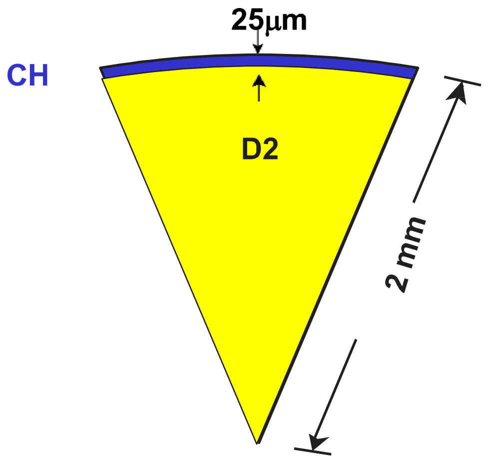
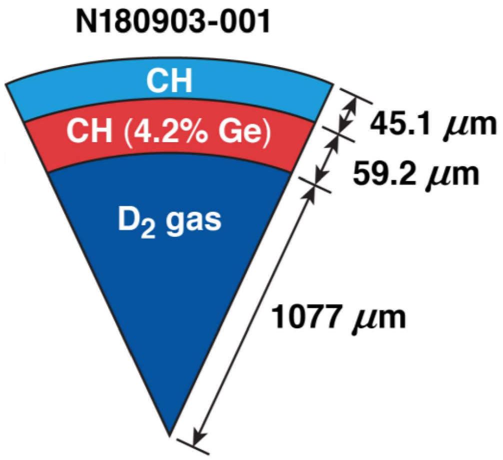
The MegaJoule Direct Drive Campaign:
NIF Experiments on the Pathway to MJ Yield

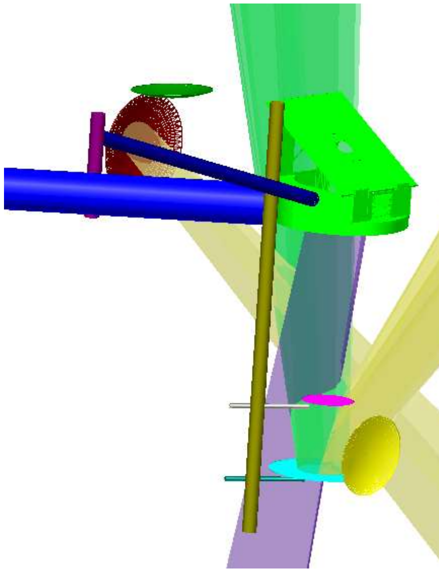
Energy coupling/symmetry



Hot electron preheat



Laser imprint



Michael Rosenberg
University of Rochester
Laboratory for Laser Energetics

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Summary

Current MJ-scale experiments lay the groundwork for high-yield direct-drive implosions on the NIF in the 2020’s

- **Extrapolation of direct-drive implosion performance from OMEGA to ignition scale on dedicated physics experiments at NIF scale**

- **The MegaJoule Direct Drive (MJDD) campaign on NIF includes three primary phys**
  1) **<u>Hot electron preheat</u> has been measured at close to tolerable levels, partially using mid-Z layers, and shown to originate from stimulated Raman scattering**
  2) **<u>Implosion symmetry and energy coupling (including cross-beam energy trans</u> been controlled with wavelength detuning, contoured shells, and beam pointi**
  3) **<u>Laser imprint</u> experiments have produced x-ray radiography data to benchmar of imprint-related instabilities and partial mitigation with multi-FM SSD or high**

- **Current NIF capabilities limit high-performance polar-direct drive (PDD) implosion convergence exploding pushers**

A staged set of proposed facility improvements will allow for increased convergence

Collaborators

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Rutherford Appleton Laboratory

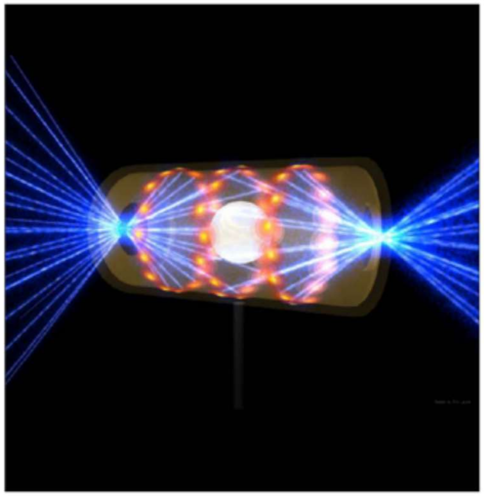
A. Colaitis
CELIA

Outline

- Laser direct-drive inertial confinement fusion
    - Scaling and motivation for NIF experiments
- MJDD experiments on NIF
    - LPI/hot electron preheat
    - Laser energy coupling/CBET/PDD symmetry
    - Laser imprint
- Current high-yield PDD implosions and pathway to MJ yield

Laser direct drive is one of three main approaches to achieving i confinement fusion ignition and high yield

Laser indirect drive

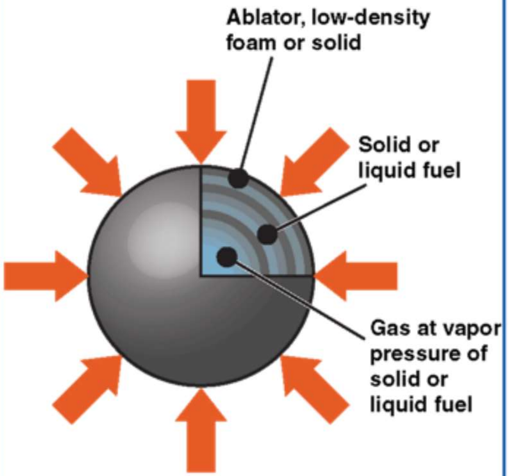


LLNL lead laboratory (LANL)

Facility

- **NIF**
  - OMEGA

Laser direct drive

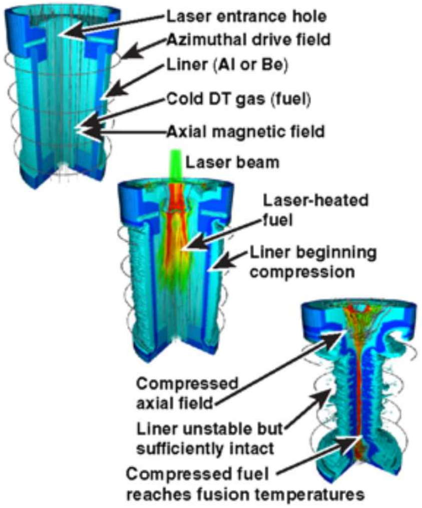


LLE lead laboratory (NRL, LLNL, LANL)

Facility

- **OMEGA**
  - NIF
  - NIKE

Pulsed-power magnetized fusion



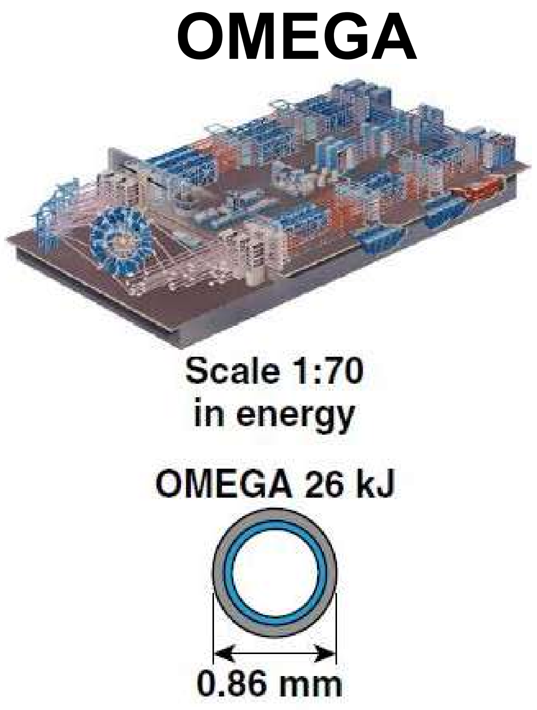
SNL lead laboratory (LLNL, LANL, LLE)

Facility

- **Z**
  - Omega
  - NIF

I2415g

Most direct-drive experiments to produce high-performance (albeit ~1/4 of igni scale) implosions are done on OMEGA, which is designed for LDD experiment

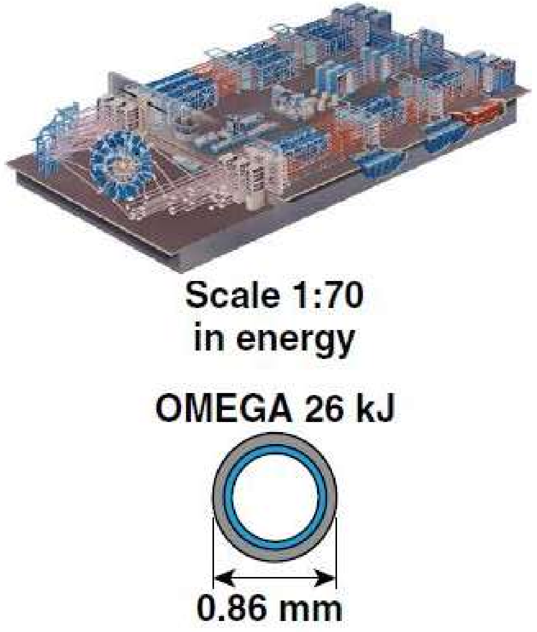


OMEGA Advantages for LDD

- Symmetric illumination
- Circular beam spots (ideal for symmetric illumination)
- State-of-the-art beam smoothing (2D smoothing by spectral dispersion, polarization smoothing)
- Cryogenic capability for LDD

NIF has laser energy (1.9 MJ) closer to ignition scale, but is not (y
optimized for high-performance direct-drive implosions

OMEGA



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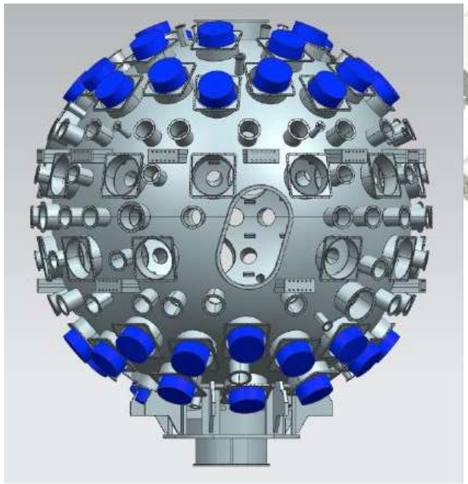
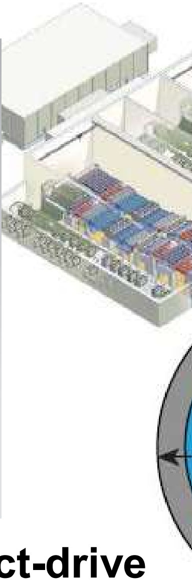
NIF





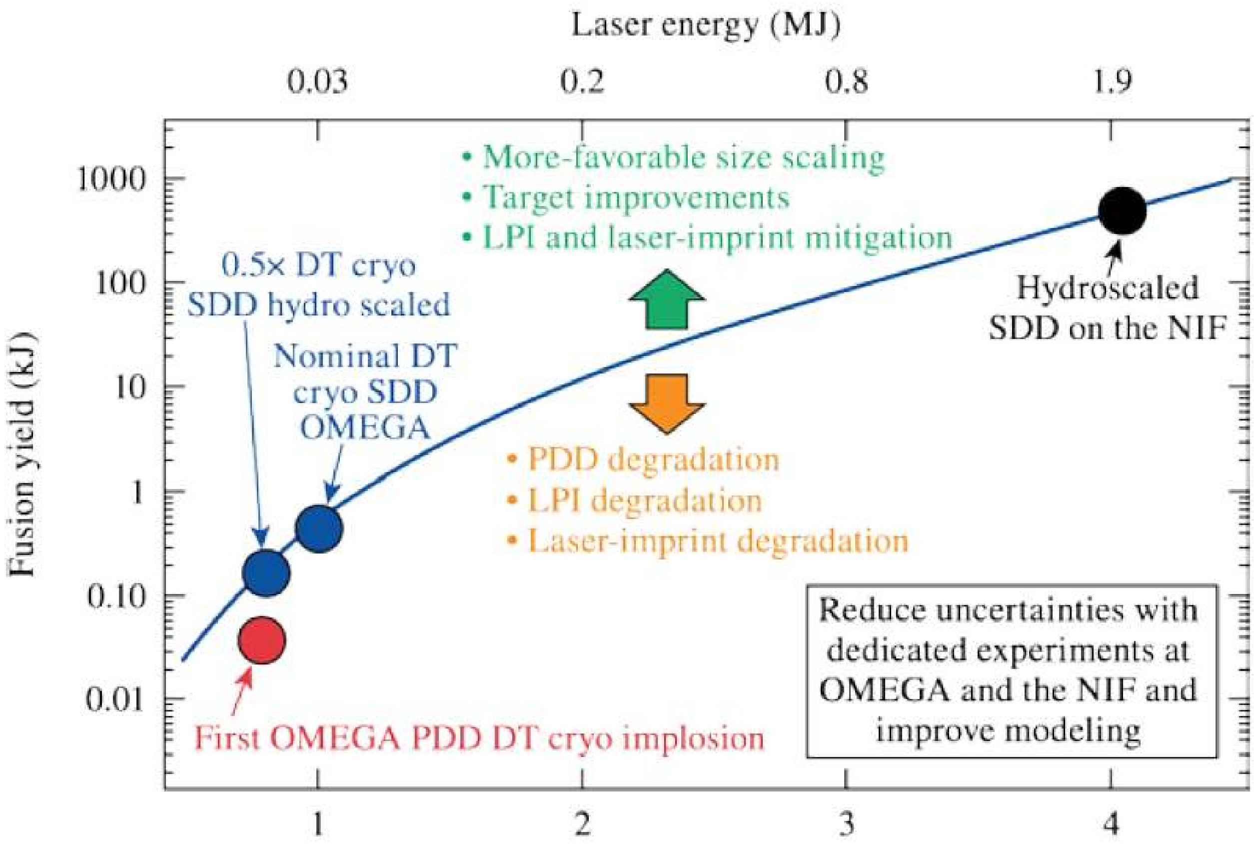
NIF optimized for indirect-drive

- Polar illumination
- Beams must be defocused for LDD
- Limited beam smoothing
- No LDD cryo capability

**Despite limitations, NIF can be utilized to learn about direct drive physics at ignition-rele
now, and with some improvements to the facility, work towards high-performance im**

Motivation

Current OMEGA cryogenic implosion yield extrapolates to ~570 k at 2 MJ laser drive assuming hydrodynamic scaling is valid



