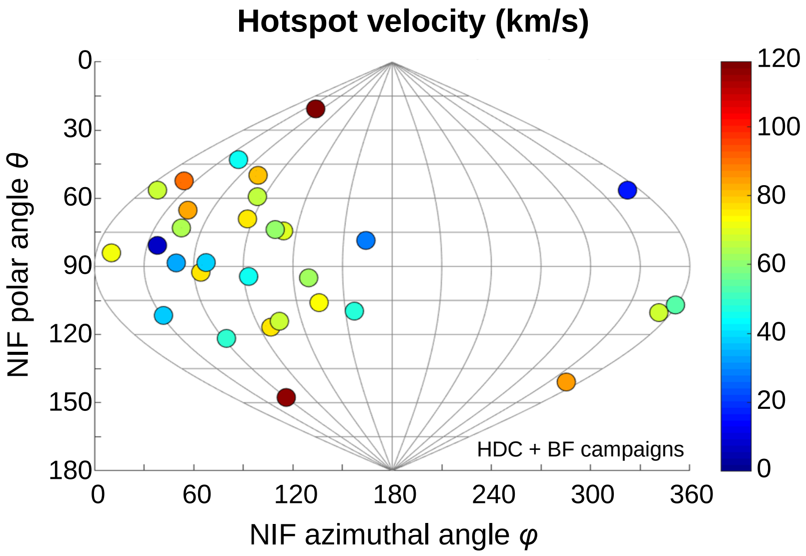
Signatures of Systematic Azimuthal Asymmetry in Nuclear Diagnosis of ICF Implosions on the NIF



H. G. Rinderknecht
University of Rochester
Laboratory for Laser Energetics

60th Annual Meeting of the American Physical Society Division of Plasma Physics
Portland, OR | 5 – 9 November 2018

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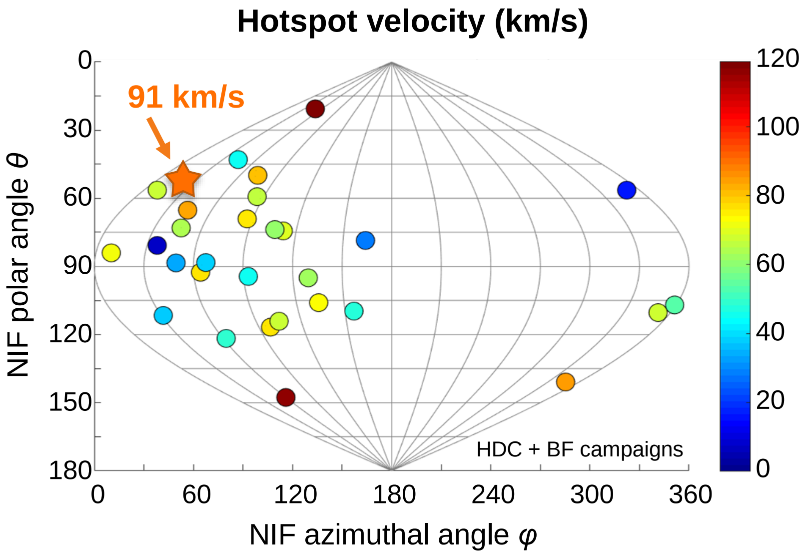

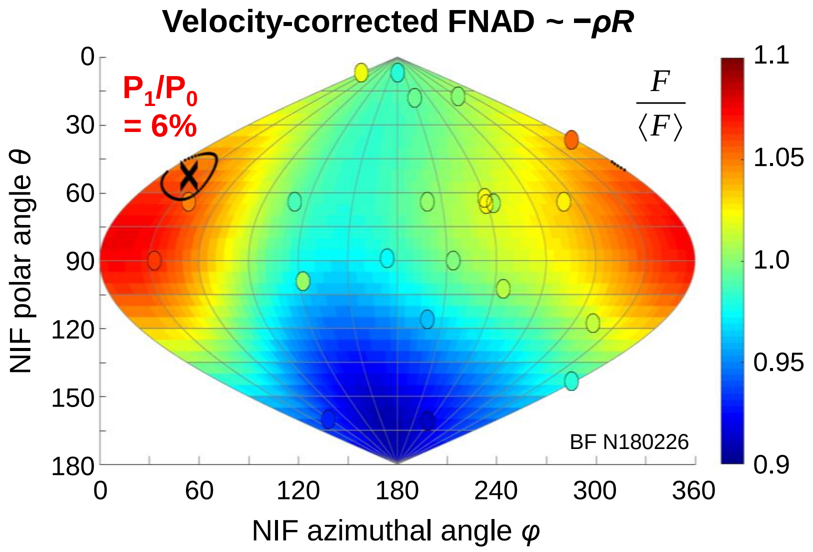

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Combining nTOF hotspot velocities and FNAD ρR maps improves understanding of stagnation asymmetry in NIF experiments

1. Hotspot velocity is systematically toward ϕ ~ 90˚ on recent DT cryogenic implosions

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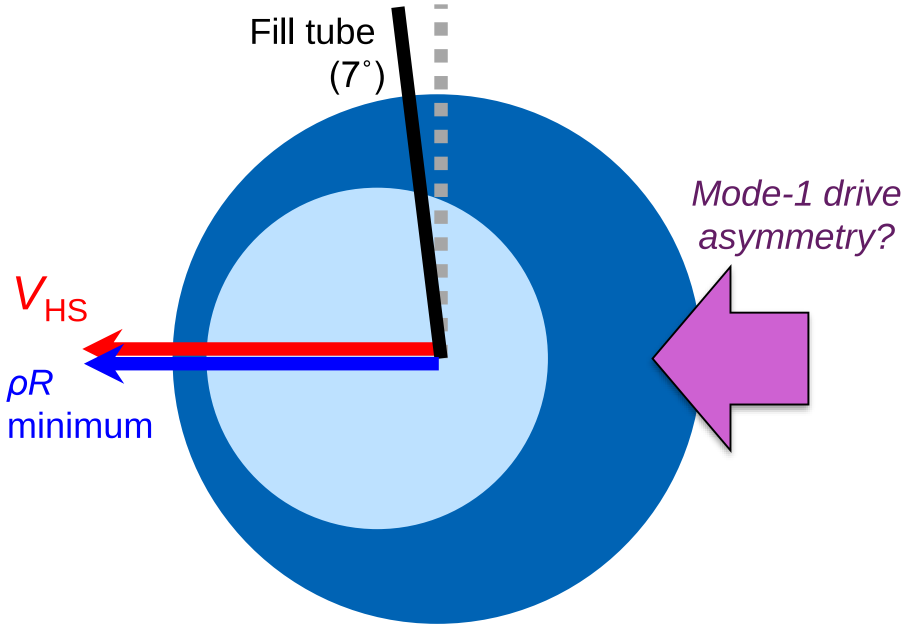
3. Mode-1 implosion asymmetry can explain both the velocity and ρR signatures



nTOF: neutron time-of-flight
FNAD: flange neutron activation diagnostics

Many thanks to my collaborators:

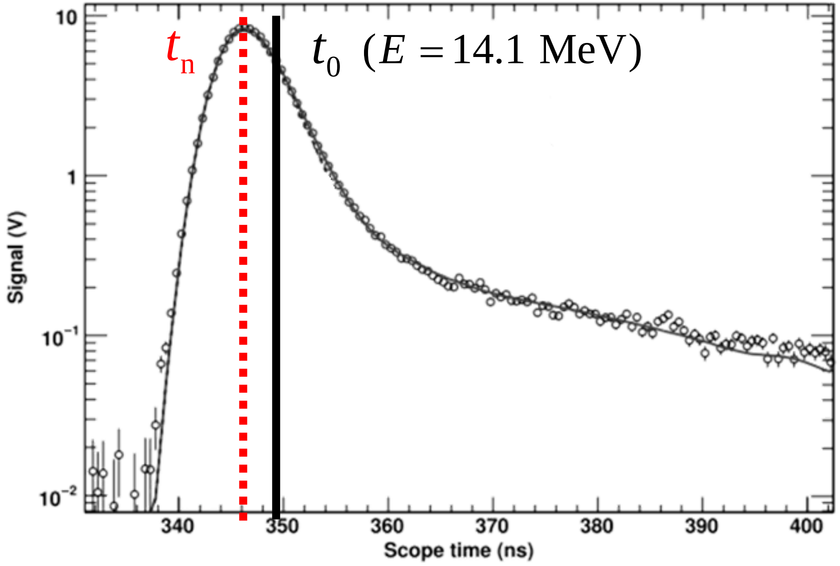
D.T. Casey, R. Bionta, R. Hatarik, A. Moore, E. Hartouni, D. Schlossberg,
G. Grim, O. Landen, P. Patel

Lawrence Livermore National Laboratory

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

DT- and DD-neutron spectra are sensitive to hotspot velocity: net velocity produces a Doppler shift in neutron energy

DT-neutron time-of-flight (nTOF) signal*

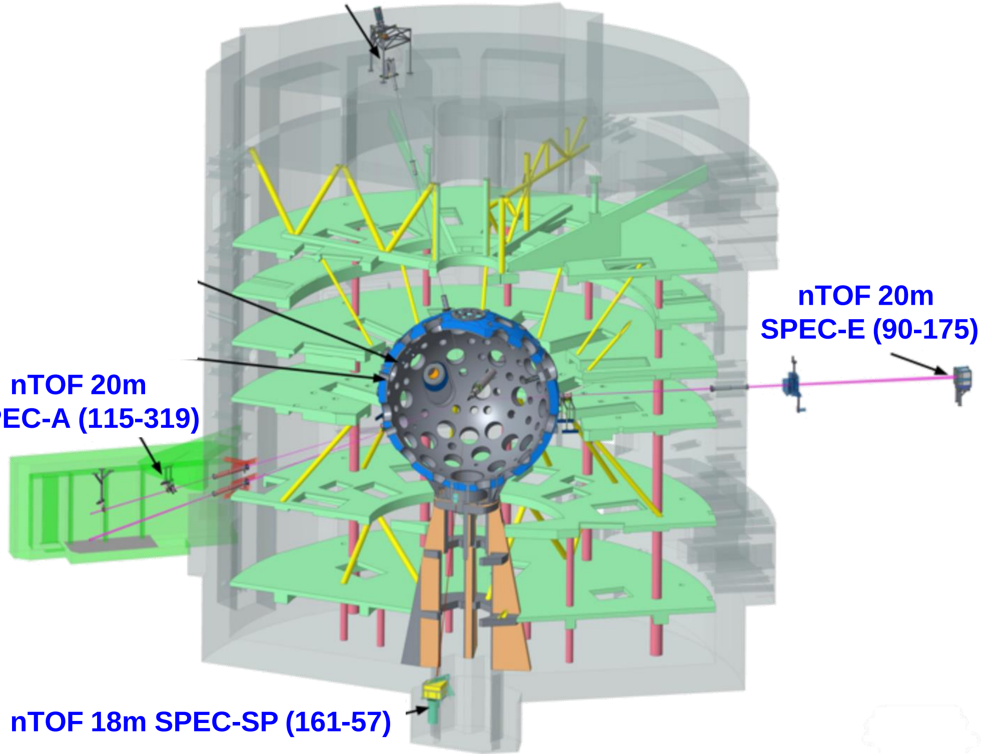


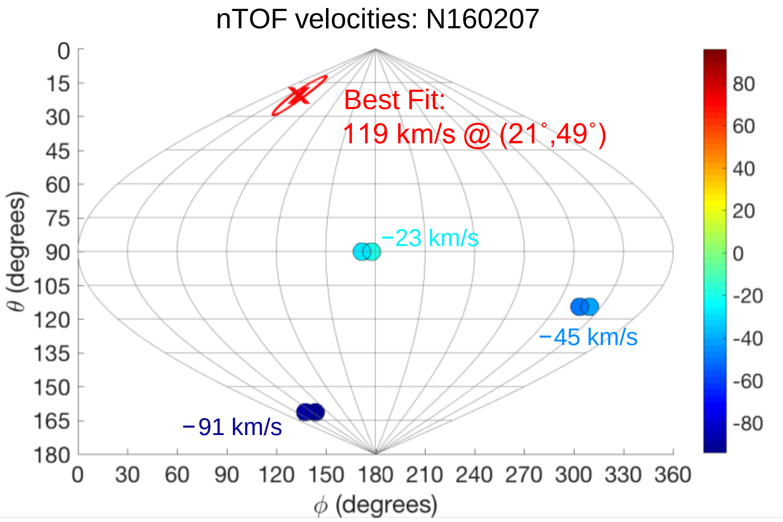
$$\mathrm{v}_\mathrm{n} = \frac{d}{t_\mathrm{n} - t_\mathrm{bang}} \approx \left(\vec{\mathrm{v}}_0 + \vec{\mathrm{V}}_\mathrm{HS}\right) \cdot \hat{d}$$

Each detector measures the hotspot velocity projected along its line of sight

*R. Hatarik et al., J. Appl. Phys. **118**, 184502 (2015).

