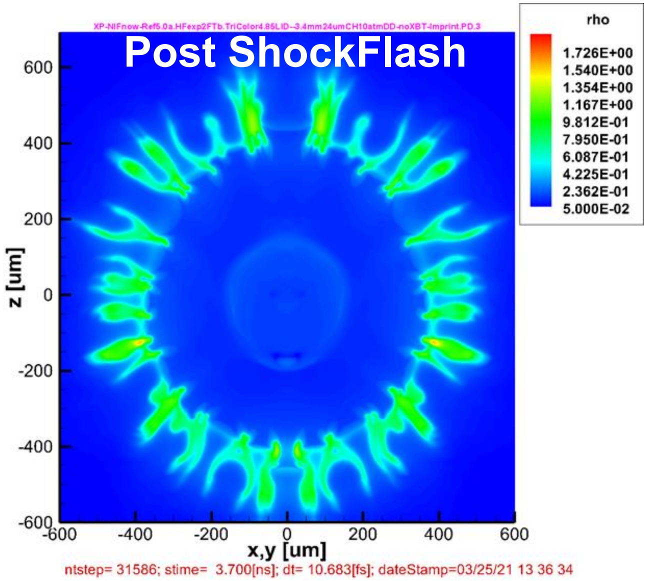
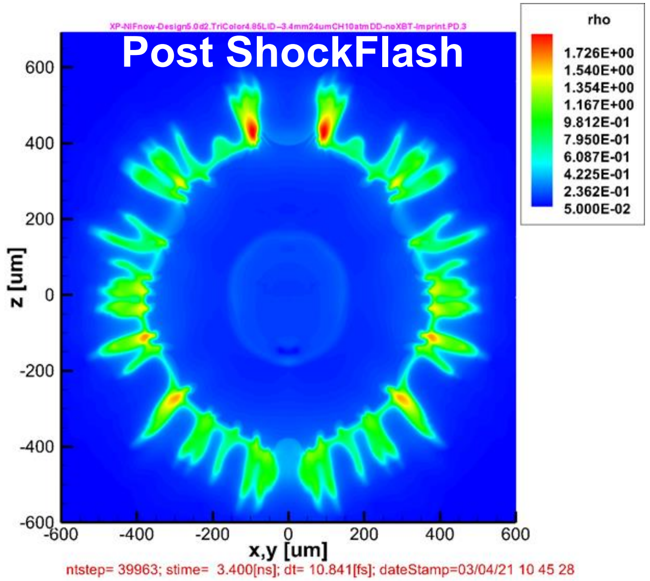
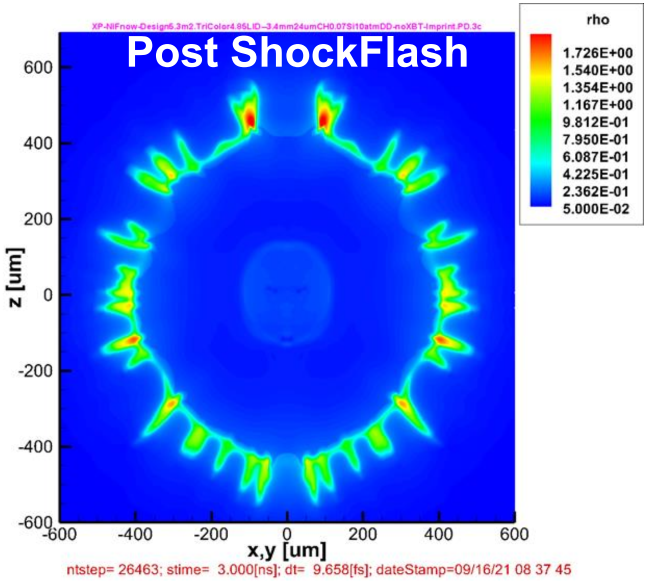
National Ignition Facility (NIF) Polar-Direct-Drive Exploding-Pusher Experiments — Improving Performance via Imprint Mitigation



Reference case



Picketed pulse reduces imprint



Picketed pulse plus Si-doped CH-shell
~equivalent no-Imprint yield

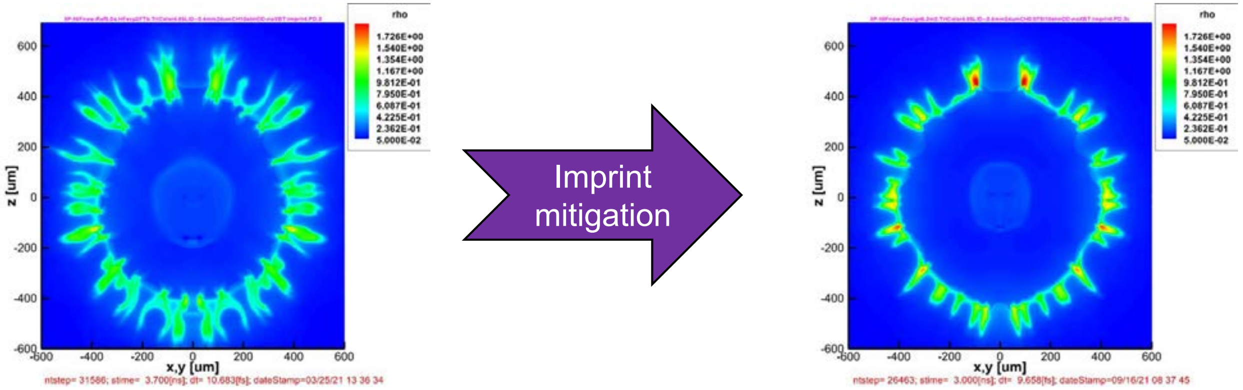
J. A. Marozas
University of Rochester
Laboratory for Laser Energetics

63rd Annual Meeting of the American Physical Society
Division of Plasma Physics
8-12 November 2021

Summary

Imprint mitigation schemes alleviate Exploding Pusher (XP) susceptibility during the final compression phase

- **XPs require imprint mitigation to realize the benefits of shape control**
  - **Current NIF allows pulse-shape (pickets) and target solutions**



Imprint mitigation

- **Target solutions offer ample imprint mitigation for XPs**
  - **Si-doped CH-shell*; split layer [Q2Q3FY22]**
  - **CH-foams; low density overcoat [future dev.]**

---

* Suxing *et al.*, LLE (202?)

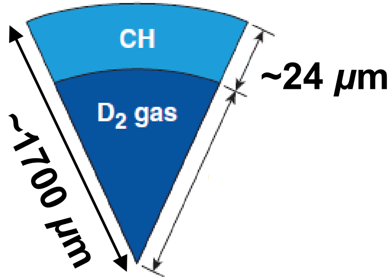
Collaborators

P. W. McKenty, T. J. B. Collins, M. J. Rosenberg,
H. G. Rinderknecht, S. P. Regan and E. M. Campbell
University of Rochester, Laboratory for Laser Energetics

C. B. Yeamans, B. Blue, L. Divol,
G. E. Kemp, and H. D. Whitley
Lawrence Livermore National Laboratory

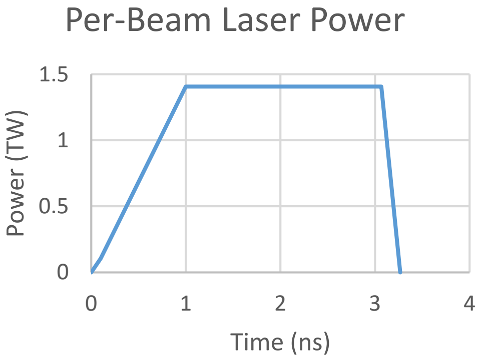
FY21 XP shots assessed symmetry control and energy coupling through beam pointing and pulse shaping

Exploding pusher
~700 kJ
~280 TW



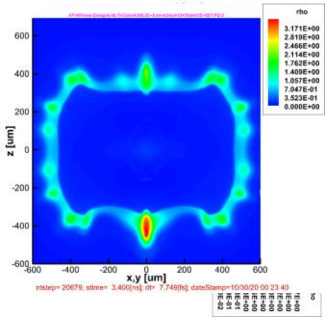
Old-pointing & pulse Reference

N201220-002

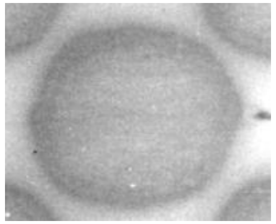


End of Acceleration

DRACO pre-shot
3.4 ns



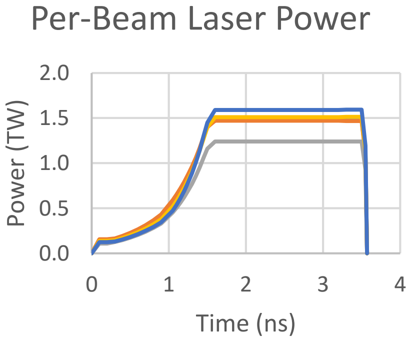
t~3.4 ns



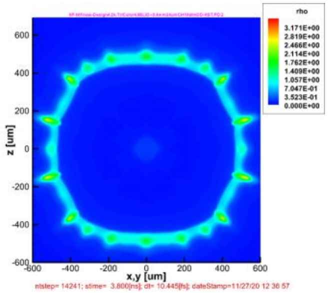
DRACO (new) pointing & pulse

- **Designed for improved symmetry and yield**

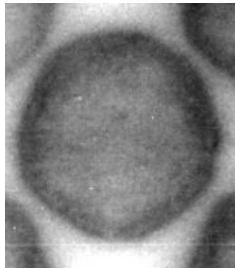
N201220-001



DRACO pre-shot
3.8 ns



t~3.7 ns



Draco preShots predict expected shape

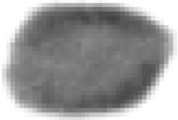
Self-emission images {equatorial view} agree with postshot simulations, achieving the expected control of the shape, however, sans the expected yield improvement

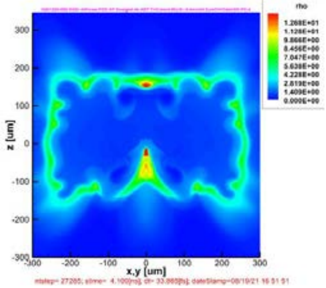
lowRes ~BT

DRACO no-Imprint postShot at Bangtime

N201220-002

t~4.2 ns

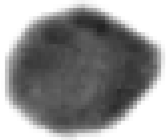


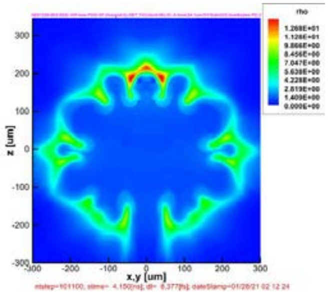


Reference config., pointing & pulse
Y_{DD} = 4.8e13 {exp.}

N201220-003

t~4.25 ns

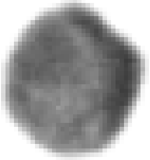


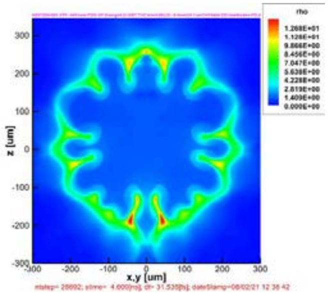


Improved pointing and ref. pulse
Y_{DD} = 4.5e13 {exp.}

N201220-001

t~4.7 ns





Improved pointing and pulse-shapes
Y_{DD} = 4.4e13 {exp.}

Experimental pulse shapes lead to additional distortion

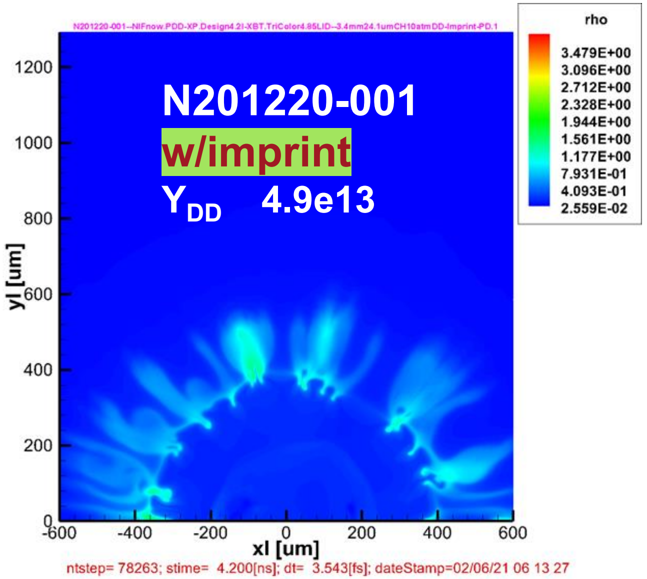
XP PostShots indicate that yield fell short of expectations due to imprint

Parameter	N201220-002	N201220-003	N201220-001
Pointing & PulseShape	Old&ramp2FT	New&ramp2FT	New&exp2FT
Exp. DD-n	4.8e13	4.5e13	4.4e13
PreShot (scaled), DD-n Draco (XBT, lowMode)	5.36e13	8.80e13	9.72e13
PostShot, DD-n Draco (XBT, lowMode)	5.97e13 {>preshot}	7.51e13 {~15% drop}	8.12e13 {~20% drop}
PostShot, DD-n Draco (XBT, Imprint)	4.58e13 {preliminary}		4.88e13 {preliminary}

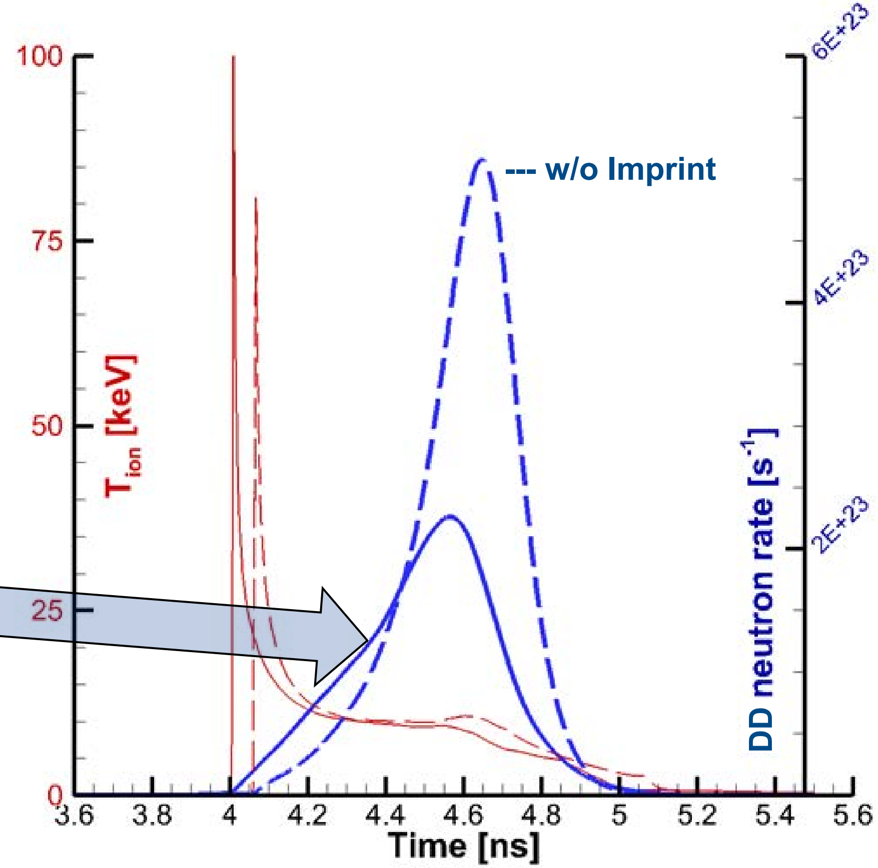
XPs require imprint mitigation to realize the benefits of shape control

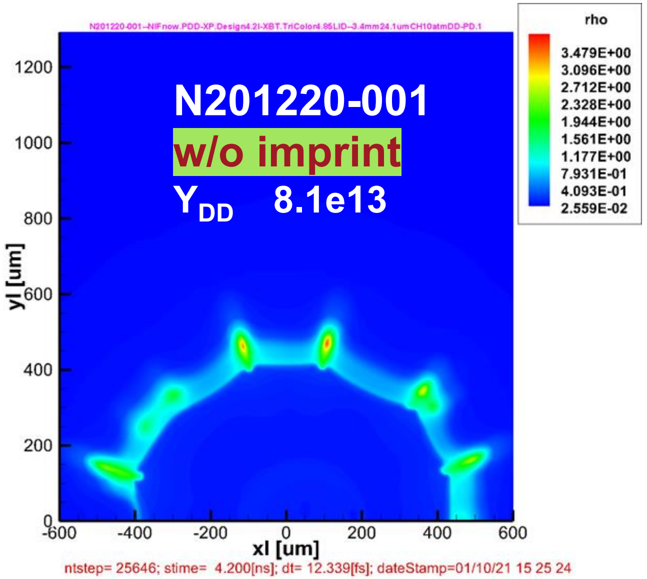
- "Improved" designs inadvertently had stronger imprint (beam overlap and defocusing)
  - during the design phase, imprint was not expected to effect XP

Recent XP shots have been showing evidence of imprint; reduced yield with dampened and wider, asymmetric burn curves (also observed in DT experiments)



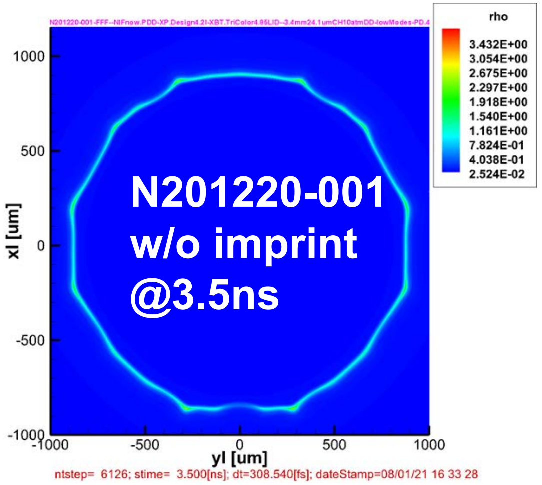
Shock impacts the shell initiating deceleration; cooling dampens burn causing asymmetric as perturbations fall inwards

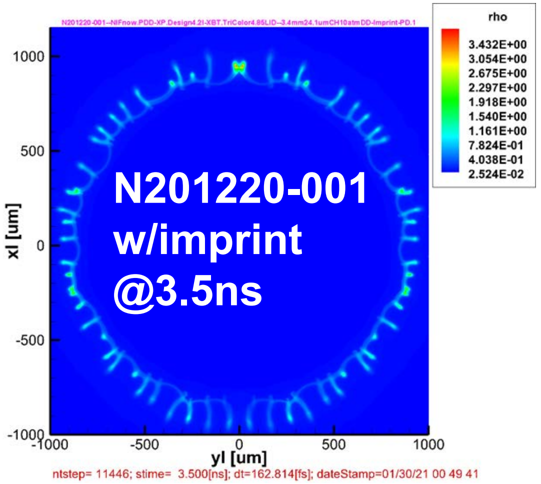




- **Postshot simulations illustrate the detrimental effect of imprint on yield**
  - **Decreased burn rate, earlier peak, asymmetric shape and wider burn-width**

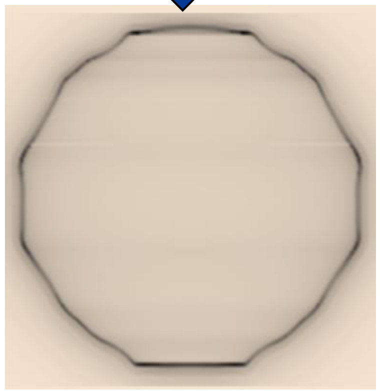
Self-emission images suggest signs of imprint when compared to simulations



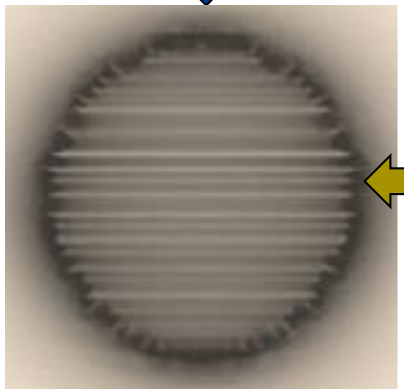


Synthetic x-ray image

Synthetic x-ray image



Spect3D @3.5ns



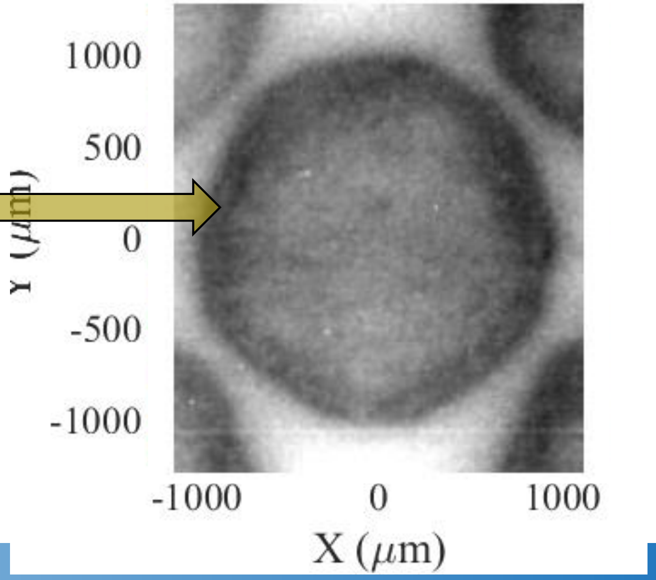
Spect3D @3.5ns

Note: Horizontal structure won't exist true 3D

Incentive for imprint mitigation shots
- July 2021: picketed pulse-shapes
- Q2Q3FY22: Si-doped CH-shells

Thickened shell from imprint corroborates experimental images

t~3.5 ns



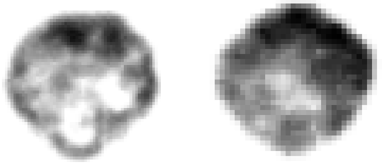
The July 2021 XP shots attempted to demonstrate imprint mitigation by comparing a reference shot to two different picketed pulse shapes

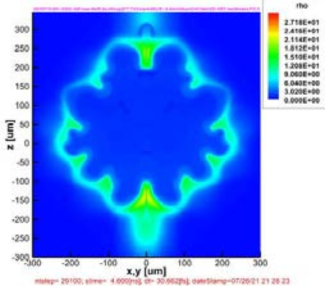
Gated x-ray self-emission images {equatorial view} show North/South asymmetry due to power imbalance

hiRes~BT **lowRes~BT** **DRACO no-Imprint postShot at Bangtime**

N210713-001

t~4.6 ns

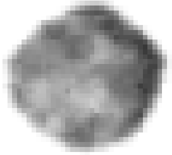


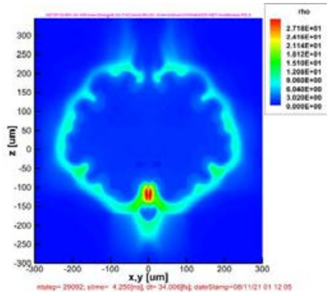


Reference, exp2FT pulse
Y_{DD} = 4.6e13 {exp.}

N210712-001

t~4.2 ns

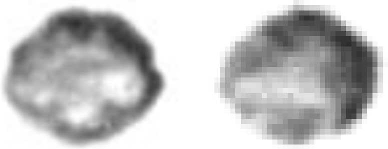


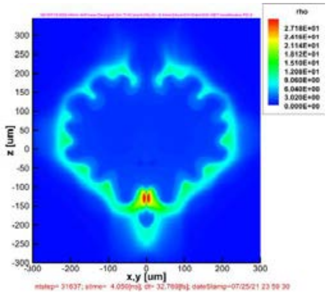


Wide-Picket pulse-shape
Y_{DD} = 5.2e13 {exp.}

N210713-002

t~4.0 ns



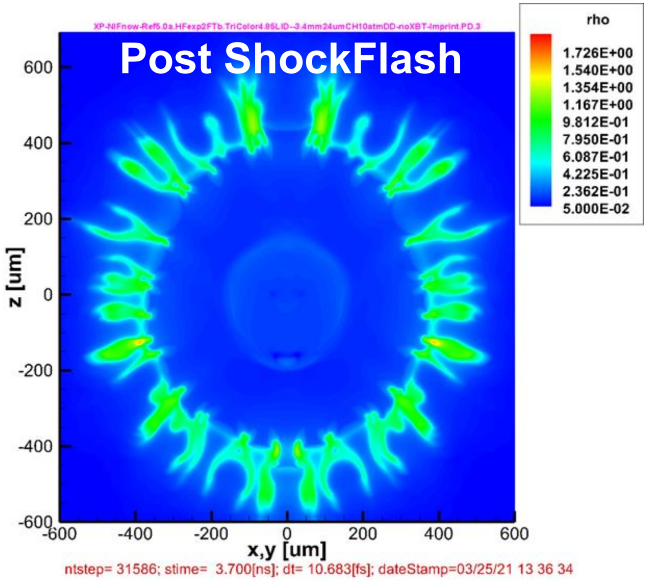


Narrow-Picket pulse-shape
Y_{DD} = 5.1e13 {exp.}

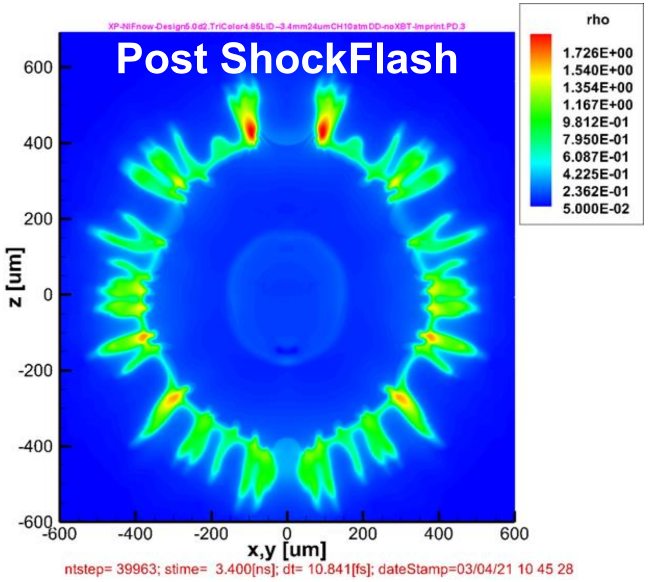
Initial imprint mitigation experiments only achieved ~10% increase due to inadequate picket formation.

