Stagnation and Burn Panel intro

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We have developed and validated a thermodynamic model fit to implosion data

- Analysis of THD & DT performance trends
  - Yield and Pressure are 3-20 times lower than post-shot simulation
  - We infer high Entropy in Hotspot, (large V, small P, small M)
  - Fuel rho-r consistent with nominal Fuel entropy, but large hotspot
  - Most likely sources of high Entropy Hotspot
    - Incomplete conversion of KE into compression (Hammer's talk)
    - Shock Mistiming/ 4th rise causing hot release of inner ice layer
    - Stronger & early 4th Shock, 5th Shock
    - Early termination of drive
  - We infer rho-r asymmetry & incomplete conversion of kinetic energy into compression
    - 3D shape , Shell breakup
  - We observe evidence of strong Mixing of ablator material into hotspot
    - Ablation front Growth factors, seeds

How Inertial Confinement Fusion works

1. Multiple shocks compress DT ice layer
   - Sets Fuel compressibility

2. DT layer accelerates to high velocity
   - Sets Implosion Energy , Mix

3. Hotspot is formed from deceleration & stagnation
   - Sets hotspot Adiabat, Mix, Shape

4. Alpha heating & bootstrap
   - Sets ignition threshold & gain

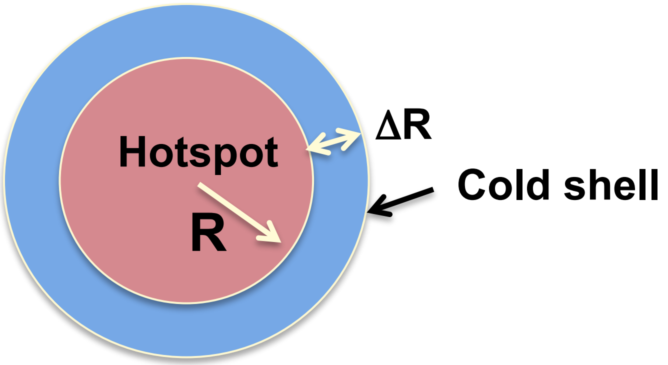
Implosion performance can be characterized by thermodynamic variables of the Hotspot and Fuel

Key Thermodynamic Variables

- Pressure
- Temperature
- Volume

+

- Energy ~ PV
- Mass ~ PV/T



Cold shell surrounds emitting hot spot

Why are these important?

$PV_{Tot} \sim E_{imp}$ Implosion Energy ~ $M v^2$

$PV^{5/3} \sim e^S$ Implosion Adiabat ~ $PV^{5/3}$, (very) sensitive to entropy $S_{hs,Fuel}$

$Y \sim P^2 T^2 V t$ Yield & Ignition threshold (P> 400 Gbar, T> 4 keV)

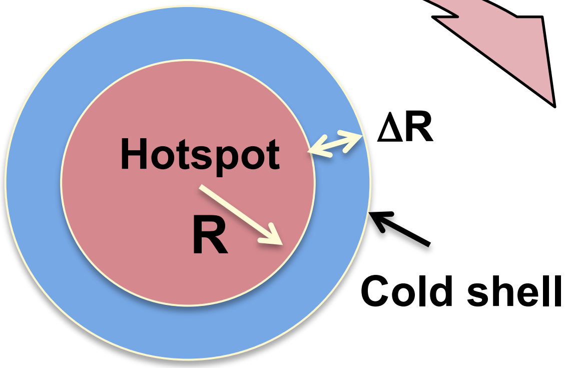
Measuring the pressure, temperature, and volume of the hotspot and fuel is important to understanding and optimizing the implosion performance

We infer the hotspot pressure, temperature, and volume using a static isobaric model fit to nuclear & x-ray data

Measured Hotspot Quantities

R_{hs}	Radius
τ_b	Duration
T_{hs}	Temperature
Y_{DT}	Yield

Inputs from experiment
- X-ray Images, waist & pole
- Burn history, x-rays
- Neutron time of Flight
- Activation
- Spectrum



Cold shell surrounds emitting hot spot

Derived Quantities

V_{hs}	Volume
ρ_{hs}	Density
P_{hs}	Pressure

Outputs from model

$$Y \sim n^2 \bullet \langle \sigma v \sim T^{4.5} \rangle \bullet Vol \bullet \tau_b$$

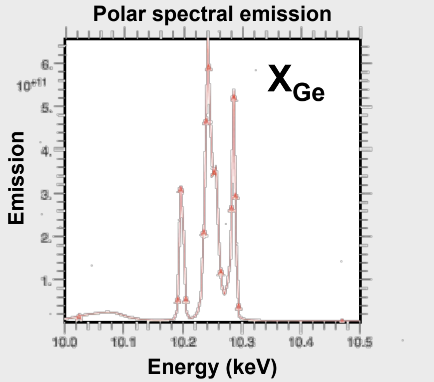
neutrons

X-rays (for now)

Hotspot Volume and temperature are measured and used to infer pressure
Cold Fuel properties further constrained by mass & neutron downscatter $\rho\Delta R$

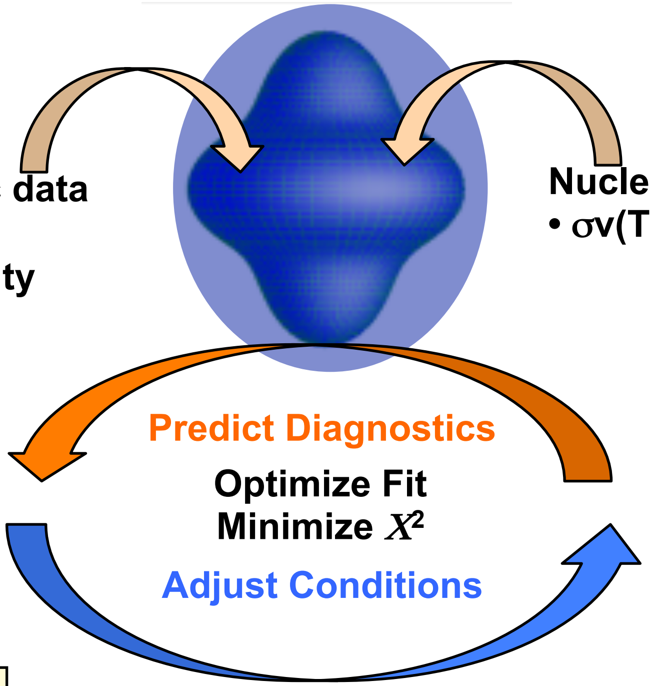
We actually use a 3D static model fit nuclear & x-ray data to derive implosion conditions on each shot

