National Implosions Stagnation Physics Working Group

LLNL

Pravesh Patel on behalf of ICF Team

October 27-28, 2015

LLNL-PRES-677148
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Stagnation

- 3D asymmetry (inefficient conversion of energy)
- Temperature (3D, 1D physics?)
- Fuel areal density (3D, 1D physics?)

Outline

- **Hot spot shape**
  - Hot spot size and shape at stagnation
  - Time-dependent swings in hot spot emission
- **Hot spot flow**
  - Residual flow velocity in hot spot
  - Residual flow velocity, or kinetic energy, in fuel/ablator
- **Hot spot temperature**
  - Ti and Te
- **Fuel areal density and asymmetry**
  - Fuel configuration at stagnation
  - Time-dependent swings in dense shell

Hot spot shape measurements for understanding stagnation in IDI

10/28/2015

National Implosion Stagnation Physics Working Group Meeting

A. Pak, N. Izumi, S. Nagel, P. Patel, T. Ma, et al.

LLNL-PRES-677148
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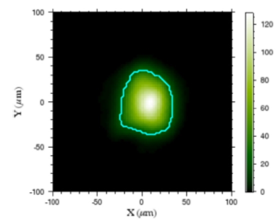
X-ray and nuclear self-emission imaging provide clues about the stagnating plasma

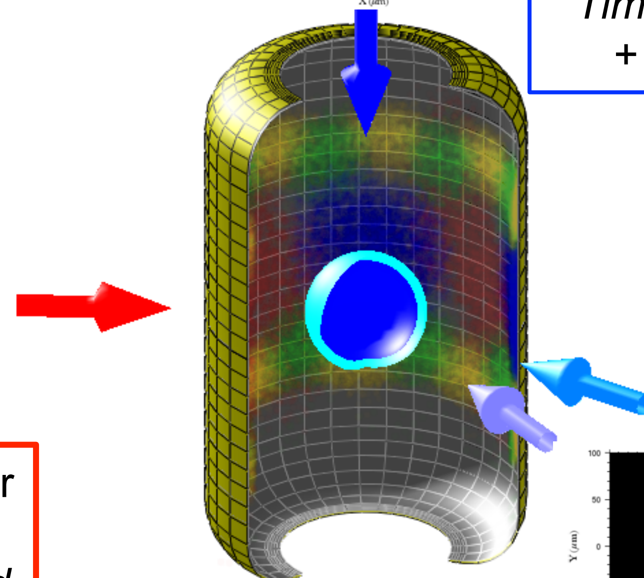
- X-ray and neutron images are recorded from multiple lines-of-sights
  - We are working on various methods to reconstruct the 3D hotspot, and check for consistency between the different imaging techniques/view angles
  - Higher temporal and spatial resolution imaging highlights small-scale features in our hot spot we did not see before

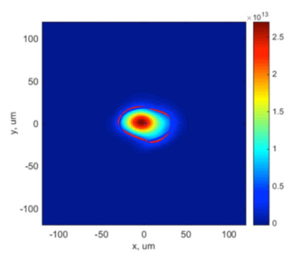
- Time-dependent swings in symmetry have been observed for many of our best performing implosions
  - Swings are indicative of inefficient conversion of kinetic energy into thermal energy of the stagnating plasma (RKE)
  - We are working to assess the relationship between in-flight and hot-spot symmetry to better understand the temporal evolution of the implosion
  - We have a set of diagnostics & platforms to measure the shape evolution throughout the implosion; however, more diagnostics are needed to better constrain symmetry!

We use 3 x-ray and 1 neutron imager on current implosion shots on NIF

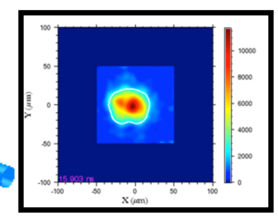


GXD/HGXD
X-ray camera
(θ,ϕ)=(0,0)
Time-resolved: 100ps
+ Time-integrated

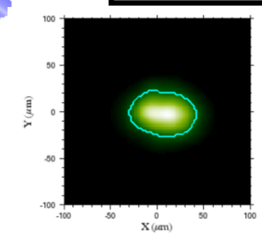




Neutron imager
(θ,ϕ)=(90,315)
Time-integrated



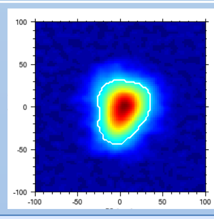
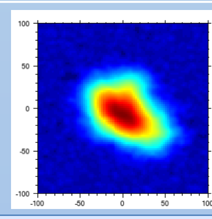
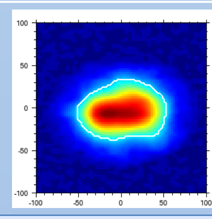
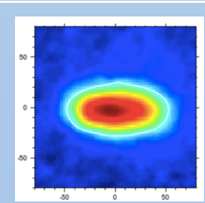
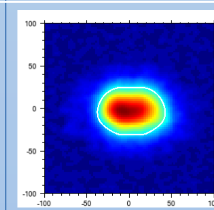
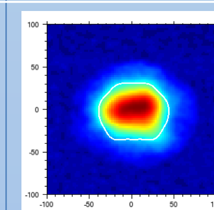
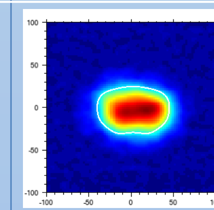
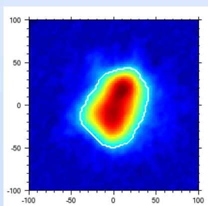
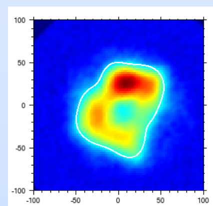
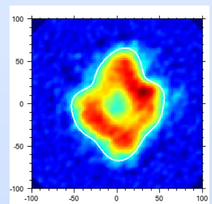
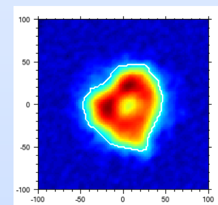
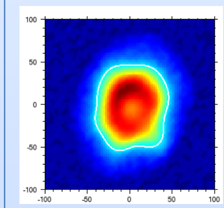
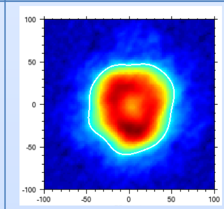
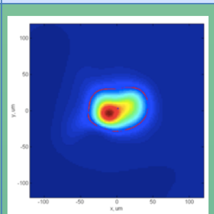
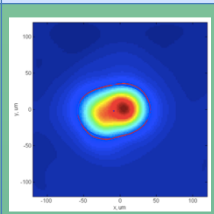
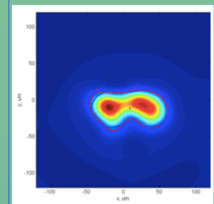
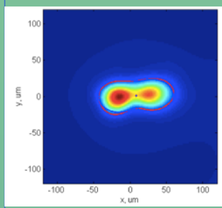
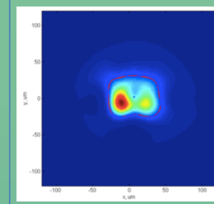
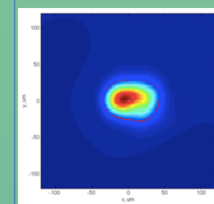
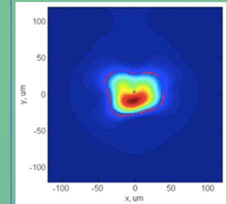
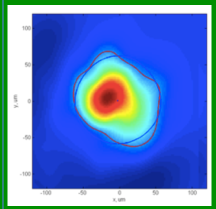
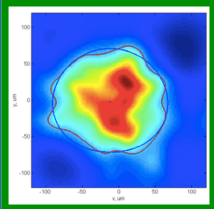
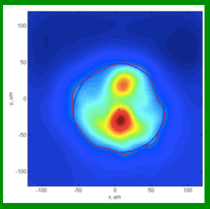
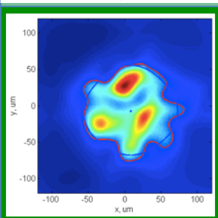
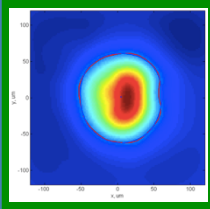
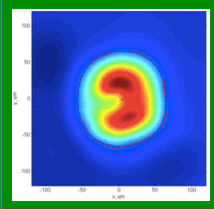
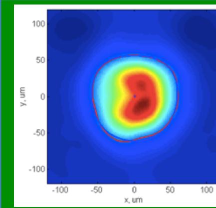
DIXI
X-ray camera
(θ,ϕ)=(90,100)
Time-resolved: 10 ps
+ Time-integrated



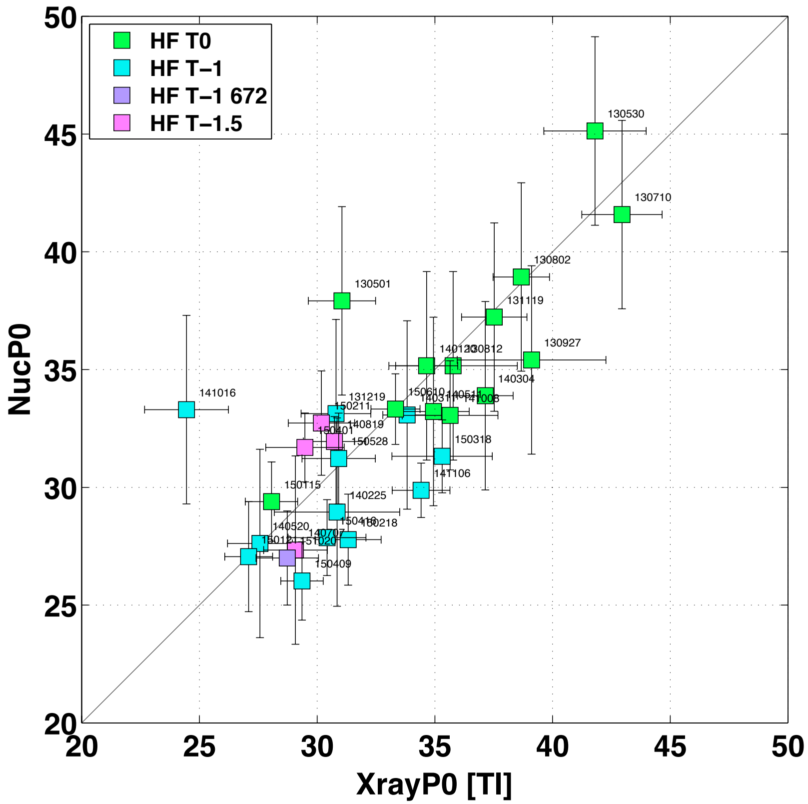
GXD/HGXD
X-ray camera
(θ,ϕ)=(90,78)
Time-resolved: 100ps
+ Time-integrated

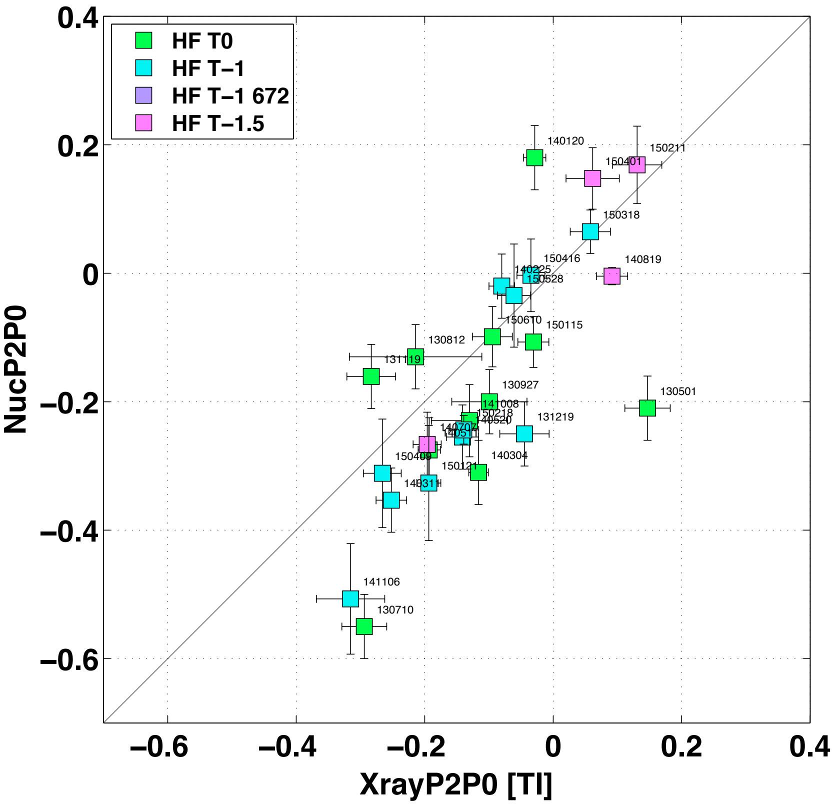
Because of the azimuthal asymmetry of the core, cannot directly compare x-ray and neutron images

Examples of images acquired for the T0 high-foots show variation from different LOS, type of imaging

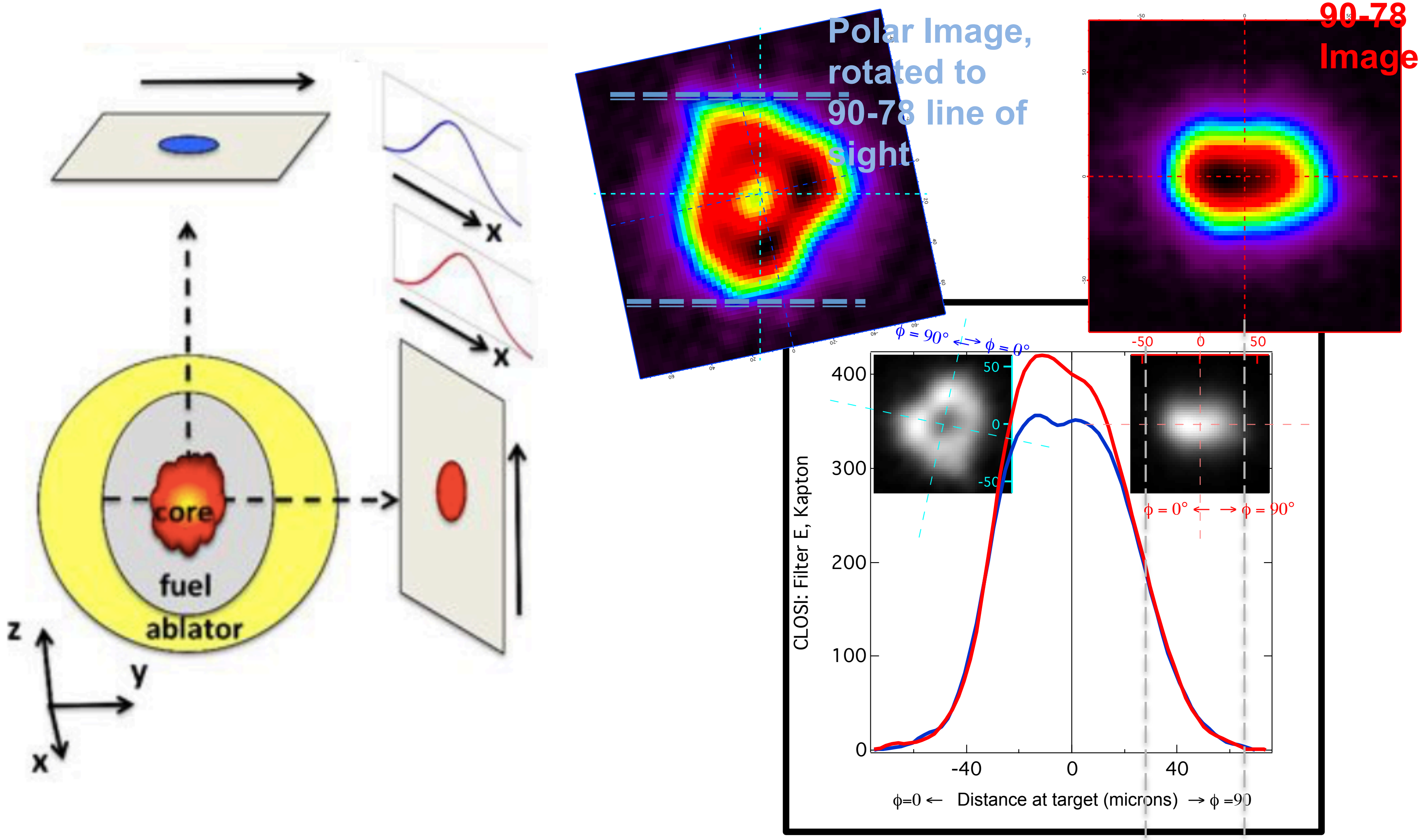
	N130501 350TW, 1.3MJ Δλ = 8.5 / 7.3	N130530 430TW, 1.5MJ Δλ = 8.5 / 7.3	N130710 430TW, 1.5MJ Δλ = 8.5 / 7.3	N130802: +700 430TW, 1.5MJ Δλ = 9.4 / 8.4	N130812 350TW, 1.7MJ Δλ = 8.5 / 7.3	N130927 395TW, 1.82MJ Δλ = 9.2 / 8.5	N131119 410TW, 1.88MJ Δλ = 9.5 / 8.8
X-Ray > 6 keV **Equatorial (90-78)**							
X-Ray > 6 keV **Polar (00-00)**		Polar detector not run					
Primary (13-15 MeV) Neutron Image **Equatorial (90-315)**							
Downscatter (10-12 MeV) Neutron Image **Equatorial (90-315)**							
Yield (DT)	**7.67 ± 0.16 e14**	**5.8 ± 0.12 e14**	**1.05 ± 0.02 e15**	**4.83 ± 0.19 e14**	**2.4 ± 0.0 5e15**	**4.4 ± 0.11 e15**	**5.22 ± 0.10e15**

Nuclear and x-ray P0's typically agree to within 10%; higher modes deviate

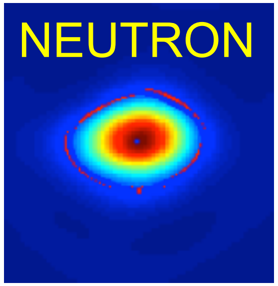


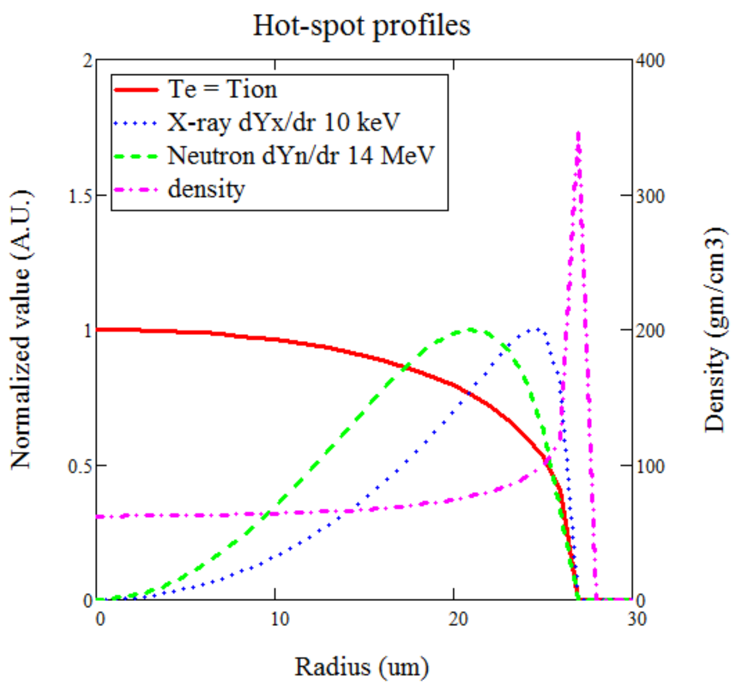


Common Line-of-Sight Integrals (CLOSI) directly compare orthogonal images by collapsing to 1D



X-ray and neutron images represent conditions at different radii of the core





X-ray emission per mass

$$\eta_\nu \approx \frac{16\pi}{3\sqrt{6\pi}} \frac{e^6}{m_e^2 c^3} \frac{Z_i^2 n_e}{\sqrt{k_B T_e / m_e} A m_p} \exp\left(-\frac{h\nu}{k_B T_e}\right)$$

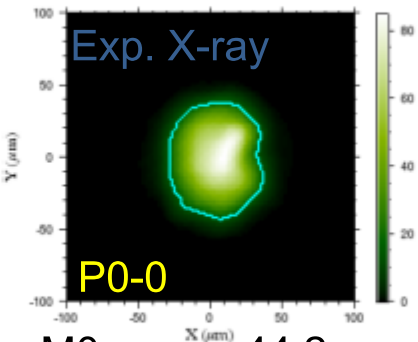
Neutron emission per volume

$$\frac{d^2 Yn}{dr \cdot dt} = 4\pi r^2 \times C_D C_T n^2 \left\langle \sigma v(T_{ion}) \right\rangle_{DT}$$

