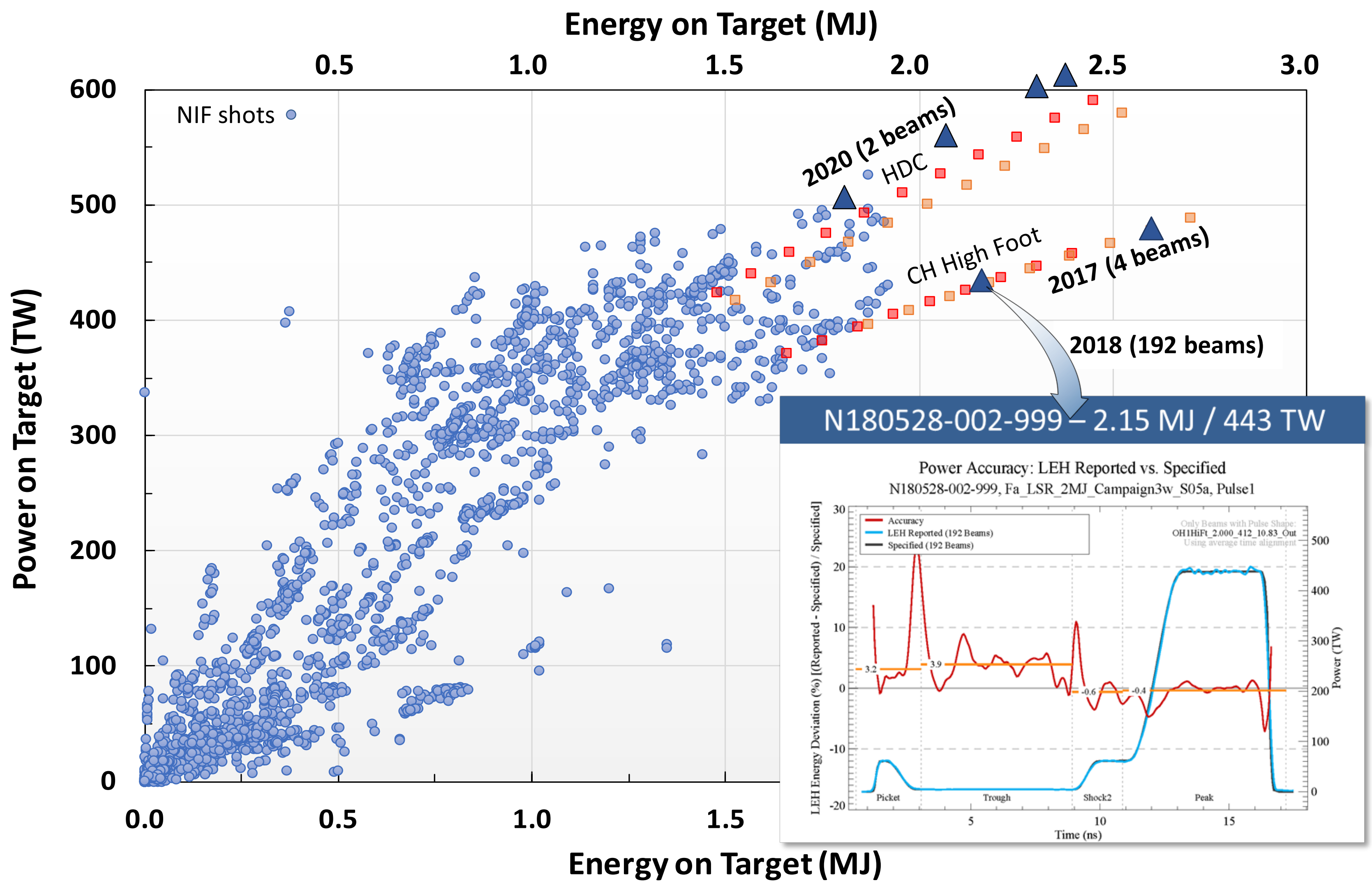
- Occurrence constrained to a narrow region on the thick side of the lenses
- Cause appears to B-integral induced intensification of the edge of the beam that is under-predicted by our models
- Subject of continuing investigation

Location of filaments as determined by microscopy*
(Shown as 430x430mm$^2$ lens images)