X-ray Spectrum



Composition

3D Hotspot Model



Atomic data
- EOS
- Opacity

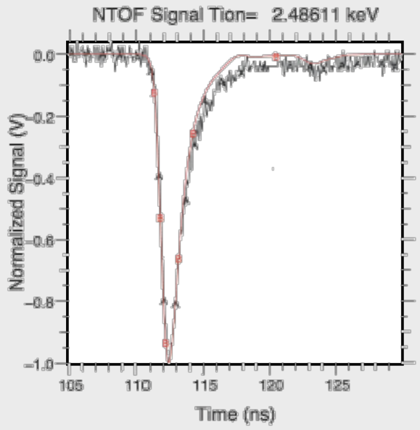
Nuclear data
- $\sigma v(T)$

Predict Diagnostics

Optimize Fit
Minimize X^2

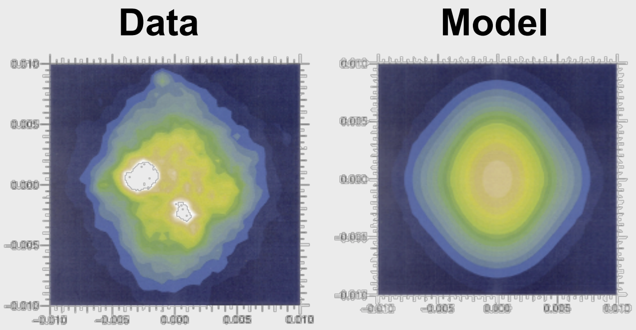
Adjust Conditions

Neutron Time-of-Flight Spectrum



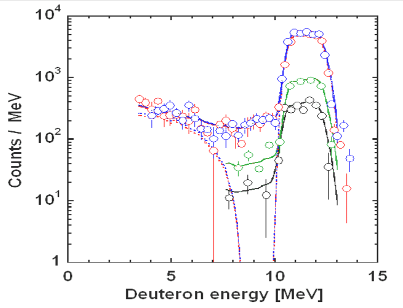
Temperature

X-ray Spatial Profiles



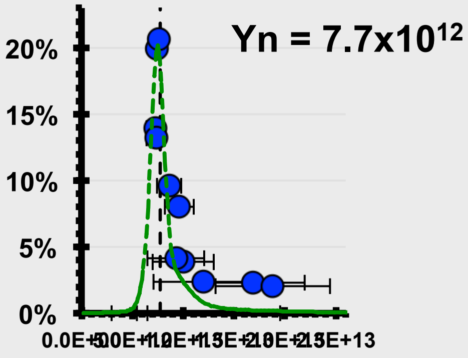
Volume

Neutron Down Scatter



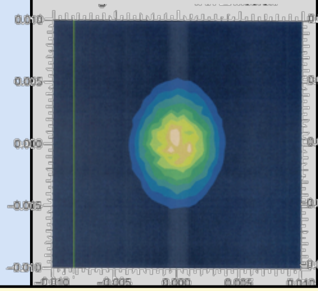
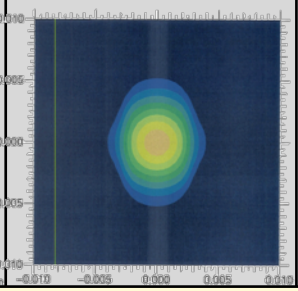
$\rho R = 0.48 \pm 0.04$ g/cm^2

Neutron Yield



Density

Validation studies in 2D indicate ~10% accuracy in hotspot pressure, density, and total energy

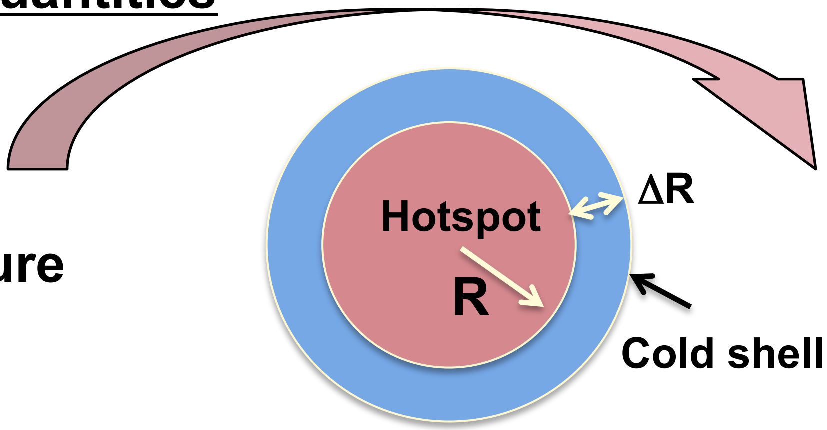
Implosion Metric	Simulation	Model Fit	Relative Error %	Spatially uniform approx
Ti (keV)	3.20	3.42	7	3.4
ρ_{ion} (g/cm^3)	23.9	24.0	1	22
Mass (μg)	18.9	20.2	6	11.5
Volume (μcm^3)	50.3	50.3	1	50.3
Energy (kJ)	6.54	6.48	-1	5.78
P (Gbar)	69.8	68.0	-1	73
Yield 10^{11}	1.05	1.07	2	1.07
X-ray image				

We have not completed the validation of accuracy for cold shell properties & total energy (initial estimates are 20-30 %)

An “idealized” uniform hotspot model provides simple estimate for pressure and expected accuracy

Measured Hotspot Quantities

R_{hs}	Radius
τ_b	Duration
T_{hs}	Temperature
Y_{DT}	Yield



Cold shell surrounds emitting hot spot

Derived Quantities

V_{hs}	Volume
ρ_{hs}	Density
P_{hs}	Pressure

$$Y_{DT} = 6.023e23\ \underbrace{(\rho_{hs}/2.5)^2 X_D X_T}_{\text{ND * NT}}\ \underbrace{\sigma v(T_{hs})}_{\text{Fusion } \sigma}\ \underbrace{4\pi/3\ R_{hs}^3}_{\text{Volume}}\ \underbrace{\tau_b}_{\text{Duration}}$$

