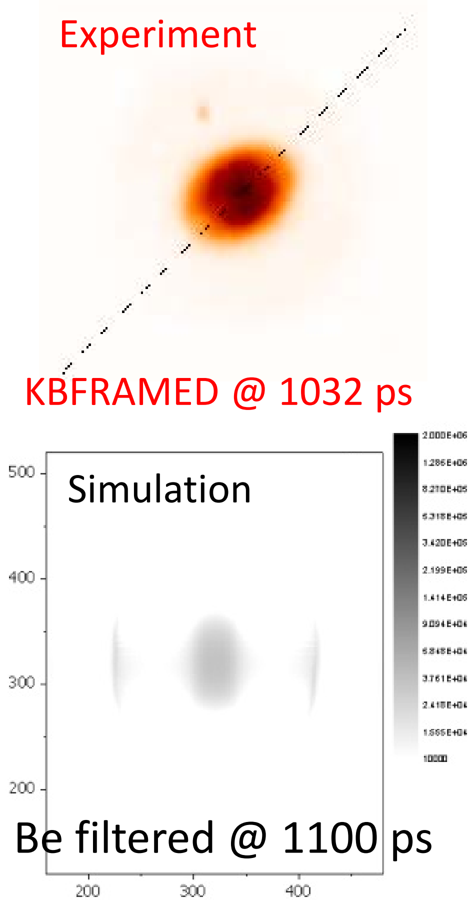
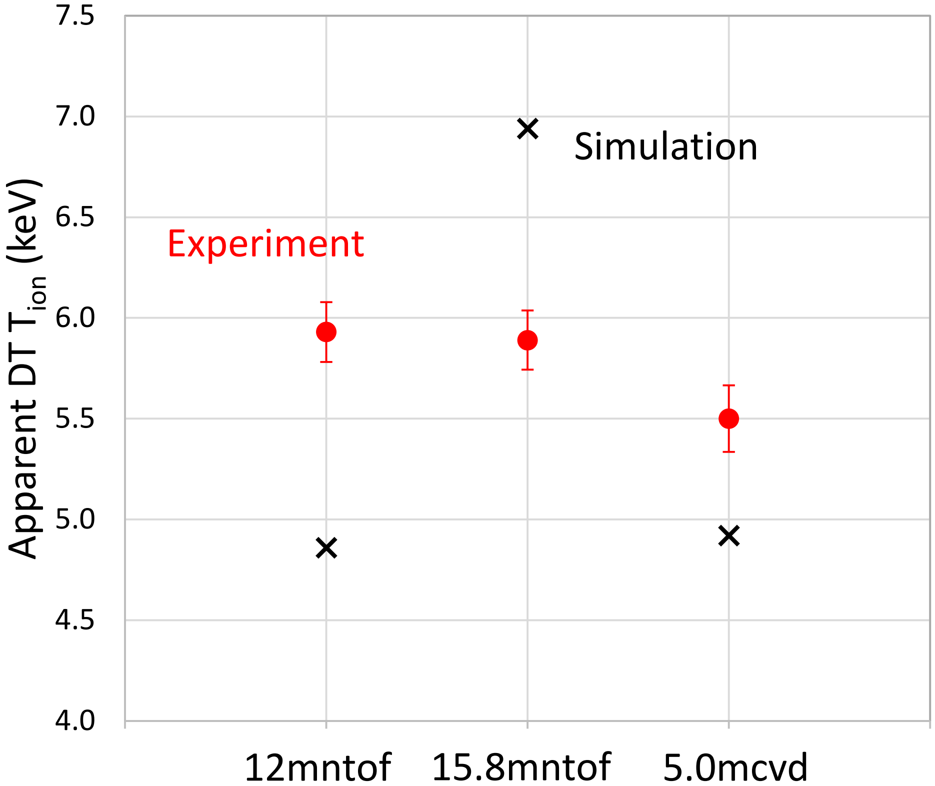
Shape vs T_{ion} in perturbed gas-filled CH implosions

Core x-ray image: Strong P2 asymmetry



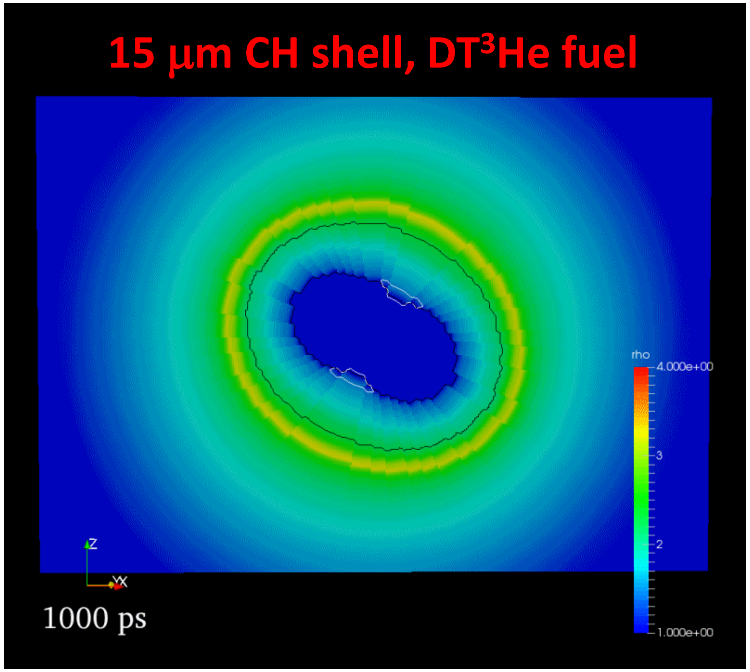
nTOF Tion: No apparent asymmetry



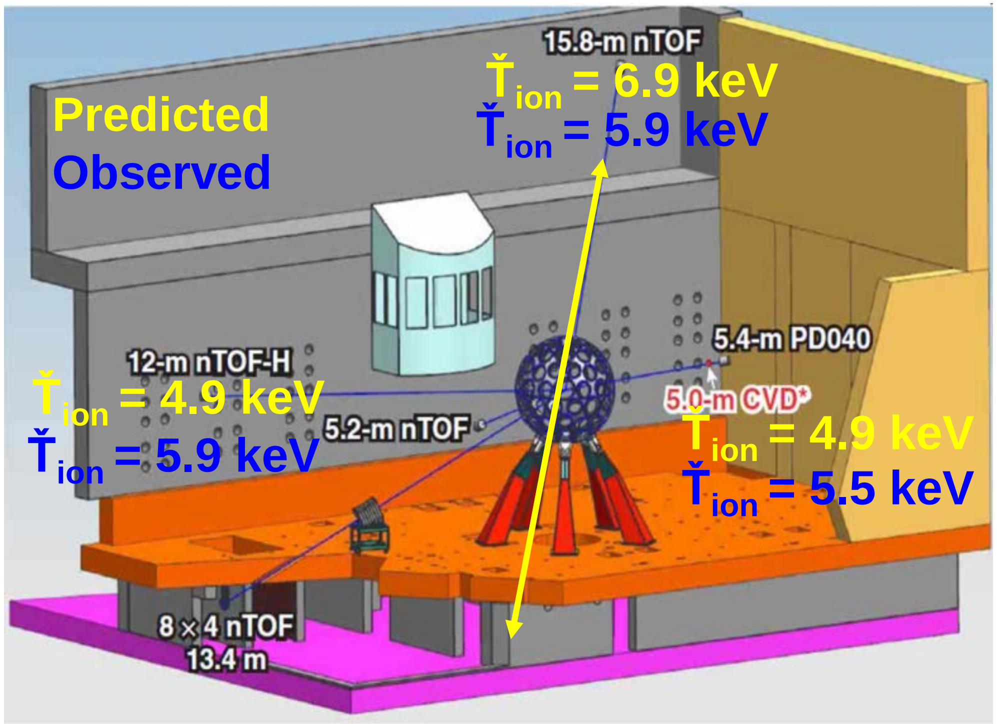
Implosions generate strongly perturbed x-ray images and symmetric Tion measurements

M. Gatu Johnson, 2nd NISP workshop, March 9, 2016

The Nov 5th OMEGA P2 velocity experiment was designed to test if we can accurately predict and measure a difference in apparent T_{ion} for asymmetrically driven implosions



Pre-shot simulation by Appelbe & Chittenden, Imperial College



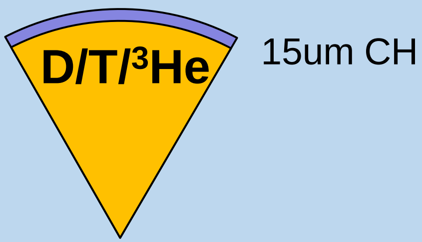
We got 5 shots for this experiment, with results very different than expected

Outline

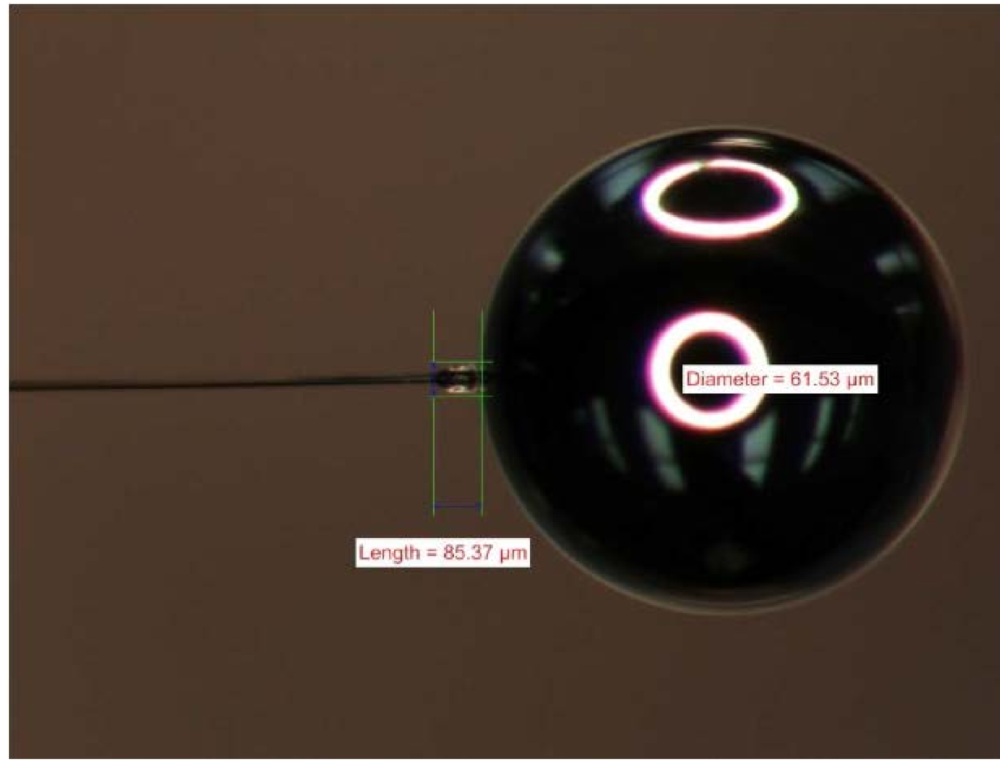
- Setup
- Results
  - nTOF Tion
  - X-ray measurements (KBRAMED, SFC3)
  - Yield
  - Bang time/burn duration (NTD)
- Interpretation/simulations (work in progress!)

15 μm plastic targets filled with 12 atm DT, 6 atm ^{3}He were shot with a 1 ns square laser pulse

OD = 860 um
Al flash coating

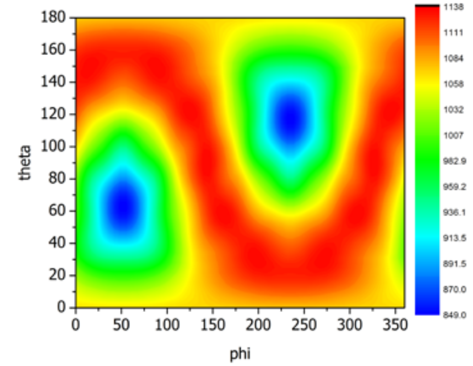


D/T/^{3}He fill:
6 atm ^{3}He + 12 atm D_2T_2
(standard LLE ~50:50 supply)



Two different P2 asymmetries were achieved by reducing the energy in two opposing cones of laser beams

Example intensity distribution:

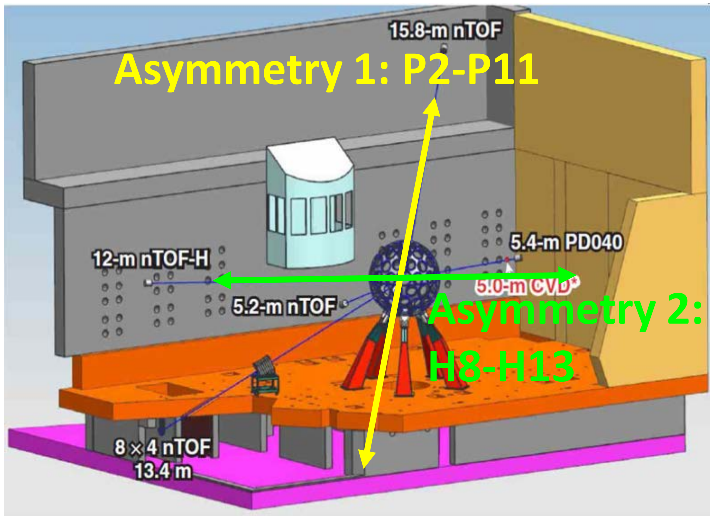


Symmetric shot:
Nominal 450 J energy on all beams

Asymmetry 1 (P2-P11):
- Energy on 10 beams surrounding P2/P11 ports reduced to 315 J