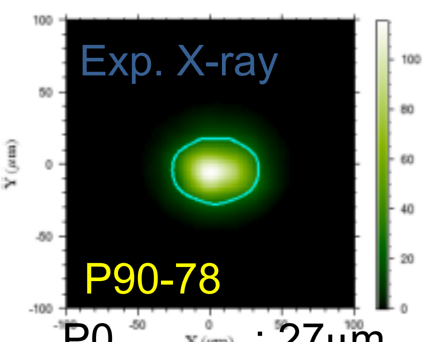
X-ray and Neutron production have different temperature and Z dependence

N. Izumi, IFSA 2015

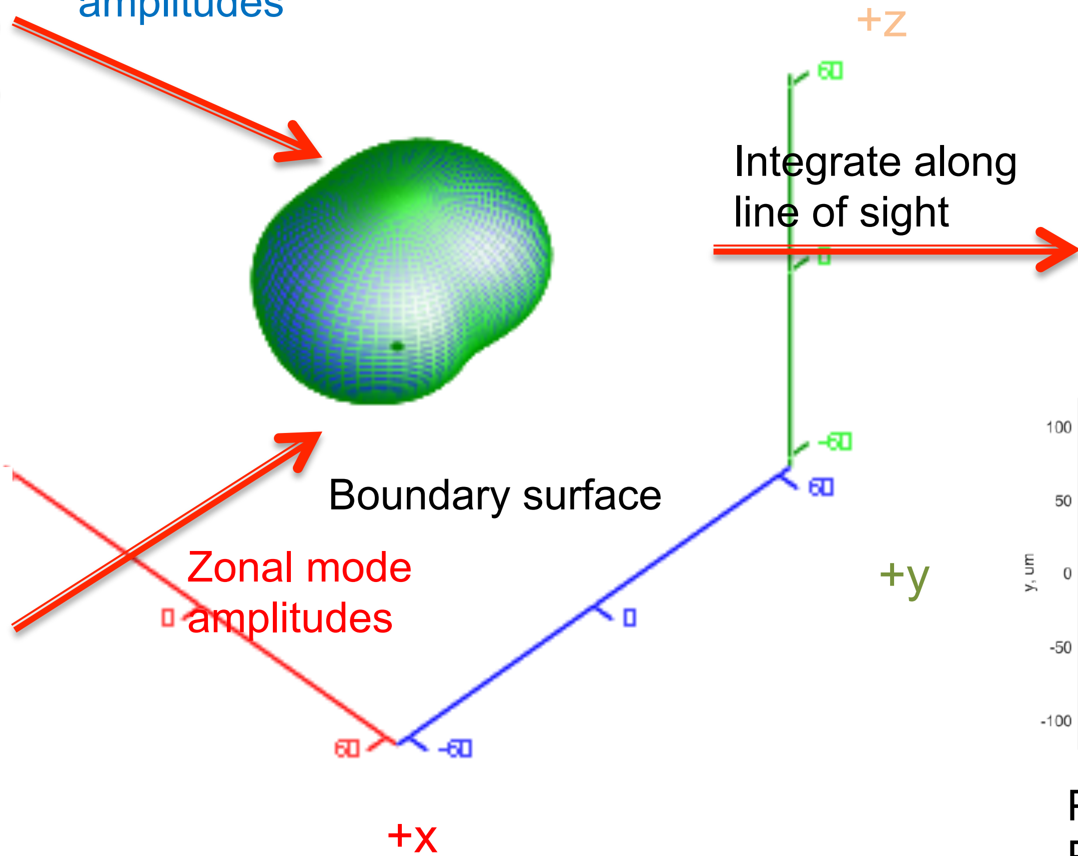
Projecting observed low mode shape to an "expected" image on 90-315 shows x-ray image agrees with neutron size for DT layered shots



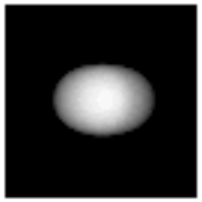
M0 :44.2μm
M4/M0 :12%



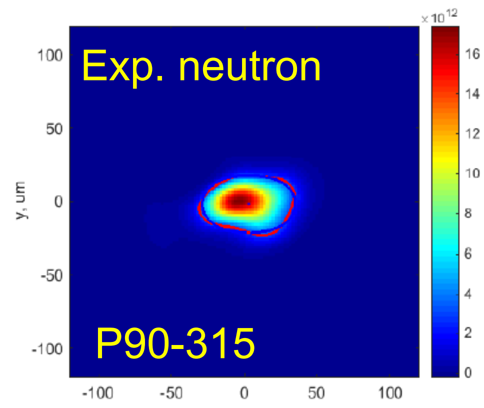
P0 : 27μm
P2/P0 :-19%



Inferred x-ray
P90-315



Inferred shape value
P0 : 30.6μm
P2/P0 : -23%



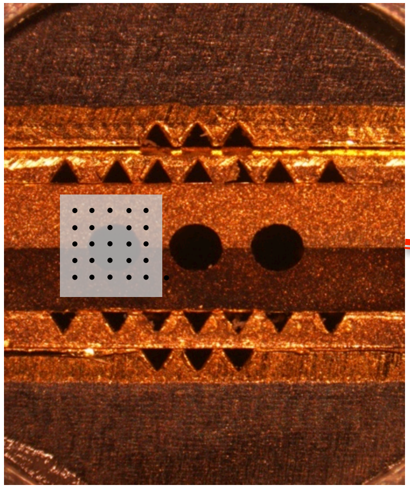
P0 : 27 ± 2 μm
P2/P0 : -33 ± 8 %

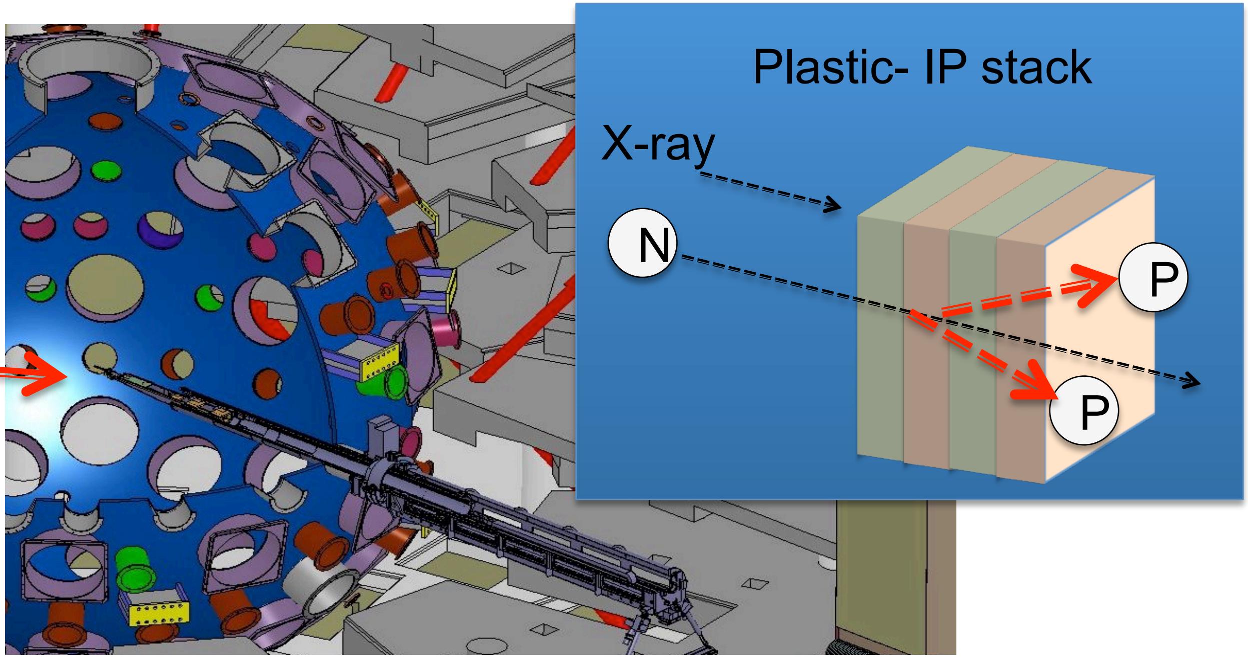
A co-aligned neutron x-ray imager (CNXI) will start providing images on the same line-of-sight

CNXI is a x-ray pinhole imager installed in the path of the neutron penumbral imager

X-ray and neutron images are recorded by stack of imaging plates and plastic n-p converter

Neutron /x-ray pinholes

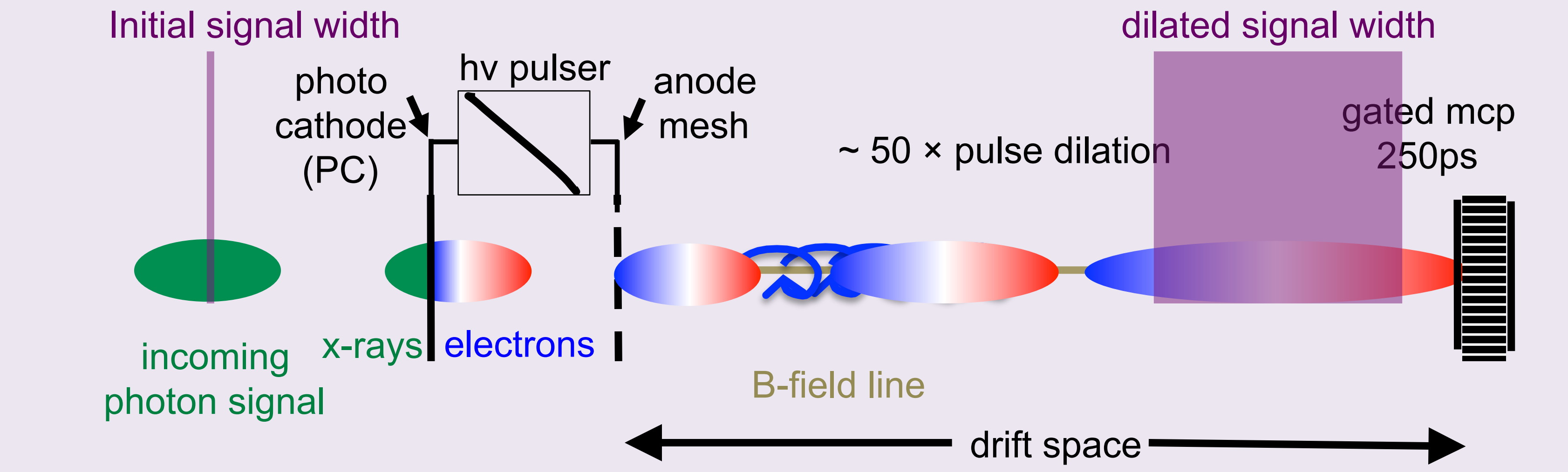




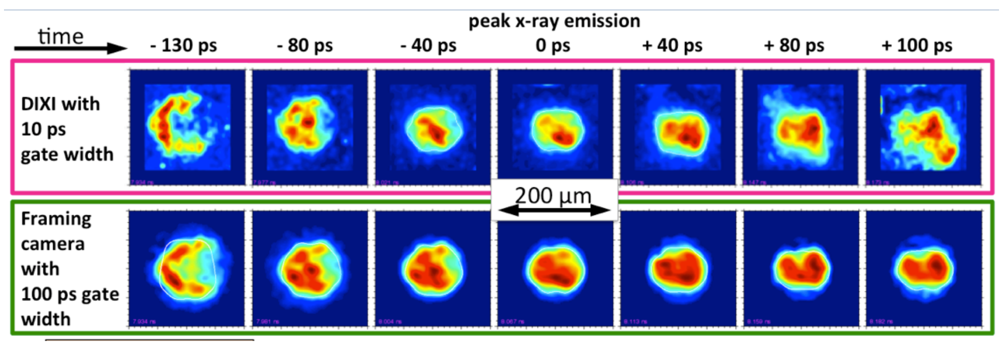
CNXI will provide the relation between the x-ray and neutron images to allow us better use of the neutron images for understanding stagnation.

The new DIXI (dilation x-ray imager) is the fastest x-ray imager built to date (<10 ps)

Working principle



Photoelectrons → accelerated by a time varying electric field → energy dispersion → signal stretches as it traverses the drift region → sampled by gated mcp

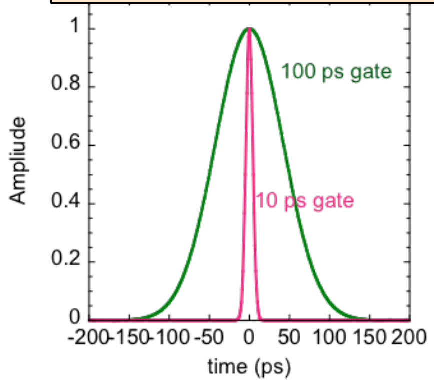


S. Nagel, IFSA 2015

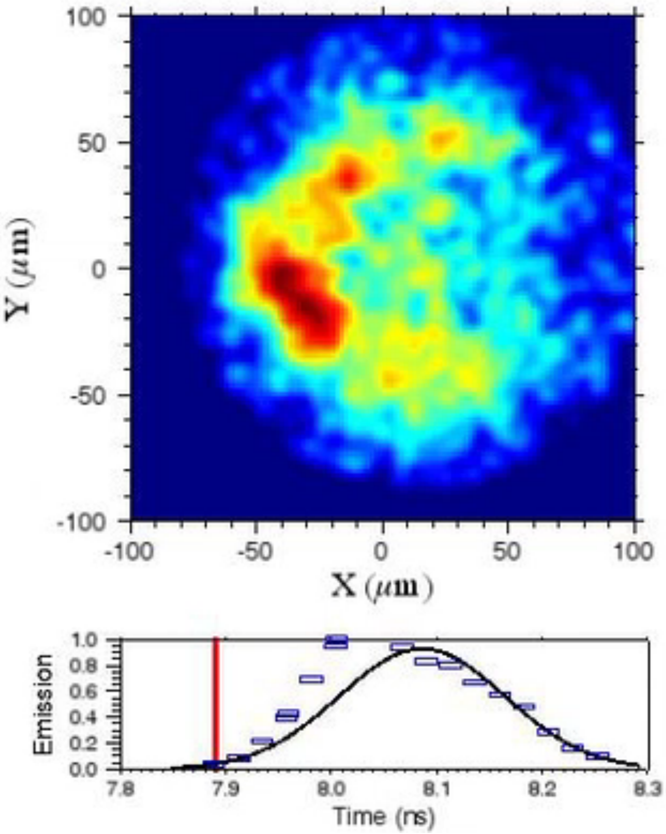
T.J. Hilsabeck *et al.*, Rev. of Sci. Instrum., **81**, 10E317 (2010)
S. R. Nagel *et. al.*, Rev. of Sci. Instrum., **83**, 10E116 (2012)

The improved 'shutter speed', allows DIXI to take images without blurring the ultra-fast evolving features

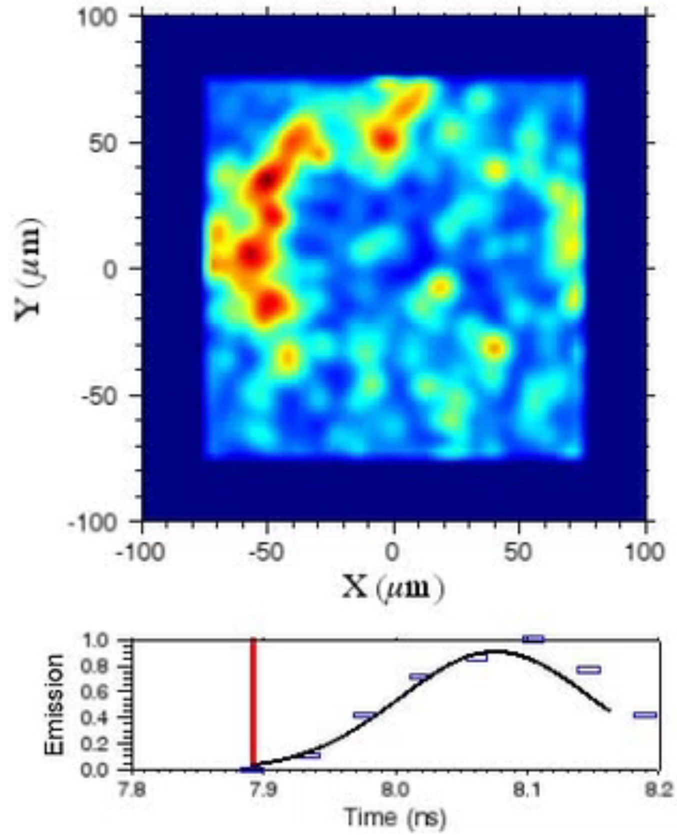
Gate width comparison



100ps 'shutter'



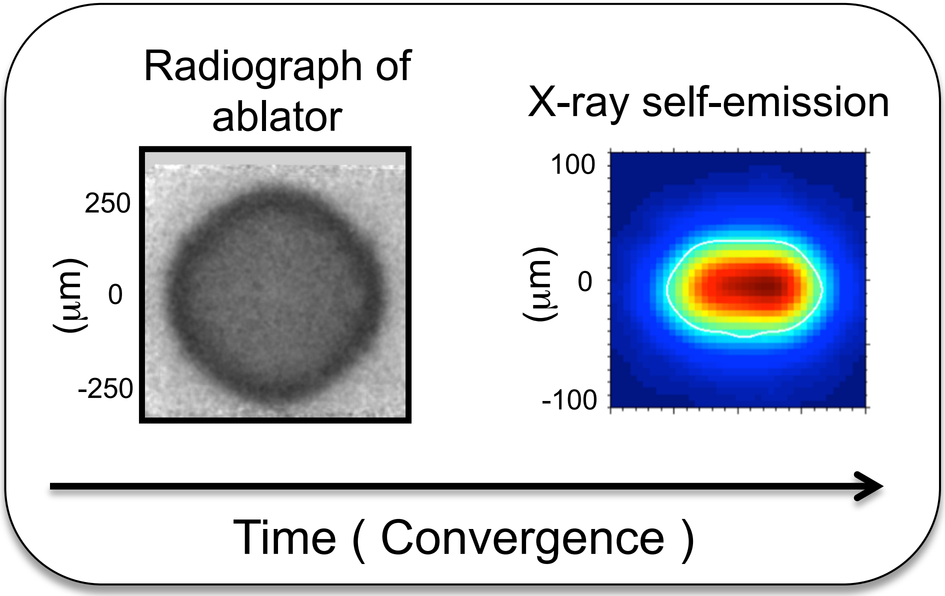
DIXI – 10 ps 'shutter'

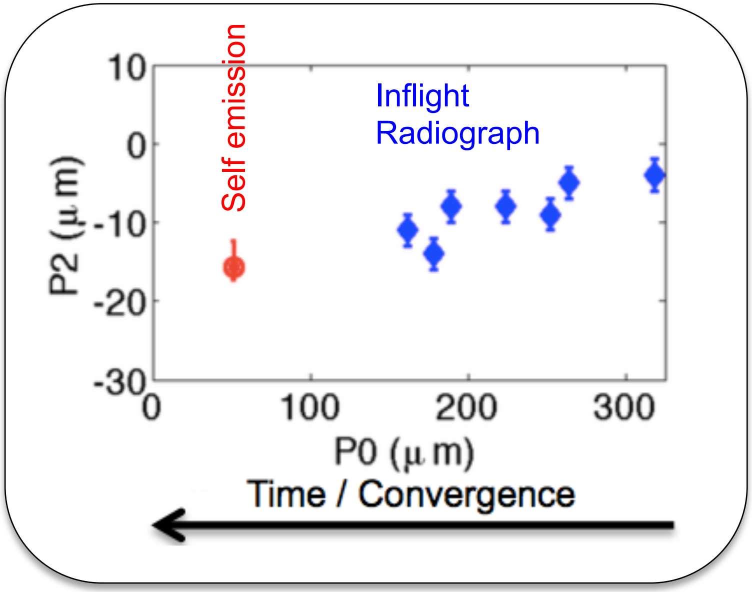


N141116

Even our best performing implosions show significant swings in shape

4 shock AS CH ablator in gas fill 575



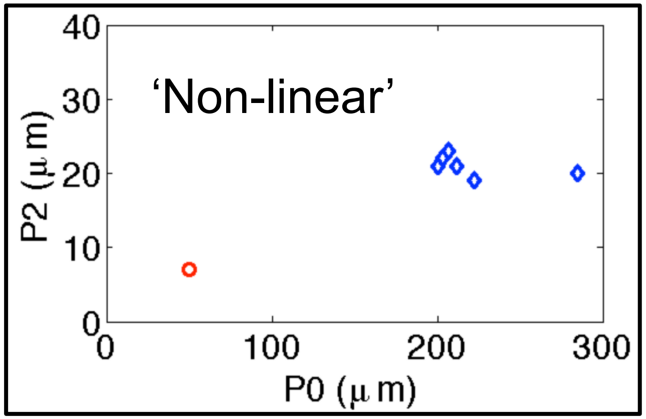


We are working to understand causes for the observed temporal evolution of the implosion symmetry