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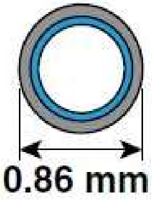
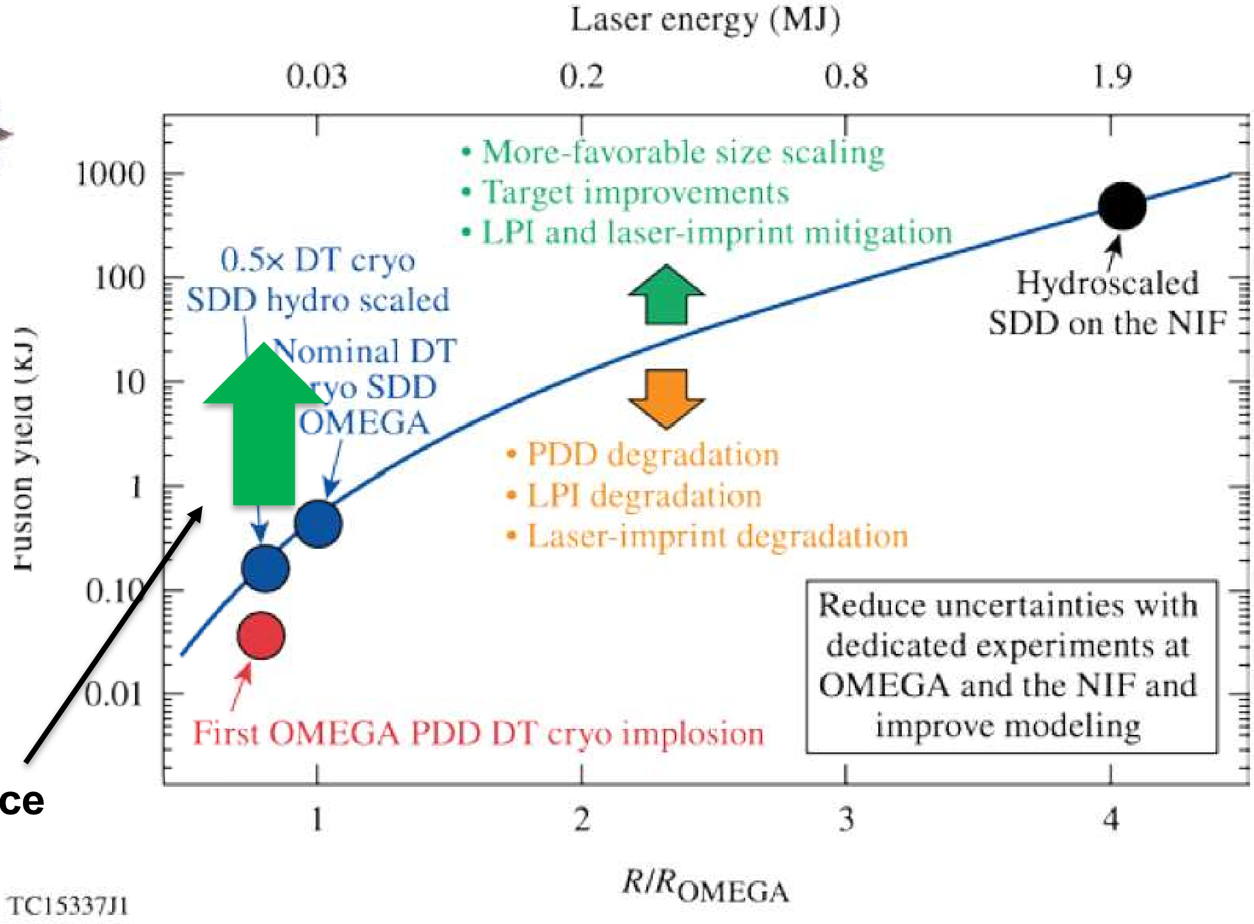
Motivation

In this context, there are two major thrusts of the direct-drive ICF effort, encompassing experiments on both OMEGA and NIF

Scale 1:70 in energy

OMEGA 26 kJ





- More-favorable size scaling
- Target improvements
- LPI and laser-imprint mitigation

- PDD degradation
- LPI degradation
- Laser-imprint degradation

Reduce uncertainties with dedicated experiments at OMEGA and the NIF and improve modeling

1) Improve performance on OMEGA*

* V. Gopalaswamy *et al. Nature* 565, 581 (2019)

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Scale 1:70
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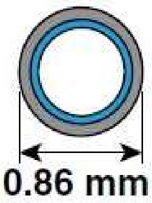
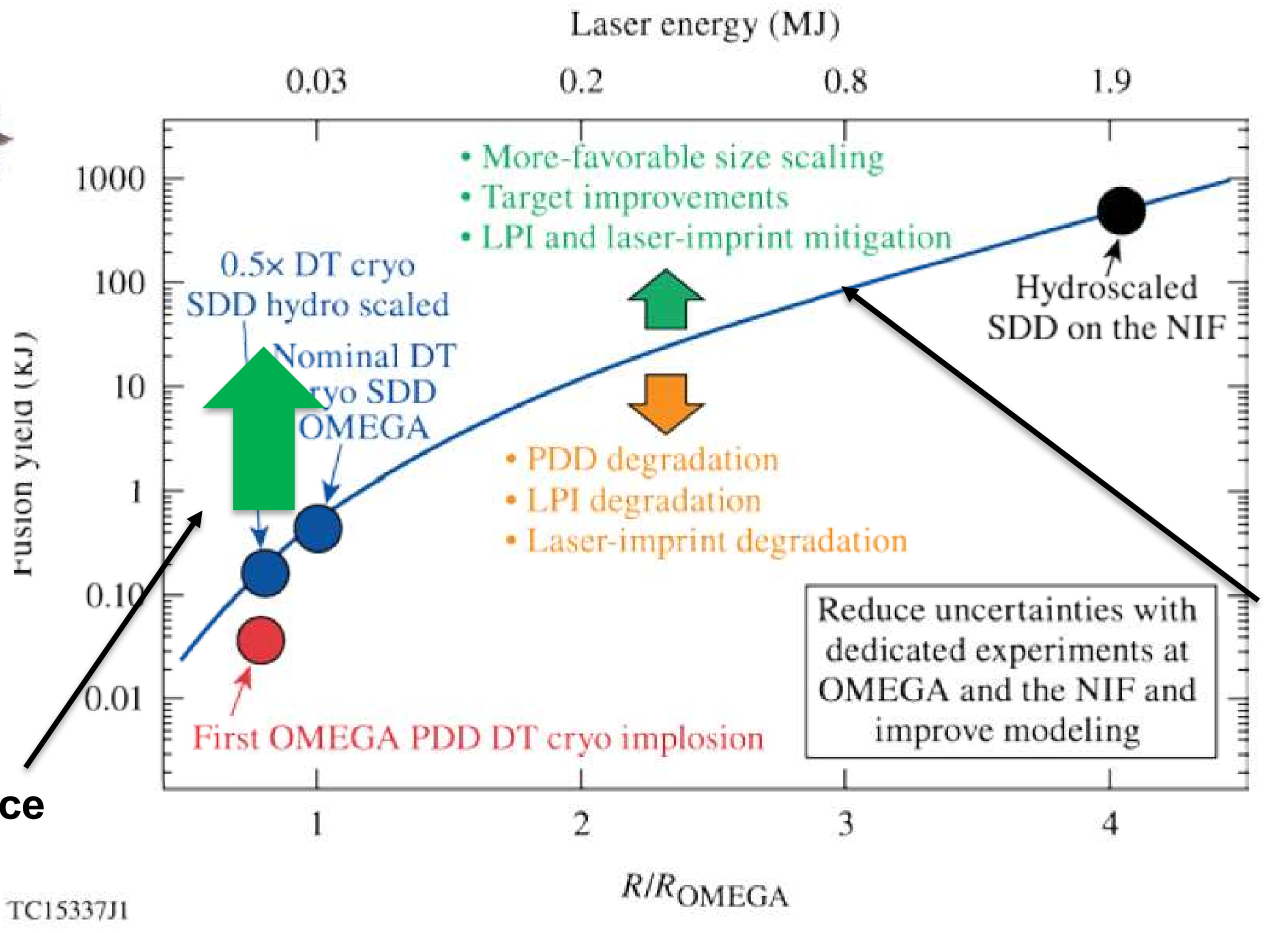




1) Improve performance on OMEGA*

2) Focused e
assess/valid
MJDD camp
experiments
necessarily
scaling: <u>Ene</u>
<u>preheat, imp</u>
<u>performance</u>
<u>implosions a</u>

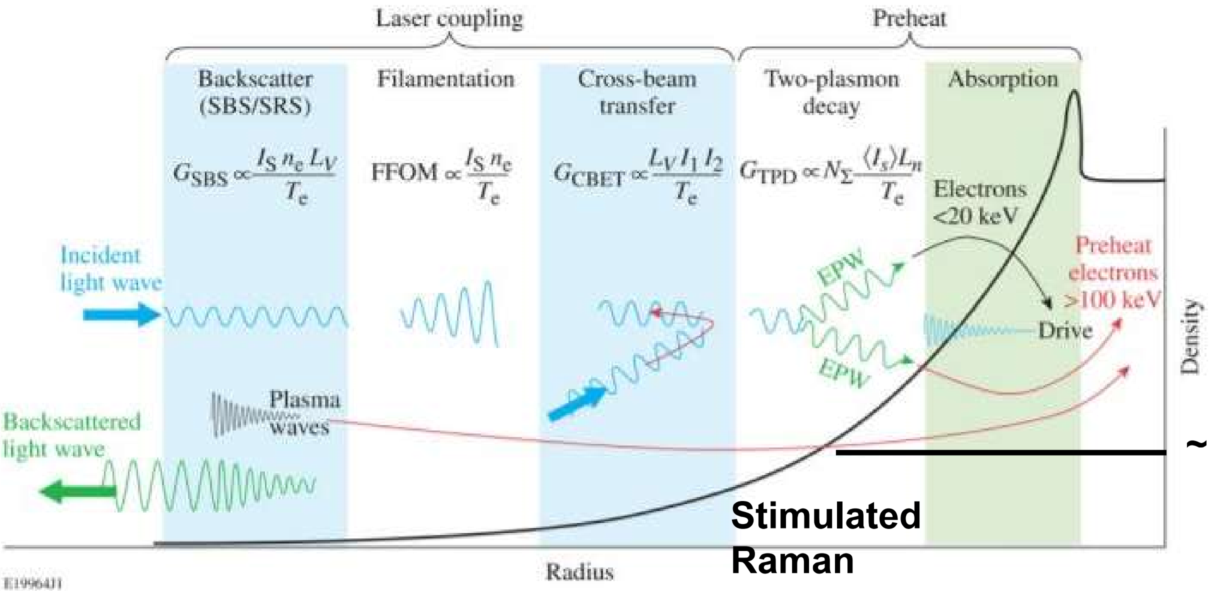
* V. Gopalaswamy *et al. Nature* 565, 581 (2019)

Motivation

NIF experiments achieve ignition-relevant coronal plasma conditi are inaccessible in OMEGA implosions

2D DRACO simulated plasma conditions at

	NIF ignition scale	NIF planar experiments	NIF sub-scale implosions
L_n (µm)	600	400-700	400
T_e (keV)	3.5 to 5	3 to 5	3.2



~0.1-0.25n_c

Stimulated Raman scattering

n_c/4 density represents region where LPI occurs

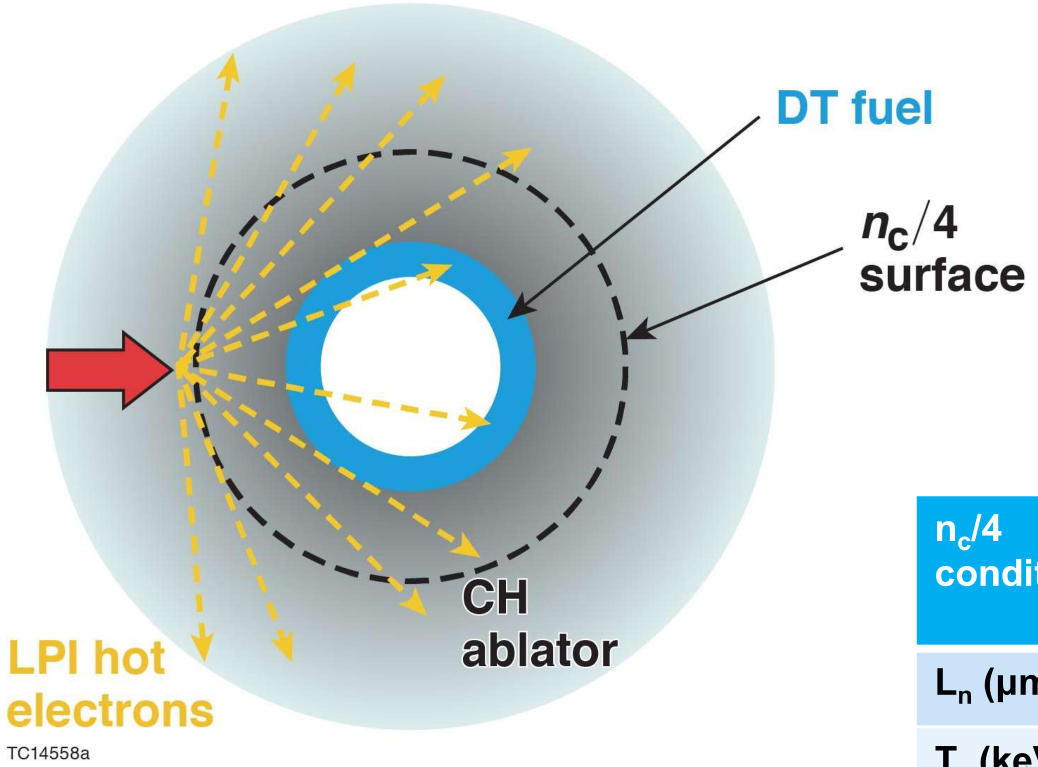
Outline

- Laser direct-drive inertial confinement fusion
    - Scaling and motivation for NIF experiments
- **MJDD experiments on NIF**
    - **LPI/hot electron preheat**
    - **Laser energy coupling/CBET/PDD symmetry**
    - **Laser imprint**
- Current high-yield PDD implosions and pathway to MJ yield

LPI and hot electron preheat has been studied in both planar and spherical ge determine preheat levels and assess mitigation at ignition-relevant scale lengt

Preheat in cryo implosions

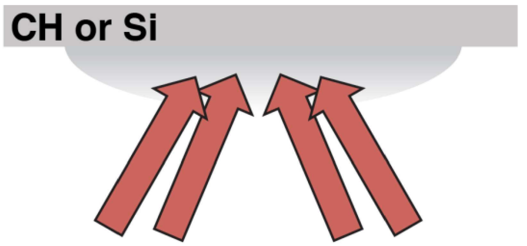
Direct-drive implosion



Designer: A. Solodov

NIF experimental platforms

Planar platform
(to study LPI mechanisms
and hot electron production)



23° and 30° beams
or
45° and 50° beams

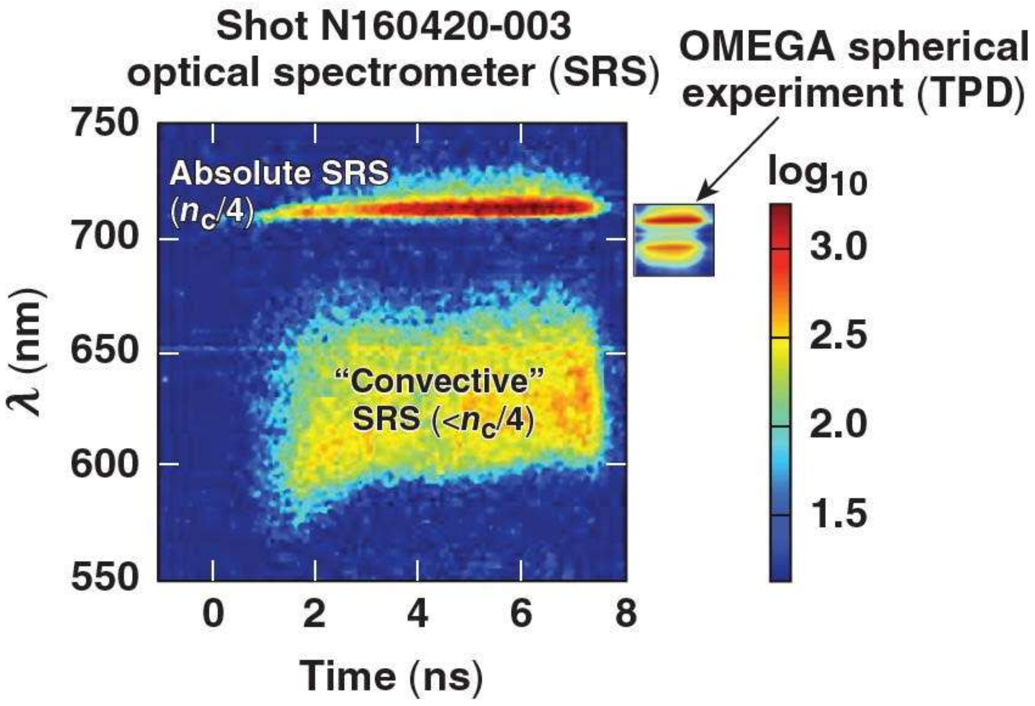
Spheri
(to study
coupling to

$n_c/4$ conditions	NIF ignition scale	NIF planar experiments	NIF spherical experiment
L_n (µm)	600	400-700	40
T_e (keV)	3.5 to 5	3 to 5	3.
I_L (W/cm^2)	(6-10)x10^{14}	(6-15)x10^{14}	3-6x10^1

Planar LPI experiments established the predominance of stimulated Raman sc (SRS) as a hot electron source

NIF: $L_n = 525\ \mu m$
$T_e = 4.5$ keV

OMEGA:* $L_n = 150\ \mu m$
$T_e = 2.8$ keV


Shot N160420-003 optical spectrometer (SRS)

OMEGA spherical experiment (TPD)