On the NIF, DT- and DD-neutron spectra are used to measure the mean hotspot velocity on up to four nTOF lines of sight

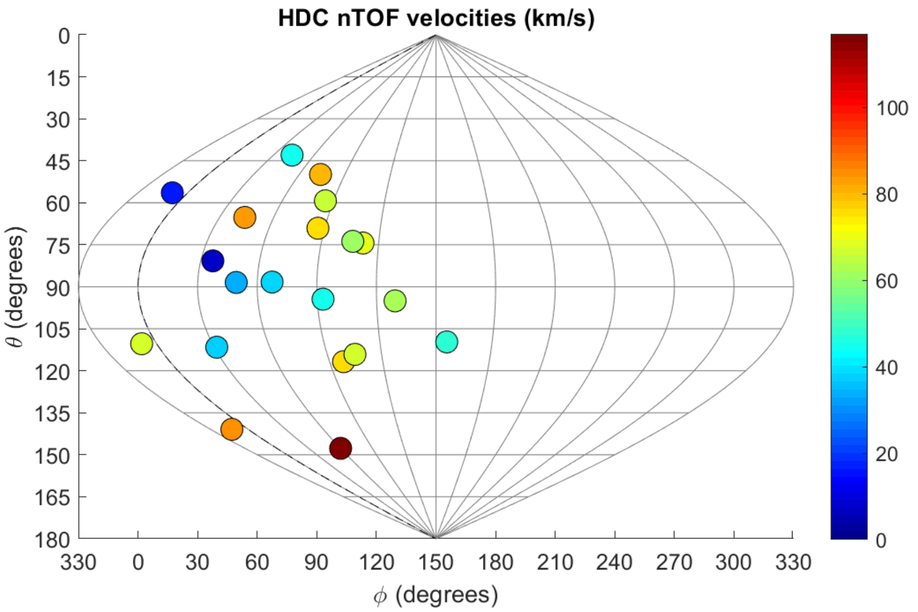


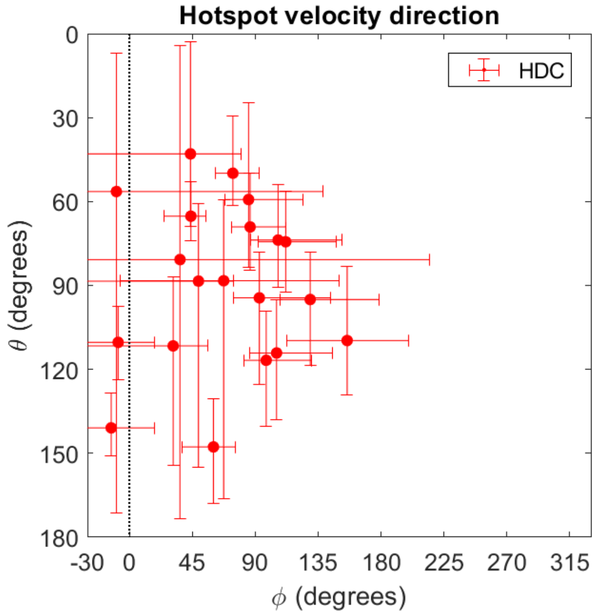


A best-fit hotspot velocity (x) and uncertainty boundary is found, using:

$$\chi^2 \leq \min(\chi^2) + \chi^2_{limit}$$

Looking at a group of cryogenic DT implosions, a pattern emerges: hotspot velocity tends toward ϕ ~ 90˚ on the equator

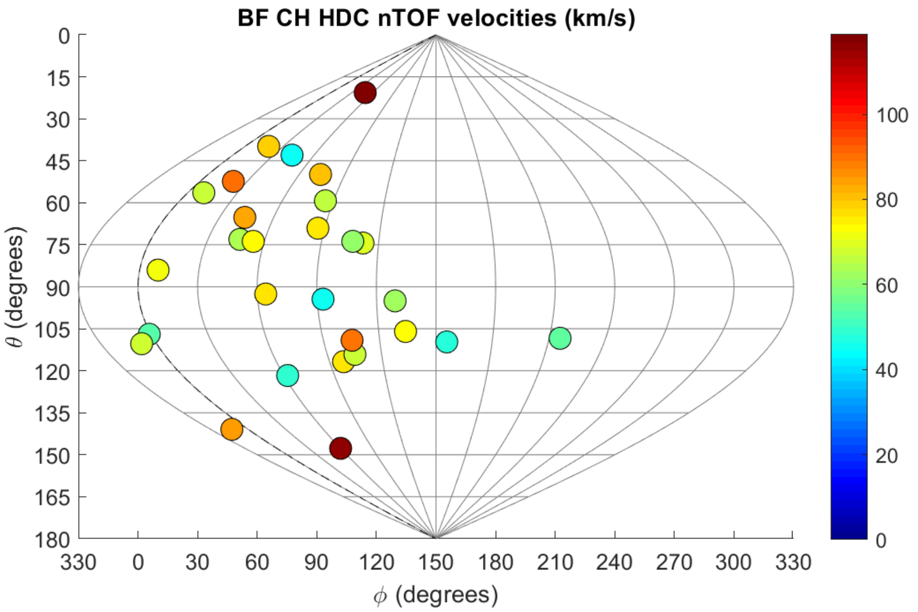


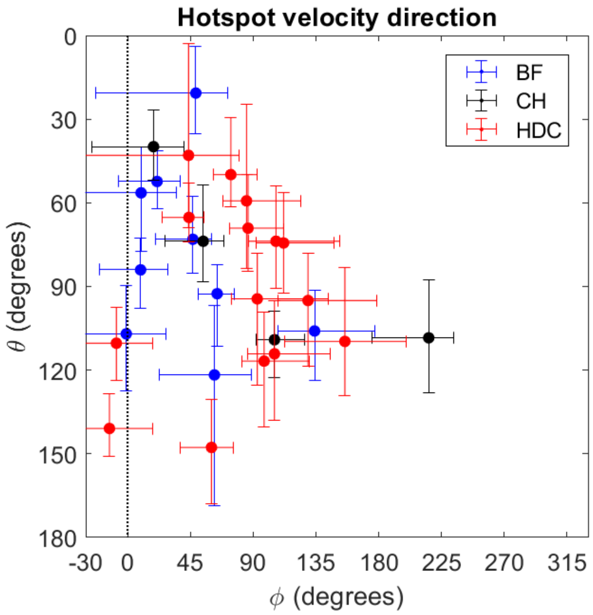


HDC: 20 shots

Showing analyzed shots, FY16—18

Looking at a group of cryogenic DT implosions, a pattern emerges: hotspot velocity tends toward $\phi \sim 90^{\circ}$ on the equator



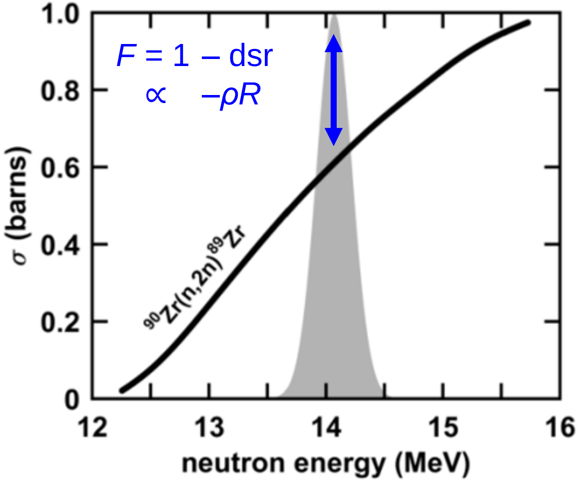


HDC: 15/20 shots
BF: 9/10 shots
CH: 4/15 shots

Showing analyzed shots, FY16—18 with V > 40 km/s

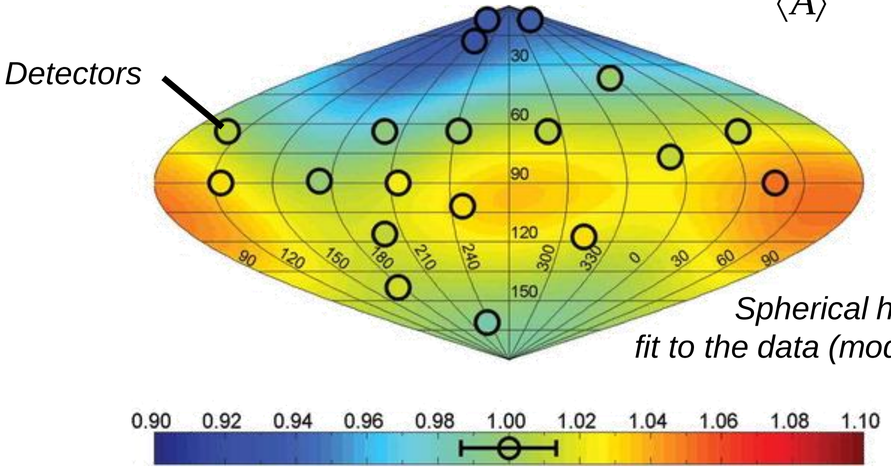
Nuclear activation detectors (NADs) diagnose variations in neutron fluence due to scattering in fuel

^{90}Zr(n,2n)^{89}Zr cross-section



$$A = \int \sigma(E) \frac{dF}{dE} dE \propto F$$

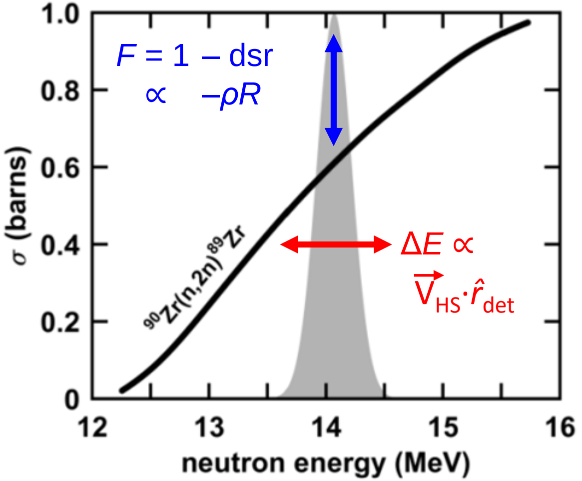
Normalized flange NAD activation: $\dfrac{A}{\langle A \rangle}$



Spherical harmonic fit to the data (modes 1, 2)

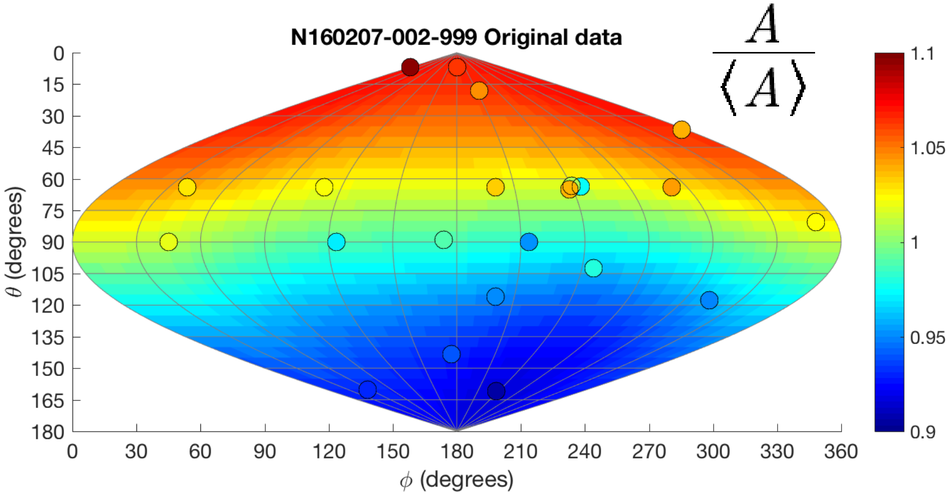
C. Yeamans and D. Bleuel, Fusion Sci. Technol. ***72****, 120 (2017).*

However, a neutron energy shift from hotspot flow velocity can cause an "offset" (mode 1) in activation patterns



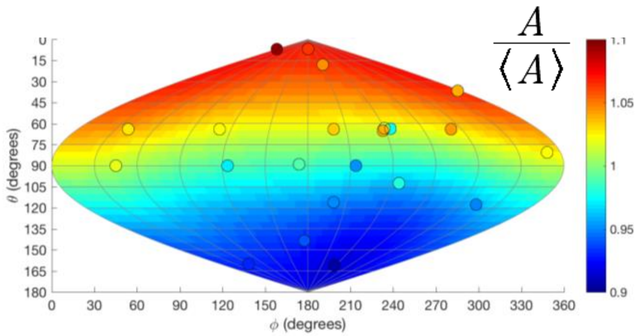
$$\frac{A}{\langle A\rangle} \approx \frac{F}{\langle F\rangle}\frac{\sigma(E)}{\sigma(\langle E\rangle)}$$

$\propto -\rho R$ $\propto V_{HS} \cos \theta_{det}$

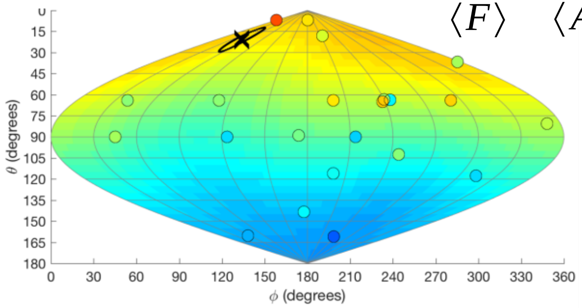


Mode-1 asymmetry in activation: is this due to velocity or areal density?

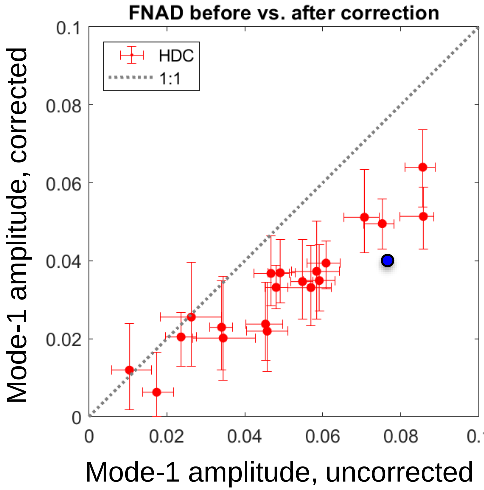
Using the mean hotspot velocity, we can correct FNAD data to infer areal-density variation (ρR)



Corrected:
V = 119 km/s



$$\frac{F}{\langle F \rangle} = \frac{A}{\langle A \rangle} \Bigg/ \left[\frac{0.032\ V_{HS} \cos\theta}{100\ \text{km/s}} \right]^{*}$$

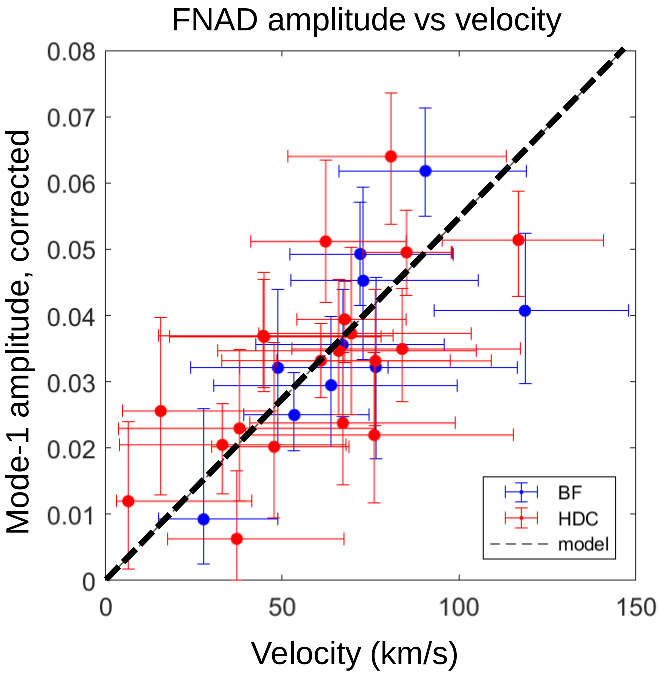


The mean hotspot velocity accounts for ~30% of FNAD mode-1 amplitude.