- Retuned pickets for reliable shape in November; hoping to achieve ~40% increase

Imprint mitigation schemes are predicted to improve XP performance, thereby realizing the benefit from shape control

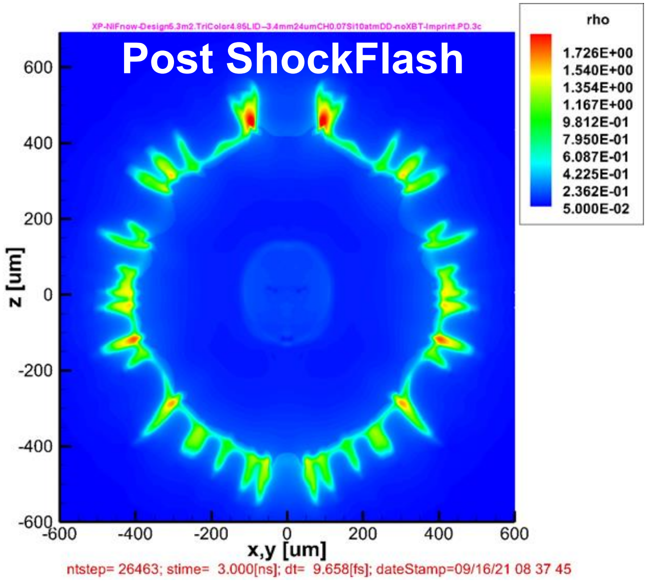


Reference case
Without mitigation



Picketed pulse predicts
yield increase ~50%

Initial experiments July 2021



Picketed pulse plus Si-doped CH-shell
~equivalent no-Imprint yield

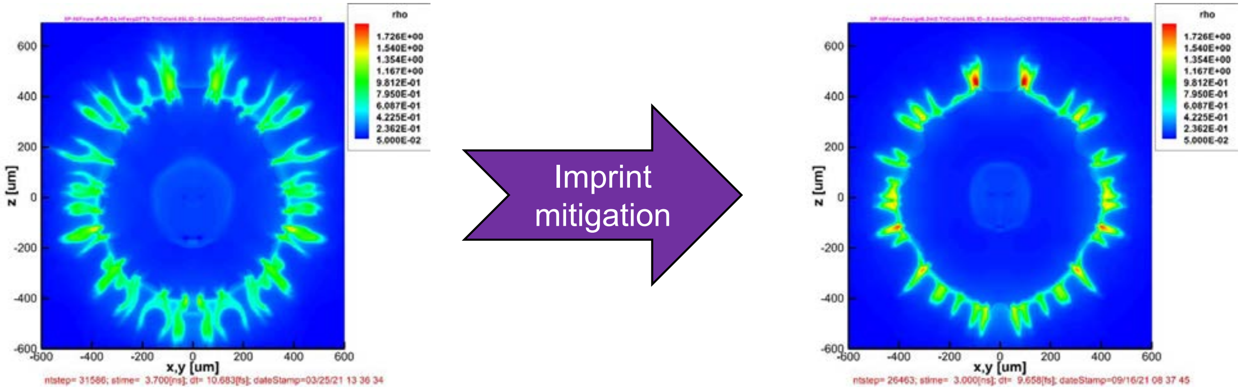
Experiments in Q2Q3FY22 scheduled to shoot Si doped CH shells

- Future experiments planned to use CH foam overcoats

Summary/Conclusions

Imprint mitigation schemes alleviate Exploding Pusher (XP) susceptibility during the final compression phase

- **XPs require imprint mitigation to realize the benefits of shape control**
  - **Current NIF allows pulse-shape (pickets) and target solutions**



- **Target solutions offer ample imprint mitigation for XPs**
  - **Si-doped CH-shell*; split layer [Q2Q3FY22]**
  - **CH-foams; low density overcoat [future dev.]**

---

* **Suxing *et al.*, LLE (202?)**

Backup --- NIF XP Shots data

XP PostShots indicate that yield fell short of expectations due to imprint

Parameter	N201220-002	N201220-003	N201220-001
Pointing & PulseShape	Old&ramp2FT	New&ramp2FT	New&exp2FT
Exp. DD-n	4.8e13	4.5e13	4.4e13
PreShot (scaled), DD-n Draco (XBT, lowMode)	5.36e13	8.80e13	9.72e13
PostShot, DD-n Draco (XBT, lowMode)	5.97e13 {>preshot}	7.51e13 {~15% drop}	8.12e13 {~25% drop}
PostShot, DD-n Draco (XBT, Imprint)	4.58e13 {preliminary}		4.88e13 {preliminary}

XPs require imprint mitigation to realize the benefits of shape control

- "Improved" designs inadvertently had stronger imprint (beam overlap and defocusing)
  - during the design phase, imprint was not expected to effect XP

MJDD NIFnow.PDD XP shots --- Q1FY21 December 2020

- **Bangtimes have mixed agreement**

Parameter	N201220-002	N201220-003	N201220-001
Pointing & PulseShape	Old&ramp2FT	New&ramp2FT	New&exp2FT
		4.2	4.65
		4.46	4.41
PreShot, BT [ns] Draco (XBT, lowMode)	3.83	3.87	4.32
PostShot, BT [ns] Draco (XBT, lowMode)			
			4.58 cf. Spider

pTOF data inconsistent with expected 450-500ps pre- & post-shot delta

"Early" due to delayed exp. rise

MJDD NIFnow.PDD XP shots --- Q1FY21 December 2020

- Tion have mixed agreement depending on sim-config.

Parameter	N201220-002	N201220-003	N201220-001
Pointing & PulseShape	Old&ramp2FT	New&ramp2FT	New&exp2FT
Tion {exp.} [keV]	7.4	7.1	7.3
PreShot, Tion [keV] Draco (XBT, lowMode)	6.87	7.38	7.60
PostShot, Tion [keV] Draco (XBT, lowMode)	6.42	6.92	7.10
PostShot, Tion [keV] Draco (XBT, Imprint)	6.50		6.79

The pulse shapes and imprint alter the shapes compared to designs at bangtime; only measured target and pulse-shapes changed; N201220

N201220-001 [FFF]
Draco Pointing, exp2FT

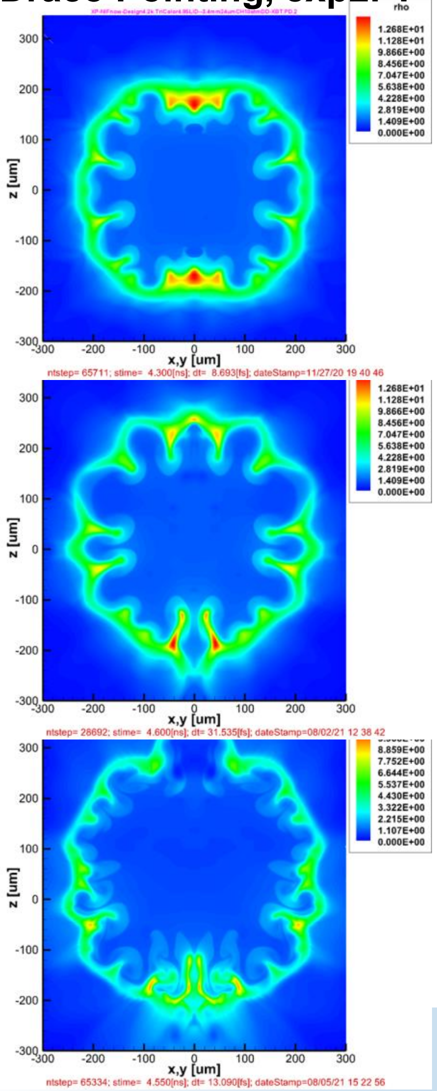
N201220-002 [DDD]
SAGE Pointing, ramp2FT

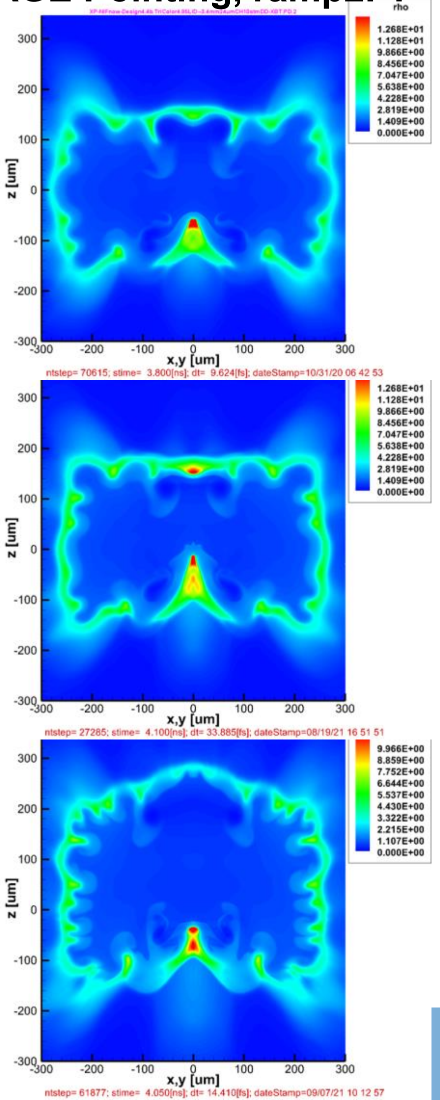
N201220-003 [EEE]
Draco Pointing, ramp2FT

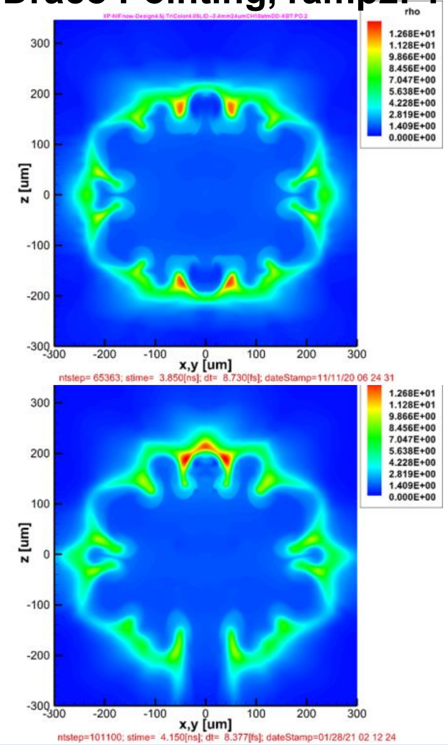
PreShot Designs

PostShots w/ Experimental PulseShapes

PostShots w/ Experimental PulseShapes & Imprint







Shot	Y_{DT} (10^{13})		T_i (keV)		t_{bang} (ns)	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
N201220-001	4.4	4.88	7.3	6.79	4.65*	4.58
N201220-002	4.8	4.58	7.4	6.50	4.21	4.08
N201220-003	4.5		7.1		4.2*	

MJDD NIFnow.PDD XP shots --- Q4FY21 July 2021
Postshots show yield fell short of expectations due to inadequate picket shapes

- Nominal XP target: 24um CH shell, 3.4mm diameter, 10atm DD-fill
- Nominal laser specs: ~290TW total peak power, ~710kJ

Parameter	N210713-001	N210712-001	N210713-002
Config	exp2FT	Wide picket	Narrow picket
Exp. DD-n	4.64e13	5.16e13	5.13e13
PreShot, DD-n Draco (XBT, lowMode)	9.77e13	9.47e13	10.1e13
PreShot, DD-n Draco (XBT, Imprint)	5.76e13		8.43e13
PostShot, DD-n Draco (XBT, lowMode)	10.7e13	10.2e13	10.9e13
PostShot, DD-n Draco (XBT, Imprint)			

- Picketed shapes were compromised and large North/South imbalances.

Imprint simulations are underway including the effects to the imprint spectrum, both SSD modulators (important for SSDMPE) and non-zero m-modes.

MJDD NIFnow.PDD XP shots --- Q4FY21 July 2021

- **Bangtimes have mixed agreement**

Parameter	N210713-001	N210712-001	N210713-002
Config	exp2FT	Wide picket	Narrow picket
X-ray BT (SPIDER) [ns]	~4.33	~4.05	~3.8
DD-n BT (pTOF) [ns]	4.72		4.19
PreShot, BT [ns] Draco (XBT, lowMode)	4.42	4.13	
PreShot, DD-n Draco (XBT, Imprint)	4.36		3.88
PostShot, BT [ns] Draco (XBT, lowMode)	4.61	4.27	4.04
PostShot, BT [ns] Draco (XBT, Imprint)			

MJDD NIFnow.PDD XP shots --- Q4FY21 July 2021

- Tion have mixed agreement depending on sim-config.

Parameter	N210713-001	N210712-001	N210713-002
Config	exp2FT	Wide picket	Narrow picket
Tion {exp.} [keV]	7.47	7.56	7.90
PreShot, Tion [keV] Draco (XBT, lowMode)	7.07	6.84	6.95
PreShot, DD-n Draco (XBT, Imprint)	6.79		6.70
PostShot, Tion [keV] Draco (XBT, lowMode)	6.91	6.75	6.92
PostShot, Tion [keV] Draco (XBT, Imprint)			

The pulse shapes and imprint alter the shapes compared to designs; the only changed is measured target and pulse-shapes; N210712-13

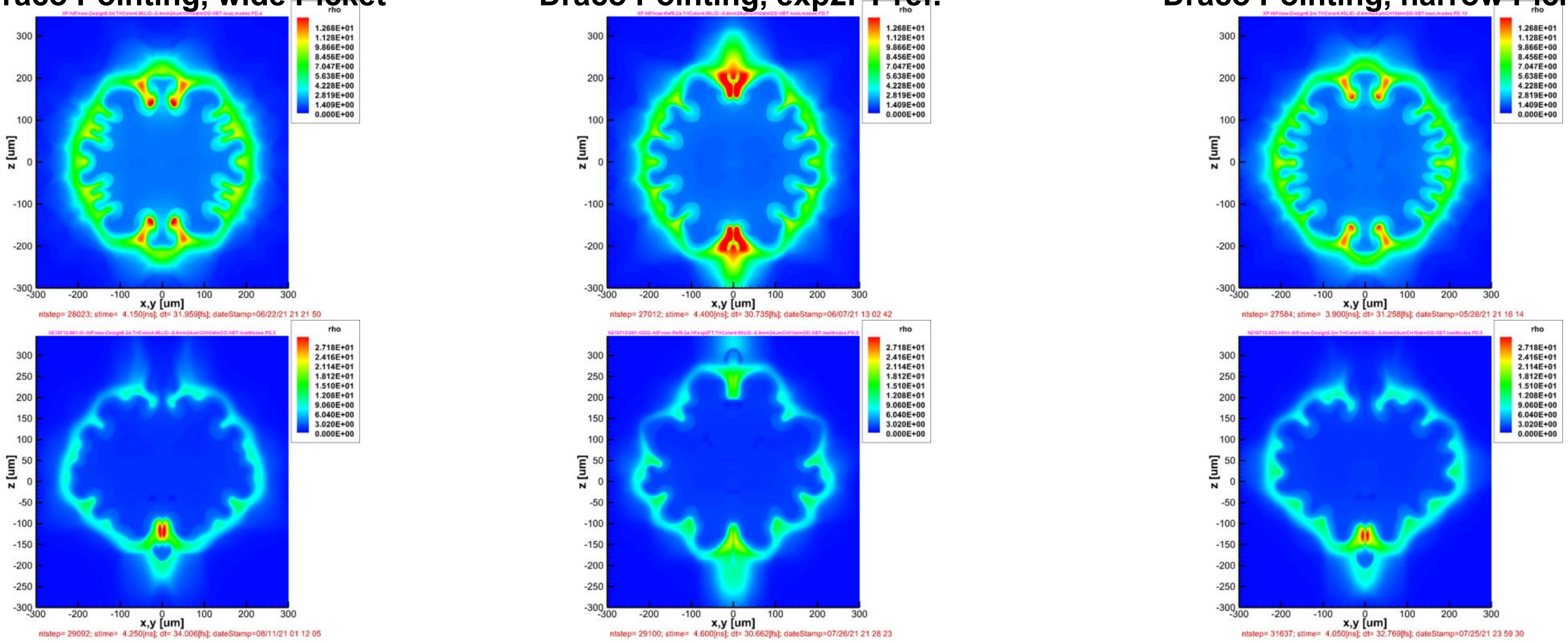
N210712-001 [III]
Draco Pointing, wide Picket

N210713-001 [GGG]
Draco Pointing, exp2FT ref.

N210713-002 [HHH]
Draco Pointing, narrow Picket

PreShot Designs

PostShots w/ Experimental PulseShapes

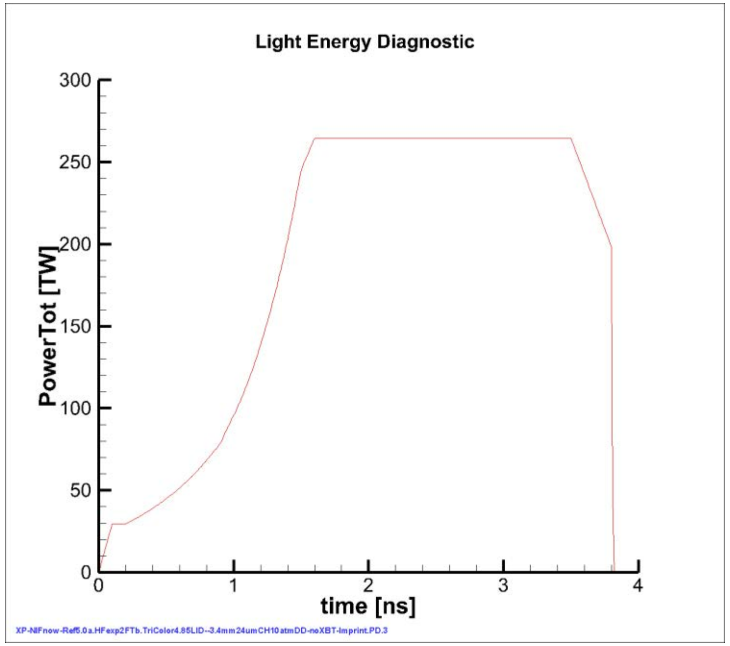


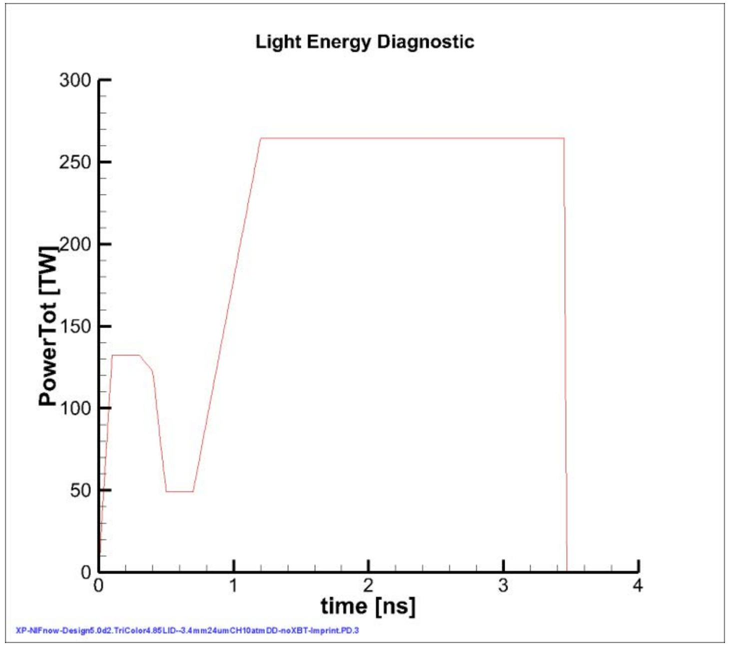
Backup --- NIF PulseShaping

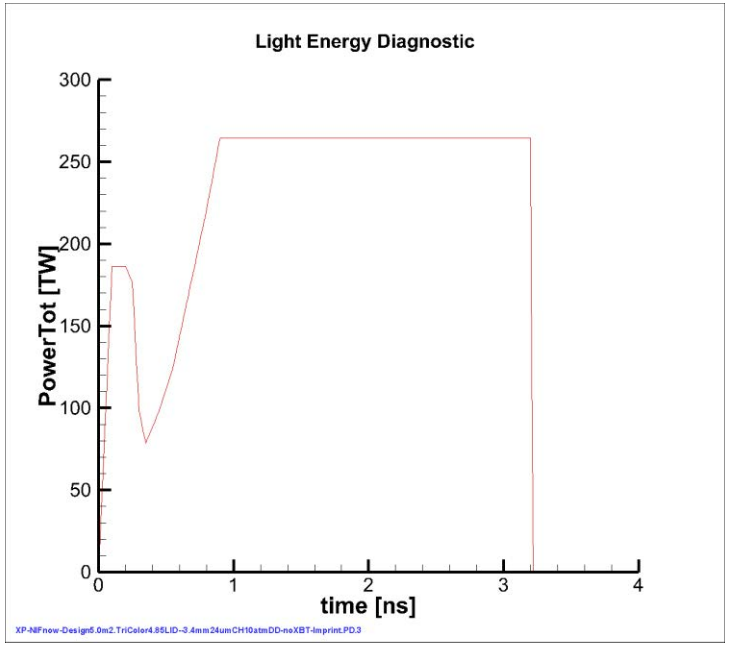
MJDD NIFnow.PDD XP shots --- Q4FY21 July 2021