M. J. Rosenberg *et al.*, *Phys. Rev. Lett.* 120, 055001 (2018)
M. J. Rosenberg *et al.*, *Phys. Plasmas* 27, 042705 (2020)

Planar LPI experiments established the predominance of stimulated Raman sc (SRS) as a hot electron source, the intensity scaling of preheat, and Si mitigati

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Shot N160420-003
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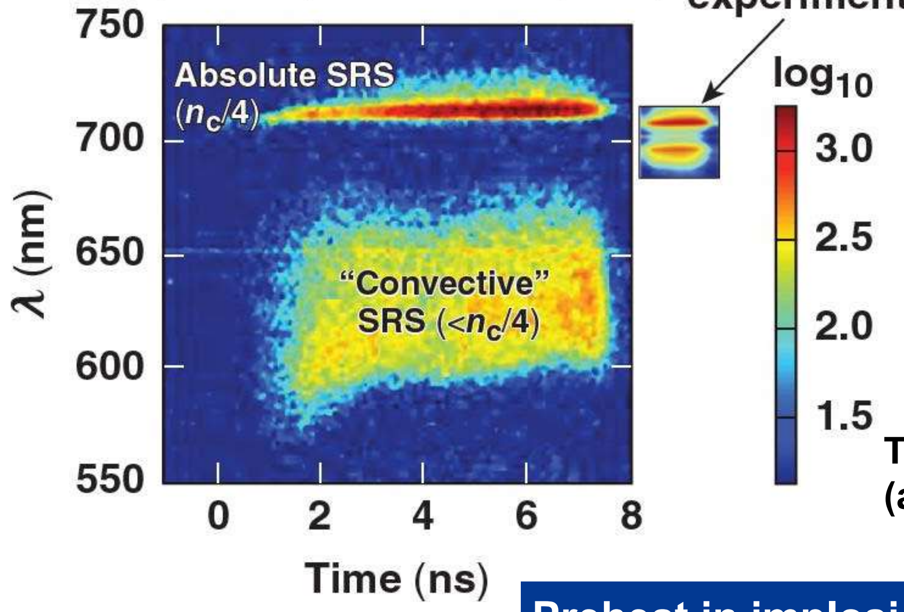
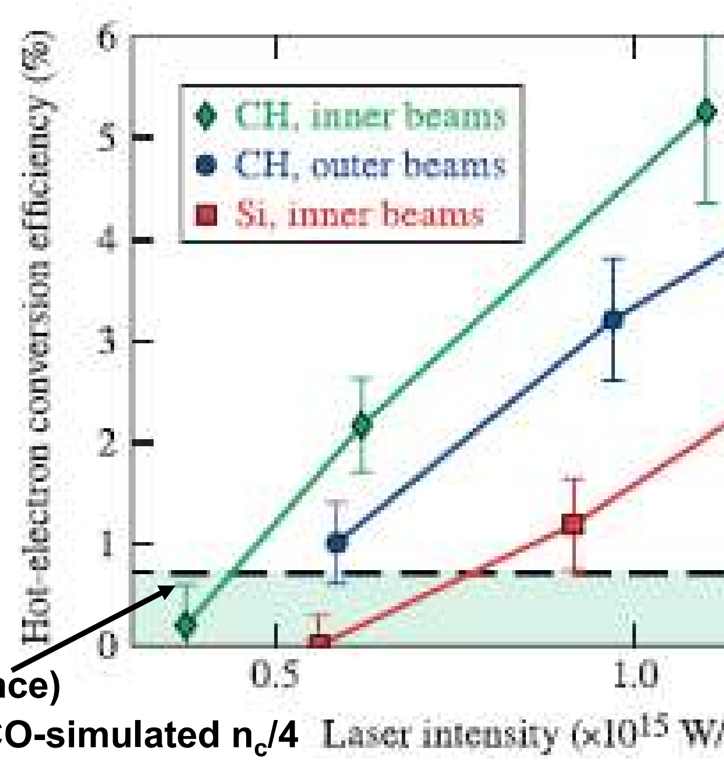




Tolerable preheat level
(assuming wide divergence)

DRACO-simulated $n_c/4$

Preheat in implosions depends not only on hot electron production, but divergence/coupling to the inner portion of the shell

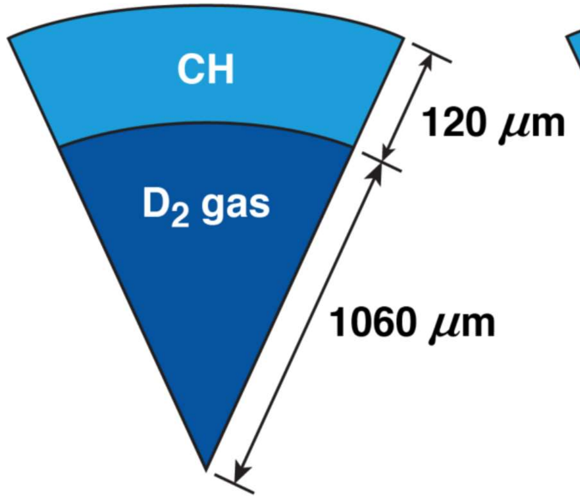
M. J. Rosenberg *et al.*, *Phys. Rev. Lett.* 120, 055001 (2018)
M. J. Rosenberg *et al.*, *Phys. Plasmas* 27, 042705 (2020)

A. A. Solodov *et al.*, *Phys. Plas*

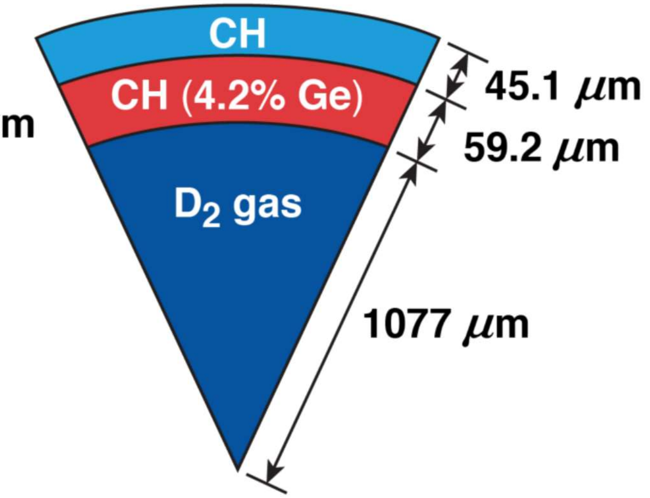
A PDD implosion platform, using Ge-doped layers, was adapted fr OMEGA* to diagnose preheat in the inner portion of the shell

NIF target designs

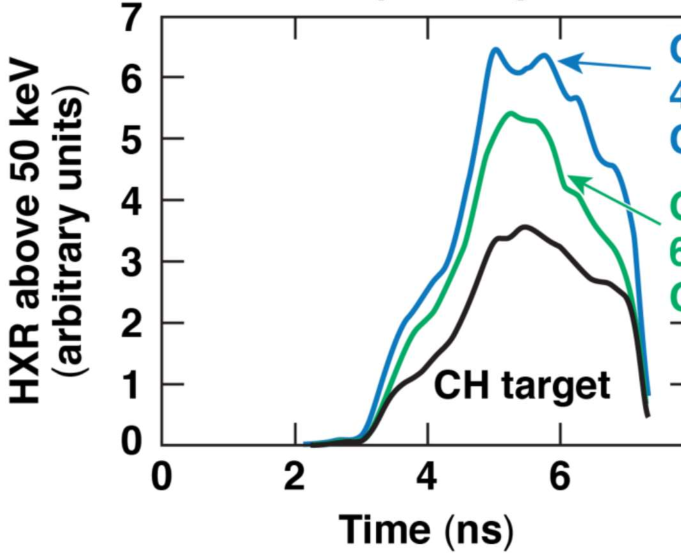
N180903-002
N190306-001



N180903-001



LILAC simulations for T_{hot} = 55
hot-electron divergence full an
of 2π, Ge-doped target at 3.9



Design: A. Solodov

E29257

For an identical laser drive and identical hot electron source, the difference in hard x-rays ∝ hot electron energy deposited in Ge-doped layer

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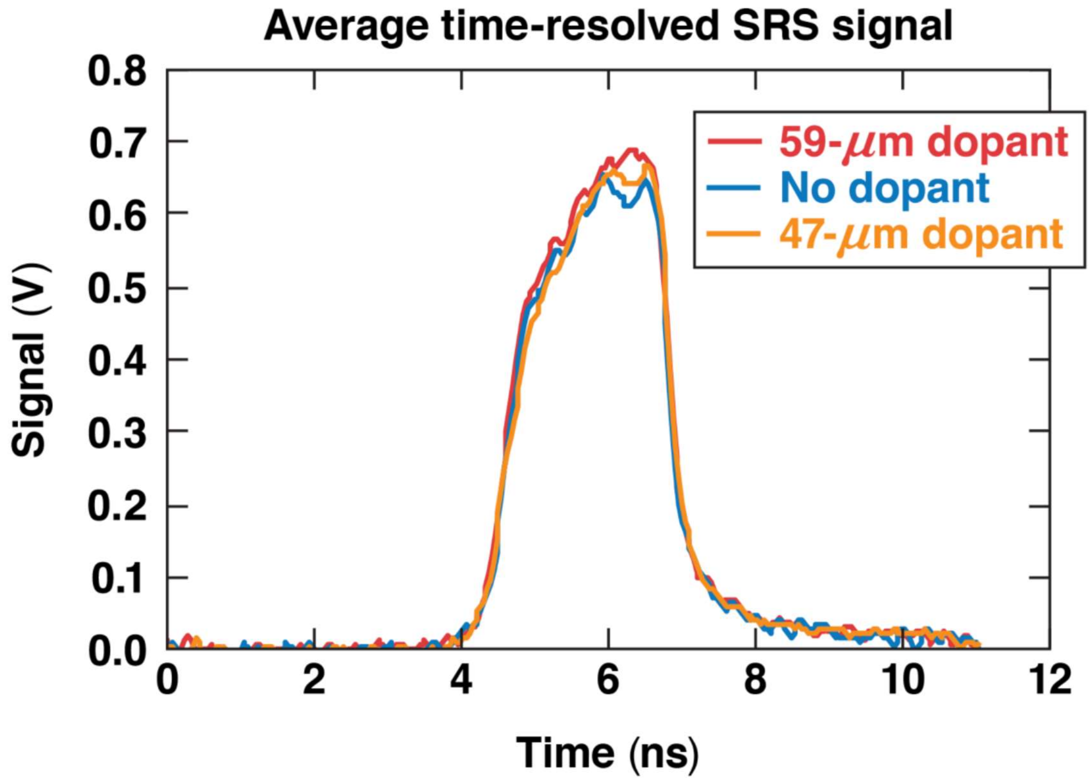
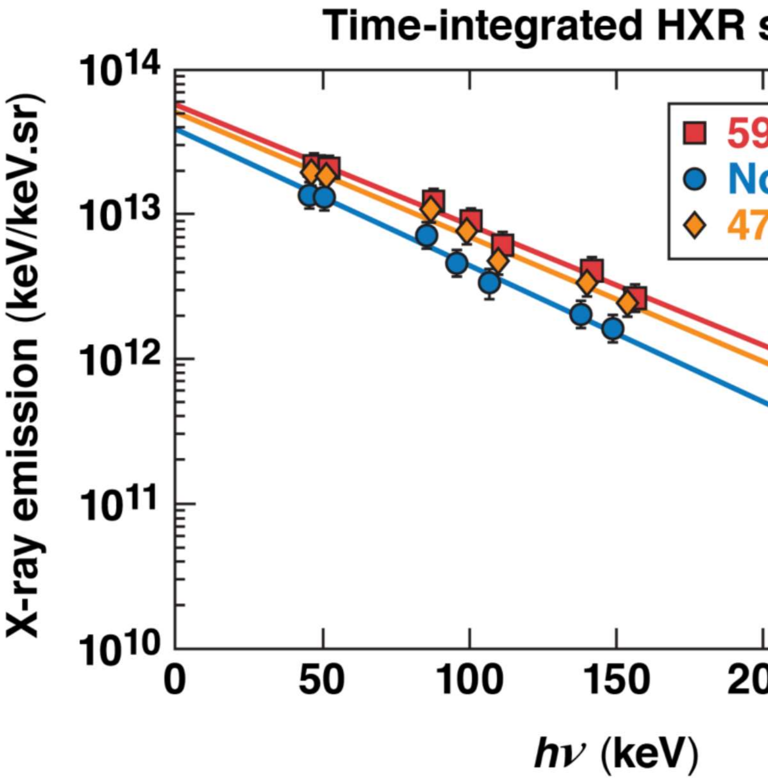
*Platform based on A. Christopherson, et al. (subr

Hard x-ray (HXR) emission on NIF shows the expected variation with Ge layer thickness, with identical LPI





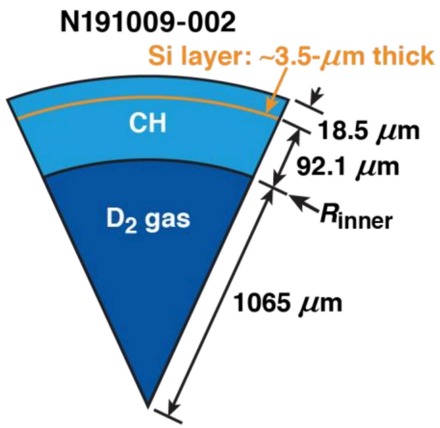
E27877a

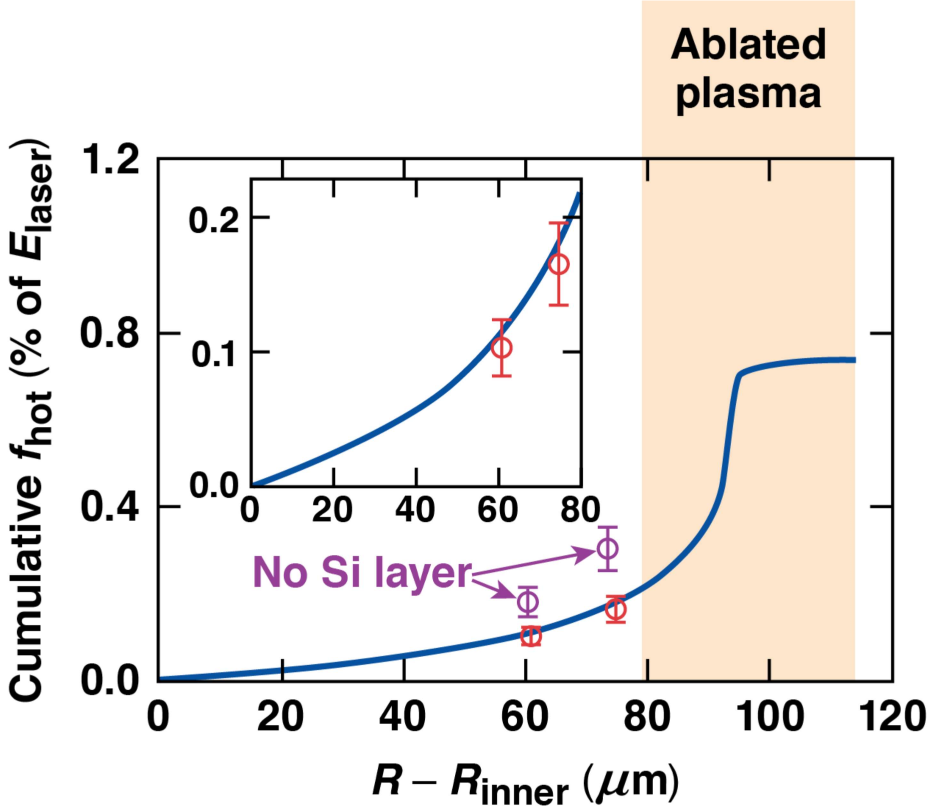
Identical LPI/hot e^- source

Different HXR emission

Hot electron preheat in NIF implosions is inferred to be ~0.2% of l over the inner ~80% of unablated shell, and ~2x lower with Si laye