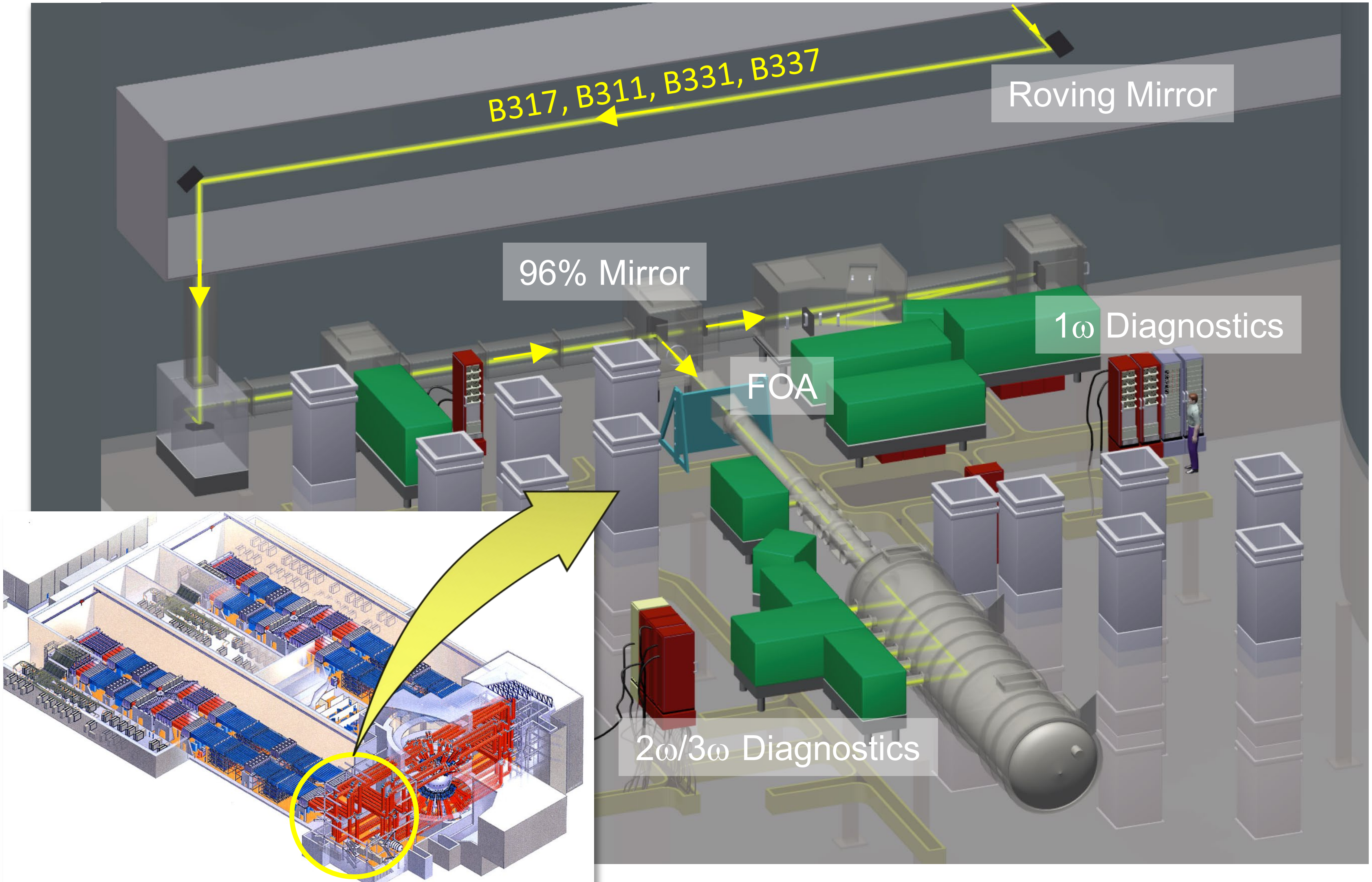



* Data from lenses used in the final phase of the campaign (IIIb)

# Building on these learnings, the NIF laser delivered 2.15 MJ to target chamber center in an ignition-quality pulse and a lower-hemisphere HDC campaign without filamenting



# Additionally, PDS was recommissioned in the IR and now in the UV to perform full-energy / power beam characterization experiments and increase our understanding of B-integral effects

