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Title: Maximizing 1D “like” implosion performance for inertial confinement fusion science

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Maximizing 1D “like” implosion performance for inertial confinement fusion science

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Abstract:

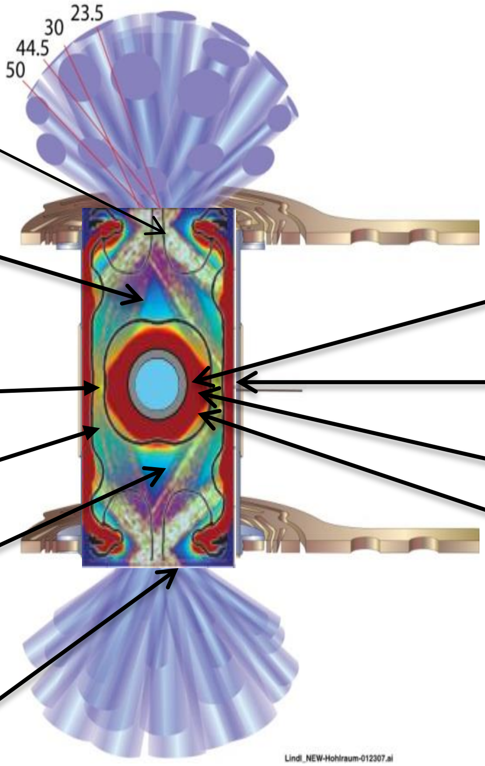
While the march towards achieving indirectly driven inertial confinement fusion at the NIF has made great progress, the experiments show that multi-dimensional effects still dominate the implosion performance. Low mode implosion symmetry and hydrodynamic instabilities seed by capsule mounting features appear to be two key limiting factors for implosion performance. One reason these factors have a large impact on the performance of ICF implosions is the high convergence required to achieve high fusion gains. To tackle these problems, a predictable implosion platform is needed meaning experiments must trade-off high gain for performance. To this end, LANL has adopted three main approaches to develop a 1D implosion platform where 1D means high yield over 1D clean calculations. Taking advantage of the properties of beryllium capsules, a high adiabat, low convergence platform is being developed. The higher drive efficiency for beryllium enables larger case-to-capsule ratios to improve symmetry at the expense of drive. Smaller capsules with a high adiabat drive are expected to reduce the convergence and thus increase predictability. The second approach is liquid fuel layers using wetted foam targets. With liquid fuel layers, the initial mass in the hot spot can be controlled via the target fielding temperature which changes the liquid vapor pressure. Varying the initial hot spot mass via the vapor pressure controls the implosion convergence and minimizes the need to vaporize the dense fuel layer during the implosion to achieve ignition relevant hot spot densities. The last method is double shell targets. Unlike hot spot ignition, double shells ignite volumetrically. The inner shell houses the DT fuel and the convergence of this cavity is relatively small compared to hot spot ignition. Radiation trapping and the longer confinement times relax the conditions required to ignite the fuel. Key challenges for double shell targets are coupling the momentum of the outer shell to the inner shell and mixing of the mid-Z material from the inner shell into the fuel. The primary theme for each of these approaches is reduced implosion convergence with the goal of achieving a 1D “like” implosion. Once established, a systematic approach to solving limiting issues for ICF can be undertaken. This presentation will discuss the approaches, results, and plans for each of these campaigns.

Establishing understandable implosions is a key step toward achieving laser based inertial confinement fusion

- A lot of progress has been made over the past few years obtaining high fuel compression and self-heating in the hot spot for ICF implosions
- However, experiments show that 3D effects are dominating performance in high velocity, high convergence implosions
  - For all ablator/target configurations
  - Low mode symmetry
  - High mode mix due to capsule mounting hardware
- Reducing implosion convergence can mitigate 3D effects and will enable a systematic approach to address these issues as we move towards ignition
- LANL has three campaigns design to establish a base in which simulation and experiments are in good agreement
  - Low Trad, High Case-to-capsule ratio beryllium capsules
  - Liquid layer targets
  - Double shell targets

Indirect Drive ICF is a complex mix of physics and engineering

Hohlraum



Peak laser Intensities

Gas fill species and optimum density

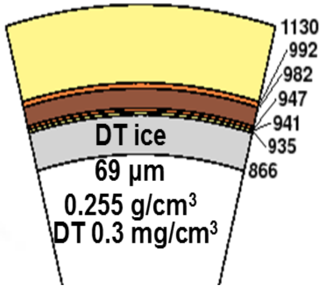
Compressed between wall and ablator blowoff (SRS)

Be ablator blowoff (SBS)

Hot Electrons

Cross beam energy transfer

Capsule

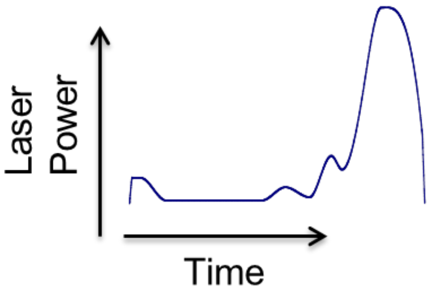


Hydrodynamic Instabilities

Tent/ fill tube defect hydro

Implosion symmetry

Fuel Adiabat



- **Stagnation**
- **Diagnostics**

Target design requires the understanding of the hohlraum/capsule coupling

High gain ICF targets directly depend on the implosion stagnation pressure

Ablation pressure
-alternate *ablator* materials

Implosion velocity
- ablator/fuel thickness

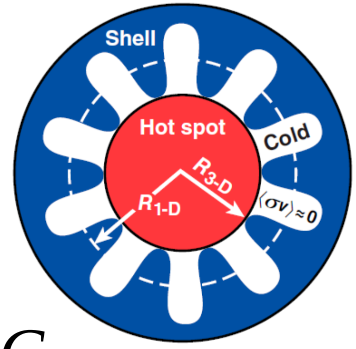
$$P_{stagnation} \sim \underbrace{p_{abl}^{1/3}\frac{v_{imp}^{3}}{\alpha}}_{\text{1D physics}}\underbrace{\left(\frac{V_{1D}}{V_{3D}}\right)^{\gamma}}_{\text{3D physics}}$$

hot-spot shape
low and high mode
- hohlraum design
- Ablators/pulse shape

Lower adiabat
(Fuel Energy/
Fermi Energy)
-*Modest* pulse shape modifications

1D physics

3D physics

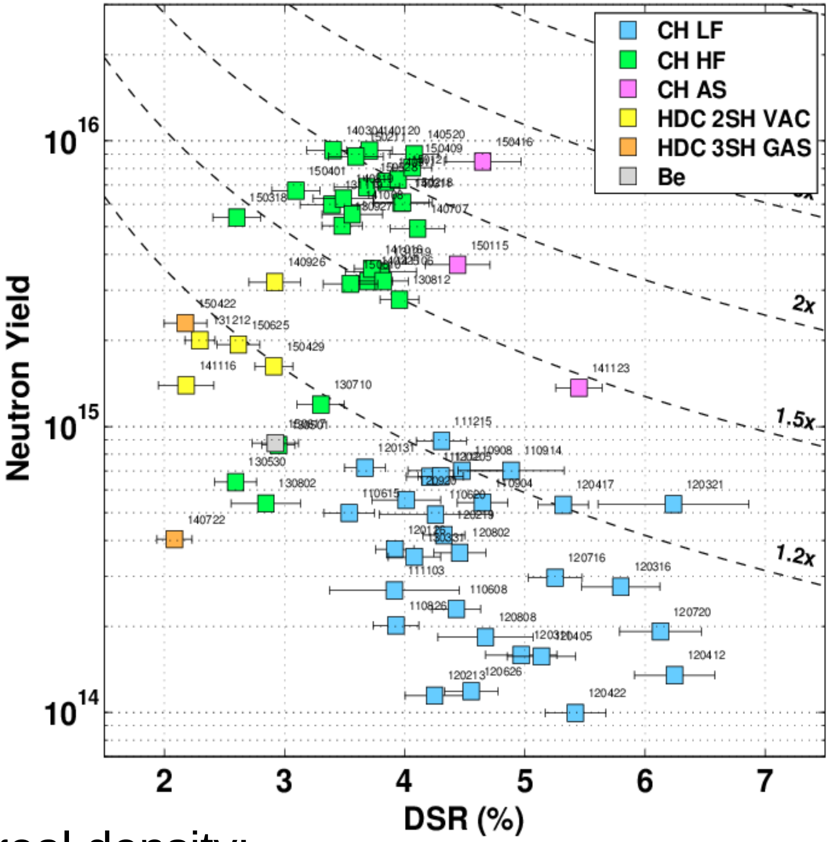


Lawson Criterion:
$P_i\tau \sim nT_e\tau \sim (m/r^3)T_e\tau > 3 \times 10^{15}$ **cm^{-3} keV s**
Tamping increases confinement time τ

$$E_{required} \sim \frac{C}{P_{stagnation}^{2}}$$

While progress towards ignition has been made, improvements are needed to achieve high gains

Yield vs Down Scattered Ratio



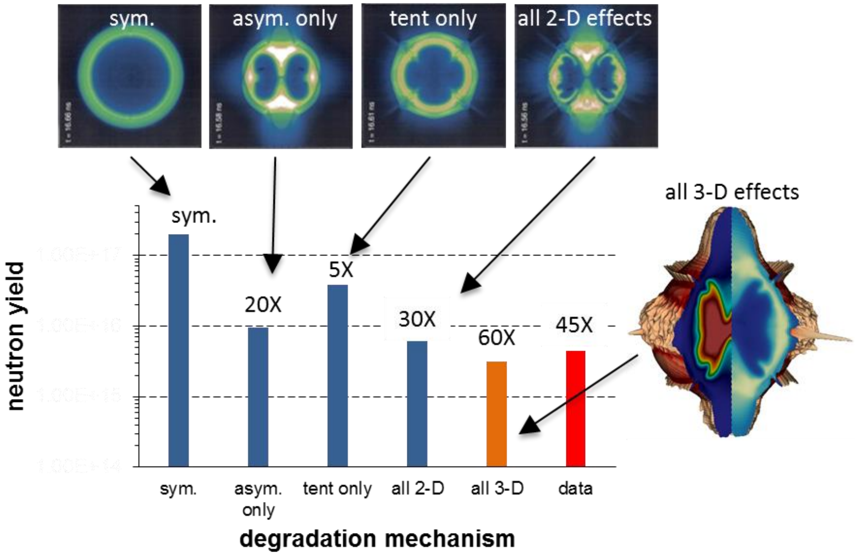
Areal density:
Down Scattered Ratio (DSR)=10-12 /13-15 MeV neutrons

High resolution 3D capsule only simulations identified primary degradation mechanisms

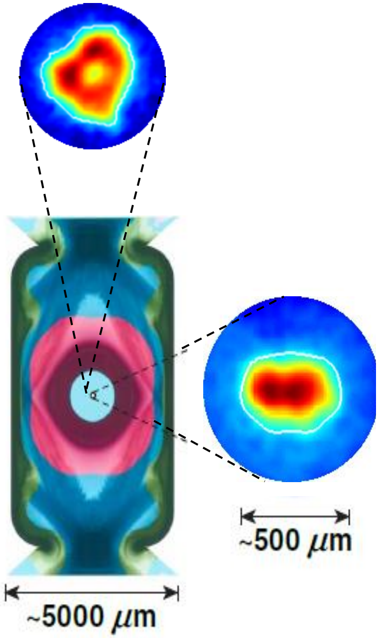
High Res sims show tent, low mode symmetry, and native roughness lead to most performance degradation

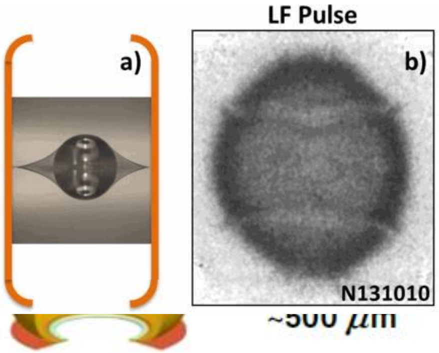
Low mode symmetry

Tent perturbation



Clark et al.