🟨 Measured

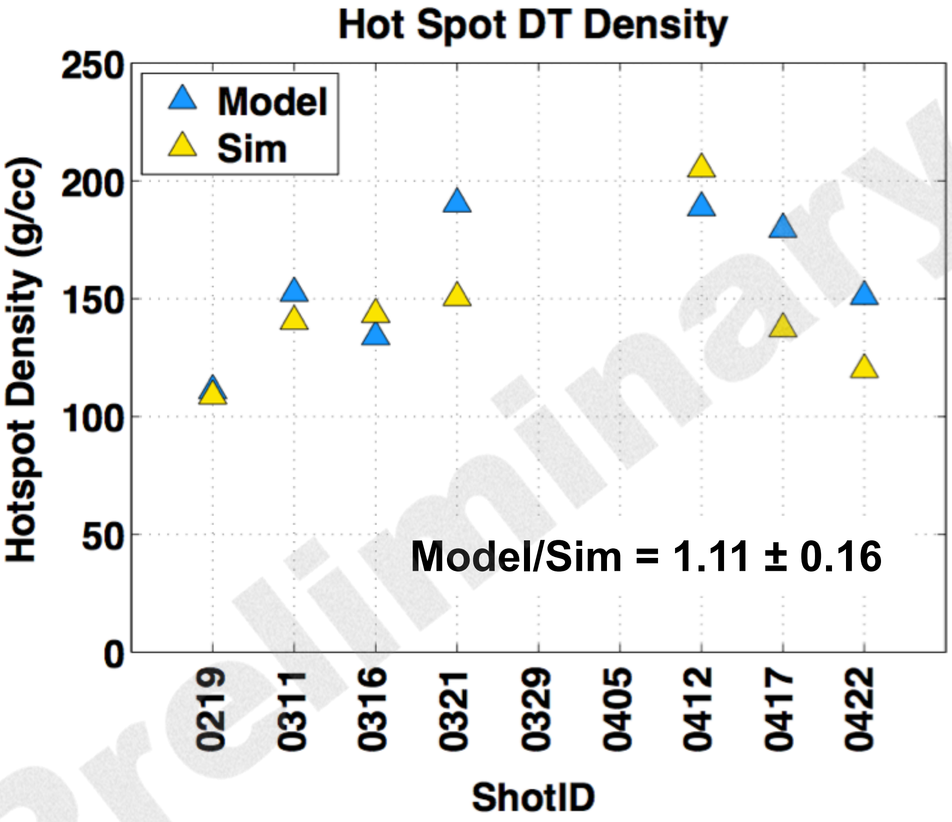
🟦 Inferred

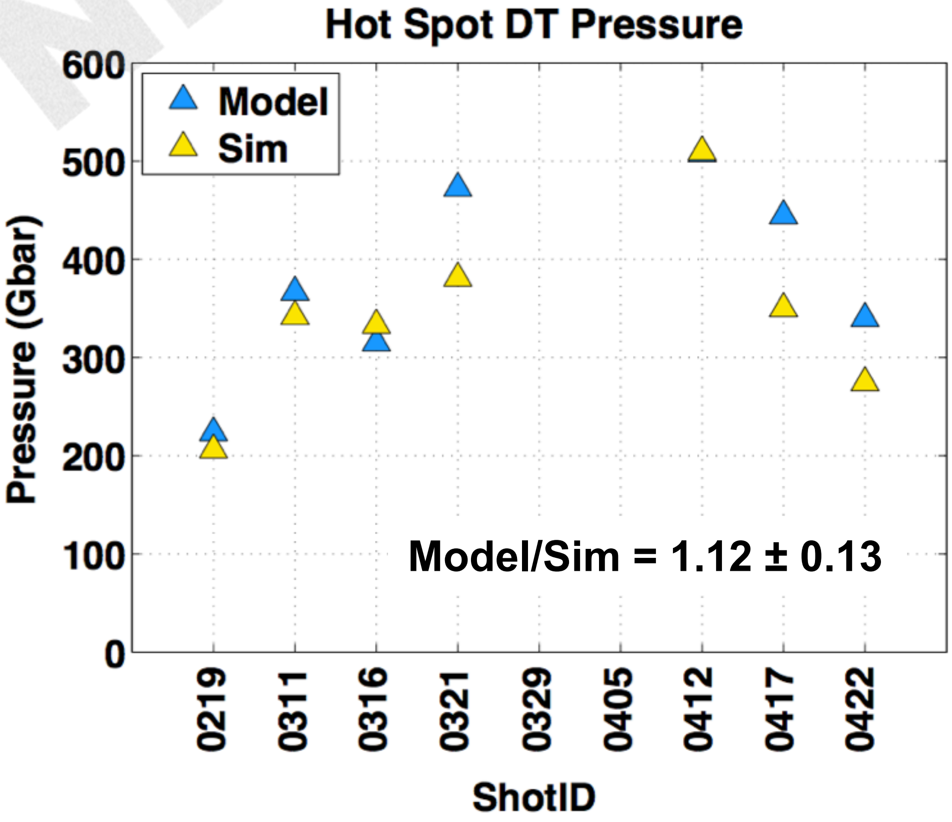
$$\boxed{P_{hs} = 0.772\,\rho_{hs} T_{hs} = 1.167e\text{-}14\, Y_{DT}^{1/2} X_D^{-1/2} X_T^{-1/2} T_{hs}^{-1.05} R_{hs}^{-3/2} \tau_b^{-1/2}}$$

20 % 20% 5% 5% 5% 20%

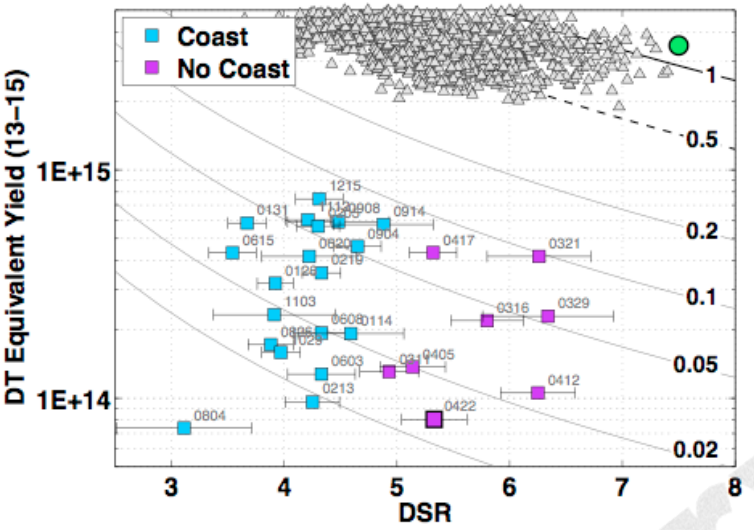
The model has been validated using 2D HYDRA synthetic data – agreement in ρ, P is better than 12%

- As input to model we used simulated Yield, Tion, XrayP0, XrayP2P0, XrayM0, XrayBW from 7 postshot simulations (Oggie's)
- We calculate model density and pressure and compare with HYDRA burn-weighted density and pressure

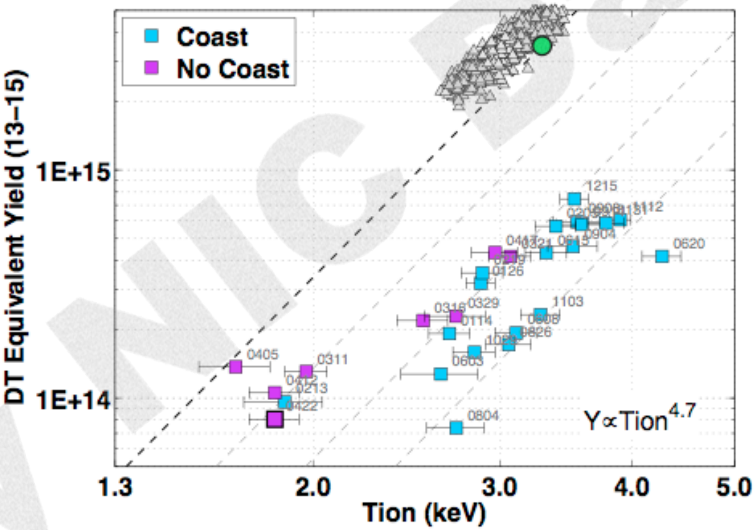




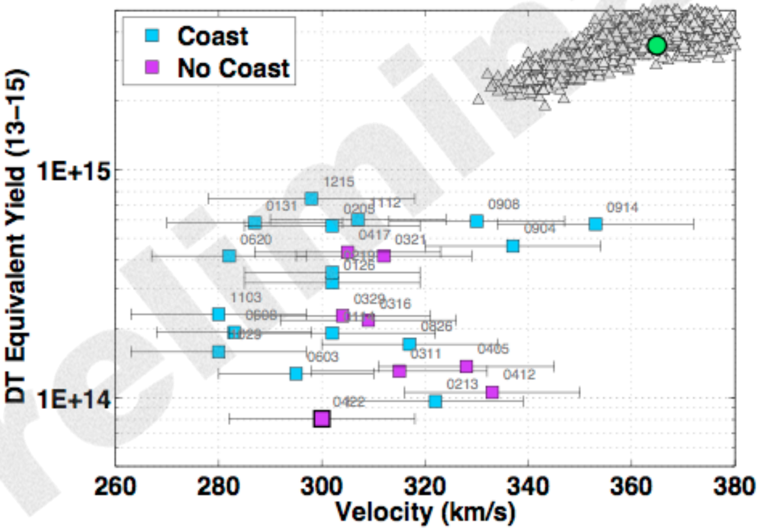
Yield and Pressure are 3-20 times lower than post-shot simulation