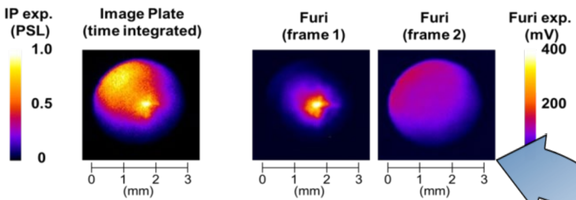




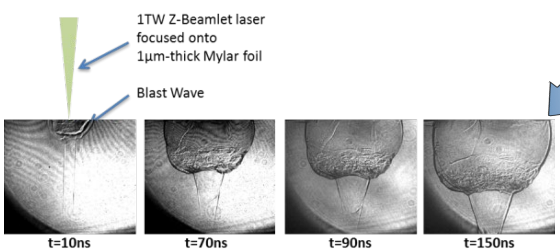

A. Handler, *et al.*, Proc. of SPIE Vol. 11259 1125918-1 (2020)

# Hybrid CMOS Multi Frame Imagers have been used in various target diagnostics, and now recently in NIF's Precision Diagnostic System*

## Collaboration between Sandia and Livermore National Labs



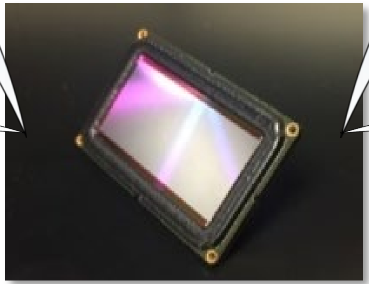

Z-Machine Gas Cell Shadowgraphs



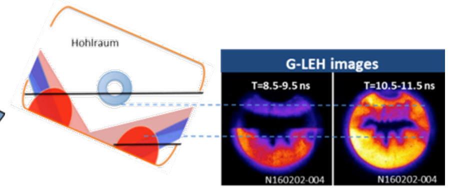

Z-Machine Target Chamber Blast Wave Propagation

Z-Machine Target Chamber Blast Wave Propagation

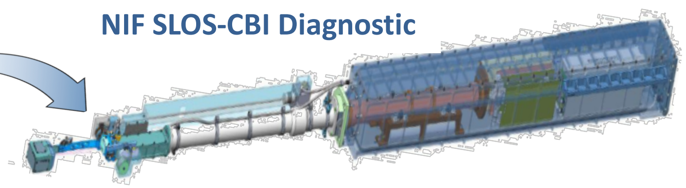
Icarus hCMOS Imager

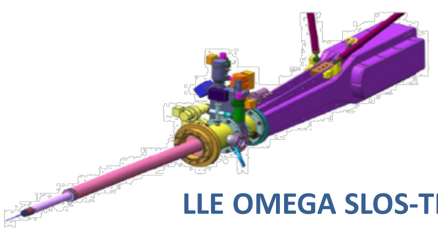


NIF Gated Laser Entry Hole (G-LEH) Diagnostic



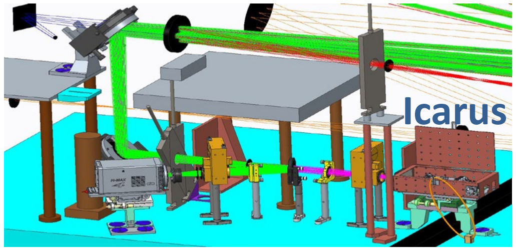

NIF SLOS-CBI Diagnostic





LLE OMEGA SLOS-TRXI Diagnostic

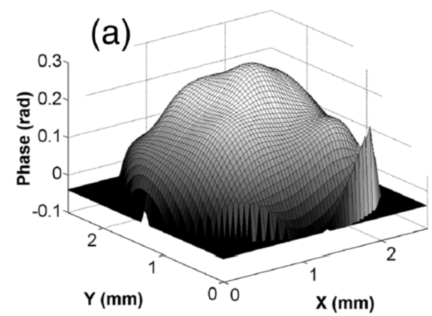
NIF Precision Diagnostic System

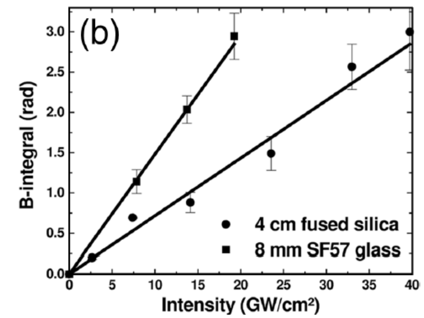



*Viewgraph Courtesy of E. R. Hurd, T. H. Tate, M. S. Dayton, L. Claus, C. E. Durand, M. Johnston, JM. Di Nicola, A. C. Carpenter, and M. O. Sanchez, Proc. of SPIE Vol. 1111413-1 (2019)