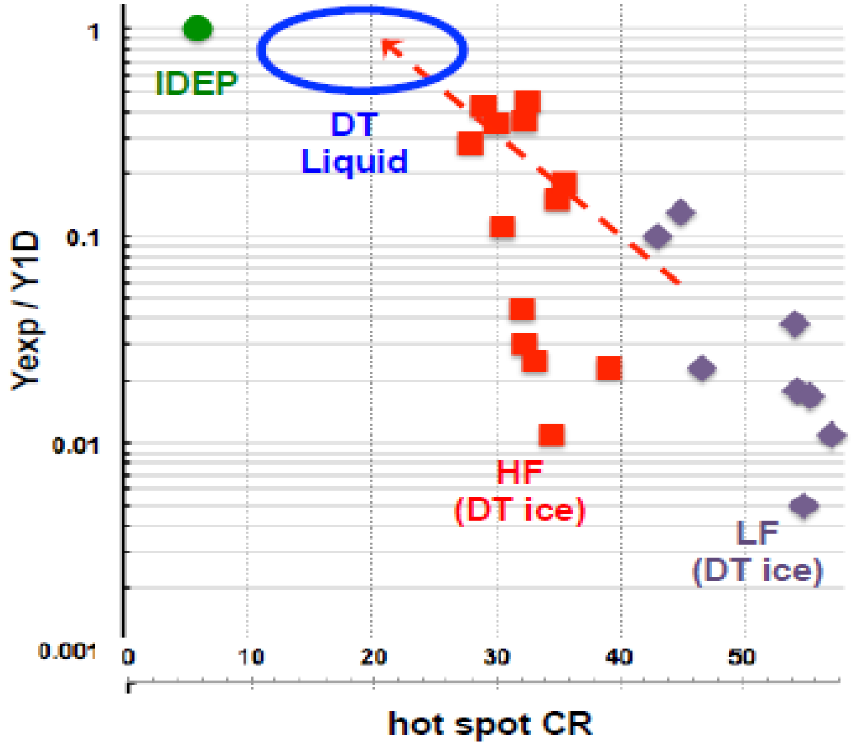




Post-NIC experiments were designed to reduce instability

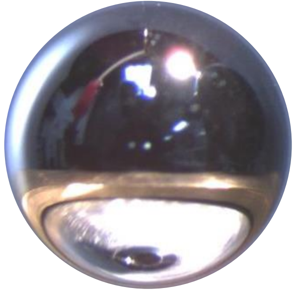
Data indicate more 1D like implosions will occur at a convergence ratio of ~20

Our hypothesis is that, without further reduction of 3D effects, experiments and 1D simulations will become similar at CR ~ 20.



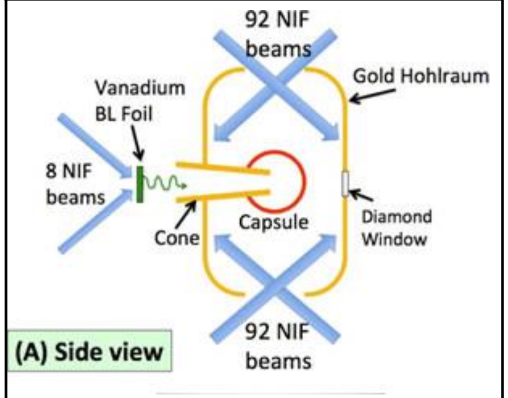
Beryllium Capsules

Cu-doped Be
(1.85 g/cc)

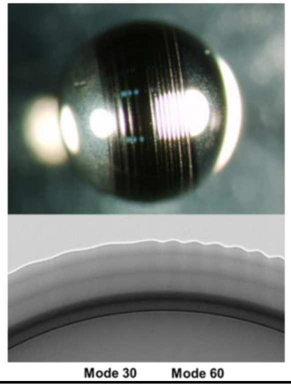


Hydro-growth radiography (HGR) data demonstrate the advantage of Be ablators for controlling ablation front hydrodynamic instability growth

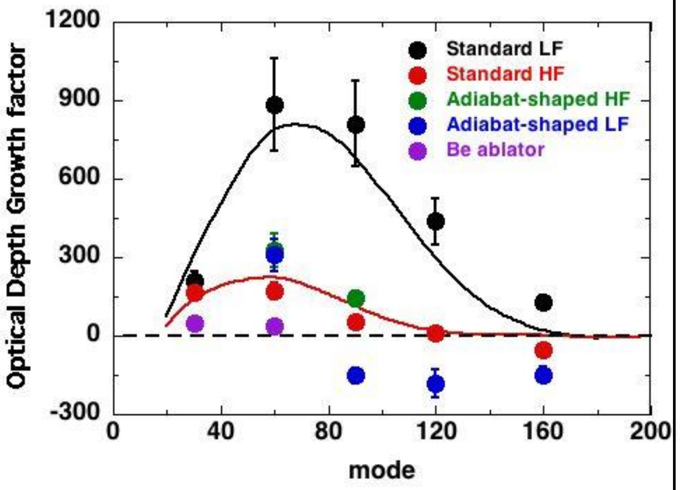
Experimental setup



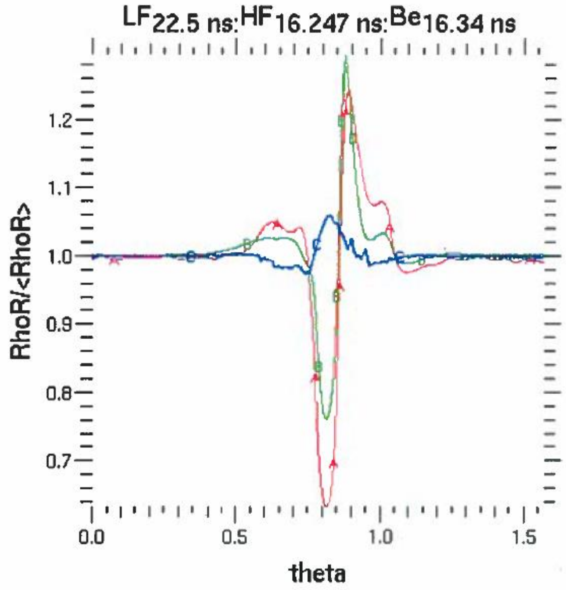
Beryllium HGR^2 capsule



Comparison of measured growth vs mode number for different ablators



Simulations of the tent perturbation growth



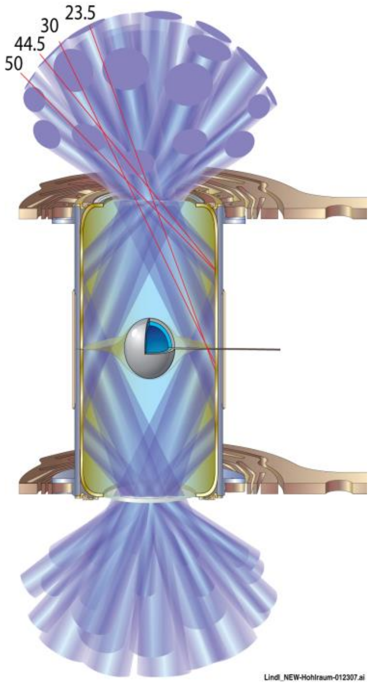
Simulation by Bruce Hammel

Beryllium reduces perturbation growth by > ~4x

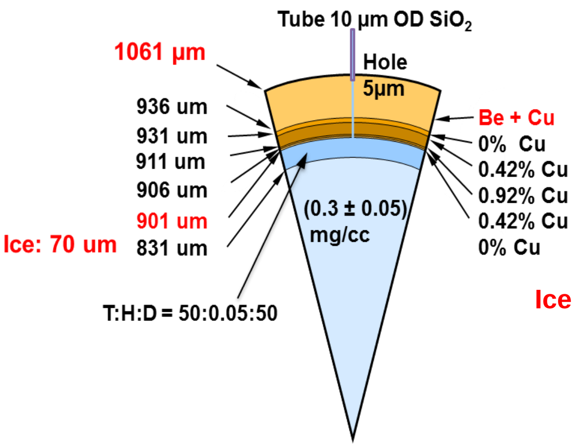
Beryllium capsules have the potential to mitigate the effects of the tent perturbations

We completed a series of experiments with beryllium capsules using the “high foot” CH-capsule platform

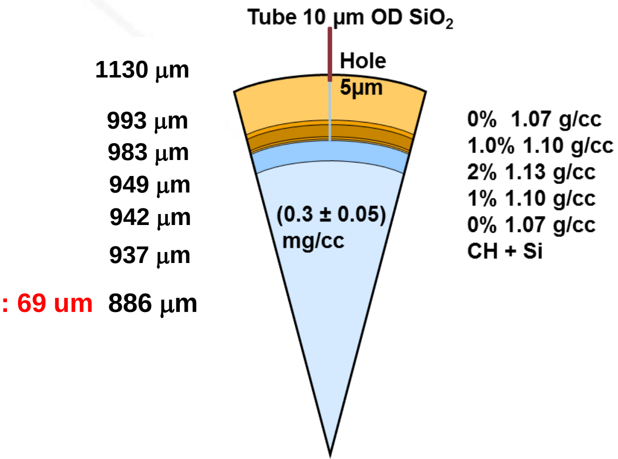
The only difference between in hohlraum fielding is the LEH diameter: 3461 μm for Be vs 3101 μm for CH

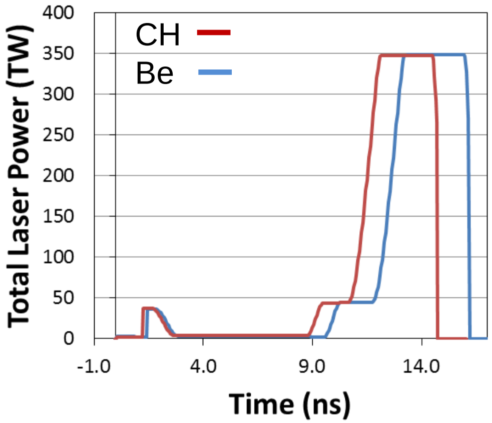


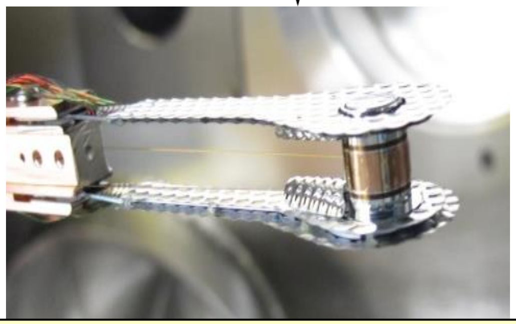
Beryllium



CH



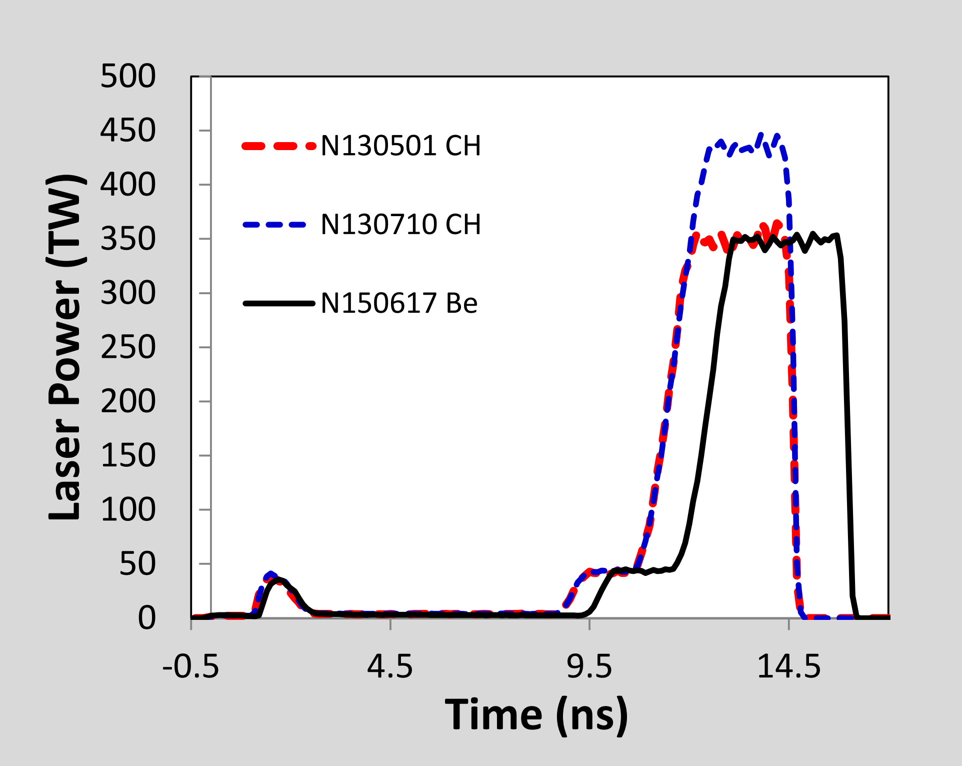




First Beryllium DT layered target

The Be DT implosion experiment used a laser pulse similar to early CH high foot shots

Be Laser pulse shape compared with early High Foot CH shots



Shot number	Power (TW)	Energy (MJ)	Peak Trad (eV)
N150617 (Be)	350	1.41	281± 4.0
N130501 (CH)	350	1.27	282± 4.0
N130710 (CH)	430	1.47	297± 4.0