The three proposed pulse-shapes

- **Reference, Design5.0d2, Design5.0m2**



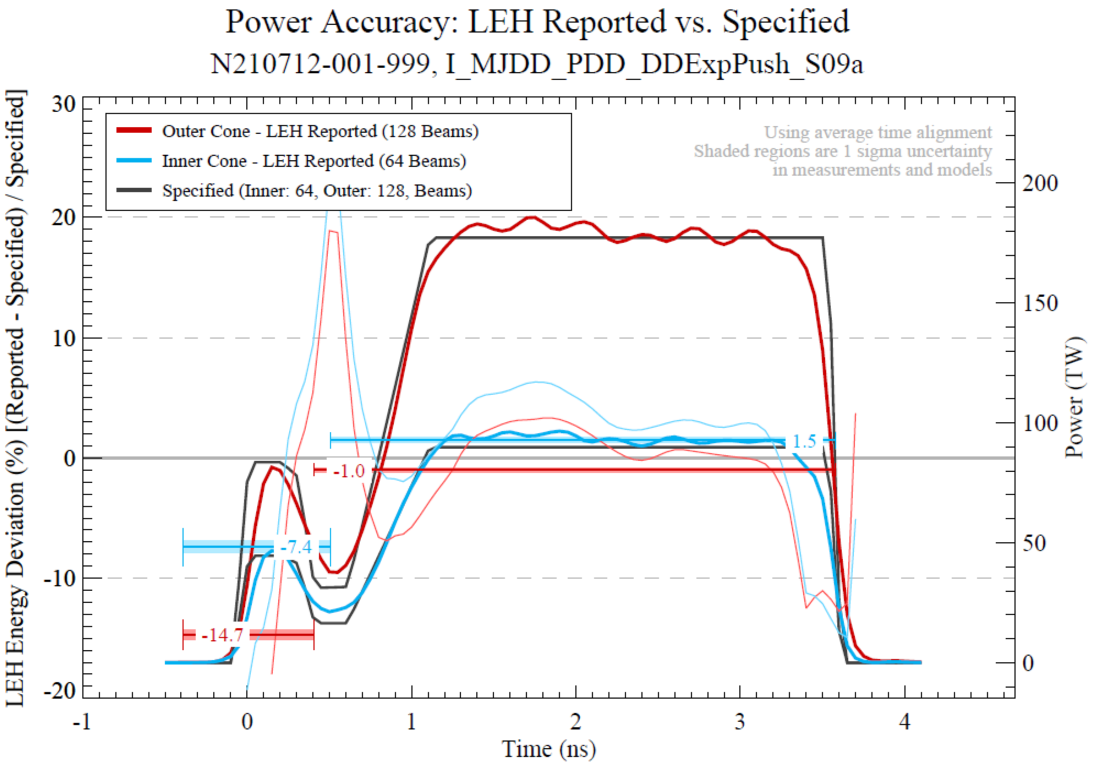


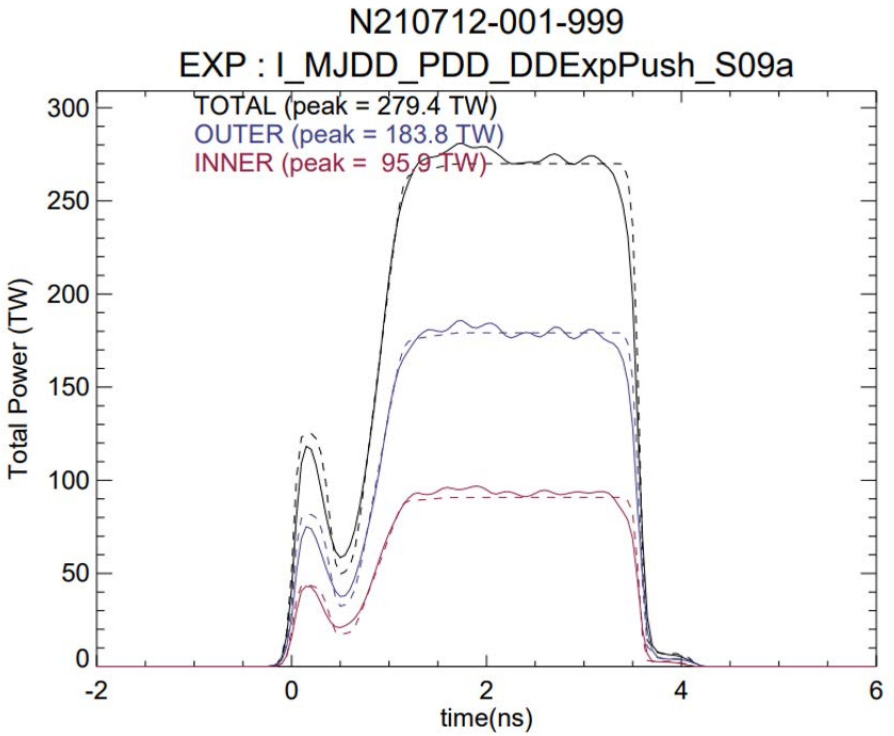


- **Picket goals to achieve imprint mitigation:**
  - **~50-60kJ; exact shape not so important**
  - **Narrow as possible; an impulse function is ideal but not necessary**
  - **Shortest dwell, and lowest power (return to zero ideal); need to rise to FT ~1ns**

Pulse shapes from July 2021 XP shots

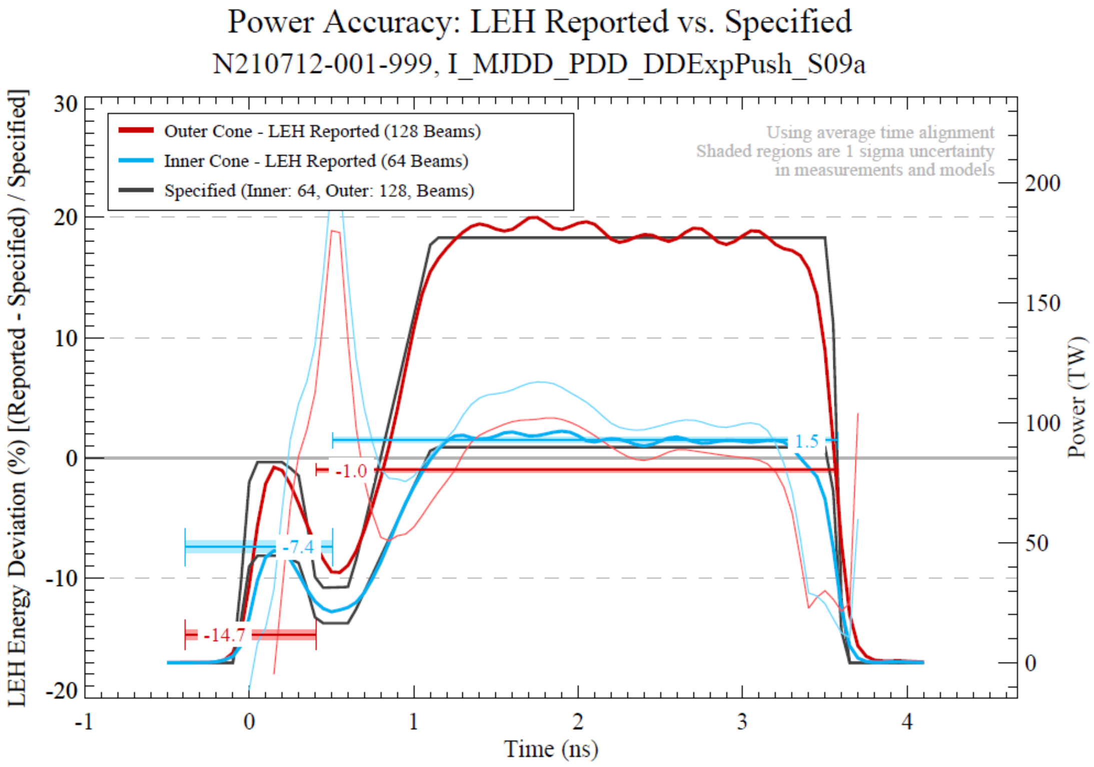
- **Wide picket not well matched, plus strong imbalances**

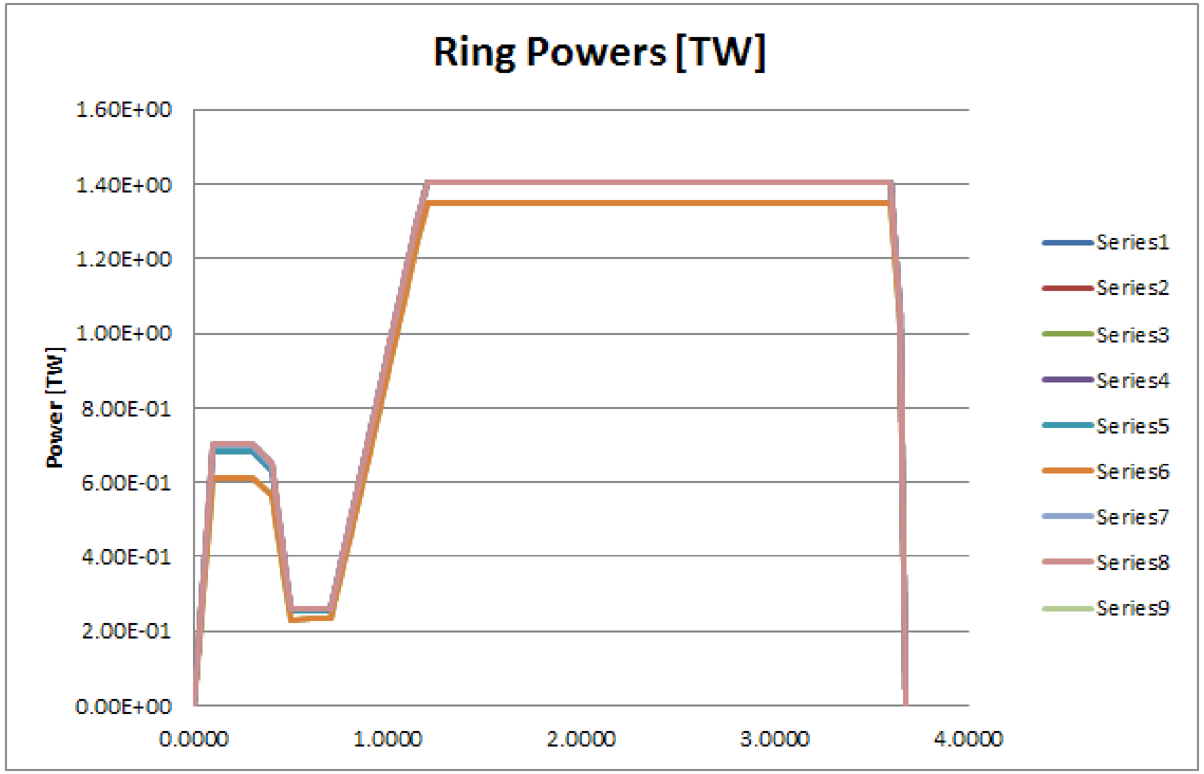




Pulse shapes from July 2021 XP shots

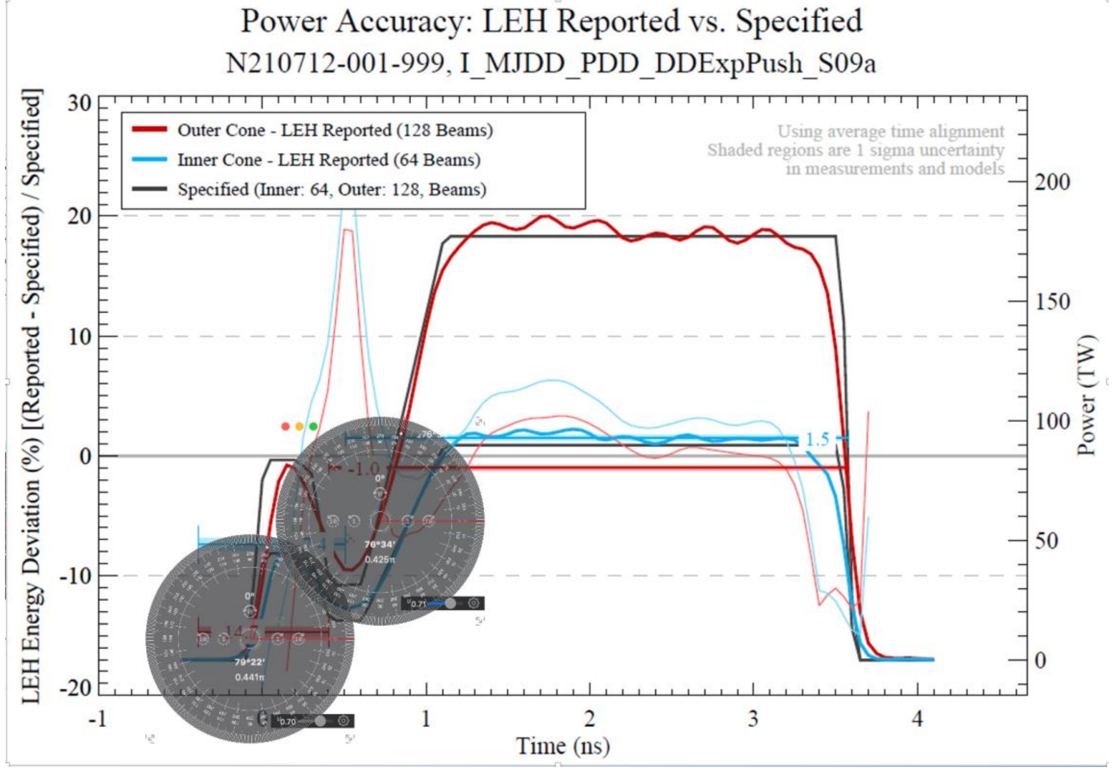
- **Black trace shown as "specified" is not exactly as-specified; 3 added 'corner' features; where did those come from?**

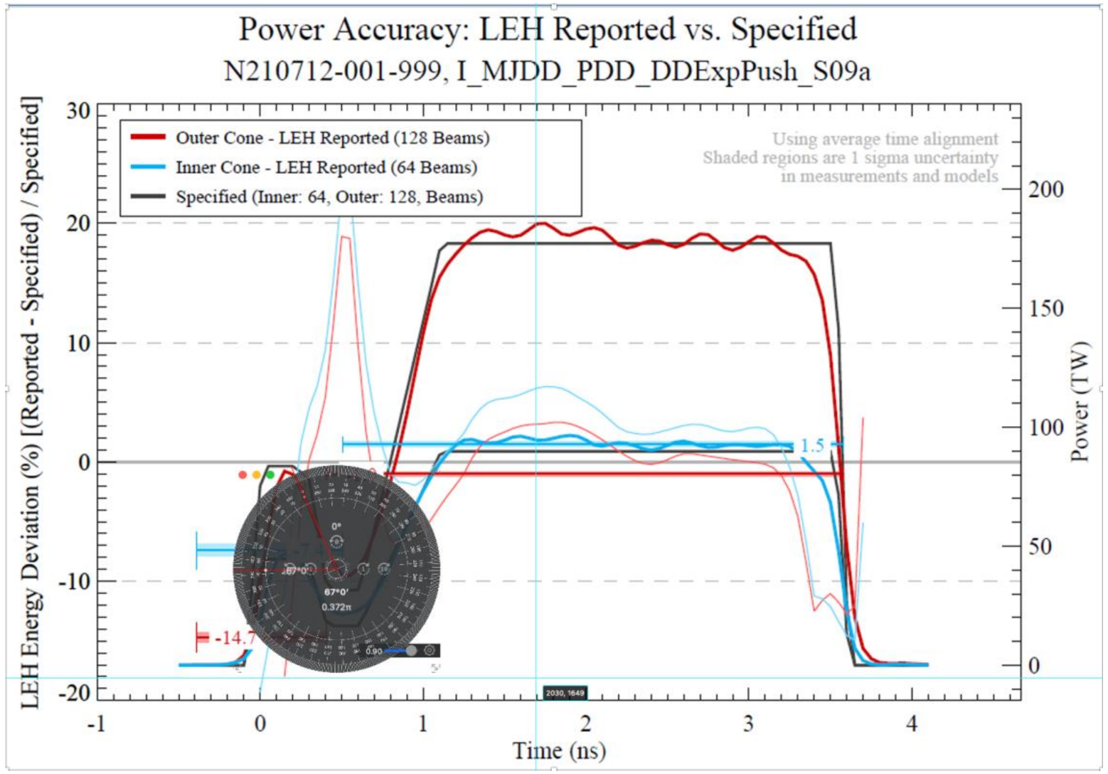




Pulse shapes from July 2021 XP shots

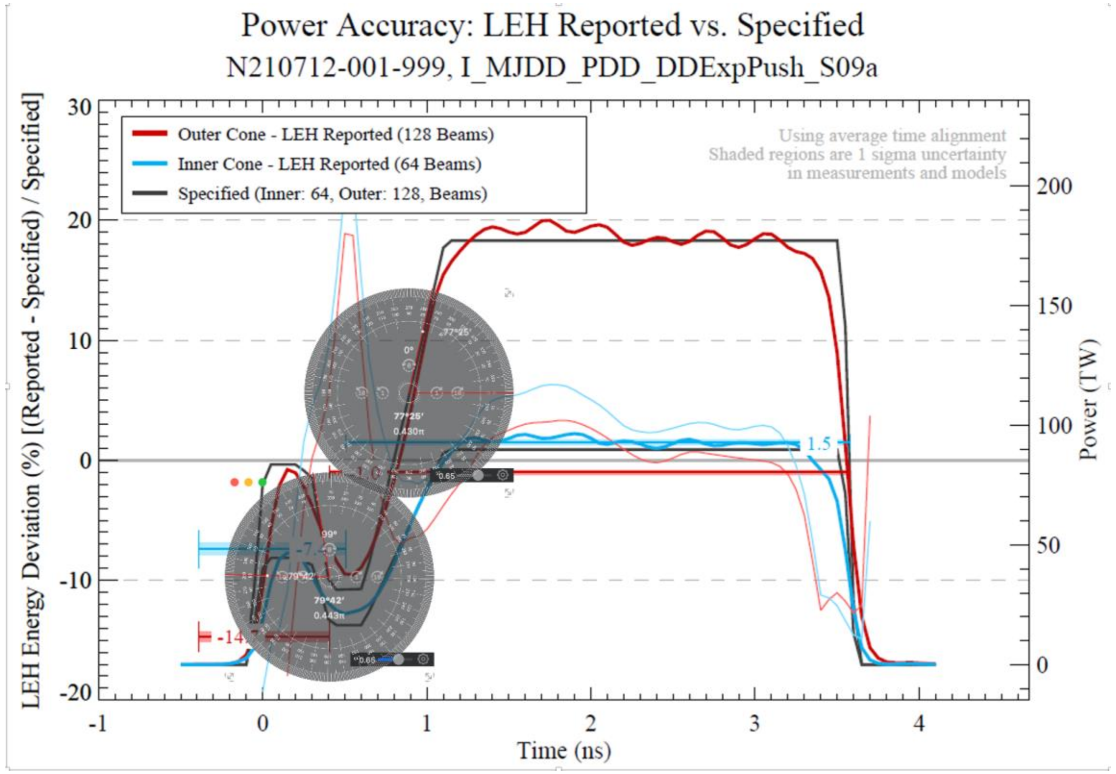
- **Slopes….**
- **Takes ~200ps to rise to 50% of peak power; half the rate in the guide**
- **Initial slope not much faster than “internal” feature rise2main; 76- vs. 79-degrees**
- **Downward slope not as fast as rising slopes; -67-degrees**





Pulse shapes from July 2021 XP shots

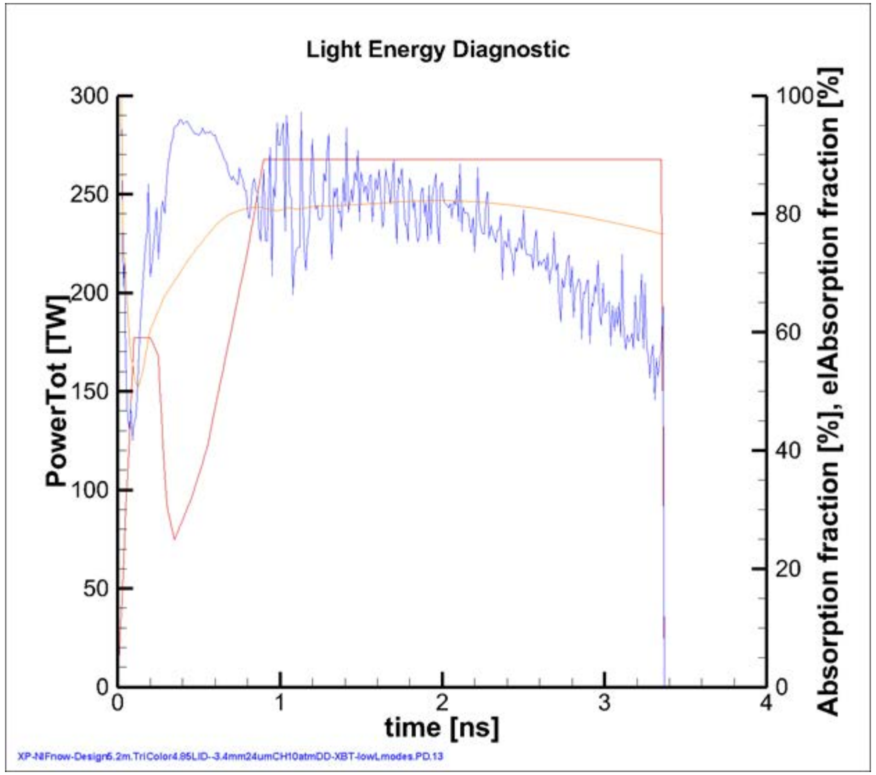
- **Slopes of the falling2dwell and rise2main are nearly the same; 77- vs. 79-degrees. Shouldn't the NIF pulse have similar slopes? Where in the guide does it say why?**