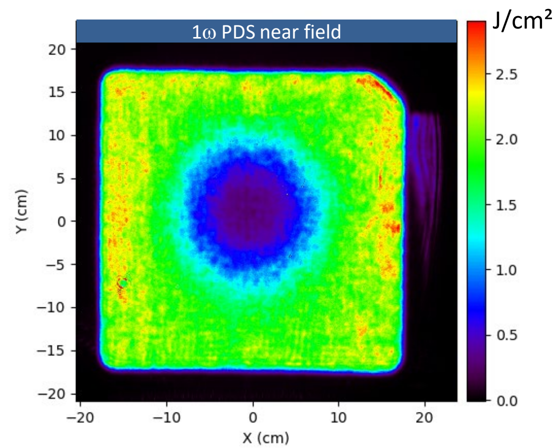
# First direct measurement of integrated nonlinear phase deposition throughout the entire IR section of NIF using a tailored beam

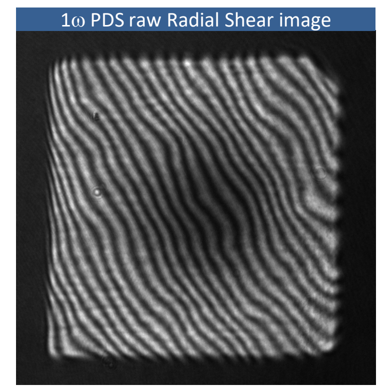
**2004:** Optics Letters*
table-top demonstration:
Gaussian fs beam, slab, WF analyzer
(low-intensity WF is subtracted)



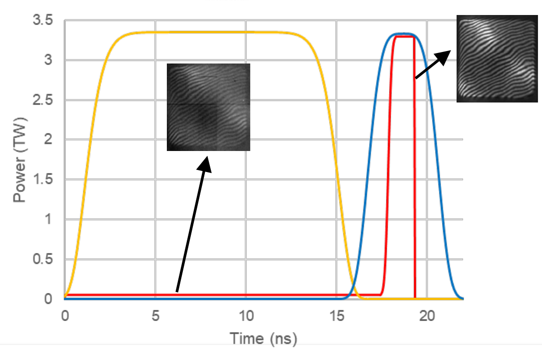



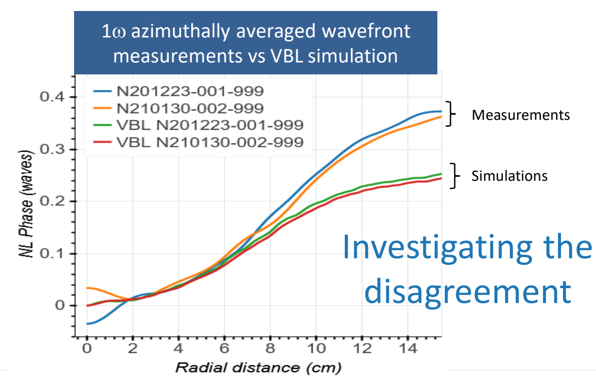

**2019:** Safe, NIF rendition, full main laser
High-B 3.3 kJ, 1ns FIT vs
2x Low-B 200J, 10ns FIT♦




**2021 Preliminary results:** updated experiment using time-resolved (with 2 Icarus gates) self-referenced radial shear interferometry






* J. P. Caumes, *et al.*, Opt. Lett. **29**, 899-901 (2004)
♦ M. Erickson, *et al.*, Proc. of SPIE Vol. 11259 1125917-1 (2020)