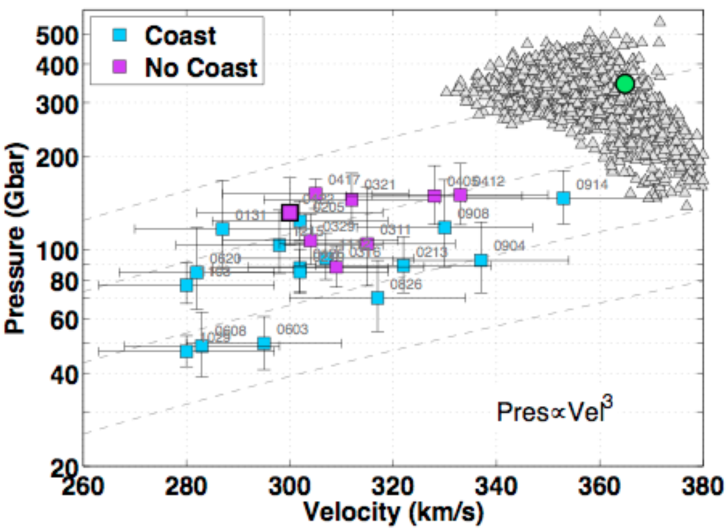
ITFX



Yield vs. Tion



Yield vs. Velocity

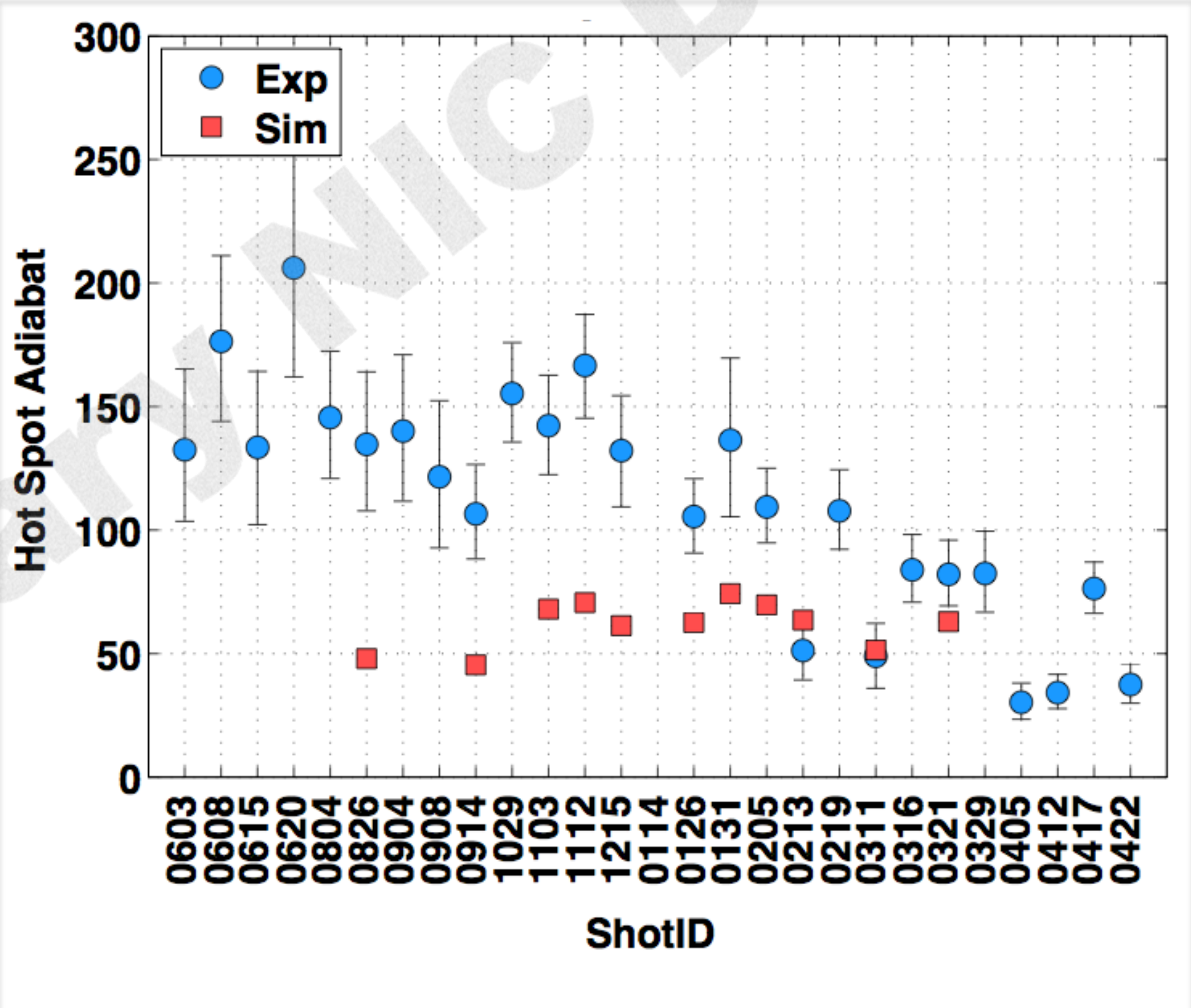


DT Pressure vs. Velocity

The Hot spot adiabat is typically 2-3 times larger than desired

- Current implosions have v~300km/s
- Anticipate higher stagnation adiabat at 370 km/s counter balanced by less coasting
- Analysis on going