*see H.G. Rinderknecht et al., *Rev. Sci. Instrum.* **89**, 10I125 (2018).

In cryogenic implosions, the corrected FNAD mode-1 amplitude (∝ *ρR* asymmetry) increases linearly with hotspot velocity

$$\frac{F}{\langle F \rangle}$$

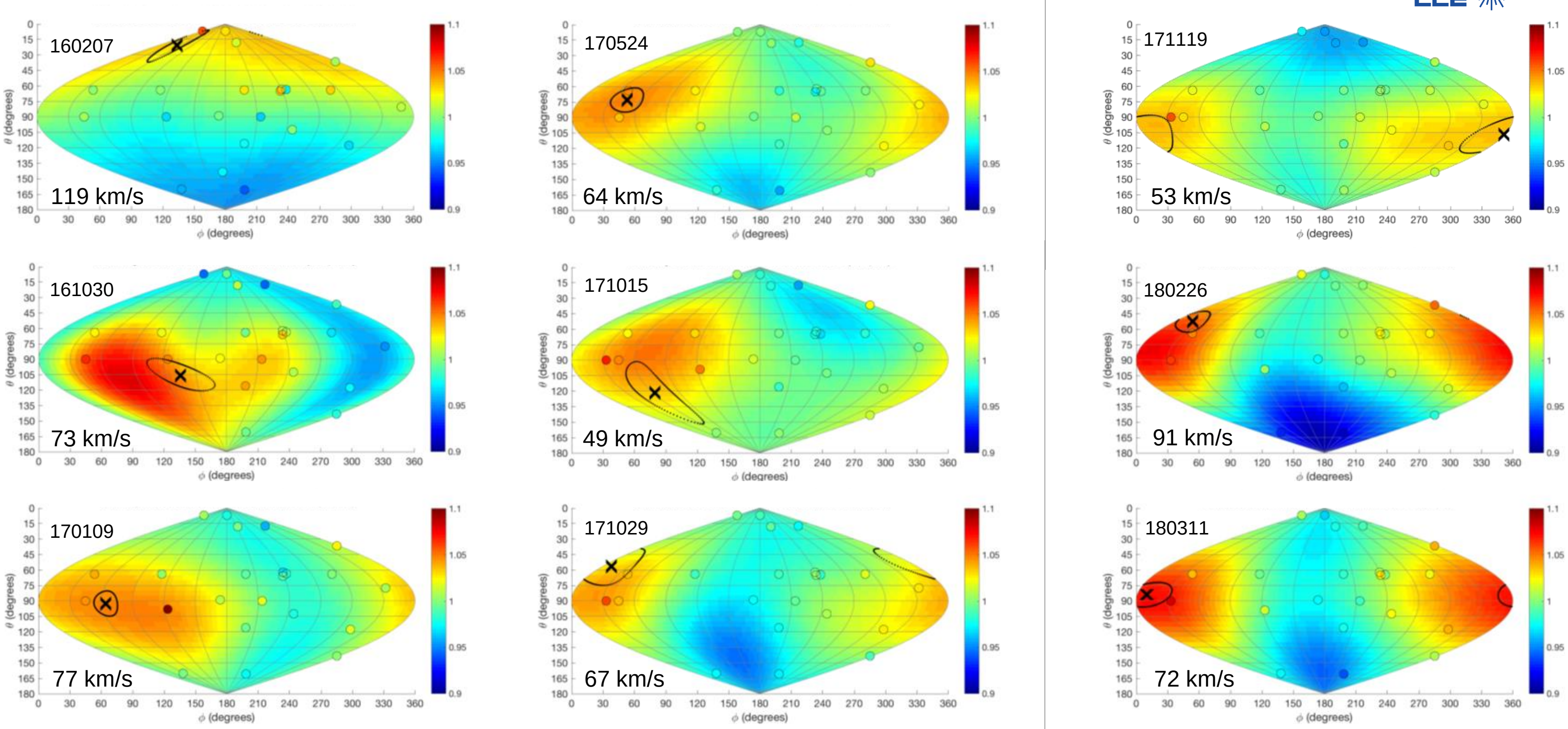


$$\frac{\ell_1}{P_0} \approx 5.5\% \left(\frac{V_{\mathrm{HS}}}{100\,\mathrm{km/s}} \right)$$

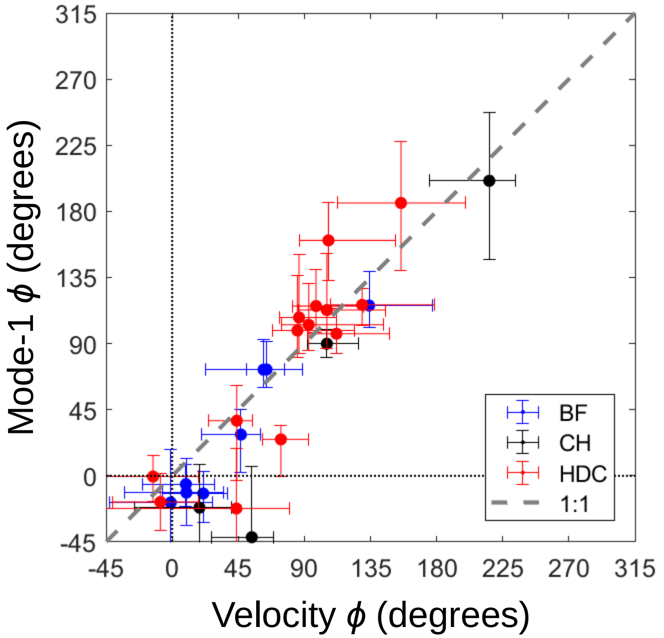
The residual FNAD mode-1 is in the same direction as the hotspot velocity on most shots

Bigfoot series:

$$\frac{F}{\langle F \rangle}$$



The residual FNAD mode-1 is in the same direction as the hotspot velocity: mean velocity and low *ρR* are toward $\phi = 90^\circ$



HDC: 15/20 shots

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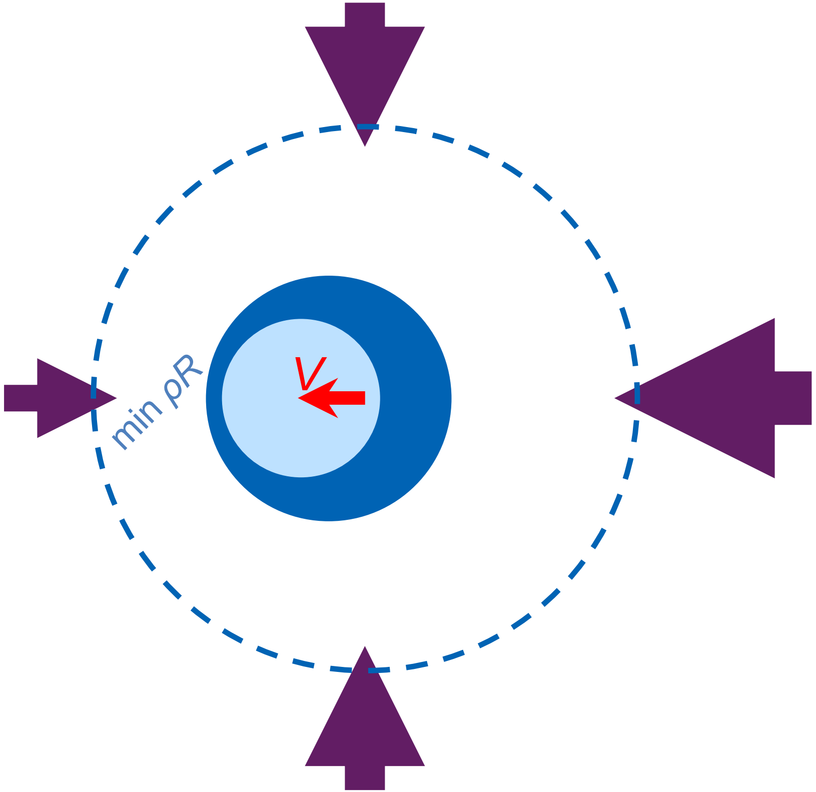
Showing analyzed shots, FY16—18 with V > 40 km/s

The following picture emerges from the data: low *ρR* and velocity in one direction can be caused by reduced compression on that side



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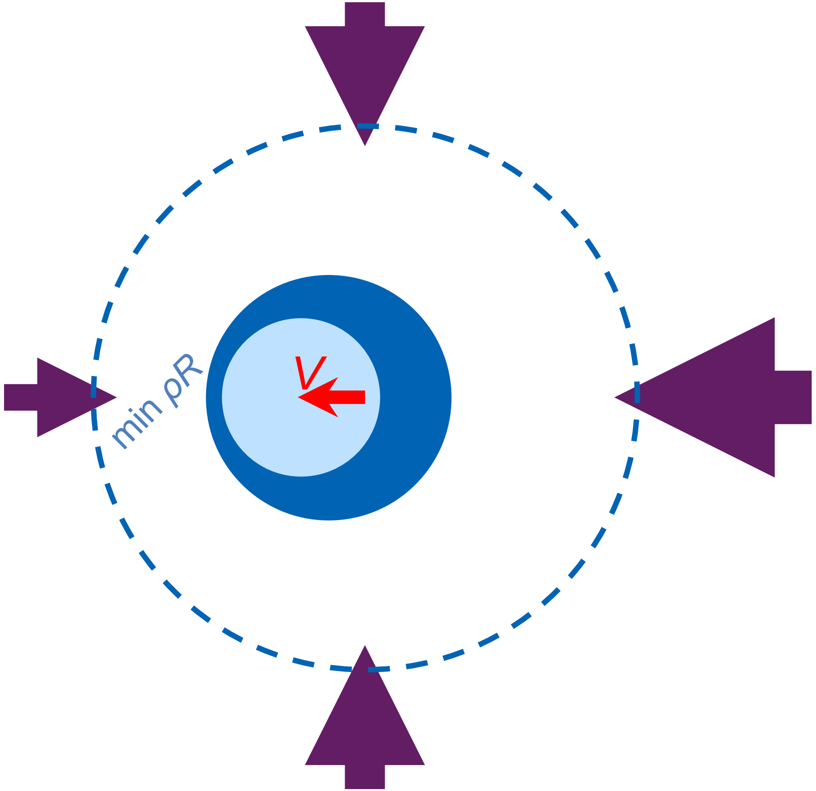
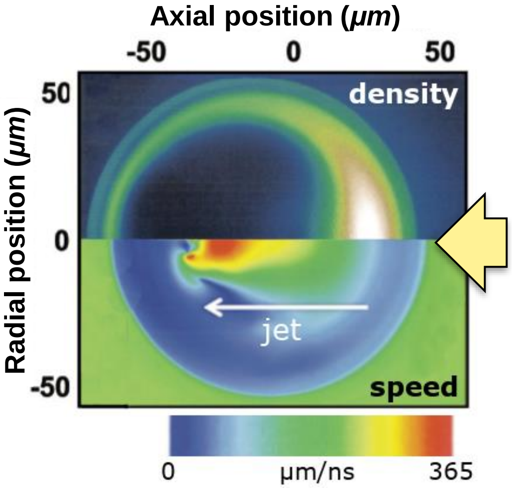
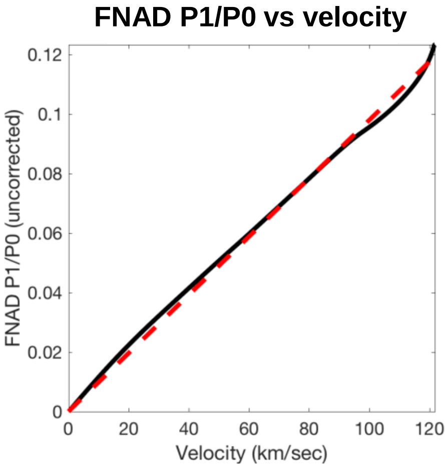


Brian Spears P1 drive shows the same trend:

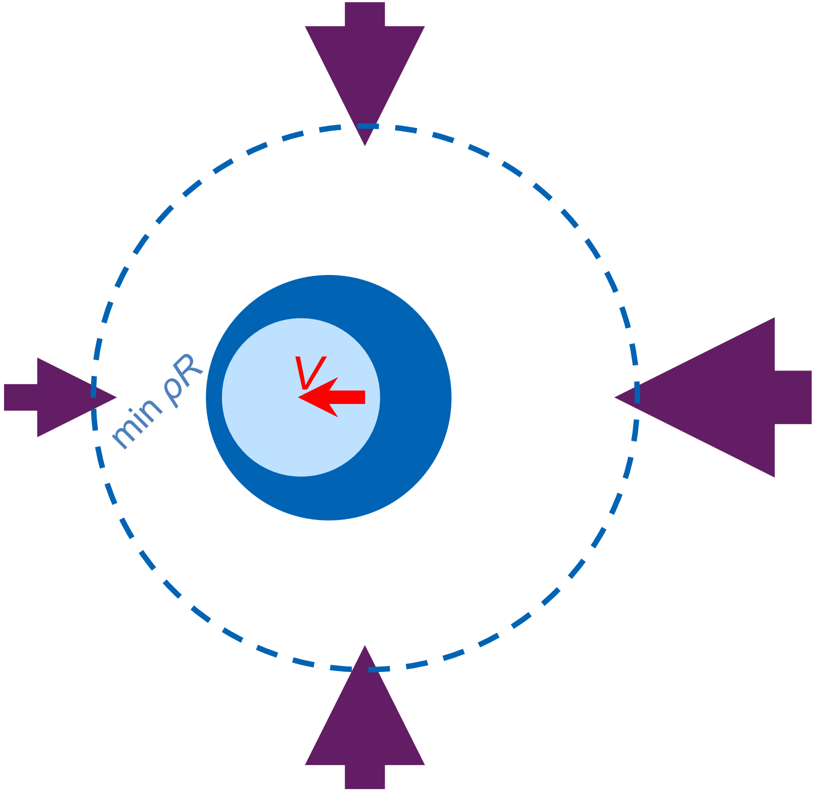




Sim: 9.8% / (100 km/s)