Incident intensity = 10^{15} W/cm^2

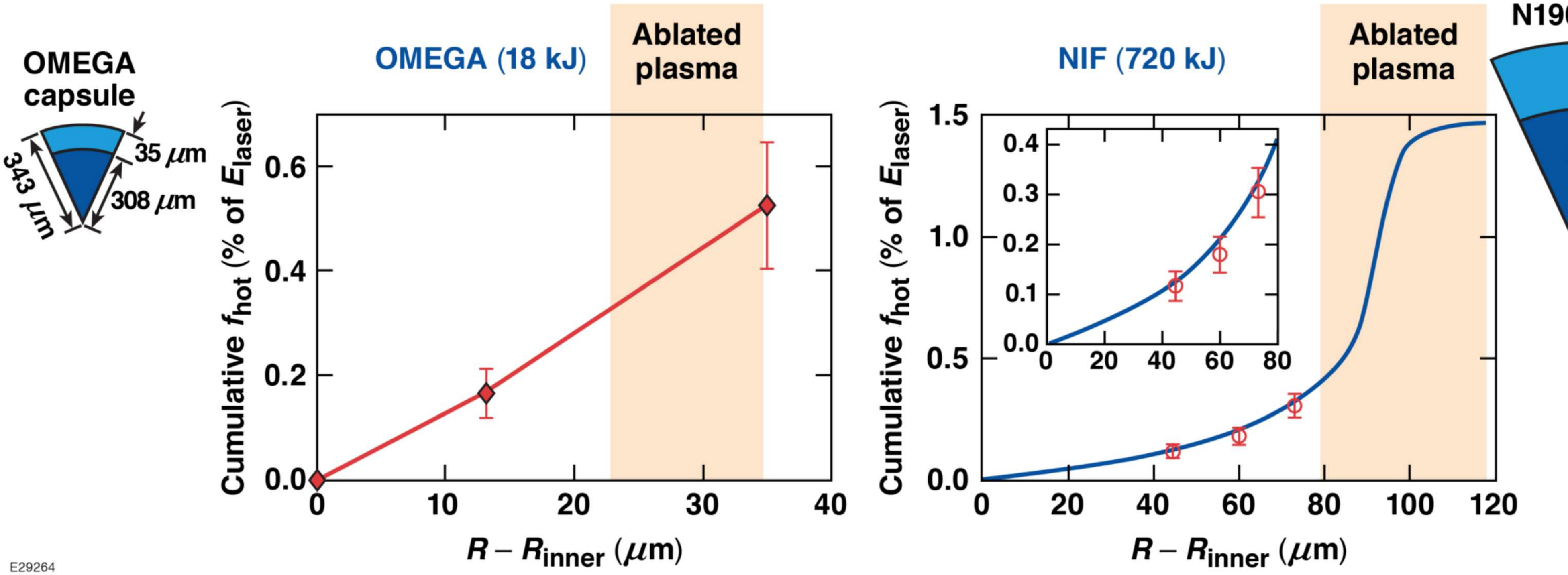




Analysis: A. Solodov

This level of preheat is close to ~0.15% limit for direct-drive ignition des

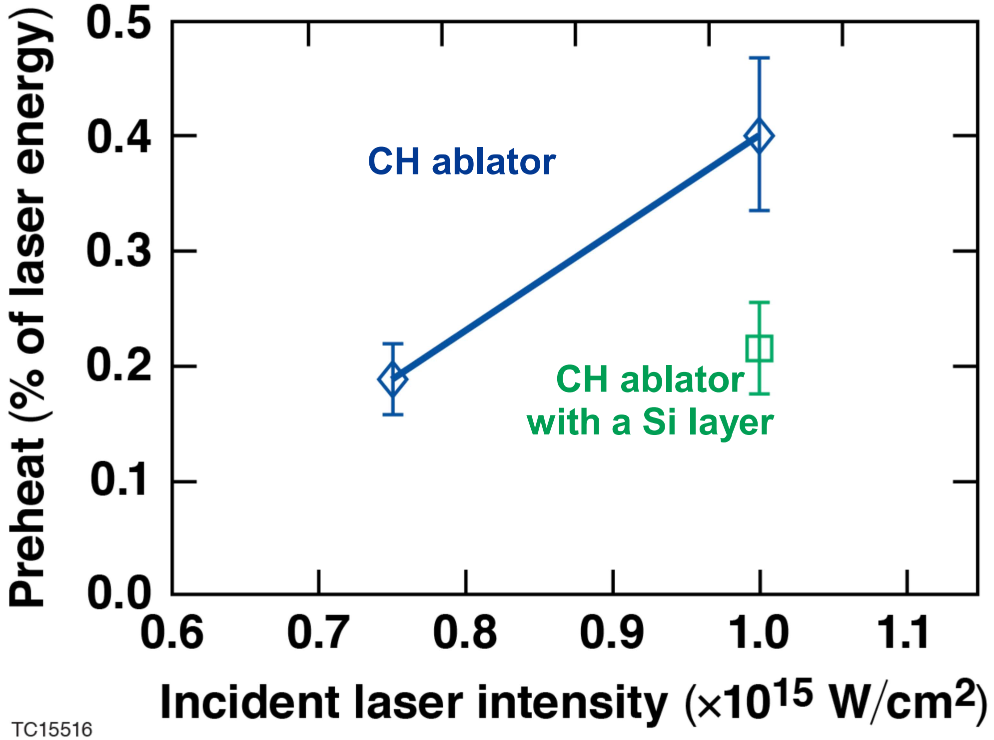
Hydrodynamically-scaled version of this experiment on OMEGA s similar fraction of laser energy coupled to the inner shell as prehe



E29264

These results support validity of hydro-scaling in warm implosions, though hot electron attenu outer ablator is important and will have to be accounted for in cryogenic implosions with ab

The goal of NIF experiments is to determine the parameter regime (e.g. intensity) that produces acceptably low preheat


Hot-electron energy deposited in the unablated shell

Analysis: A. Solodov

TC15516

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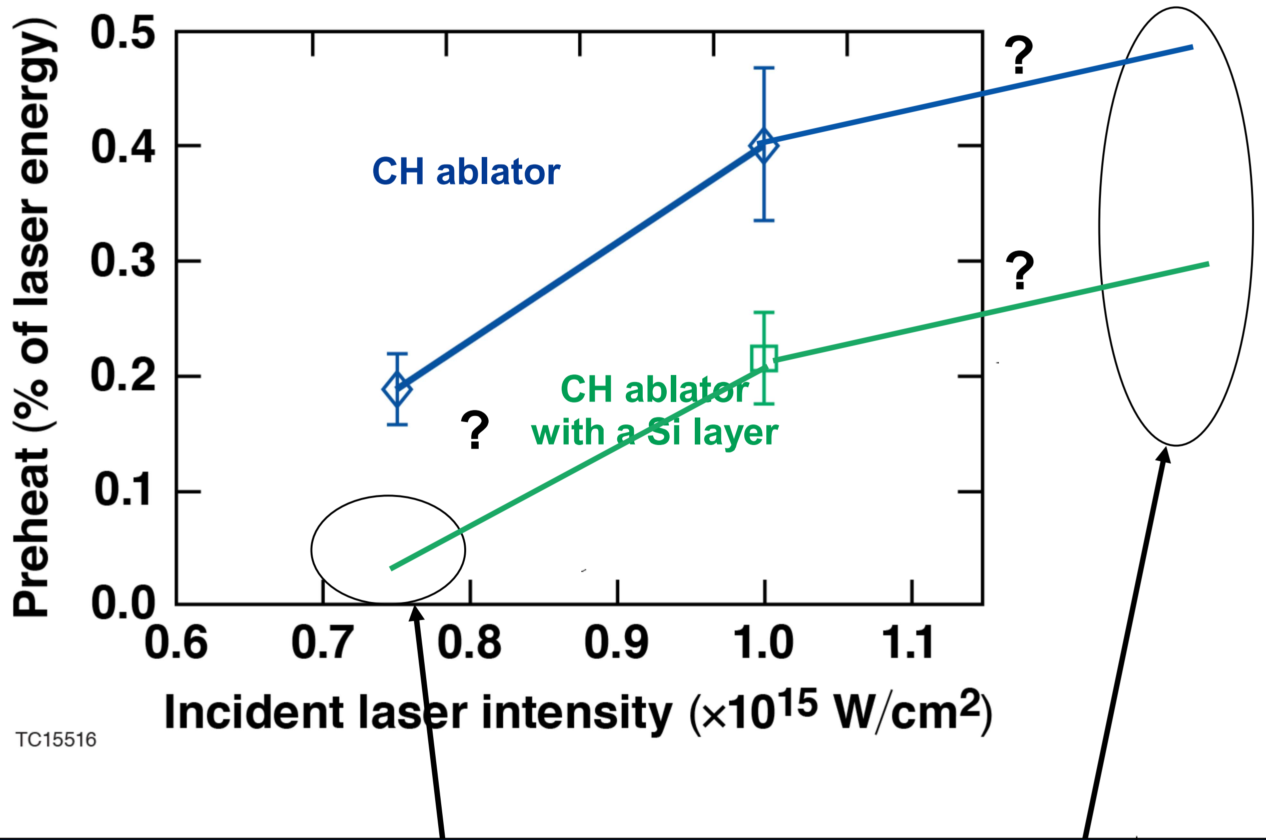
Hot-electron energy deposited in the unablated shell



Analysis: A. Solodov

TC15516

Goal of NIF experiments this year is to calculate preheat vs. intensity with and with

These data can be used to estimate likely preheat levels in ignitio scale cryogenic at 10^{15} W/cm^2 on-target intensity

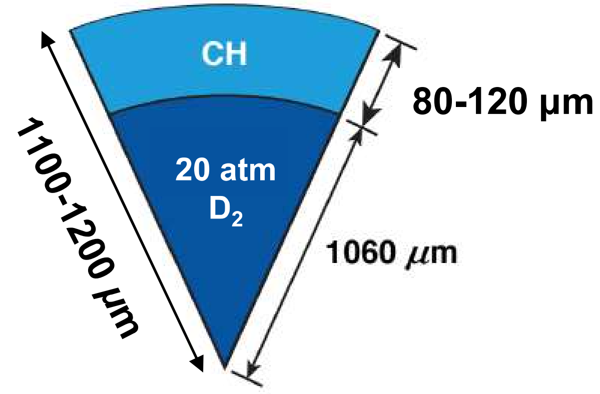
	Multiplier	Preheat (% of laser)
Preheat into inner 80% of unablated shell in warm subscale NIF implosion	-	~0.2%
Increase scale length to full scale*	~1.5-2	~0.3-0.4%
Increase convergence ratio at end of pulse	~0.4-0.8	~0.15-0.3%
DT shell and some DT in ablator	~1-1.8	~0.15-0.5%
Improve beam smoothing	~0.8	~0.12-0.4%
Si layer	~0.5	**~0.06-0.2%**
Total		**~0.1-0.2%?**

On-target intensity close to 10^{15} W/cm^2 looks to be OK (so far) for preheat – further experiments are planned to study effect of convergence, mitigation with Si dopant, and ignition-scale capsules

Note: current preheat results are near-“worst case scenario” given poor beam smoothing

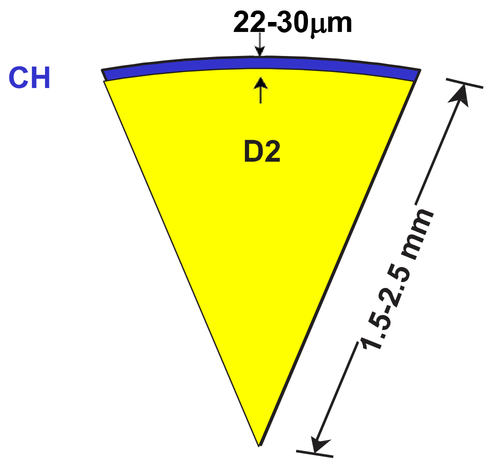
Energy coupling/symmetry experiments have been conducted in spherical-geometry platforms at a variety of convergence ratios

PDD implosion platform (CBET/Δλ)



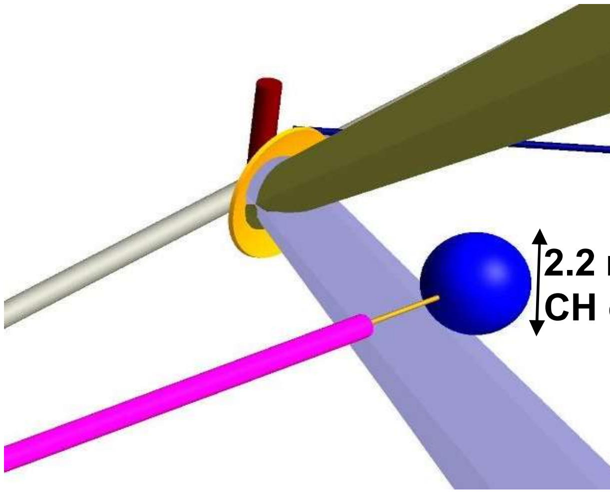
CR ~12

“Exploding pusher” platform



CR ~7

**Solid spher
radiography pla**



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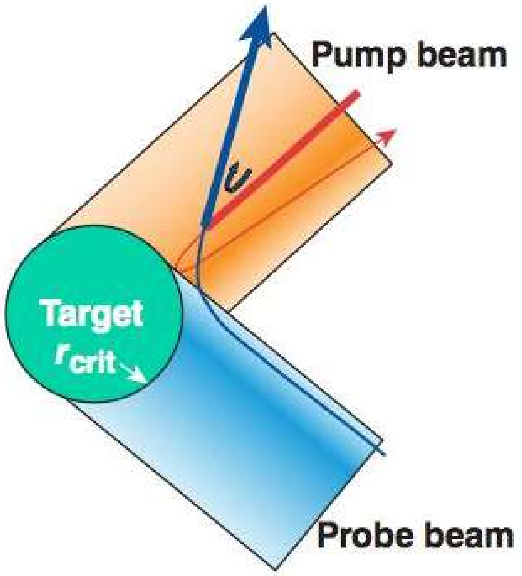
Integrated implosion experiment

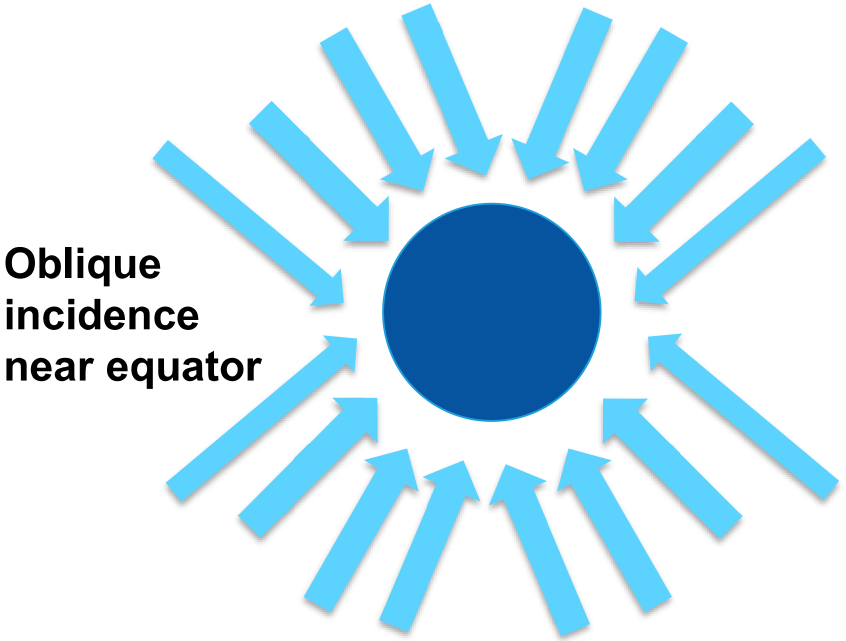
**Focused
coupling ex**

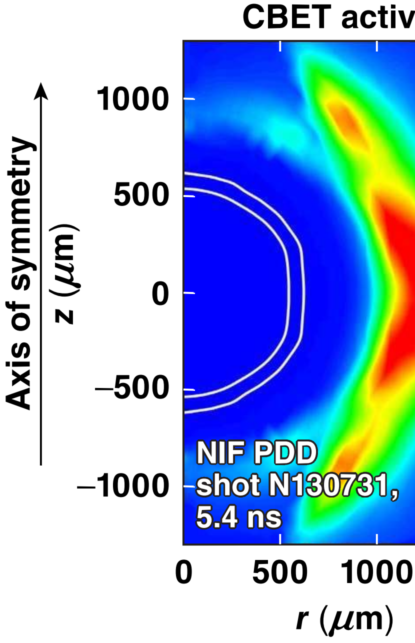
In polar direct drive (PDD) implosions, cross-beam energy transfer (CB
a primary energy loss mechanism and occurs predominantly near the e

CBET is the transfer of laser energy from ingoing (pump) rays to outgoing (probe) rays