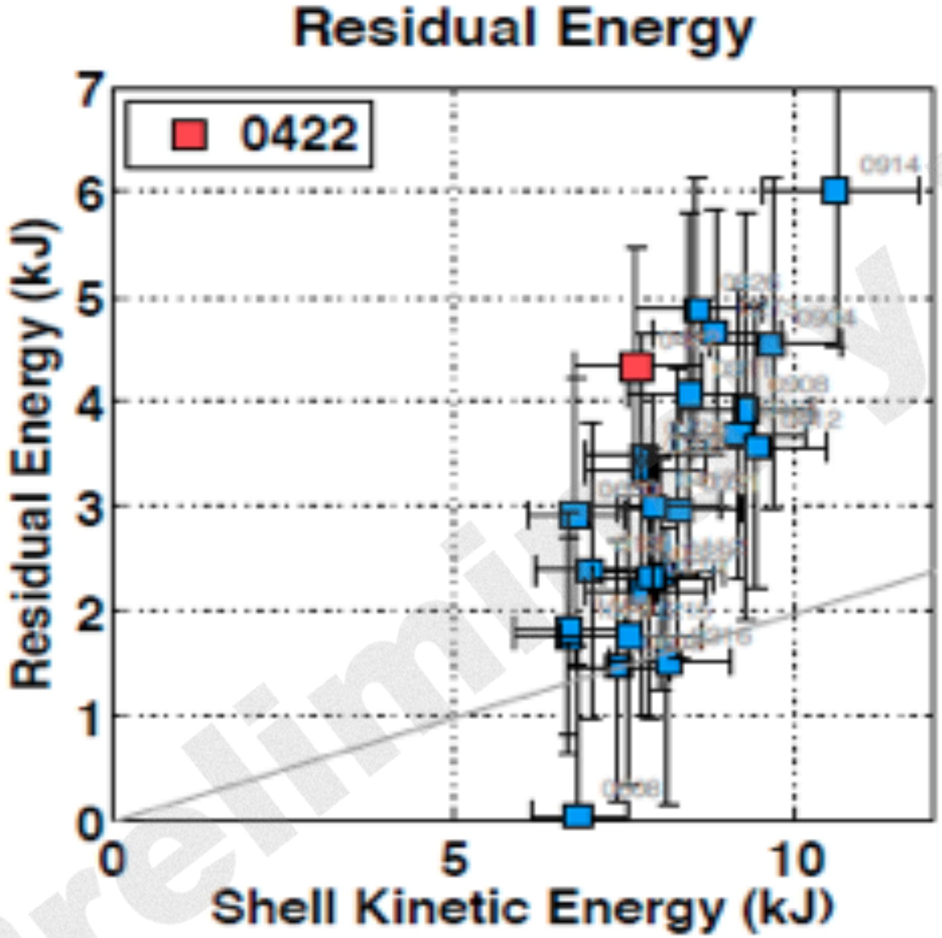
Hot spot adiabat



Springer/Cerjan analysis

We infer an incomplete conversion of kinetic energy into compression possible related to rho-r asymettry

Deficit of PV energy of the Fuel at stagnation relative to known fuel kinetic energy

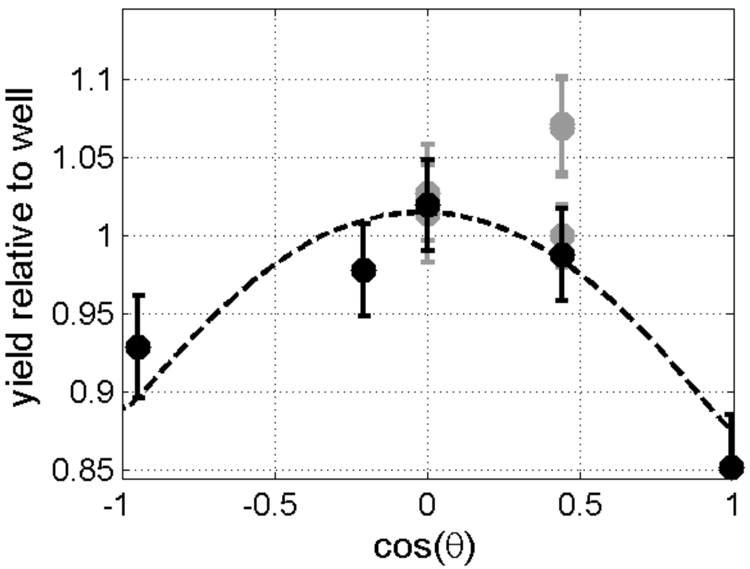


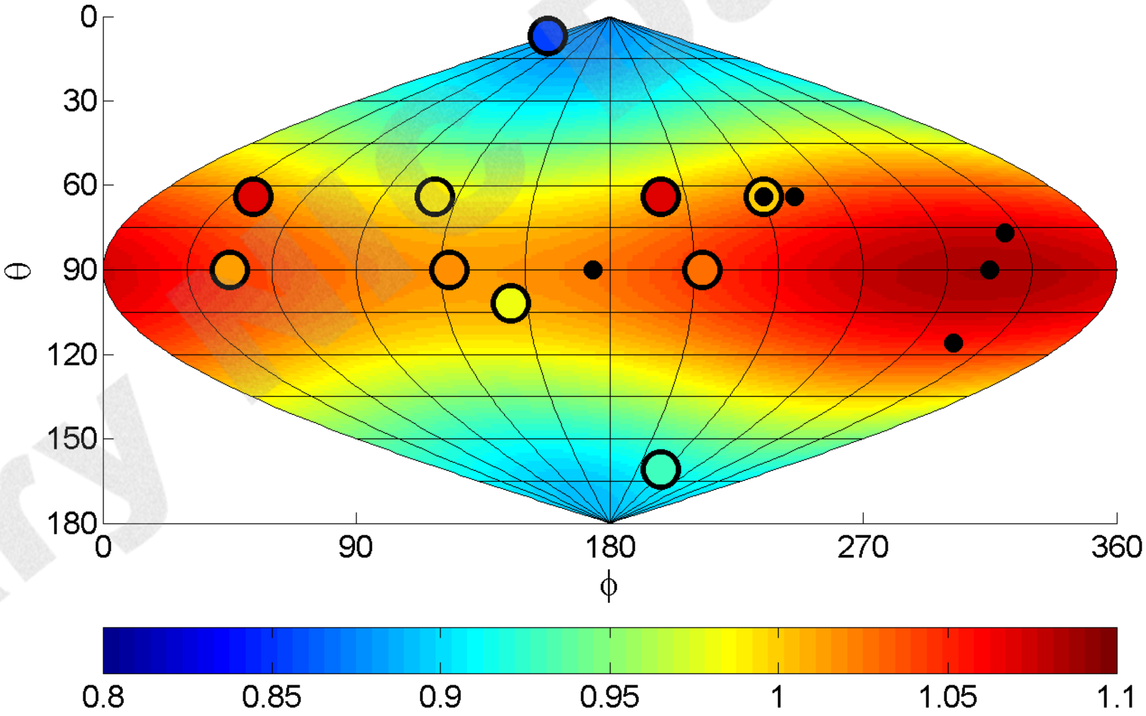
Energy and Adiabat determine Pressure

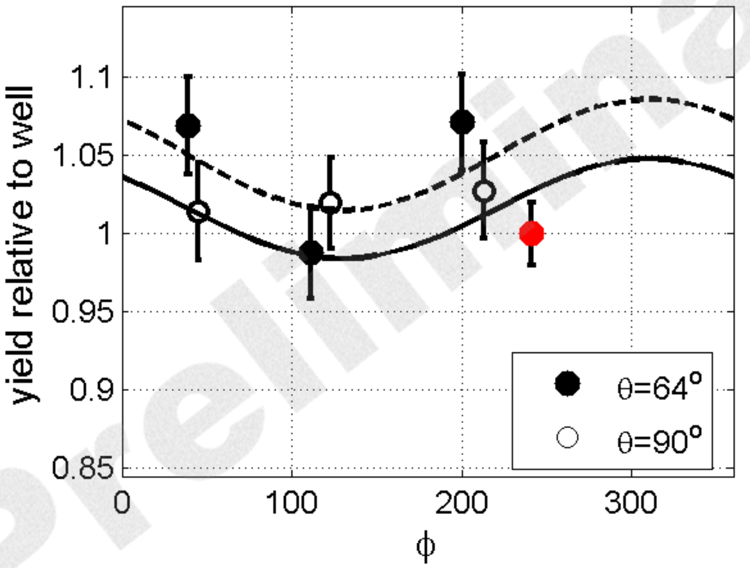
- $E = 3/2\ P(V_{hs} + V_{fuel})\ \sim ½\ Mv^2$
- $P = 4/100^{5/3}\ \alpha\ (M/V_{fuel})^{5/3}$

$$P\ \sim 2.5e\text{-}35\ \alpha^{-3/2}\ (E_{tot} - E_{hs} - E_{res}\ /M_{fuel})^{5/}$$