Asymmetry 2 (H8-H13):
- Energy on 6 beams immediately surrounding H8/ H13 ports reduced to 371 J
- Energy on next set of 6 beams reduced to 304 J

(same intensity distribution as for asymmetry 1)



- Asymmetry 1 was designed to maximize Tion in 15.8mntof LOS, minimize for 12mntof LOS
- Asymmetry 2 was designed to flip asymmetry 1 to maximize the observable differences

Outline

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- Results
  - nTOF Tion
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  - Yield
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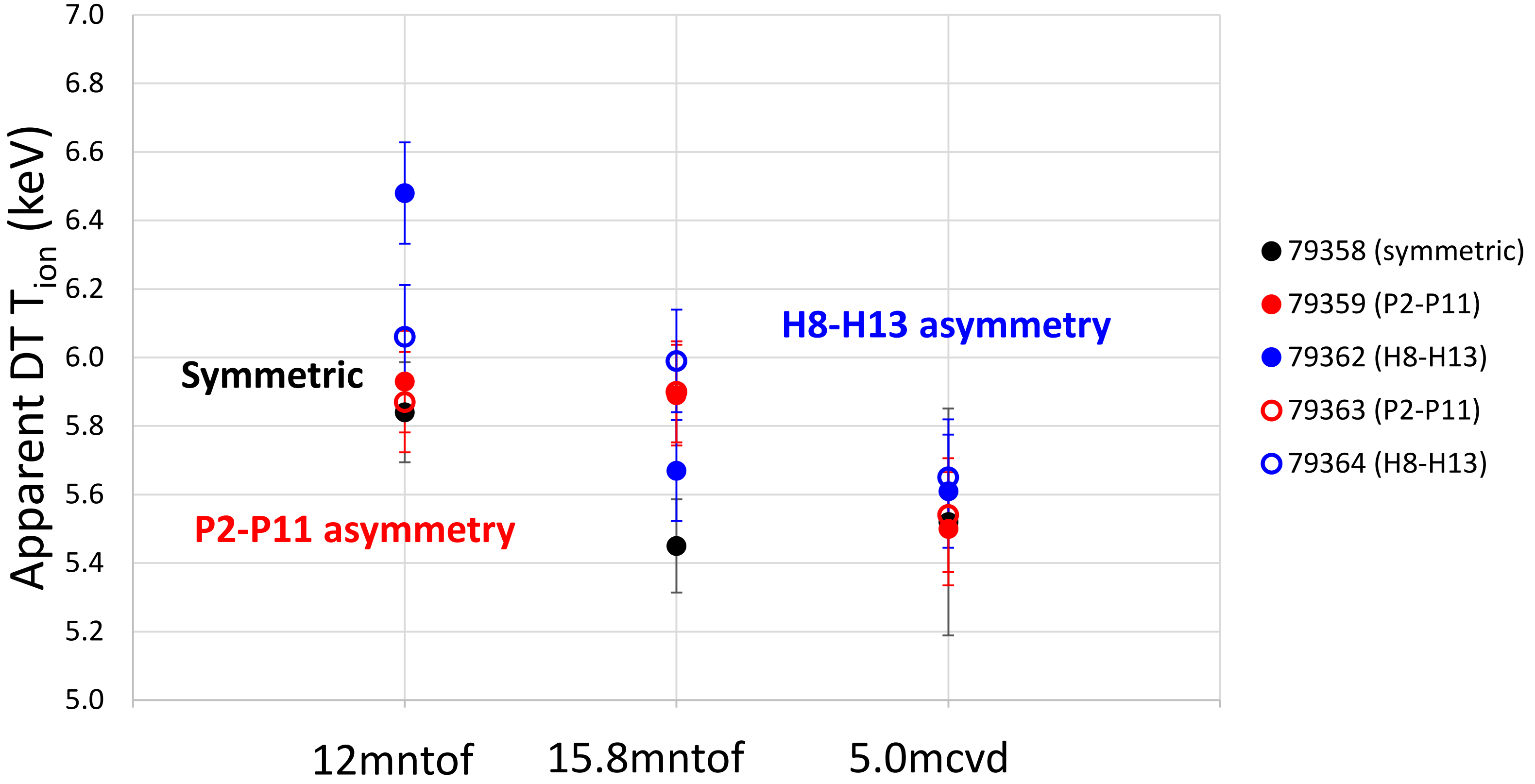
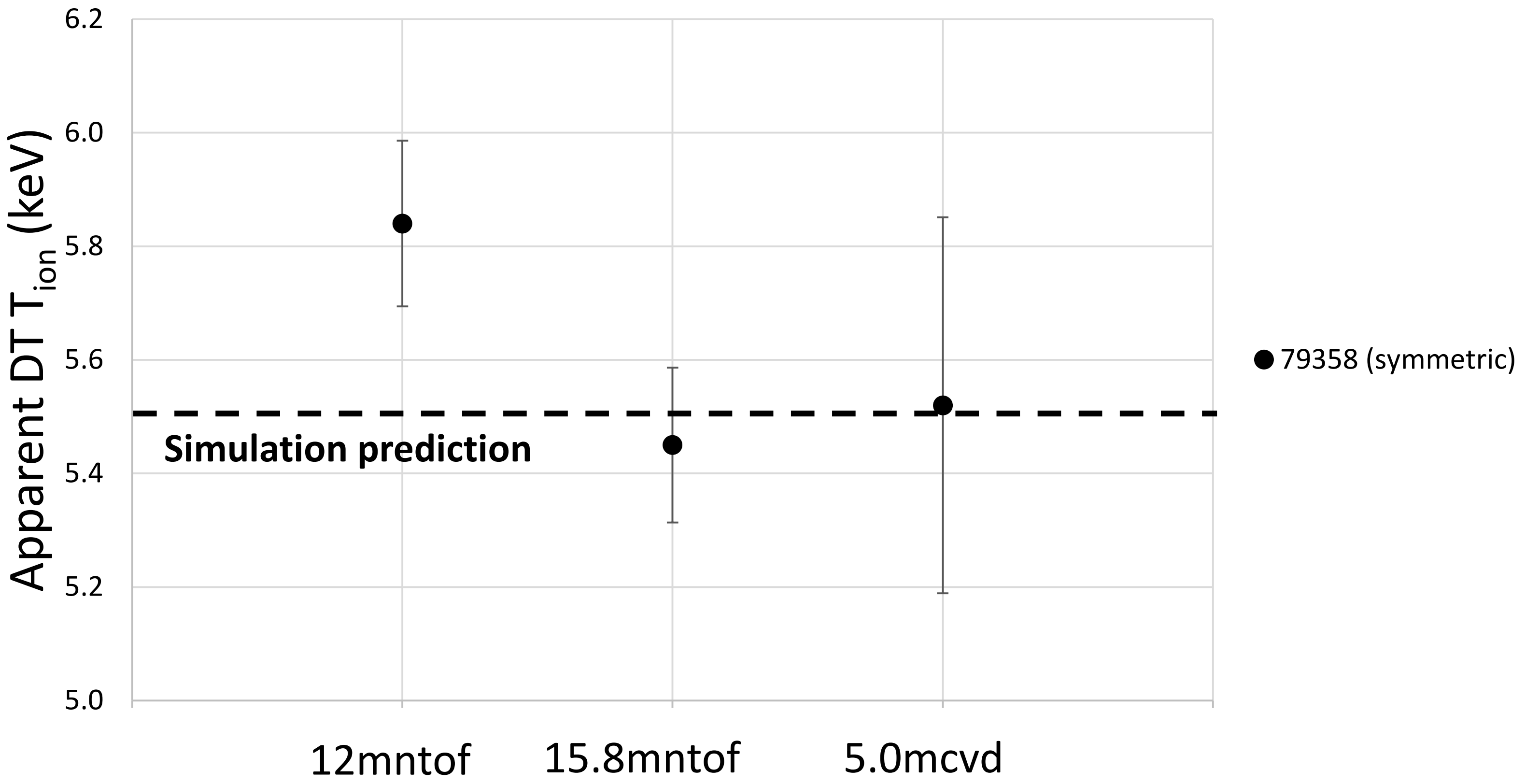
- Interpretation/simulations (work in progress!)