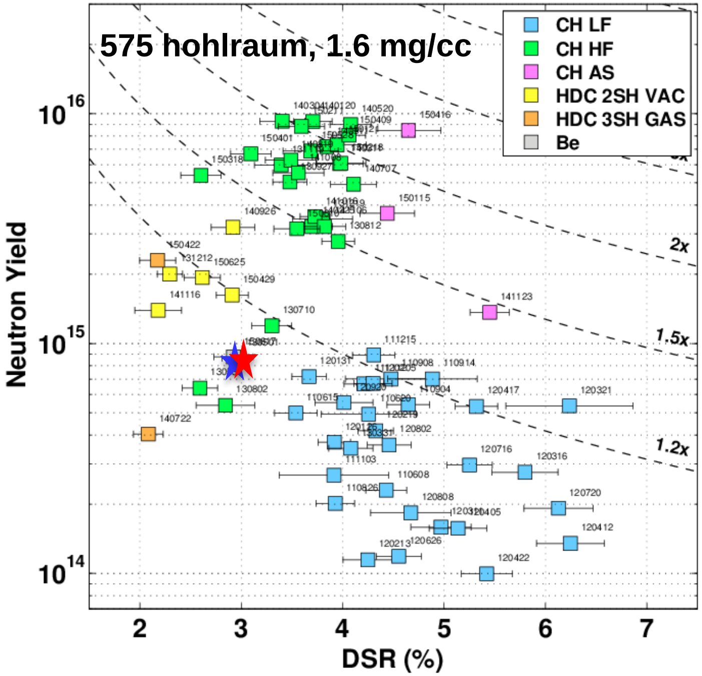
Beryllium pulse is slightly longer because it was designed on a lower adiabat with ~150 kJ more energy

The performance of the first beryllium capsule DT implosion is similar to the first high foot CH shots

Ablator	Be	CH
Shot	N150617	N130501
Power(TW)	350	351
Energy(MJ)	1.41	1.27
Y(13-15 MeV)	7.8e14±1.7e13	7.7e14±1.6e13
T_{ion}(keV)$^{\#}$	3.65±0.13	2.96±0.13
DSR(%)	3.2±0.24	2.95±0.14

Areal density:
Down Scattered Ratio (DSR)=10-12 /13-15 MeV neutrons

Yield vs DSR



Results consistent with recent modelling of high foot shots suggesting 3D effects are degrading implosion performance

Images of x ray self-emission and neutron images at peak compression indicate low mode asymmetries are similar for both CH and Beryllium ablators

N150617 Be

N130501 CH

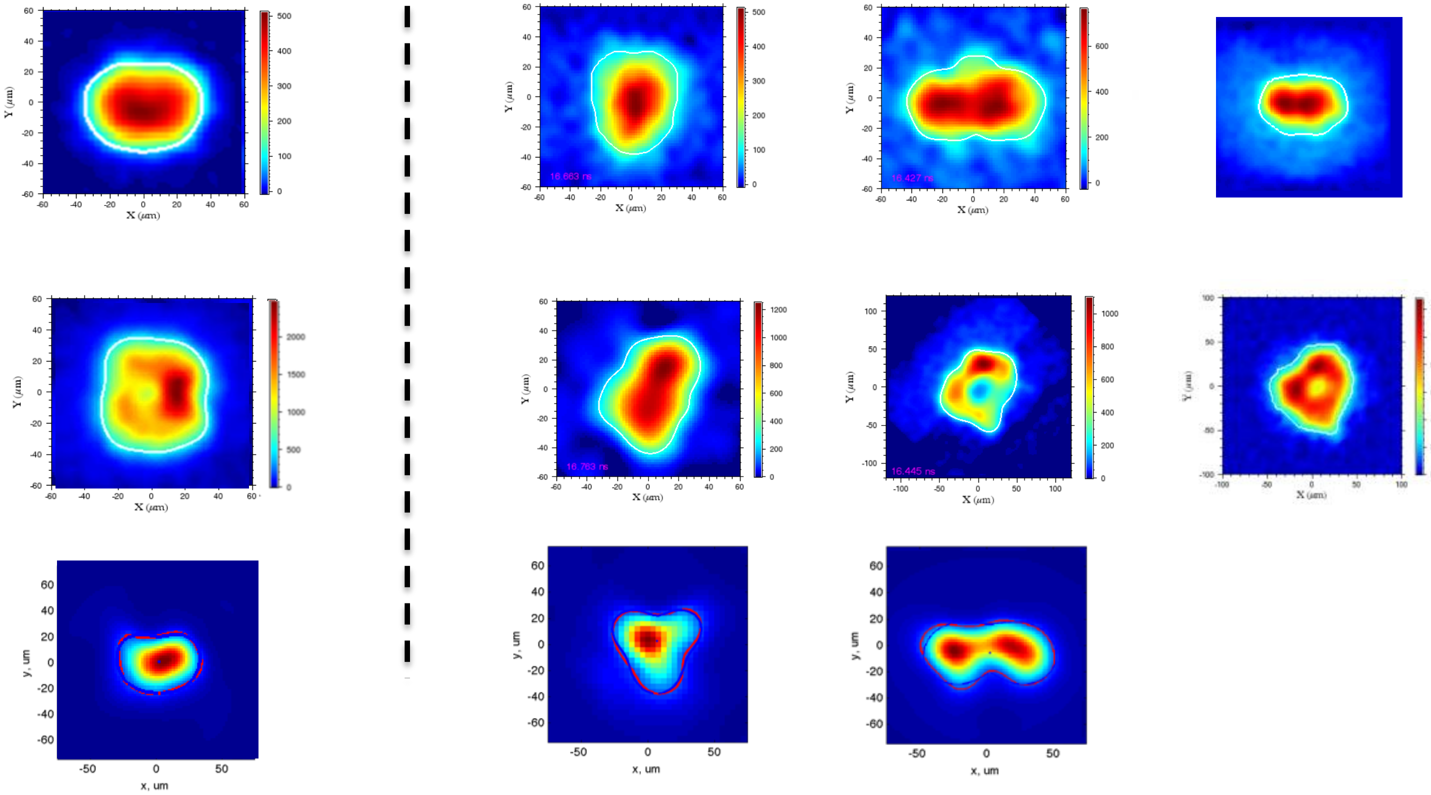
N130710 CH

N130812 CH

Equator

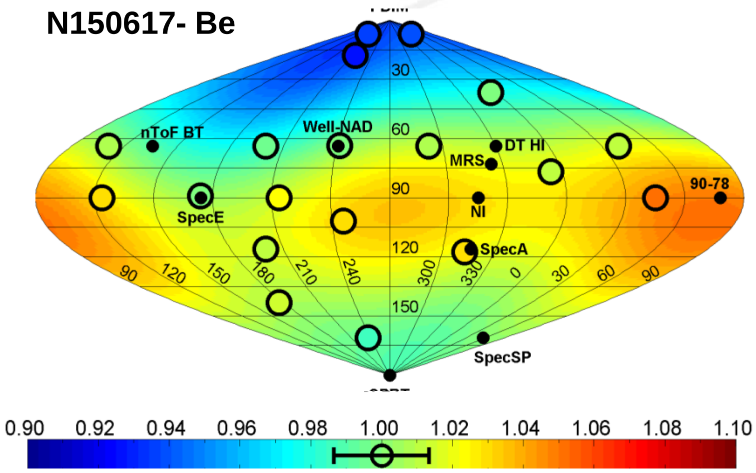
Pole

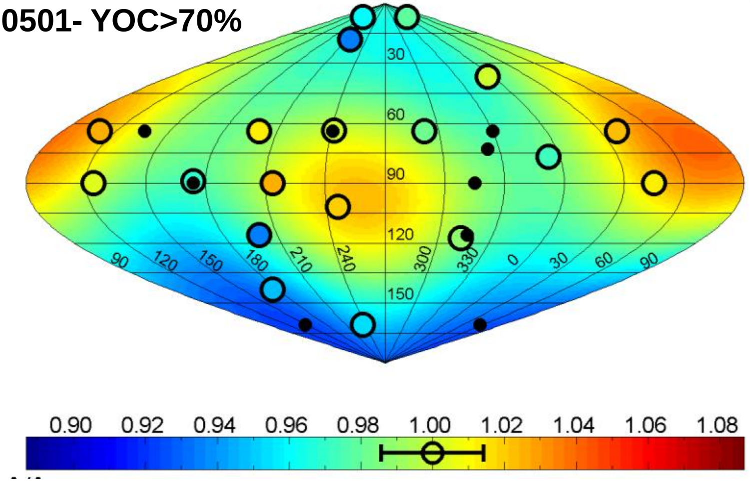
Neutron Imaging System

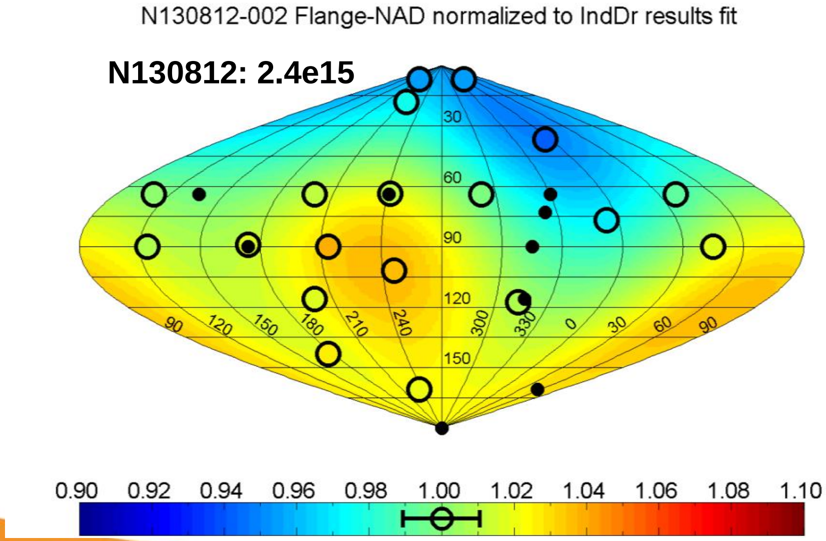


This is consistent with work by Clark et al. suggesting low mode asymmetries domination performance for low velocity high foot implosions

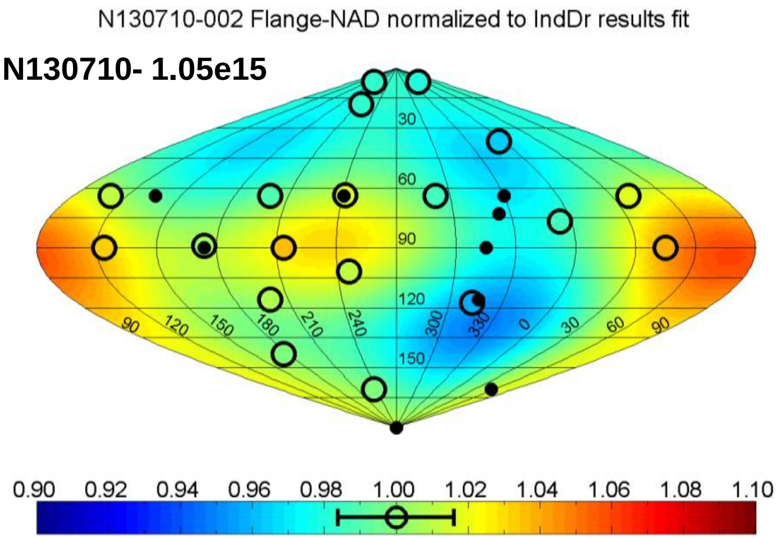
FNADs data shot little difference between the shots


N150617- Be


N130501- YOC>70%


N130812-002 Flange-NAD normalized to IndDr results fit

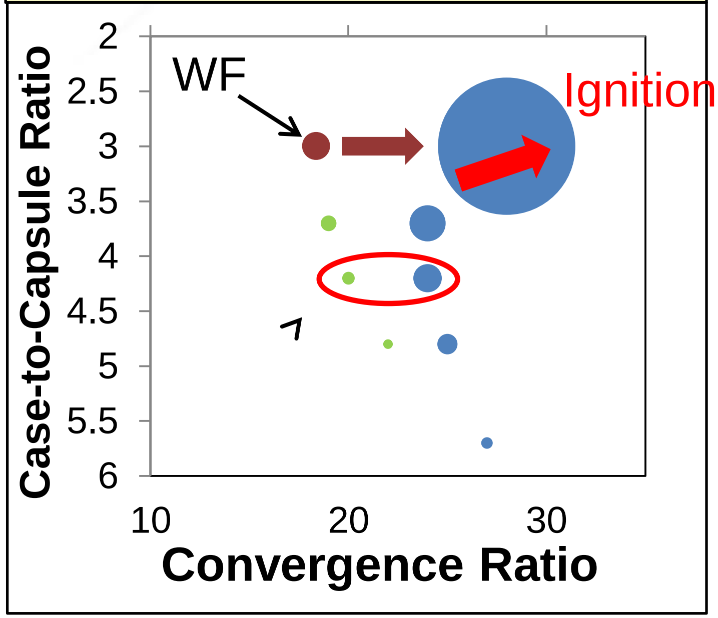
N130812: 2.4e15


N130710-002 Flange-NAD normalized to IndDr results fit

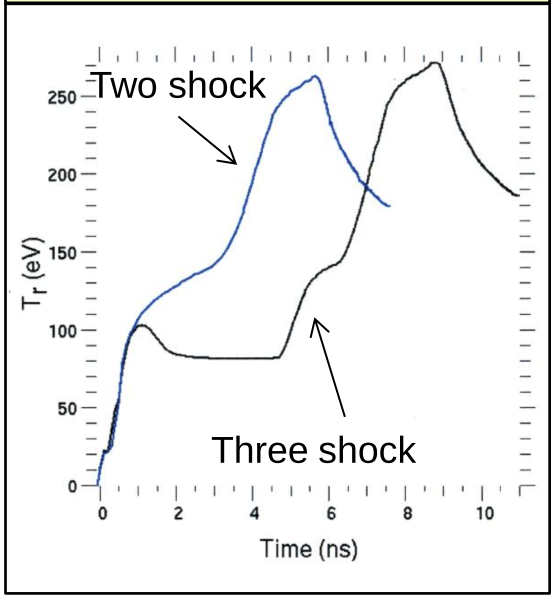
N130710- 1.05e15

Going to a higher case-to-capsule ratio and a lower convergence should make obtaining a 1D like implosion easier and provide a platform to test Be vs CH & HDC