PDD illumination geometry



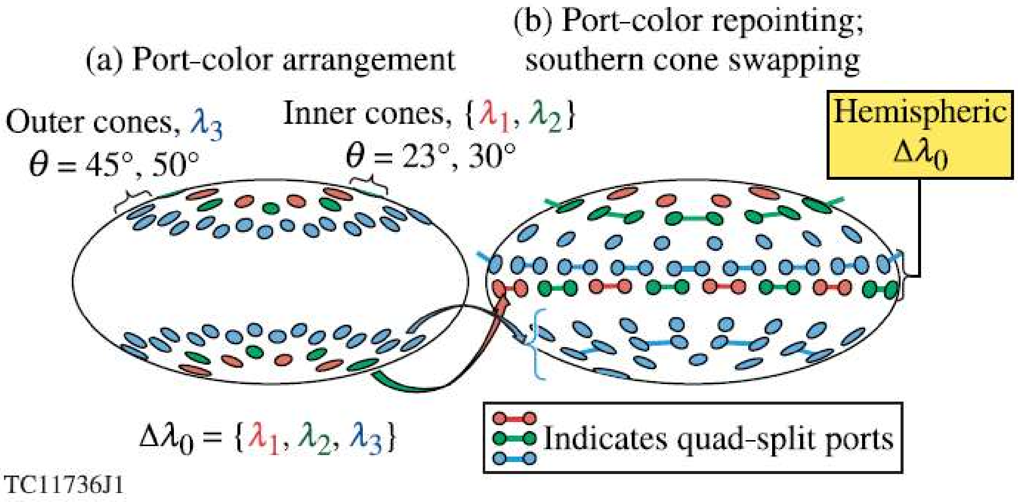


Wavelength detuning (Δλ) between interacting beams is one option for CBET

P. B. Radha *et al.*, *Phys. Plasma*

PDD implosions used cone-swapping to produce hemispheric wavelength detuning across the equator

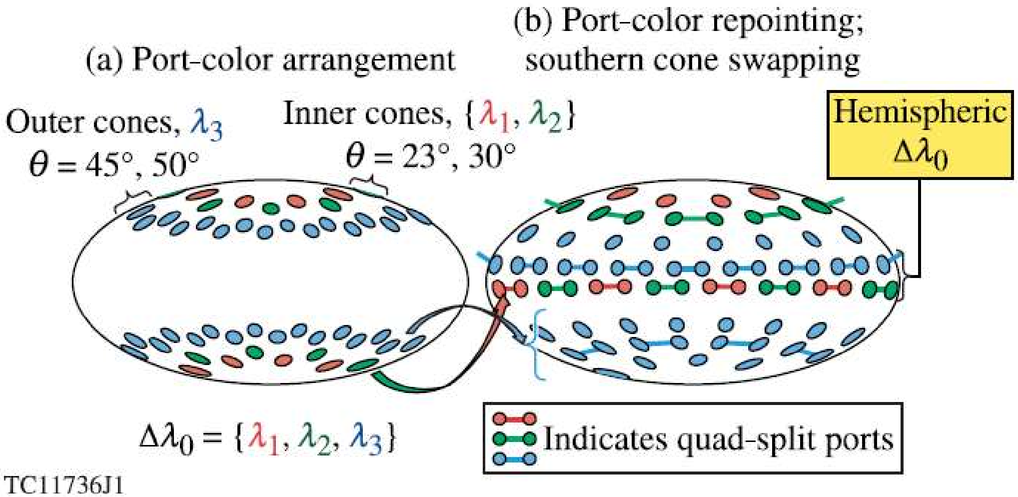
Cone-swapping for Δλ across the equator



Design and simulations: J. Marozas
X-ray analysis: M. Hohenberger and D. Turnbull

PDD implosions with hemispheric ±2.3 Å (UV) demonstrated partial mitigation of CBET, as predicted by 2D DRACO simulations

Cone-swapping for Δλ across the equator



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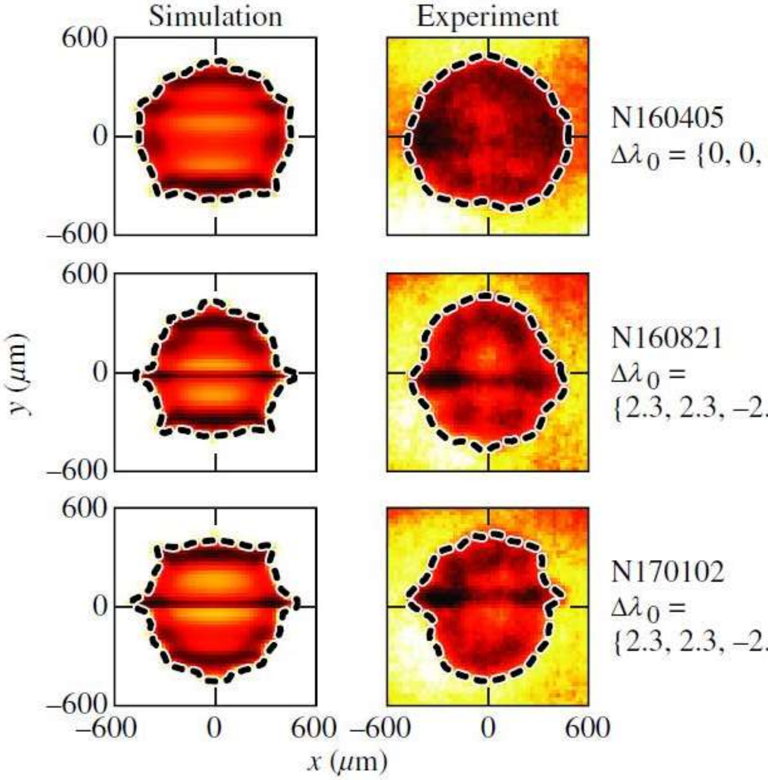
Design and simulations: J. Marozas
X-ray analysis: M. Hohenberger and D. Turnbull

X-ray radiographs

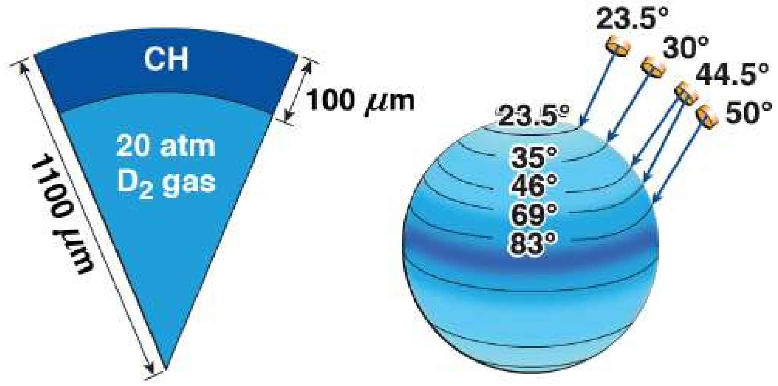


- ±2.3 Å (UV) is current NIF limit – need >±3 Å, ideally ±6 Å for greatly enhanced energy
- Flexible color/port-mapping will be implemented in 2022 to avoid cone-swapping and

J. A. Marozas *et al.*, *Phys. Rev.*

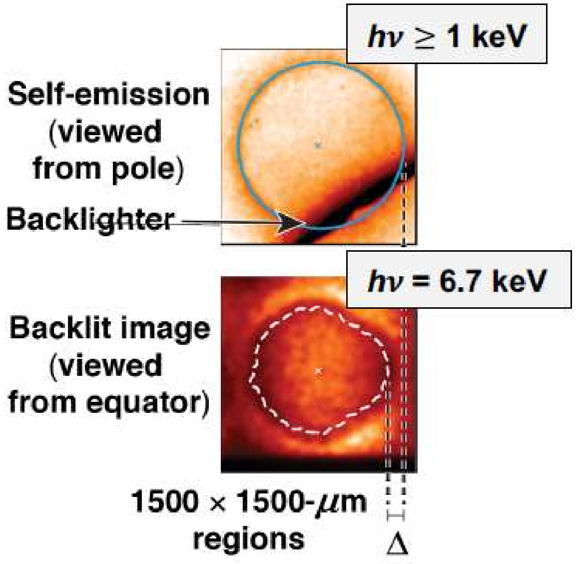
One problem for implosions is that we have been unable to simultaneou the ablation front and inner shell trajectories – shell puffing up due to i

NIF PDD implosion
(0.65 MJ, 1.2 x 10^{15} W/cm^2)



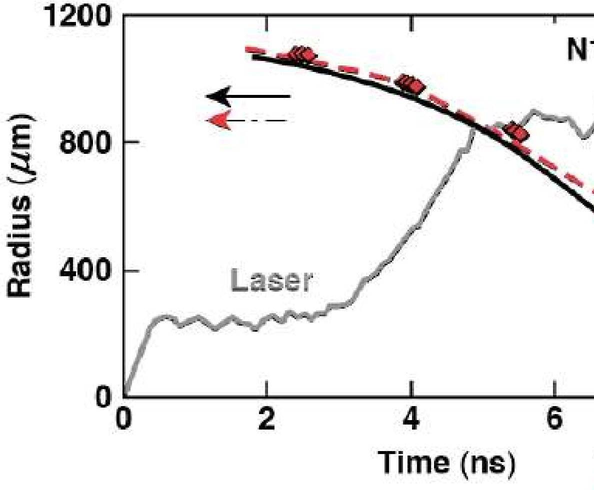
TC11724d

Measured gated x-ray images
(dx = 30 μm, dt = 100 ps)



TC11725e

Shell trajector



$E_{\mathrm{min}} \propto V_{\mathrm{imp}}^{-6}$

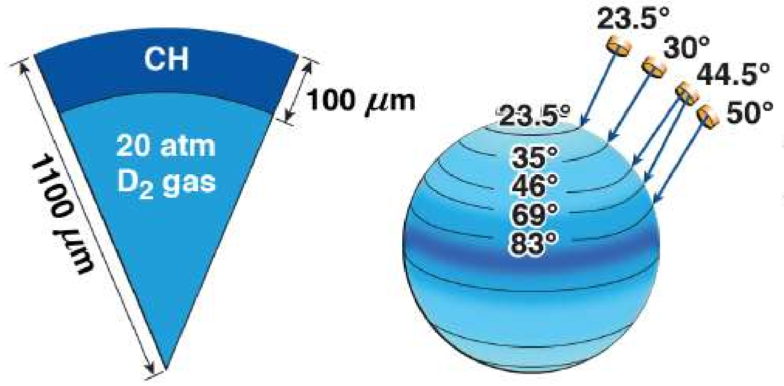
Backlit image: V_{imp} matches within 1%
Self-emission image: V_{imp} overpredicted by 9%, attributed to imprint and Rayleigh-Taylor

Concern about imprint has led our energy coupling campaign to lower convergence

P. B. Radha *et al., Phys. Plasma*

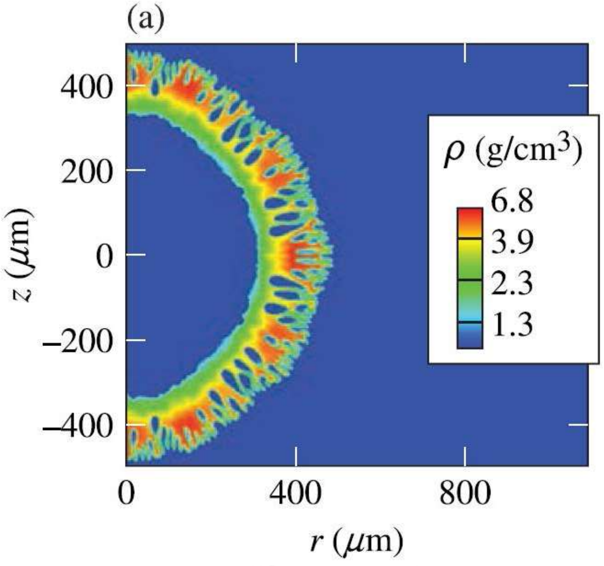
One problem for implosions is that we have been unable to simultaneou the ablation front and inner shell trajectories – shell puffing up due to i

NIF PDD implosion
(0.65 MJ, 1.2 x 10^{15} W/cm^2)



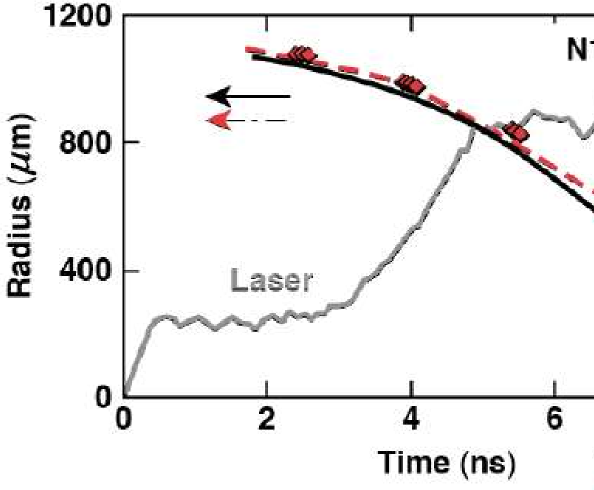
TC11724d

2D DRACO simulated density
(with laser imprint)



TC11725e

Shell trajectory



$E_{\mathrm{min}} \propto V_{\mathrm{imp}}^{-6}$

Backlit image: V_{imp} matches within 1%

Self-emission image: V_{imp} overpredicted by 9%, attributed to imprint and Rayleigh-Taylor

Concern about imprint has led our energy coupling campaign to lower convergence

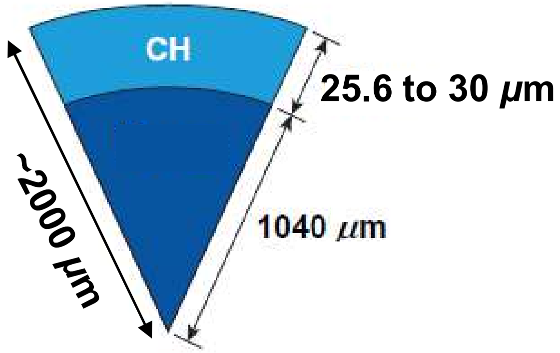
P. B. Radha *et al., Phys. Plasma*

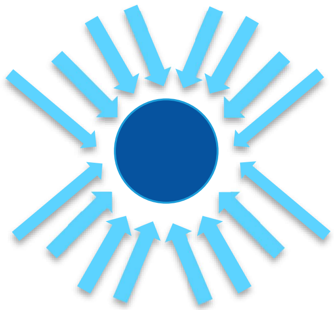
Lower convergence implosions, less sensitive to imprint, are now bein assess/improve energy coupling and symmetry

Parameter	“Standard” implosions	“Exploding pushe
Shell diameter	2.3 mm	3-5 mm
Shell thickness	120 μm	25 μm
Primary implosion mechanism	Ablation/compression	Shock
Convergence ratio	~12	~7
Physics issues	Laser energy coupling Hydro instabilities (e.g. imprint-seeded RT)	Laser energy coup [less susceptible t instabilities]

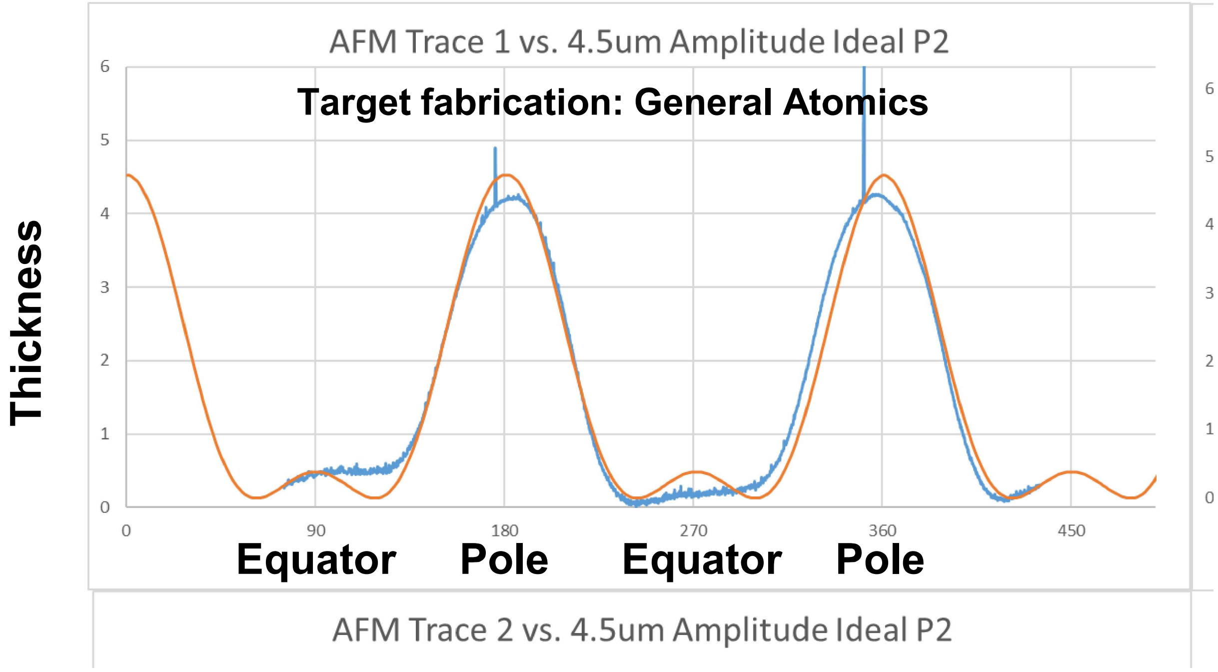
Exploding pusher experiments studied shell contouring as a means to implosion symmetry and improve energy coupling along the equator