B. Spears *et al.*, Phys. Plasmas **21**, 042702 (2014).

The following picture emerges from the data: low ρR and velocity in one direction can be caused by reduced compression on that side



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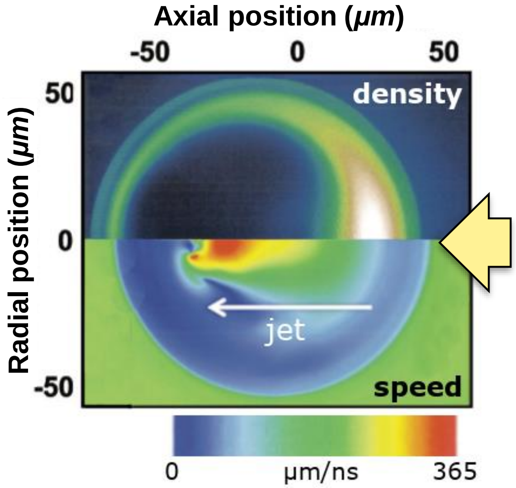

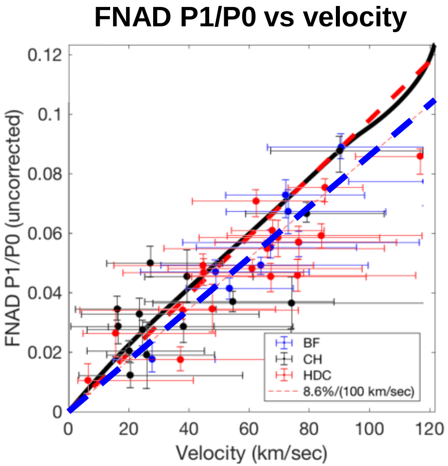

Sim: 9.8% / (100 km/s)

Data: 8.6% / (100 km/s)

B. Spears *et al.*, Phys. Plasmas **21**, 042702 (2014).

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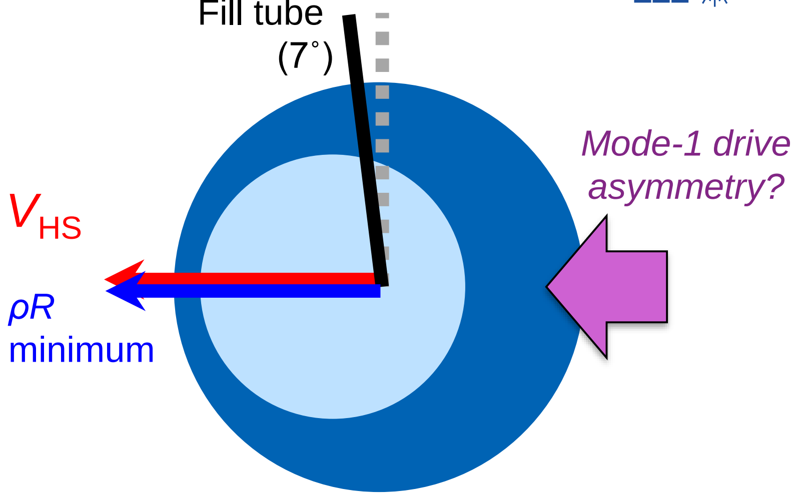


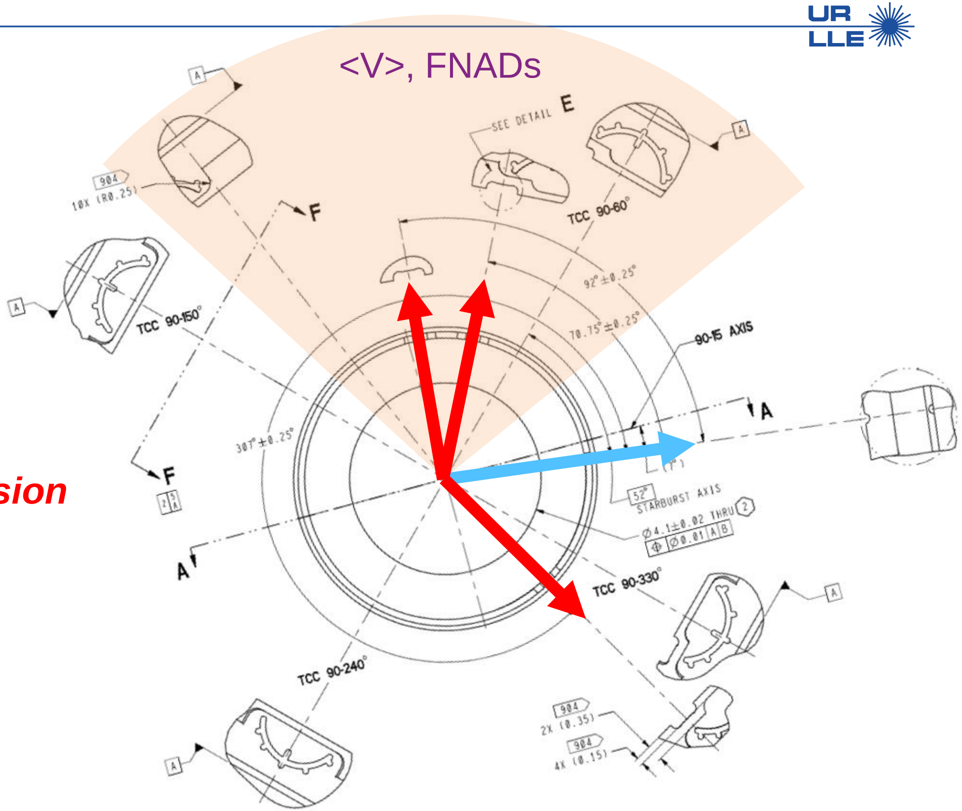
Related talks on causes of the observed asymmetry:

- A. Pak, *Impact of fill tube perturbation on HDC implosions* ***this session (BO6:2)***
- K. McGlinchey, *Simulating radiation asymmetries and fill tubes* ***this session (BO6:3)***
- R. Nora, *3D Hydra capsule studies on effect of hohlraum windows* ***this session (BO6:4)***
- D. Schlossberg, *Experiments with laser-driven mode-1 asymmetry* ***this session (BO6:7)***
- T. Ma, *Experimental investigation of mode-1 asymmetries* ***this session (BO6:11)***
- C. Young, *3D radiation asymmetries using dynamic view factor model* ***Monday pm (CO6:2)***
- O. Landen, *Sensitivity of yield and compression to asymmetry* ***Tuesday (GO6:5)***

Appendix – backup slides

The source of the $\phi = 90^\circ$ asymmetry is currently under investigation

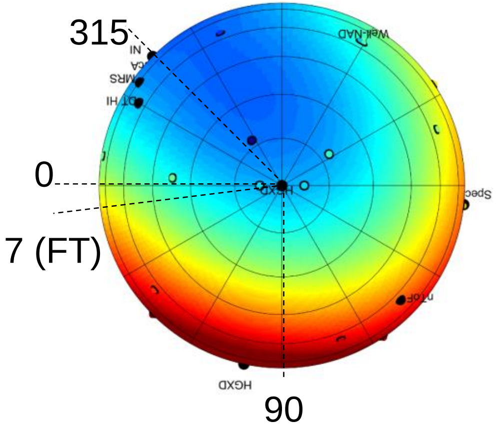
- **Drive asymmetries:**
  - **Hohlraum positioning offset (*X*)**
  - **2*ω* unconverted light asymmetry**
  - **…**
- **Target asymmetries:**
  - **Fill tube (7˚): *see A. Pak, this session***
  - **Diagnostic patches*: see T. Ma, this session***
  - **…**



See also O. Landen, *Tuesday (GO6:5):*
"Sensitivity of yield and compression to velocity, shock timing, coast time and asymmetry in indirect-drive NIF implosions,"

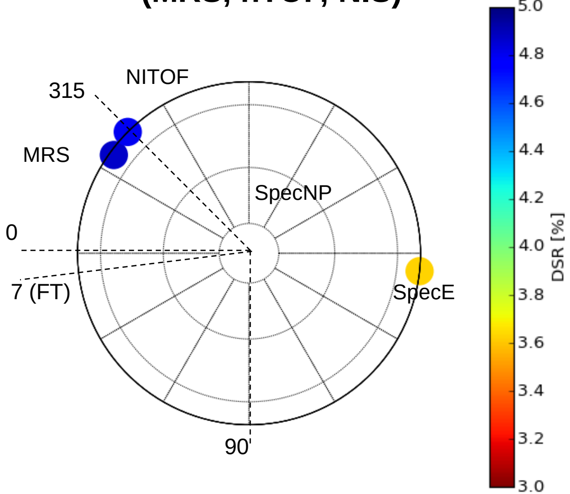
Azimuthal asymmetry is suggested by many diagnostics: we are now beginning to put together the pieces of this mode-1 puzzle

Flange NADs



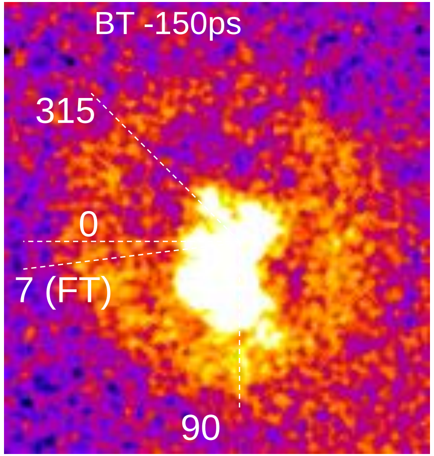
C. Yeamans & D. Bleuel,
Fusion Sci. Technol. 72, 120 (2017)

Down-scattered neutron ratio (MRS, nTOF, NIS)



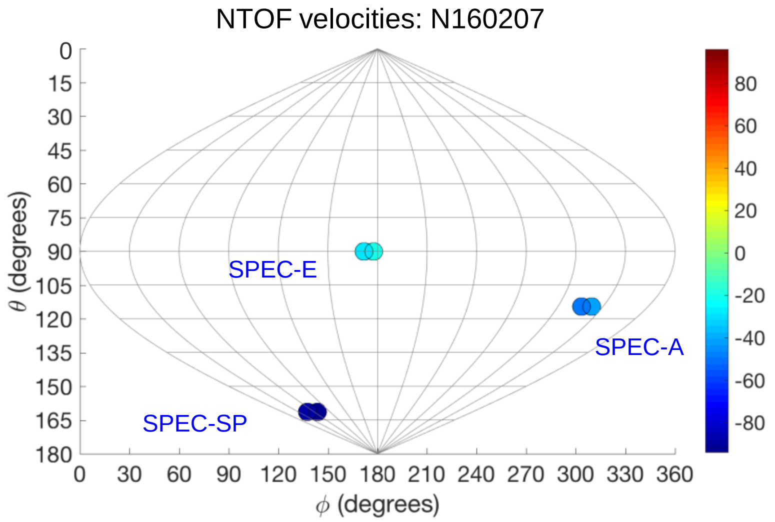
NTOF: R. Hatarak, et al., *J. Appl. Phys.* 118, 184502 (2015)
MRS: J.A. Frenje, et al., *Phys. Plasmas* 17, 056311 (2010)
NITOF: F. E. Merrill, et al., *Rev. Sci. Instrum.* 83, 10D317 (2012)

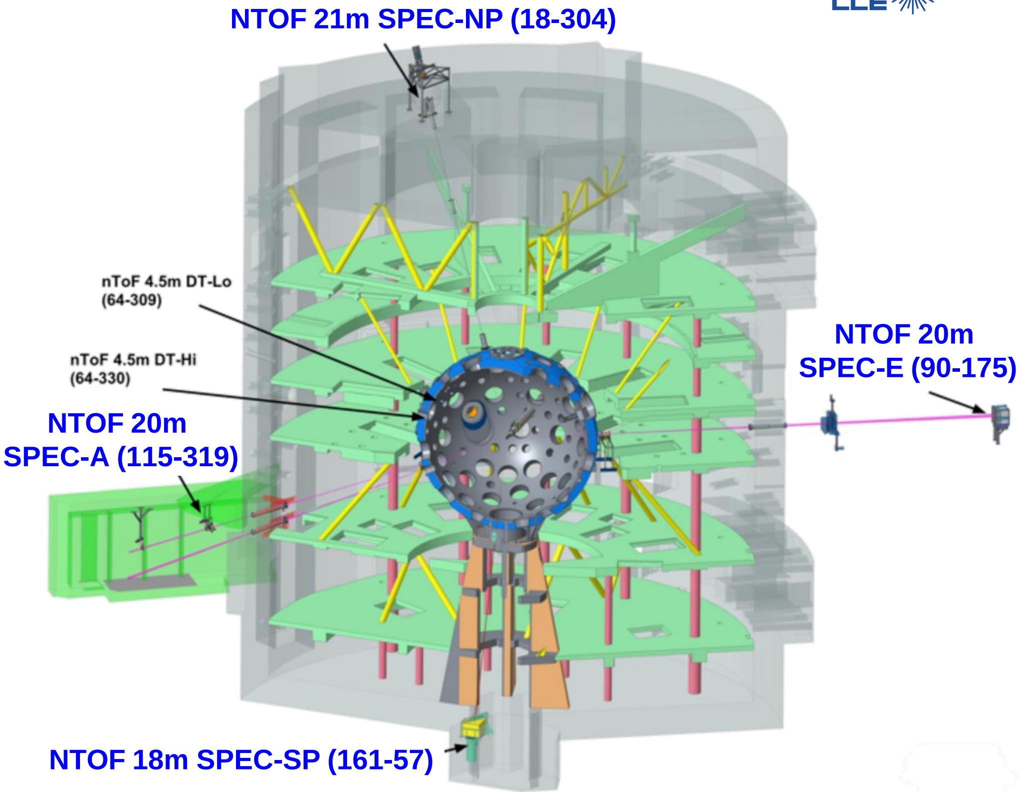
X-ray late-time images



A. Pak, et al.,
Phys. Plasmas 20, 056315 (2013)

On the NIF, DT- and DD-neutron spectra are used to measure mean hotspot velocity on up to four NTOFs line of sight