N120205-002 Rho-r asymmetry at stagnation



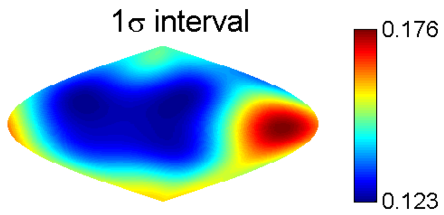




a_0=0.9952
a_{10}=-0.006284
a_{11}=0.0228
a_{1-1}=0.02728
a_{20}=-0.05477

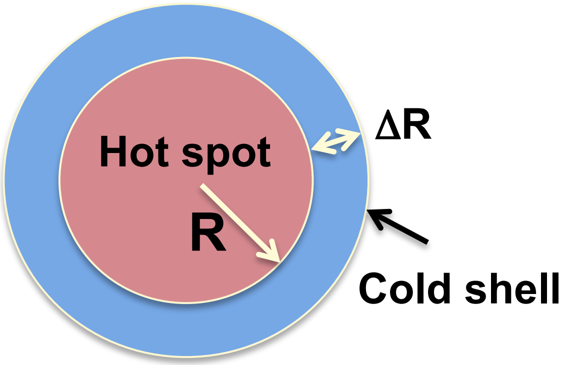
Well-NAD: 1.0272
MRS: 1.0744
nToF BT: 1.0332
SpecA: 1.0535
specE: 1.0249
NI(90-315): 1.086

|Y1m|: 0.036104 +- 0.061907
adjR^2=0.448



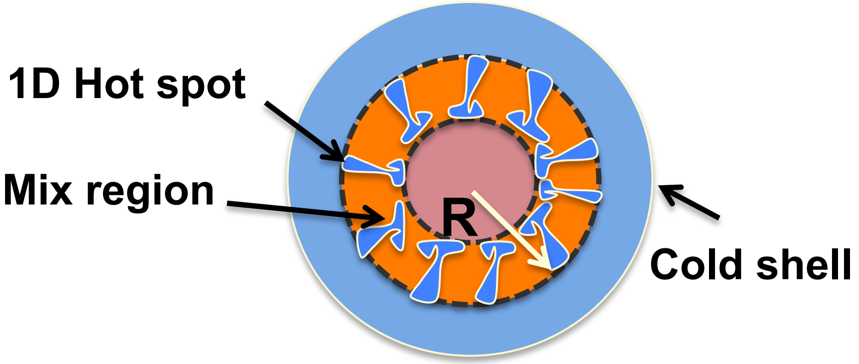
In 3D the hotspot can appear to be smaller than the 1D implosion.

1-D Implosion



Cold shell surrounds emitting hot spot

3-D Implosion



- Mix region too cold to emit neutrons/ x-rays too hot to compress.
- $R_{hs} < (M_{fuel} / 4\pi \rho r_{fuel})^{1/2}$

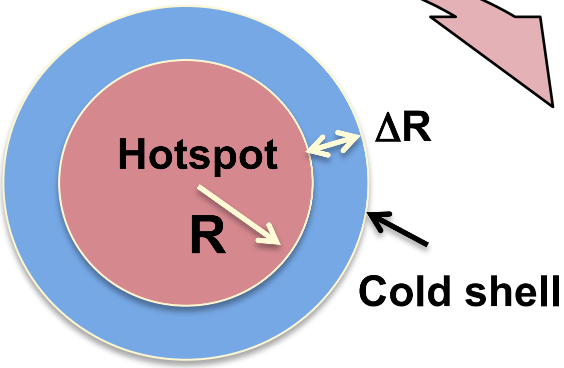
We infer the minimum and maximum stagnation PV energy using two extremes
1.) Smallest Fuel volume (Place Fuel in close to hotspot, minimize Fuel mass)
2.) Largest 1D hotspot (Maximize 1D hotspot, use all 170 ug mass)

We infer the mix mass and shell attenuation by adding impurity to match x-ray yield data

Measured Hotspot Quantities

R_{hs}	Radius
τ_b	Duration
T_{hs}	Temperature
Y_{DT}	Yield

Inputs from experiment
- X-ray Images, waist & pole
- Burn history, x-rays
- Neutron time of Flight
- Activation
- Spectrum
- X-ray Yield



Cold shell surrounds emitting hot spot

Derived Quantities

V_{hs}	Volume
ρ_{hs}	Density
P_{hs}	Pressure

Outputs from model

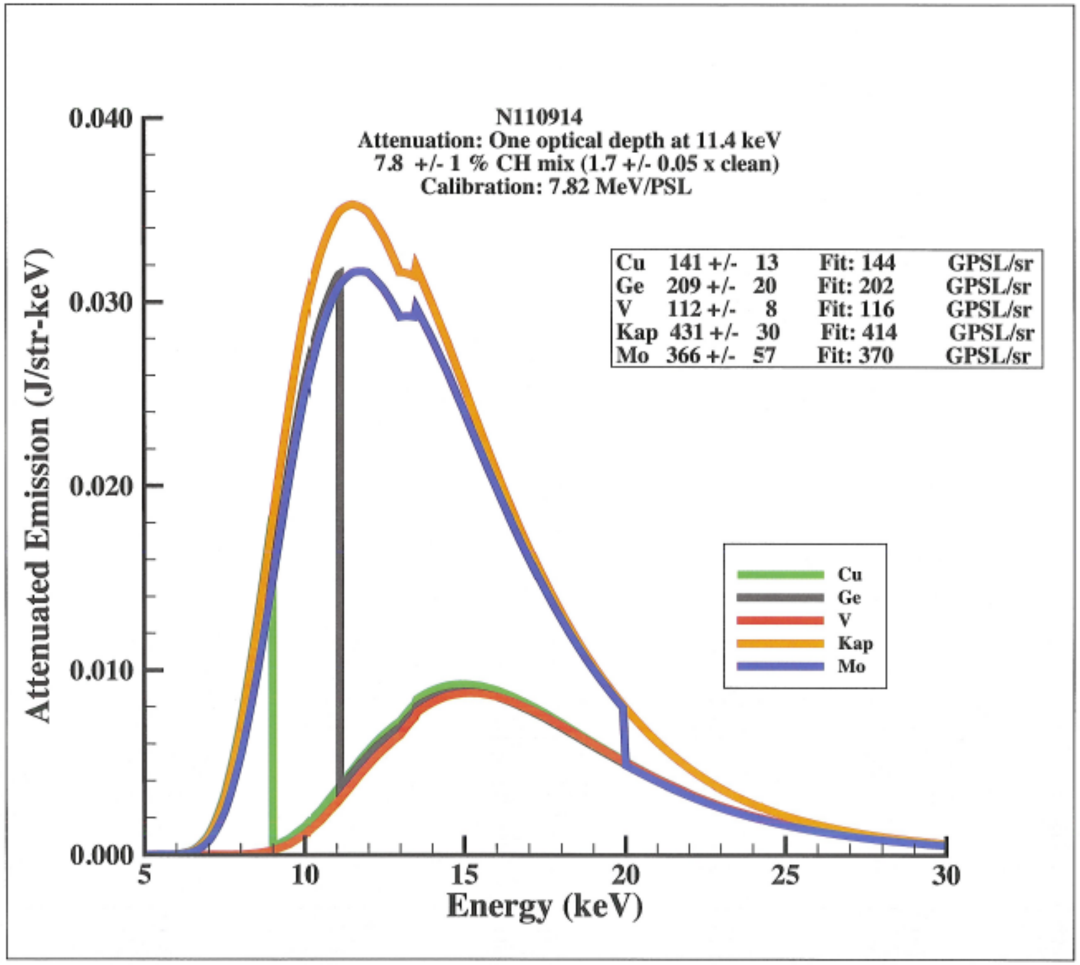
$$Y_x \sim n_{DT}^2 \cdot Vol \cdot \tau_b \cdot \langle Bv\ K_{ff}\rangle (1+xZ)(1+xZ^2)\ \tau_{shell}$$