No significant T_{ion} asymmetry was seen for any of the three drive schemes

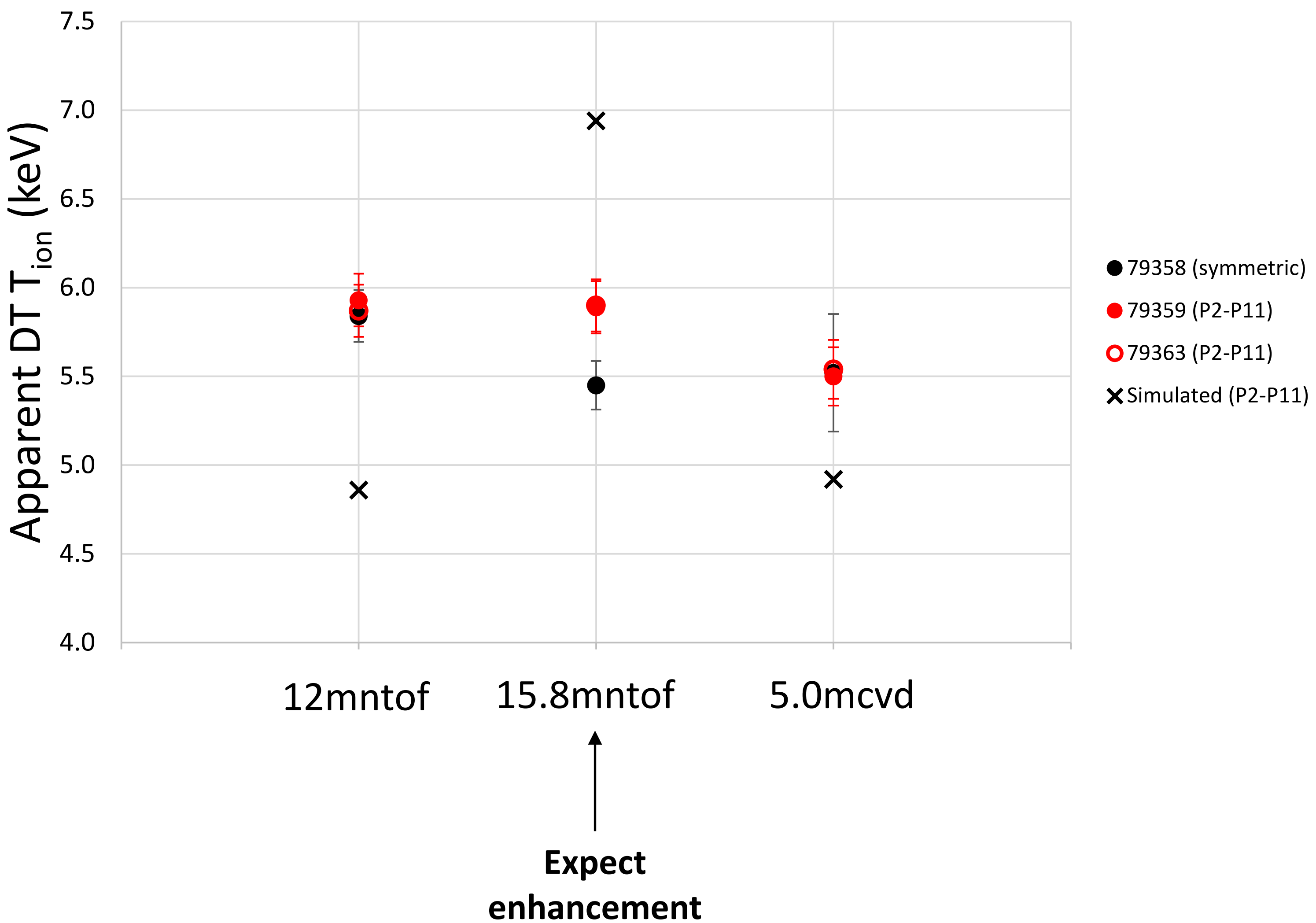


T_{ion} for the symmetric shot is pretty close to predicted

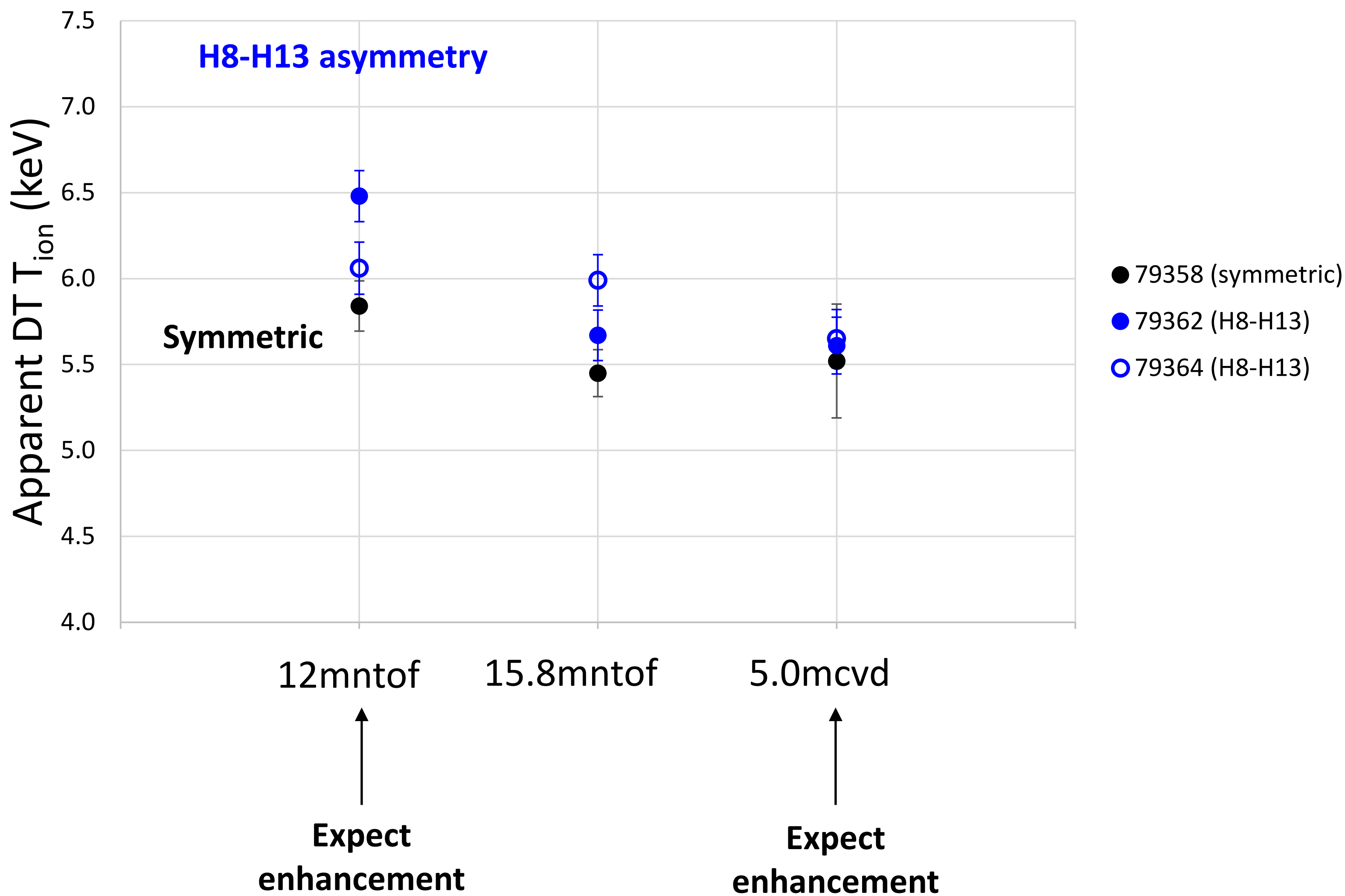


Simulation prediction for symmetric implosions: 5.5 keV including fluid velocity broadening, 5.23 keV without flow

P2-P11 asymmetry does show a small T_{ion} enhancement in the 15.8m line-of-sight relative to symmetric – this goes in the right direction



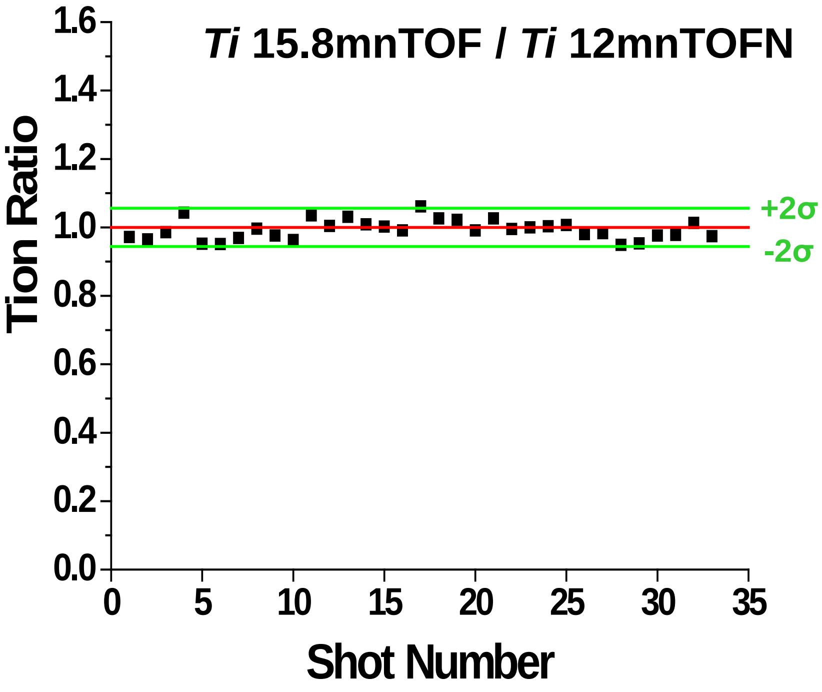
The H8-H13 asymmetry shows a T_{ion} enhancement in the 12m line-of-sight relative to symmetric as expected, but there is also an enhancement for 15.8m and no enhancement for 5mcvd



A quantitative look at the Tion variations shows that the symmetric shot is no more symmetric than at least one shot of each asymmetry type

V. Glebov: 2σ variation for warm implosions is ~7%:

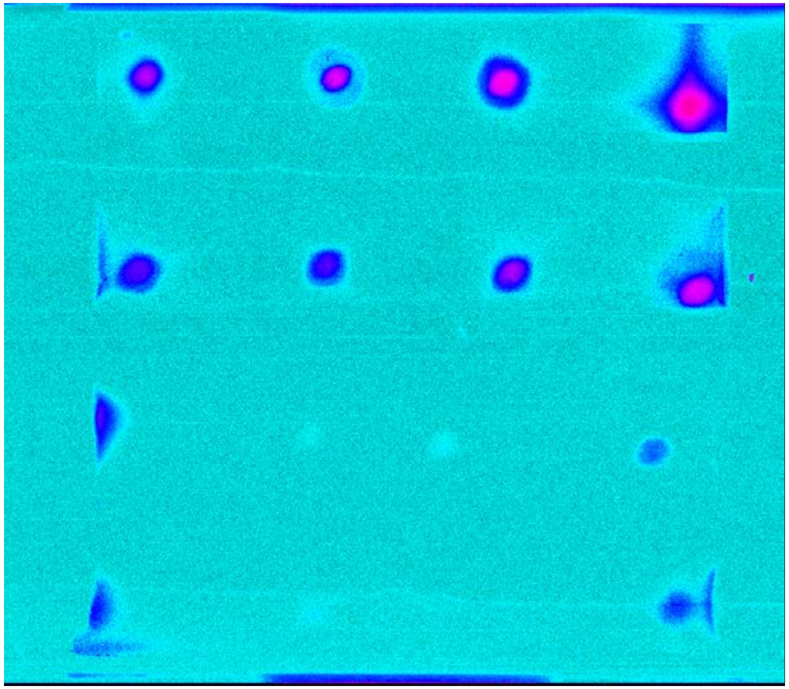
2015 room-temperature targets



		Dev. from average:				
Shot #	Average Tion (keV)	5mcvd	12mntof	15.8mntof	Shot Type	χ^2_{red} (symm)
79358	5.62	1.9%	-3.7%	3.2%	symm	2.0
79359	5.79	5.3%	-2.4%	-1.7%	P2-P11	2.2
79362	5.94	5.9%	-8.4%	4.7%	H8-H13	9.3
79363	5.78	4.4%	-1.5%	-2.0%	P2-P11	1.6
79364	5.91	4.7%	-2.4%	-1.3%	H8-H13	1.8

While no clear asymmetry is seen in the Tion data, clear asymmetry signatures are seen in x-ray images

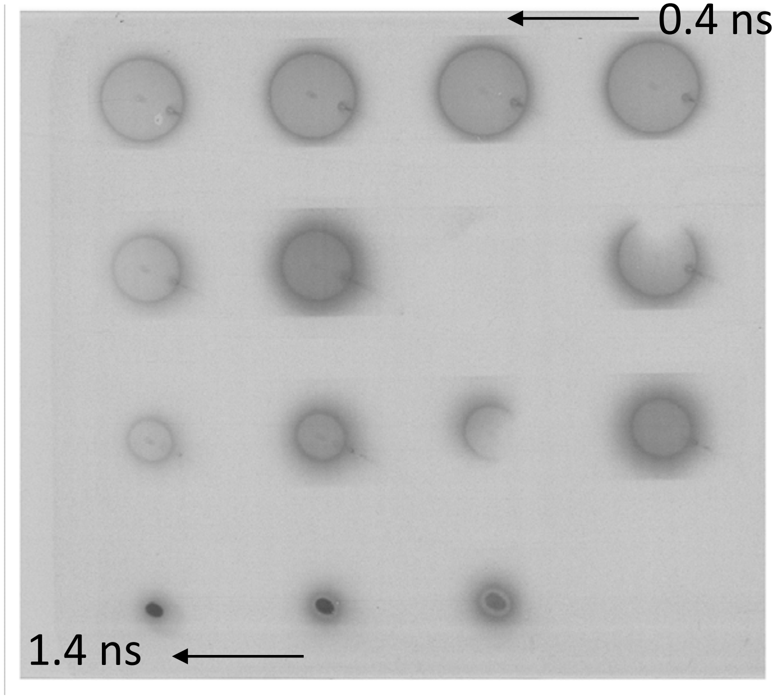
KBRAMED from shot 79359 with **P2-P11 asymmetry**



KBFRAMED should see 99% of the P2-P11 and 8% of the H8-H13 asymmetry

Angle to P2-P11: 81°
Angle to H8-H13: 5°

Framing camera data from shot 79363 with **P2-P11 asymmetry**



SFC3 (fielded in TIM2) should see 98% of the P2-P11 and 67% of H8-H13 asymmetry

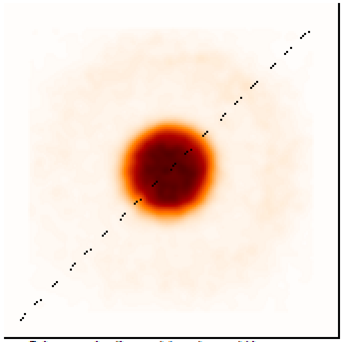
Angle to P2-P11: 79°
Angle to H8-H13: 42°

Fred Marshall has analyzed KBFRAMED data from four shots – the asymmetries seen are all in the right direction

79358 Symmetric

t = 1.032 ns

PSF smoothed image



Lineout indicated by dotted line

Inferred fit

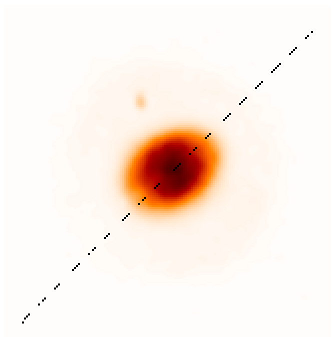
Ro (microns):	51.82+/- 1.22
maximum:	1.458+/- 0.001
exponent:	5.61+/- 0.01
a/b:	1.035+/- 0.000
phi (deg):	65.6+/- 0.0
background:	0.039+/- 0.001

"As round as it gets"

79359 P2-P11

t = 1.032 ns

PSF smoothed image



Lineout indicated by dotted line

Inferred fit

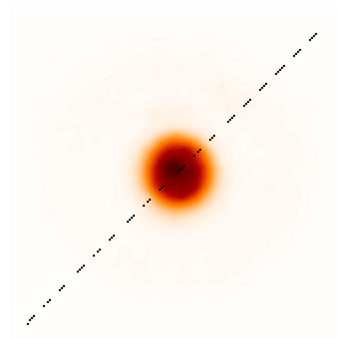
Ro (microns):	43.67+/- 0.01
maximum:	0.498+/- 0.001
exponent:	3.25+/- 0.01
a/b:	1.219+/- 0.000
phi (deg):	31.4+/- 0.0
background:	0.010+/- 0.000

fit semi major axis direction 31.4 degrees, which is within alignment uncertainty of the direction of P2

79362 H8-H13

t = 1.032 ns

PSF smoothed image



Lineout indicated by dotted line

Inferred fit

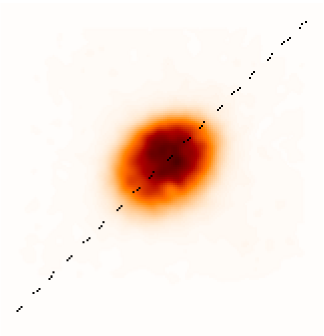
Ro (microns):	39.56+/- 1.96
maximum:	0.595+/- 0.001
exponent:	3.55+/- 0.01
a/b:	1.075+/- 0.000
phi (deg):	96.6+/- 0.0
background:	0.009+/- 0.001

direction of the semi major is 96.6 degrees which is in the approximate direction of the center of the port as seen from KBF