R. Hatarik, RSI 2018 (in press)

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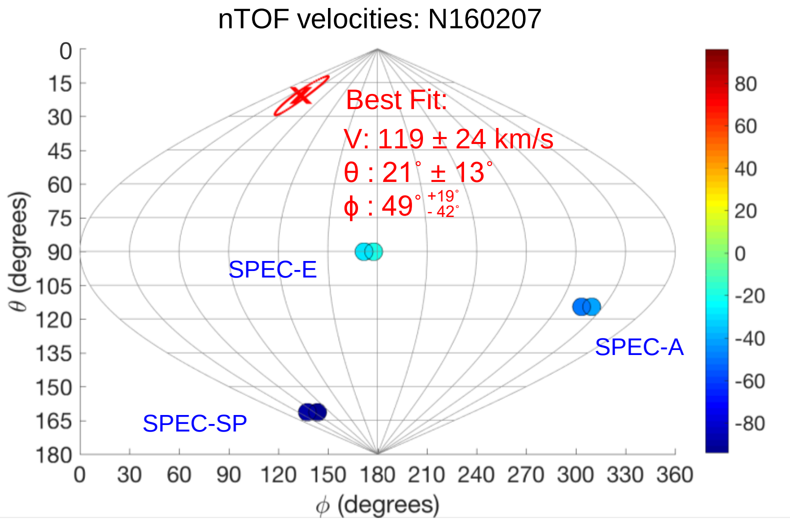
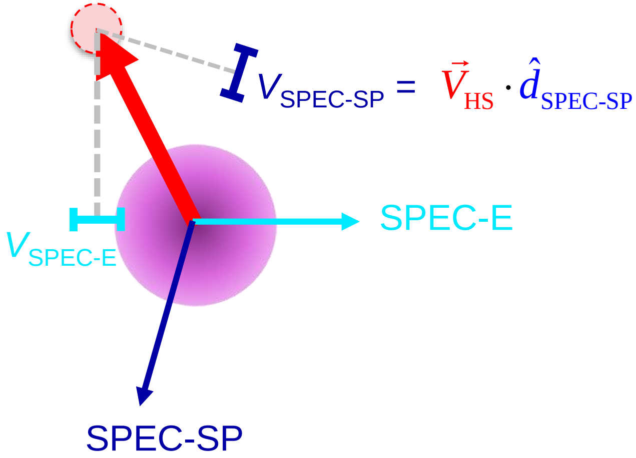
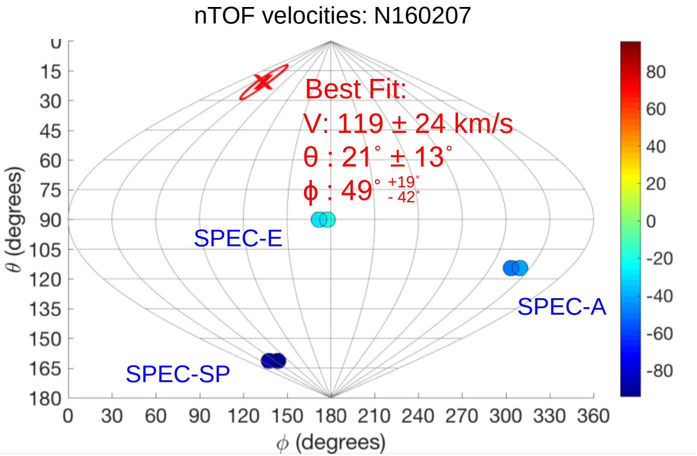


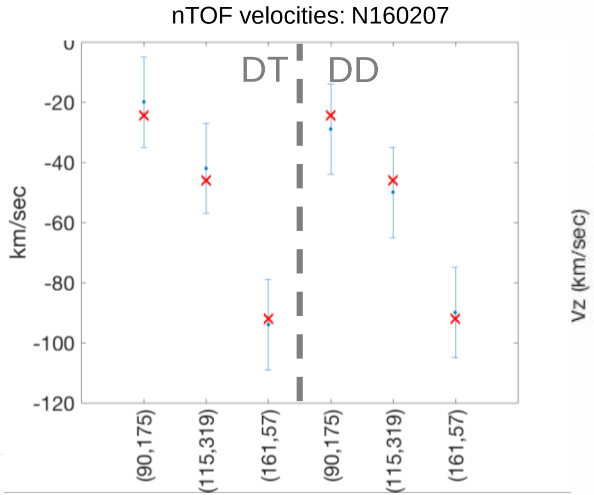


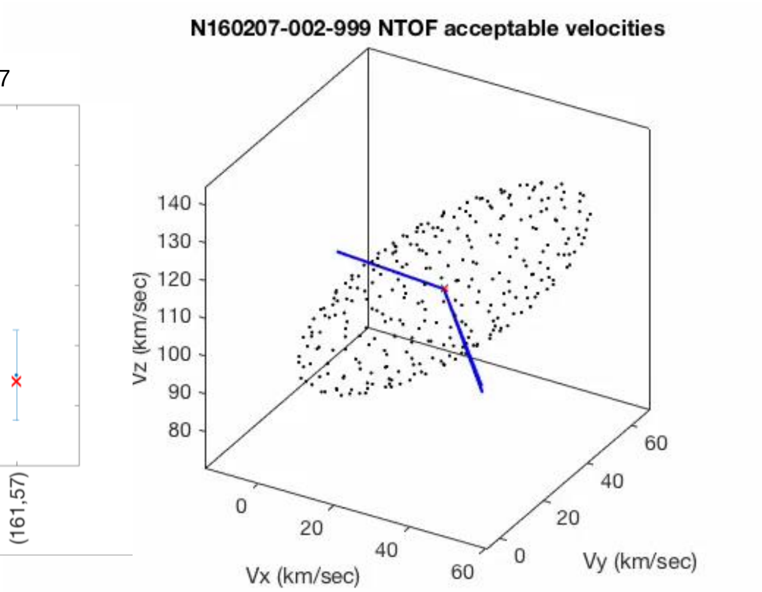
A single best-fit velocity (x) and uncertainty boundary is found, using:

$$\chi^2 \leq \min(\chi^2) + \chi^2_{limit}$$

Uncertainties in the measurements allow a range of solutions: an envelope of "acceptable" mean velocity is calculated using a reduced χ^2 method







"Acceptable" velocity vectors are found near the best fit that satisfy:

$$\chi^2 \leq \min(\chi^2) + \chi^2_{\text{limit}}$$

This population defines uncertainties in *V*, *θ*, and *ϕ*.

~300 points on the boundary are found

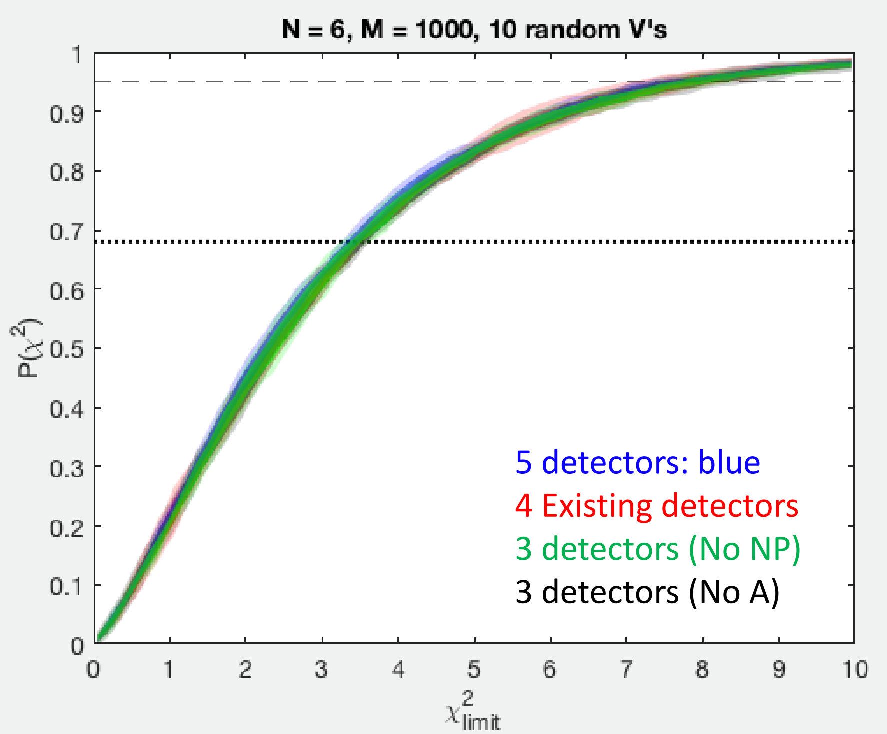
Regardless of the number of detectors, the χ^2 limit to contain the true velocity 68% of the time is $\chi^2_{limit} = 3.45$

UR LLE

Condition defining uncertainty region in velocity space:

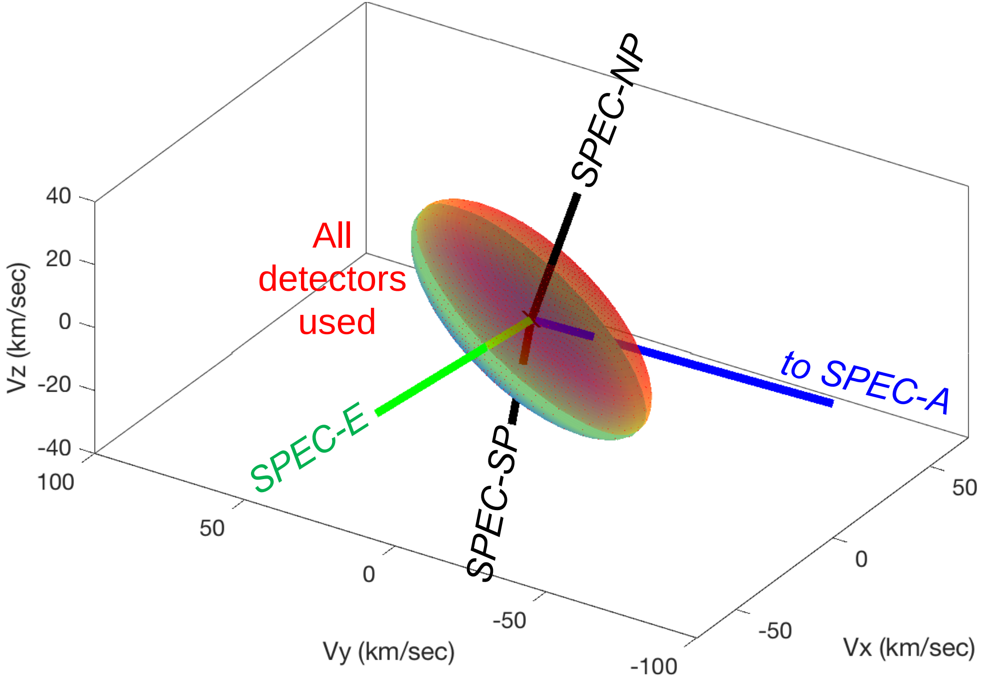
$$\chi^2 < \mathrm{Min}(\chi^2) + \chi^2_{limit}$$

Value of χ^2_{limit} …
…from statistical theory: 3.51
…from numerical study: 3.45 ± 0.1



(At least) three "perpendicular" detectors are needed: without SPEC-E or SPEC-A, sensitivity along one horizontal axis is lost

Velocity uncertainty boundaries (χ^2_{limit} = 3.45)