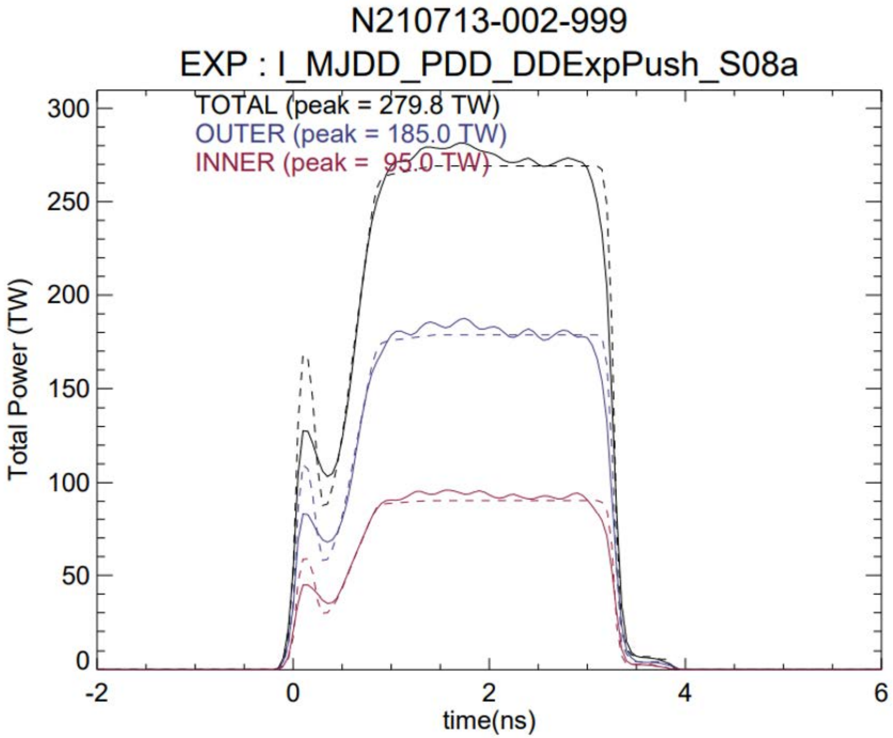

Power Accuracy: LEH Reported vs. Specified

N210712-001-999, I_MJDD_PDD_DDExpPush_S09a

Pulse shapes from July 2021 XP shots

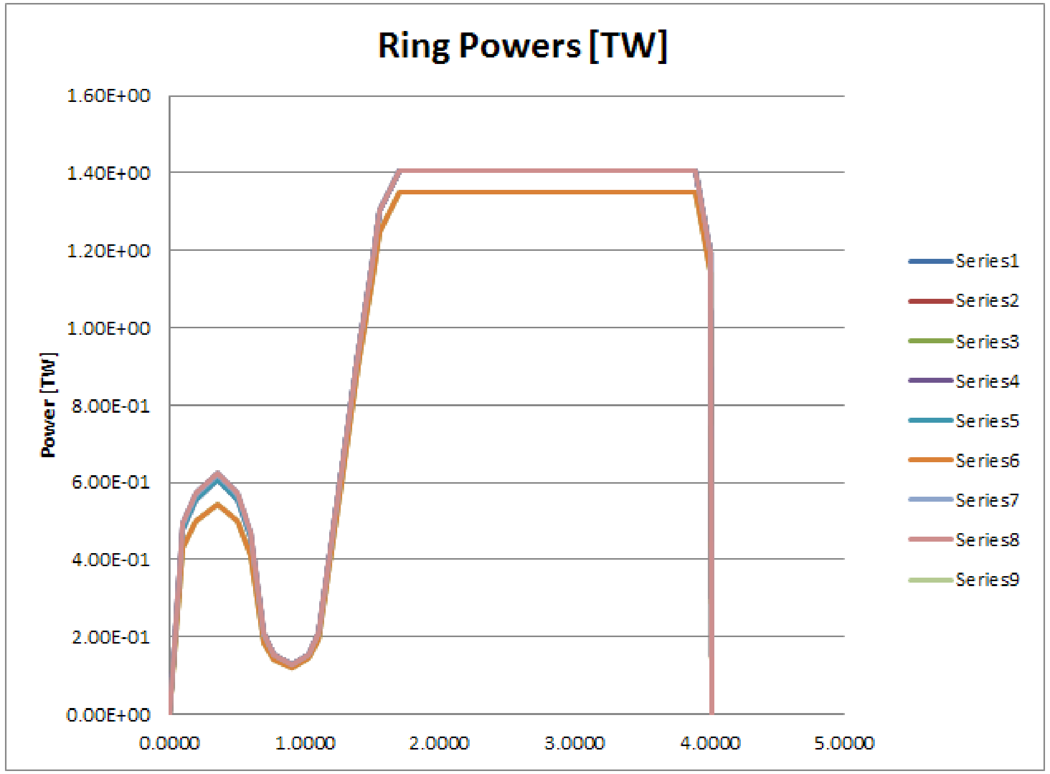
- **Narrow picket not well matched --- more like a step than a picket, plus strong imbalances**



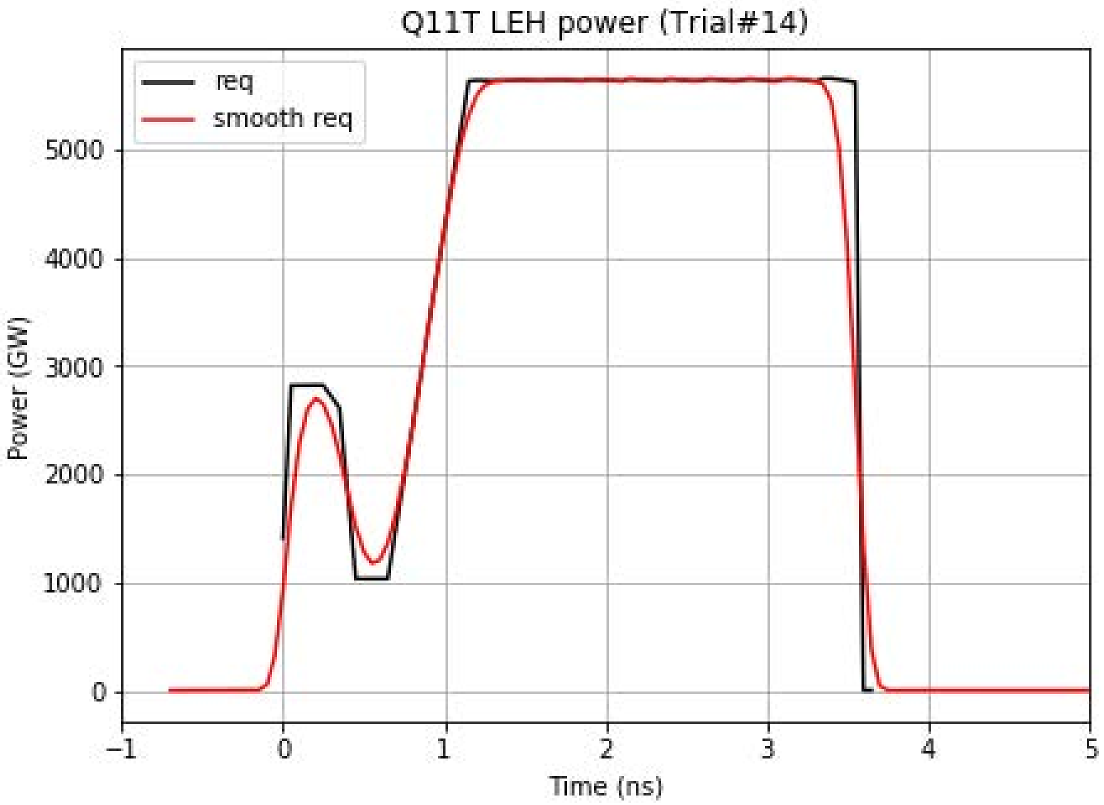


Attempted this pulse, but it failed in simulations w.r.t. imprint mitigation – dwell too long and imprinted too long in picket

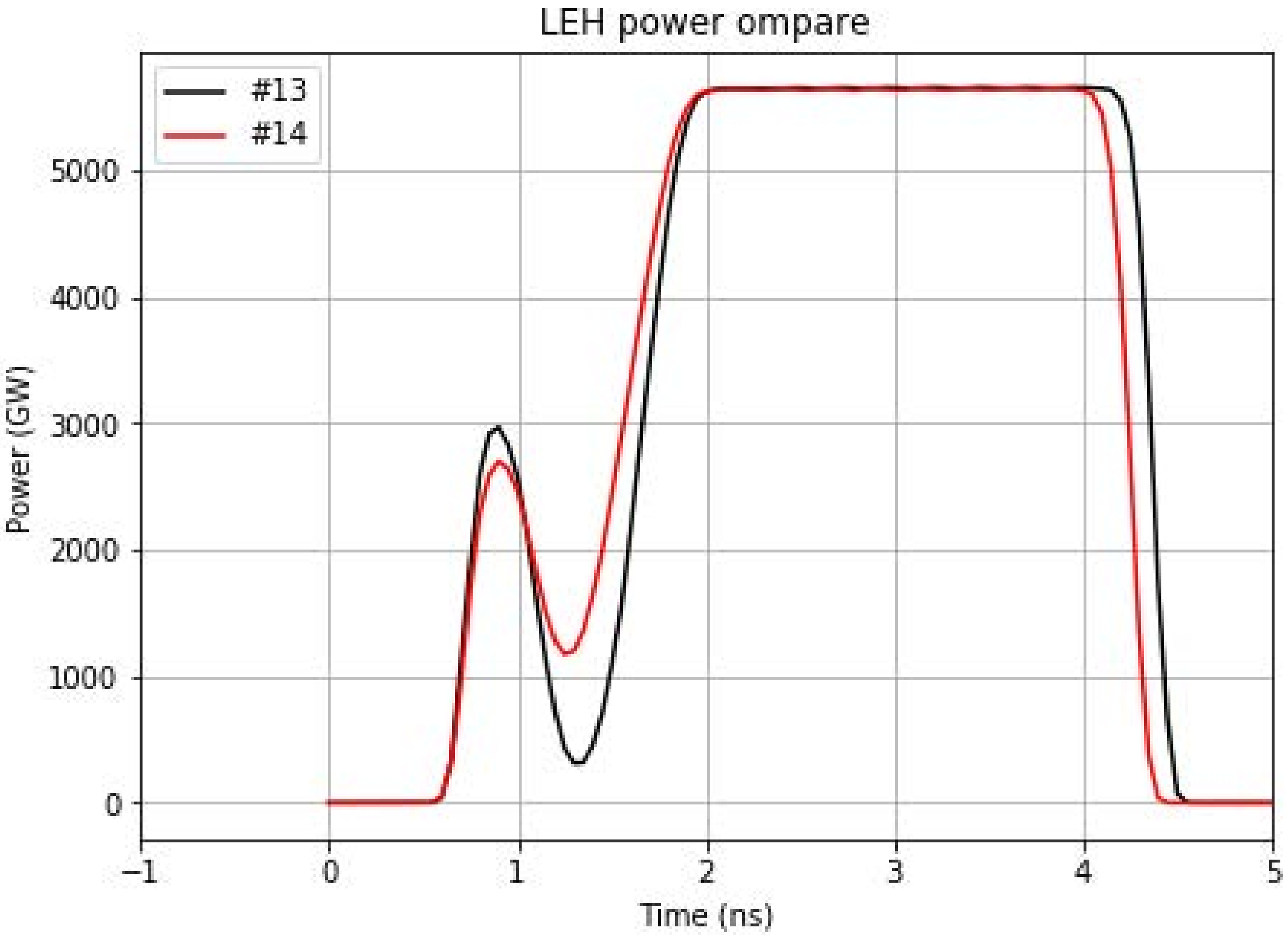
- **Increase picket & dwell duration by 200ps, rounding the picket and dwell**



#13 & #14 pulse shapes

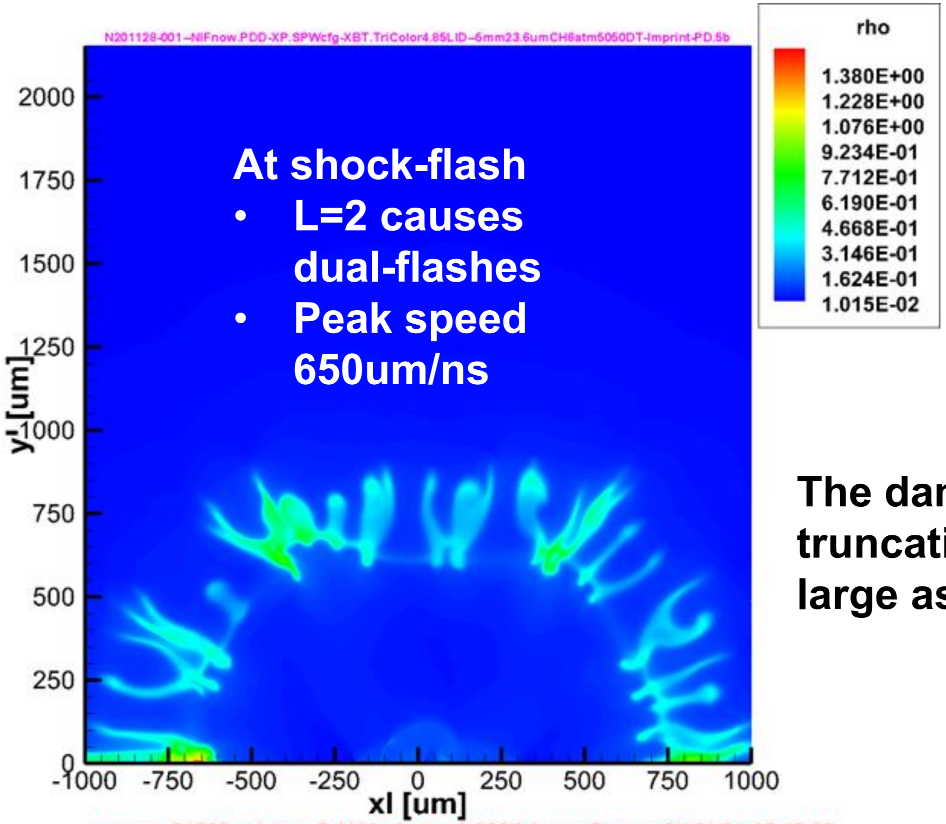


#13 & #14 comparison



Backup

Including some imprint and CBET brings the simulation closer to experiment and hints at potential elimination of compression yield in experiment

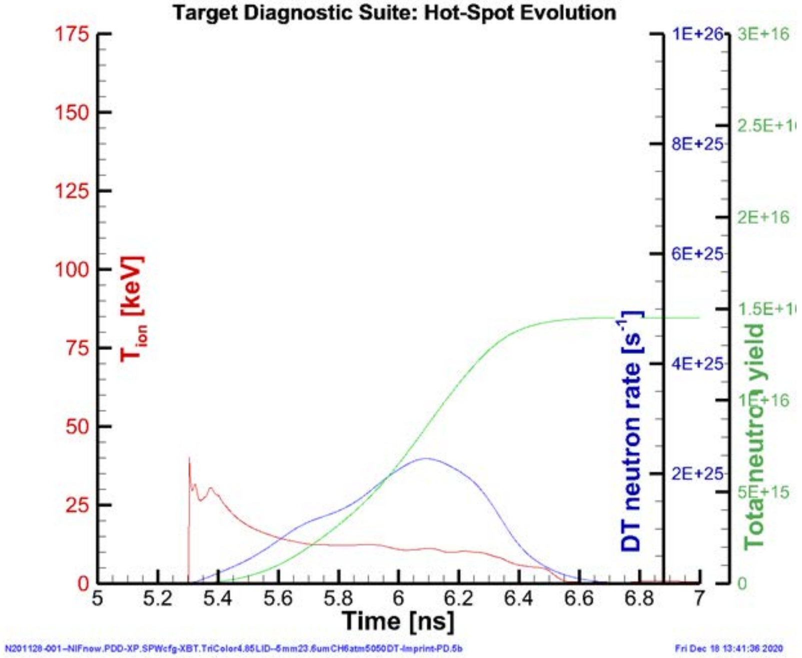


At shock-flash

- L=2 causes dual-flashes
- Peak speed 650um/ns

ntstep= 51509; stime= 5.400[ns]; dt= 9.382[fs]; dateStamp=01/21/21 15 48 00

The dampened (not full truncation) burn-curve shows large asymmetry



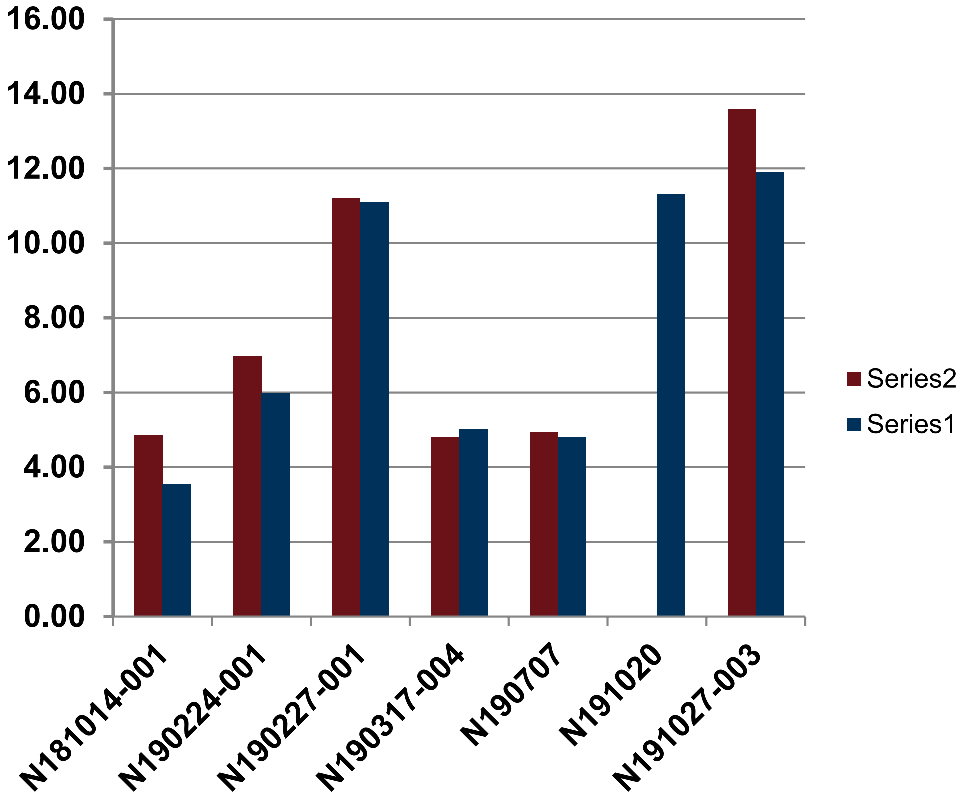
N201128 001 Exp. vs. Sim	Y_{DT} (10^{15})	T_i (keV)	t_{bang} (ns)	t_{burn} (ps)
Exp.	**6.35**	**8.17**	**6.29**	**505**
noCBET ref.	51.3	12.4	5.81	250
CBET	28.9	9.39	6.16	360
Imprint&CBET	14.5	9.22	6.09	634

- Imprint barely effects the absorption
- Slows the average shell speed but advances the the distorted inner shock-front (see next slide)
- Similar burn-curve base (cf. no imprint), but with dampened compression phase leads to wider burn-width

Backup --- XP and Draco

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets

Shot	Y_{DT} (10^{15})		T_i (keV)		t_{bang} (ns)		t_{burn} (ps)	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
N181014	3.56	4.85	6.30	6.49	5.52	5.54	618	430
N190224	5.97	6.97	7.65	10.29	4.88	4.41	502	322
N190227	11.1	11.2	8.94	9.65	4.22	4.25	452	300
N190317	5.01	4.83	7.37	8.20	4.58	4.38	607	402
N190707	4.81	4.94	11.14	12.0	2.71	2.84	311	202



- **NIF experiments will help further code validation/verification to provide a means to design targets, reaching >100-kJ DT fusion yields at low convergence (~10)**
- **The XP platform allows the study of some required NIF improvements to achieve high-convergence implosions such as CBET mitigation and far-field spot profile, as well as our modeling of heat conduction***

---

* H. D. Whitley *et al.*, Physics Archive, https://arxiv.org/abs/2006.15635 (2020).

The XP targets on the NIF provide a viable direct-drive platform while under non-ideal illumination conditions

- The XP platform generates a high neutron flux*, albeit at low areal density (ρR), using simple targets
  - ideal “open” platform to study implosion physics modeling†, NIF improvements, and neutron-survivability device testing*
- Moderately robust to the NIF current laser configuration
  - Spot-shape nonuniformity; size & shape
  - Modest laser smoothing; intended for SBSS
  - Modest wavelength separation (CBET mitigation)

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets.

Saturation of the performance at Y 10^{16} is likely caused by limited implosion symmetry and imprint growth. The path forward includes mitigation strategies.

- Mitigation
  - Symmetry; Draco pointing and pulse-shape strategy
  - Imprint: picketed pulses and target solutions

Experiments by C. Yeamans (LLNL)

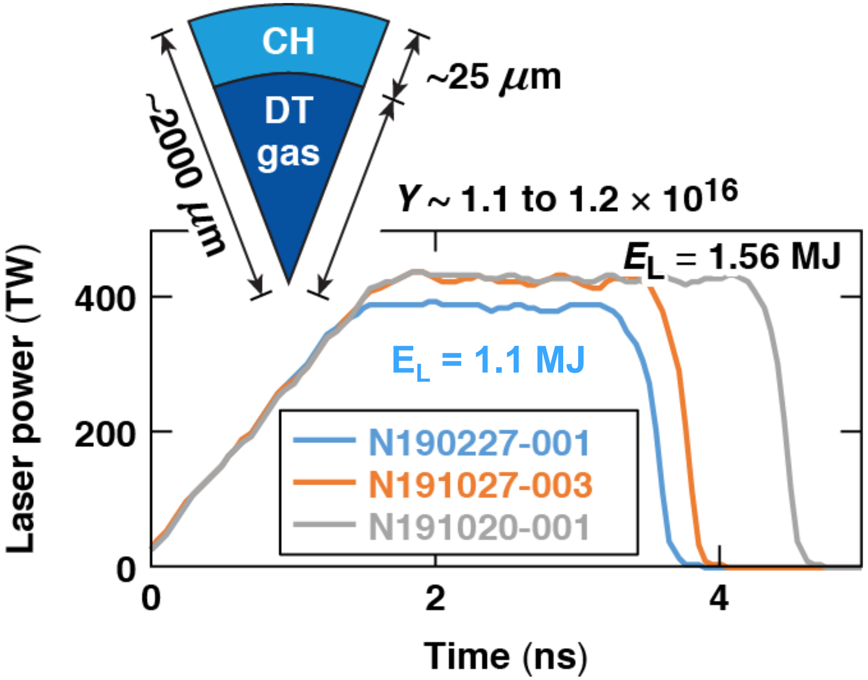
*C. B. Yeamans *et al.*, “High Yield Polar Direct Drive Fusion Neutron Sources at the National Ignition Facility,” submitted to Nuclear Fusion.

†J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018);

NIF: National Ignition Facility

CBET: Crossed-Beam Energy Transfer

XP are high v_{imp} PDD warm implosions on the NIF that couple up to E_k = 100 kJ and E_{hs} = 30 kJ, producing $Y_{DT} > 1 \times 10^{16}$



- The XP platform generates a high neutron flux,* albeit at low areal density (ρR), using simple targets
  - ideal "open" platform to study implosion physics modeling[†], NIF improvements, and neutron-survivability device testing*
- Moderately robust to the NIF current laser configuration
  - Spot-shape nonuniformity; size & shape
  - Modest laser smoothing; intended for SBSS
  - Modest wavelength separation (CBET mitigation)

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets.