79363 P2-P11

t = 0.993 ns

PSF smoothed image



Lineout indicated by dotted line

Inferred fit

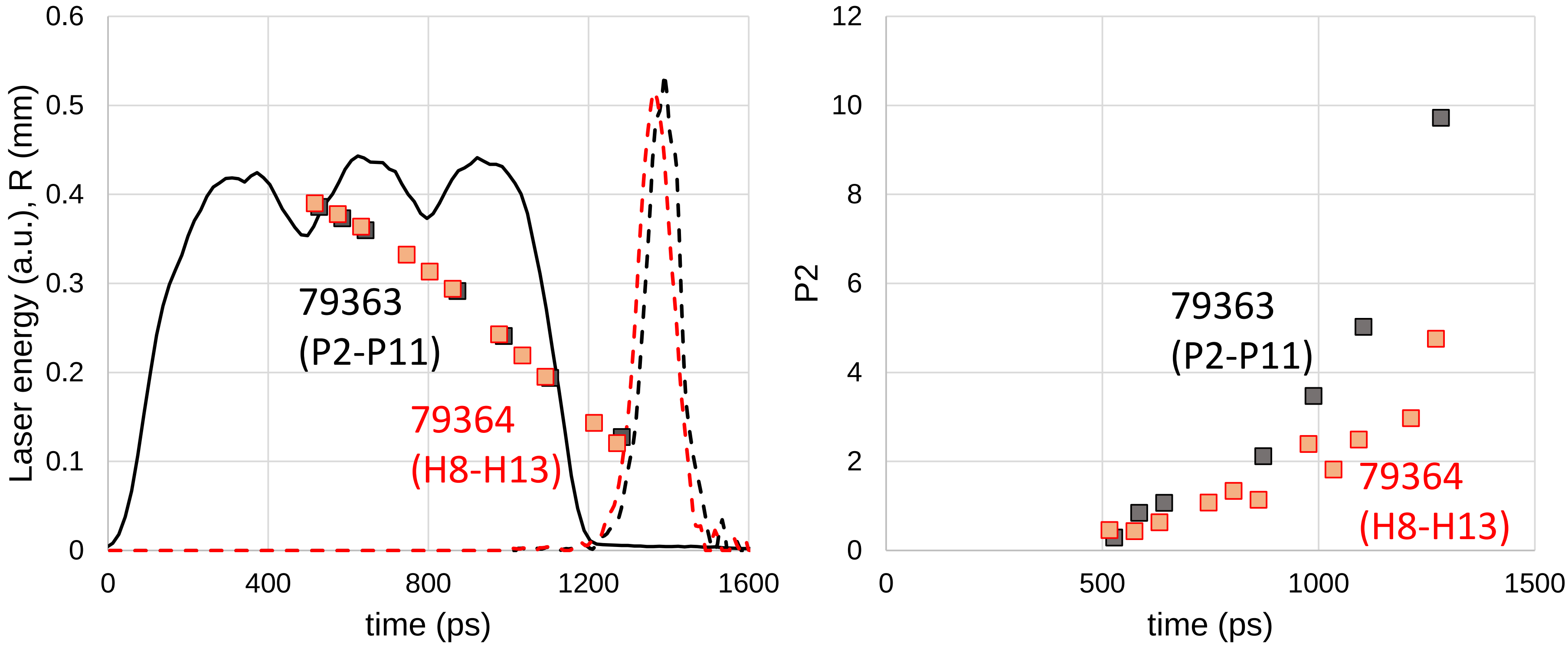
Ro (microns):	48.62+/- 0.03
maximum:	0.641+/- 0.002
exponent:	2.87+/- 0.02
a/b:	1.300+/- 0.000
phi (deg):	36.5+/- 0.0
background:	0.008+/- 0.001

79364 H8-H13

Analysis pending

KBFRAMED sees 99% of a P2-P11 asymmetry and 8% of an H8-H13 asymmetry

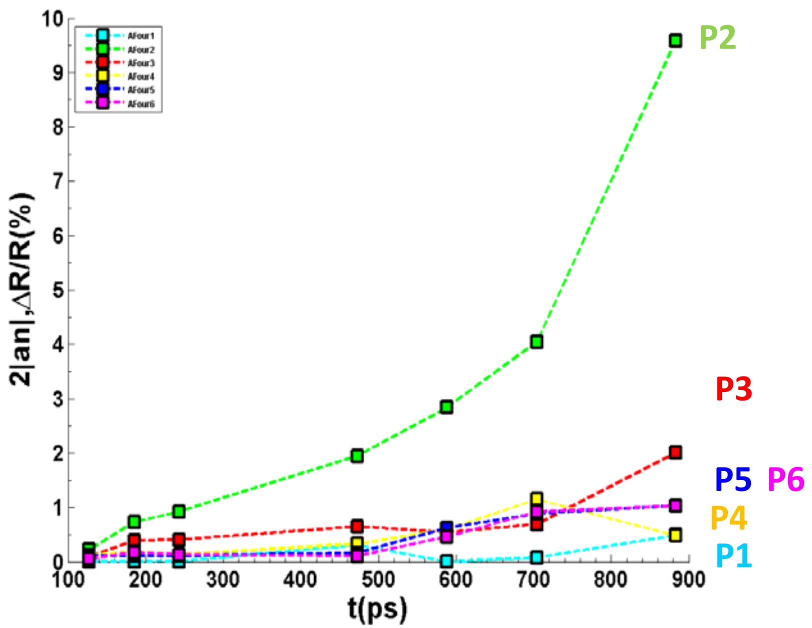
Tomline Michel has analyzed SFC3 data: P2-P11 and H8-H13 asym. give different P2 as observed from the TIM2 line-of-sight as expected



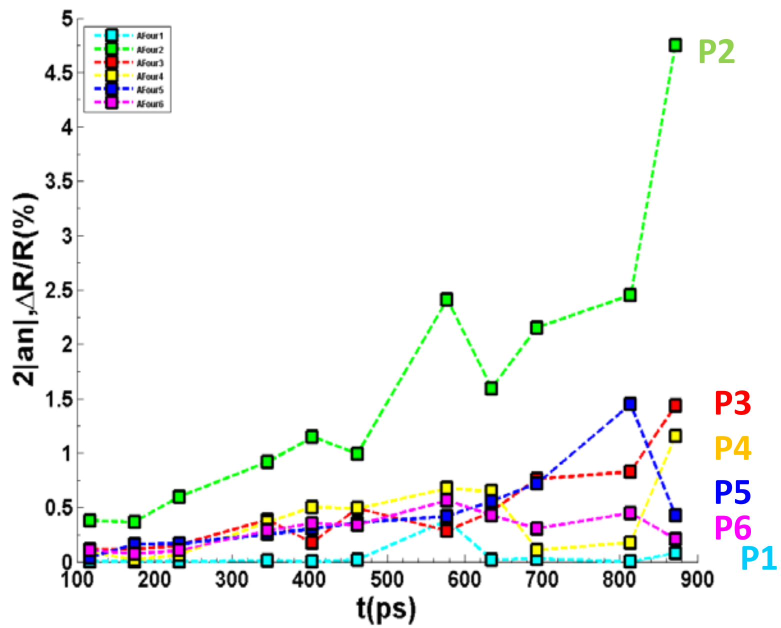
TIM2 sees 98% of a P2-P11 asymmetry and 67% of an H8-H13 asymmetry

The P2 is the only significant asymmetry, and it is growing consistently throughout the implosion

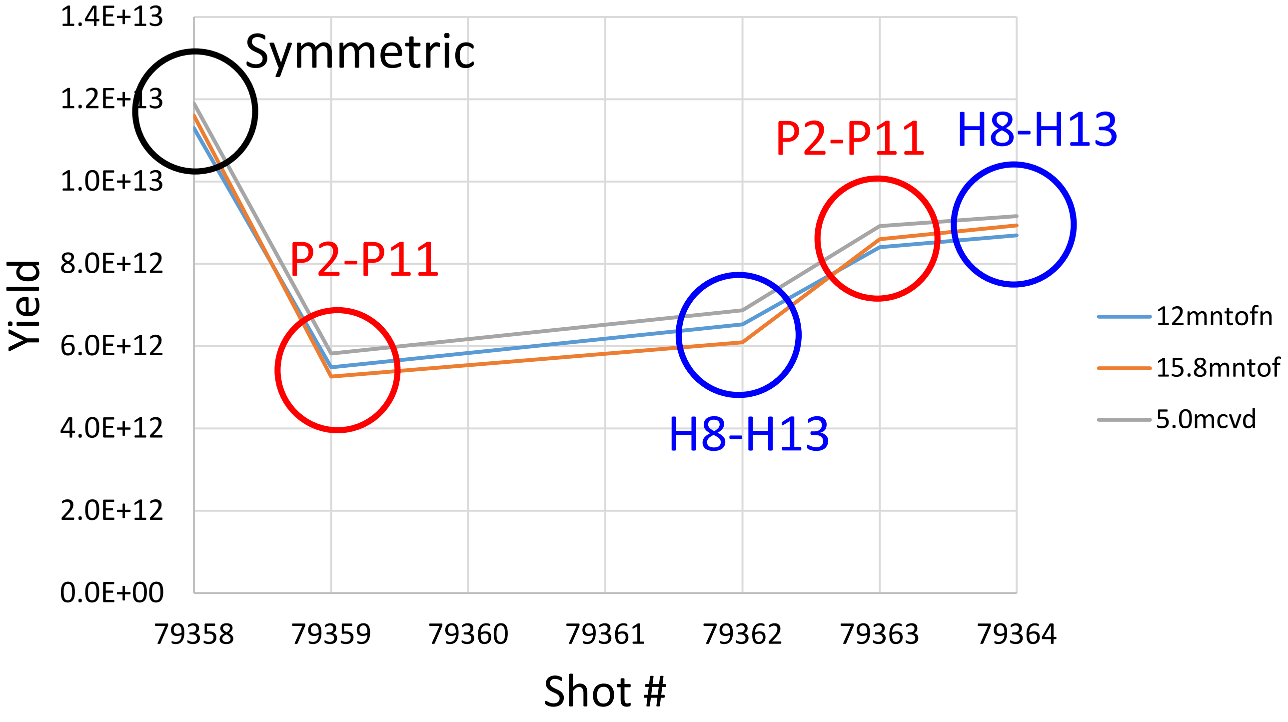
79363 (P2-P11)



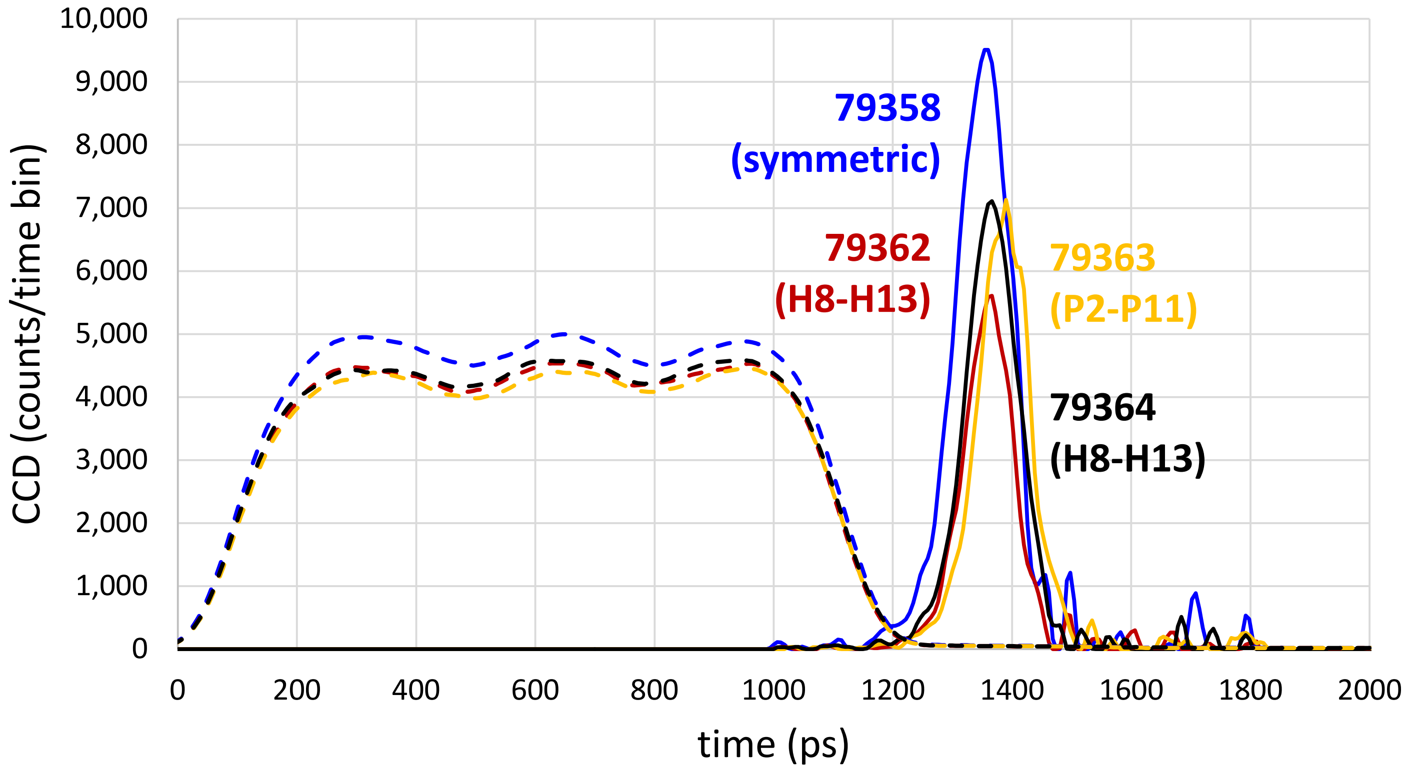
79364 (H8-H13)



Yields for the asymmetric implosions come in at 48-77% of the yield for the symmetric implosion



Bang times/burn durations were measured with cryo NTD and came in very similar for all implosion types