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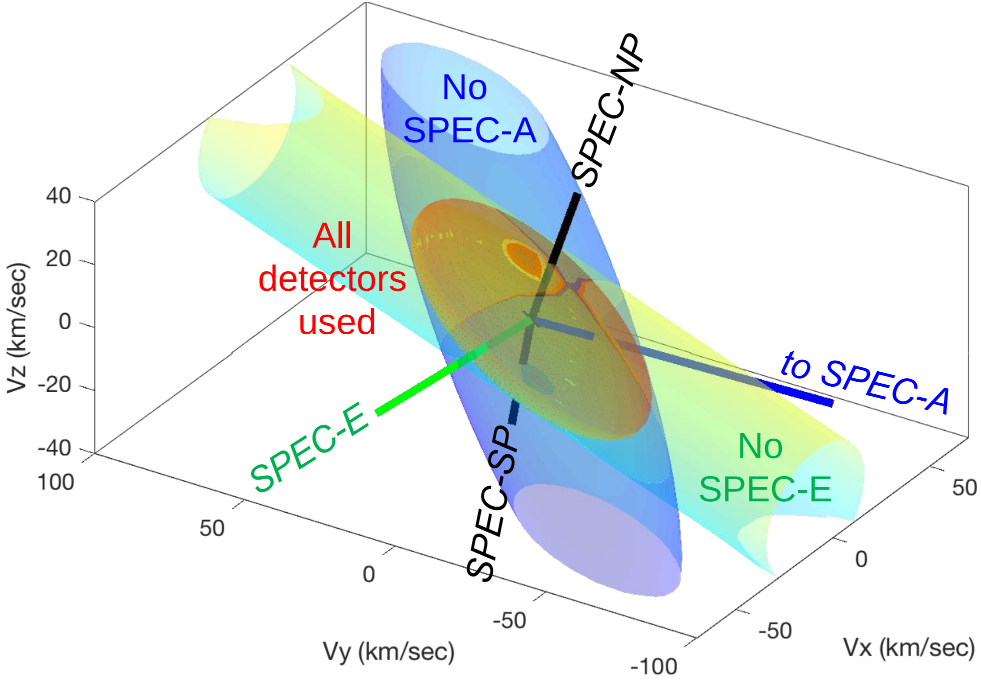
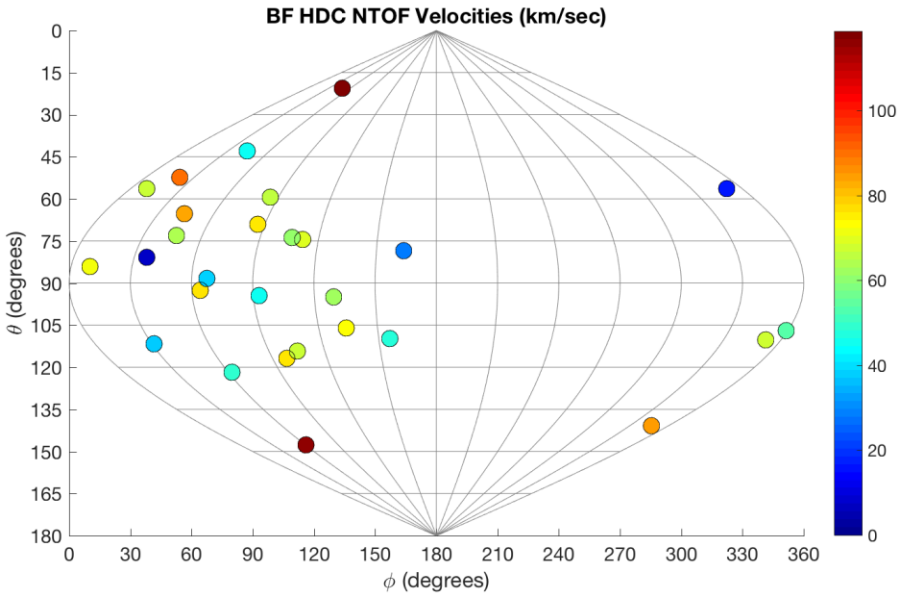
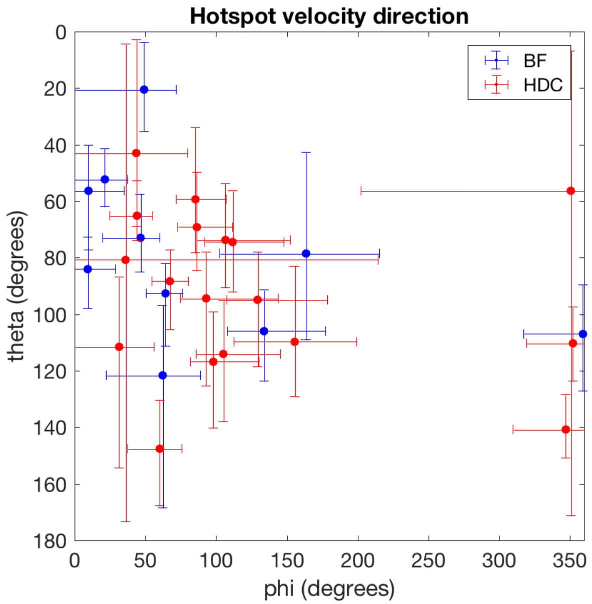


SPEC-E, SPEC-A, and one other detector are needed to perform this analysis.

Looking at a group of cryogenic DT implosions, a pattern emerges: hotspot velocity tends towards ϕ ~ 90˚ on the equator.





HDC: 18 shots

BF: 10 shots

Showing analyzed shots, FY16—18

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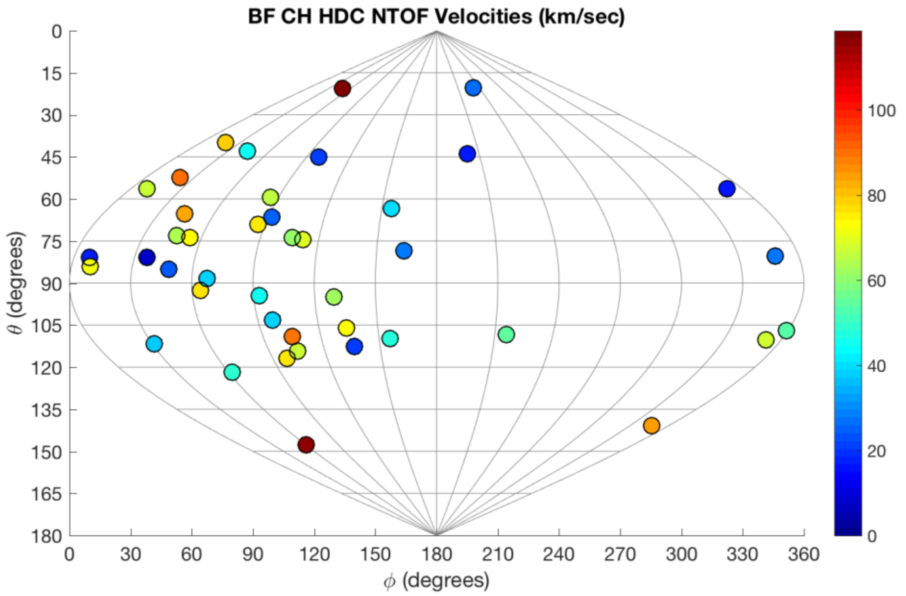
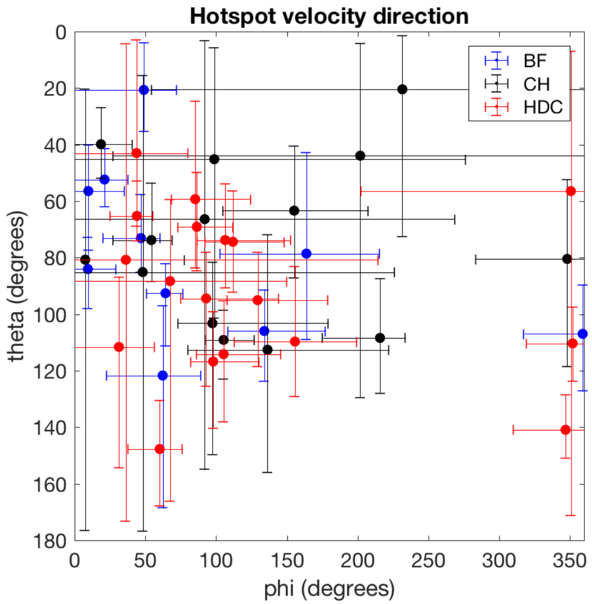


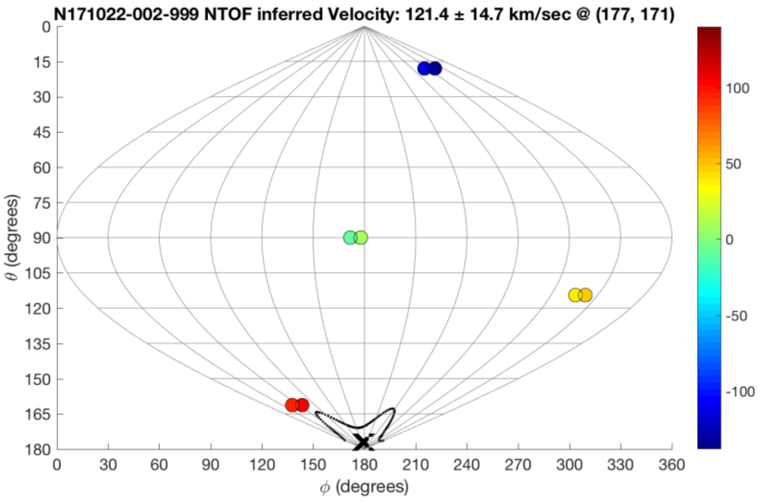


HDC: 18 shots
BF: 10 shots
CH: 14 shots

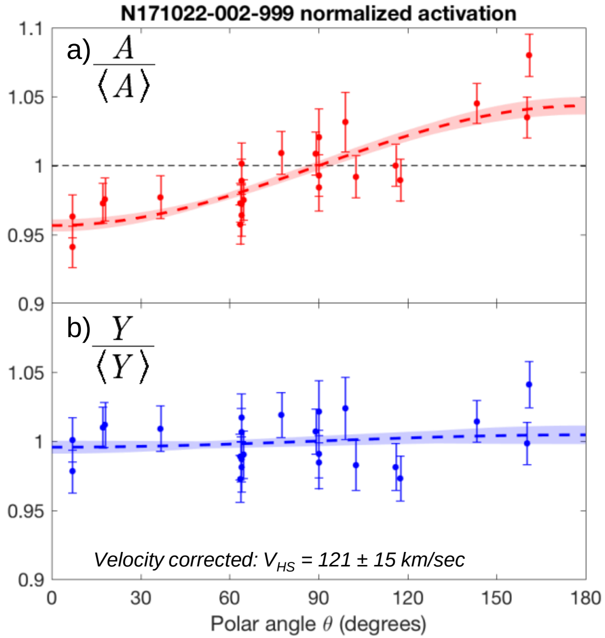
Showing analyzed shots, FY16—18

Test case

On "antipodal" shot with imposed drive asymmetry and low ρR_{fuel},* velocity correction eliminates the observed FNAD asymmetry



N171022-002-999	km/sec	θ	ϕ
nTOF velocity	121 [+16, -14]	177˚ [+3,-14]	171˚ [±180]



Before correction:
P_1/P_0 = -4.3% ± 0.5%

After correction:
P_1/P_0 = -0.4% ± 0.6%

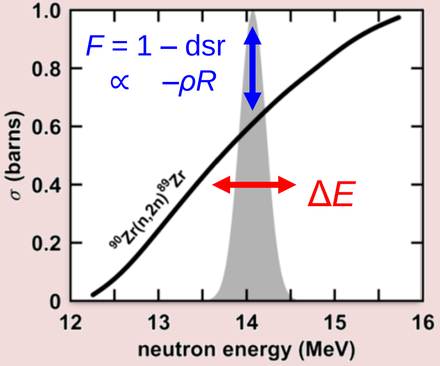
Entire FNAD mode-1 is accounted for by velocity correction, as expected.

T_i = 4.27 keV
dsr = 0.44

*See D. Schlossberg, this session (BO6:7)

To interpret flange NAD data, hotspot velocity must be accounted for: change in activation, fluence, and scattering

#1: Change in activation with neutron energy

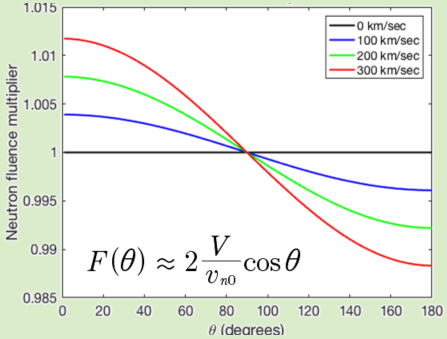


$$A = \int \sigma(E) \frac{\mathrm{d}F}{\mathrm{d}E} \mathrm{d}E$$

Shift in activation is interpolated from ENDF:

$$\frac{A}{\langle A \rangle} \approx \frac{\sigma(E)}{\sigma(\langle E \rangle)}$$

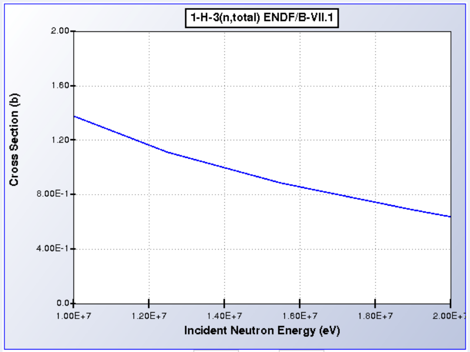
#2: Change in neutron fluence with velocity



Effect	Magnitude of Activation Change
1. ΔE → activation	2.81% cos θ / (100 km/s)
2. Kinematic ΔFluence	0.39% cos θ / (100 km/s)
3. ΔE → scattering	0.078% cos θ / (100 km/s) / (1 g/cm^2)
TOTAL:	3.2% cos θ / (100 km/s)

#3: Change scattering with neutron energy

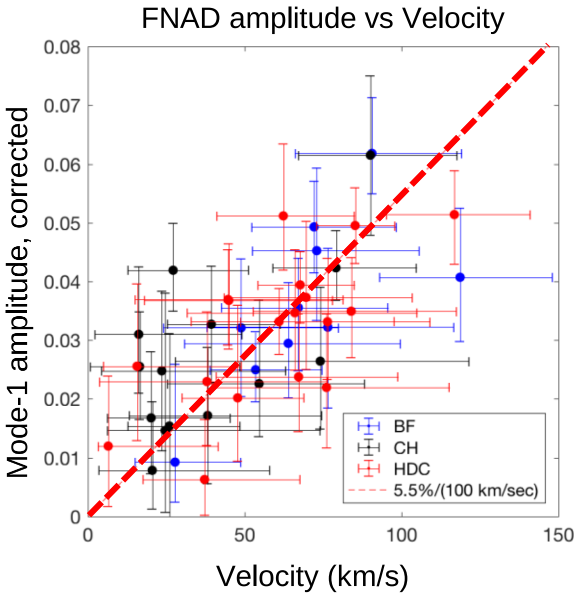
n,T cross section



For more info: H. Rinderknecht *et al.*, Rev. Sci. Instrum. **89**, 10I125 (2018).