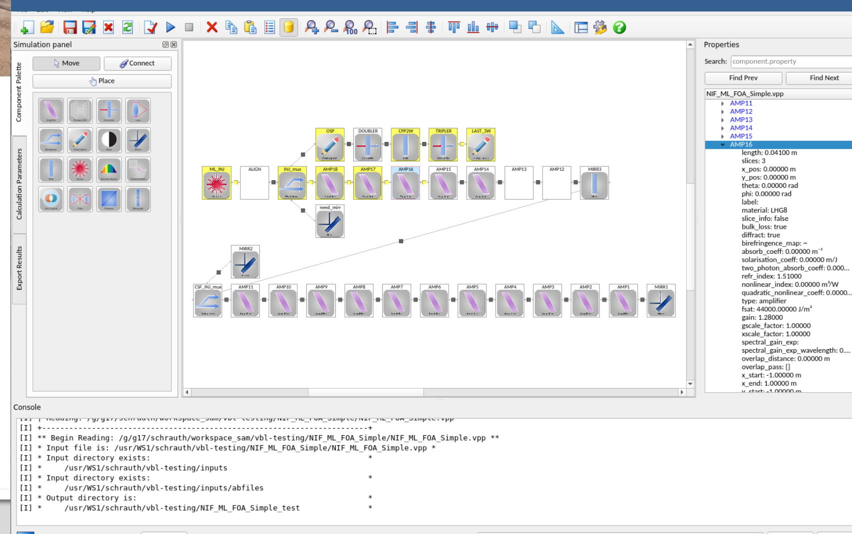
# Virtual Beam Line (VBL++): As of early 2019, we combined two of the Lawrence Livermore Lab's "Powerhouses"

National Ignition Facility, Lawrence Livermore, most energetic laser in the world, 2.15 MJ UV


HPC Lassen, Lawrence Livermore, Ranked #17* Top500, 23 Peta FLOPS

*Top500 from Nov. 2020

Virtual Beam Line VBL++



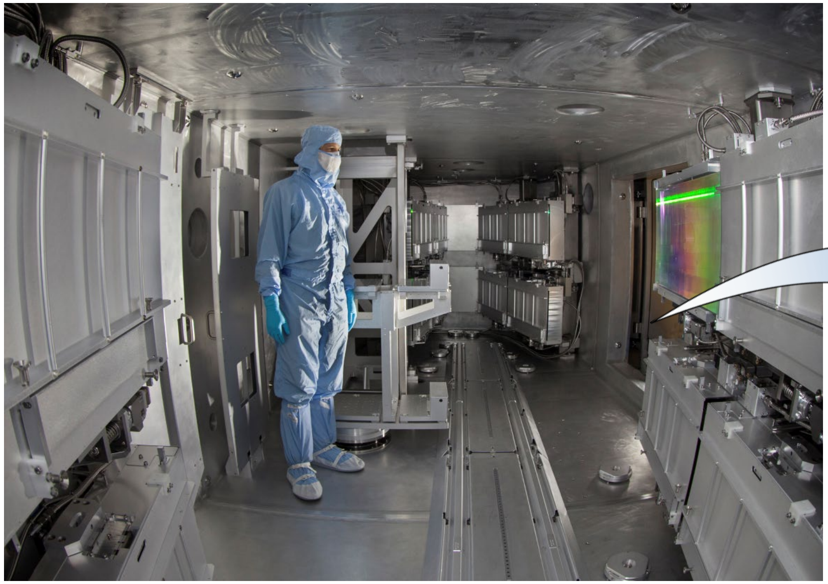

https://www.llnl.gov/news/llnl/virtual-beam-line-now-available

VBL

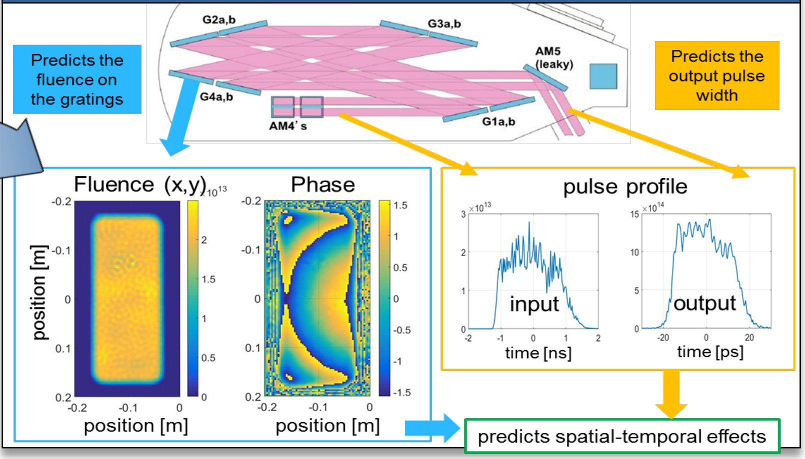
**VBL++ team:** K. McCandless, S. Schrauth, T. Epperly, B. Fishler, J. Nelson, M. Osawe, J. Penner, A. River, A. Shah and JM Di Nicola