Saturation of the performance at Y 10^{16} is likely caused by limited implosion symmetry and imprint growth. The path forward includes mitigation strategies.

- Mitigation
  - Symmetry; Draco pointing and pulse-shape strategy
  - Imprint: picketed pulses and target solutions

Experiments by C. Yeamans (LLNL)

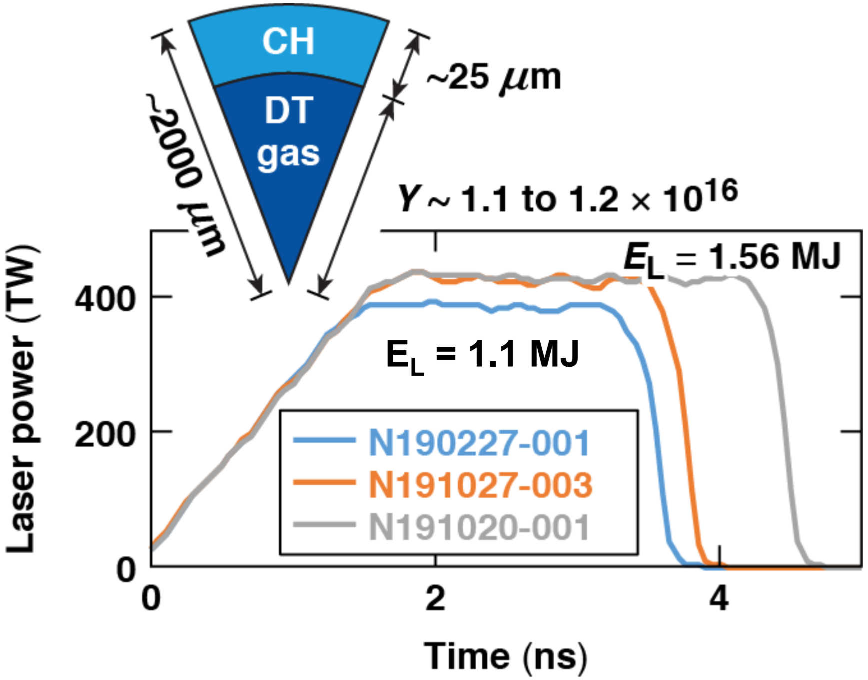
*C. B. Yeamans *et al.*, "High Yield Polar Direct Drive Fusion Neutron Sources at the National Ignition Facility," submitted to Nuclear Fusion.

[†] J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018);

NIF: National Ignition Facility

CBET: Crossed-Beam Energy Transfer

XP are high v_{imp} PDD warm implosions on the NIF that couple up to E_k = 100 kJ and E_{hs} = 30 kJ, producing $Y_{DT} > 1 \times 10^{16}$



$$\eta_{\text{H}} \sim \frac{p_{\text{abl}} v_{\text{imp}}}{I}\text{ ; IFAR} \sim v_{\text{imp}}^2 / (p_{\text{abl}}^{2/5}\ \alpha^{3/5});\ p_{\text{abl}} \sim I^{2/3}(A/Z)^{1/3}$$

- High α to improve stability while high v_{imp} increases hydroefficiency and decreases stability
- v_{imp} > 800 um/ns
- CR ~ 6 to 10
- Incident drive intensity I = 8 to 9 × 10^{14} W/cm^2
- Hot-electron preheat does not affect performance (α is too high)

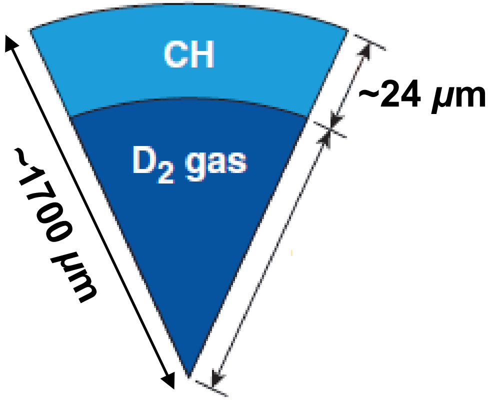
Saturation of the performance at Y 10^{16} is likely caused by limited implosion symmetry and imprint growth. The path forward includes mitigation strategies.

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets.

Experiments by C. Yeamans (LLNL)
CR: convergence ratio

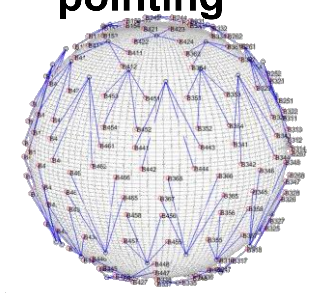
Recent FY21 exploding pusher experiments assessed control of symmetry and energy coupling through laser pointing and pulse shaping

Exploding pusher
~700 kJ
~280 TW

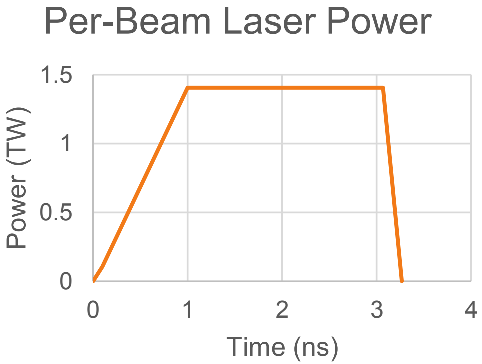


Design: J. Marozas

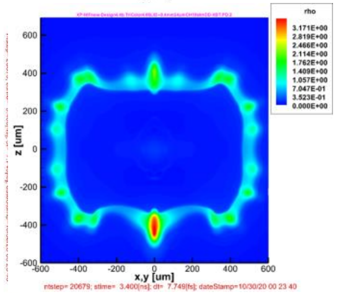
SAGE (old) pointing



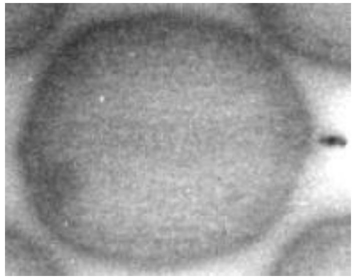
N201220-002



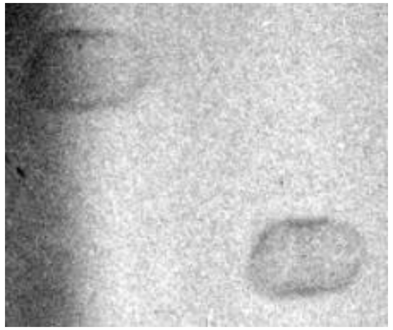
DRACO pre-shot 3.4 ns



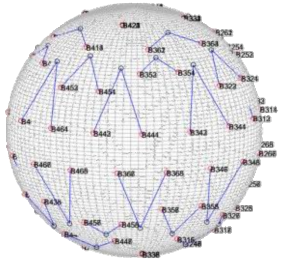
t~3.0 ns



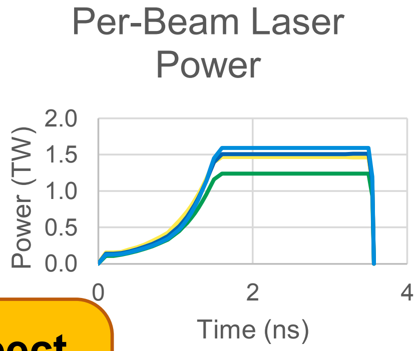
t~3.8 ns



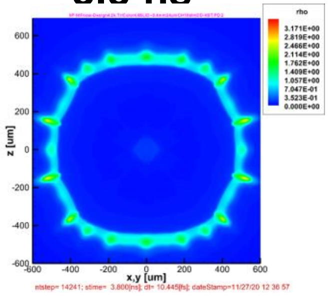
DRACO (new) pointing



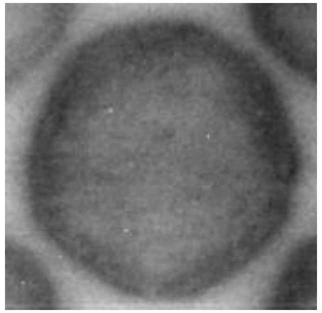
N201220-001



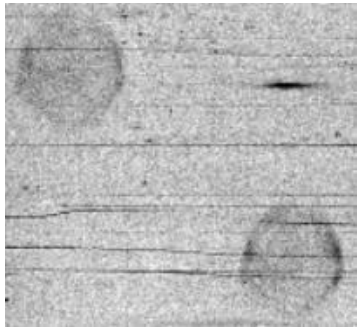
DRACO pre-shot 3.8 ns



t~3.5 ns



t~4.3 ns



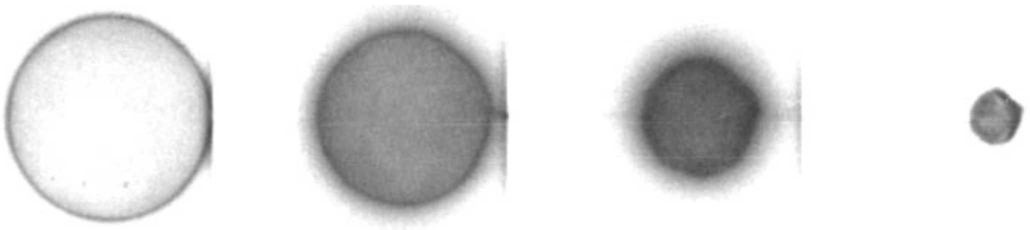
2 mm

Design-001 maintains shape aspect ratio while 002 distorts in time implying a velocity nonuniformity

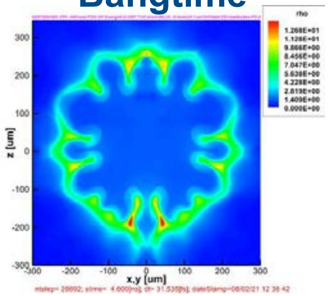
Qualitative 2D shape improvement close to pre-shot predictions

Gated x-ray self-emission images show agreement with postshot simulations, achieving the expected control of the shape

N201220-001t~1.5 ns t~2.5 ns t~3.5 ns t~4.3 ns

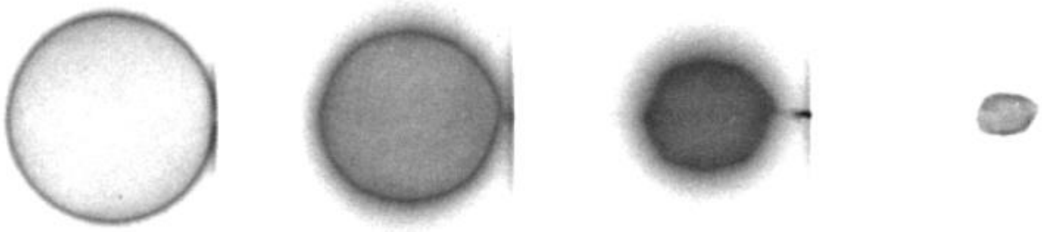


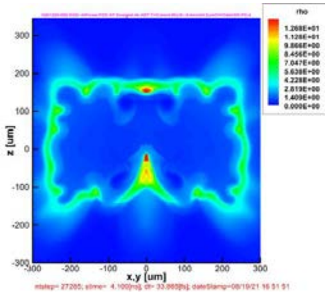
DRACO postShot at Bangtime



Improved pointing and pulse-shapes

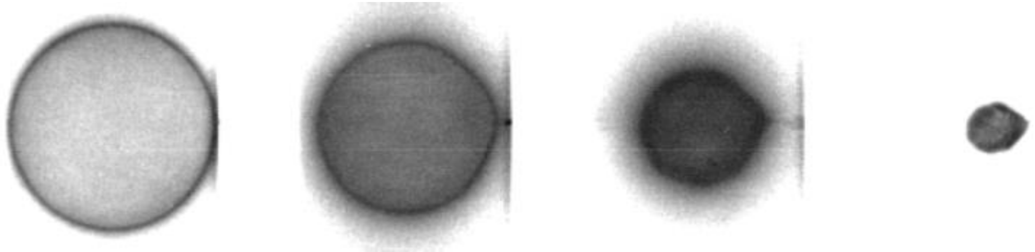
N201220-002t~1.0 ns t~2.0 ns t~3.0 ns t~3.8 ns

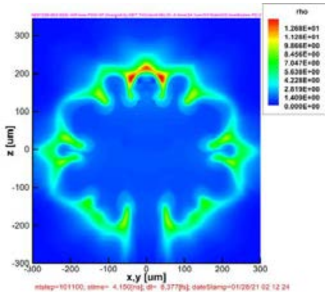




Reference config.

N201220-003t~1.0 ns t~2.0 ns t~3.0 ns t~3.85 ns

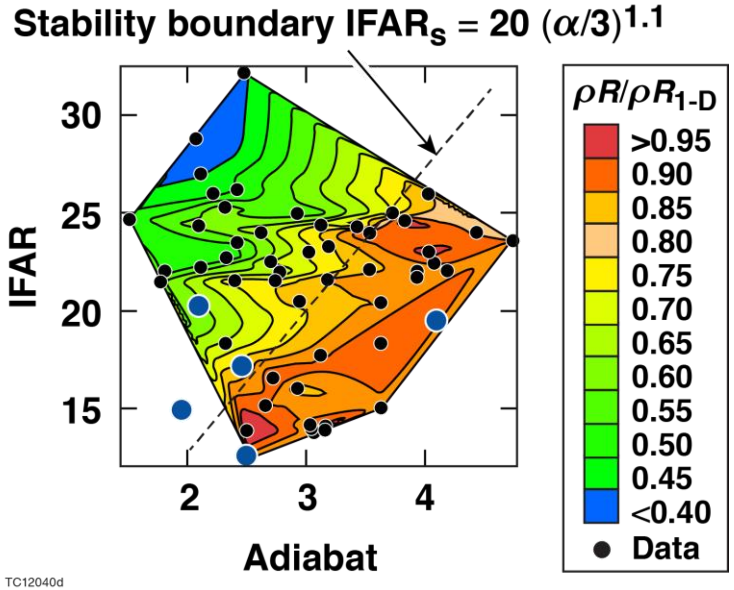




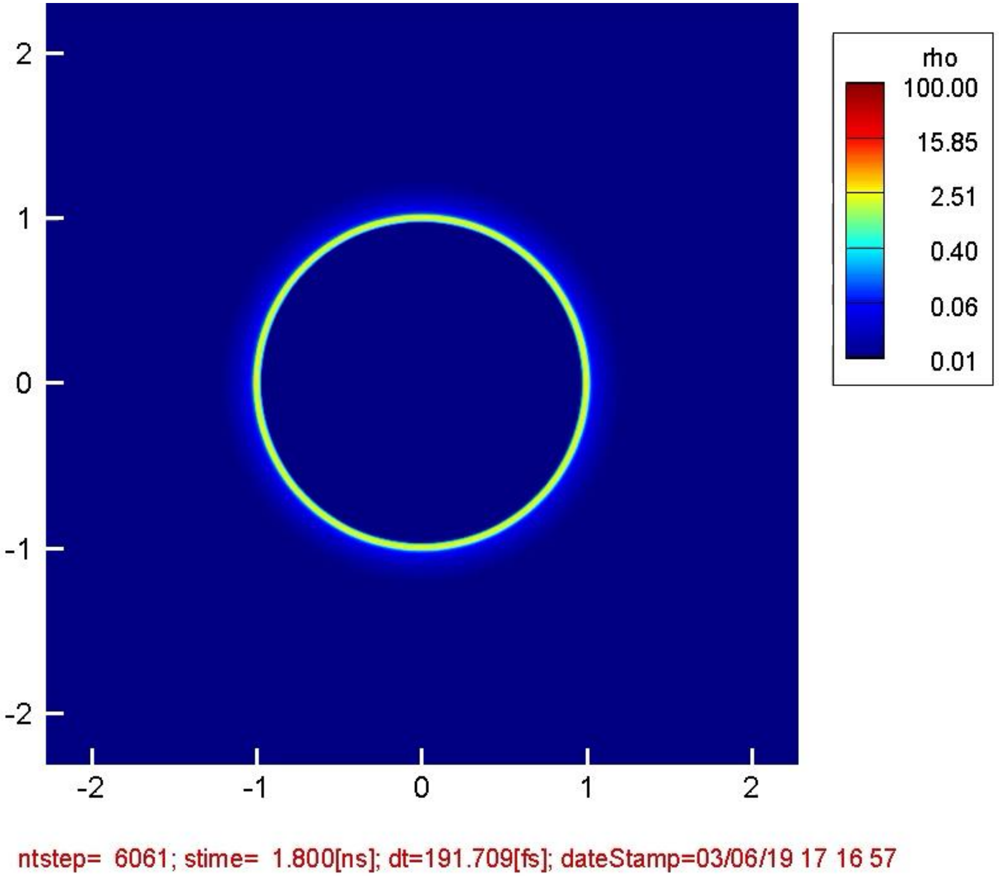
Improved pointing and ref. pulse

Simulations are employed to study the effect of imprint on target performance

- **Imprint has a strong impact on target performance**
  - **Compromises the shell integrity and lowers density and temperature and increases surface area**
- **Laser smoothing techniques mitigate imprint**
- **Simulations help gauge the laser smoothing requirements and guide target designs**

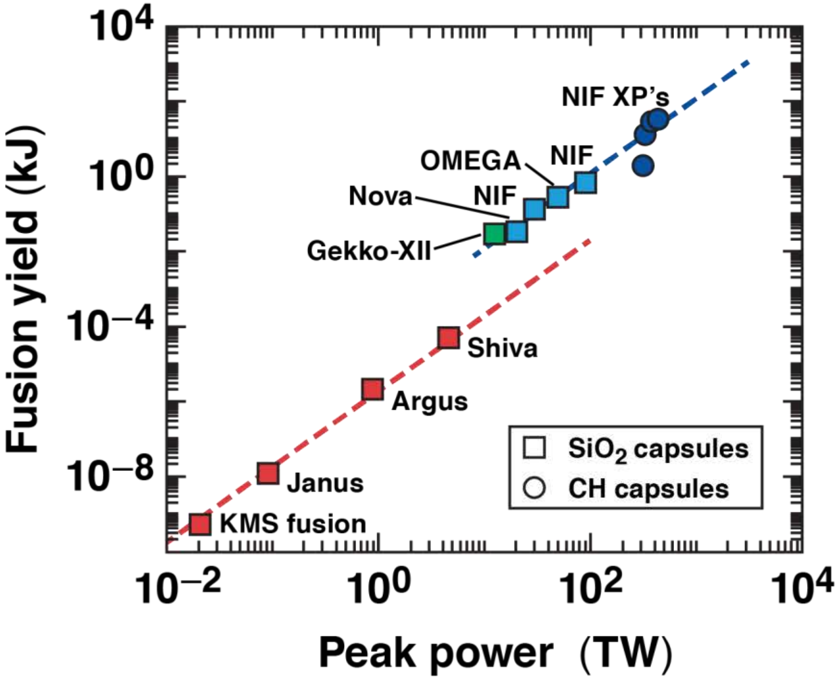


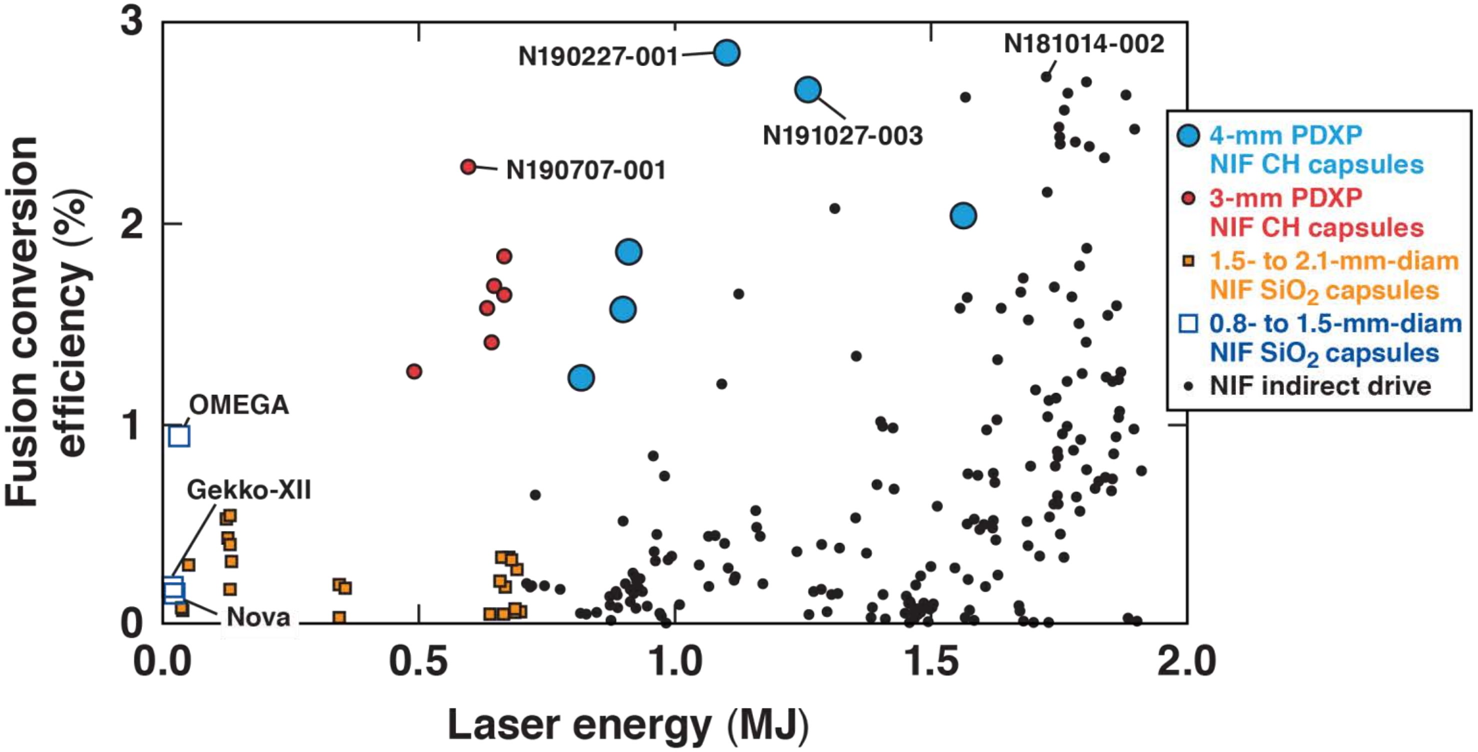
Imprint simulation* follows the shell in flight



***2-D *DRACO* Imprint Simulations with LLE Ray Trace, performed by T. Collins (2019).**

XP targets on the NIF are being employed to study laser–energy coupling and implosion dynamics in an effort to push toward high yields to prepare the pathway toward ignition



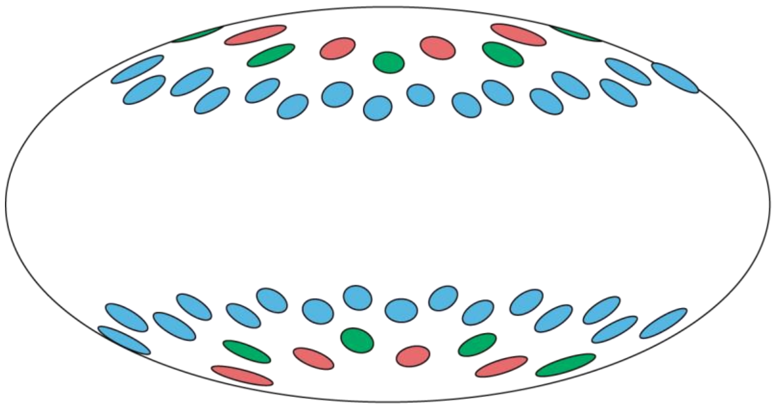


E29393

XP targets can achieve large DT$_n$ yields owing to their high implosion speed ~700 to 900 μm/ns, but their high electron preheat, low convergence and low ρR all prevent a propagating burn wave, i.e,. ignition.