800 kJ, 280 TW laser drive





Shell contoured designed based on 2D DRACO simulations of previous experiment



Shell thicker near the poles,
thinner near the equator

Design: P. Mc

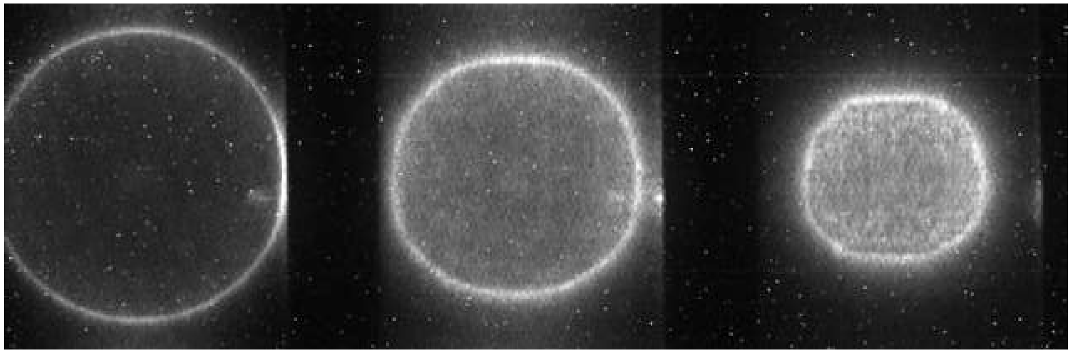
The contoured shell eliminated a 5% in-flight P2, in agreement with pos simulations

X-ray self-emission images

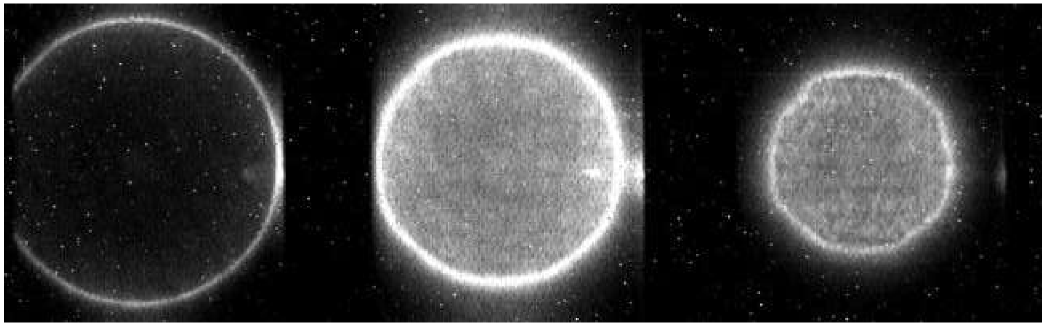
Equatorial (90-124) view

t~2 ns t~3 ns t~4 ns

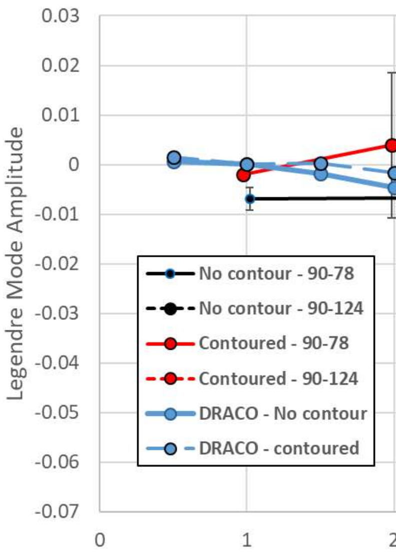
N200715-001: without contour



N201021-002: contoured shell



Measured and simula



Simu

The effect of the shell contour on performance was likely positive*, though complicated by differences in gas pressure

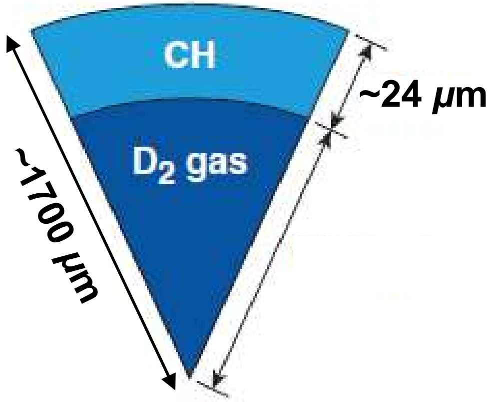
Parameter	N200715-001	N201021-002
Shell contour	No	Yes
Laser energy	785 kJ	804 kJ
Gas pressure	6.57 atm	5.46 atm
DD-n yield	1.1e12	1.1e12

***Yield was the same, but this is likely attribute
gas pressure on the shot with the contour, wh
suggest caused a ~30-40% drop in yield**

Energy coupling/symmetry

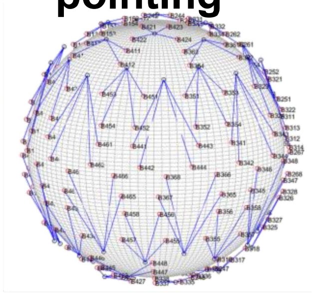
Recent experiments demonstrated control of symmetry and energy cou through laser pointing and pulse shaping

Exploding pusher
~700 kJ
~280 TW

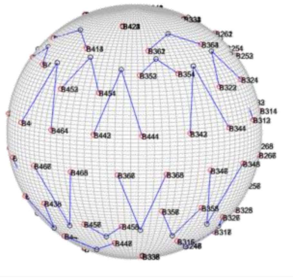


Design: J. Marozas

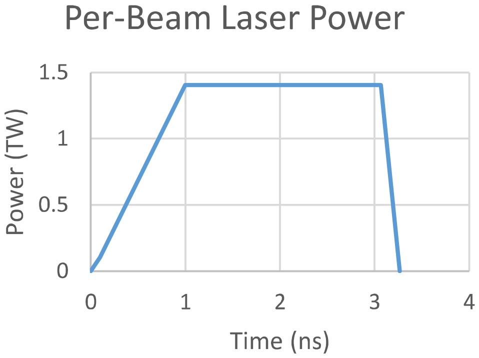
SAGE (old) pointing



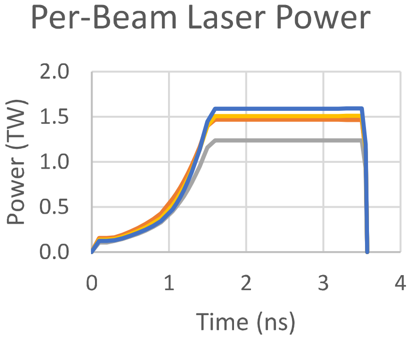
DRACO (new) pointing



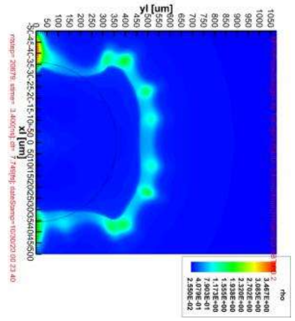
N201220-002



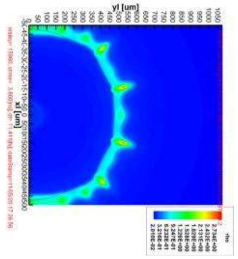
N201220-001



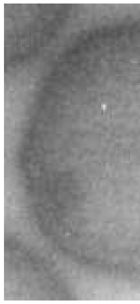
DRACO pre-shot 3.4 ns



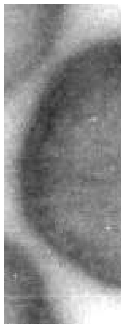
DRACO pre-shot 3.8 ns



t



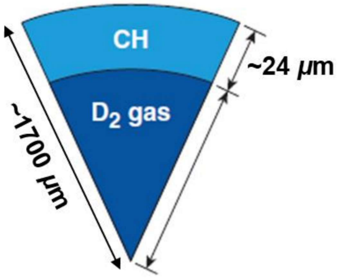
t~



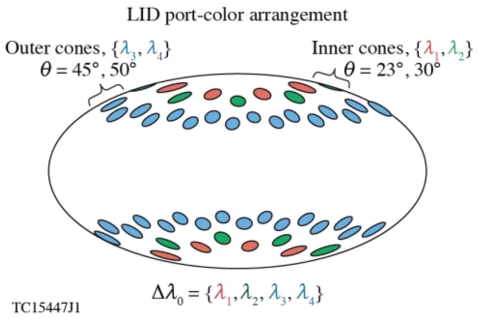
Yields were the same ~4.5e13; DRACO predicted 001 ~9e13, 002 ~5e13; shape improve translate to expected improvement in yield – post-shot simulations suggest laser imprint

Upcoming experiments will test a new flexible color/port-mapping capa more effectively mitigate CBET in PDD using wavelength detuning

Exploding pusher
~700-800 kJ
~270-300 TW



Current color/port-mapping (symmetric about the equator)



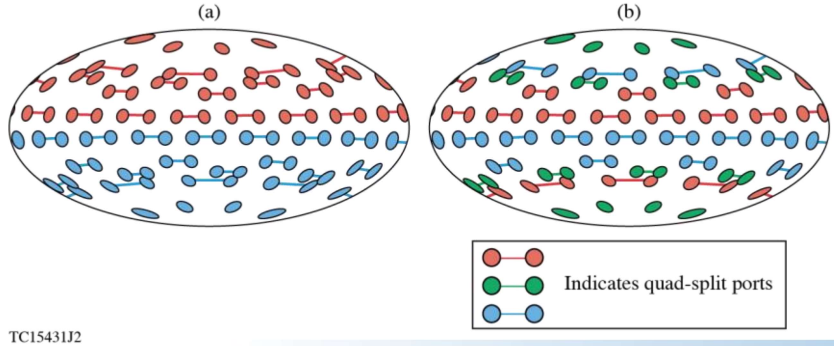
fC2Pm Config TriColor-BiColorHemi	North→Eq	Eq→South	f_{abs}
Bi-color	RRRR	BBBB	Pendi
Tri-color Var#1	GGBB	RRGG	79.1
Tri-color Var#3	BBBG	RRGG	82.1

*Δλ = ±4.5 A (

Options for flexible color/port-mapping

Bi-color hemispheric

Tri-color (example)

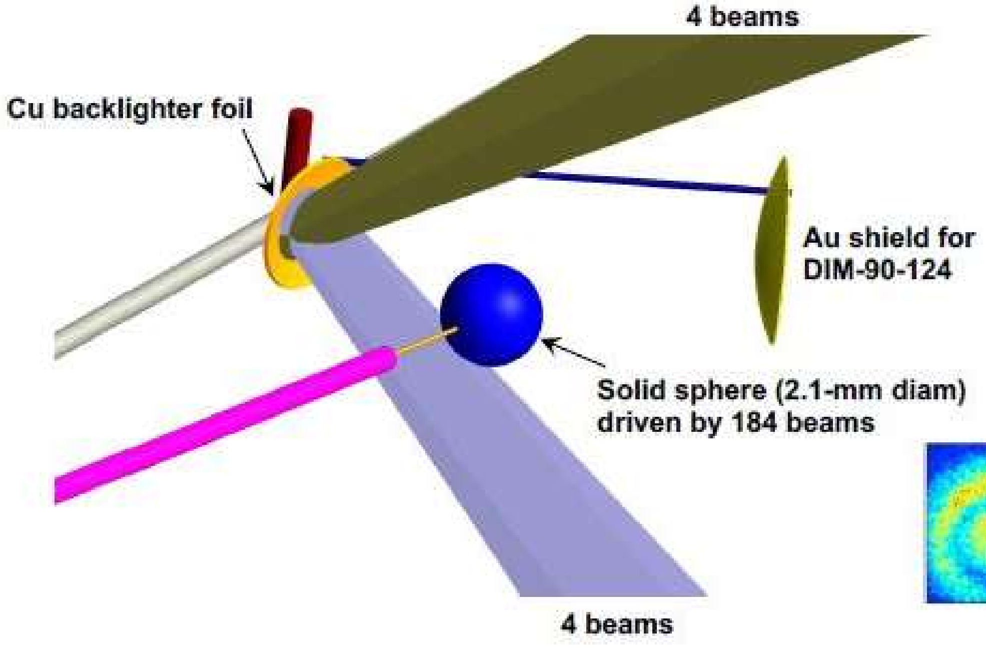


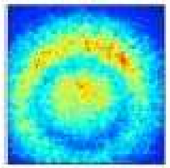
Design: J. Marozas (LLE)

TC15431J2

Solid spheres are completely impervious to imprint and provide an isol test of energy coupling and CBET modeling

Solid sphere radiography platform design

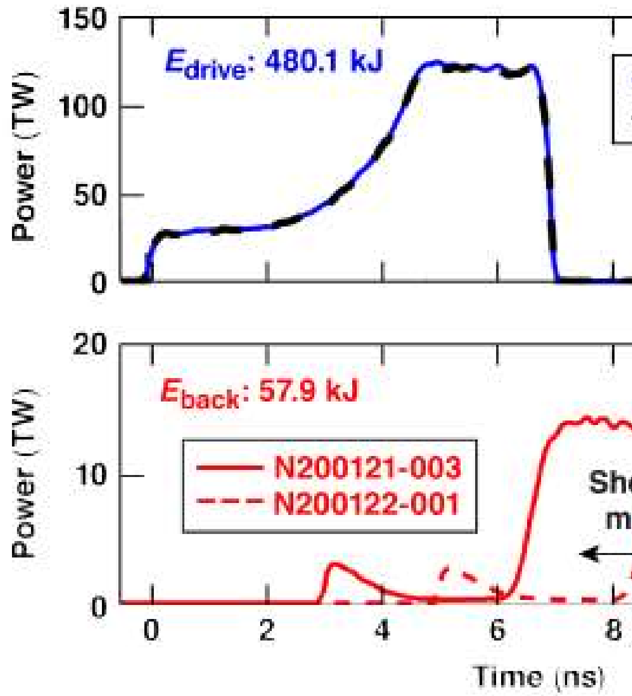




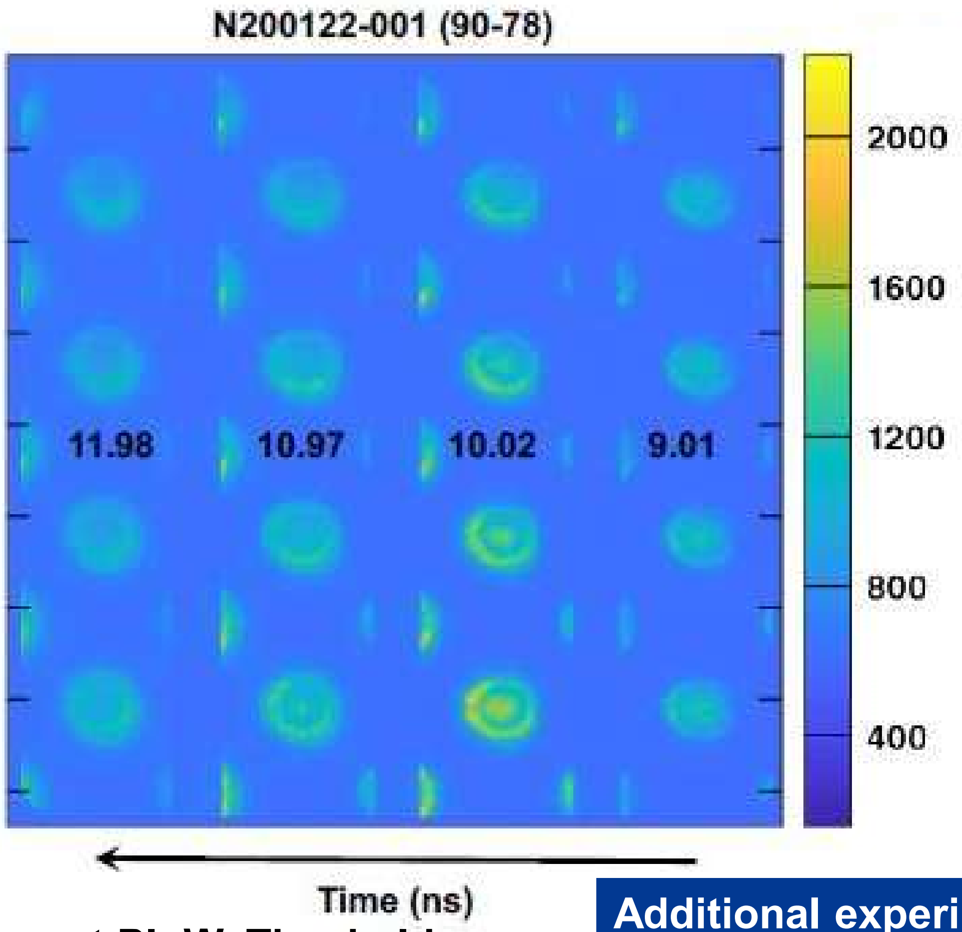
Time-resolved x-ray radiograph of spherical shock wave