Acknowledgements to CEA-LMJ for Miró-VBL++ collaborations

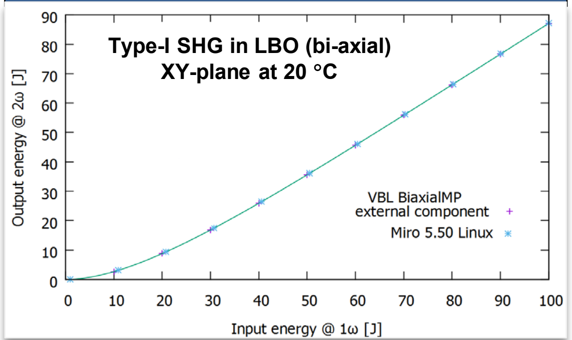
# HPC implementation also enables the deployment of more computationally-intensive physics models in VBL++ for CPA lasers



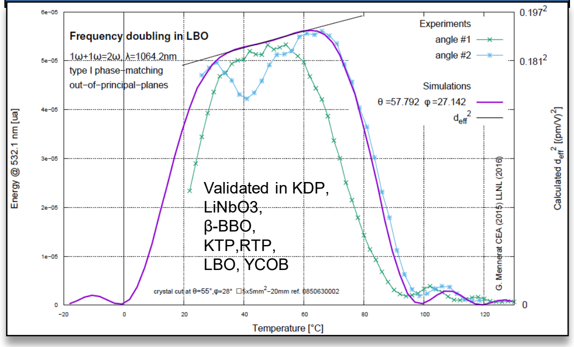
## Generalized Q-matrix approach to model 3D spatio-temporal coupling in grating compressors



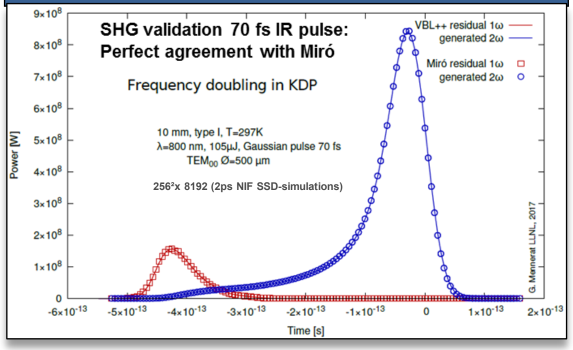

## Freq. Conversion in Arbitrary crystal (e.g. green pumps like HAPLS)




## SHG temperature tolerances out of principal planes arbitrary crystals




## Broadband frequency conversion (FMAM effects with SSD phase-modulation)






Contributions from VBL++ Physics Team: F. Morrissey, G. Menneral, S. Schrauth, T. Lanier and R. Sacks

# Summary

- We had a challenging year but obtained exciting results with record fusion yield
- We embarked in a multi-year program to mitigate obsolescence, provide new capability and improve the performance (3-5x on key metrics) of some of sub-systems (e.g. master oscillator room) that have the largest impact on the 3$\omega$ power accuracy and balance
- We demonstrated with various campaigns and simulations that NIF has the potential for higher energy and power performance
- We deployed advanced beam characterization diagnostics, executed campaigns and enhanced our modeling codes to understand the true NIF limits

# The National Ignition Facility Laser Performance Status

JM. Di Nicola, D. Kalantar, S. T. Yang, D. Alessi, S. Ammula, T. Bond, M. Bowers, B. Buckley, A. Calonico-Soto, W. Carr, L. Chang, J. Chou, S. Cohen, A. Deland, P. DeVore, G. Erbert, M. Erickson, C. Filip, J. Folta, N. Gottesman, A. Gowda, A. Handler, J. Heebner, V. Hernandez, S. Herriot, R. House, C. Kinsella, T. Lanier, B. MacGowan, K. Manes, K. McCandless, R. Muir, B. Olejniczak, M. Ordoñez, C. Orth, E. Padilla, A. Pao, L. Pelz, S. Rana, B. Raymond, S. Schrauth, S. Sommer, T. Suratwala, M. Spaeth, B. Van Wonterghem, A. Wargo, L. Wang, P. Whitman, N. Wong, P. Wegner and D. Larson

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LLNL-PROC-819559

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

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LLNL-PROC-819559

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