X-rays

Impurity concentration
(2% CH doubles emission)

X-ray emission can be used to determine impurity mix and pressure providing we have absolute calibration of x-ray yield and account for absorption through shell

We observe evidence of Mixing of ablator material into hotspot – and agreement between x-ray and neutron Y

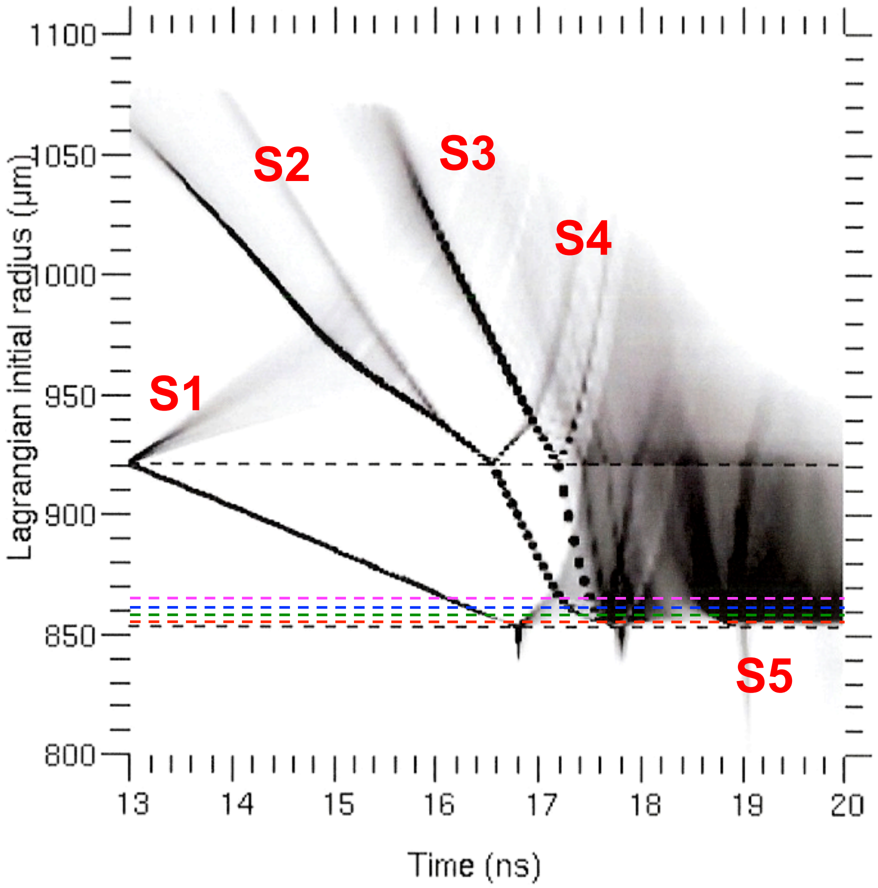


N110914 with a mix mass of 7.8 +/- 1 % (448 +/- 50 ng) matches all Ross pair channels to 5%

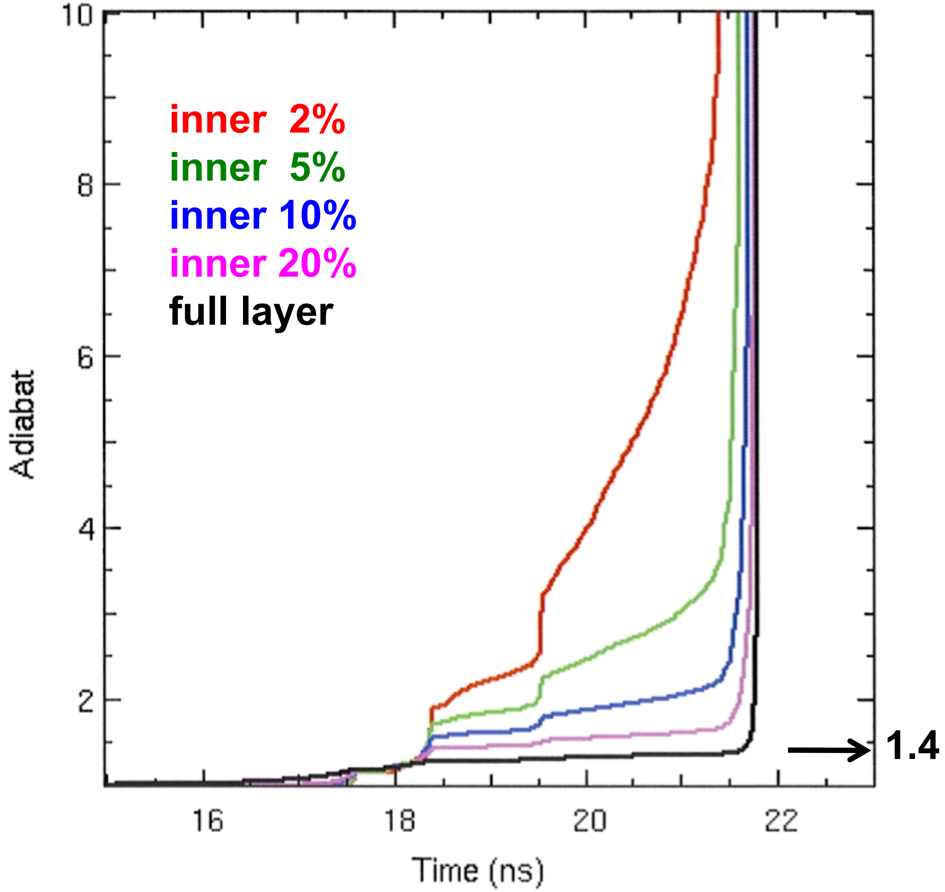
Shell attenuation of 5 +/- 1% at 8 keV from Cu – V data