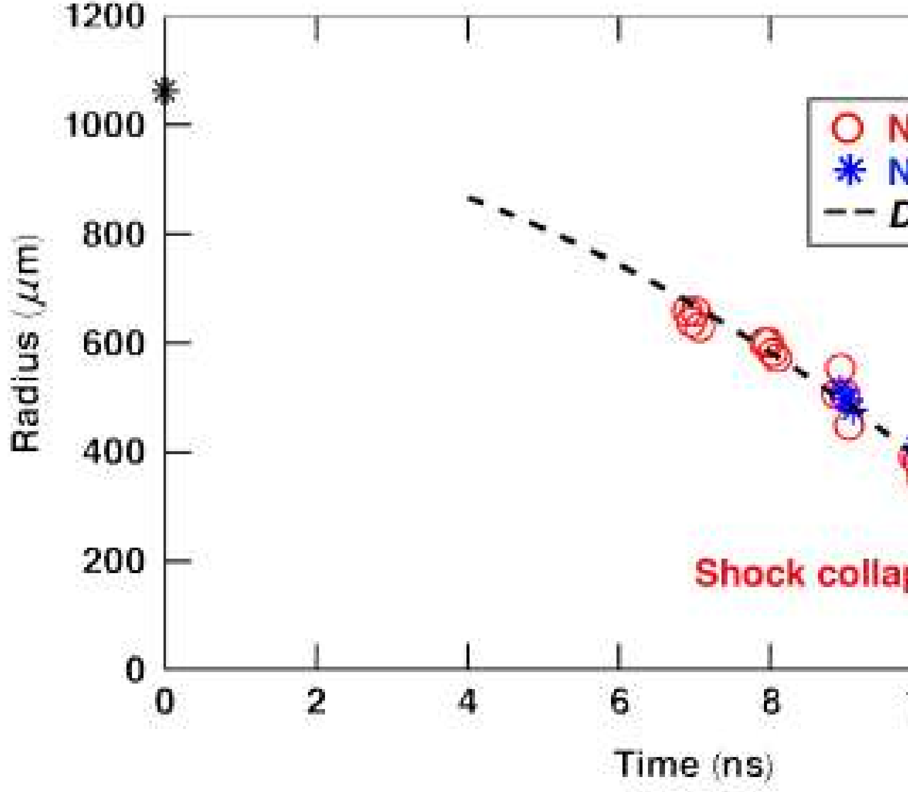
Experiment PI: W. Theobald
Designer: R. Bahukutumbi

Laser dri
($8x10^{14}$ W/cm^2 intens



Shock trajectory inferred from radiographs and x-ray flash time are in good agreement with 2D DRACO simulations



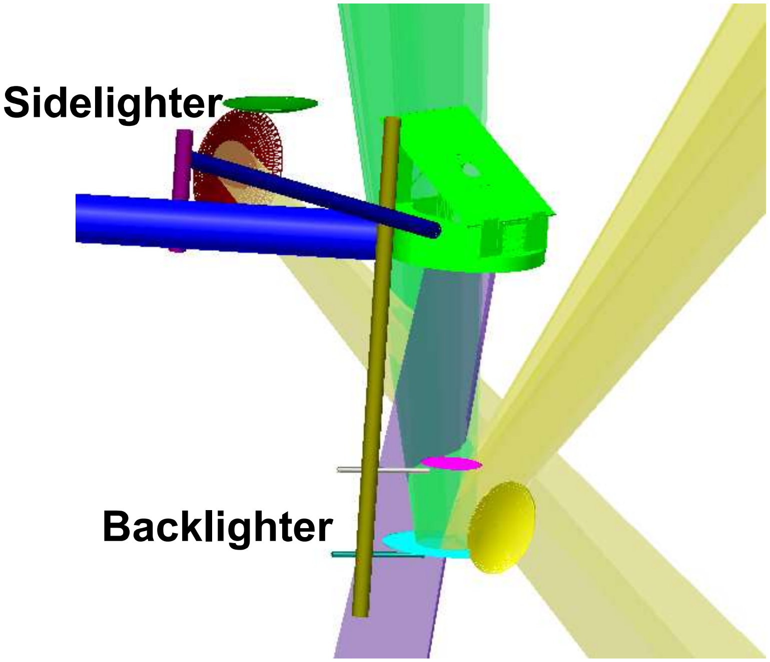


Experiment PI: W. Theobald
Designer: R. Bahukutumbi

Additional experiments will scan laser intensity and test modeling
scaled versions of these experiments are planned for

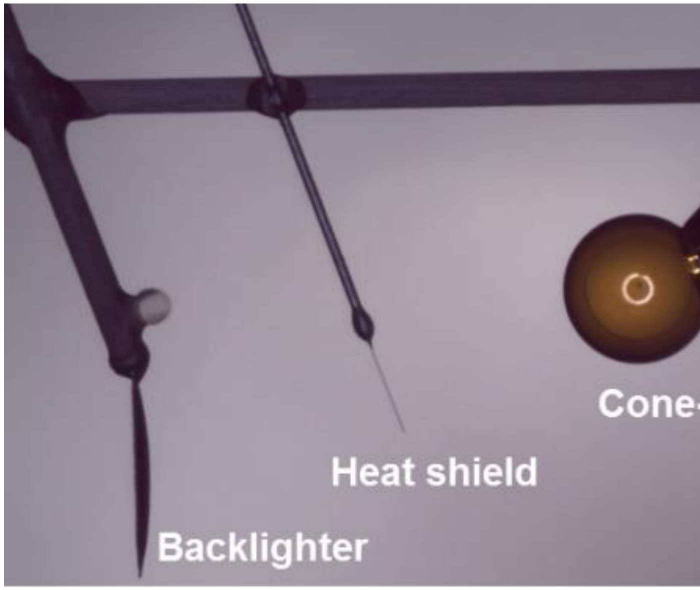
Laser imprint experiments are conducted on NIF to benchmark m
and develop mitigation techniques

Planar Imprint Platform



Experimental PI: M. Hohenberger (LLNL), M. Rosenberg
Theory PI: A. Shvydky

Spherical Imprint Platfor

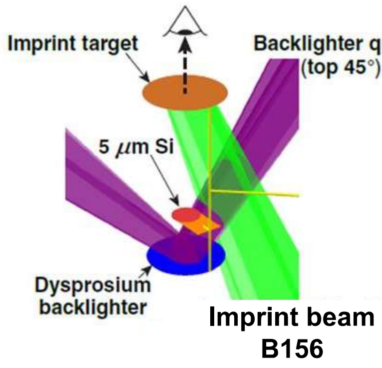


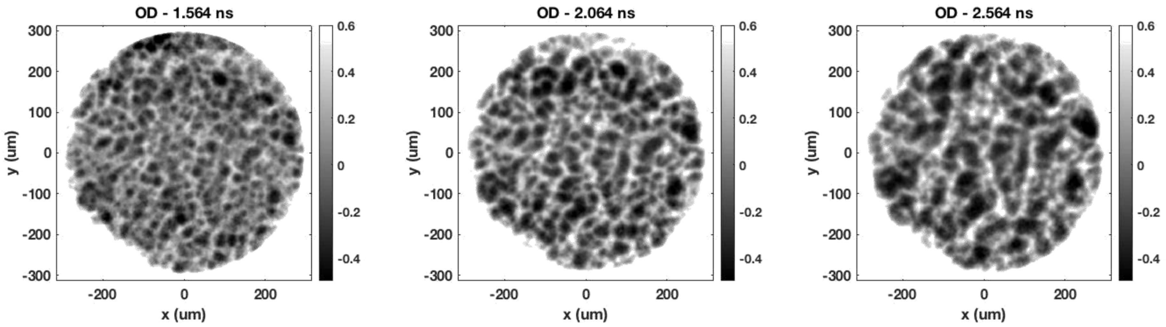
Experimental PI: M. Karasik (N
Theory PI: A. Shvydky

Ultimate goal is to set requirements for laser and/or target solutions for imprint mitigation (how much/what is needed?)

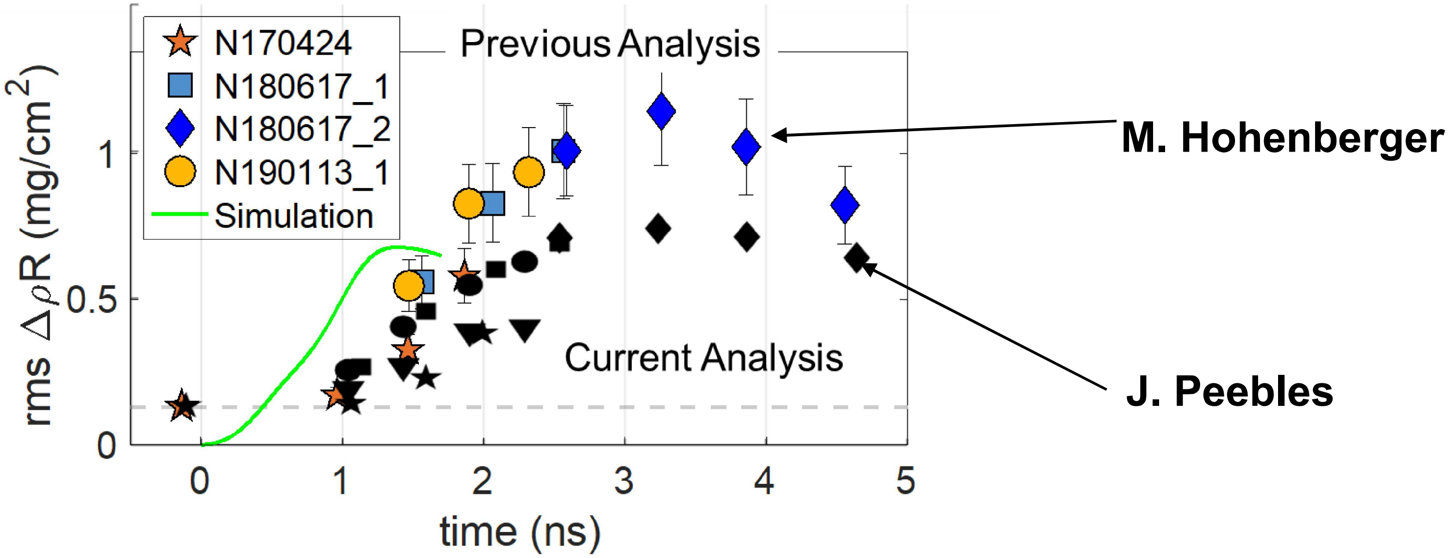
Imprint

Planar single-beam imprint experiments have produced excellent data t imprint calculations – a discrepancy is observed (depending on analysi





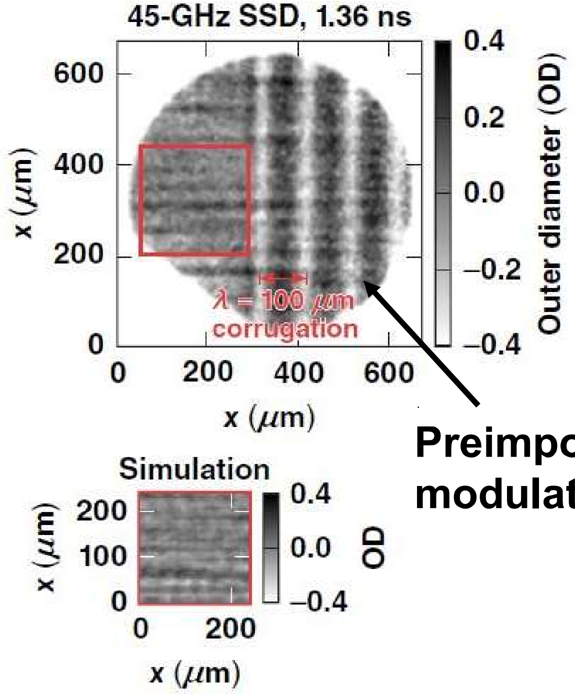
RT bubble m
imprint is vis
HYDRA predi
and earlier/lo
observed exp



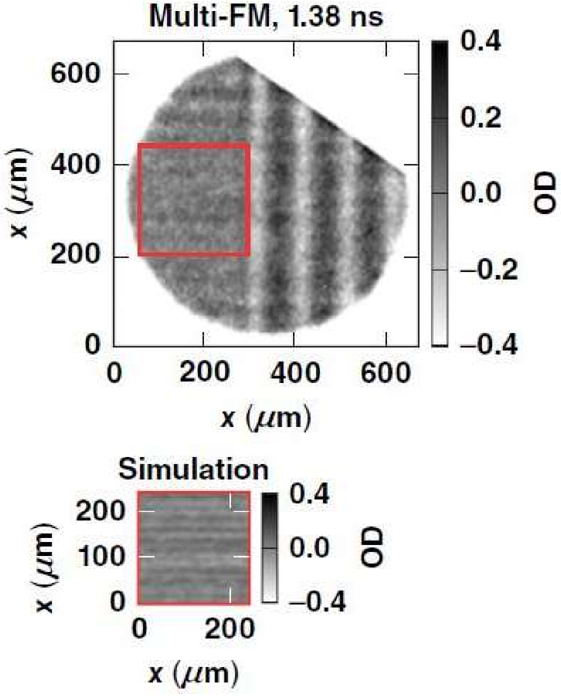
Analysis: M. Hohenberger (LLNL), J. Peebles, L. Antonelli (York)
Simulations: A. Shvydky

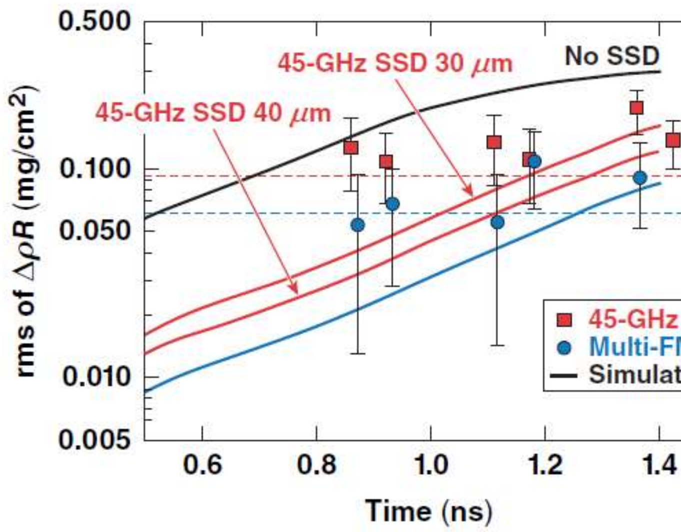
Sidelighting was developed to validate modeling

Imprint mitigation using multi-FM SSD on 1 quad was demonstrated in planar geometry