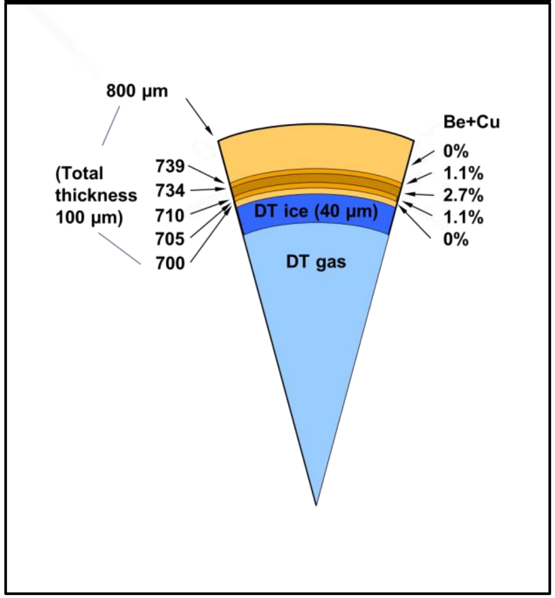
Yield vs CCR and Cr for beryllium designs



X ray drive history for lower Trad designs



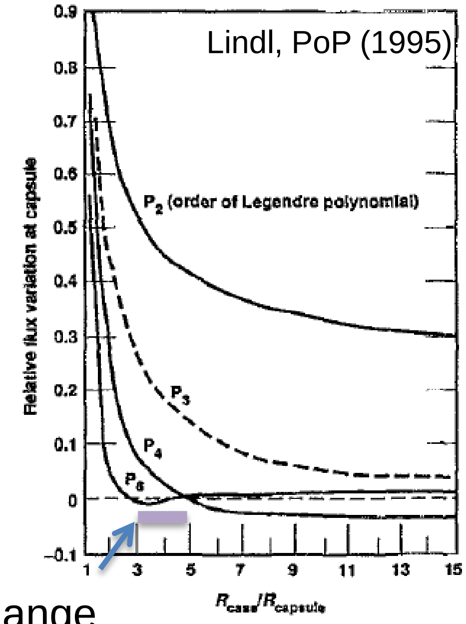
Capsule design



- Experiments have shown a CCR of 4.2 with a convergence ratio of 15 – 20 produces round implosions
- Symmetry driven by hohlraum dynamics more than radiation pattern
  - *Plasma blow-off*
  - *Proximity of laser beams*

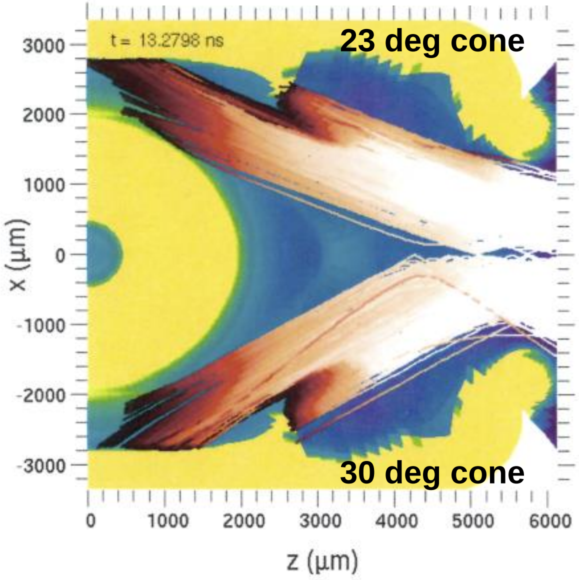
A high case-to-capsule ratio increases the physical separation between hohlraum wall and capsule blow-off plasmas, allowing for better inner cone propagation

Flux variation as function of case-to-capsule ratio

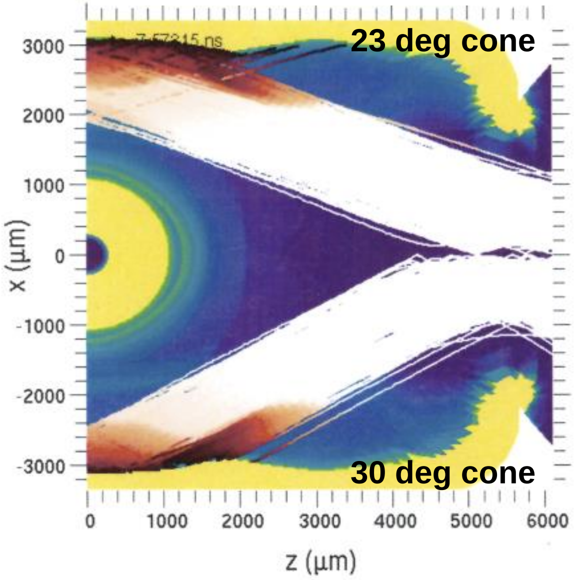


Range

End of pulse, 1.1 mm O.R. capsule



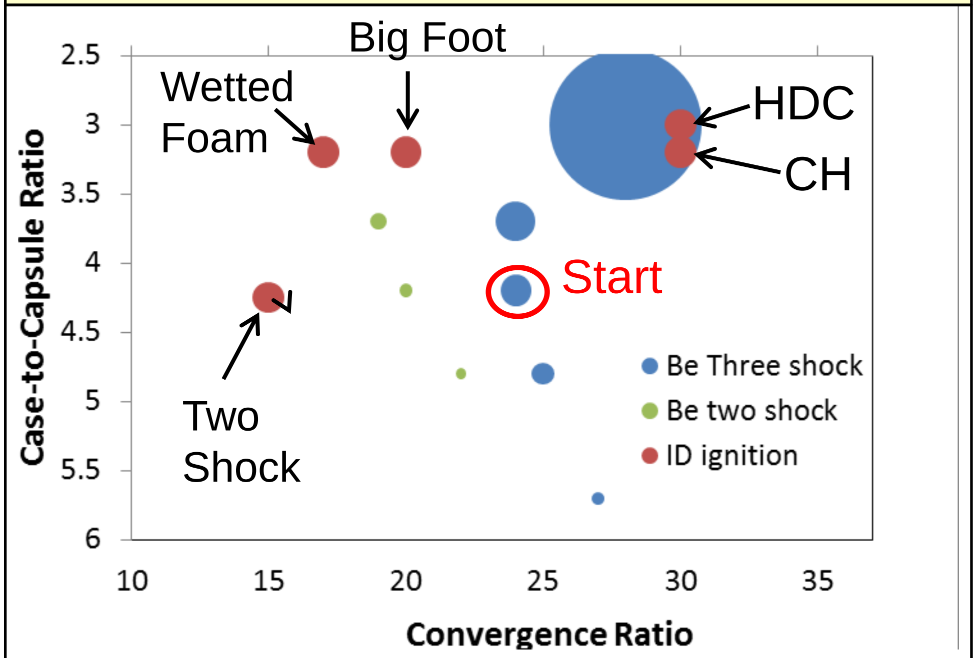
End of pulse, 0.6 mm O.R. capsule



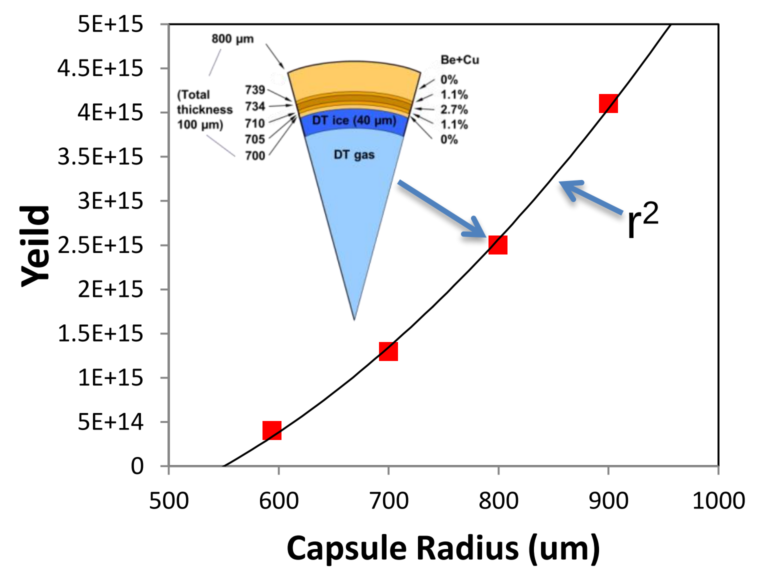
- To control the symmetry, the coupling between the capsule and hohlraum must be understood.
- We will start with a case having good symmetry and increase the capsule size to systematically find the largest capsule having a round implosion in a 672 hohlraum

Our design's have hydro-scaled the capsules for a fixed hohlraum size to compare performance

Yield vs CCR and CR for beryllium designs with respect to other ignition base camps



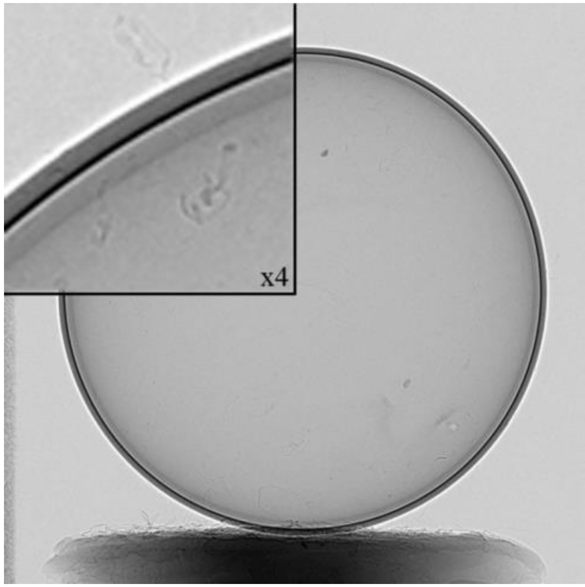
The experimental design tests hydro-scaling (~r^2)



- Two shock experiments demonstrated round implosions with convergence ratio of 15 – 20
- Hydro-scaling may be a means to down select ablators, but needs to be tested

Our current designs focus on round implosions with high YOC, not ignition

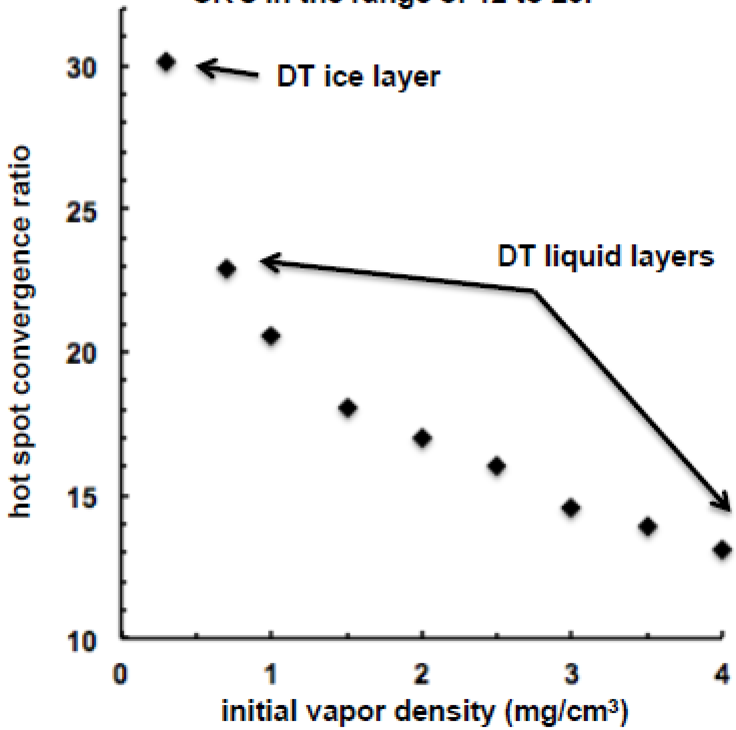
Liquid layer capsules



Liquid fuel layers are another approach to controlling the convergence

- **With liquid fuel layers the initial hot spot mass can be controlled via fielding temperature of target**
  - *Different temperatures have different vapor pressures*
  - *More mass in the hot spot reduces convergence mitigating the impact of implosion symmetry and hydro instabilities*
  - *Adjusting the mass in the hot spot changes the partition of energy between cold fuel and hot spot*

Simulations indicate that DT liquid layer capsules can be used to access hot spot CR's in the range of 12 to 25.