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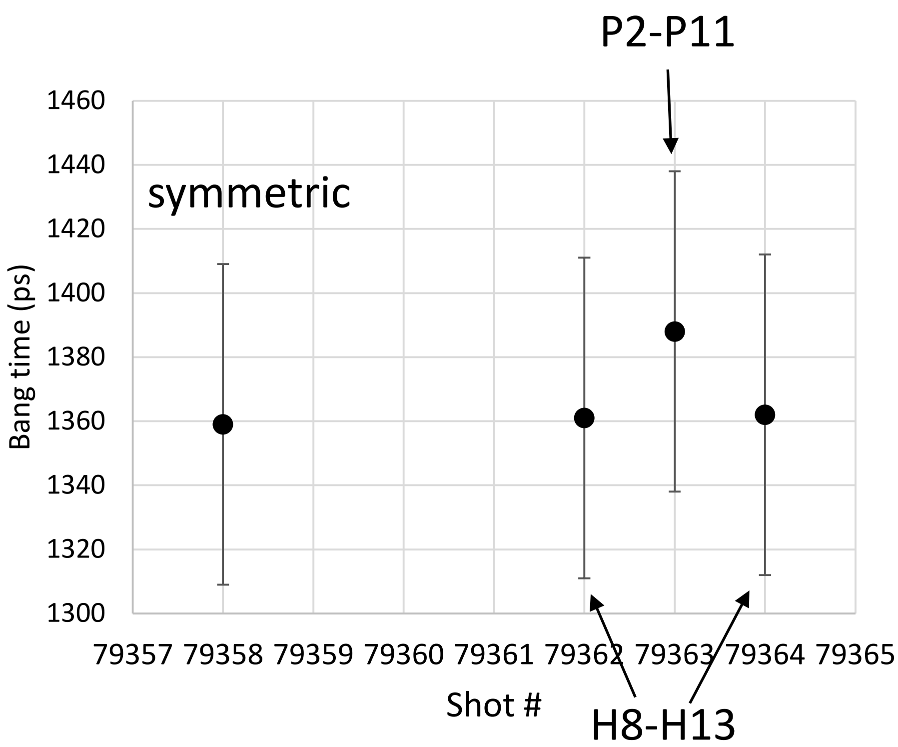
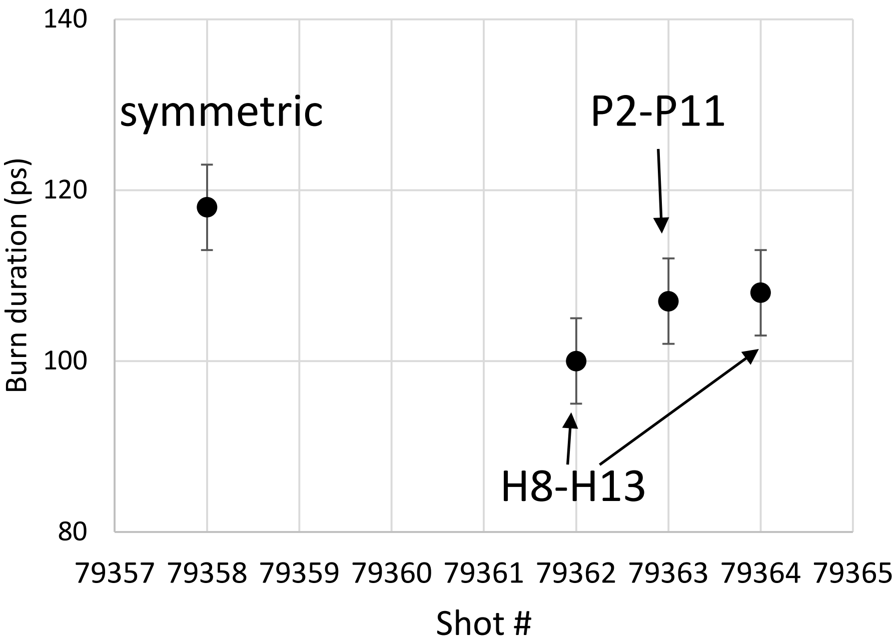




Cryo NTD data was lost on P2-P11 shot 79359

Outline

- Setup
- Results
  - nTOF Tion
  - X-ray measurements (KBRAMED, SFC3)
  - Yield
  - Bang time/burn duration (NTD)
- Interpretation/simulations (work in progress!)

Together with Imperial College, we are investigating several different hypothesis for why the results did not come in as expected

- High-mode asymmetries perturbing the P2 asymmetry
  - LLE predicts performance for 15μm CH-shell implosions to be dominated by high-mode asymmetry due to laser imprint*
  - Appears enough to reduce but not eliminate the flow signatures
  - Signatures to look for: Reduced x-ray asymmetry?

- Radiation losses truncating the burn
  - Radiation losses $\rightarrow$ cooling of the fuel before the asymmetry develops $\rightarrow$ low neutron yield from the high-flow times, with maintained hydrodynamics
  - Signatures to look for: reduced yield, maintained x-ray asymmetry but reduced Tion asymmetry

- External asymmetry seeds perturbing the P2 asymmetry
  - Jetting of glue spot, or issue with beam power balance
  - Signatures to look for: perturbed asymmetry in x-ray images, similar impact on symmetric and asymmetric shots, burn truncation

*P.B. Radha et al., Phys. Plasmas 12, 032702 (2005); P.B. Radha et al., Phys. Plasmas 12, 056307 (2005)

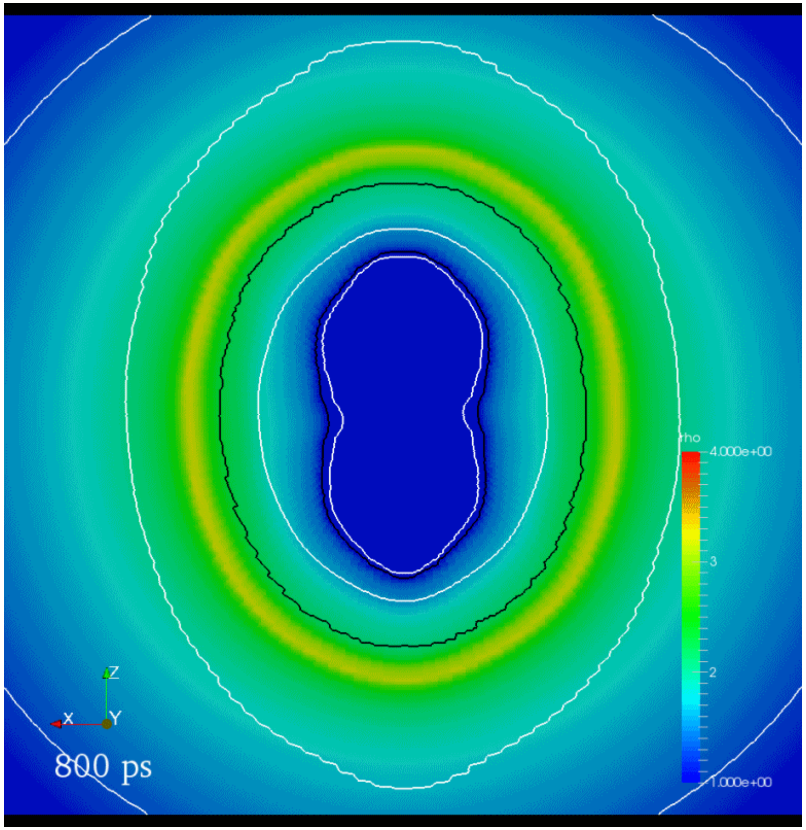
Imperial is using the 3D Chimera code for these simulations, initialized with a 1D Hyades simulation after laser turn-off but before the shock hits the center

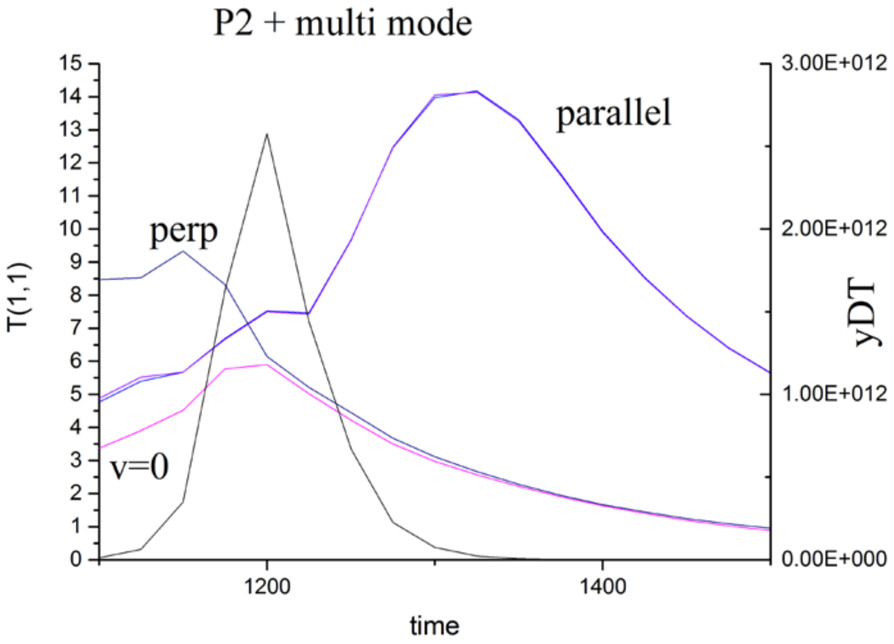
Some features of Chimera*:

- Eulerian mesh
- Fully explicit solution method
- Hydrodynamic motion solved using a 2nd order van Leer advection algorithm with a von Neumann-Richtmyer artificial viscosity
- Ablator and fuel materials are advected separately with an approximate interface maintained using a SLIC based method
- Separate electron and ion energy equations are solved using tabulated equation of state data for energy densities, pressures, sound speed and ionic charge, for each material, which are calculated offline using the Frankfurt Equation of State (FEoS) model
- Electron and ion thermal conductivities and equilibration rates are calculated using the Epperlein-Haines modifications to the Braginskii formulae
- For the electron thermal conduction, a flux limiter of 0.04-0.06 is used
- **Time-resolved neutron spectra produced along multiple LOS as a function of ion temperature and density of each simulation cell**

*J. Chittenden et al., "*Signatures of Asymmetry in Neutron Spectra and Images Predicted by 3D Radiation Hydrodynamics Simulations of Indirect Drive Implosions*", submitted to PoP (2016)

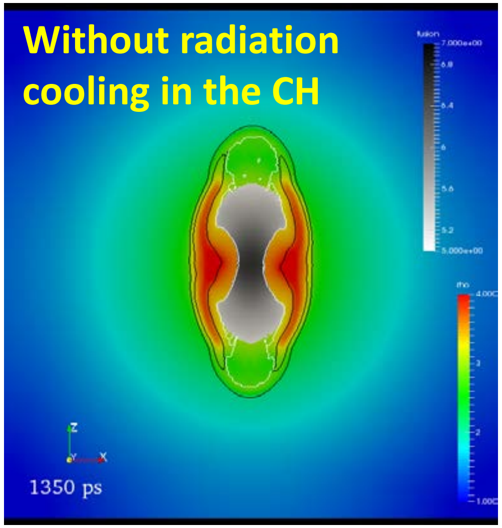
The high-mode asymmetry hypothesis has been tested in Chimera simulations

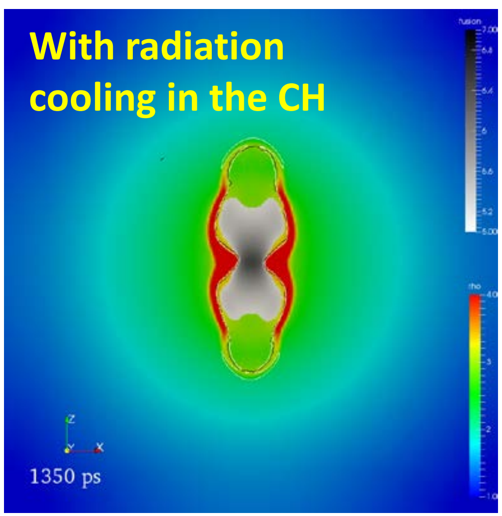




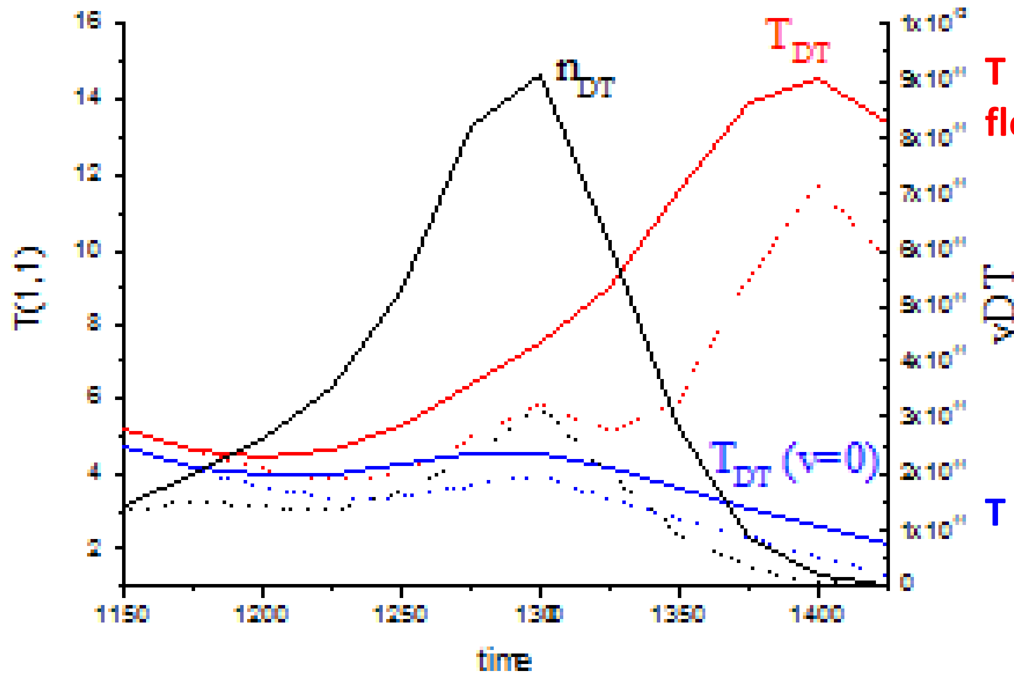
An appreciable difference is still seen in "Tion" depending on direction (~1 keV)