In cryogenic implosions, the corrected FNAD mode-1 amplitude ($\propto$ *ρR* asymmetry) increases linearly with hotspot velocity

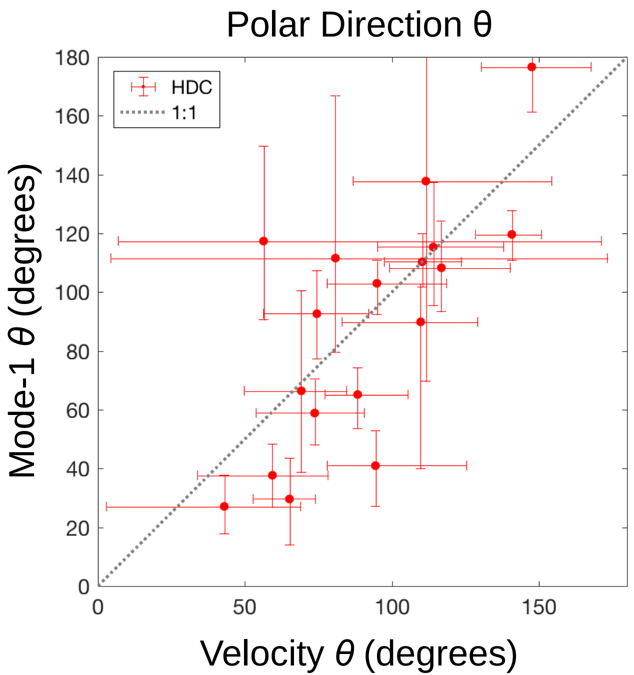
$$\frac{F}{\langle F \rangle}$$

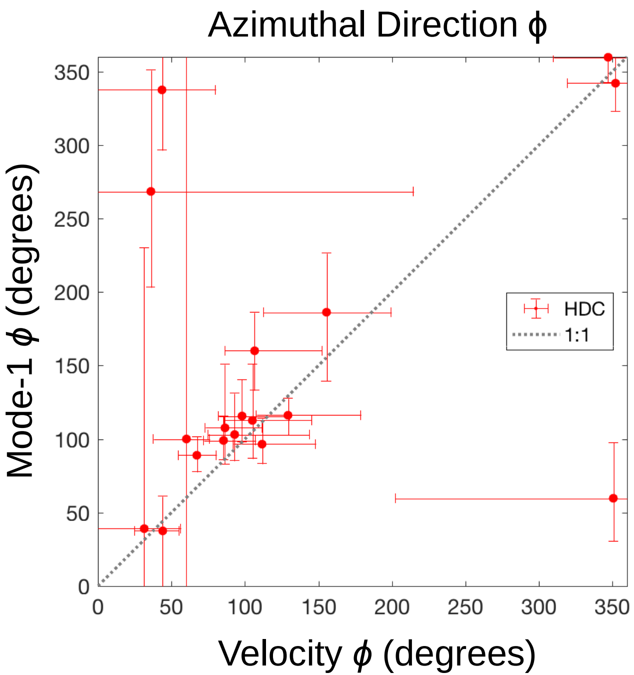


$$\frac{\ell_1}{P_0} \approx 5.5\% \left(\frac{V_{\mathrm{HS}}}{100\,\mathrm{km/s}} \right)$$

High velocities (> 50 km/sec) and mode-1 amplitudes (> 4%) are observed in all campaigns.

The residual FNAD mode-1 is in the same direction as the hotspot velocity: mean velocity and low *ρR* are toward $\phi = 90^\circ$

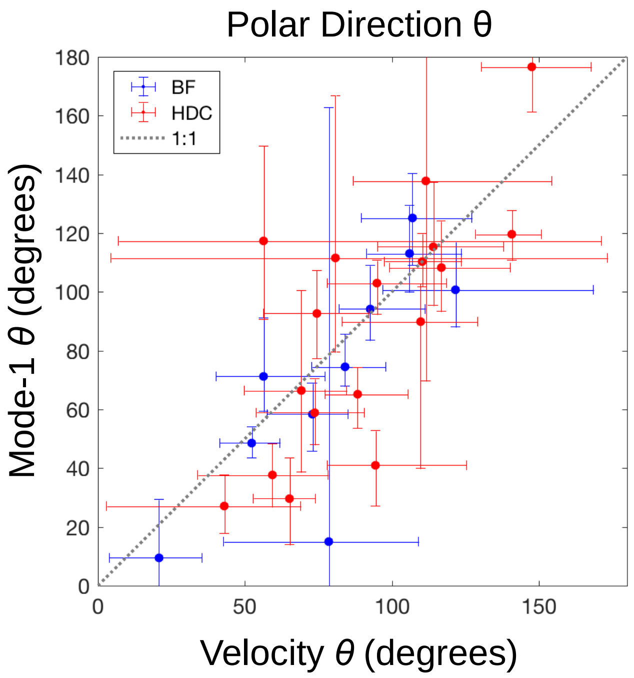


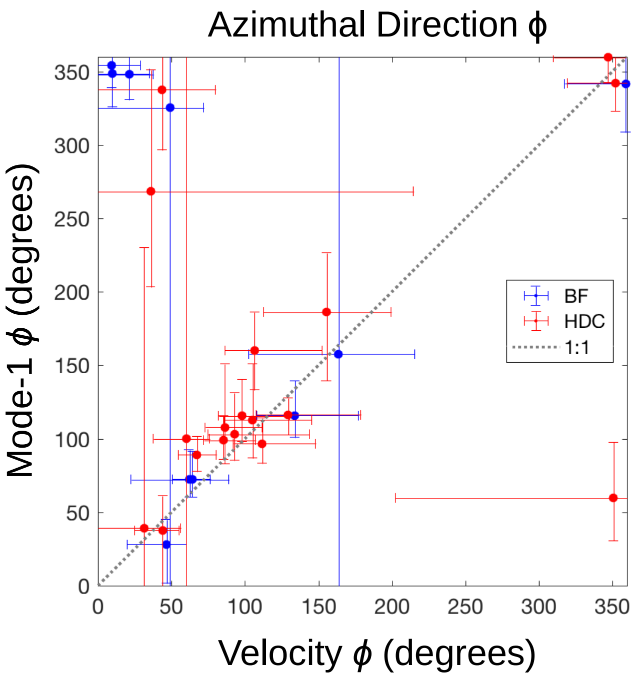


HDC: 18 shots

Showing analyzed shots, FY16—18

The residual FNAD mode-1 is in the same direction as the hotspot velocity: mean velocity and low *ρR* are toward *ϕ* = 90˚

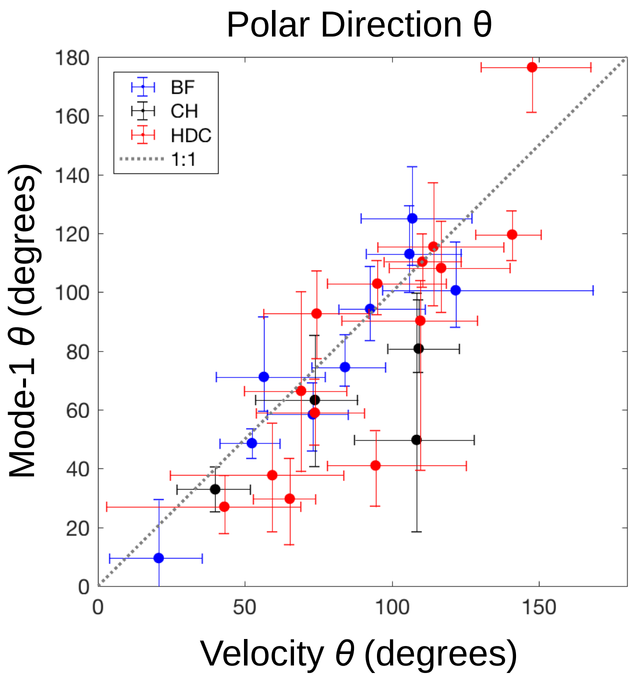


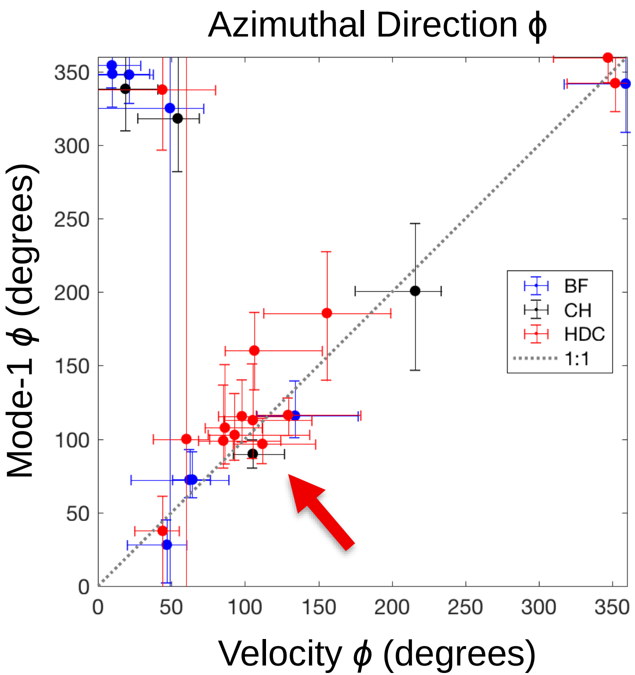


HDC: 18 shots
BF: 10 shots

Showing analyzed shots, FY16—18

The residual FNAD mode-1 is in the same direction as the hotspot velocity: mean velocity and low *ρR* are toward *ϕ* = 90˚





Showing analyzed shots, FY16—18 with V > 40 km/s

HDC: 14/18 shots
BF: 9/10 shots
CH: 6/14 shots

A cohesive picture of azimuthal asymmetry emerges from comparing hotspot velocity and *ρR* mode-1 amplitude

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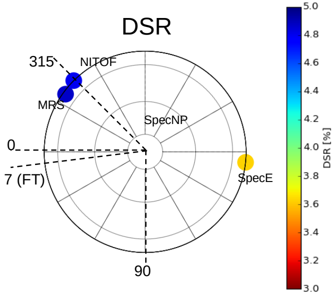
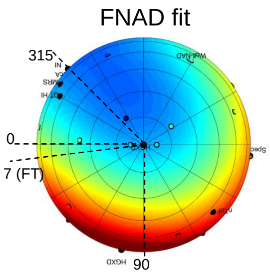
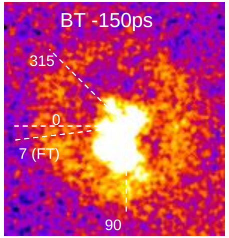
Additional diagnostic comparisons

- Downscattered ratio (MRS, nTOF, NIS)





- X-ray late-time images

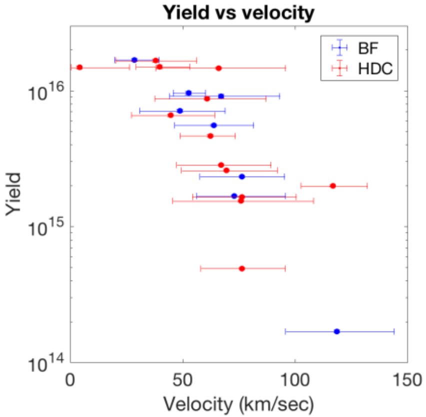


- Neutron imaging (Volegov, Casey, …)

Test hypotheses & fix asymmetry

- ~~Hohlraum positioning offset~~
- Fill tube (5 μm vs 10 μm)
- Diagnostic patches (this summer)
- 2ω unconverted light asymmetry
- …

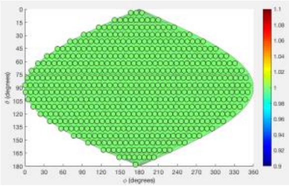
Model development



- Analytical model for comparing magnitude of burn-averaged <*V*>, *ρR* mode-1 (Springer)
- Impact on performance
- …

Spherical harmonic (“$Y_{\ell m}$”) normalization: amplitude = (max – mean)

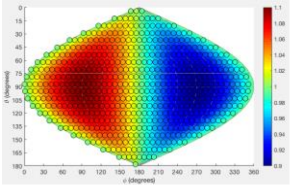
ℓ = 0:



$a_{00} = 1 \rightarrow$ data = 1

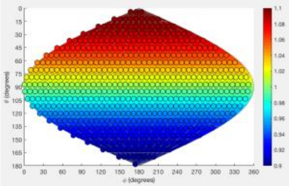
ℓ = 1:

m = -1



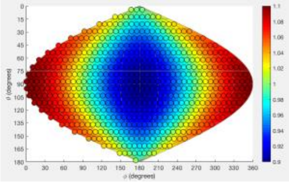
$a_{1,-1} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

m = 0



$a_{1,0} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

m = +1

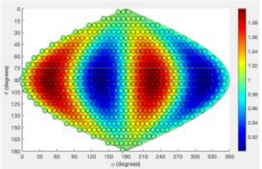


$a_{1,+1} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

$$P_1 = \sqrt{\sum_{m=-1}^{+1} a_{1,m}{}^2}$$
$$\theta_1 = \cos^{-1}(a_{1,0})$$
$$\phi_1 = \tan^{-1}(a_{1,-1}/a_{1,+1})$$

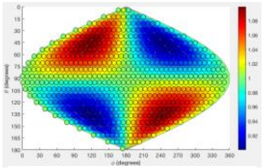
ℓ = 2:

m = -2



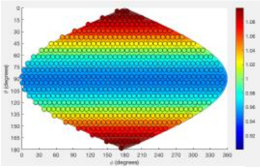
$a_{2,-2} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

m = -1



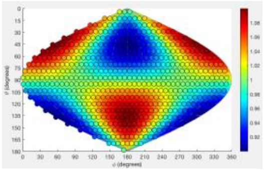
$a_{2,-1} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

m = 0



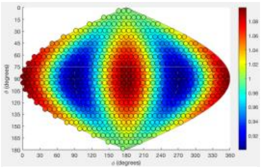
$a_{2,0} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.05

m = +1



$a_{2,+1} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

m = +2



$a_{2,+2} = 0.1 \rightarrow$
(max – mean) = 0.1,
(mean – min) = 0.1

On conversion from FNAD variation to absolute ρR_{fuel}:

Say any scattering removes a neutron from activation.

$$Y = \exp\left(-\rho R\, \sigma_{DT} / M_{DT}\right)$$

Then the observed activation is normalized as:

$$\frac{Y}{\langle Y \rangle} = \exp\left[\frac{\langle \rho R \rangle \sigma_{DT}[\langle E \rangle] - \rho R(\theta)\, \sigma_{DT}[E(\theta)]}{M_{DT}}\right]$$

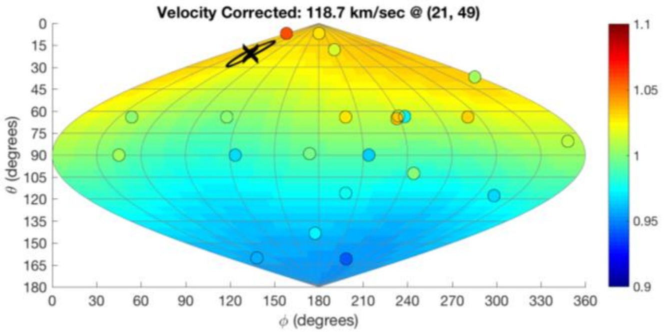
We care about $\rho R(\theta)$, and σ_{DT} is nearly constant. So we can solve for $\Delta\rho R = \rho R - \langle\rho R\rangle$:

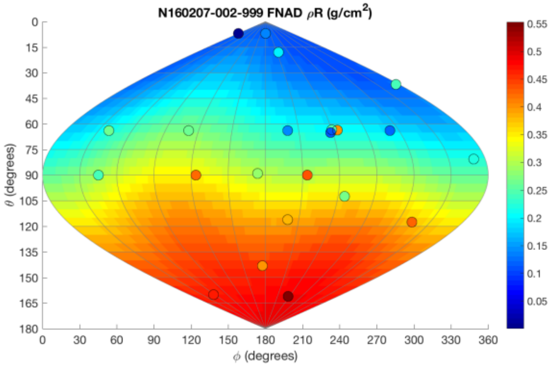
$$\Delta\rho R = -\frac{M_{DT}}{\langle \sigma_{DT} \rangle} \ln\left(\frac{Y}{\langle Y \rangle}\right) \approx -\ln\left(\frac{Y}{\langle Y \rangle}\right)[4.64\ \mathrm{g/cm^2}]$$

We can use the formula $\langle\rho R\rangle = 18.8$ DSR g/cm^2 to get the relative variation:

$$\frac{\Delta\rho R}{\langle \rho R \rangle} \approx -\ln\left(\frac{Y}{\langle Y \rangle}\right)\left[\frac{25\%}{DSR}\right] \approx -\frac{\Delta Y}{\langle Y \rangle}\left[\frac{25\%}{DSR}\right]$$

This means a 10% variation in Y implies an 80—90% variation in ρR.