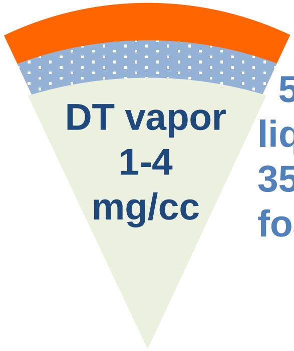


R. E. Olson and R. J. Leeper, Phys. Plasmas 20, 092705 (2013).

First experiments on NIF successful with both D_2 and DT liquid layers

Foam-lined capsules are fabricated by a LLNL/GA team

Point Design

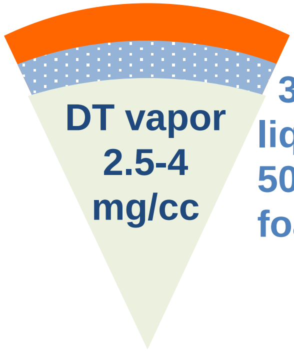


64um HDC
844um IR

DT vapor
1-4
mg/cc

50um DT
liquid layer
35 mg/cc
foam

Current Ability

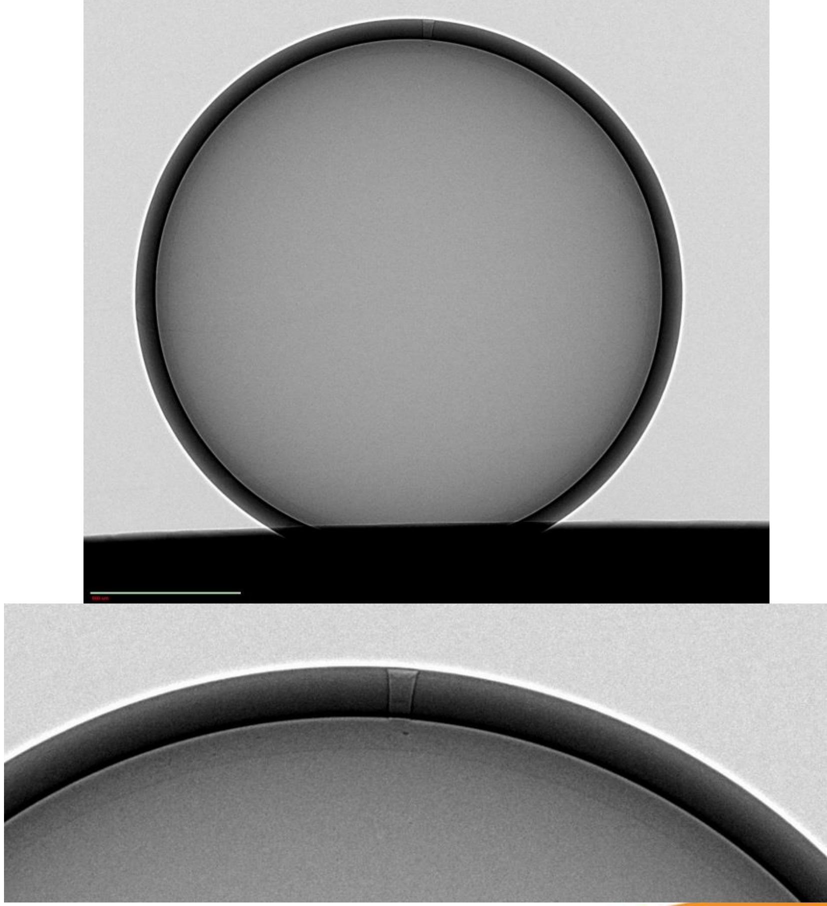


64um HDC
844um IR

DT vapor
2.5-4
mg/cc

30-40um DT
liquid layer
50-80 mg/cc
foam

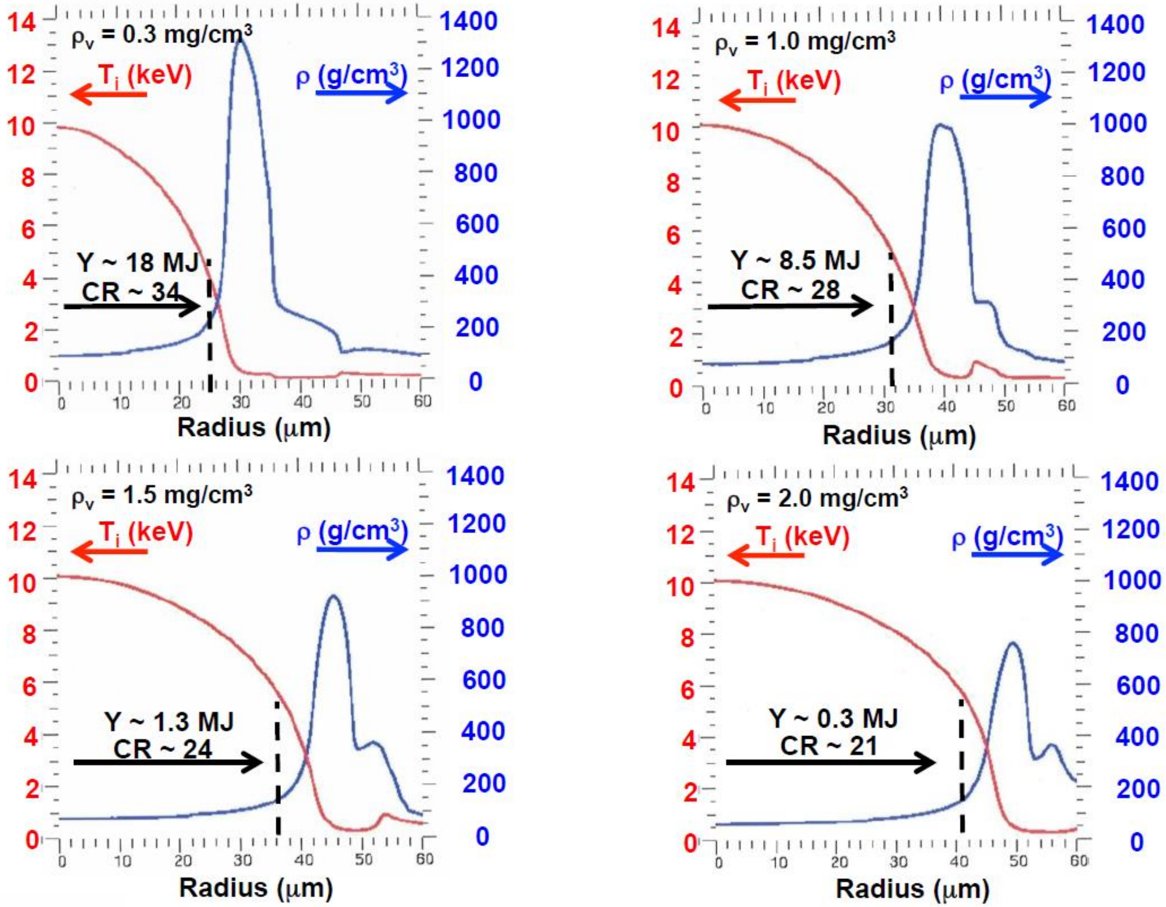
Foam-lined capsule radiograph



Technique developed by LLNL target fab:
J. Biener et al., Nuclear Fusion 52, 062001 (2012)
T. Braun et al., ACS Applied Materials and Interfaces 8, 2600 (2016)

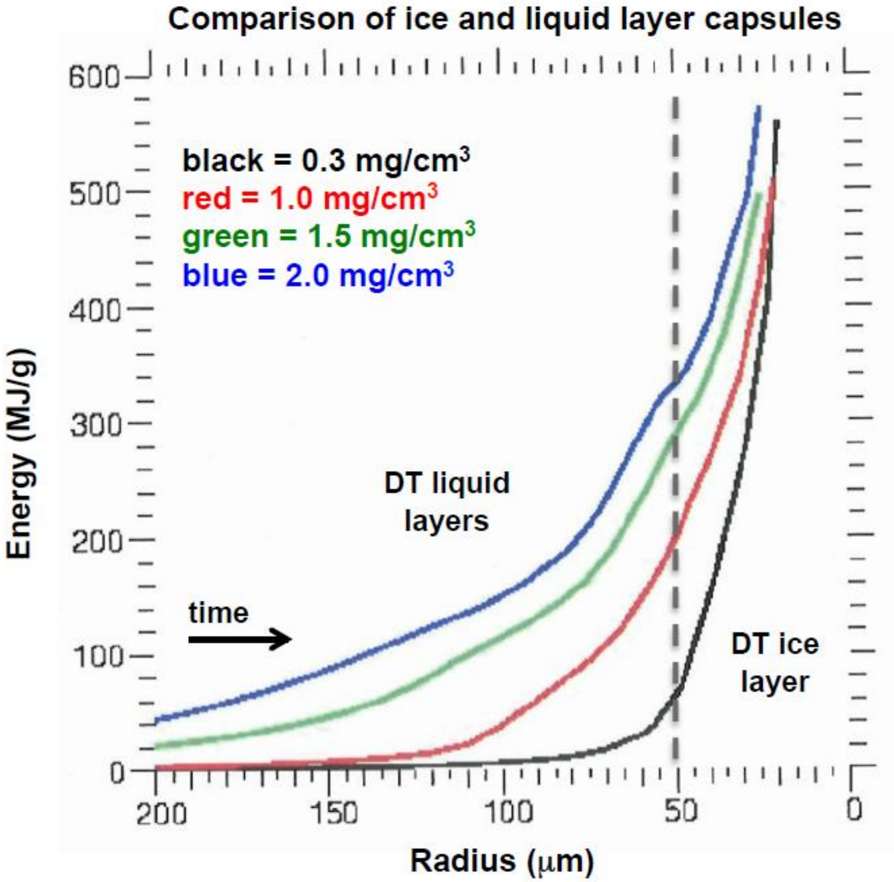
> Current capsules are not at the point design, but are adequate for physics studies.

Stagnation occurs at larger radius as vapor pressure is increased reducing the convergence ratio



The trade-off is the partitioning of energy between the hot spot and the cold fuel compression which changes the gain

As the capsule implodes, the hot spot specific energy is gained at larger radius in liquid layered implosions



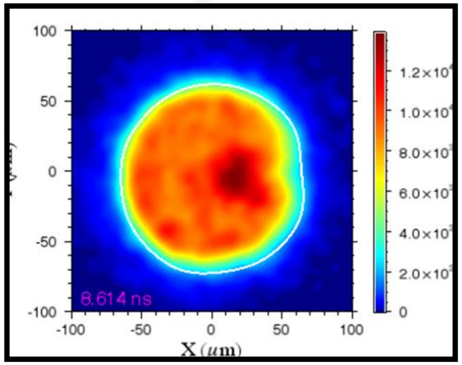
The change in hot spot formation with convergence should be measurable via Gamma Reaction History

X ray self-emission images from first liquid layer experiments show shape within NIC requirements