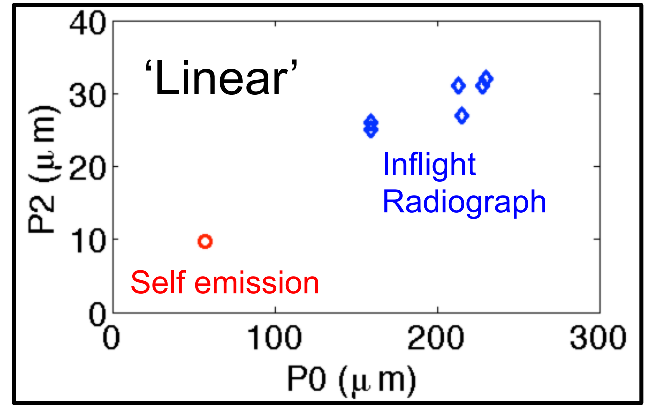
These shape swings lead to residual kinetic energy which degrade yield

Temporal trends in shape are a function of hohlraum gas fill and case-to-capsule ratio

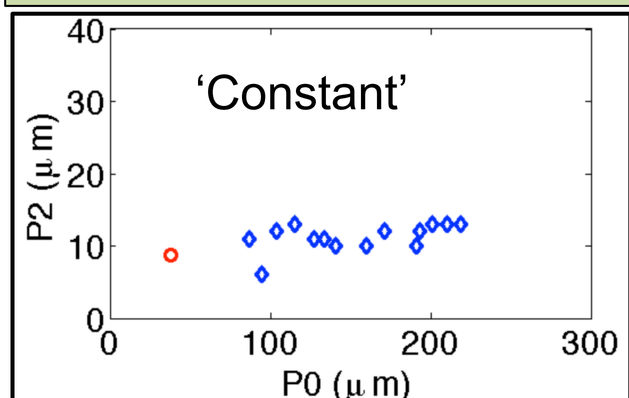
High Foot T0, C2C=2.6



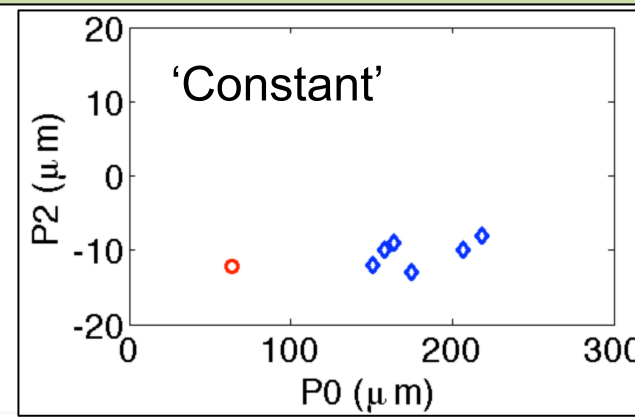
High Foot T-1, C2C=2.6



2 shock NVH CH, C2C=4.25



2 shock LGF HDC, C2C=3.1

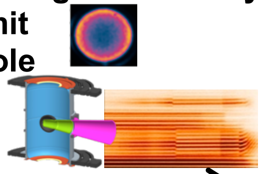


C2C=case to capsule ratio

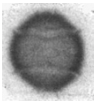
Experimental measurements of symmetry seek to constrain the shape evolution throughout the implosion

Current diagnostics

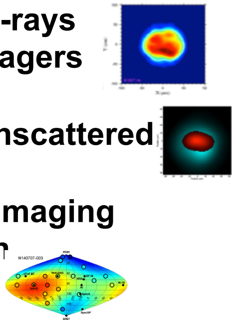
Picket + Trough / Shock Symmetry
- Re-emit
- Keyhole



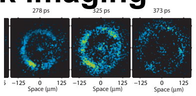
Peak Velocity
- 2DConA

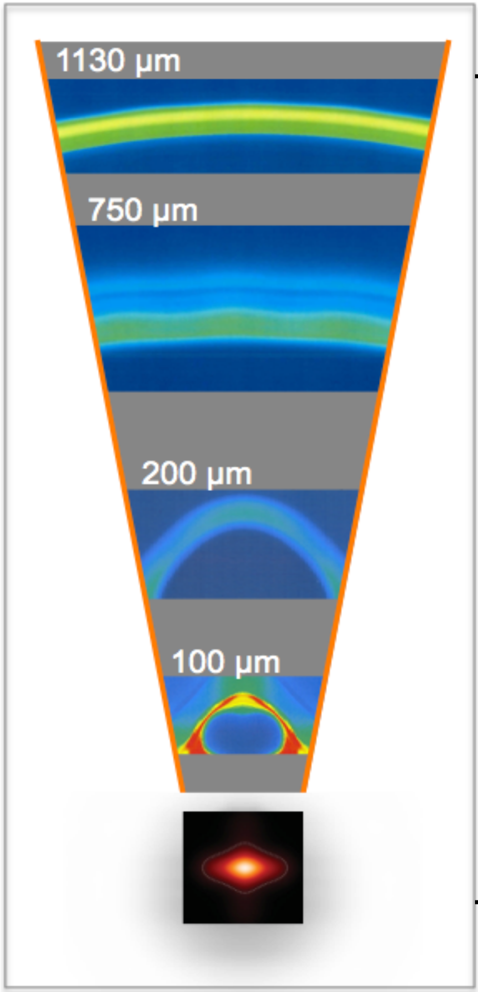


Stagnation / Peak Compression
- Self-emission x-rays
  - Gated imagers
  - DIXI
- Primary & Downscattered Neutrons
  - Neutron Imaging
- ΔρR distribution
  - FNADs



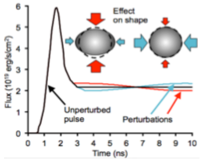
Post-stagnation
- Outgoing shock imaging



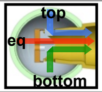


Diagnostics in development

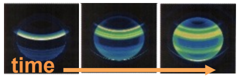
Trough Symmetry
- Foam Ball



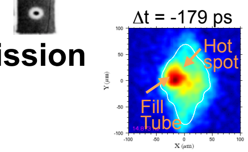
Shock Symmetry
- 5-Axis Keyhole



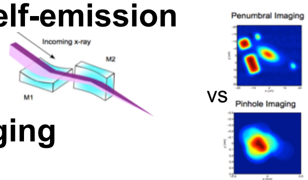
Inner Beam Propagation vs. Time
- Gated SXI



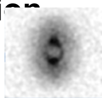
Between peak velocity & stagnation
- Late-time 2DConA
- Early-time self-emission



Higher resolution self-emission stagnation imaging
- KBO
- Penumbral imaging



Imaging of Cold fuel at stagnation
- Compton Radiography



Co-aligned Neutron & X-Ray

…and more lines of sights for x-ray and neutron imaging

We need to better understand our hot spot imaging to accurately infer stagnation conditions

Thus far we have 'tuned' symmetry based on the x-ray images. Is this the correct thing to do?

- CNXI will provide insight to the x-ray/neutron image discrepancy by imaging along the same LOS
- DIXI and other diagnostics will provide higher temporal and spatial resolution

Removing swings in symmetry is important for improving the performance of IDI implosions. Hypotheses for what is causing the swings:

- Capsule support tent creates a hydrodynamic instability that drives self emission shape oblate
- Hohlraum drive is modified by a reduction in inner beam power that drives the implosion oblate
  - CBET
  - Au/hohlraum plasma impeding the inners

Mitigations:

- Larger case to capsule ratio
- Reducing the hohlraum fill
- Changing the hohlraum material
- Thicker ablator

Hot spot flows in the stagnation phase for the IDI platform

Brian K Spears

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Both neutron and x-ray diagnostics measure hot spot flow

- Layered implosions show bulk velocity (translation)
  - Seen in neutron spectral peak shift
  - Comparable observations made by x-ray image motion
  - Often large, but source unknown
- Diagnostics capture higher order flows (swirling, shear, turbulence)
  - Neutron spectra show temperature anisotropy
  - Xray images show relative motion of various intensity contours
  - Working more precise measurement and analysis
- Hot spot flows are coupled to residual kinetic energy (RKE)
  - RKE is mostly locked in the shell
  - Estimated by an inferred energy balance

Hypotheses for flow center on symmetry perturbations

- X-ray drive is asymmetric
  - Intrinsic hohlraum behavior (smoothing, spot motion, features)
  - LPI (beam propagation, backscatter, CBET)
- Engineering structures are damaging
  - Mounting tent severs portions of implosion
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  - Fill tube UV exposure and oxygenation
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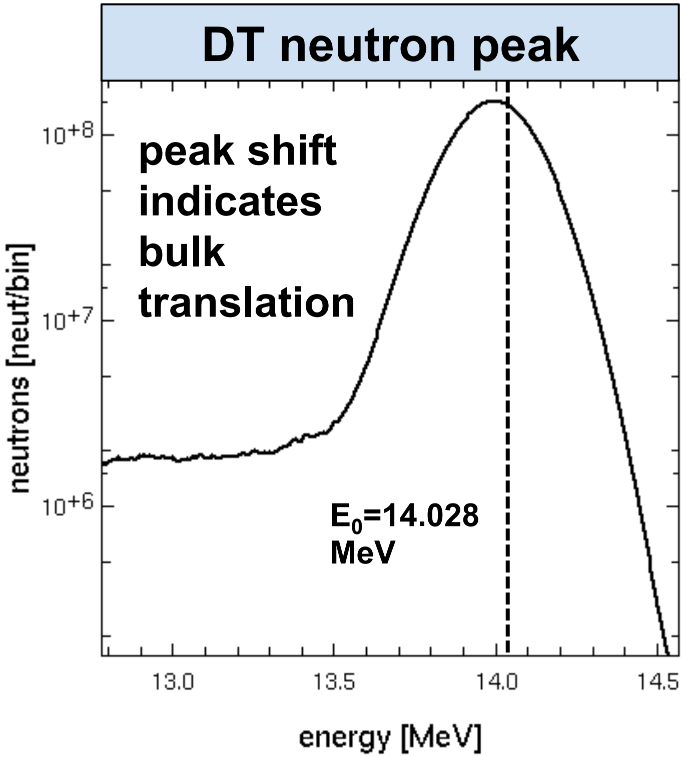
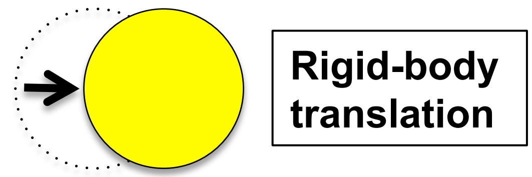
Neutron spectrometers measure bulk velocity from spectral peak shift



Primary neutron peak location gives translational or bulk velocity

Translating hot spot



$$t = \frac{d}{v_n + \overline{v}_{fluid}}$$

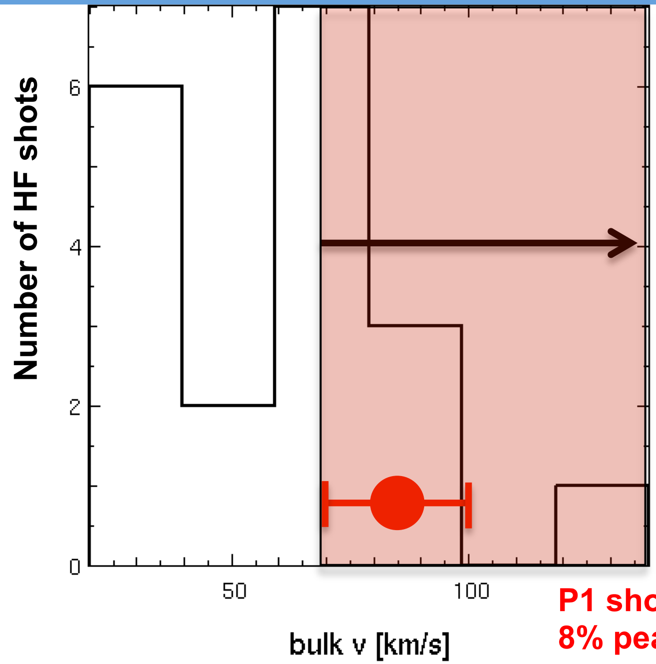
Velocity components measured on 3 nearly orthogonal lines of sight

15 km/s precision for components

Measure speed and direction of hot spot translation

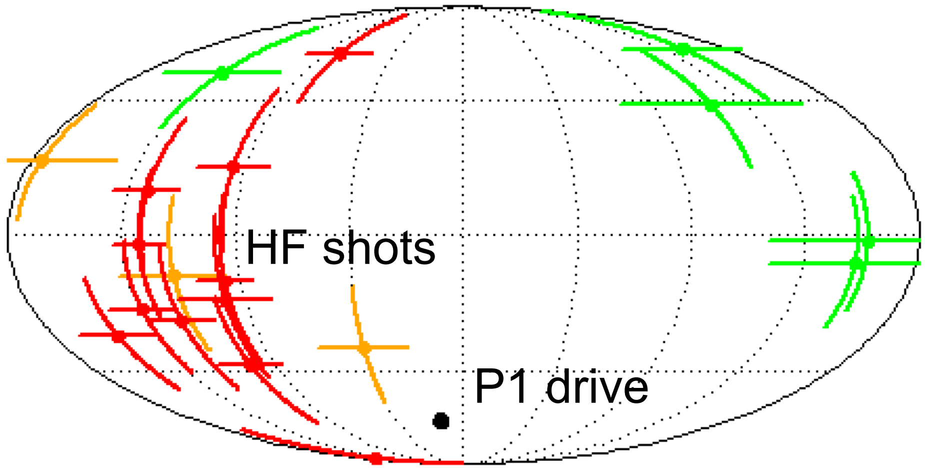
Many HF shots show large bulk velocities

Average HF bulk velocity is 60 km/s; P_1 was 85 km/s



P1 shot N150318
8% peak to valley
power imbalance

Large bulk velocities tend to cluster



> 60 km/s
30 - 60 km/s
< 30 km/s

8 of 19 HF shots have velocities larger than the P_1 shot

We haven't yet identified what is producing these perturbations

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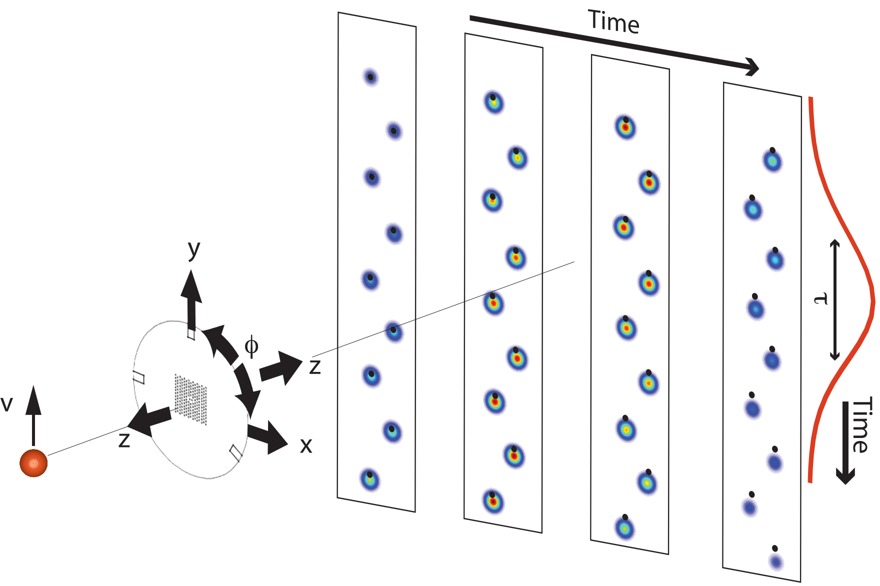
Which of these can cause clustered bulk translations?

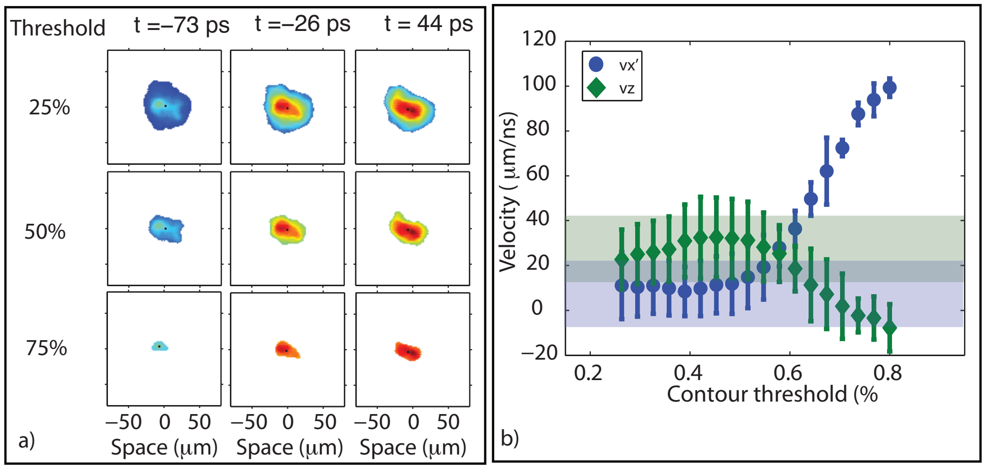
X-ray image contours also indicate bulk velocities

Setup



Residual motion is inferred by minimizing the difference in the expected and measured centers of x-ray emission

Results – Layered HF implosion



15 km/s precision for components (comparable to neutrons)

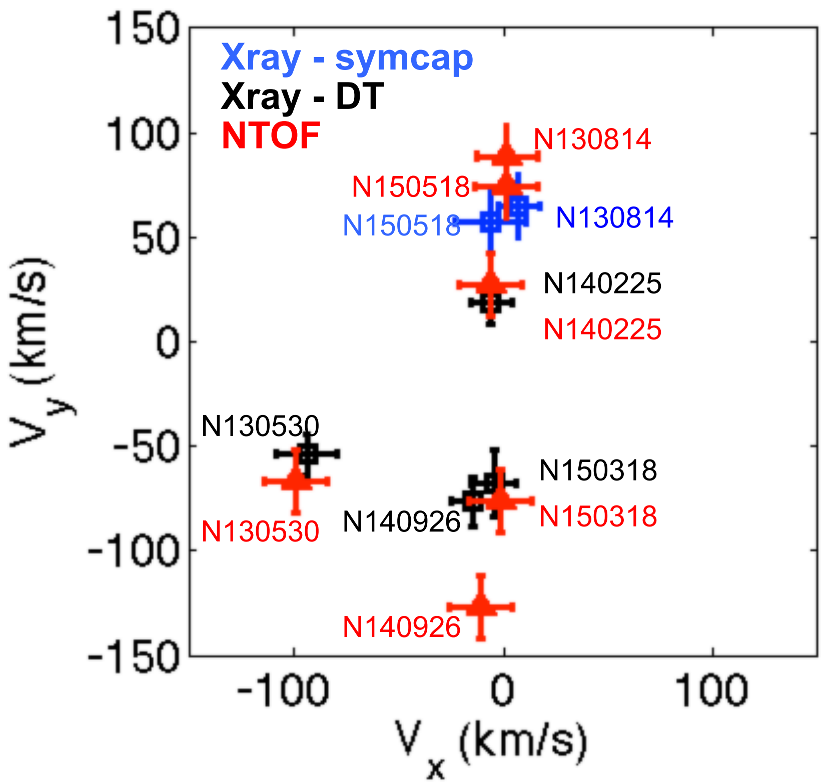
At lower intensity thresholds, the inferred residual motion is consistent with the neutron time of flight measurements.