The radiation loss hypothesis is currently being investigated





Solid: Without radiation cooling in the CH
Dashed: With radiation cooling in the CH



T with flow

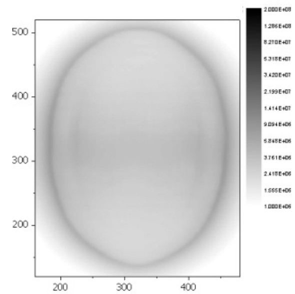
T no flow

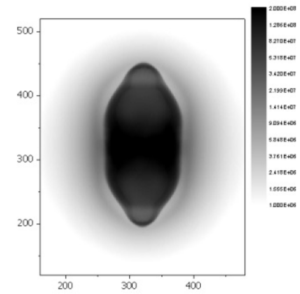
Adding radiation loss in the simulation does reduce/eliminate the Tion asymmetry but not the x-ray asymmetry

t=1100 ps

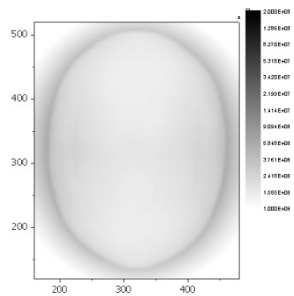
t=1275 ps

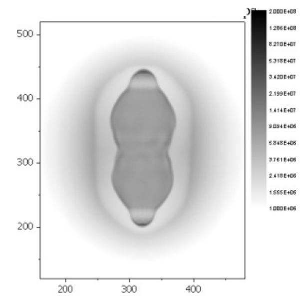
Simulation, no radiation loss



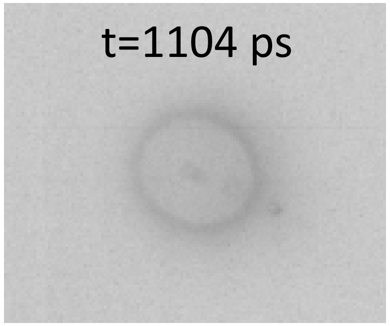


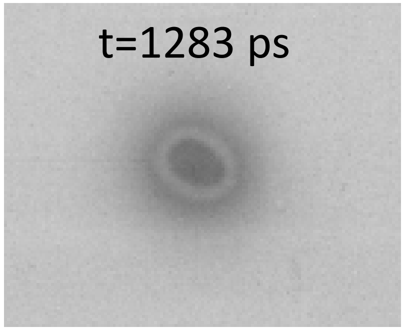
Simulation, with radiation loss





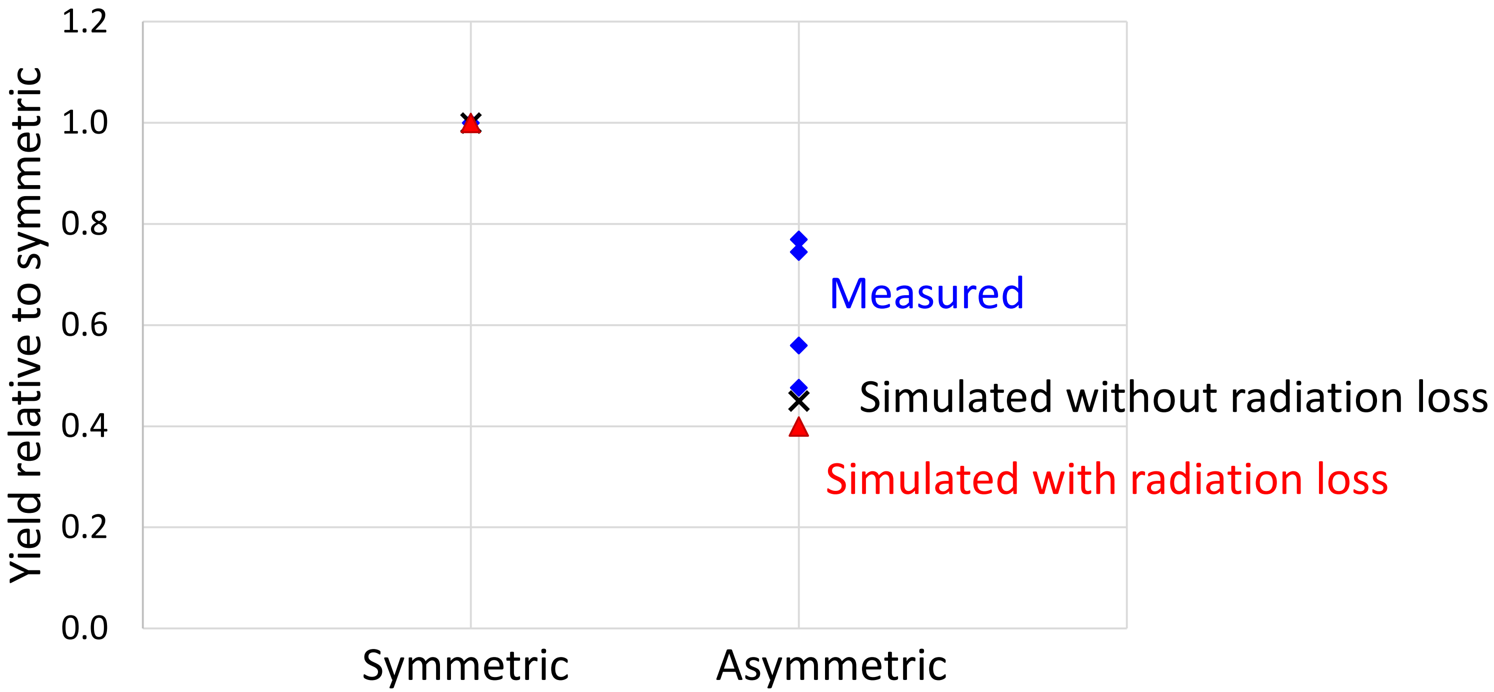
TIM2 framing camera measurement
(should see 98% of the P2-P11 asymmetry)





The measured x-ray asymmetry appears smaller than simulated - could this be an indication that high-mode asymmetries are contributing as well?

The measured difference in yield between symmetric and asymmetric implosions is smaller than predicted



The lower-than-expected yield reduction might be an indication that external asymmetry seeds impact symmetric and asymmetric implosions alike?

Could the glue spots be jetting into the implosion, perturbing symmetrically and asymmetrically driven implosions alike?

Shot	Glue spot diameter [um]	length [um]	stalk length [um]
79358	77.05	98.12	1063.75
79359	83.15	97.56	993.35
79362	61.53	85.37	1018.29
79363	56.54	80.93	973.39
79364	61.53	79.82	888.58

TPS2 is 37° from P2-P11 and 71° from H8-H13

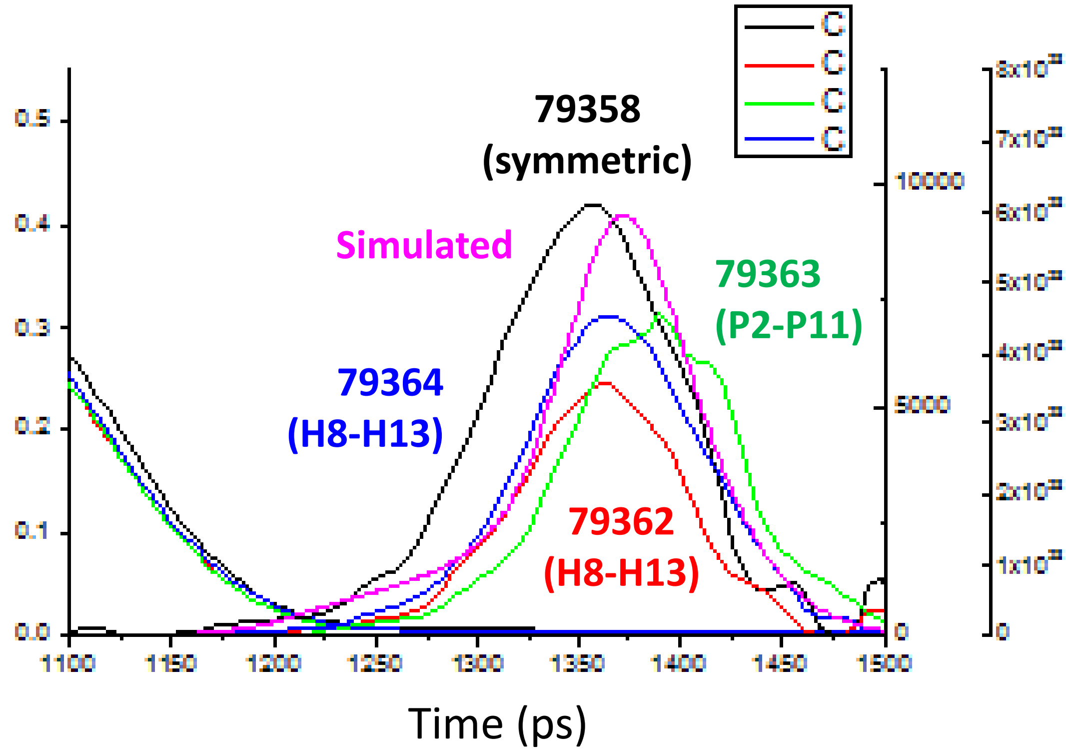
→ Glue spot jetting might reinforce P2-P11 asymmetry, distort H8-H13 asymmetry?

Target for shot 79362

TPS2 is 77° from 12mntof, 68° from 5mcvd and 39° from 15.8mntof

I.V. Igumenshchev et al., Phys. Plasmas (2009)
B. Haines, IFSA 2015

Simulations give a burn history similar to cryo-NTD measured



<u>Notes:</u>

1. The simulation used a perfect 1ns square laser pulse with not up-down ramp – this is artificially corrected for by delaying the burn by 100 ps
2. The simulation is 50:50 D:T (no 3He) and gives a clean yield of 6e13. The amplitude of the simulated trace has been normalized to match the data

A controlled experiment to test our understanding of flows did not produce the expected result

- Round x-ray images and isotropic Tion don't necessarily have to go together!

- The results could likely be explained by a combination of:
  - high-mode non-uniformity due to e.g. laser imprint
  - external low-mode asymmetry seeds such as e.g. glue spot jetting
  - radiation losses truncating the burn

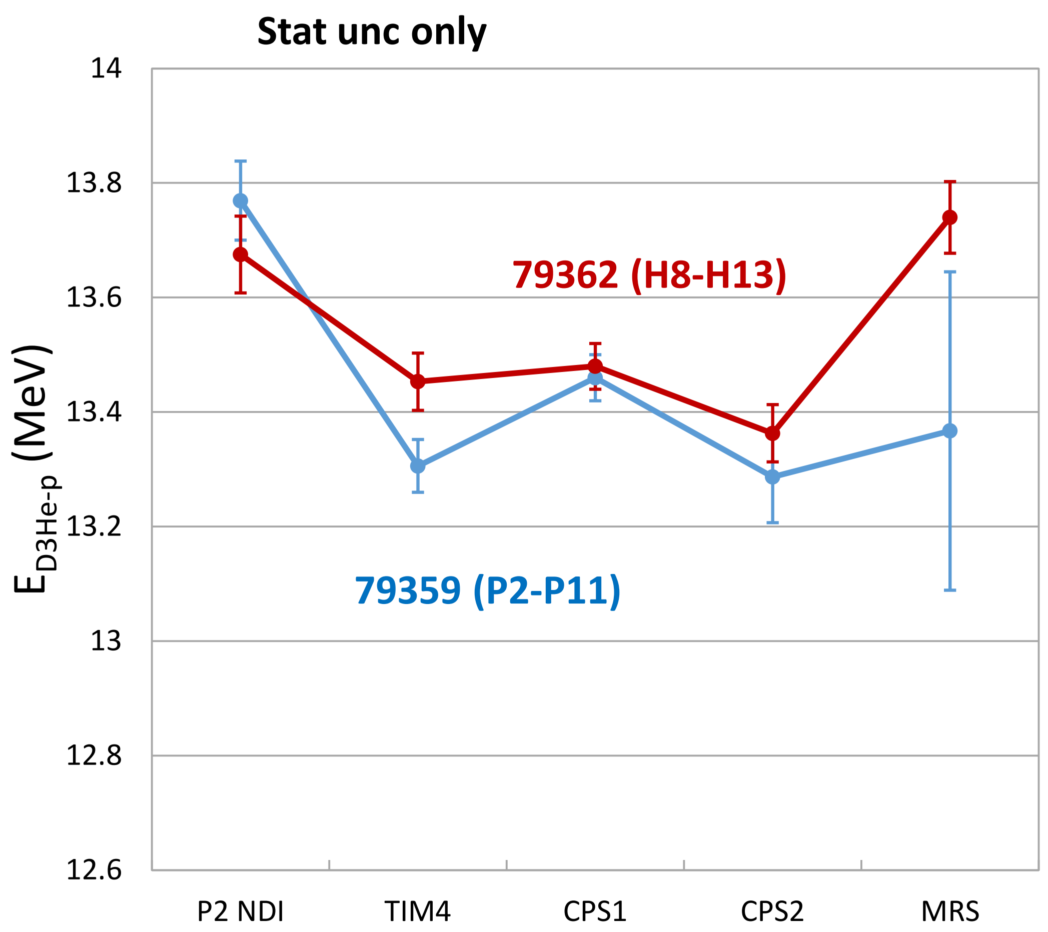
- **Do these results contradict or support our current understanding of the stagnated core?**