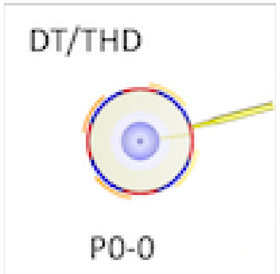
Polar IP

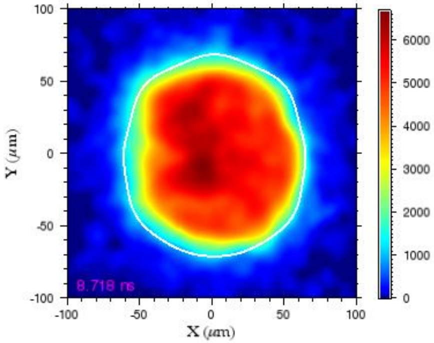
Equator

N160421

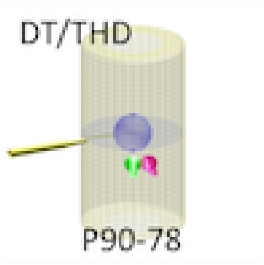


M0:	**68.8 ± 5.4 μm**
M2/M0:	**(1.8 ± 11.1)%**

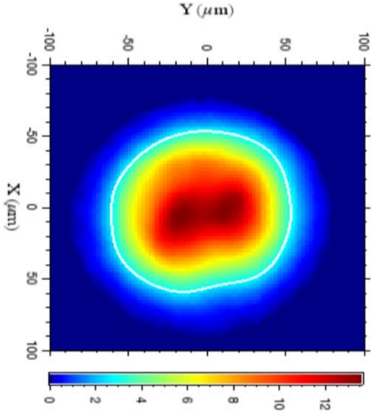




P0:	**64.7 ± 4.7 μm**
P2/P0:	**(7.7 ± 1.3)%**
P4/P0	**(-3.8 ± 1.0)%**

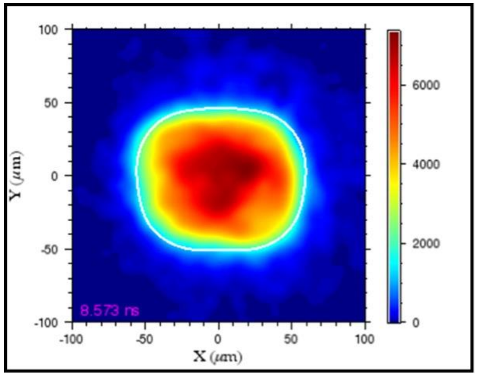


N160626



M0:	**57.1 +0.5/-2.9 μm**
M2/M0:	**(3.6 +0.5/-1.7)%**

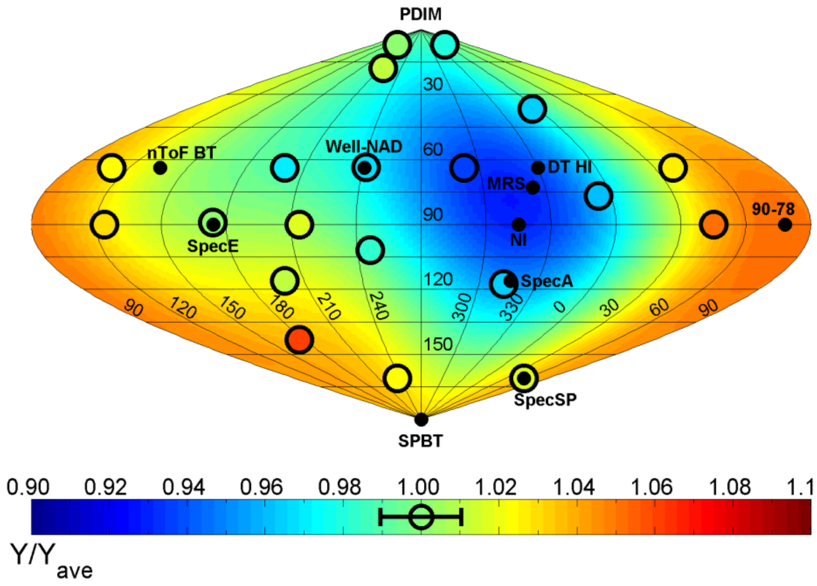
Target had imperfections on surface and liquid layer



P0:	**53.6 ± 4.4 μm**
P2/P0:	**(-8.8 ± 1.2)%**
P4/P0	**(-8.2 ± 2.4)%**

Flange NAD data show similar morphology but smaller amplitude than a comparable HDC ice shot

N160120 (HDC campaign ice layer)

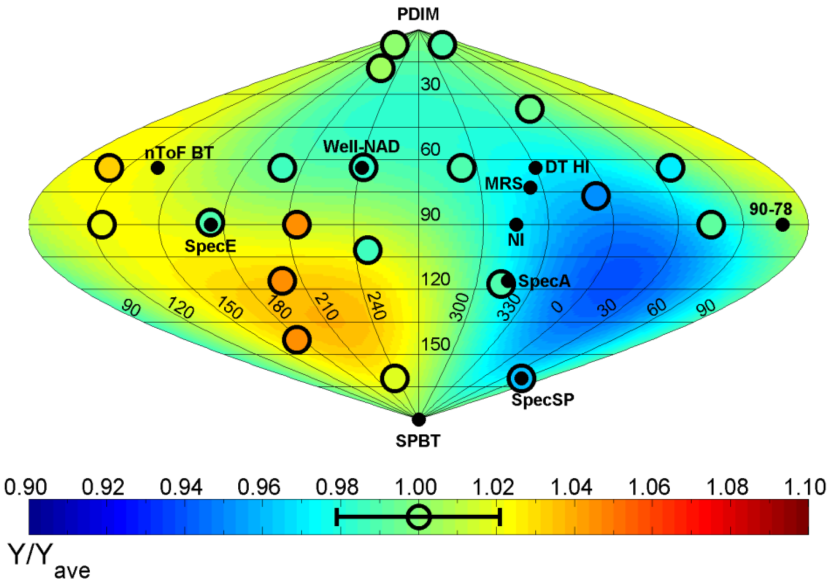


Coefficients:
adx2y2=-0.01441
adxy=0.038352
adxz=0.011188
adyz=0.013636
adz2=0.017681
apx=-0.035249
apy=0.093693
apz=-0.041749
as=3.5497

Fit values:
Well-NAD: 0.97181
MRS: 0.93204
nToF BT: 1.0132
SpecA: 0.95168
SpecE: 1.0056
NI: 0.93026
DT HI: 0.93946
SPBT: 1.0329
SpecSP: 1.0357

plot generated 28-Jan-2016 09:18:53

N160421 (wetted foam, CR~14)



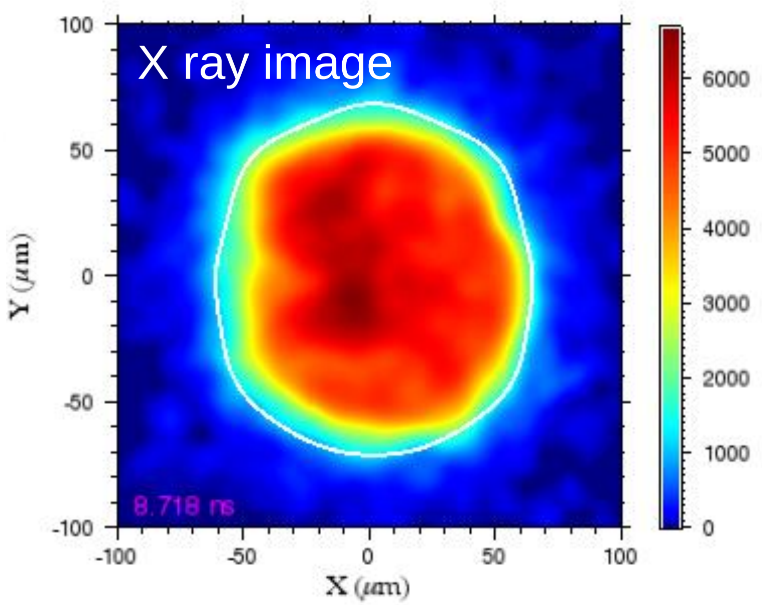
Coefficients:
adx2y2=-0.021279
adxy=-0.0048142
adxz=0.036232
adyz=0.032408
adz2=0.0063486
apx=-0.06821
apy=0.0071655
apz=-3.3785e-05
as=3.53

Fit values:
Well-NAD: 0.99013
MRS: 0.96869
nToF BT: 1.0189
SpecA: 0.97149
SpecE: 1.0165
NI: 0.97039
DT HI: 0.97111
SPBT: 0.99982
SpecSP: 0.97841

plot generated 28-Apr-2016 11:38:58

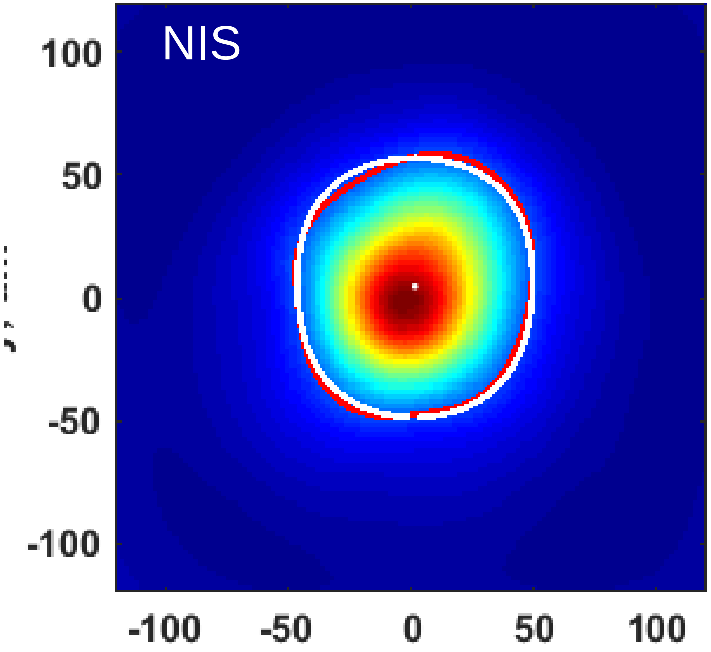
This platform can study the growth of low-mode asymmetries in the stagnated hot spot / dense fuel as a function of CR.

The neutron image is smaller than the X ray image which might lead to a measure of mixing of the fuel into the hot spot



P0: 64.7 ± 4.7 μm

P2/P0: (7.7 ± 1.3)%



P0: 51 μm

P2/P0: 8 %

Liquid layer targets provide many opportunities to diagnose hot spot formation not attainable with ice layers

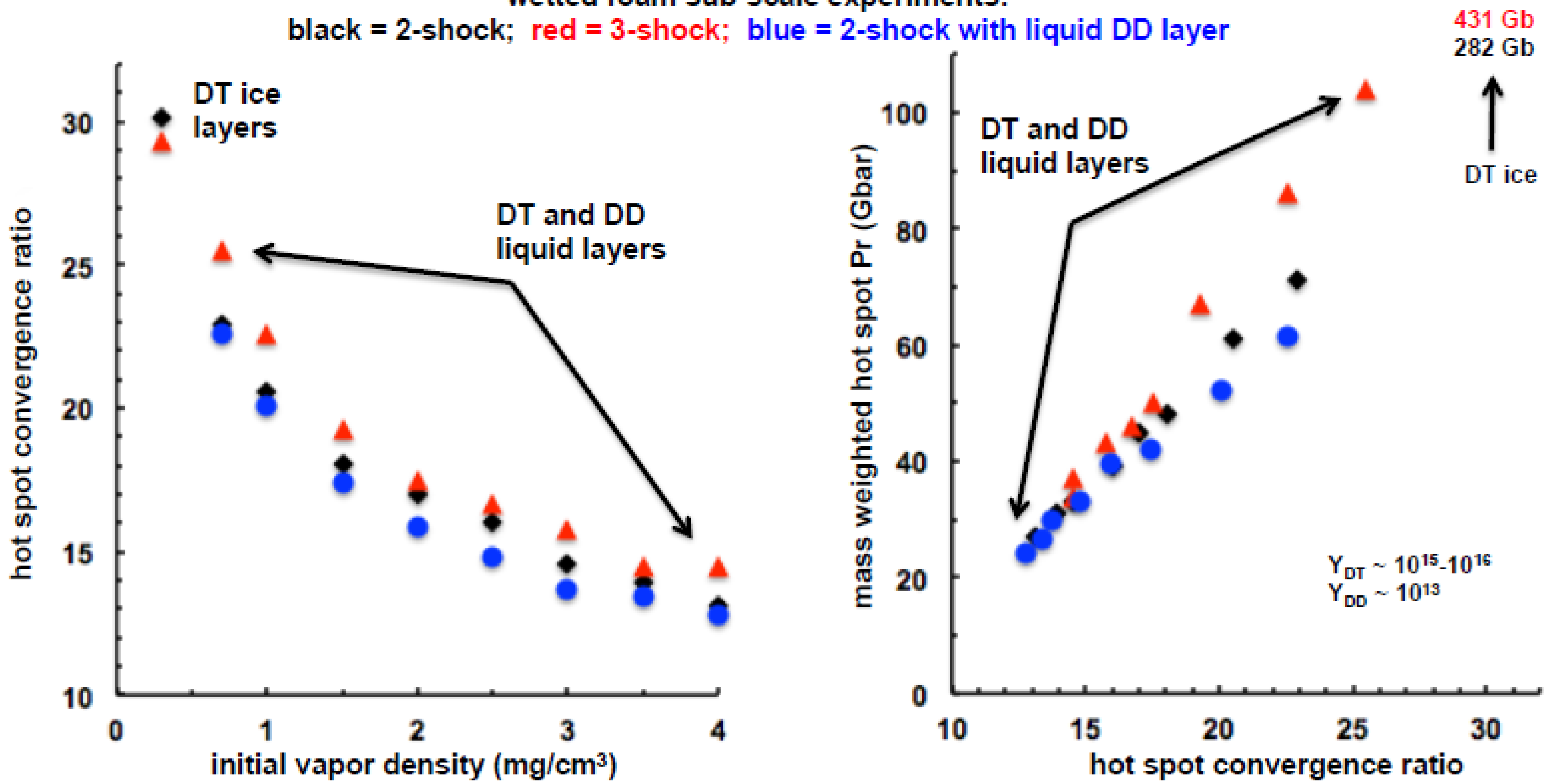
Hydra post-shot simulations match most observables to within error bars, indicating a predictable implosion with robust hotspot formation at our reduced CR