1. Multiple shocks compress DT ice layer

Rev 5 shock trajectories



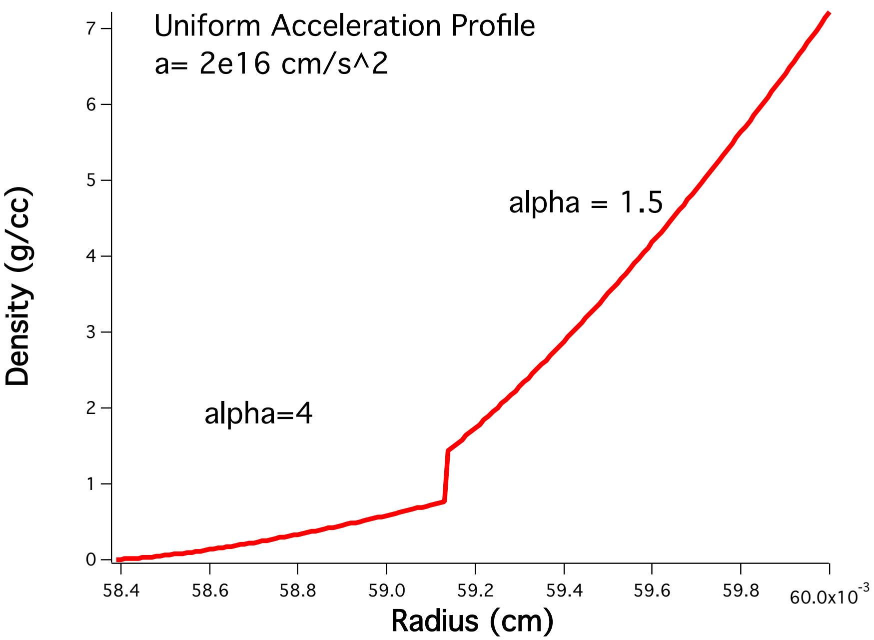
Rev 5 Fuel adiabat history

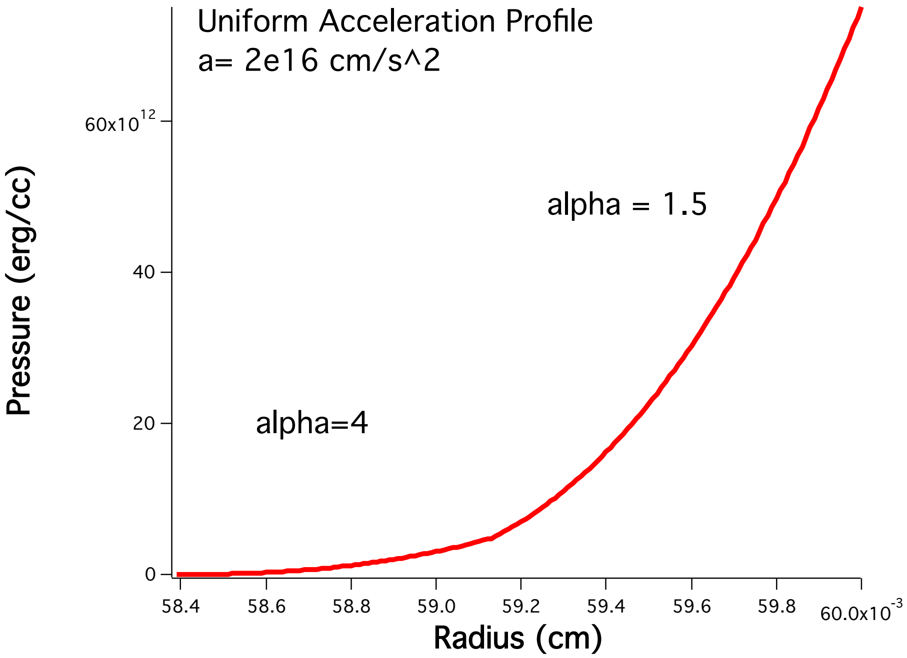


- Shock timing & fifth shock set inflight adiabat
- Inner 5% (mass 8 ug) has adiabat < 4 prior to stagnation
- Hotspot adiabat (mass 8 ug) 60 – 200 is acquired during stagnation

2. DT layer accelerates to high velocity

Fuel density depends on acceleration $P = \rho r a \sim \alpha \rho^{5/3}$





Thickness ~ 16 um, Sound speed ~ 40 km/s -> 400 ps transit time

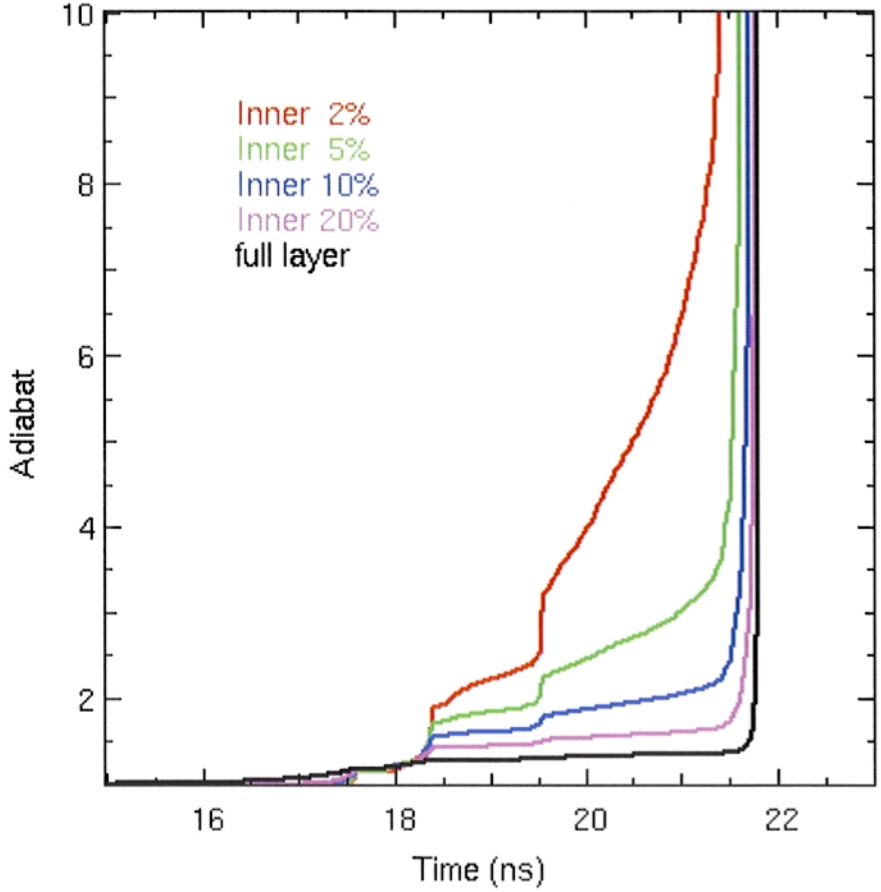
“Coasting” sudden drop in acceleration from outside, inside still accelerates

Fuel can develop a differential velocity
Thickness increases, density drops

dv = a dt = 80 km/s
2 fold in 400 ps

3. Hotspot is formed from deceleration & stagnation

Rev 5 Fuel adiabat history



- Hotspot adiabat (60- 200) is much higher than inflight values
  - Heat flow from the hotspot
  - Stagnation with hotspot

How Inertial Confinement Fusion works

1. Fuel assembly
   - Conversion efficiency of kinetic energy into PV energy
   - Rho-r asymmetry
   - Roles of target features (capsule roundness, fill tubes, holes in hohlraum)
   - Laser issues – beam imbalance, x-beam transfer, power imbalance
   - Diagnostics – need movies of final assmebly

2. Hotspot Formation
   - Stagnation versus inflight adiabat?
   - Role of coasting on hotspot adiabat?
   - Do we have a 5th shock?
   - Magnetic Fields – dense materials in hotspot w/o cooling
   - Role of kinetics, species separation
   - Mat'l properties (EOS, opacity, conductivity,)
   - Turbulent energy in HS, Fuel

How Inertial Confinement Fusion works

3. Transport in hotspot (radiation, conduction, particle)
   - Mat’l properties
   - Radiative loss
   - electron ion equilibrium?
   - Do we have strong magnetic fields & what is their consequence?
   - Maxwellian ion electron distributions?

NIC