Appendix

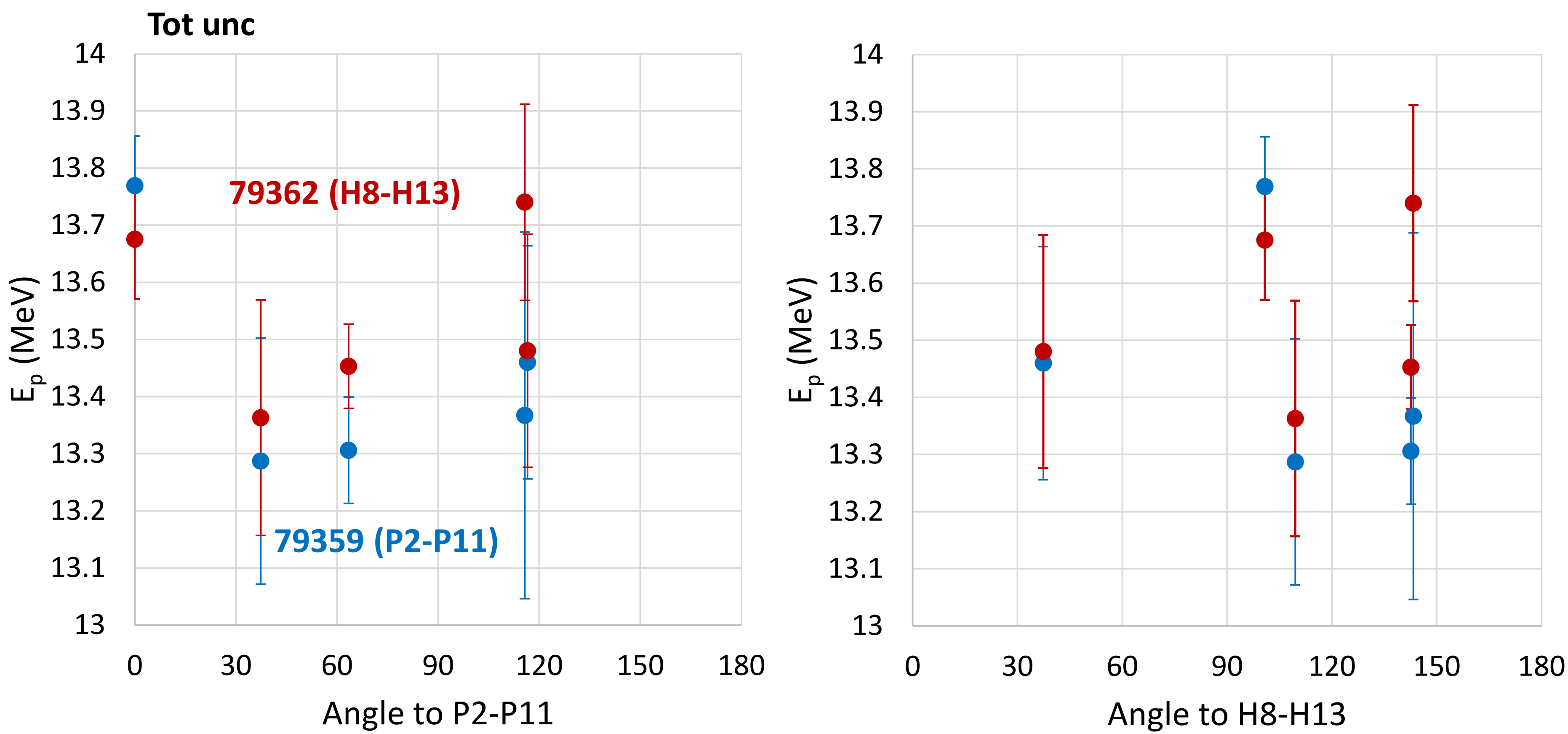
Next steps…

- There is more data to look at:
  - Can we learn anything from pinhole camera and GMXI images?
  - 3dp2 directional velocity and T_{ion} measurements – is there a P1?
  - ρR asymmetry measurements from D^3He downshifts from remaining shots
  - PCIS data to look at core size
  - Scattered light/absorption measurements
- Generate synthetic diagnostic results from simulations to compare to data
  - X-ray images – is the asymmetry quantitatively smaller than predicted?
  - Burn history – is it shorter than predicted?
  - Yields – how do we reconcile that they are similar for symmetric and asymmetric implosions?
- **Use a different simulation tool to compare to? (e.g., Hydra or Draco)**

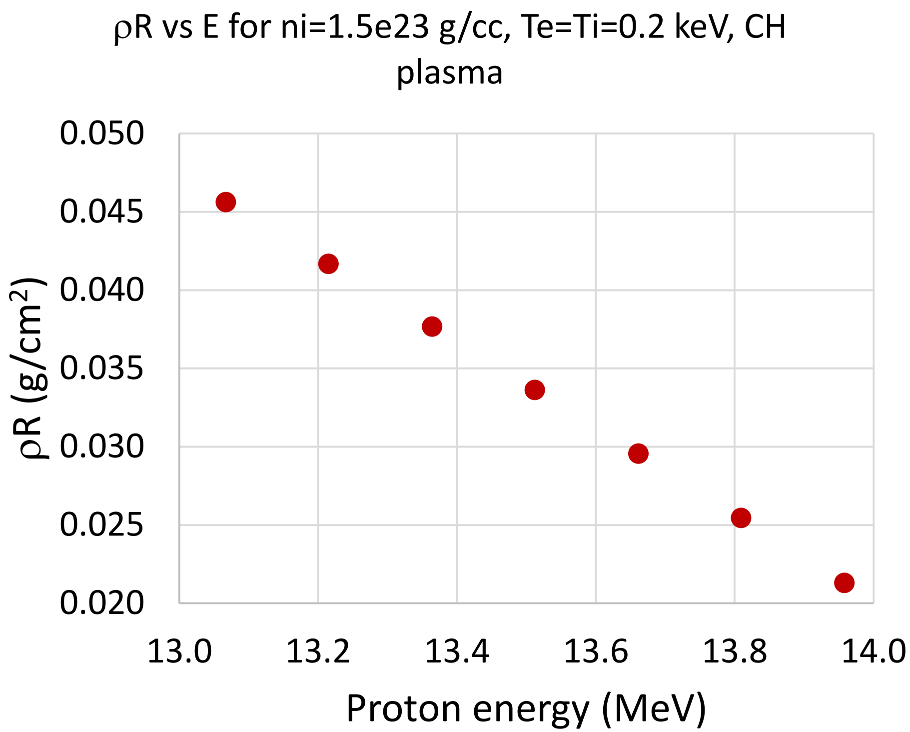
No significant ρR asymmetries are observed outside of error bars on 79359 and 79362 (only two shots analyzed so far)

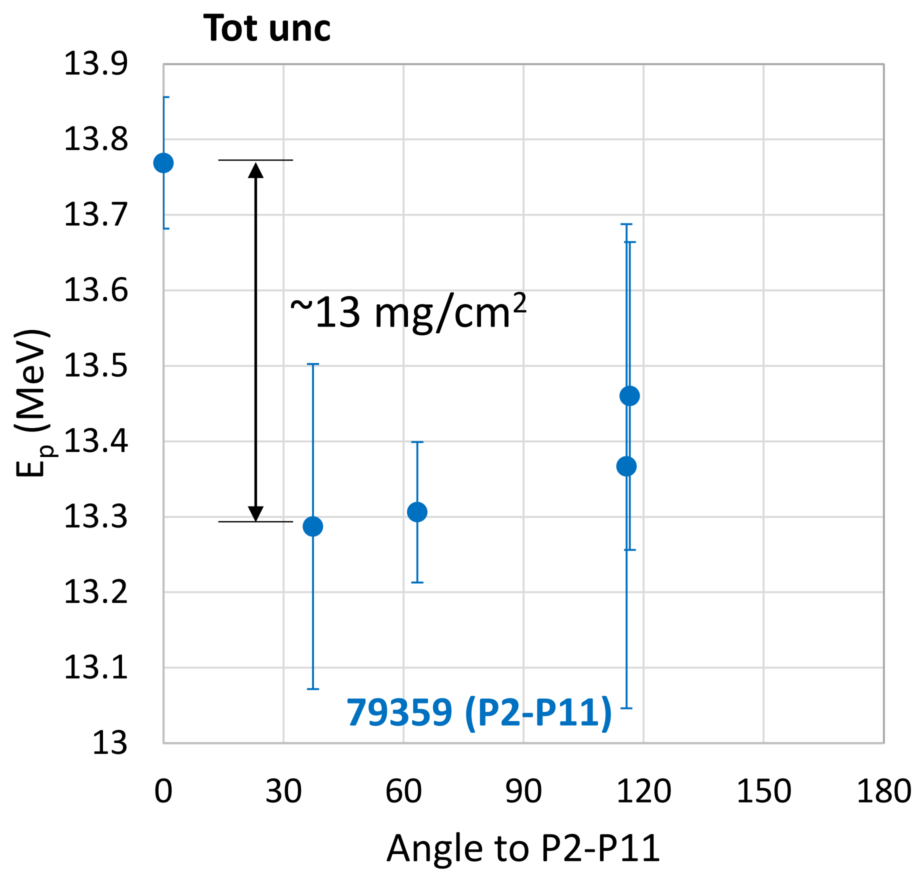


No significant ρR asymmetries are observed outside of error bars on 79359 and 79362 (only two shots analyzed so far)

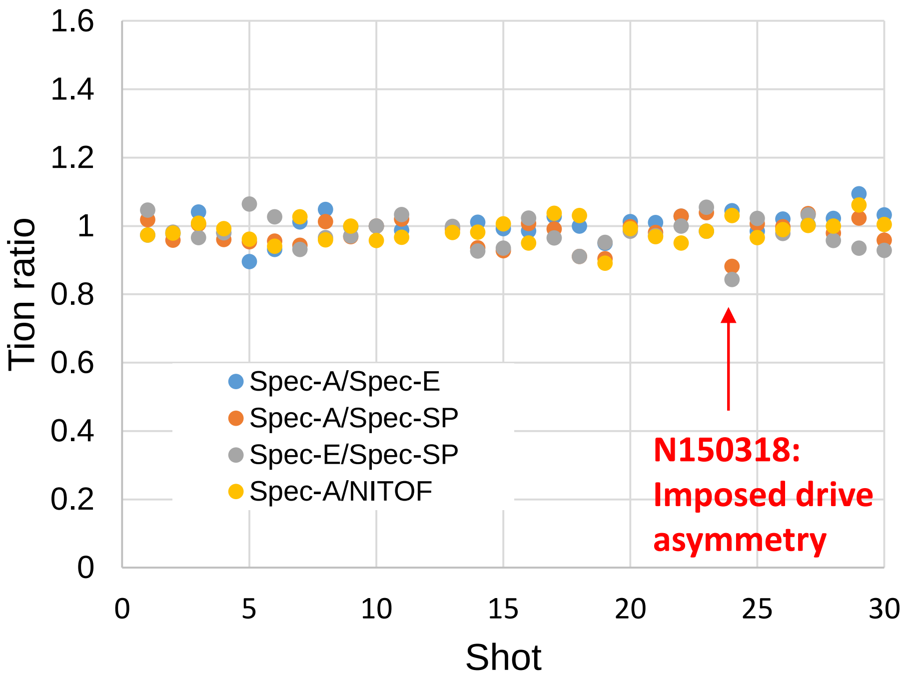


Observed energy differences correspond to ρR differences of ~35-48 mg/cm^2 (not considering error bars), with the thinnest spot being in the P2 LOS

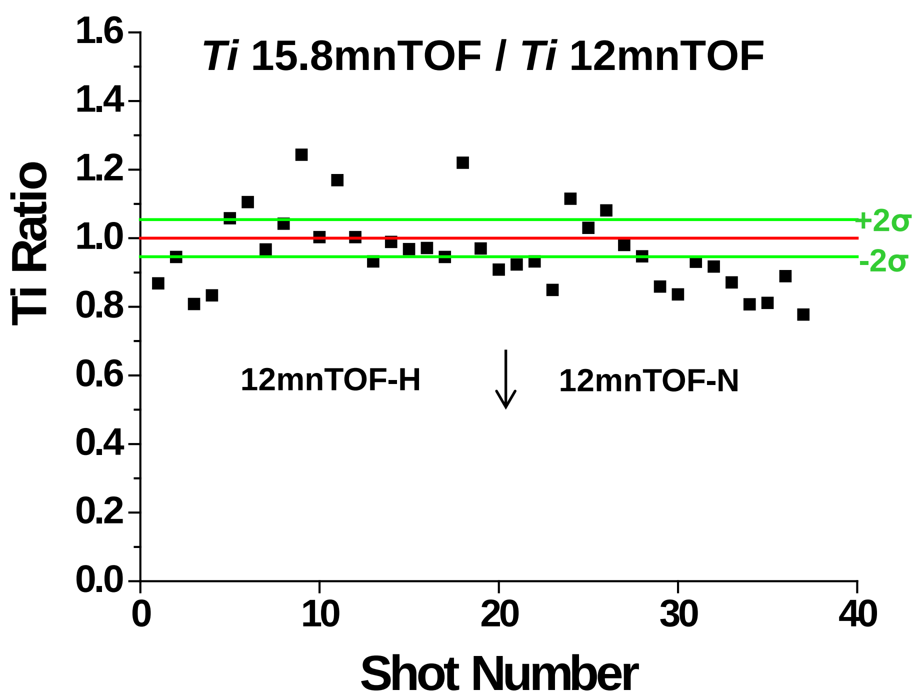




Puzzle: Line-of-sight variations in OMEGA T_{ion} measurements are substantially larger than LOS variations in NIF T_{ion} measurements