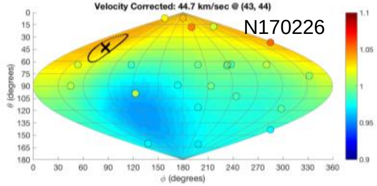


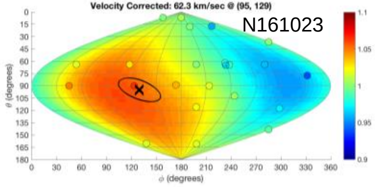


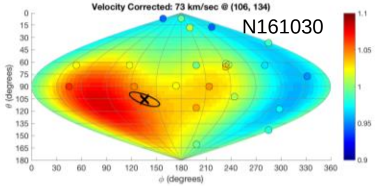
CAVEAT:
Neutron scattering & finite hotspot sizes inhibit direct areal density inference. Due to finite sources, FNADs cannot resolve high modes.

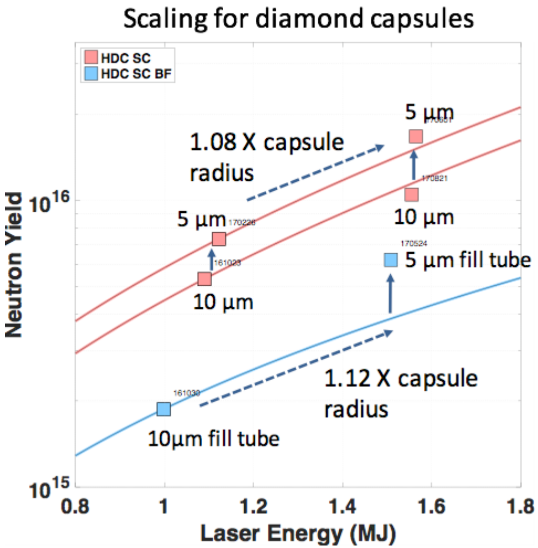
Appendix: simple fill-tube model

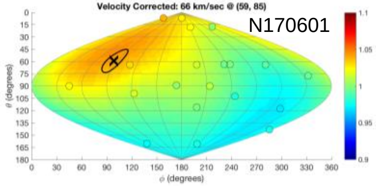
Velocity and FNAD data for a series of HDC implosions with 5/10µm fill tubes can test the hypothesis that fill-tube jets are causing these effects

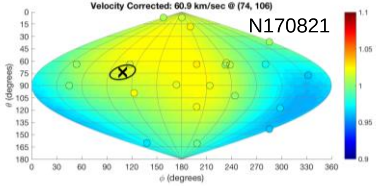


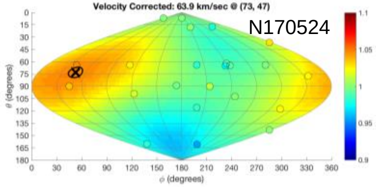












Comparing HDC implosions with 5μm vs 10μm fill tubes: hotspot velocity is ~60 km/sec for both cases, in the direction ϕ = 90˚± 40˚

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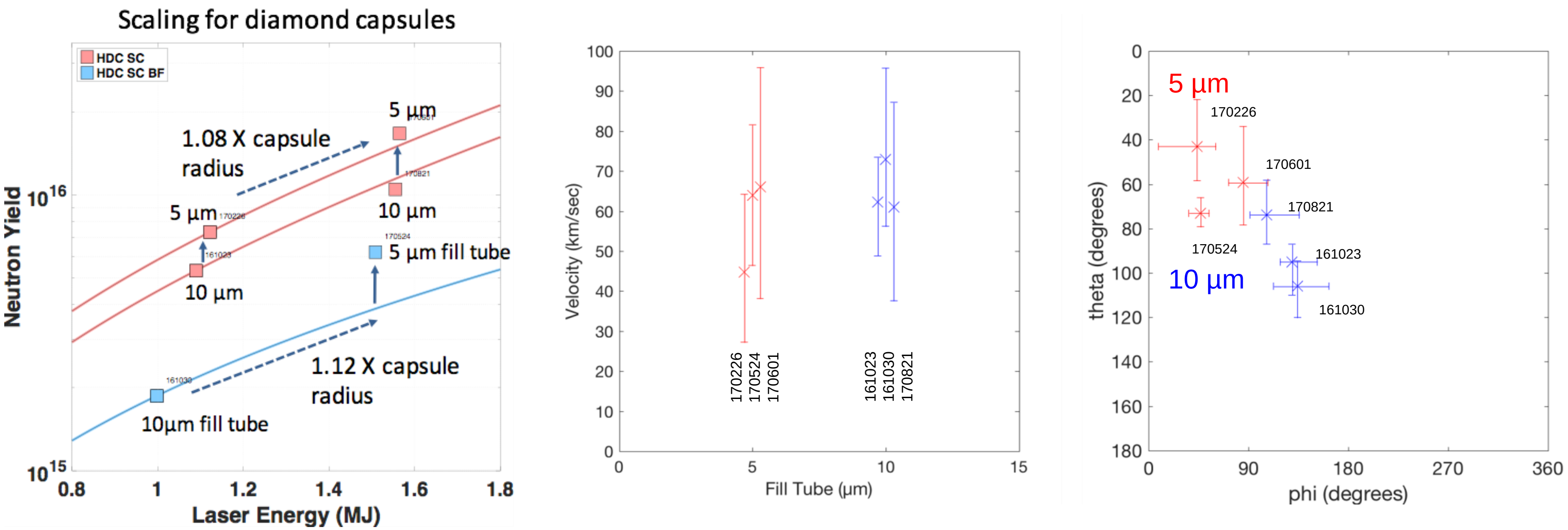
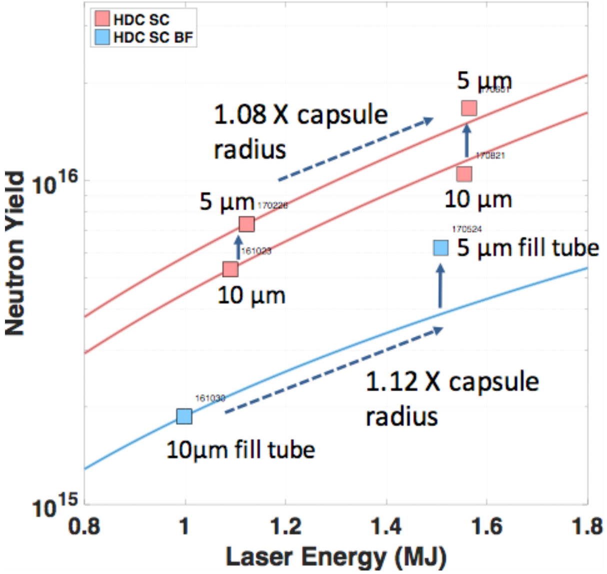
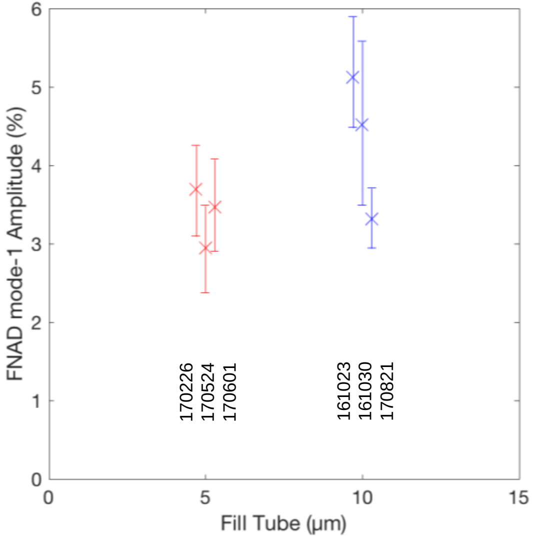


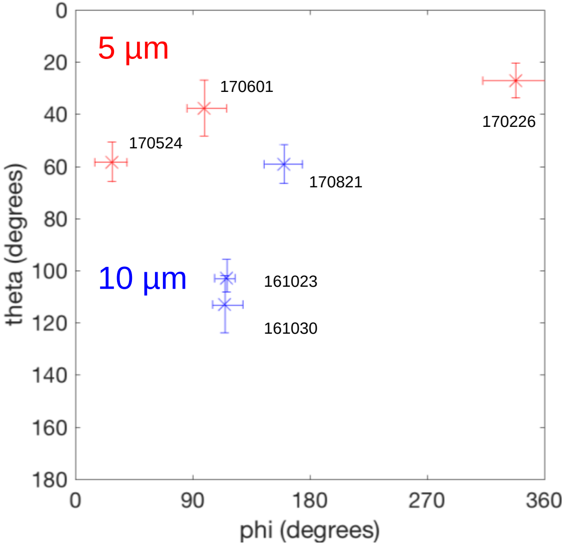
What about fill tubes?

FNAD data tells a similar story: mode-1 asymmetry ~ 3—5%, with systematic variation in the direction of asymmetry

Scaling for diamond capsules



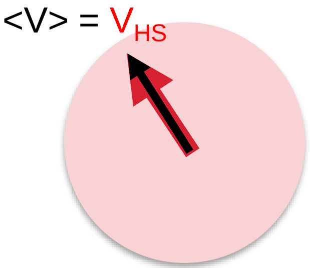




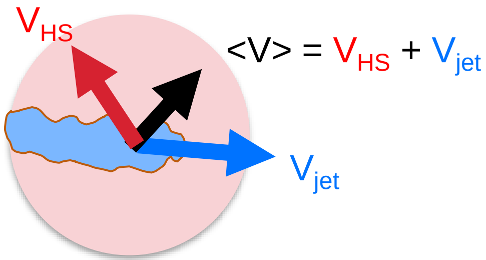
What about fill tubes?

The systematic difference in asymmetry direction suggests a hypothesis:
1. All hotspots have average velocity V_{HS}
2. 10 µm fill-tube injects a flow with velocity V_{jet}

5 µm:



10 µm:



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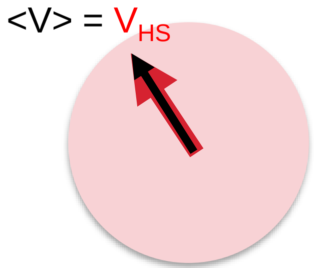
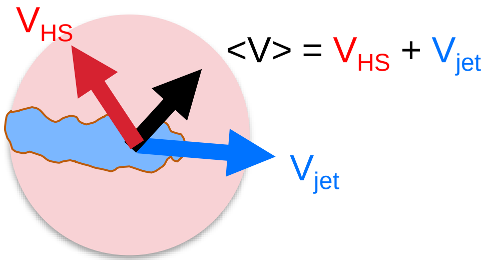
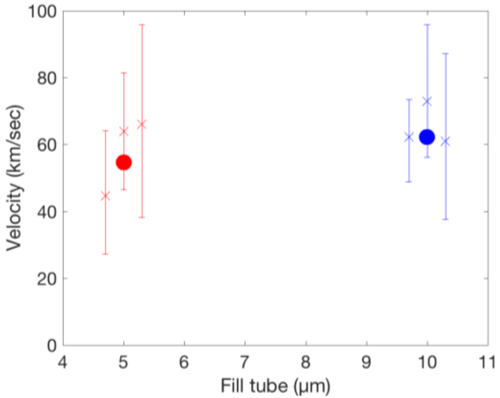
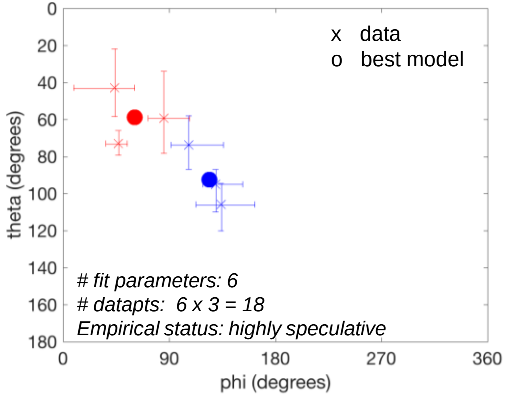


10 µm:







Assuming the weight of the two features is the same, the best fit with this hypothesis is:

V_{HS} = 55 km/sec toward (59˚, 61˚)

V_{jet} = 66 km/sec toward (118˚, 169˚)