X-ray data shows routine bulk velocity consistent with neutron data

v_x-v_n, difference between neutron and x-ray bulk velocity

	Mean	Standard deviation
Magnitude	9.0 km/s	13.3 km/s
Direction	10.3°	13.9°

X-ray and neutron velocity summary in the equatorial plane (90°,168°)



Drive asymmetry - N130814, N150318, N150118
Ice layer asymmetry – N130530
Nominal CH and HDC – N140225, N140926

Multiple techniques suggest the bulk velocity is real and appreciable

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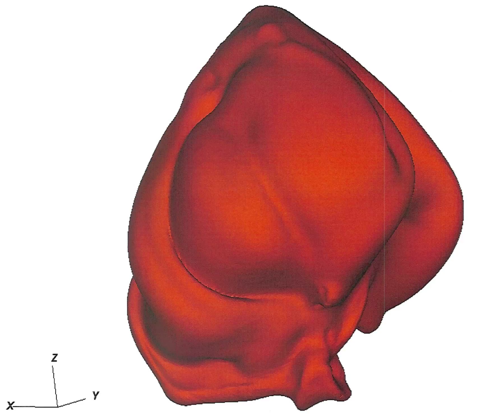
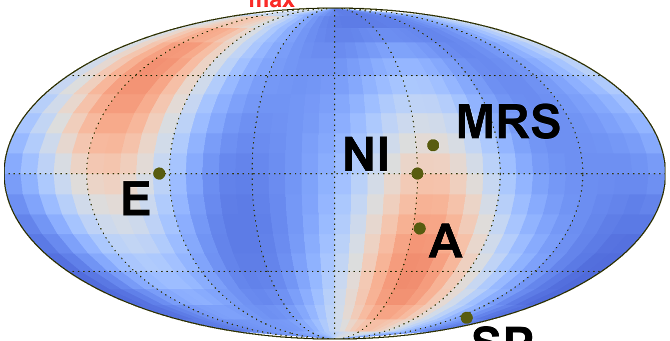
Asymmetric 3D simulations show angular temperature variations due to flow

Asymmetric flow in distorted hot spot



Apparent temperature distribution from simulated peak widths



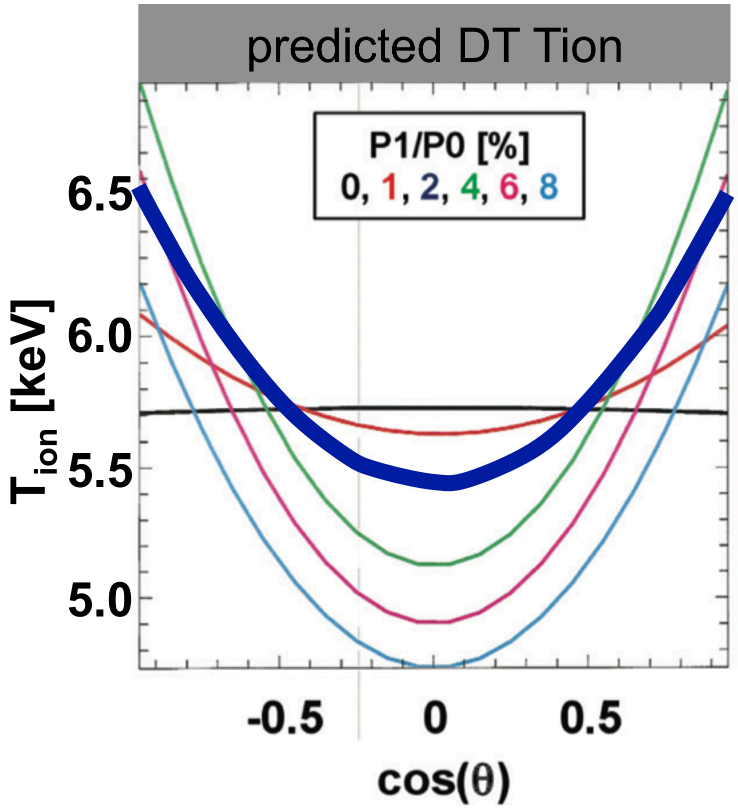
Detector	T_{Brysk}
SpecE	3.49
SpecA	3.56
SpecSP	2.96
NITOF	3.50
MRS	3.39

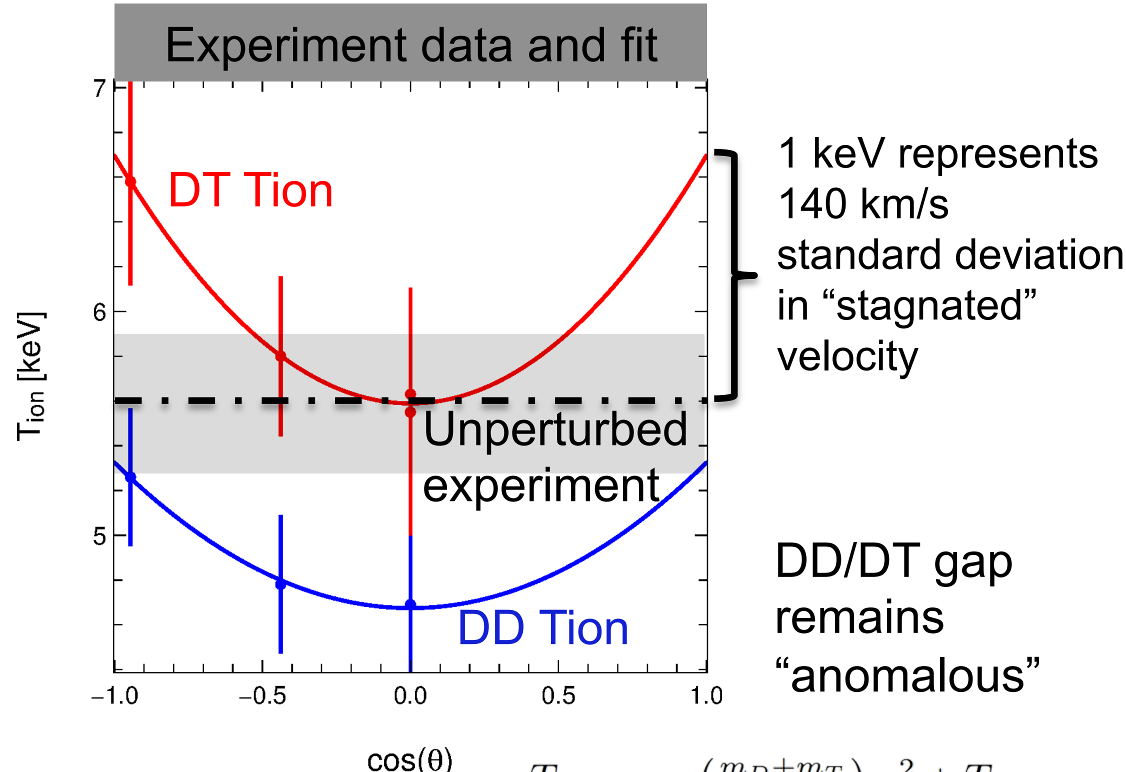
- Thermal temperature is 2.3 keV
- Apparent temperatures span 2.9 to 4.0 keV – depending on direction
- Detector array typically samples 50% of full PTV

Hot spot flow can be estimated from temperature differences

P_1 perturbed experiments confirm our ability to measure flow-induced temperature variation

- Preshot simulations predict 1 keV temperature variation due to flow
- Experiments show very similar variation, amplitude and shape



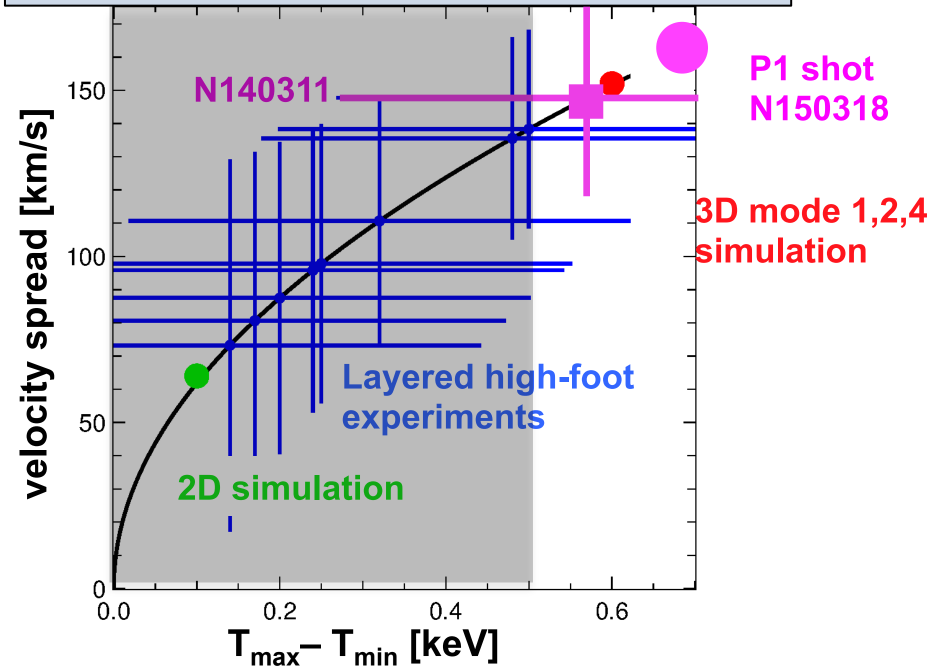


$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

We can measure 1 keV apparent Tion anisotropy, but temp is still wrong

So, is the high foot apparent T_{ion} usually isotropic or not?

Expected Tion variation is nearly observable



$$T_{Brysk} = \left(\frac{m_D + m_T}{k}\right)\sigma_v^2 + T_{thermal}$$

The NIF data cannot (currently) distinguish between isotropy and the expected level of anisotropy

- **Post shot simulations suggest Tion anisotropy of ~ 300 - 400 eV**
- **Detectors would typically sample ~ 150-200 eV**

- **Detectors can measure down to 500 eV anisotropy**

See M. Gatu Johnson paper

We need neutron spectrometers that can measure 300 eV anisotropy

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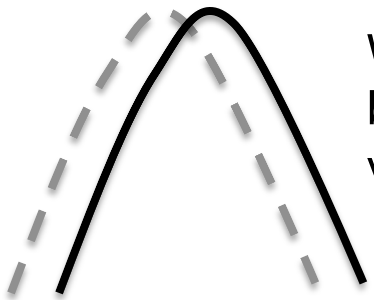
Which of these can cause increased apparent temperature?

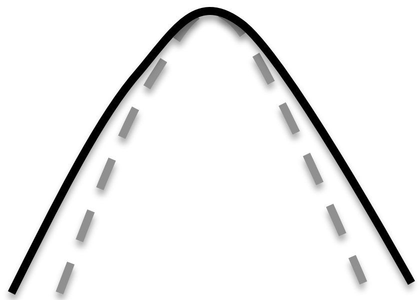
Stagnation measurements can be much more informative

First moment:
peak shift ~ f(bulk velocity, $T_{thermal}$)



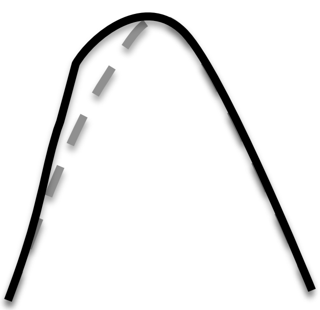
What's the bulk velocity?

Second moment:
Width ~ f($T_{thermal,}$flow variance)



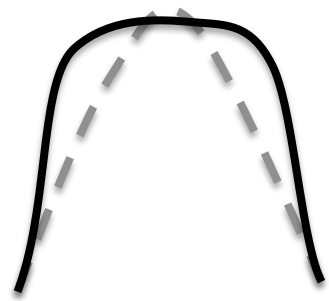
What's the apparent temp, thermal temp,residual flow?

Third moment:
Skew ~ cov($T_{thermal,}$flow)



Is the hot stuff moving fast?

Fourth moment:
Kurtosis ~ variance of Tion

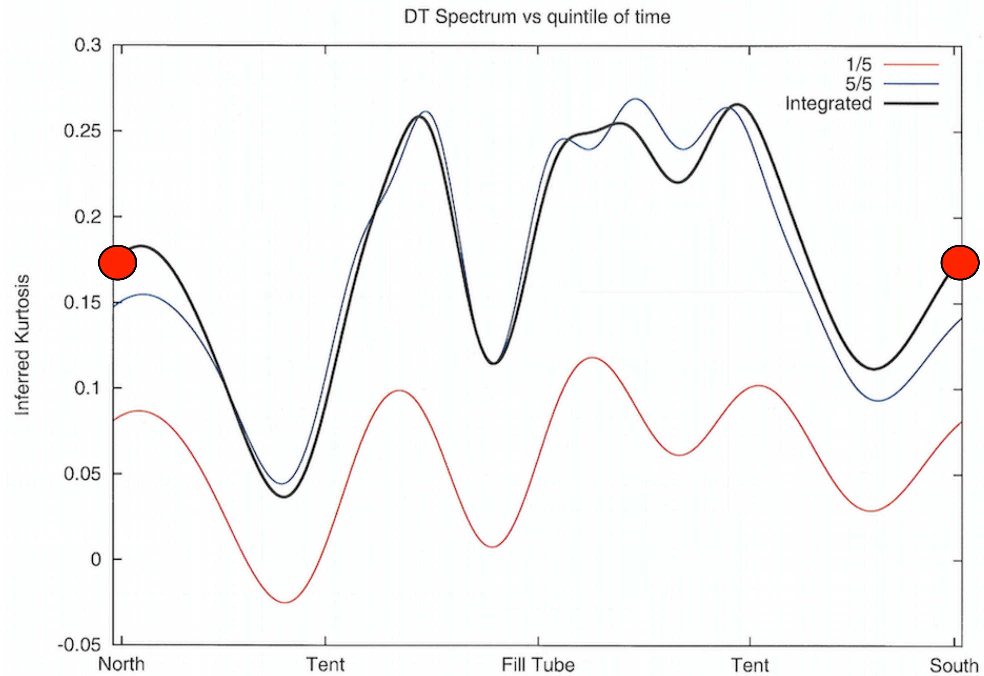


How broad is the distribution of thermal temperatures?

New measurements will constrain hot spot flows for code validation

The kurtosis shows hot spot cooling and flow effects

1. Positive kurtosis suggests temperature variation during burn
2. Negative kurtosis implies velocity variation.
3. Variation with angle is due to velocity.
4. Kurtosis would be constant with LOS in a spherical or stagnant implosion



scalar

Vary with line of sight (tensors)

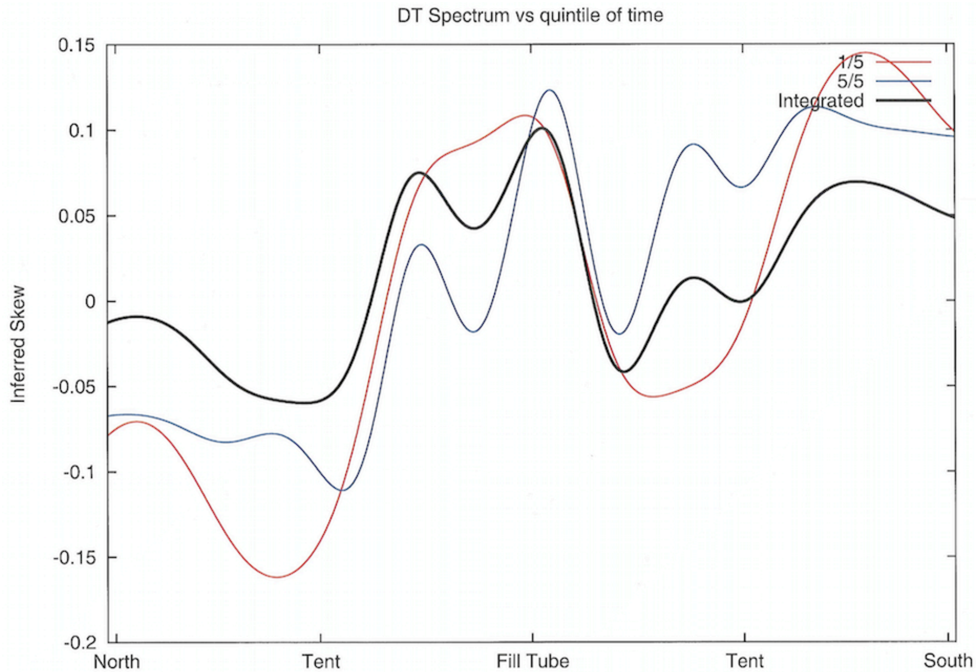
$$\mathrm{Kurt}(\omega) = \frac{3\,\mathrm{Var}(\tau) + 6\,\mathrm{Cov}(\tau, u_\Omega, u_\Omega) + \mathrm{Cov}(u_\Omega, u_\Omega, u_\Omega, u_\Omega) - 3\,\mathrm{Var}(u_\Omega)^2 + \ldots}{\mathrm{Var}(\omega)^2}$$

L=0, 2, 4 in direction → antipodes are identical

Kurtosis variation with line of sight is another direct measure of stagnation and stagnation asymmetry – need it to ~ 5% precision

Skewness gives us insight to the flow speed of the hot material

1. Skew gives correlation of temperature and velocity
2. Is the hottest material moving fast? Slow?



Vary with line of sight (tensor)

$$\text{Skew}(\omega) = \frac{\overbrace{3\text{Cov}(\tau, u_\Omega)}+\overbrace{\text{Cov}(u_\Omega, u_\Omega, u_\Omega)}+\ldots}{\text{Var}(\omega)^{3/2}}$$

L=1, L=3 in direction → antipodes measure odd modes

Skewness gives us a picture of the partition of mechanical and thermal energy – need it to ~ 3-5% precision

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Residual Kinetic Energy

- We define RKE as the kinetic energy of the DT fuel (hot spot & cold fuel) at bangtime
- We define a frational RKE as the ratio of the KE of the DT fuel at BT to *either* (i) the peak fuel KE, or (ii) the total energy delivered to the fuel up to BT (including IE of the fuel at peak velocity and work done on the fuel by the ablator during deceleration)
- Simulations with applied P2 and P4 drive asymmetries show:
  - A nominal 1D implosion has near-zero residual kinetic energy
  - Yield and stagnation pressure are strongly correlated with the total RKE
  - The partition of RKE is 70-100% in the dense fuel, and 0-30% in the hot spot
- Experimental measurements:
  - We don't have a good way of measuring total RKE (we have an approximate model based on energy balance, but it's not good to the ~1-2 kJ level)
  - Direct measurements of the fuel shape and volume would be the most valuable, to give a qualitative idea of cold fuel motion, and a semi-quantative measure of the internal energy of the fuel

NIF nToF systems report weighted ion temperature measurements from layered implosions

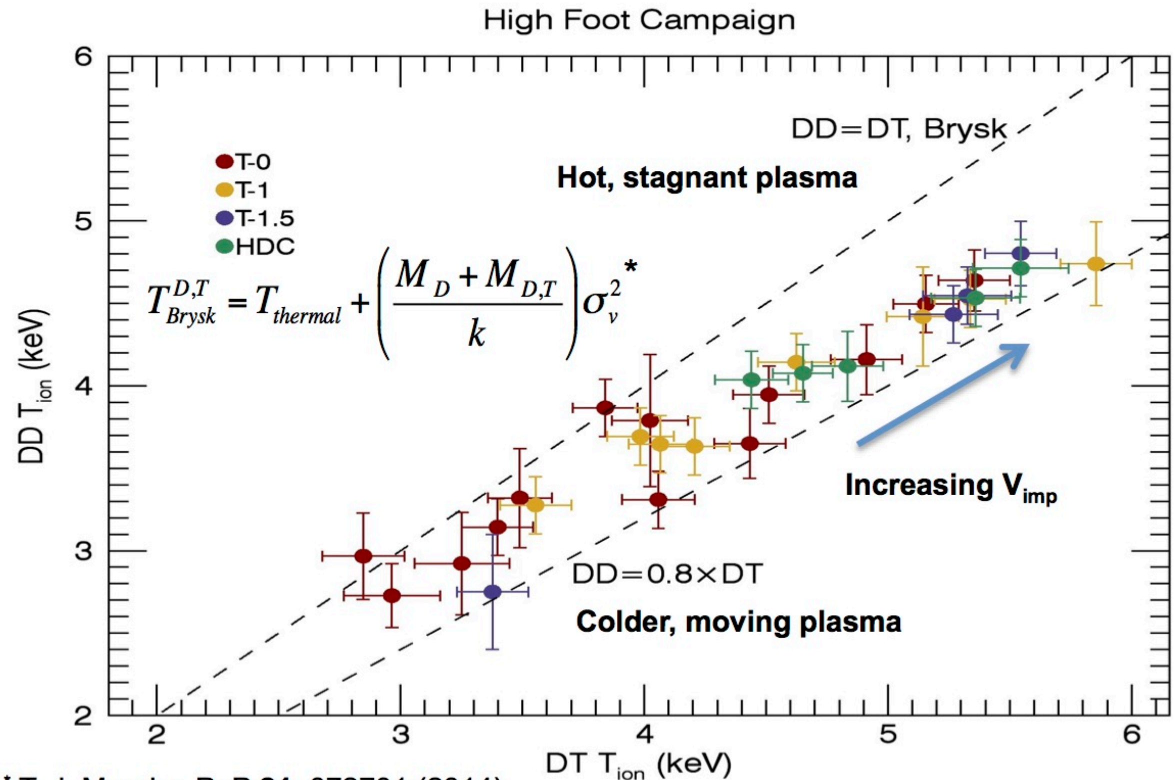
- Weighted temperatures result from estimating the 2nd moment of the DT and DD neutron birth spectra using nToF data.
- Weighted temperatures are integrated over the burn volume and history.

$$\left\langle T_{BW}^{DT} \right\rangle = 4\pi \int_{-\infty}^{\infty} dt \int_{0}^{\infty} dr r^2 \left(1 - f_D\right) f_D n_{ion}^2(r) \left\langle \sigma v\left(T(r,t)\right)\right\rangle_{DT} T(r,t) \Big/ Y_n^{DT}$$

$$\left\langle T_{BW}^{DD} \right\rangle = 2\pi \int_{-\infty}^{\infty} dt \int_{0}^{\infty} dr r^2 f_D^2 n_{ion}^2(r) \left\langle \sigma v\left(T(r,t)\right)\right\rangle_{DD} T(r,t) \Big/ Y_n^{DD}$$

- The weightings ensure that the two measurements, TDT & TDD, will be *different* and dependent on the temperature and density spatial profiles and history, as well as the concomitant reactivity difference.