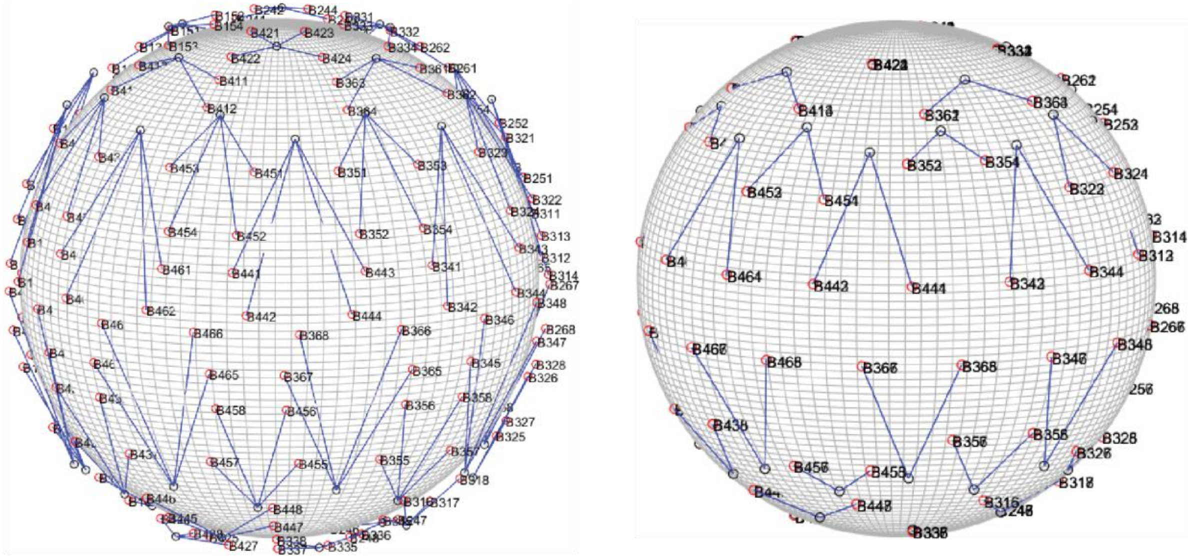
The NIF beams must be repointed for direct-drive experiments owing to its clustered polar port arrangement; referred to as polar direct drive (PDD)

LID port-color arrangement



TC15447

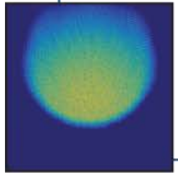
LDD-PDD port repointing designs



NIF facility enhancements are required to perform CR > 15 PDD experiments

Symmetry and coupling

XP:

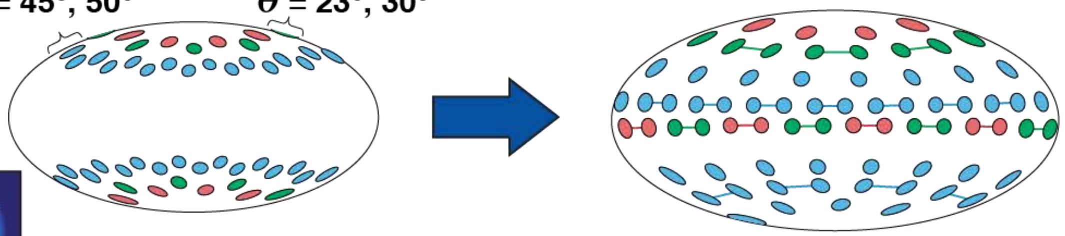


Port-color arrangement

Outer cones, λ_3 Inner cones, $\{\lambda_1, \lambda_2\}$

θ = 45°, 50° θ = 23°, 30°

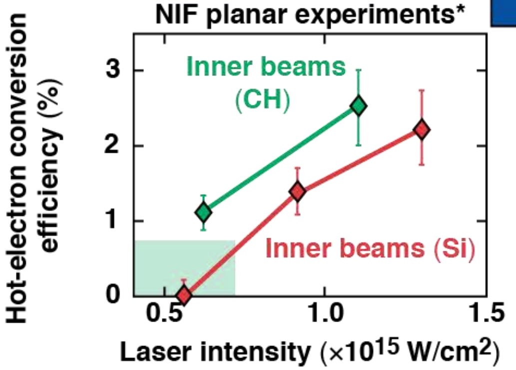
Flexible color-to-port mapping



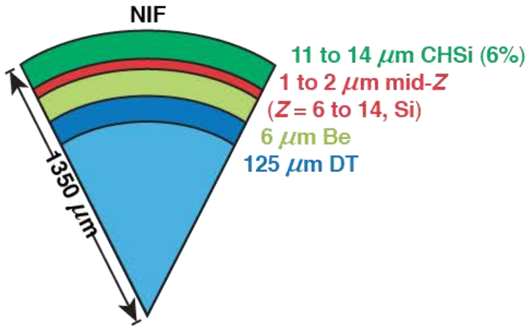
Current

Required to reduce CBET

Preheat



Target solution**



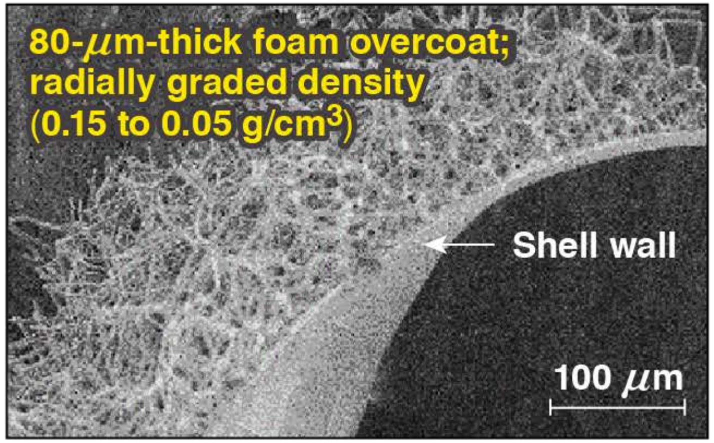
E29182a

Imprint mitigation

Multi-FM/2-D SSD + Target solution

LLE effort

Printed polymer shell with a randomized foam structure on the outer surface for imprint reduction



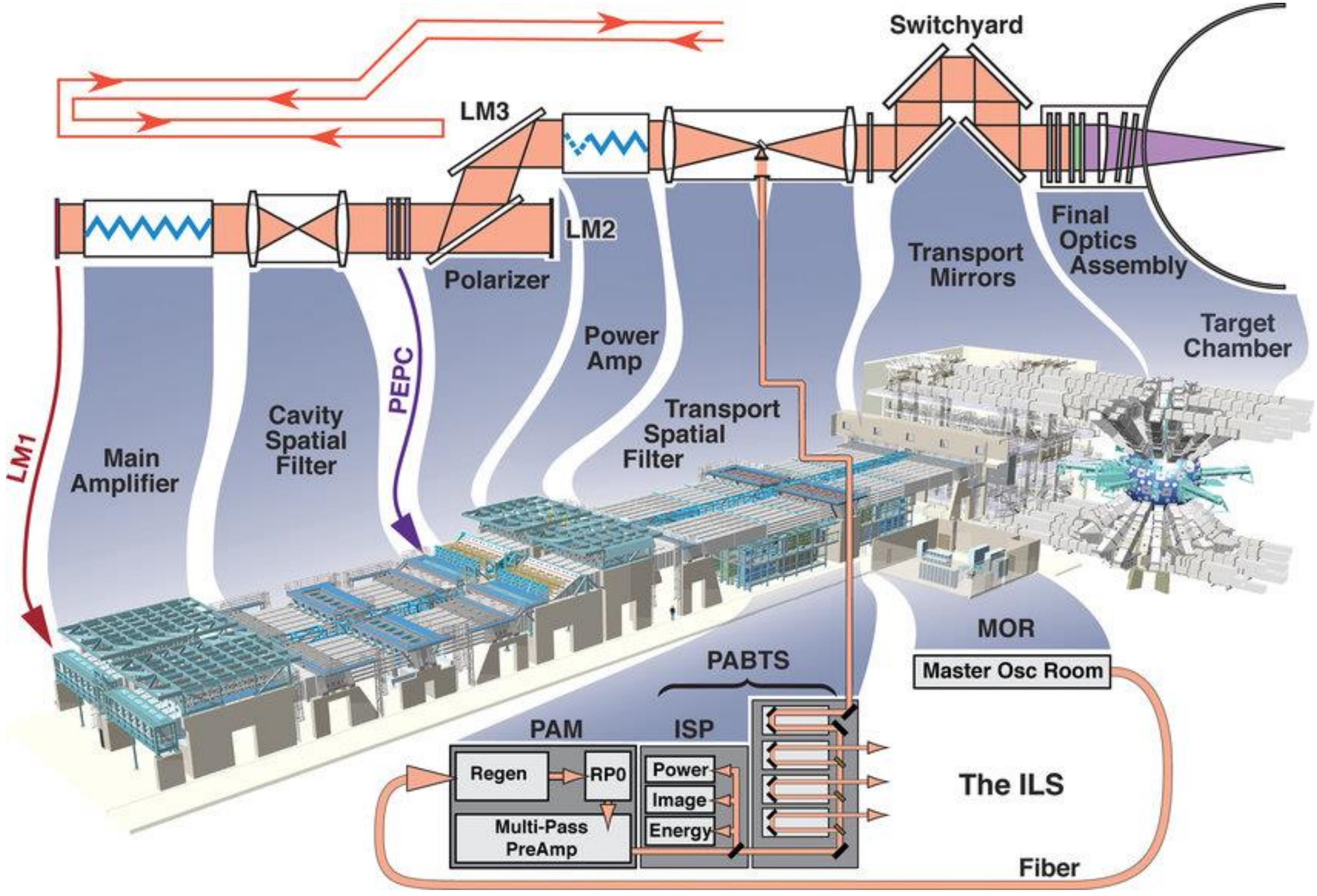
Experiments are underway to understand acceptable laser-target parameter space.

---

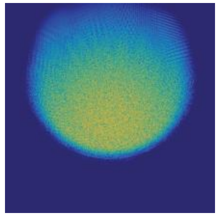
* A. A. Solodov *et al.*, Phys. Plasmas 27, 052706 (2020).
** V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

FM: frequency modulation
SSD: smoothing by spectral dispersion

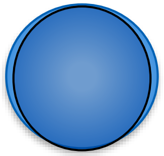
The XP platform will evaluate optimal pulse shape, spot-shapes (DPP), contoured shells, flexible color-to-port mapping (fC2Pm), and larger color separation ($\Delta\lambda_0$ detuning)



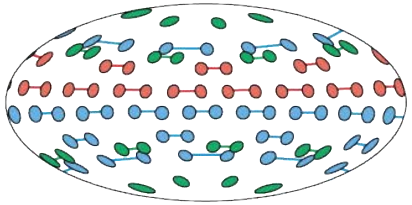
PDD-DPP



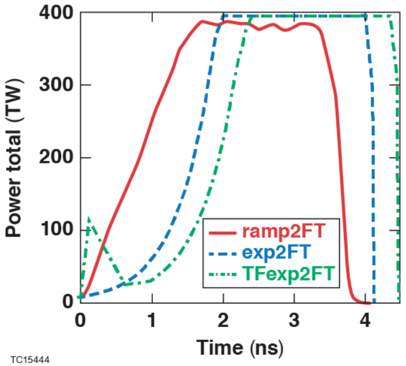
Contoured shell



fC2Pm with large $\Delta\lambda_0$



Pulse shapes



BackUp

Backup --- ICF Physics

The DT-plasma fuel assembly areal density (ρR) is a key ICF performance parameter

- **The Lawson criterion defines a simple condition required for ignition:**
  - **ignition: (fusion products power density) × (containment-time) > (plasma energy density)**

for 50-50 DT plasma: $\boldsymbol{n^2/_4 \langle\sigma v\rangle Q\tau > 3nk_{\mathrm{B}}T}$

solving for $n\tau$:* $\boldsymbol{n\tau > \frac{12k_{\mathrm{B}}T}{\langle\sigma v\rangle Q} \approx 10^{14}\colon 10^{15}[\mathrm{s/cm^3}]}$

Lawson Criterion

- **Containment time can be approximated by disassembly time; i.e., related to the ion sound speed traversal across the fuel assembly as**

$$\langle\tau\rangle \cong \frac{R_{\mathrm{f}}}{4c_s}, n \equiv \rho/m \Rightarrow \mathrm{n\tau} \cong \frac{\rho R_{\mathrm{f}}}{4\langle M_i\rangle c_s}$$

$\boldsymbol{\rho R_{\mathrm{f}} \gtrsim 3\ [\mathrm{g/cm^2}]}$ **for efficient burn, i.e., large gains**

The areal-density, ρR, can be expanded to express other important ignition criteria…

---

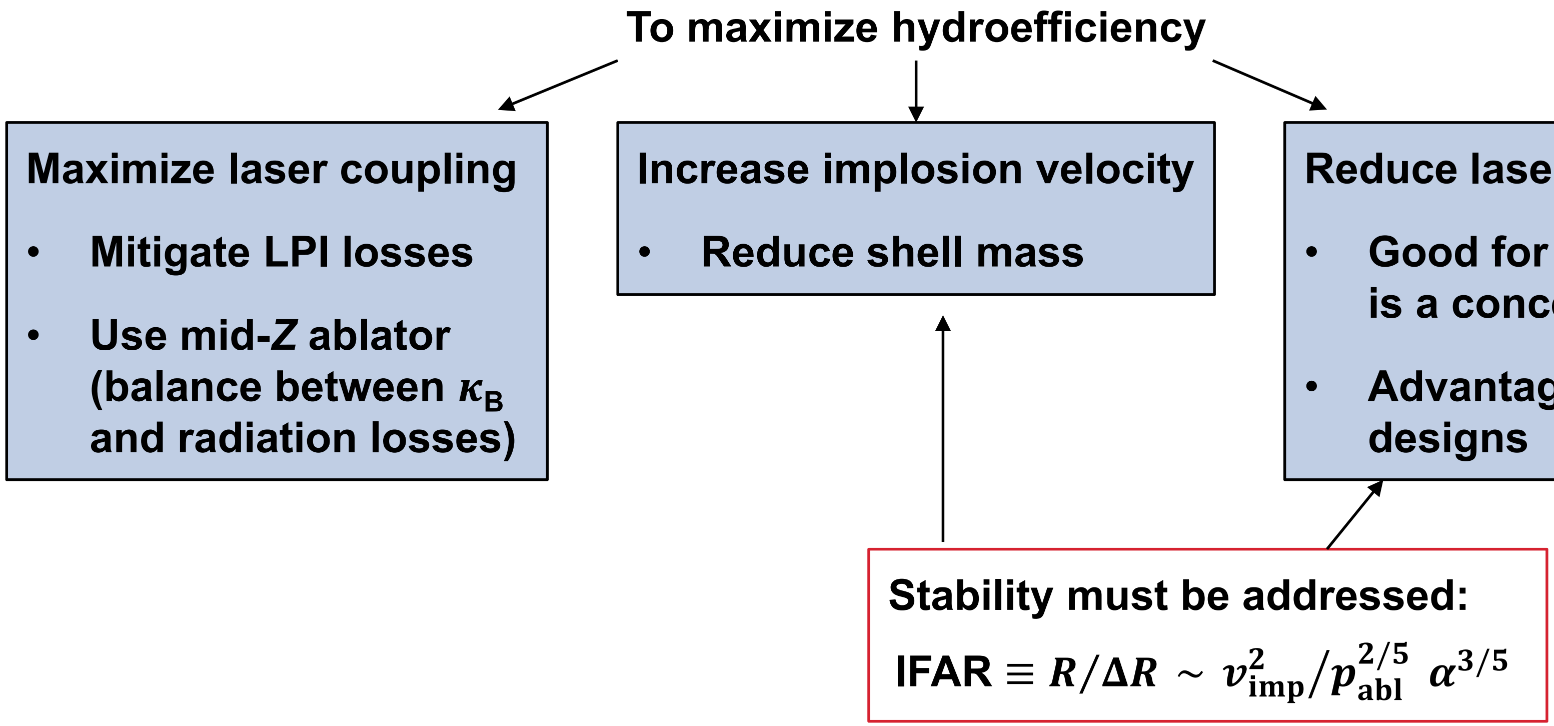
* $Q_{DT} = 17.6\ \mathrm{MeV}$

Maximizing hydroefficiency is key for successful ICF implosions

- Hydroefficiency $\eta_H = E_k/E_L$

$$\boxed{\eta_H \sim \frac{p_{abl}V_{imp}}{I}}$$

$$p_{abl} = f_{abs}\, I^{\frac{2}{3}}$$



To maximize hydroefficiency

Maximize laser coupling

- Mitigate LPI losses
- Use mid-*Z* ablator (balance between κ_B and radiation losses)

Increase implosion velocity

- Reduce shell mass

Reduce laser intensity

- Good for LPI but stability is a concern
- Advantage in multi-shell designs

Stability must be addressed:

IFAR $\equiv R/\Delta R \sim v_{imp}^2/p_{abl}^{2/5}\ \alpha^{3/5}$

While working on mitigating the deleterious effects of LPI, the LDD program on the NIF and OMEGA leverages on v_{imp} and adiabat to maximize the performance.

LPI: laser–plasma instability
IFAR: in-flight aspect ratio

The DT-plasma fuel assembly areal density (ρR) is a key ICF performance parameter

- The Lawson criterion defines a simple condition required for ignition:
  - ignition: (fusion products power density) × (containment-time) > (plasma energy density)

for 50-50 DT plasma: $n^2/_4 \langle \sigma v \rangle Q \tau > 3 n k_\mathrm{B} T$

solving for $n\tau$:* $n\tau > \frac{12 k_\mathrm{B} T}{\langle \sigma v \rangle Q} \approx 10^{14}\!:10^{15} \left[\mathrm{s/cm^3}\right]$ **Lawson Criterion**

- Containment time can be approximated by disassembly time; i.e., related to the ion sound speed traversal across the fuel assembly as

$$\langle \tau \rangle \cong \frac{R_\mathrm{f}}{4 c_\mathrm{s}},\ n \equiv \rho/m \Rightarrow \mathrm{n\tau} \cong \frac{\rho R_\mathrm{f}}{4 \langle M_i \rangle c_\mathrm{s}}$$

$\rho R_\mathrm{f} \gtrsim 3 \left[\mathrm{g/cm^2}\right]$ for efficient burn, i.e., large gains

$$\rho R \sim \frac{\left(P_\mathrm{abl}^2/I\right)^{1/3} E_\mathrm{L}^{1/3}}{\sqrt{\alpha}}$$

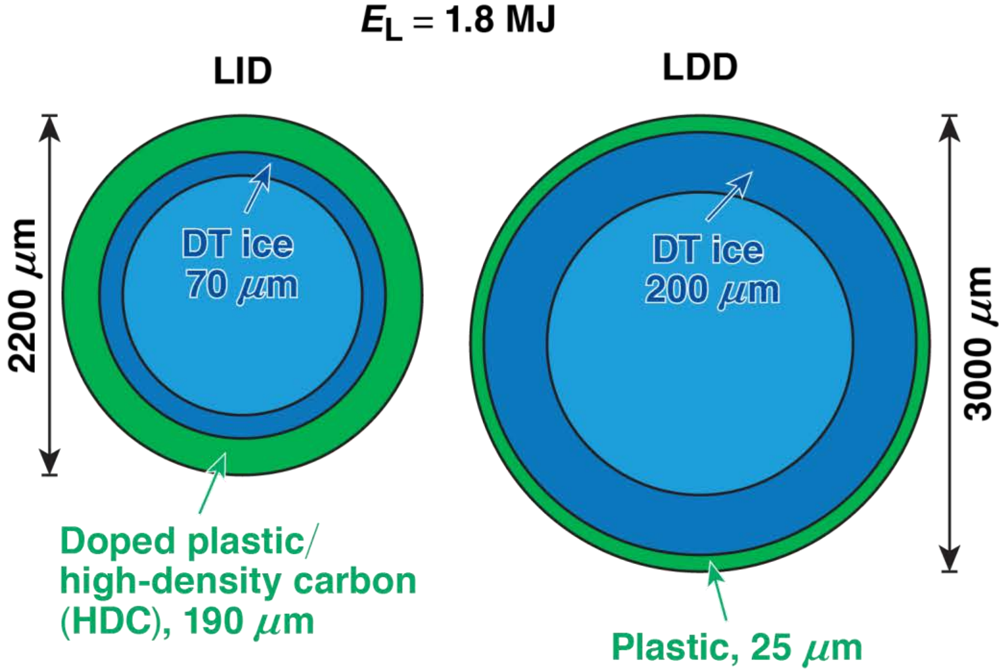
The areal-density, ρR, can be expanded to express other important ignition criteria…

$$P_\mathrm{hs} > 250\ \mathrm{Gbar} \left(\frac{E_\mathrm{hs}}{10\ \mathrm{kJ}}\right)^{-1/2} = P_\mathrm{th}$$

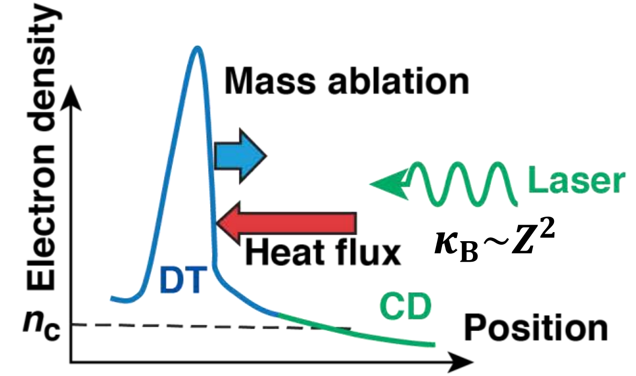
---

* $Q_\mathrm{DT} = 17.6\ \mathrm{MeV}$

LDD couples more energy to the hot spot compared to LID, which means more fuel mass and thinner ablators



Thinner plastic maximizes drive efficiency



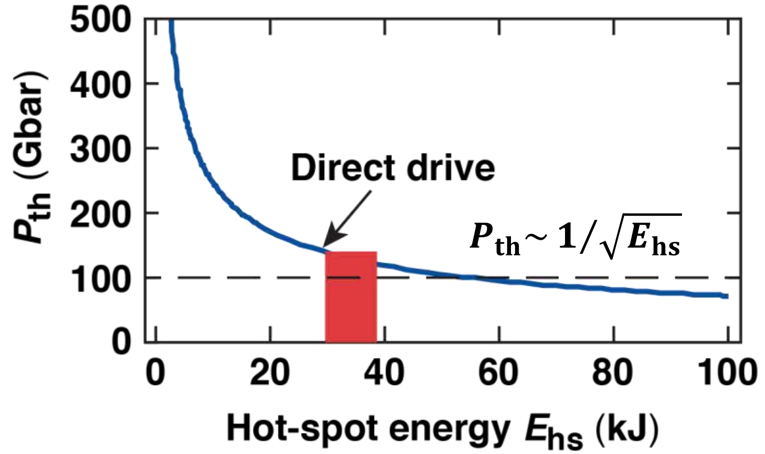
Atomic number

$$m_{\mathrm{abl}} \sim I^{1/3}\left(\frac{A}{Z}\right)^{2/3}$$

$$p_{\mathrm{abl}} \sim I^{2/3}\left(\frac{A}{Z}\right)^{1/3}$$

Ion charge

Threshold hot-spot pressure for ignition



LDD ignition: CR > 22, P_{hs} > 120 Gbar, P_{hs} > 350 Gbar has already been demonstrated in LID implosions.