	N160421	Hydra Postshot
Yield (10^{14})	4.5 ± 0.1	6.4
Xray bang time (ns) (Spider)	8.63 ± 0.03	8.60
Neutron burn width (ps)	313 ± 30	283
DSR (%)	0.82 ± 0.08	0.83
T_{ion}, burn avg. (keV)	3.2 ± 0.1	2.9
GXD hotspot radius (μm)	64.7 ± 4.7	62.9
NIS hotspot radius (μm)	50.6 ± 2.2	53
GXD Inferred P_{hs} (Gbar)	16.5 ± 2.3	18.5
NIS Inferred P_{hs} (Gbar)	21.4 ± 2.2	23.5

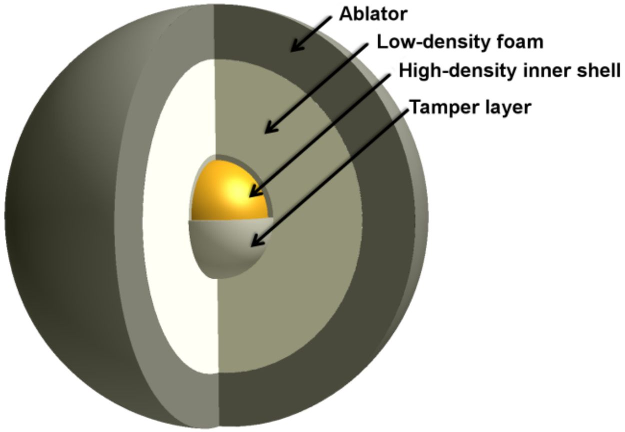
Yield degradation effects due to mix from the fill tube, tent, and capsule surface roughness will be analyzed

We will use hot spot size, neutron yield, T_{ion}, and burn width to infer hot spot pressure as a performance metric

wetted foam sub-scale experiments:
black = 2-shock; red = 3-shock; blue = 2-shock with liquid DD layer

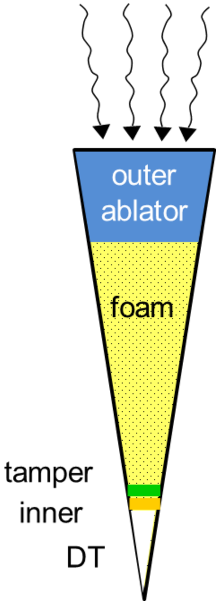


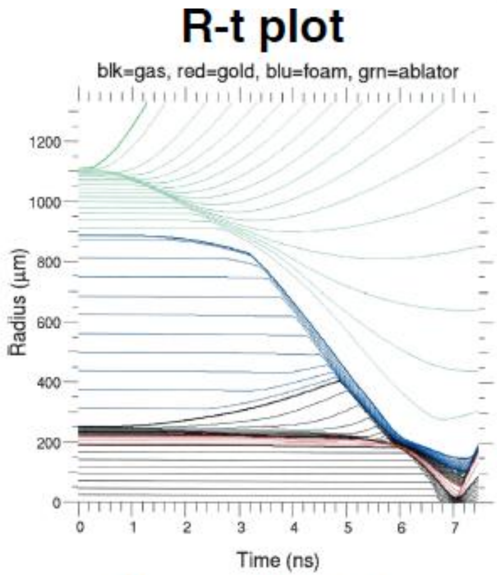
Double Shell ICF Targets



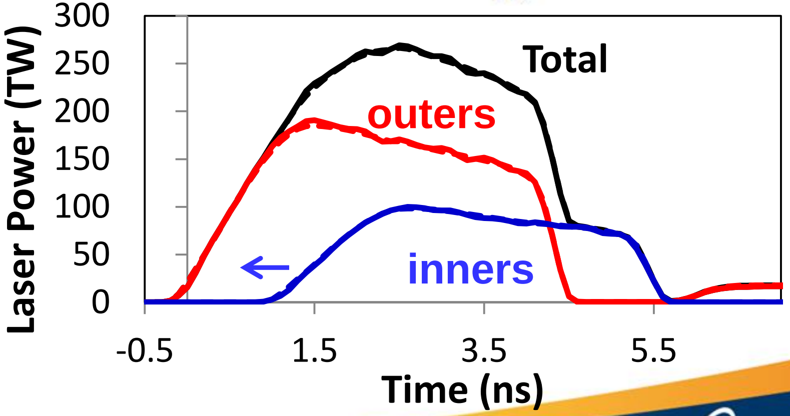
LANL is evaluating double shells as another path to reduce the convergence of the capsule

- DS targets isolate driver from fuel filled inner shell capsule
- Outer shell is driven and collides with inner shell compressing it
- Inner shell convergence is low
- Take advantage of
  - Tamping of the inner shell
  - Radiation trapping
- DS trade of physics for target complexity
- Lower yields





Y_{1D} ~ 250 kJ



Double Shells offer the potential for α-heating, burn, and possible ignition in more robust implosions

Performance/Design Metrics	Volume Ignition with Double-Shells	Hot-spot Ignition with Single-Shells
Pusher Convergence Ratio (1)	C.R. < 10	C.R. > 30
Pusher Implosion Velocity	v_{imp} ~ 250 km/s	v_{imp} ~ 380 km/s
Pulse shaping/shock timing	impulsive, few ns	3-4-shock, 7-20 ns
Calculated Ignition Temperature	central T_{ion} < 4 keV	central T_{ion} ~ 8-10 keV
Sensitivity to LPI/asymmetries	Low/unclear	High
Use of vacuum hohlraum	Yes	Uncertain^2
Sensitivity to uncertainties in ablative-drive physics	Low	High
Pusher inflight aspect ratio (IFAR)	Low	High
Requires fuel layer?	No	Yes
Sensitivity to mix at gas-pusher interface	Most sensitive^3	Least sensitive
Capsule fabrication	Most challenging	Less challenging

1) Pusher C.R. defined as ratio of initial fuel radius to hot spot radius

2) HDC ablators can possibly use near-vacuum hohlraums

3) Double-shell is insensitive to low-Z mix due to radiation trapping, can possibly use low-Z anti-mix layer to prevent high-Z mix

Challenges exist, but payoffs could greatly outweigh the risks

Key Physics Uncertainties for Robust Burn in Double Shells

Shape & Hohlraum Coupling

- How do hohlraum hard x-rays impact symmetry?
- Can we tune inner shell implosion symmetry via cone fraction?
- What is the impact of gas-fill?

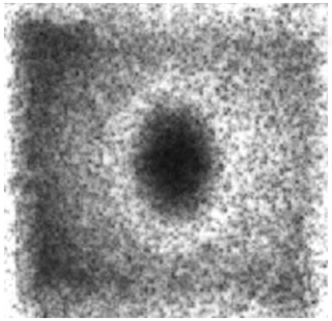
Shell collision, velocity & adiabats

- What outer shell conditions lead to the “best collision” for the inner shell?
- How well can we determine and modify pusher (inner shell) adiabat?

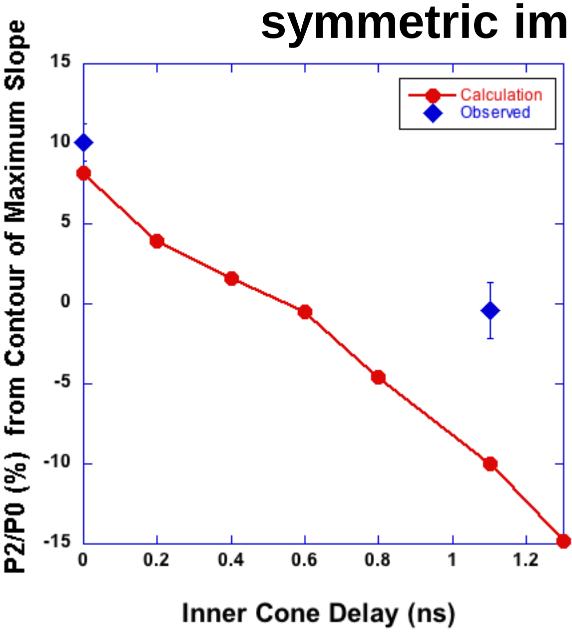
Mix measurement & mitigation

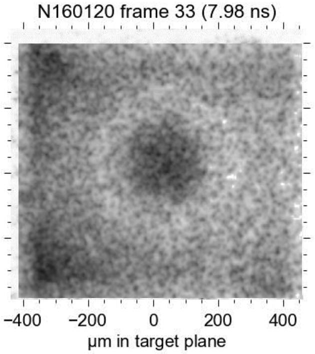
- Can a tamper layer mitigate inner shell breakup?
- How can we measure and assess the impact of 4π mix on burn?
- How can we measure and assess the impact of mix from the fill-tube?
- Can a low-Z anti-mix layer be used to mitigate 4π mix into the fuel?

The first experiments using a double shell pulse shape shot symmetry control of single shell via pulse timing

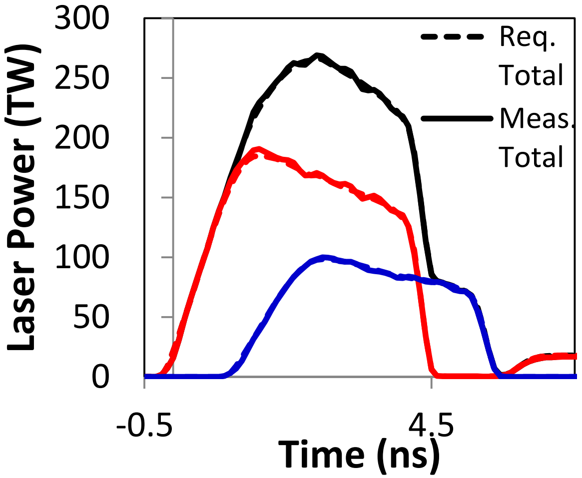


First shot demonstrated symmetric implosion





- 4.5-ns reverse ramp
- ° 1 MJ energy
- 97 – 98.5% coupling
- Be(Cu) outer shell
- symmetry tuning tested



FY17 experiments will examine:

Mid-Z inner shell behavior

Collision elasticity

Shell instability

Establishing understandable implosions is a key step toward achieving laser based inertial confinement fusion

- A lot of progress has been made over the past few years obtaining high fuel compression and self-heating in the hot spot for ICF implosions
- However, experiments show that 3D effects are dominating performance in high velocity, high convergence implosions
  - For all ablator/target configurations
  - Low mode symmetry
  - High mode mix due to capsule mounting hardware
- Reducing implosion convergence can mitigate 3D effects and will enable a systematic approach to address these issues as we move towards ignition
- LANL has three campaigns design to establish a base in which simulation and experiments are in good agreement
  - Low Trad, High Case-to-capsule ratio beryllium capsules
  - Liquid layer targets
  - Double shell targets

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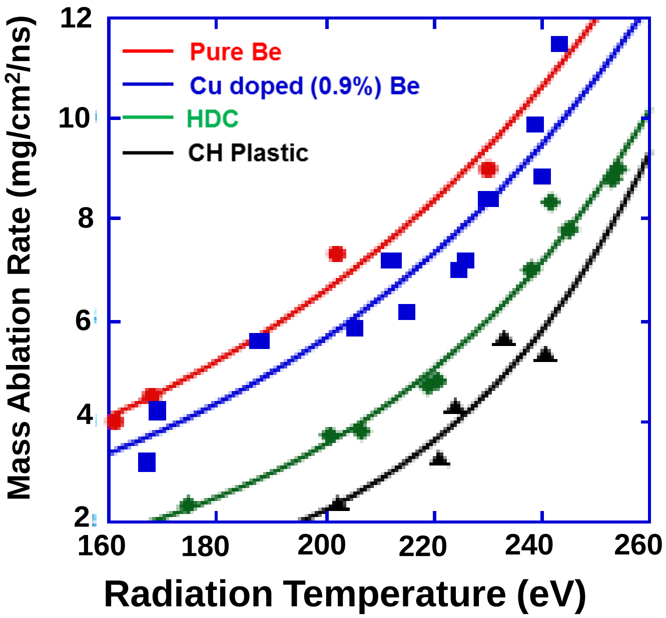
EST.1943

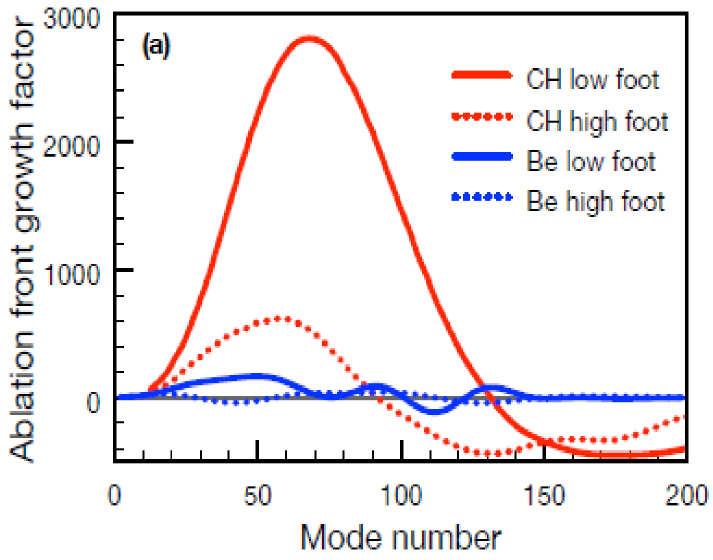
Beryllium has key advantages as an ICF ablator

Low opacity lead to higher mass ablation rate



Olson et al. Phys Plasmas 18, 032706 (2011).