NIF weighted temperature differences are larger than expected for a static, equimolar, Maxwellian fluid



* T. J. Murphy, PoP **21**, 072701 (2014)

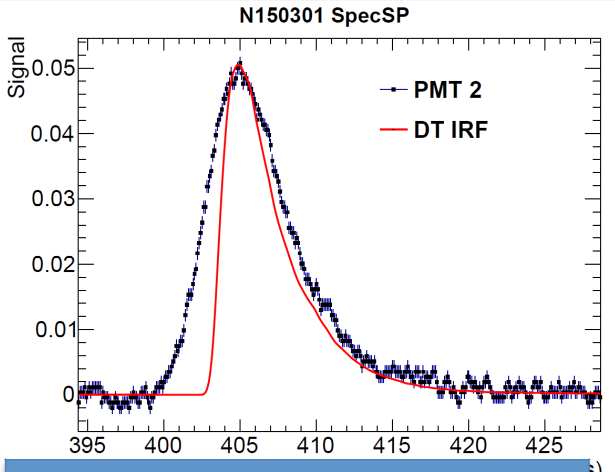
More sophisticated analysis methodology is required to understand the sensitivity of this and other temperature differences to the assumptions above…

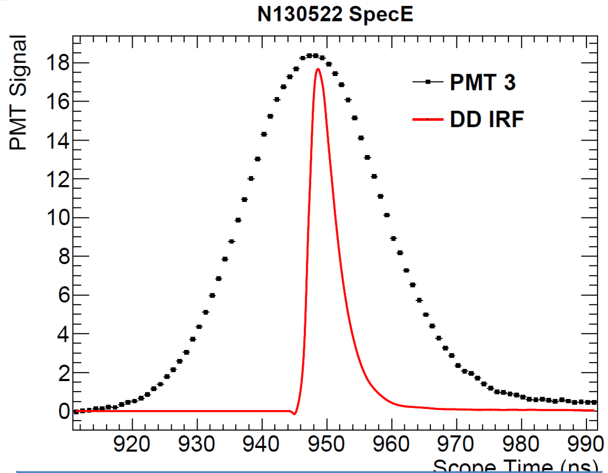
Directions of current efforts…

- Improved analysis methods
  - More sophisticated burn dynamics models that release the constraints of the above assumptions
  - More sophisticated spectral models that incorporate higher moments
  - Improved fitting methods that incorporates DD and DT moments in a correlated manner
  - Inclusion of YDD and YDT temperature dependence
  - Improved uncertainty estimates

- Improved measurements
  - Addition of a 5th nToF system at 21.6 m in northern hemisphere and nearly opposite of south pole measurement station
  - Improved recording precision
  - Improved characterization of system performance
  - Improvements to the performance of system components

nToF DT weighted temperature uncertainties are dominated by systematic effects





PMT#	SpecSP	SpecE	SpecA
1	2.11	2.38	2.13
2	2.04	2.25	2.05
3	2.37	2.07	2.04
σ	0.17	0.16	0.05

PMT#	SpecSP	SpecE	SpecA
2	2.32	2.30	2.32
3	2.35	2.29	2.33
σ	0.01	0.01	0.01

Current estimates

Source	Unc. (eV)
IRF (Relative)	120
Scattering	50
Fit Type	100
Fit Results	50-100
Timing Shot	?
IRF Global	?
Total	~200

A rigorous methodology is being implemented to more accurately determine the systematic uncertainties.

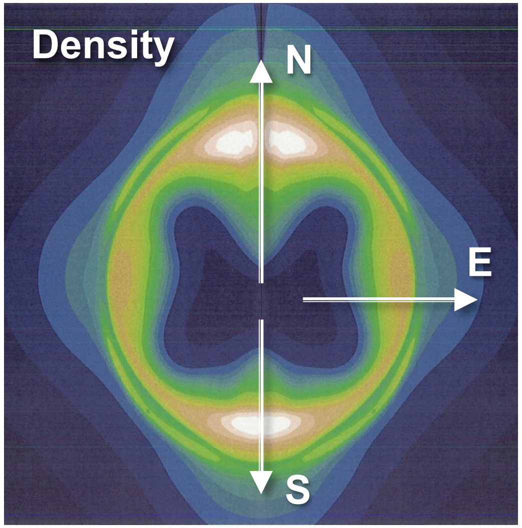
The methodology incorporates a non-diagonal covariance in the χ^2 ***minimized in the forward fit.***

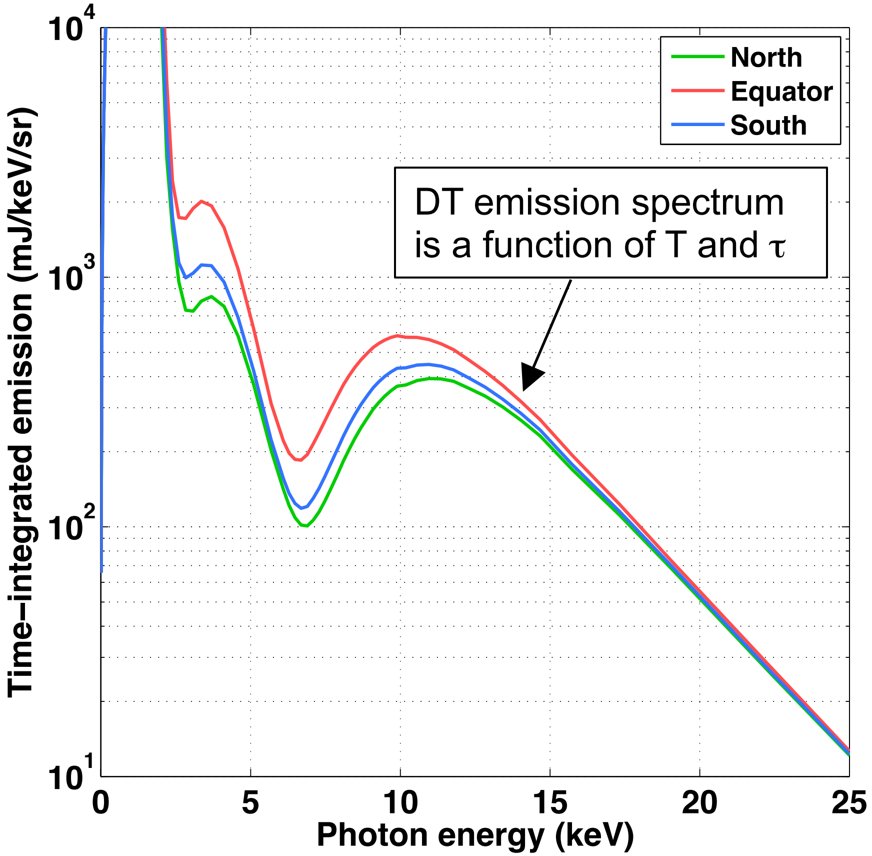
Are electron and ion temperatures measuring the same thing?

- Ti>Te during shock phase, but we expect temperatures to equilibrate during compression, prior to any significant neutron production
- Hot spot plasma spans a range of temperatures in space and time
- We can define a neutron-averaged temperature, T_{DT} or T_{DD} (due to difference in reactivity scaling $T_{DT}>T_{DD}$)
- NTOF Brysk width is weighted by sqrt(T) so lower temperature regions have stronger weighting (hence single "Brysk" temperature fit to neutron width will be slightly lower than neutron-averaged temperature
- X-rays emission is emissivity-weighted, but x-rays and neutrons have the same density weighting and similar temperature weighting so they sample essentially the same plasma conditions (if x-ray frequency is a few times the temperature)
- Hence, temperature measured by x-ray continuum slope is very close to the neutron-averaged temperature

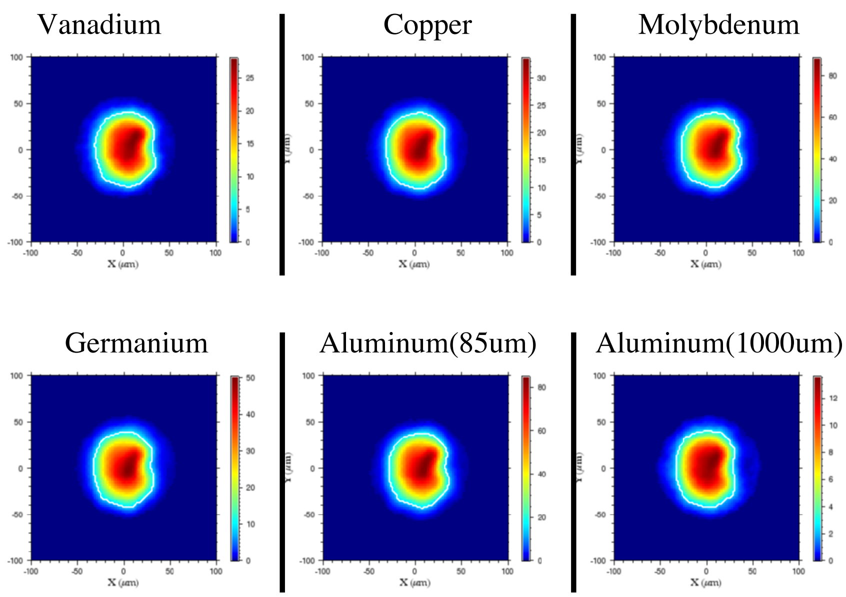
Current measurements are based on x-ray continuum

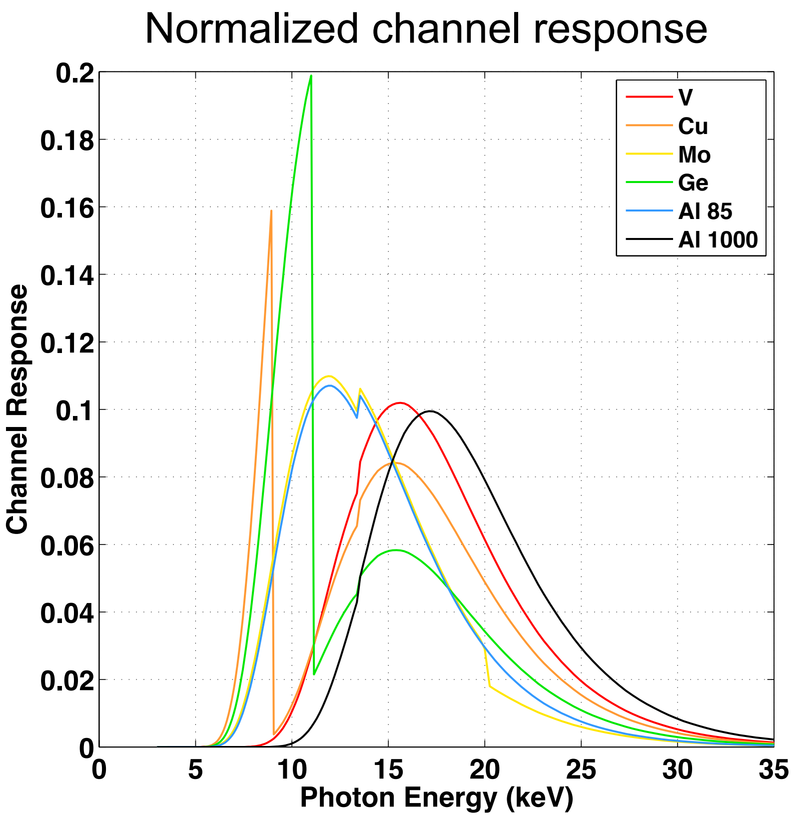
High-foot simulation





Ross pair imager measures x-ray emission in six channels

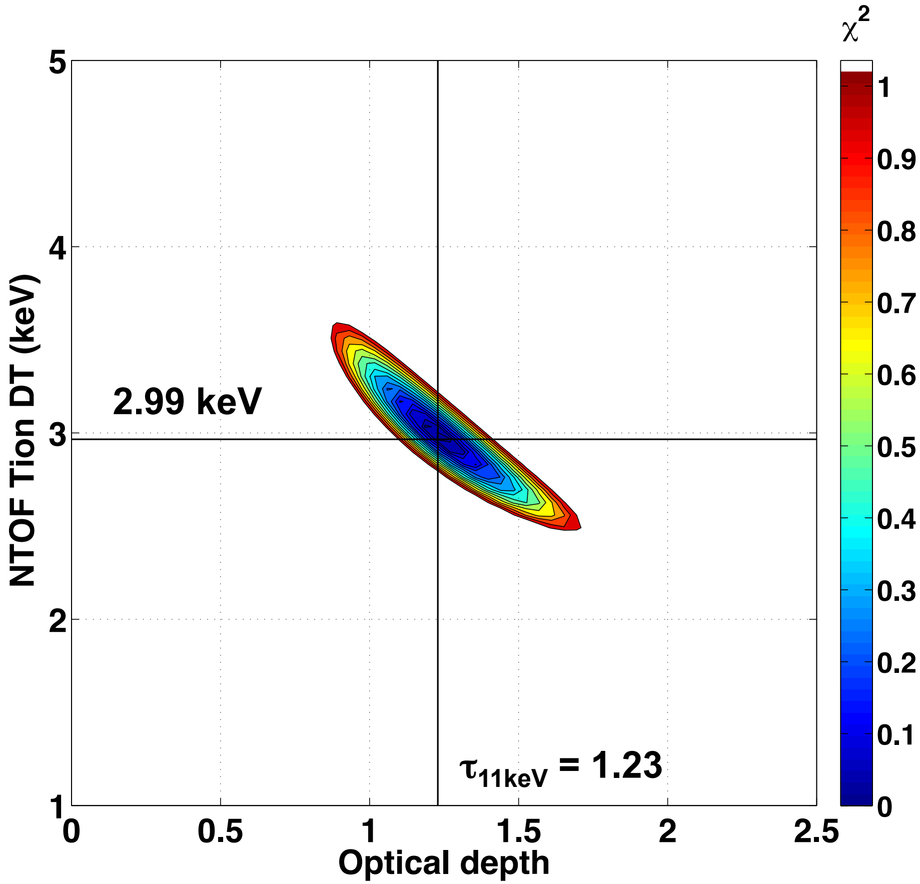




T. Ma *et al.,* RSI **83,** 10E115 (2012)

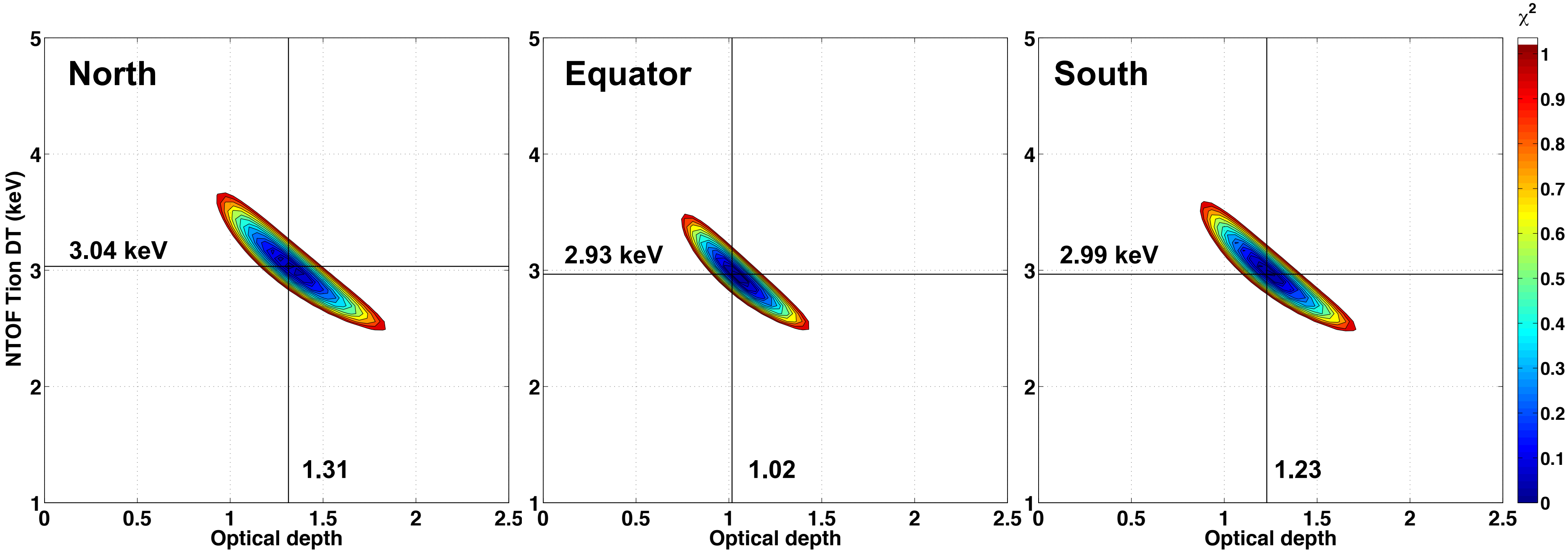
N. Izumi *et al.,* RSI **83,** 10E121 (2012)

Using synthetic x-ray output from simulation we can infer a temperature and optical depth



Simulation value of NTOF DT Tion (btifwhm) = 3.04 keV

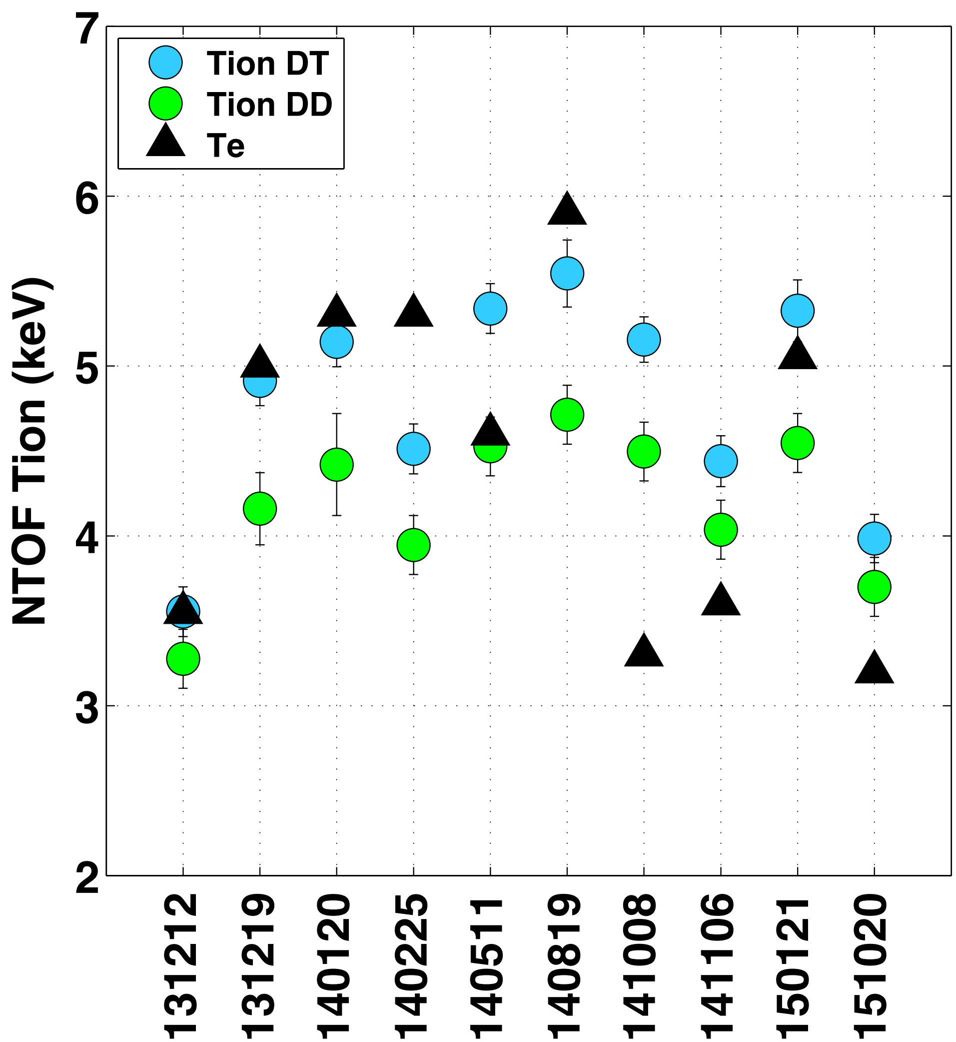
Inferred values in three separate directions