Two critical parameters for ignition are hot-spot pressure and internal energy

From the Lawson Criterion:*

$$(\rho R)_{\mathrm{hs}} \times T_{\mathrm{i}} > 0.3\ \mathrm{g/cm^2} \times 5\ \mathrm{keV}$$

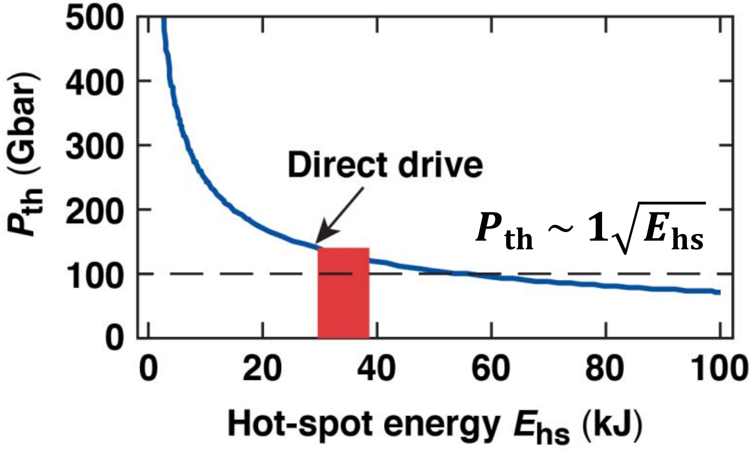
$$\boxed{P_{\mathrm{DT}} = 2\rho T/2.5m_{\mathrm{p}}}$$

$$P_{\mathrm{hs}} = 100\ \mathrm{Gbar}\left(\frac{100\ \mu\mathrm{m}}{R_{\mathrm{hs}}}\right)$$

$$\boxed{E_{\mathrm{hs}} = 3/2\ P_{\mathrm{hs}}V_{\mathrm{hs}}}$$

$$\boxed{P_{\mathrm{hs}} > 250\ \mathrm{Gbar}\left(\frac{E_{\mathrm{hs}}}{10\ \mathrm{kJ}}\right)^{-1/2} = P_{\mathrm{th}}}$$

Threshold hot-spot pressure for ignition



E29127b

To burn the main fuel: Gain > 1, ρR > g/cm^2

$$\boxed{\rho R \sim \frac{\left(P_{\mathrm{abl}}^2/I\right)^{1/3} E_{\mathrm{L}}^{1/3}}{\sqrt{\alpha}}}$$

---

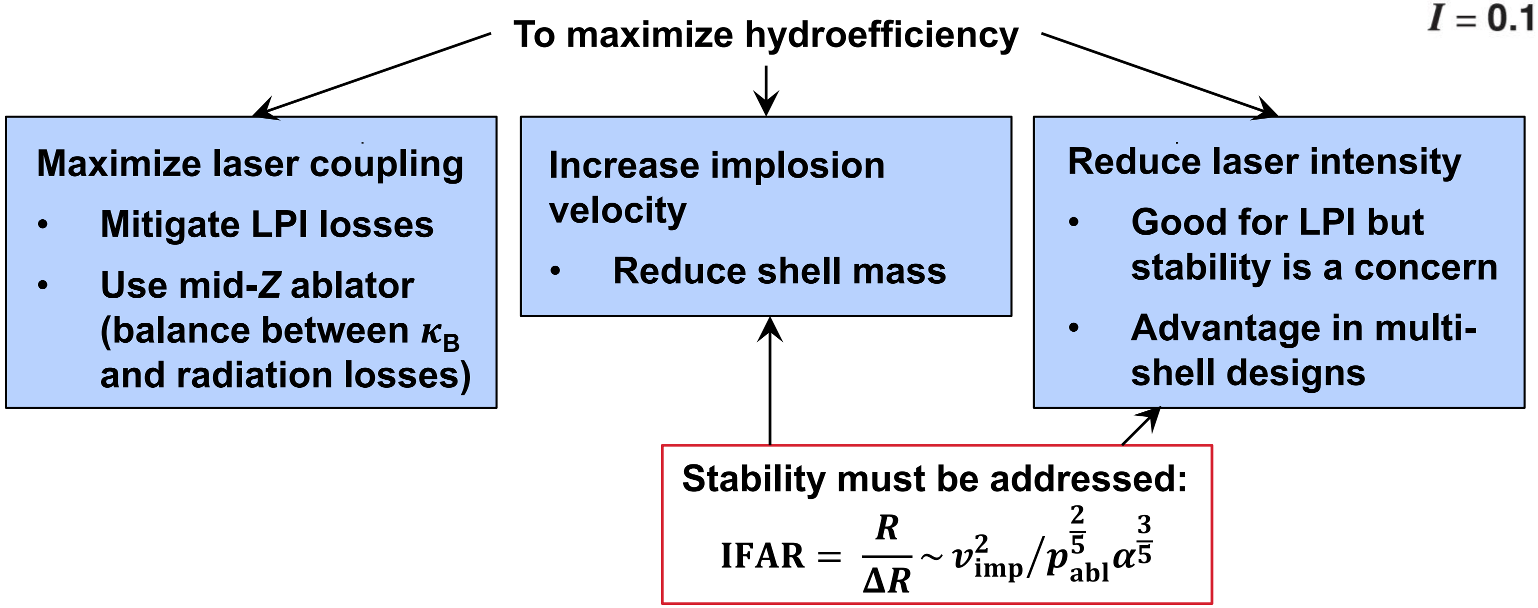
* R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

Maximizing hydroefficiency is key for successful ICF implosions

Hydroefficiency $\eta_{\mathrm{H}} = E_{\mathrm{k}}/E_{\mathrm{L}}$

$$\boxed{\eta_{\mathrm{H}} \sim \frac{p_{\mathrm{abl}} v_{\mathrm{imp}}}{I}}$$

$$p_{\mathrm{abl}} \sim f_{\mathrm{abs}} I^{\frac{2}{3}}$$



To maximize hydroefficiency

Maximize laser coupling
- Mitigate LPI losses
- Use mid-Z ablator (balance between κ_{B} and radiation losses)

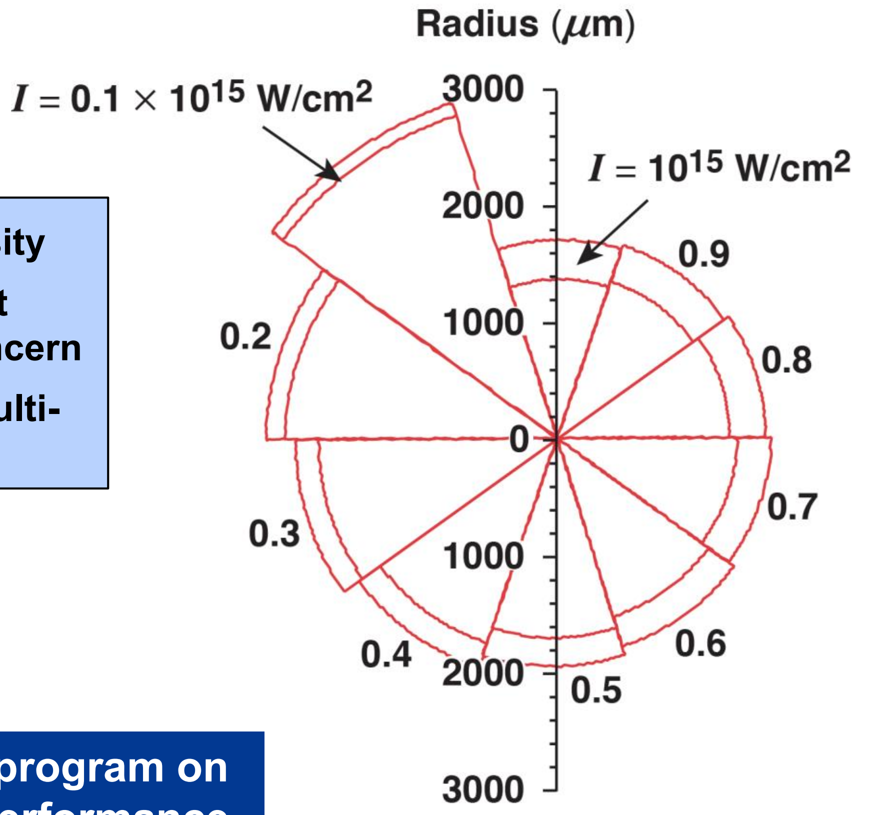
Increase implosion velocity
- Reduce shell mass

Reduce laser intensity
- Good for LPI but stability is a concern
- Advantage in multi-shell designs

Stability must be addressed:

$$\boxed{\mathrm{IFAR} = \frac{R}{\Delta R} \sim v_{\mathrm{imp}}^{2} / p_{\mathrm{abl}}^{\frac{2}{5}} \alpha^{\frac{3}{5}}}$$

Shell aspect ratio increases as I decreases (same V_{imp})

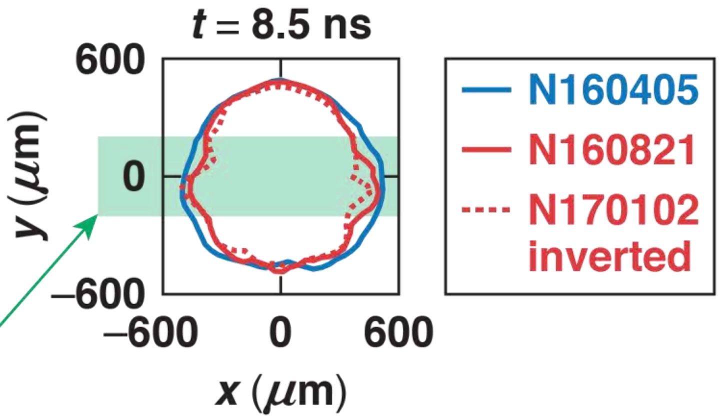


While working on mitigating the deleterious effects of LPI, the LDD program on the NIF and OMEGA leverages on v_{imp} and adiabat to maximize the performance.

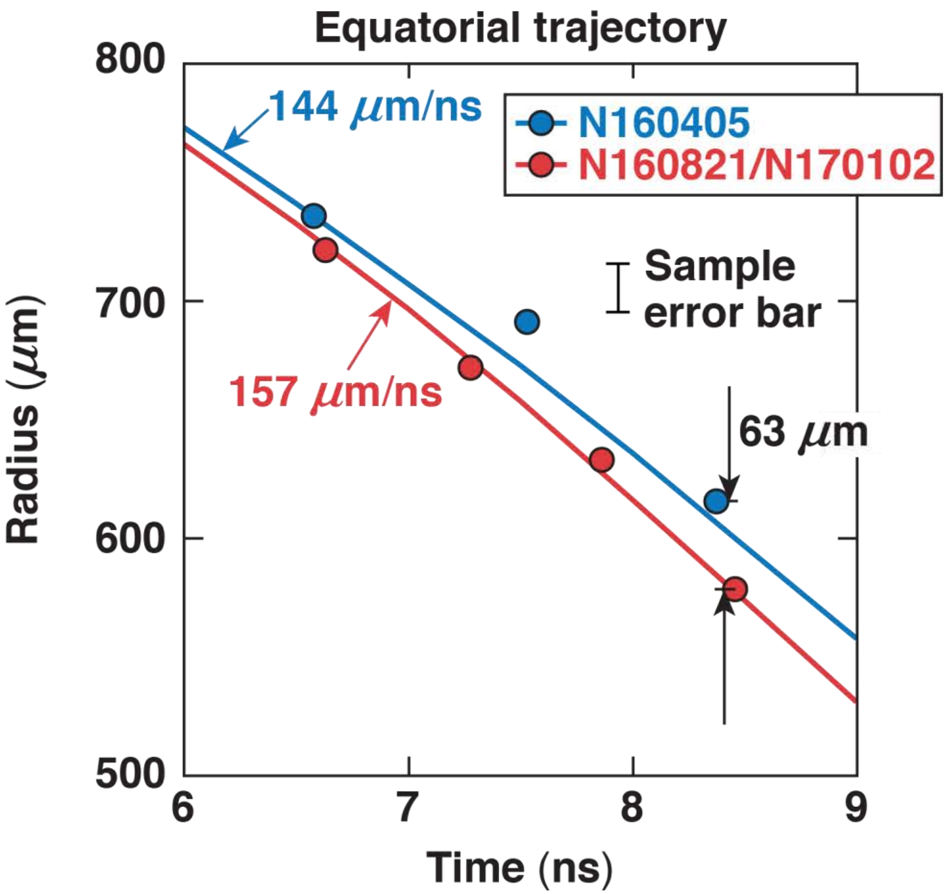
LPI: laser--plasma instability
IFAR: in-flight aspect ratio

Improved equatorial coupling from wavelength detuning is inferred from gated radiographs

- **The predicted and measured trajectories* show the expected faster implosion speeds near the equator**



The surface-weighted average ±15° defines the equatorial trajectory



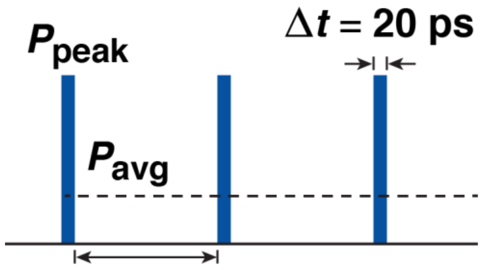
TC13351b

---

* Analysis by D. Turnbull

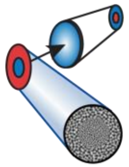
Laser energy coupling loss caused by CBET can be mitigated in different domains that can be combined; temporal, spatial, and spectral

- **Temporal domain**
  - multiplexing the beams reduces interaction

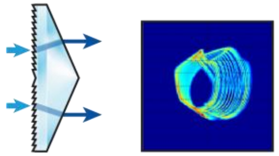


  - STUD* pulses

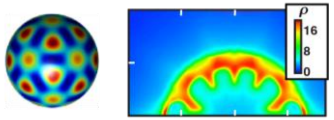
- **Spatial domain** (reduce interaction volume)
  - dynamic spot shape
    - two stage**



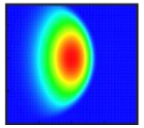
    - Graxicon***



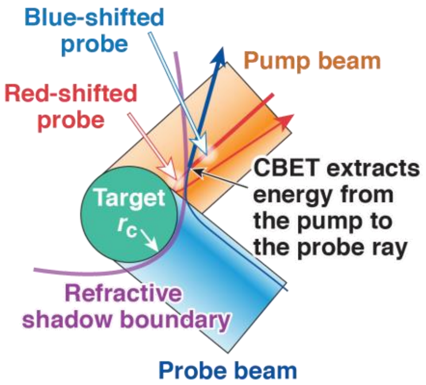
    - KrF lasers (NRL)
  - spots smaller than target (e.g., R_{75})†



  - spot-masking apodization (SMA)



- **Spatial domain**
  - wavelength detuning; Dm$_0$



  - wide bandwidth within each beam (e.g., SRRS‡)
  - lower intensity per band and incoherence disrupts growth

---

* STUD: spike trains of uneven duration and delay; B. Afeyan and S. Hüller, EPJ Web Conf. 59, 05009 (2013).

** D. H. Froula *et al.*, Phys. Plasmas 20, 082704 (2013).

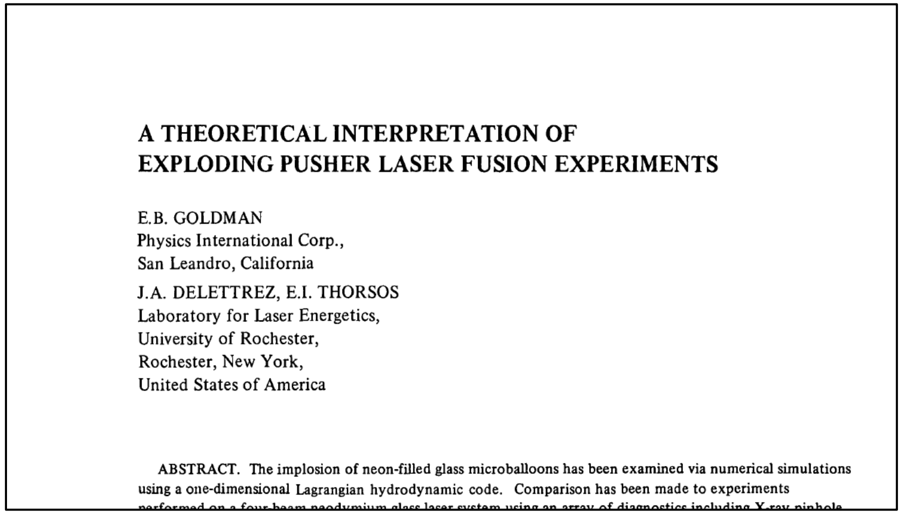
*** T. J. Kessler and H. Huang, presented at the Ninth International Conference on Inertial Fusion Sciences and Applications (IFSA 2015), Seattle, WA, 20–25 September 2015 (Abstract Mo.Po.61).

† S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016); 059903(E) (2016).

‡ SRRS: stimulated rotational Raman scattering; J. Weaver *et al.*, “Spectral and Far-Field Broadening due to Stimulated Rotational Raman Scattering Driven by the Nike Krypton Fluoride Laser,” to be published in Applied Optics.

The XP platform has a long history dating back to the early days of ICF, circa 1970’s

- **Thin-shelled glass microballoons filled with DT gas were shot with an intense short laser burst**

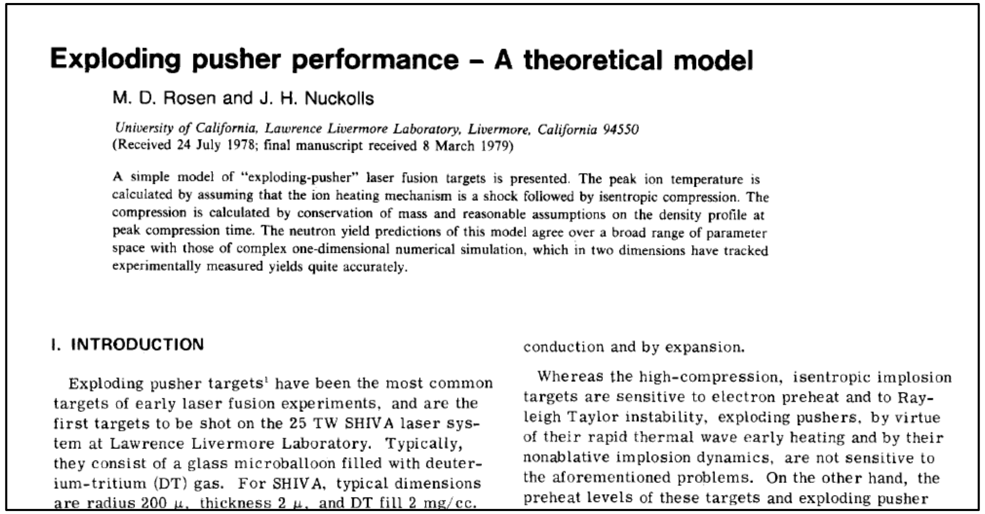


A THEORETICAL INTERPRETATION OF
EXPLODING PUSHER LASER FUSION EXPERIMENTS

E.B. GOLDMAN
Physics International Corp.,
San Leandro, California

J.A. DELETTREZ, E.I. THORSOS
Laboratory for Laser Energetics,
University of Rochester,
Rochester, New York,
United States of America

ABSTRACT. The implosion of neon-filled glass microballoons has been examined via numerical simulations using a one-dimensional Lagrangian hydrodynamic code. Comparison has been made to experiments performed on a four-beam neodymium glass laser system using an array of diagnostics including X-ray pinhole



Exploding pusher performance – A theoretical model

M. D. Rosen and J. H. Nuckolls

University of California, Lawrence Livermore Laboratory, Livermore, California 94550
(Received 24 July 1978; final manuscript received 8 March 1979)

A simple model of “exploding-pusher” laser fusion targets is presented. The peak ion temperature is calculated by assuming that the ion heating mechanism is a shock followed by isentropic compression. The compression is calculated by conservation of mass and reasonable assumptions on the density profile at peak compression time. The neutron yield predictions of this model agree over a broad range of parameter space with those of complex one-dimensional numerical simulation, which in two dimensions have tracked experimentally measured yields quite accurately.

I. INTRODUCTION

Exploding pusher targets[1] have been the most common targets of early laser fusion experiments, and are the first targets to be shot on the 25 TW SHIVA laser system at Lawrence Livermore Laboratory. Typically, they consist of a glass microballoon filled with deuterium-tritium (DT) gas. For SHIVA, typical dimensions are radius 200 μ, thickness 2 μ, and DT fill 2 mg/cc.

conduction and by expansion.

Whereas the high-compression, isentropic implosion targets are sensitive to electron preheat and to Rayleigh Taylor instability, exploding pushers, by virtue of their rapid thermal wave early heating and by their nonablative implosion dynamics, are not sensitive to the aforementioned problems. On the other hand, the preheat levels of these targets and exploding pusher

A NIF XP*

How do they work?...

---

* M. J. Rosenberg *et al.*, Phys. Plasmas 21, 122712 (2014).

The XP platform has a long history dating back to the early days of ICF, circa 1970's

- Thin-shelled glass microballoons filled with DT gas were shot with an intense, short laser burst
    - the laser energy rapidly heats the electrons
        - preheats the DT electrons (reduces convergence, low ρR)
        - causes ~1/2 the shell-mass to explosively ablate (high stability)
    - the imploding inner ~1/2 -shell acts as a piston, driving a strong inward shock (high speeds)
        - heats the ions to thermonuclear temperatures, producing fusion reactions
    - the exploding outer shell and imploding/compressing inner shell led to these targets being called exploding pushers

The XP platform has a long history dating back to the early days of ICF, circa 1970’s

- **Thin-shelled glass microballoons filled with DT gas were shot with an intense, short laser burst**
  - **the laser energy rapidly heats the electrons**
    - **preheats the DT electrons (reduces convergence, low ρR)**
    - **causes ~1/2 the shell-mass to explosively ablate (high stability)**
  - **the imploding inner ~1/2 -shell acts as a piston, driving a strong inward shock (high speeds)**
    - **heats the ions to thermonuclear temperatures, producing fusion reactions**

  - **the exploding outer shell and imploding/compressing inner shell led to these targets being called exploding pushers**

Current XP experiments use similar concepts, scaled to higher energy and similar aspect ratio targets but leveraging shaped pulses to drive the remaining shell during compression, further increasing the DT_n yield.