Preimposed modulation



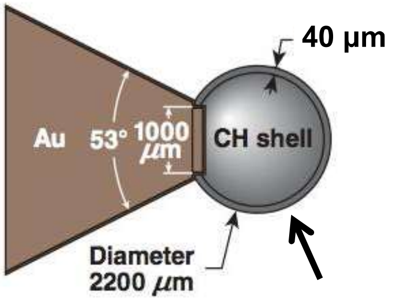


Experiment/analysis: M. Hohenberger (LLNL)
Simulations: A. Shvydky

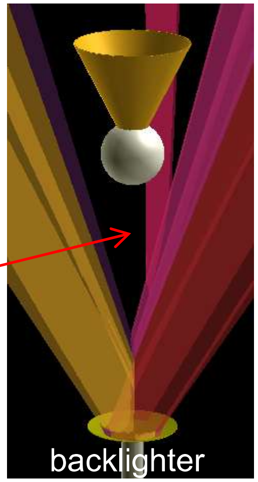
A next step for the imprint campaign may be the use of Fresnel zone plate imaging to achieve ~5 μm resolution (vs. 15 μm now)

Imprint

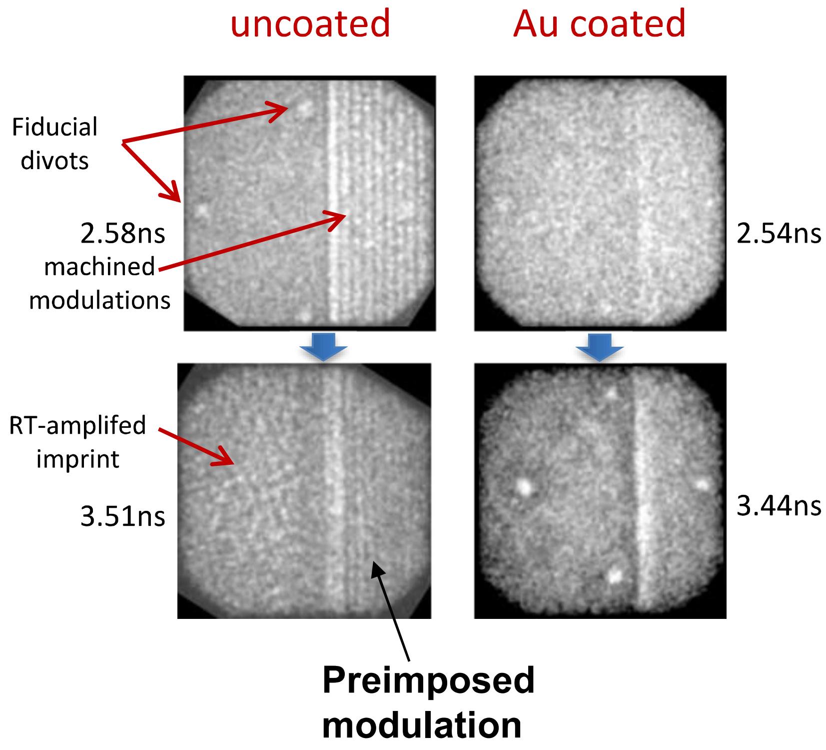
Cone-in-shell imprint experiments are assessing imprint from multiple overlapping beams and testing high-Z overcoats

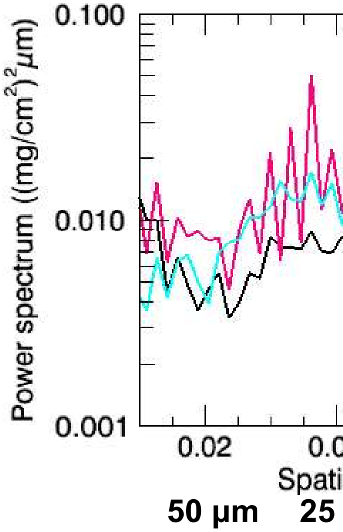


400 Å Au coating
or uncoated



early beam for
soft x-ray prepulse
to expand the
coating
200J, at -10ns





Experiments/analysis: M. Karasik (NRL)
Design: A. Shvydky

Reduced growth of ~20-50 μm
further analysis is o

Imprint mitigation with high-Z overcoat: Karasik *et al. Phys. Plasmas* 28, 032710 (2021)

MJDD Campaign – what have we learned so far?

- Energy coupling/symmetry/CBET: symmetry and energy coupling can be controll
  wavelength detuning, shell contouring, and beam pointing
  - *Next steps:* test flexible color/port-mapping wavelength detuning, solid spher
    experiments to benchmark modeling at different intensities/# of shocks

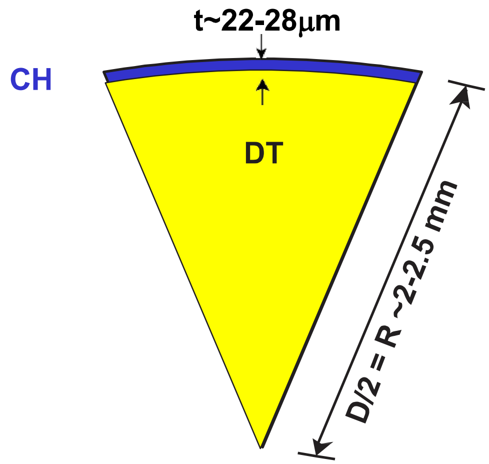
- LPI/preheat: SRS is the predominant hot electron source; preheat is close to toler
  levels for intensity ~10^{15} W/cm^2; Si layers are an effective mitigation strategy
  - *Next steps*: experiments to aid extrapolation of preheat in ignition-scale cryo

- Laser imprint: we have two good platforms for studying imprint and imprint mitig
  multi-FM SSD and high-Z coatings have some effect
  - *Next steps*: Benchmarking 3D calculations of imprint; higher imaging resolut
    other target solutions for imprint mitigation?

Outline

- Laser direct-drive inertial confinement fusion
    - Scaling and motivation for NIF experiments
- MJDD experiments on NIF
    - LPI/hot electron preheat
    - Laser energy coupling/CBET/PDD symmetry
    - Laser imprint
- **Current high-yield PDD implosions and pathway to MJ yield**

Current high-yield PDD implosions ("exploding pushers") are conducted with t LLE/LLNL Neutron Sources Working Group, and have routinely produced yield



High-yield PDD experiments

Shot	E [MJ]	P [TW]	Length [ns]	D [mm]	t [um]	SSDbw [GHz]	P [at
N190227-001	1.1	400	3.7	4	25	90	8
N191020-001	1.6	430	4.6	4	29	90	8
N191027-003	1.3	440	3.9	4	23	90	8
N201128-001	1.6	470	5.1	5	24	45	6
N201221-002	1.8	480	5.0	5	22	45	6
N210213-001	1.8	490	4.6	5	23	45	6
Next shot	1.9	450	5.0	5	28	90	8

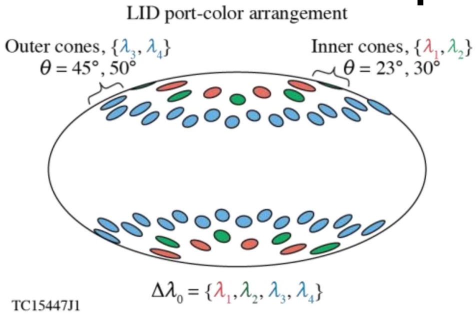
Experiments: C. Yean
Designs: G. Kemp (LL

Near-term goal: 2x10^{16} (~50 kJ)

Yeamans *et al. Nuclear Fusion* 61, 046031 (2021)

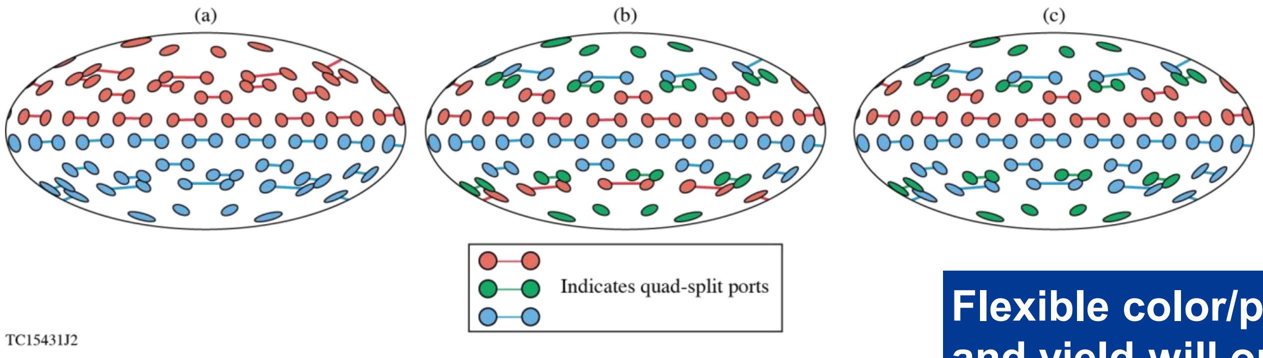
Near-term improvement in wavelength detuning (flexible color/port mapping in will facilitate better energy coupling and performance in PDD implosions

Current color/port-mapping (symmetric about the equator)



Options for flexible color/port-mapping

Bi-color hemispheric **Tri-color** **Balanced tri-color**



Configuration	Pulse shape	Energy (MJ)	Total peak power (TW)	Abs fract
N190227 {reference sim.} => $[N190227]_{ref}$	ramp2FT	1.1	385	8
$[Mod2]_{ref}$ and ±3 Å UV with fC2Pm	exp2FT	1.1	395	8
$[Mod2]_{ref}$ and ±4.5 Å UV with fC2Pm	exp2FT	1.1	395	8
$[Mod2]_{ref}$ and ±6 Å UV with fC2Pm	exp2FT	1.1	395	9

Design: J. Marozas

Flexible color/port-mapping is helpful, but significant g and yield will only be realized when wavelength detuni > ±3 Å UV (currently limited to ±2.3 Å UV)

Proposed NIF facility improvements go hand-in-hand with steps u convergence and implosion performance (i.e. yield)

1) Current NIF
   - Low-convergence (CR≤10) implosions (“exploding pushers”)
   - Physics goal: optimize symmetry in current NIF, validate code
   - Yield: 50 kJ (~2e16)

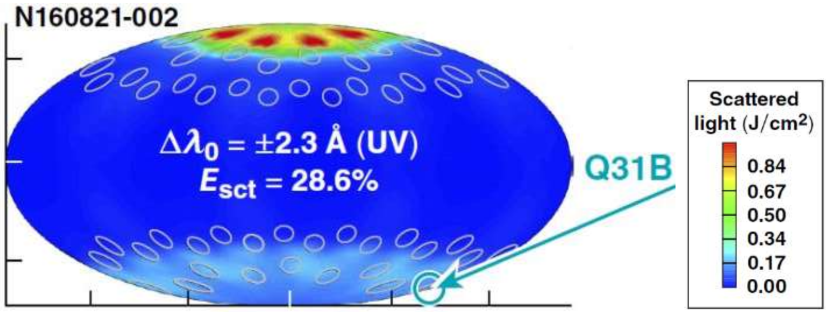
2) Flexible color/port-mapping, ±6 Å UV, and PDD phase plates (~mid
   - Low-convergence (CR≤10) implosions (“exploding pushers”)
   - Physics goal: improve symmetry, absorption >85%
   - Yield: 100 kJ (~4e16)

3) PDD cryogenic target system, beam smoothing (~late 2020s)
   - Warm and cryogenic ablatively-driven implosions (CR~15-20)
   - Physics goal: increased compression, alpha heating, burning
   - Yield: 300 kJ (~1e17) to 1 MJ (~4e17)

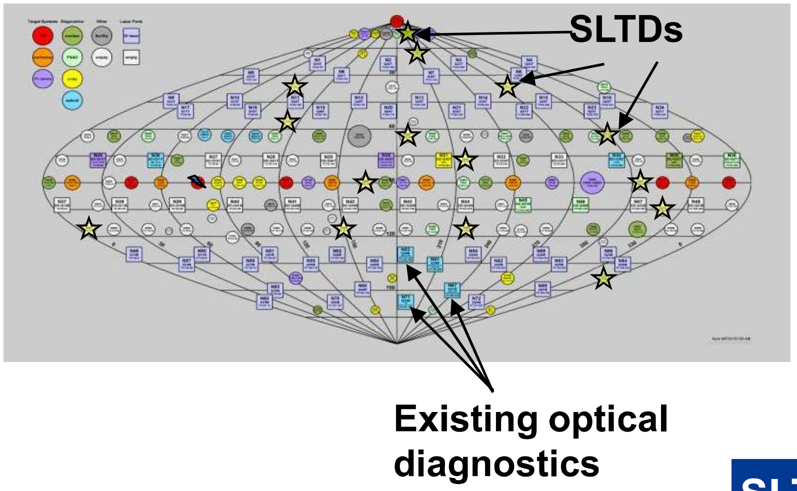
LDD 2020 Report, Physics goals #1-4

New diagnostics will contribute to improved understanding, e.g. s light diagnostics (SLTD) at a variety of angles

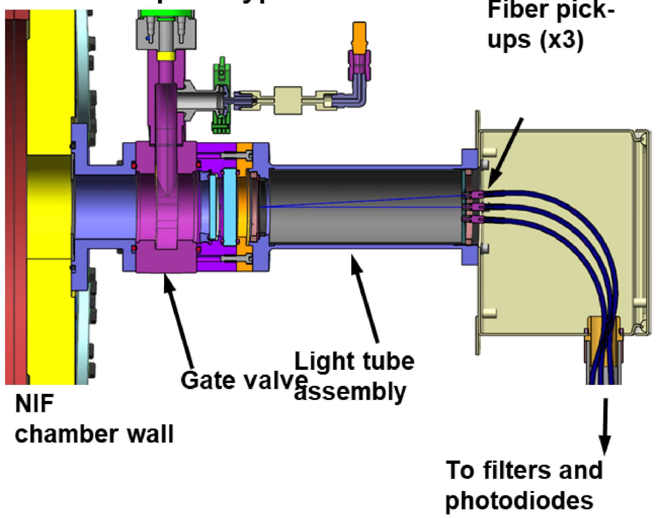
PDD implosion
Simulated scattered light



NIF chamber map

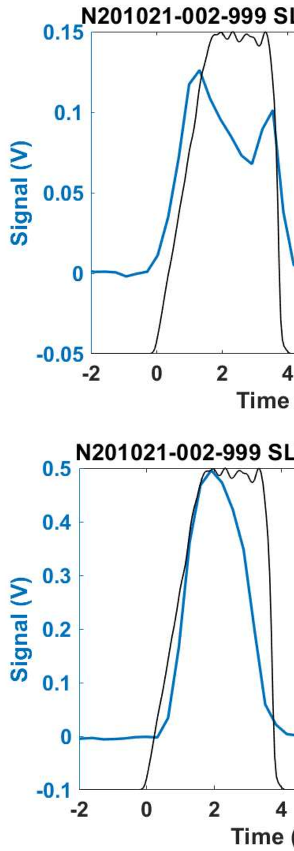


SLTD prototype schematic



SLTD schedule	
1 SLTD unit	April 2018
6 SLTD units	August 2019
11 SLTD units	January 2021
15 SLTD units	Late 2021

SLTD sam



SLTD suite will constrain modeling of scattered light angular distr and facilitate inference of total scattered light in direct-drive expe

Rosenberg *et al. Rev. Sci. Instrum.* 92, 033511 (2021)

Summary/Conclusions

Current MJ-scale experiments lay the groundwork for high-yield direct-drive implosions on the NIF in the 2020’s

- Extrapolation of direct-drive implosion performance from OMEGA to ignition scale on dedicated physics experiments at NIF scale

- The MegaJoule Direct Drive (MJDD) campaign on NIF includes three primary phys
  1) <u>Hot electron preheat</u> has been measured at close to tolerable levels, partially m using mid-Z layers, and shown to originate from stimulated Raman scattering
  2) <u>Implosion symmetry and energy coupling (including cross-beam energy transf</u> been controlled with wavelength detuning, contoured shells, and beam pointin
  3) <u>Laser imprint</u> experiments have produced x-ray radiography data to benchmar of imprint-related instabilities and partial mitigation with multi-FM SSD or high

- Current NIF capabilities limit high-performance polar-direct drive (PDD) implosion convergence exploding pushers

A staged set of proposed facility improvements will allow for increased convergence