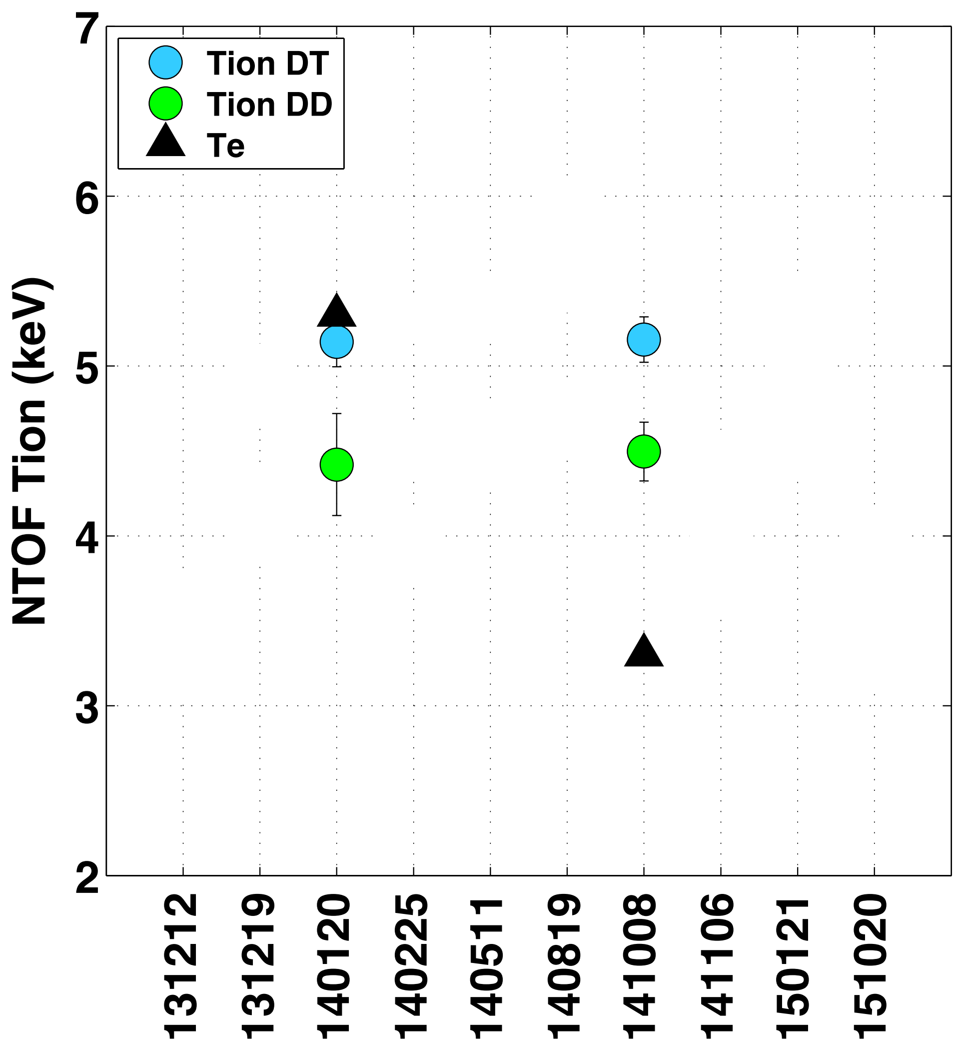
Inferred values (3.04, 2.93, 2.99 keV) are <3% of code value

- A 1D hot spot model calculates the burn-avg NTOF Tion of a 2D distorted hot spot quite well
- Ablator attenuation is varying in space and time, but a single value representing the 'average' does quite well
- We can compensate for large angular distortions in the spectrum, provided we can infer the directional attenuation

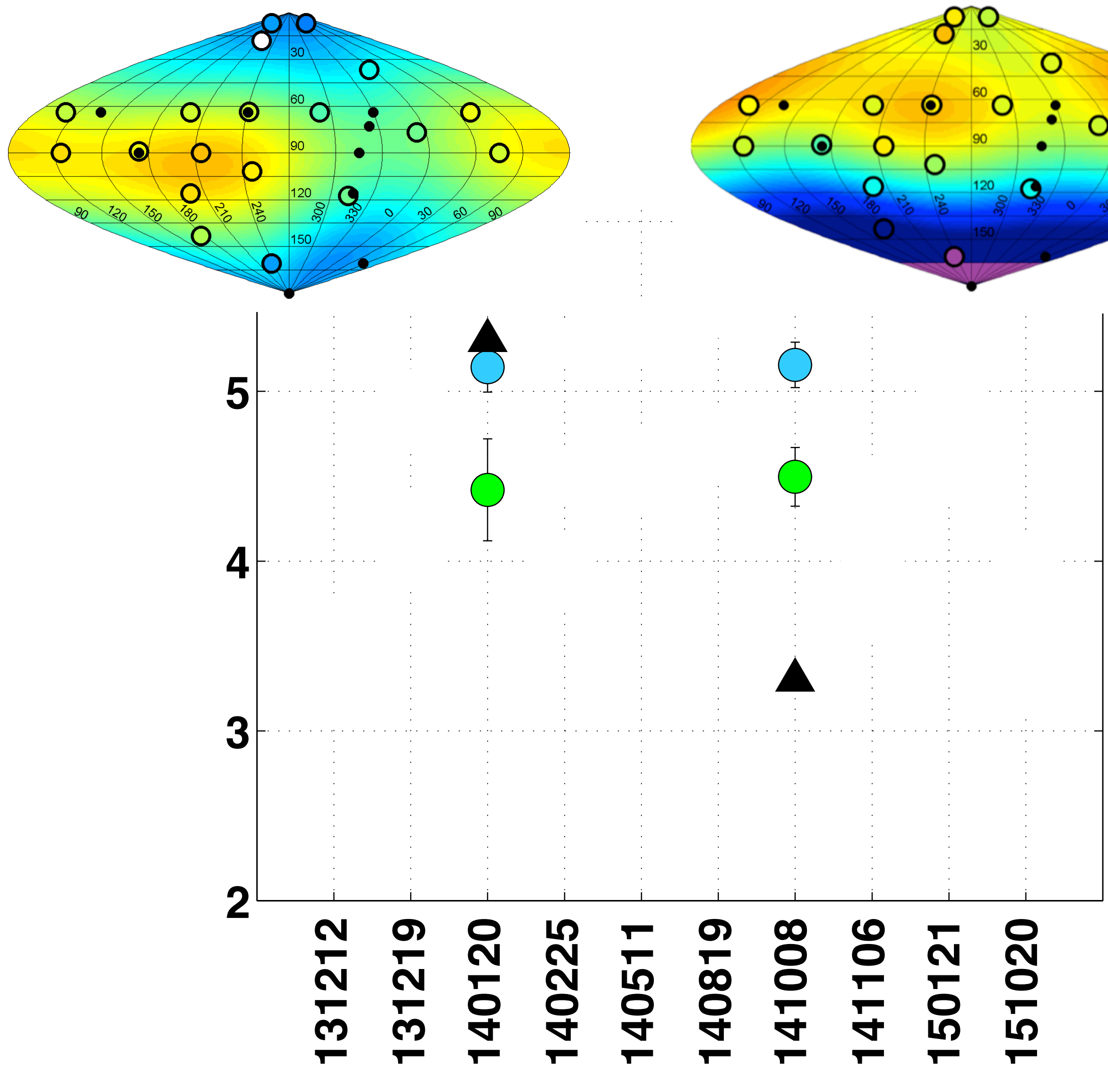
Te vs. Ti for layered implosions



N141008 was repeat of N141020 with modified second shock

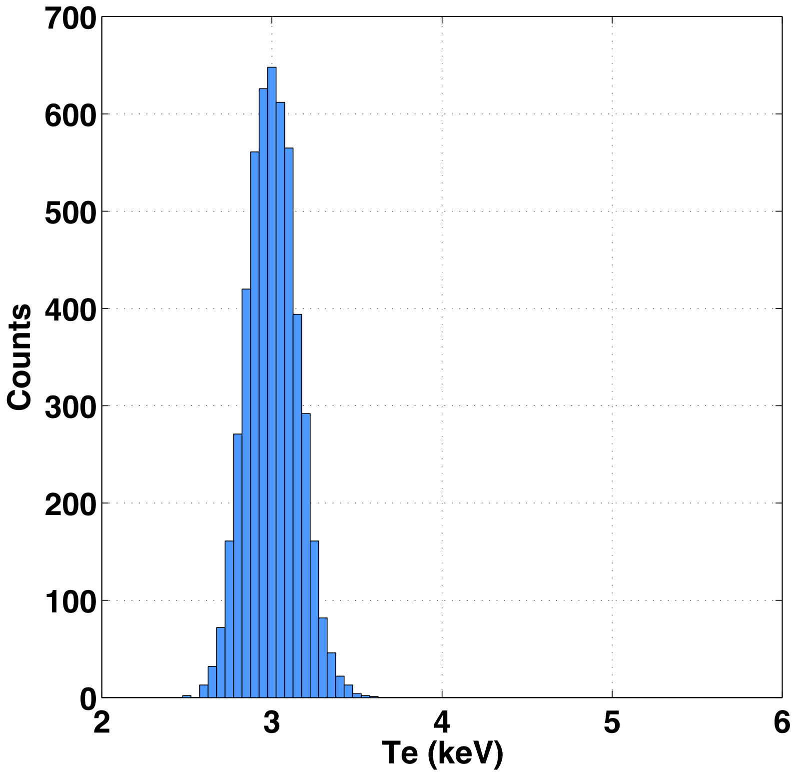


N141008 (modified second shock) had unexplained large FNAD asymmetry

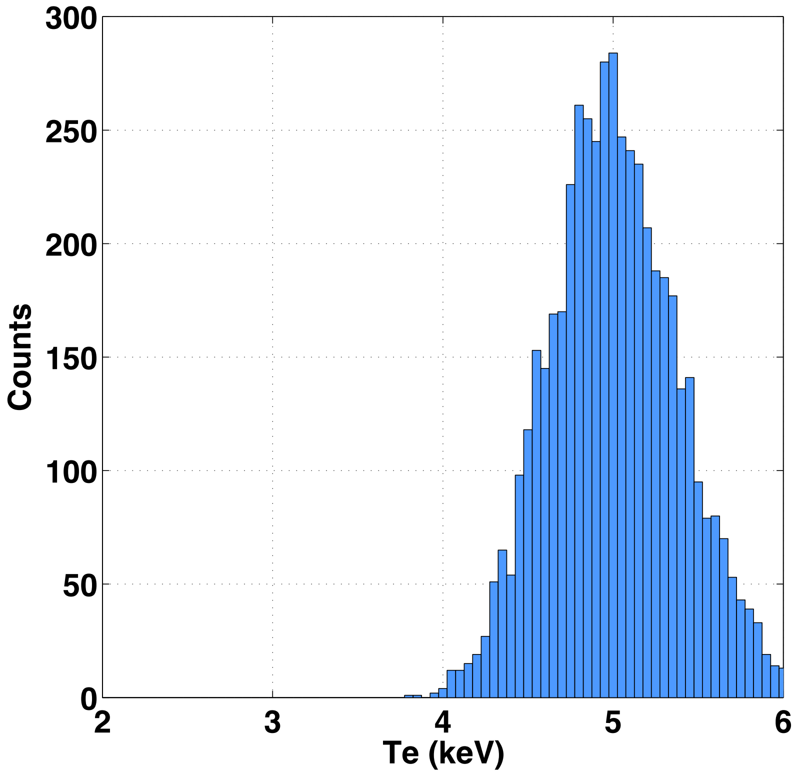


Error analysis

- Assume +/- 2% random error in channel



T_e = 3.0 ±0.15 keV



T_e = 5.0 ±0.38 keV

Improving the measurement

- Higher energy Ross pair channel
  - Design with higher-Z filter and larger pinholes should reduced Te uncertainty by factor of ~3x
- Time-resolved Te with SPIDER
  - Analysing data to extract Te. Higher energy channel will reduce uncertainty
- South-pole bang time (SPBT)
  - Analysing new 22 keV channel
- Spectroscopic continuum measurement
  - NXS 10-18 keV channel with 1D imaging slit
  - New spectrometer with HOPG in 1st and 2nd order

Inferences of shell asymmetry in indirect drive experiments at NIF

10/28/2015

National Implosions Stagnation Physics Working Group Meeting

LLNL-PRES-XXXXXX

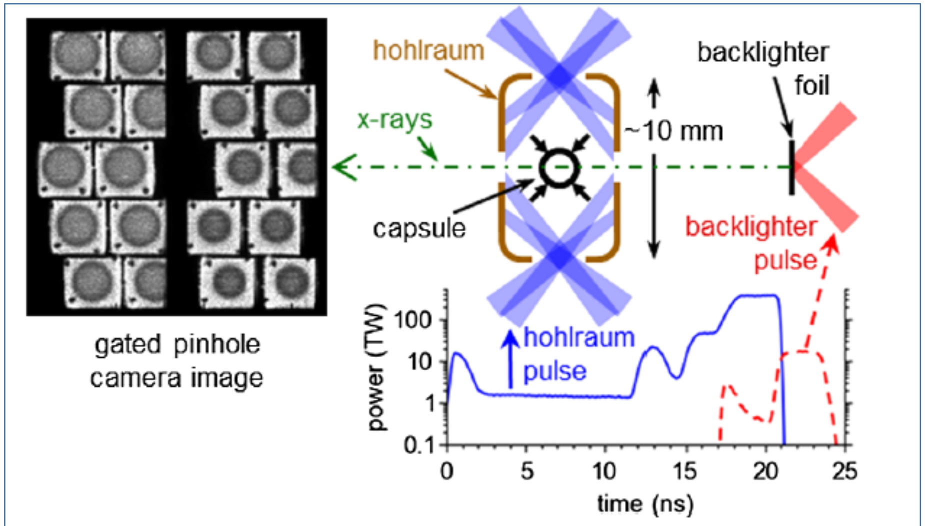
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

We use a variety of techniques to make inferences of shell symmetry at stagnation but we currently lack direct unambiguous images of the shell

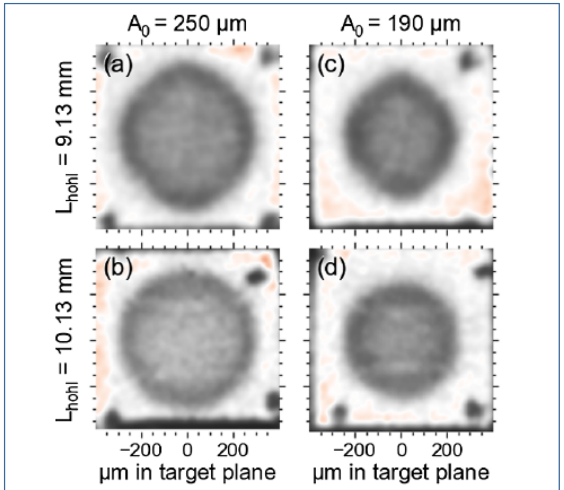
- Inflight x-ray radiographs show that shell integrity & symmetry during stagnation is a serious concern
- Anisotropy in the measured DT yield over 4π is sensitive to shell asymmetry
- Anisotropy in the down-scattered neutrons is also sensitive to shell asymmetry
- Integrated fits to multiple diagnostics are used to attempt to reconstruct a self consistent picture
- There is opportunity for significant advancement in our understanding of the stagnated shell from new diagnostics or techniques

Inflight x-ray radiography (2DConA) clearly show strong shell perturbations before stagnation in some implosions

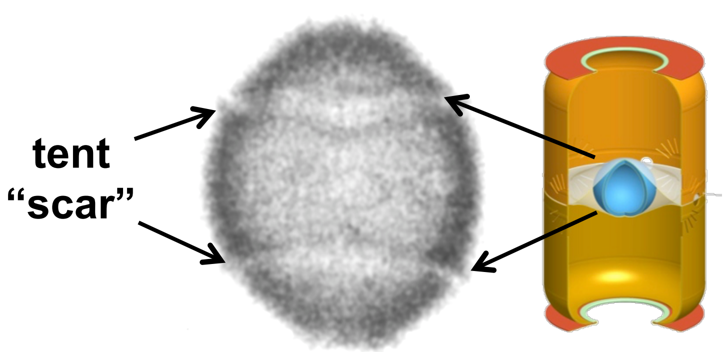


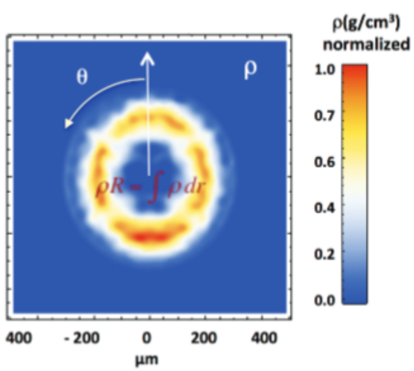
Rygg *et al.*, *PRL* **112**, 195001 (2014)

Observations of P2 & P4 distortions

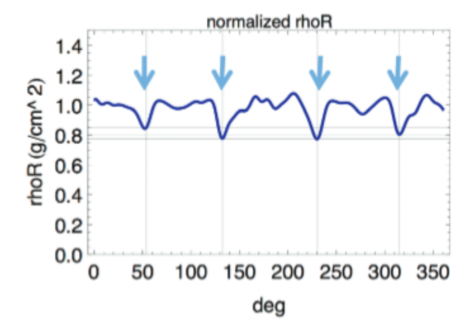


Observations of high mode tent distortions





a)



b)

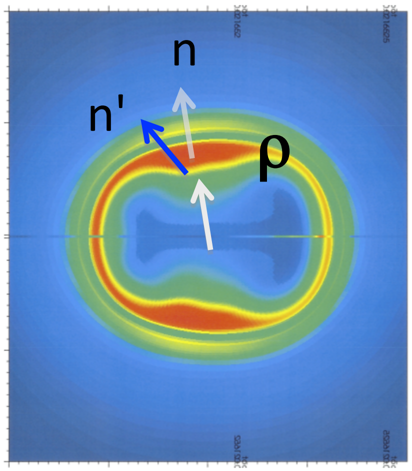
J. E. Field et al., RSI 85, 11E503 (2014)., S. R. Nagel et al., POP 22, 022704 (2015).

Tommasini *et al.*, POP **22**, 056315 (2015)

Perturbations of the shell early in time result in significantly perturb implosion

Nuclear measurements are sensitive to shell symmetry in two principle ways: attenuation (FNADS, MRS, NTOFs) and scattering (NIS, MRS, nTOFs)

Attenuation (FNADS, MRS, NTOFs)

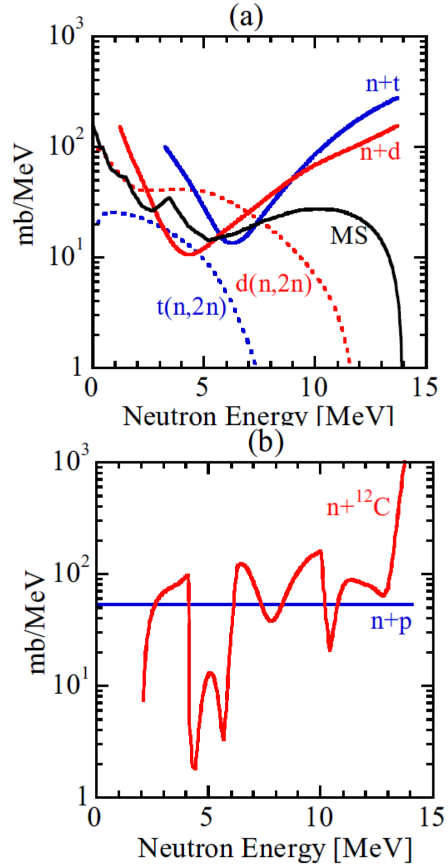


$$Y(\Omega) = Y_p e^{-\rho L(\Omega)\langle\sigma_{DT}\rangle/m_{DT}}$$

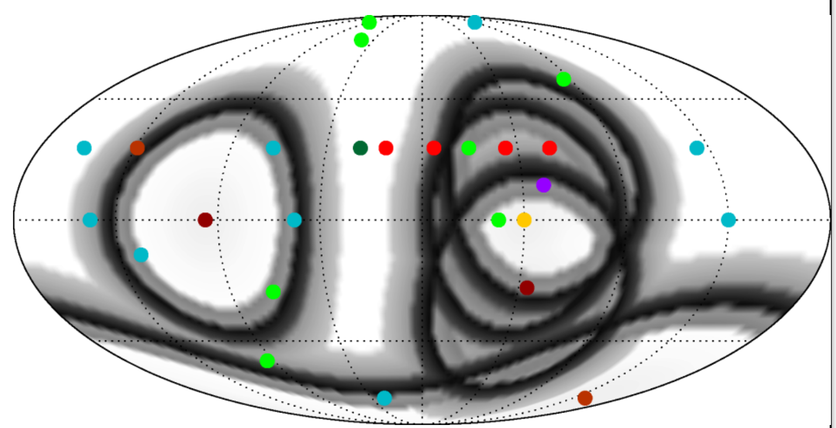
D. L. Bleuel et al.,
RSI 83, 10D313 (2012).

$$\Delta[\rho R(\Omega_1)] = -\frac{m_{DT}}{\langle\sigma_{DT}\rangle} ln\,[R_{SA}]$$

scattering (NIS, MRS, nTOFs)



Plot Dave Munro



- well NAD
- f NAD
- f NAD (new)
- MRS

shading: DT differential cross section for 10-12 MeV for DSR instruments

- 4.5 m nTOF
- Spec nTOF
- NITOF
- (new BT, SpecSP)

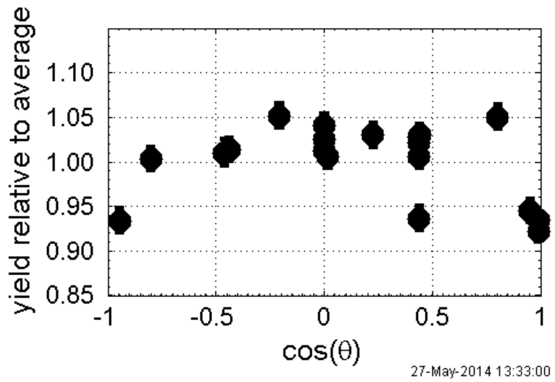
$$\rho R = \rho R_{dt} + \rho R_{CH} \approx 21\ \mathrm{dsr}_{dt} + 179\ \mathrm{dsr}_{CH}(g\ cm^{-2})$$

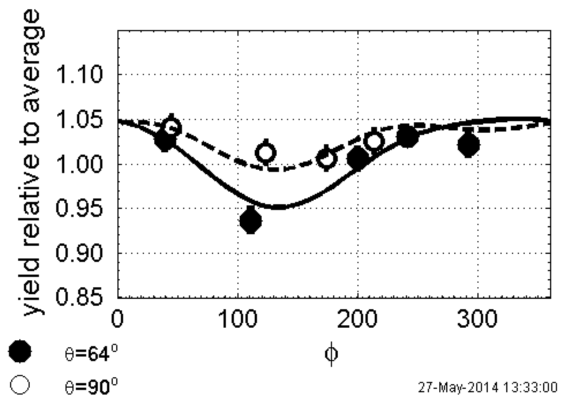
J. A. Frenje et al., Nuclear Fusion 53, 043014 (2013).