Higher ablation velocity leads to more stabilization at the ablation front



[S. Yi, et al, Phys. Plasmas 21, 092701 (2014)]

$$P_{ablation} = \frac{1}{1+\frac{1}{4}\left(\frac{e_{ion}}{(Z+1)kT}\right)} \frac{\sigma T^4 F_{Sheild}}{\sqrt{\left(\frac{\bar{Z}+1}{\bar{A}}\right)kT}}$$

S. P. Hatchett

Ablative RT growth

$$\gamma = \sqrt{\frac{kg}{1+kL}} - \beta k V_a$$

- Higher ablation velocity gives more ablative stabilization
- Lower opacity enables designs at larger case-to-capsule ratios with lower drive

Under similar hohlraum conditions, CH, HDC, Be capsule performance is similar

1.6 mg/cc He fill 575 Au hohlraum

Ablator	Be	CH
Shot	N150617	N130501
Power(TW)	350	351
Energy(MJ)	1.41	1.27
Y(13-15 MeV)	7.8e14 ± 2e13	7.7e14 ± 2e13
T_{ion}(keV)#	3.65±0.13	2.96±0.13
DSR(%)	3.2±0.24	2.95±0.14

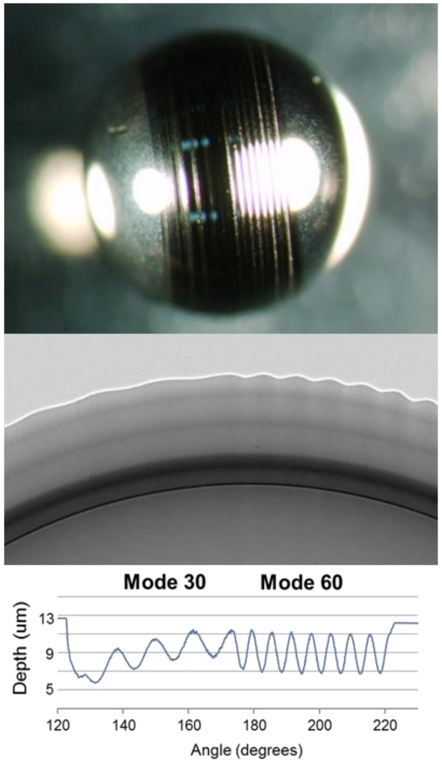
1.6 mg/cc He fill 575 Au + 700 hohlraum

Ablator	HDC	CH
Shot	N140722	N130802
Power(TW)	430	430
Energy(MJ)	1.48	1.5
Y(13-15 MeV)	3.7e14 ± 8e13	4.8e14 ± 9e13
T_{ion}(keV)#	3.38±0.15	2.85±0.17
DSR(%)	2.08±0.15	2.84±0.29

This is consistent with recent modelling of high foot shots suggesting 3D asymmetry and the capsule tent are degrading implosion performance

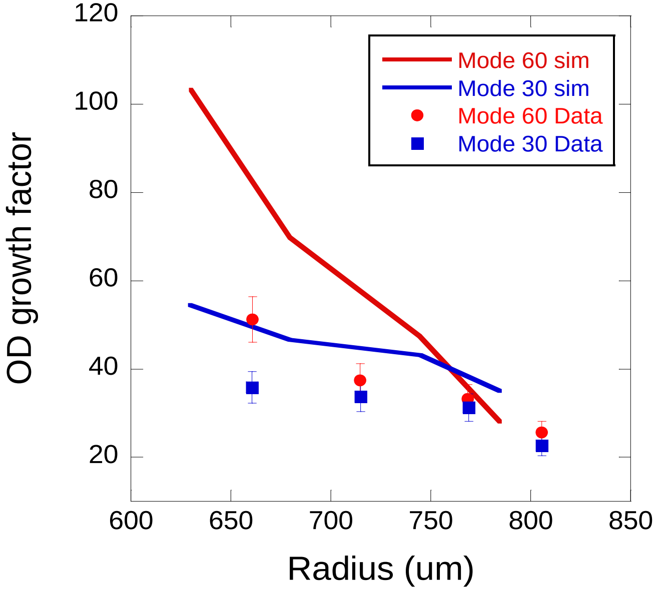
The first hydro-growth radiography (HGR) data show lower growth at the ablation front than predicted

Beryllium HGR[2] capsule



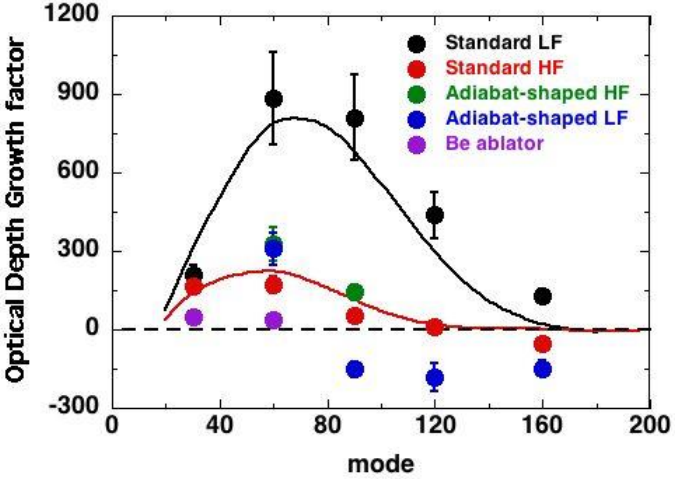
[2] Smalyuk, et al.

Comparison of measured growth factors vs simulated values[1]



[1] Yi and MacPhee

Comparison of measured growth factors for different ablators

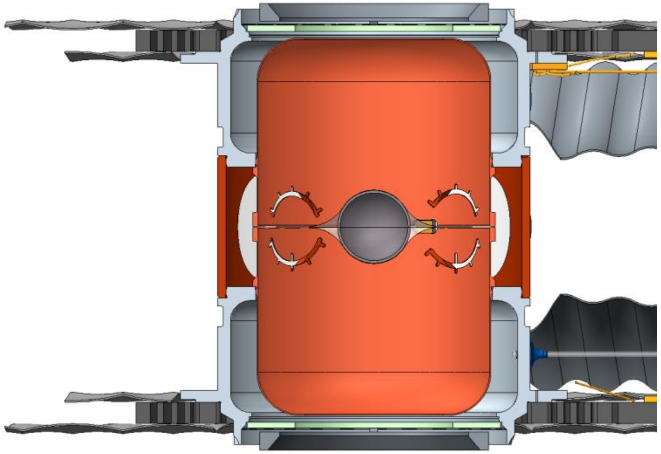


The experimental team executed a “PQ series” of 3 shots over the last 3 months

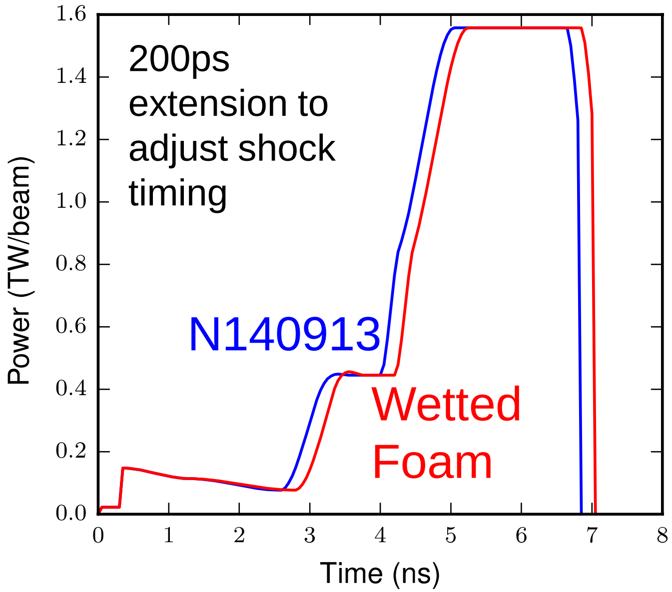
These shots used a subscale HDC design in 575 Au NVH as the starting point

- **N160320**
  First shot using a liquid layer; also the first D_2 layer on NIF. Shot at 26K, 4 mg/cc vapor (CR~14).
- **N160421**
  Changed to DT layer, shot at 26K, 4 mg/cc vapor (CR~14).
- **N160626**
  DT layer at higher CR, shot at 24.6K, 2.5mg/cc vapor density (CR TBD).

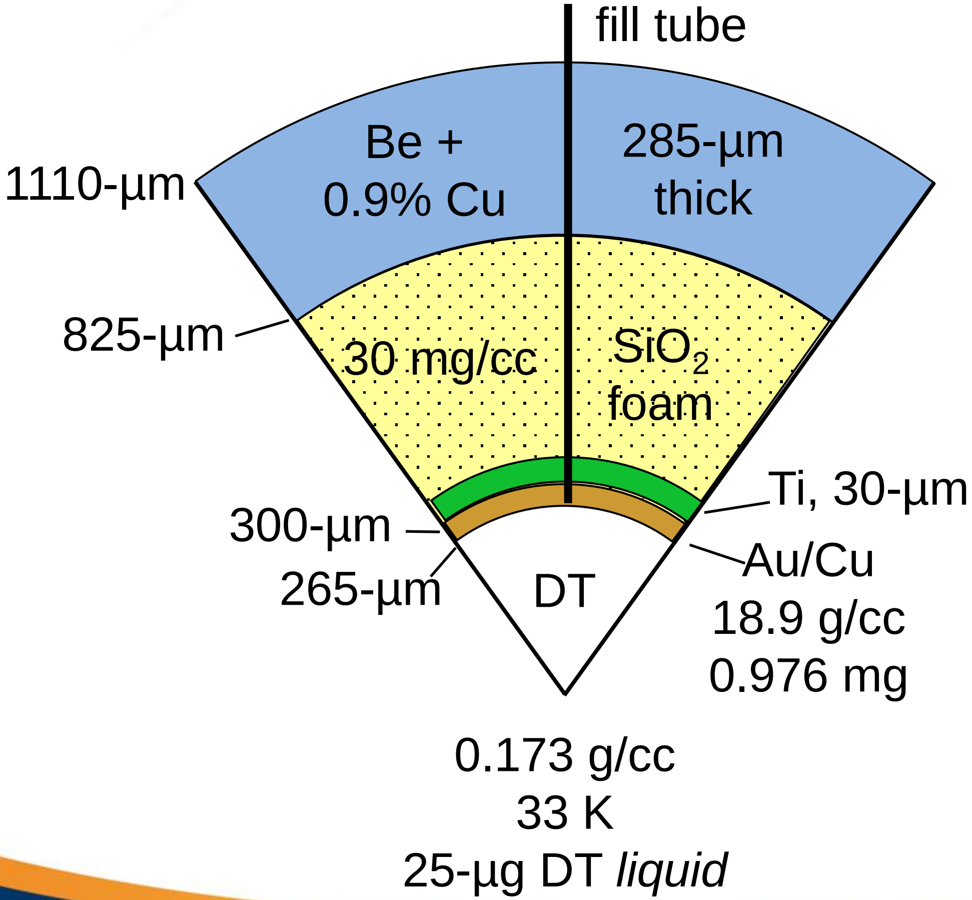
Still need to show that we can go to “high” CR (~20-25) and control



Au 575 +700 um hohlraum, Cryo-Tarpos
3.373 LEH diameter
0.032 mg/cc He hohlraum fill,
HDC undoped capsule



1.8-MJ design trades yield for performance by optimizing the pusher/fuel interface fall line



Fall-line-optimized double shell

- 1.8 MJ laser energy
- 4.5-ns reverse ramp pulse
- T_r = 308 eV
- 5.75-mm near-vacuum hohlraum (0.032 mg/cc He gas fill)

- 1-D clean yield ~ 2.1 MJ (29% burn)
- 1-D fall-line mix ~ 1 MJ (burn dudded behind fall line)
- 1-D RAGE + BHR mix ~ 0.9 – 1.4 MJ

2-D simulations for issues of mix, fill-tube, concentricity, etc. ongoing …