The XP platform has a long history dating back to the early days of ICF, circa 1970’s

- **Thin-shelled glass microballoons filled with DT gas were shot with an intense short laser burst**
  - **the laser energy rapidly heats the electrons, driving an inward heat wave into the shell and DT gas preheating the DT electrons (reduces convergence, low ρR)**
    - **the thermal wave heats the shell ions (strong coupling) but not the DT ions (weak coupling)**
    - **the rapid deposition causes ~1/2 the shell mass to explosively ablate (high stability)**
  - **the imploding inner 1/2-shell acts as a piston driving a strong inward shock (high speeds)**
    - **this shock wave principally heats the ions**
    - **the inner shell continues to move inward behind the shock front, compressing the post-shock DT gas, further heating the ions to thermonuclear temperatures, producing fusion reactions**
    - **the shock and compression cause $T_i \gg T_e$, while the weak coupling preserves the imbalance**
  - **the exploding outer shell and imploding/compressing inner shell led to the moniker exploding pushers**
  - **eventually the thermal pressure builds and the return shock impacts the shell, both contributing to deceleration and halting compression**
    - **fusion reactions continue until the DT is cooled by thermal conduction and expansion**
- **Current XP experiments use similar concepts but with larger targets with similar aspect ratios and shaped pulses that continue to drive the remaining shell during compression, further increasing the DT_n yield**

The XP platform has a long history dating back to the early days of ICF, circa 1970's

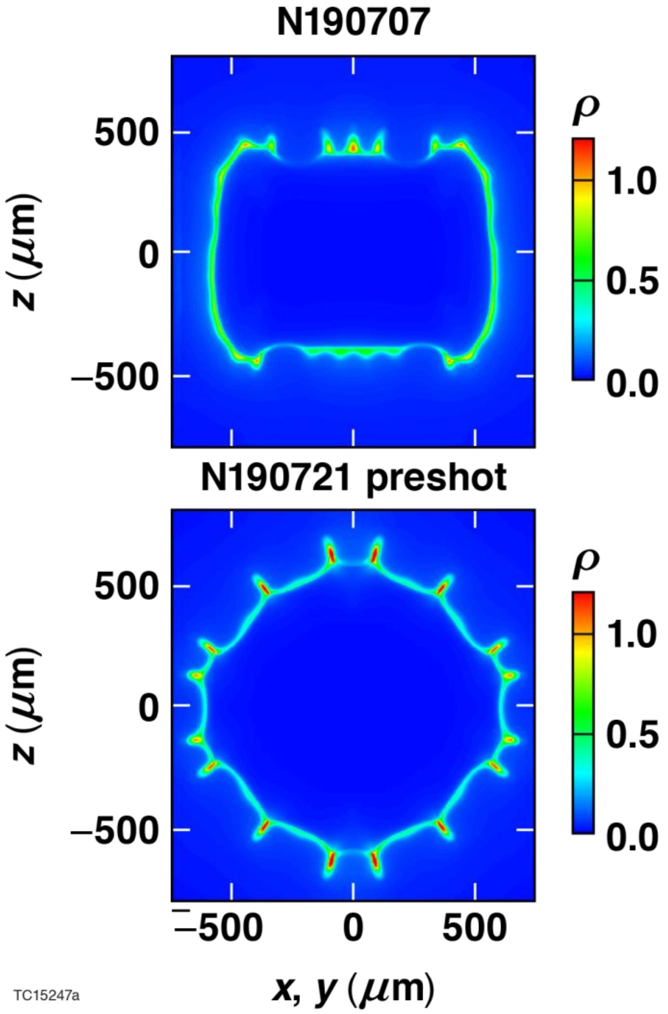
- Thin shelled glass microballoons filled with DT gas were shot with an intense short laser burst
  - the laser energy rapidly heats the electrons, driving an inward heat wave into the shell and DT gas preheating the DT electrons (reduces convergence, low ρR)
    - the rapid deposition causes ~1/2 the shell-mass to explosively ablate (high stability)
  - the imploding inner ~1/2-shell acts as a piston driving a strong inward shock (high speeds)
    - the inner shell continues to move inwards behind the shock front compressing the post-shock DT gas, further heating the ions to thermonuclear temperatures producing fusion reactions
    - eventually the thermal pressure builds and the return shock impacts the shell both contributing to deceleration and halting compression
    - fusion reactions continue until the DT is cooled by thermal conduction and expansion
    - the exploding outer-shell and imploding/compressing inner-shell led to these targets being called exploding pushers

Current XP experiments use similar concepts scaled to higher energy and similar aspect ratio targets, but leveraging shaped pulses to drive the remaining shell during compression, further increasing the DT_n yield.

Upcoming XP experiments on the NIF hope to increase neutron yield using improved pulse shapes and pointings based on 2-D simulations that include necessary physics

Elements of the new design

- Dual shocks improve yield while remaining high adiabat and predominantly “shock yield”
- The pulse shape improves separation of shell from shock, improving yield
- Steep main pulse rise improves coupling
- Simpler quad splitting improves power imbalance
- Repointing and pulse shapes yield rounder implosions
- Extensible
    - large targets with optimized DPP’s >100 kJ

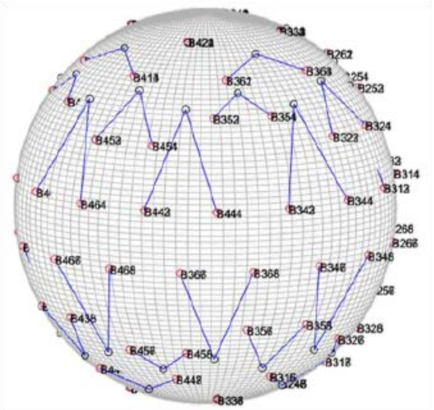


TC15247a

Better symmetry control and enhanced coupling is predicted to triple the yield in warm PDD implosions on the NIF

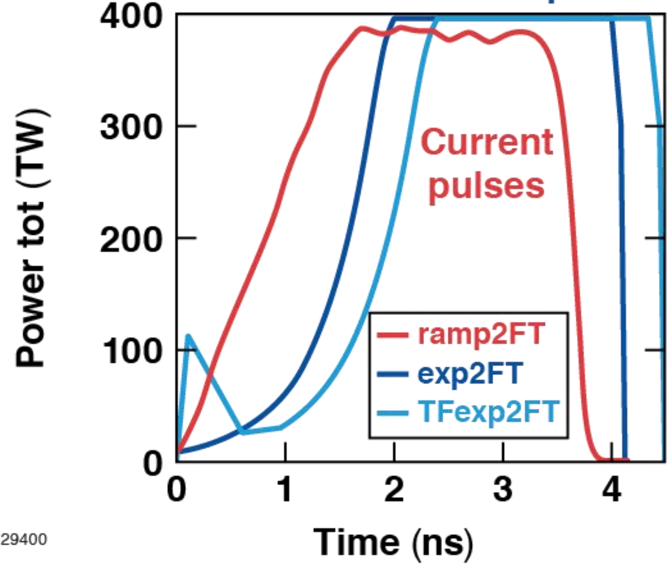
E_L 1.1 MJ	Puls shape	P_{max} (TW)	Abs (%)	Y_{DT} ($\times 10^{16}$)	Notes
Current (N190227)	ramp2FT	385	81	1.1	Has severe shell distortion
New pointing	ramp2FT	385	80	1.5	Improved shell morphology, increases yield
New pointing and pulse = *A*	exp2FT	445	80	1.9	Improved shape and speed
A and $\Delta\lambda = \pm 3$ Å with fC2Pm*	exp2FT	445	83	1.9	Marginal improvement
A and $\Delta\lambda = \pm 4.5$ Å with fC2Pm	exp2FT	445	89	3.2	Better coupling
A and $\Delta\lambda = \pm 6$ Å with fC2Pm	exp2FT	445	91	>3.2	Can be optimized better

Target shimming to improve symmetry was successfully tested on the NIF this year.



New pointing

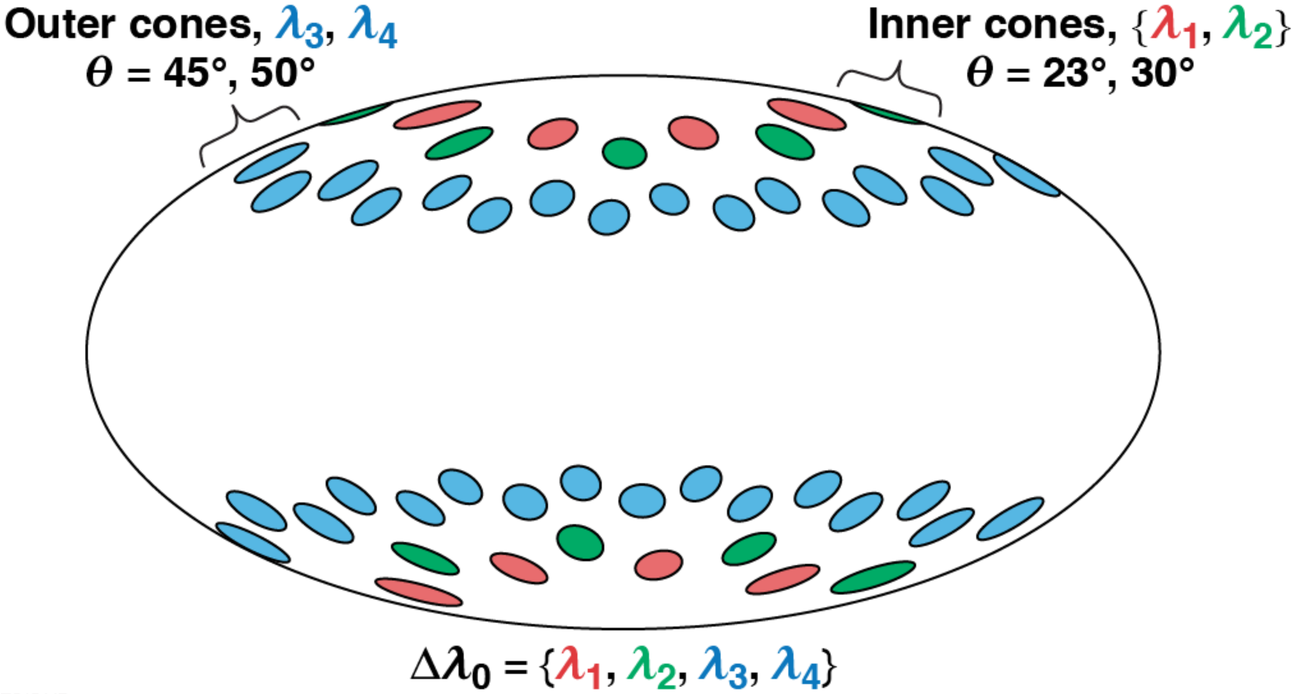
New pulses



E29400

The NIF LID four-color laser sources are currently fixed into a symmetric pattern

LID port-color arrangement

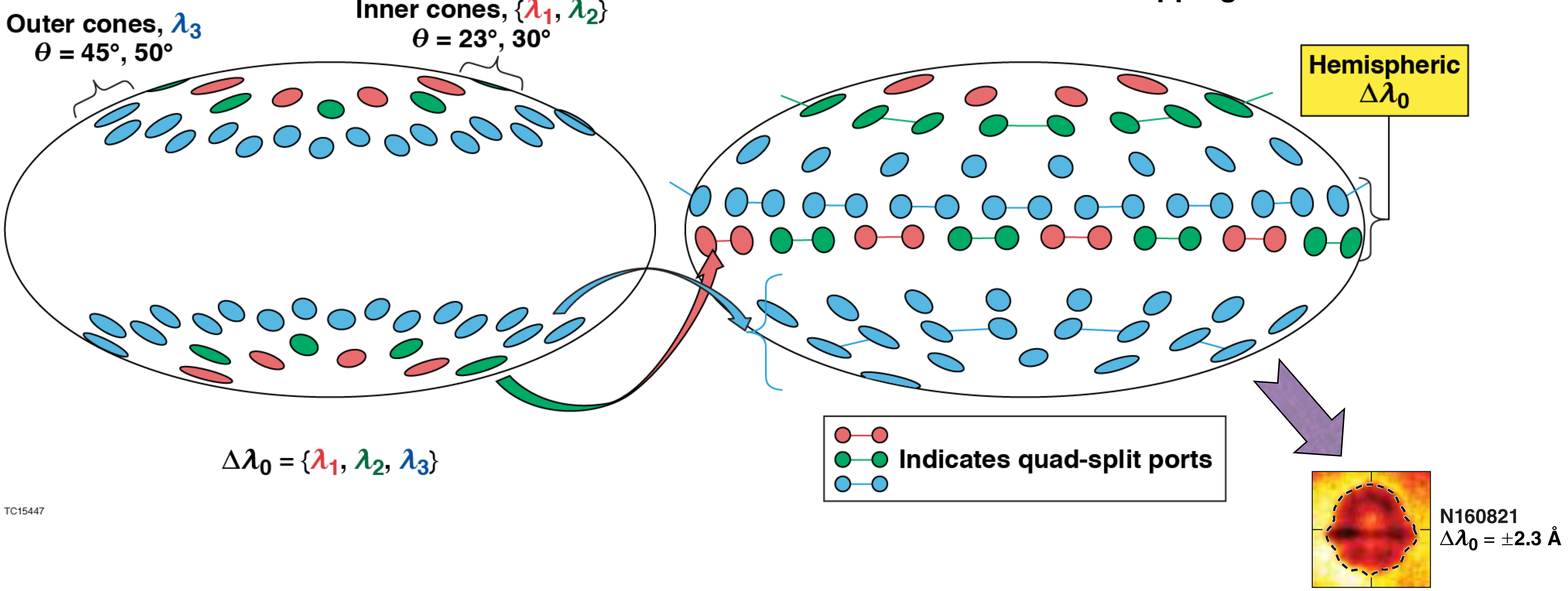


TC15447

Early NIF PDD experiments employing wavelength detuning to study CBET mitigation used extreme repointing to induce a hemispheric color change

Port-color arrangements

Port-color repointing; southern cone swapping



$\Delta\lambda_0 = \{\lambda_1, \lambda_2, \lambda_3\}$

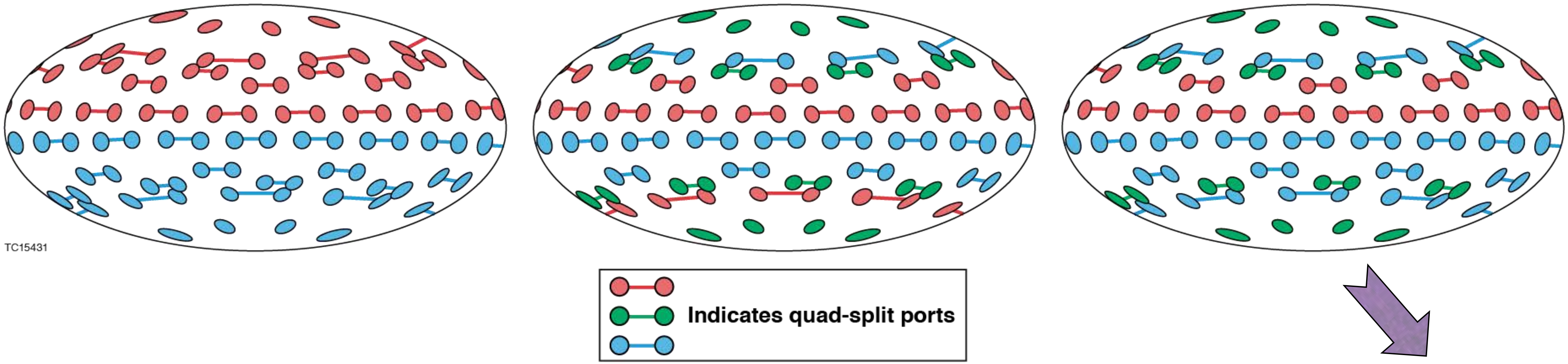
TC15447

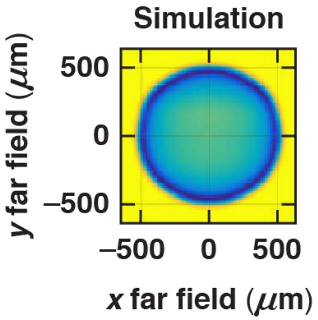
---

* J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018).

The NIF fiber-optic front end will be updated to flexibly remap the four-color sources to a variety of port configurations to help mitigate CBET

Flexible color-to-port mapping (fC2Pm) with large $\Delta\lambda_0$

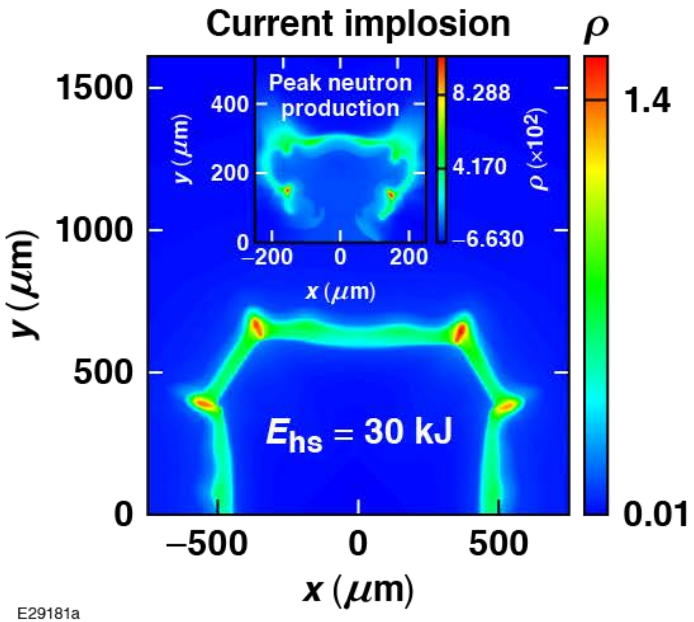




The new front-end remapping eliminates the need for extreme repointing to induce a hemispheric color change.

The performance of current implosions can be improved by better symmetry control and enhanced laser coupling

- **CBET mitigation strategies** – smaller SMA spots, $\Delta\lambda = \pm 6$ Å ⇒ $E_k = 100 \rightarrow 120$ kJ
- **Symmetry control strategies** – pulse shaping, repointing, PDD phase plates ⇒ $E_{hs}/E_k = 30\% \rightarrow 50\%$

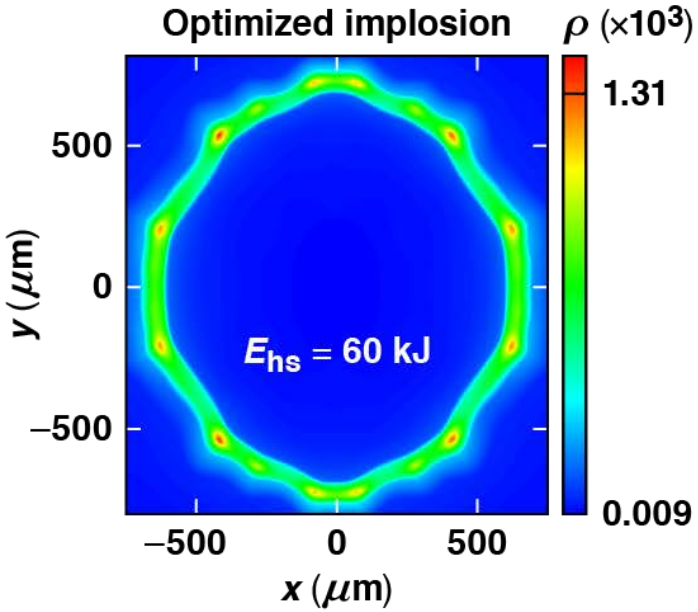


E29181a

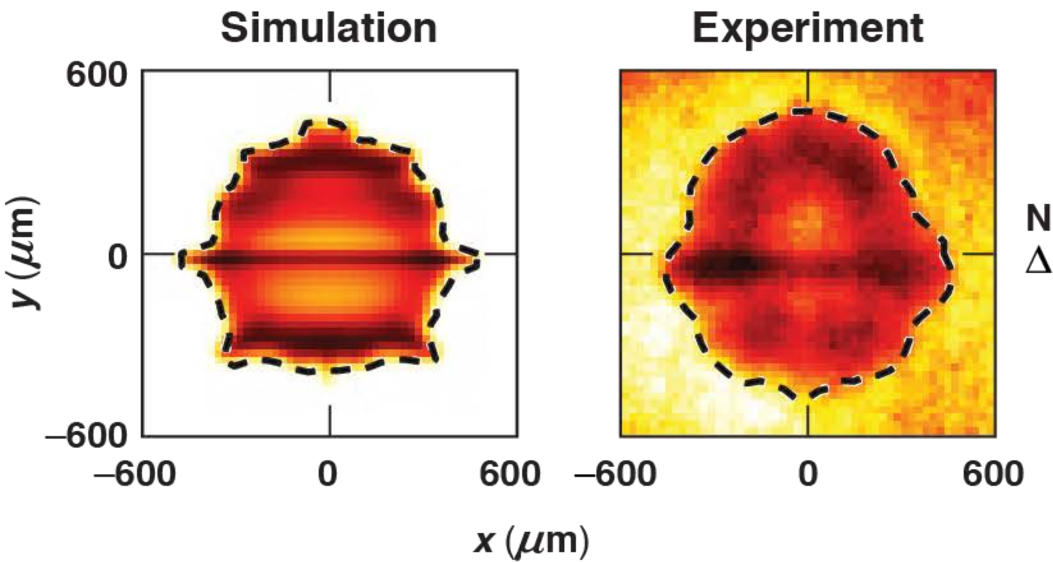
***DRACO* simulations**

Shot	Y_{DT} (10^{15})		T_i (keV)		t_{bang} (ns)	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
N181014	3.5	3.9	6.3	8.6	5.5	4.9
N190224	6.0	7.0	7.7	10.3	4.9	4.4
N190227	11.1	11.2	9.0	9.7	4.2	4.2

100-kJ goal ⇒



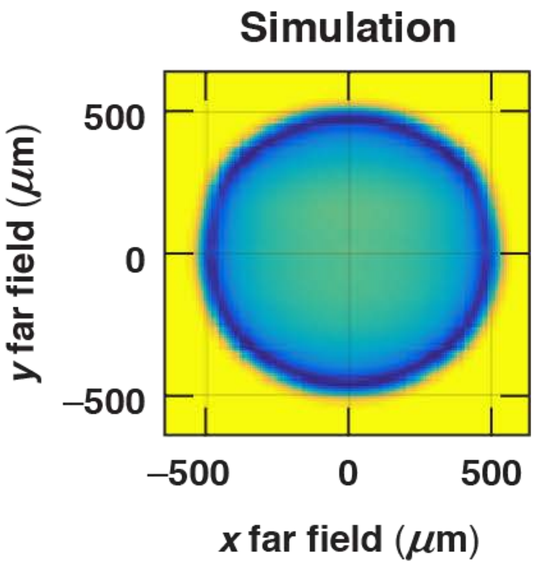
Application of both large wavelength detuning, fC2Pm, and optimized PDD spot shapes promises large returns for high-convergence PDD experiments on the NIF



N160821
$\Delta\lambda_0 = \pm 2.3$ Å

TC13885e

Next step...



Low convergence XP: ➔ >100kJ yield
High Convergence: alpha burner, ignition