Nuclear activation data is used to measure anisotropy in yield and infer asymmetry of shell – example N140520

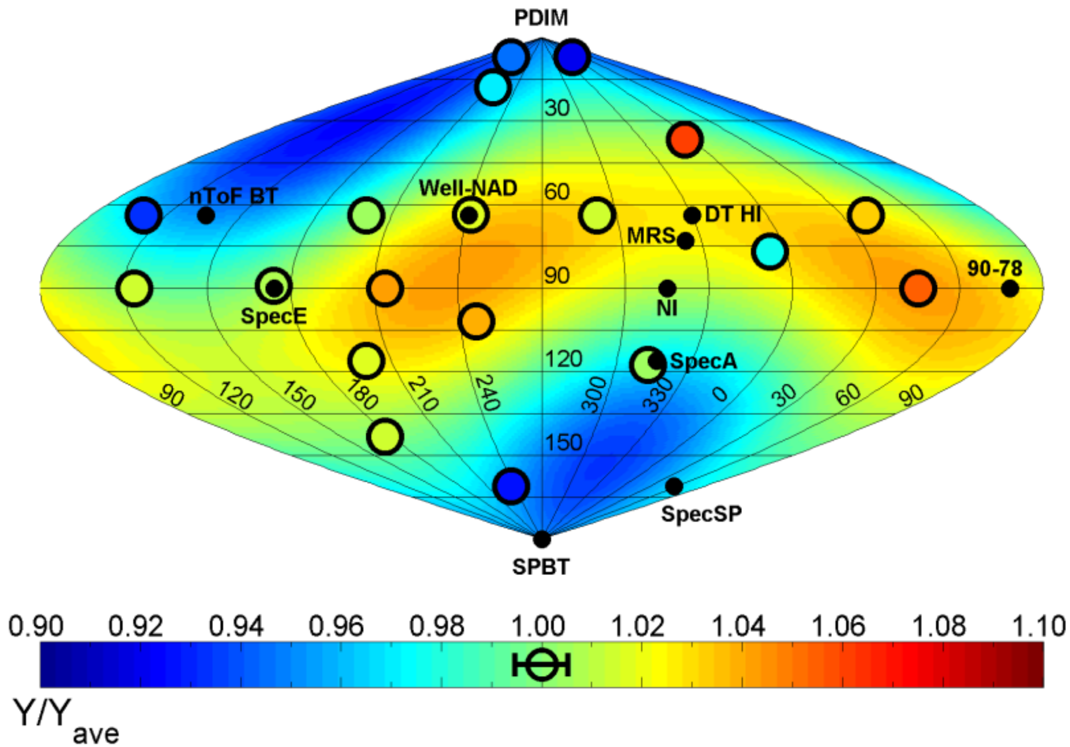
Charles Yeamans

N140520 – HF 388TW, 1.76 MJ, a DU hohlraum





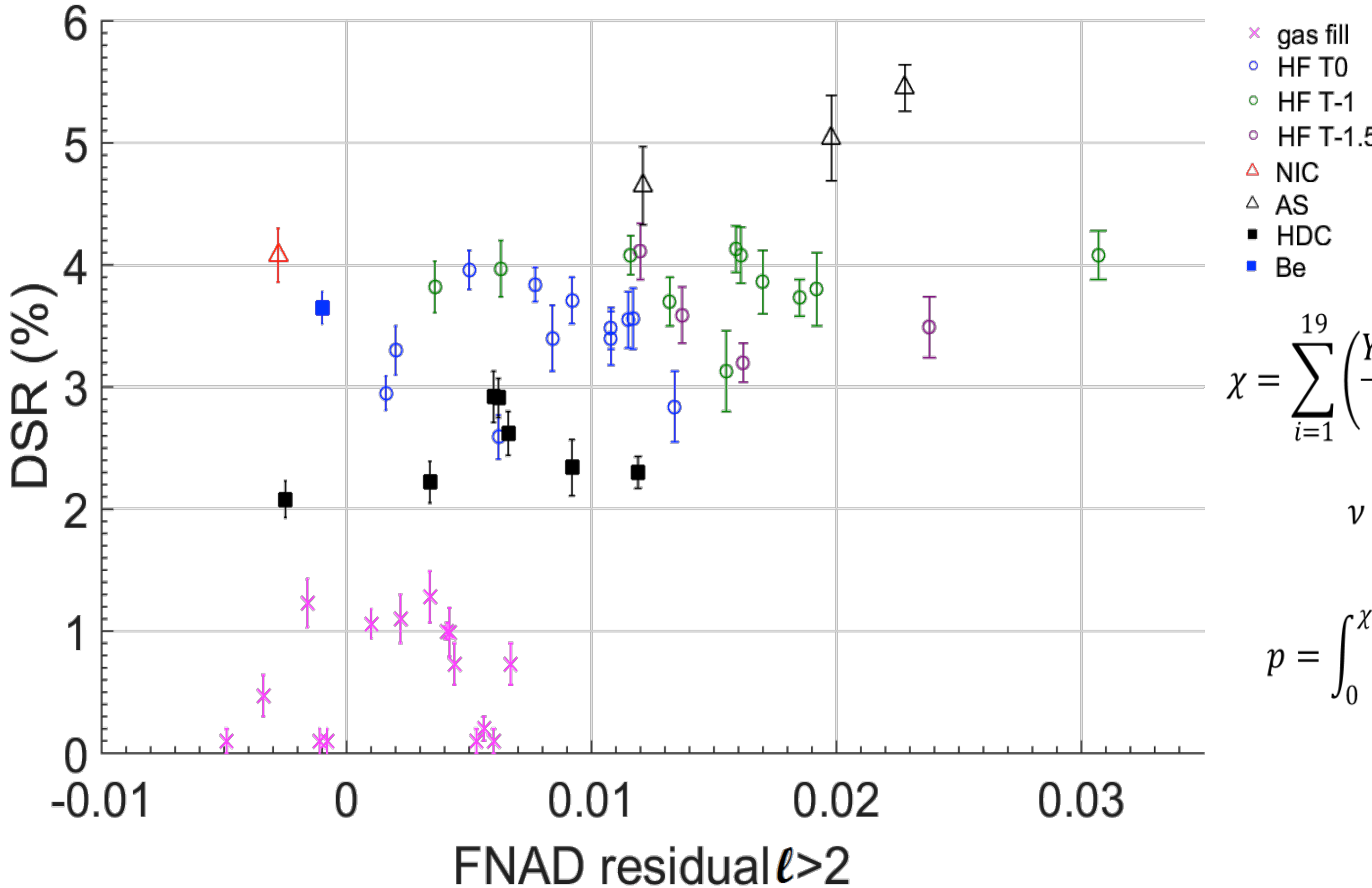
N140520-001 Flange-NAD normalized to IndDr results fit



Yield anisotropy implies significant low mode perturbations in shell in high performing implosions

With increased compression the residual from FNAD l≤2 increases suggesting more high mode variation in the stagnated shell over 4π

Charles Yeamans



$$\chi = \sum_{i=1}^{19} \left(\frac{Y_{rel,i} - Y_{fit,i}}{\sigma_i + \sigma_{res}} \right)^2$$

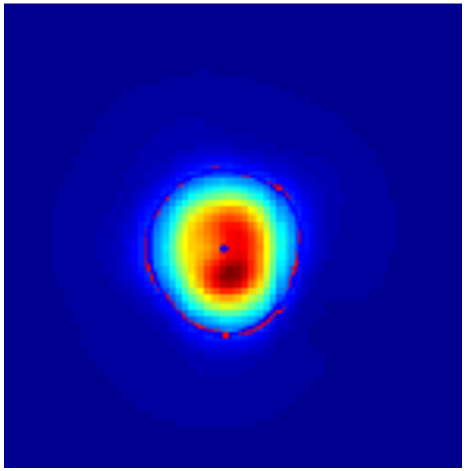
$$\nu = 10$$

$$p = \int_0^{\chi} \frac{t^{\frac{\nu-2}{2}} e^{-\frac{t}{2}}}{2^{\frac{\nu}{2}} \Gamma\left(\frac{\nu}{2}\right)} dt$$

High mode perturbations in shell increase with increasing ρR

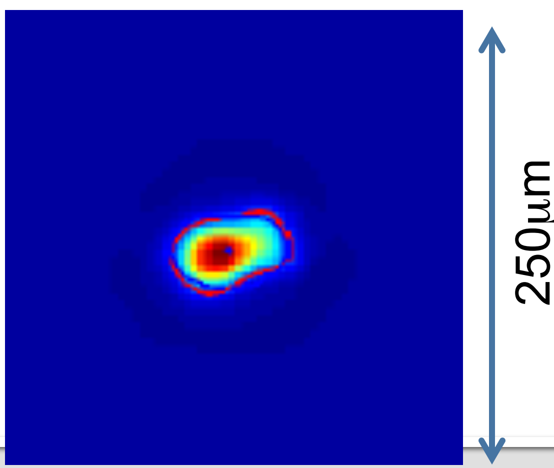
The DSR on N140520 shows some LOS variation which may be a symptom of asymmetry, the neutron images likewise show some evidence of asymmetry

6-12 MeV

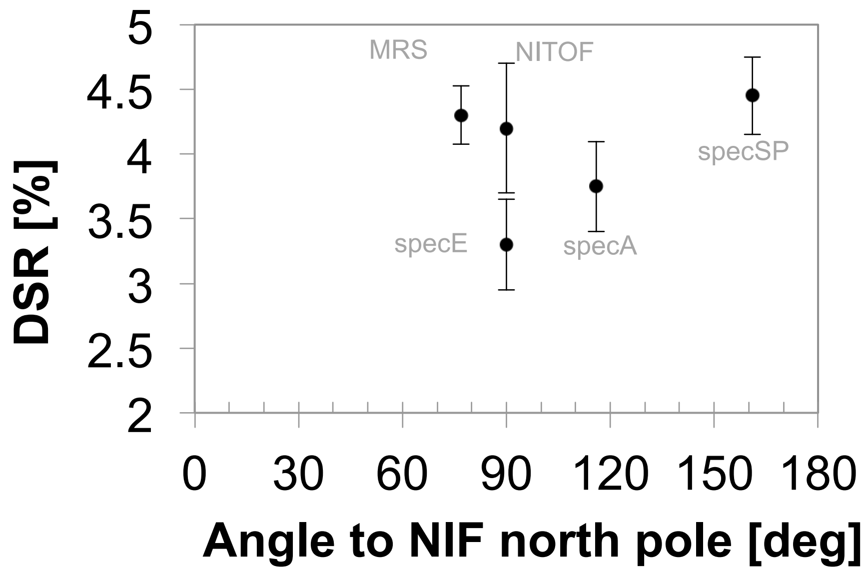


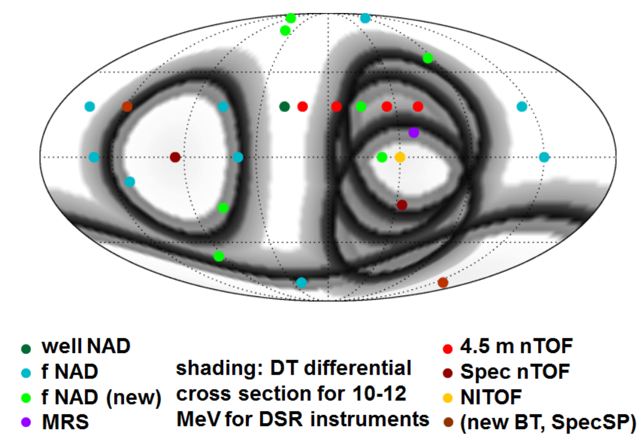
P0=42.57 um
P2/p0=7%
P3/P0=1%
P4/P0=0%

13-17 MeV

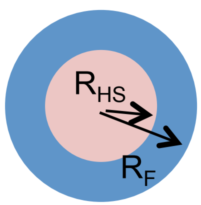


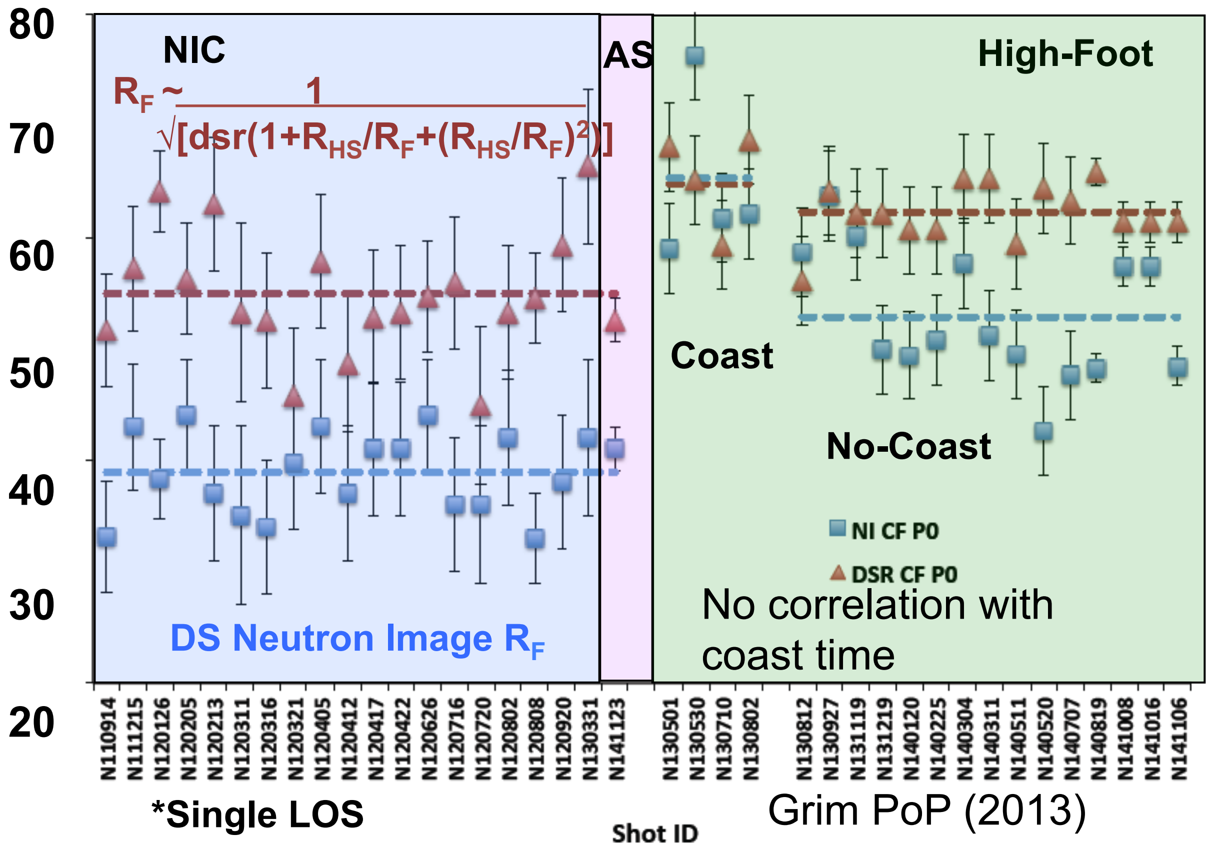
P0=27.62 um
P2/p0=-25%
P3/P0=-1%
P4/P0=1%





Down-scattered neutron images are generally smaller than expected from simple DSR model* possibly due to ice/ablator mix or low mode asymmetry



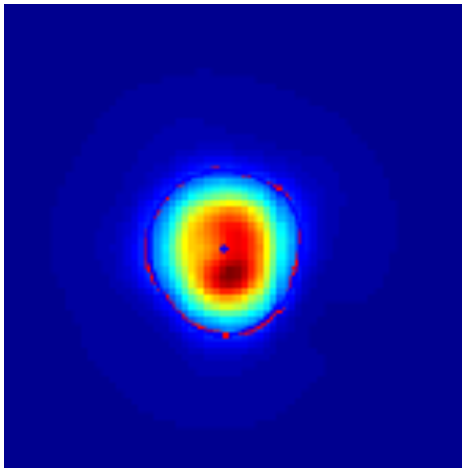


*G. P. Grim et al., Physics of Plasmas 20, 056320 (2013).

Low mode perturbations in shell make ρR on the pole hard to see in DSn image

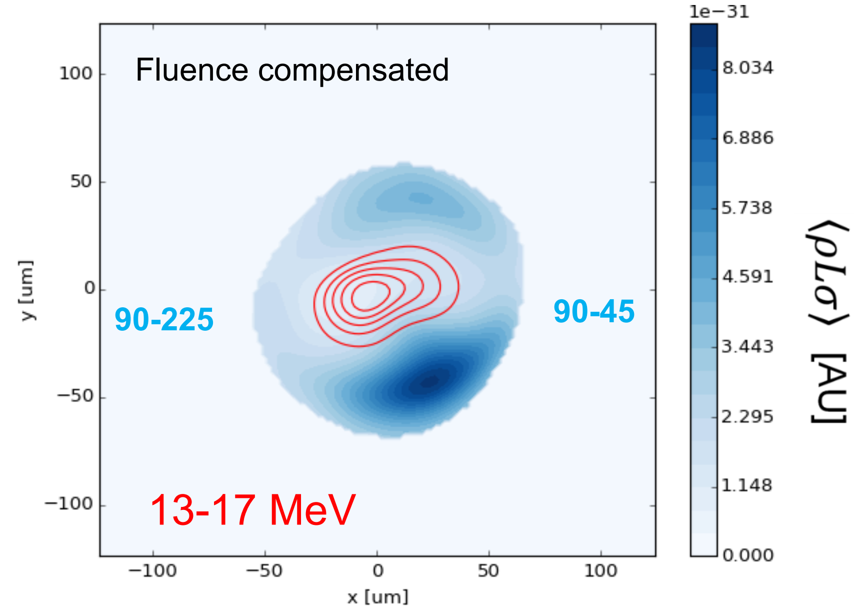
If we attempt to take the primary neutron fluence out of the down-scattered image can that make low mode asymmetry easier to see?

6-12 MeV



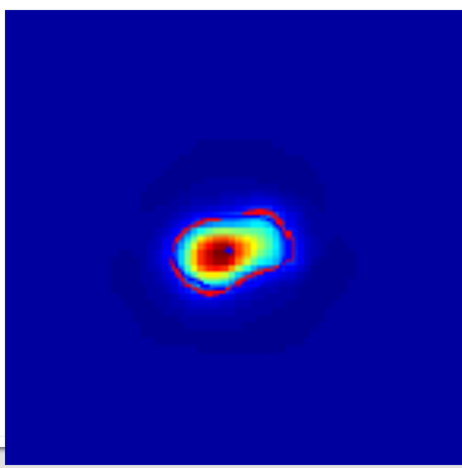
N140520

$$\frac{\text{DSnI}}{\psi} =$$

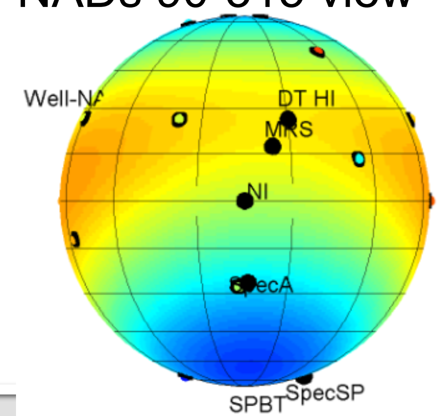


Estimate
DT fluence ψ

13-17 MeV

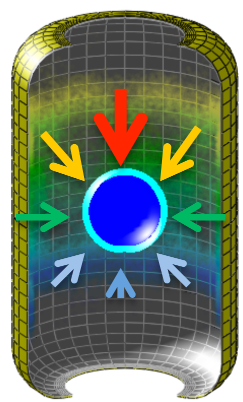


FNADs 90-315 view

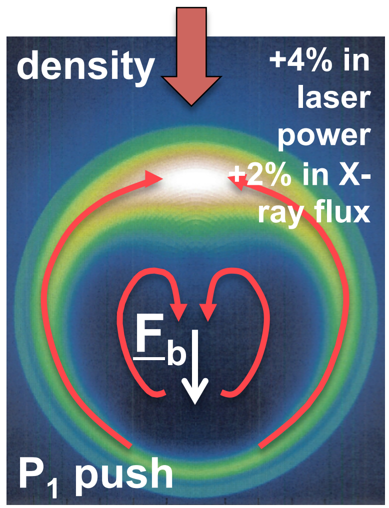


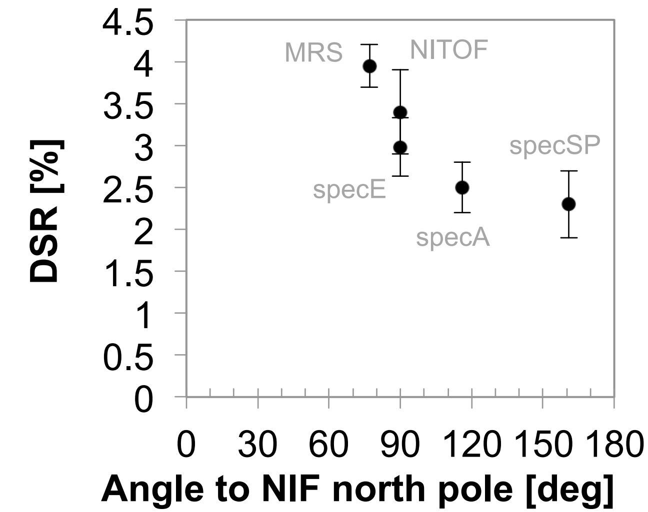
N140520 was repeated with a +-4% intentional P1 drive imbalance [N150318] and the nuclear diagnostics signatures of the shell symmetry behaved as expected

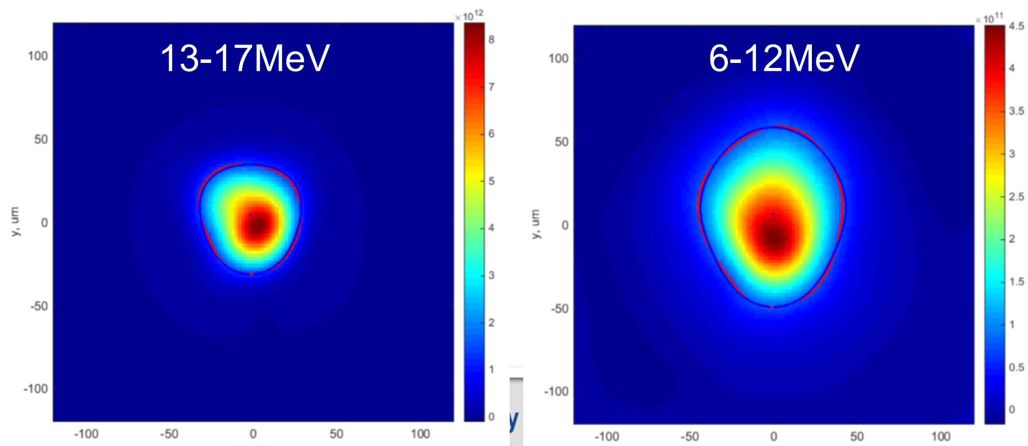
Drive asymmetry
P1: ± 4% (laser)



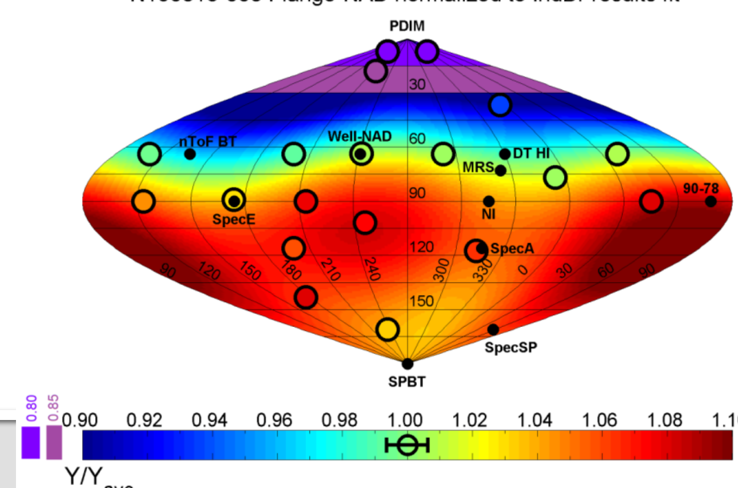
B. K. Spears et al., POP 21, 042702 (2014).



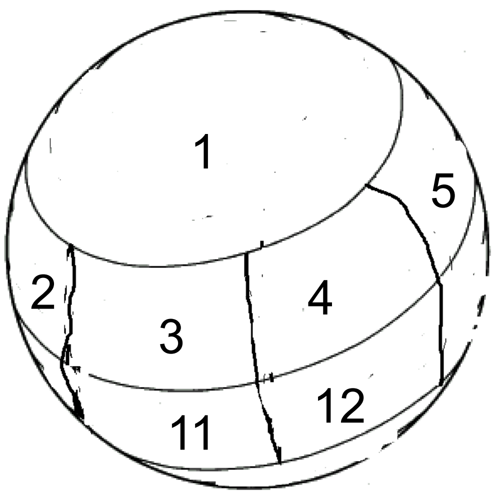


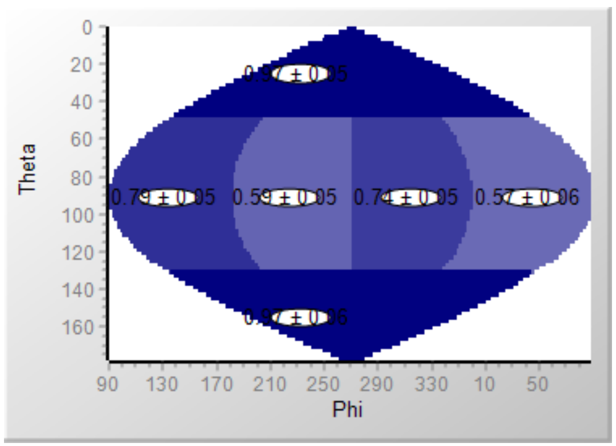


N150318-003 Flange-NAD normalized to IndDr results fit

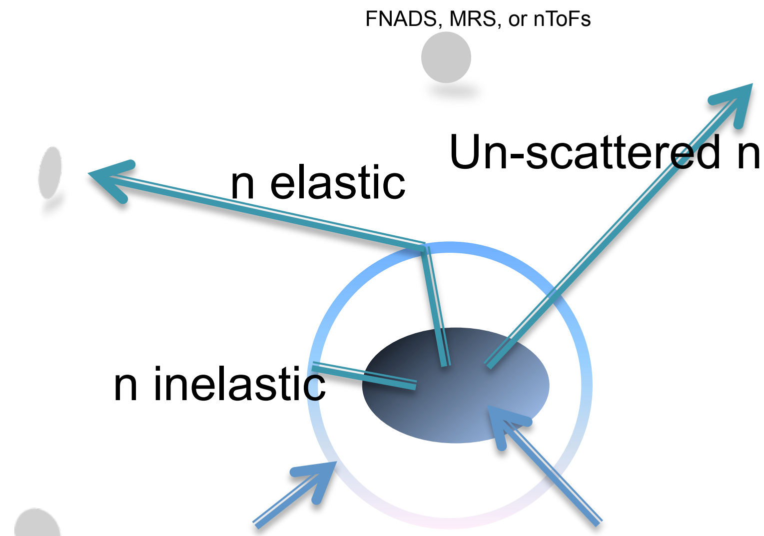


R. Bionta has developed a 6 ρR segment data-driven Monte Carlo fit to the FNAD and nTOF DSR/Yn data





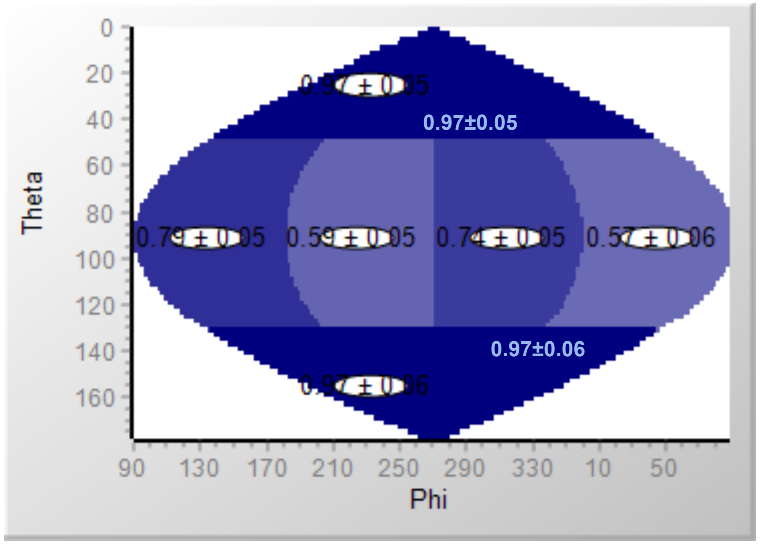
Fast Monte Carlo fit to 19 FNAD, the nToF and MRS yields and *dsr* for a total of 27 measurements:



Thin shell of dt ice with ρR but no thickness placed at NIS dsr image 17% P0

3-D Gaussian matches NIS 17% primary P0, P2, P4

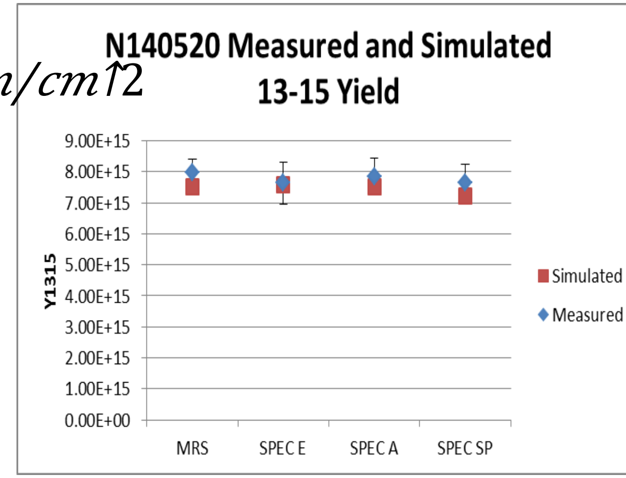
Bionta's six segment fit suggests more areal density on the poles with some azimuthal asymmetry on N140520



$$\chi_\nu^2 = 1.7 \quad Y_B = (8.64 \pm 0.07) \times 10^{15}$$

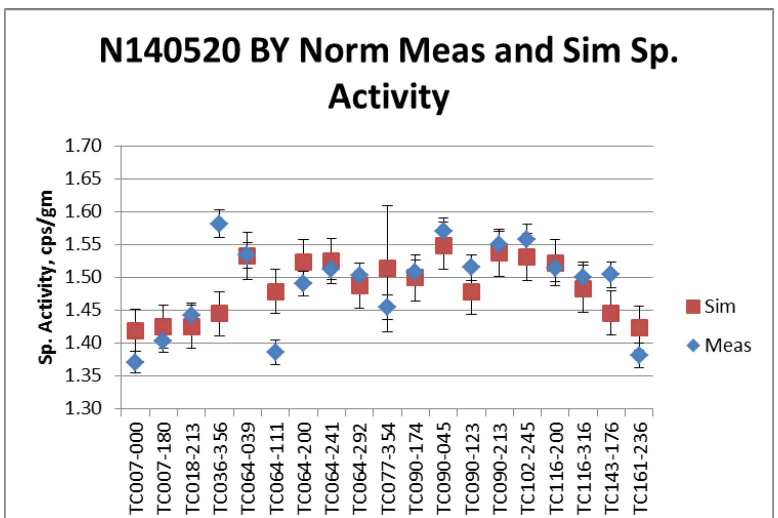
	ρR	$\pm \sigma_{\rho R}$
1	0.97	0.05
2	0.57	0.06
3	0.79	0.05
4	0.59	0.05
5	0.74	0.05
6	0.97	0.06

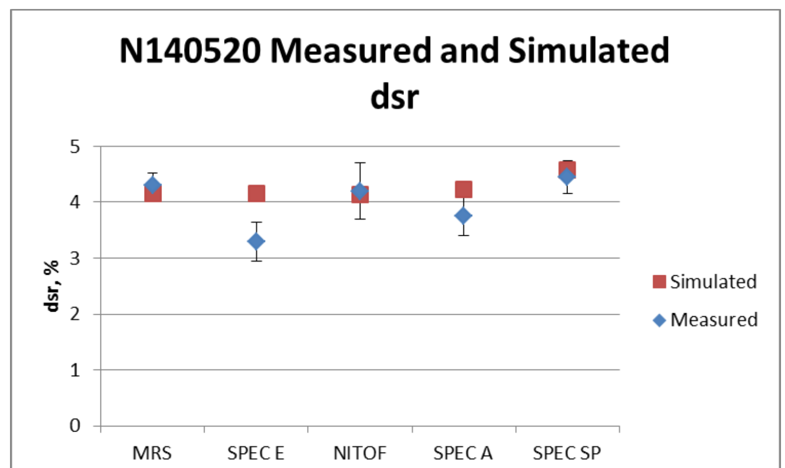
gm/cm^2



Source Distribution

σ_x	14.9	μm
σ_y	12.6	
σ_z	12.2	

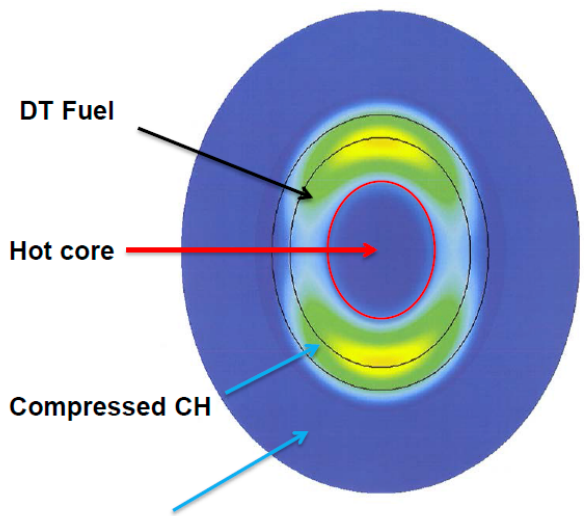




High Foot DT, 1.78MJ, 390TW, DU nominal hohl, 1.6mg/cc He fill, 1xSi, T-1 shell, 0.8K quench

The Cerjan/Springer static fit combines multiple measurements to attempt to reconstruct the stagnated hotspot and shell

Static Isobaric Model Overview



Density distribution

The pressure, density and temperature are deduced from an isobaric model fit to the x-ray and nuclear data.

Input from experiment
- X-ray Images: equator and pole
- Burn history: x-ray or GRH
- Neutron time of Flight (NTOF) trace
- Yield (13-15 MeV)
- DSR

χ^2 fit

P_{hs}, $\rho(r,\theta,\varphi)$, $T(r,\theta,\varphi)$

Output

Derived parameters
- Volume
- Hot core Energy (PV)
- Hot core density
- Neutron images
- Directional neutron spectra

11/6/2012

Virtual Campaign

Fit Parameters

P_{hs}

$\rho_{hs}(r,\theta,\varphi)$ $\rho_{shell}(r,\theta,\varphi)$

parameterized in $Y_{lm}(\theta,\varphi)$

EOS model

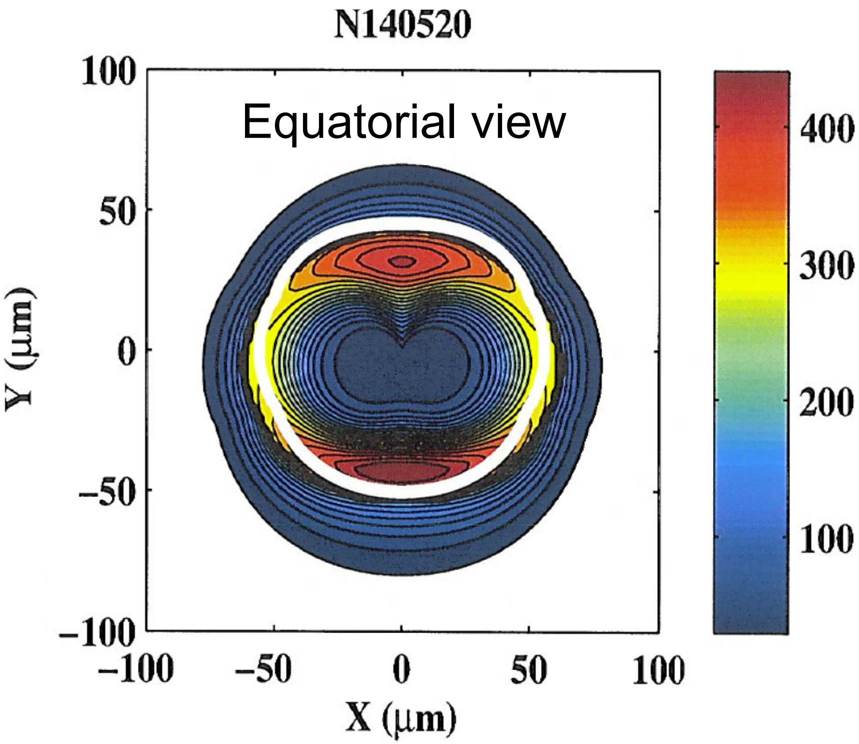
$T(r,\theta,\varphi)$

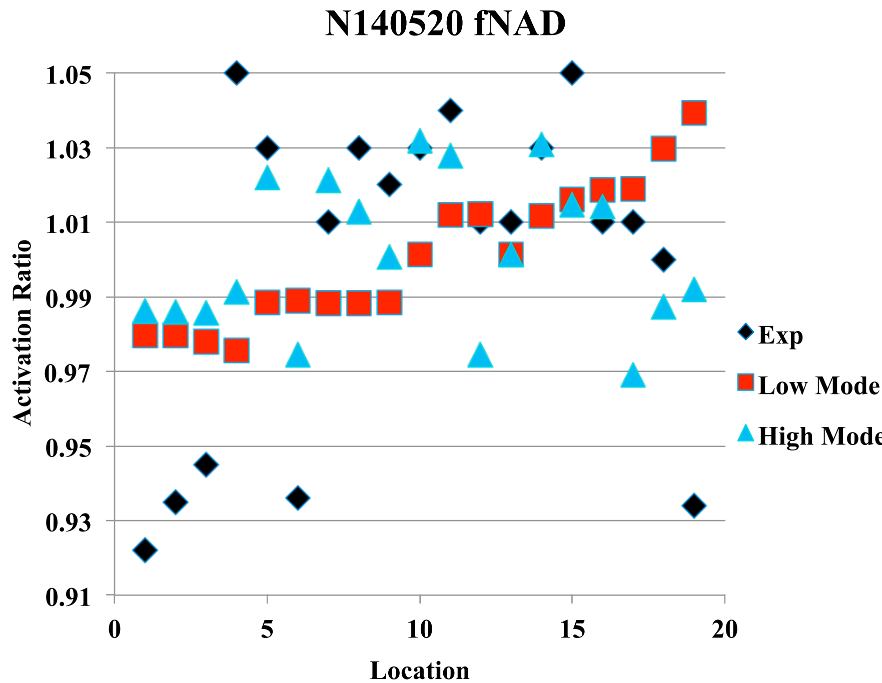
3D (P,ρ,T)

Opacity Model (x-ray image)
Caughlan-Fowler (TN burn)

C. Cerjan, P. T. Springer, and S. M. Sepke, POP **20** 056319 (2013).

The Cerjan/Springer fit on N140520 also suggests more ρR on the poles



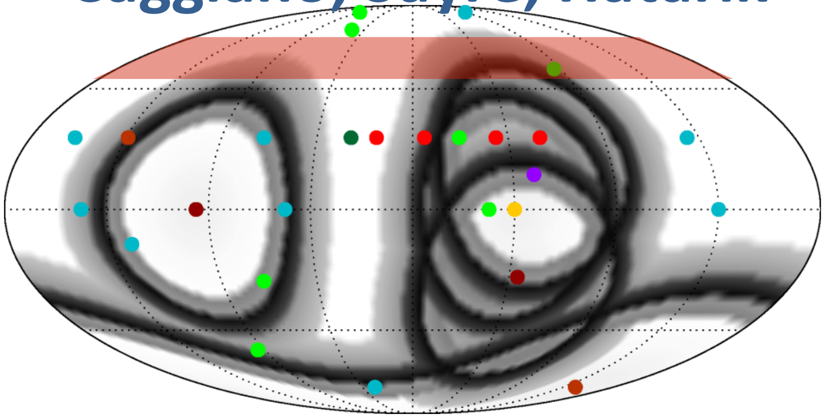


	Exp	Low Mode	High Mode
SpecA	0.0375	0.0413	0.0419
SpecE	0.0330	0.0392	0.0424
MRS	0.0445	0.0451	0.0409
NITOF	0.0430	0.0437	0.0412
SpecNP		0.0524	0.0465
NIS		0.0878	0.0833

C. Cerjan, P. T. Springer, and S. M. Sepke, POP **20** 056319 (2013).

Where we are going…

North pole nTOF
Caggiano, Sayre, Hatarik



Compton radiography
Riccardo Tommasini

Self Compton radiography
Niko Izumi

Instant FNADS
Ellen Edwards
Charles Yeamans

Dynamic models
Gaffney/Hammer/Springer

More FNADS