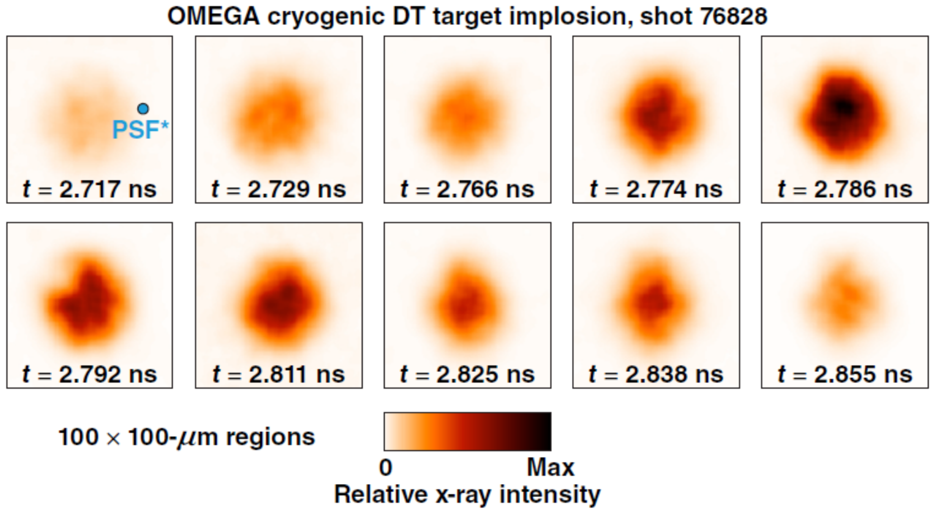


2015 cryogenics targets

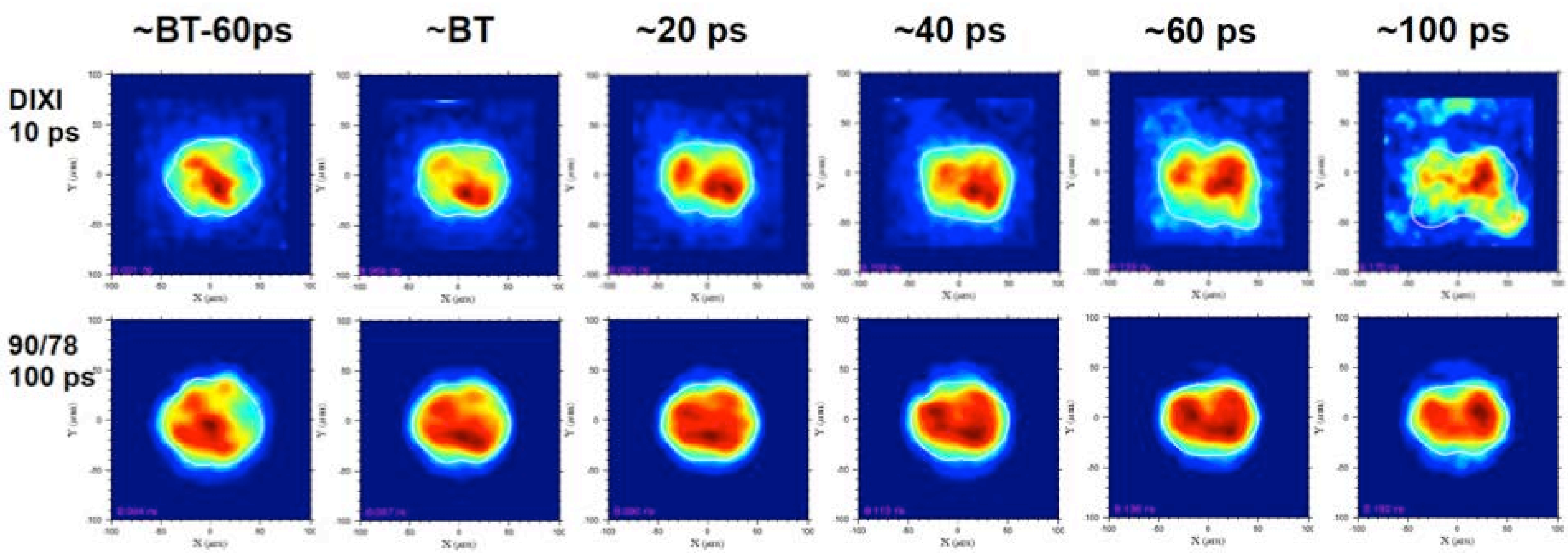


A possible explanation for this is that asymmetric flows are more prevalent in OMEGA than NIF implosions?

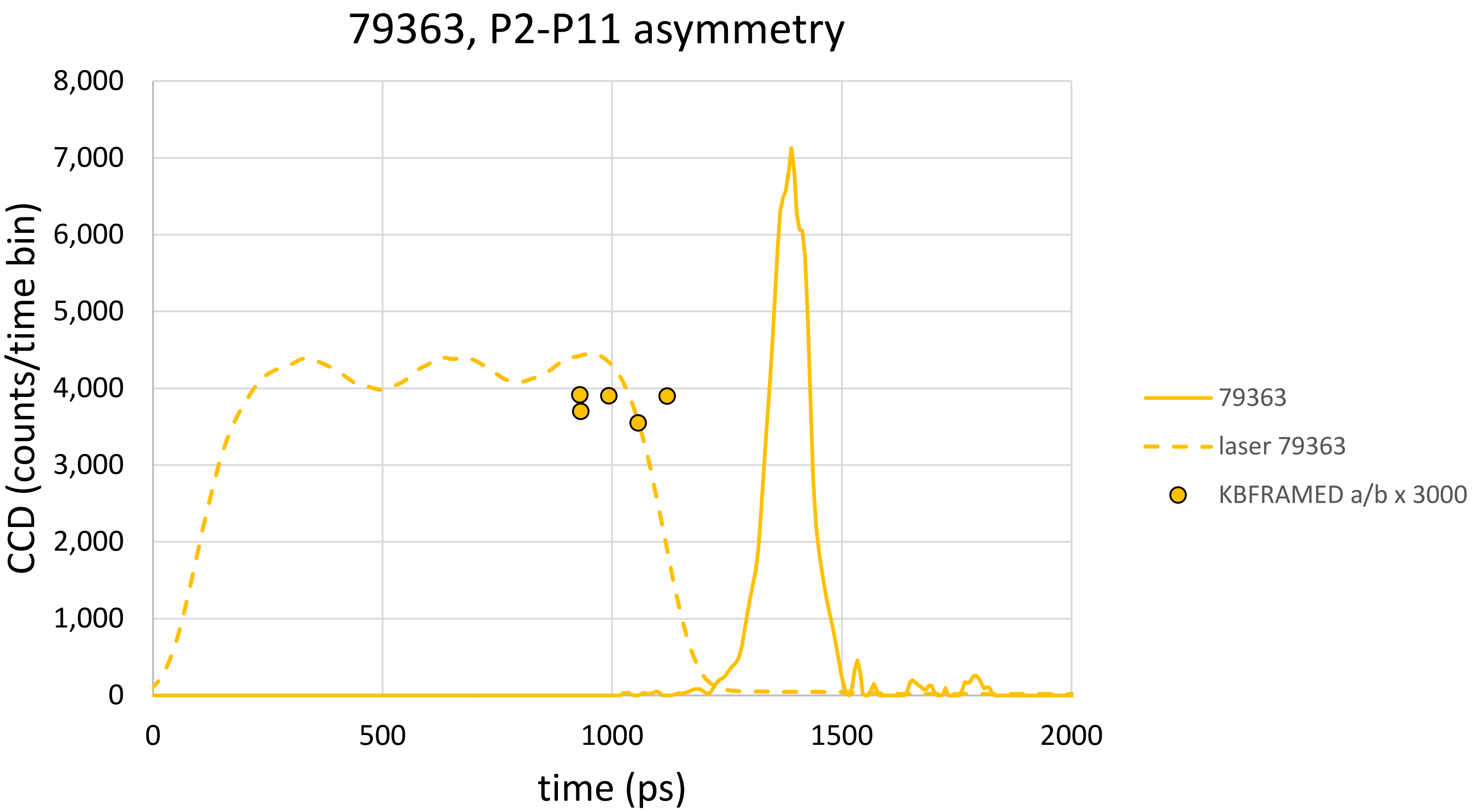
Puzzle: At the same time, x-ray images from OMEGA cryo appear more symmetric (??) than from NIF HiFoot implosions



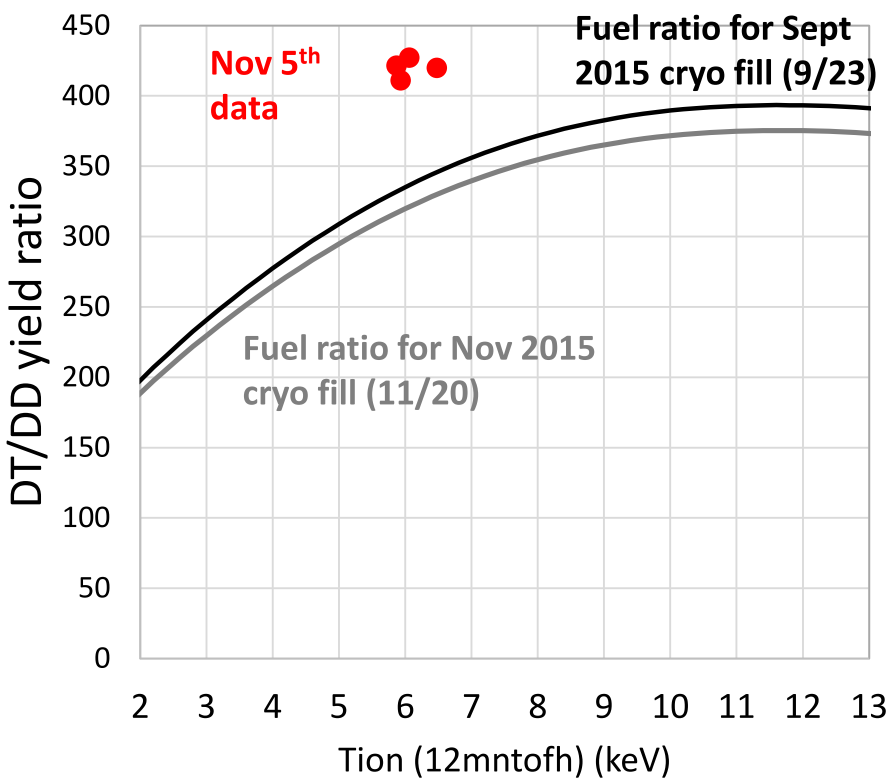
KBframed has 30-ps temporal resolution and 6-μm spatial resolution, and records an image every 15 ps in the 4- to 8-keV photon-energy range.

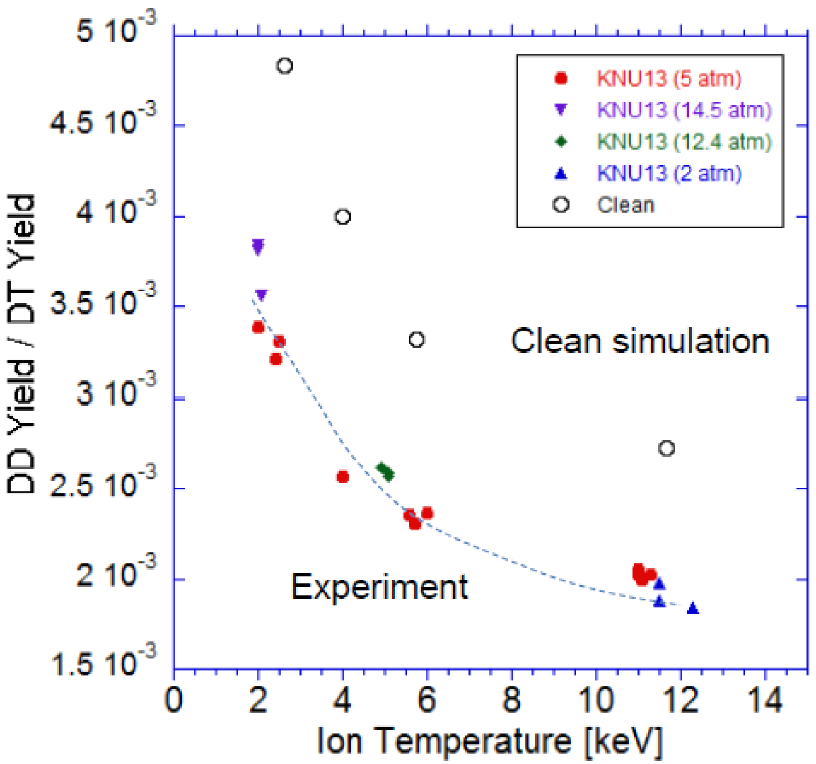


Usable KBFRAMED images fall right at the end of the laser pulse – images at later times were lost due to microscope misalignment



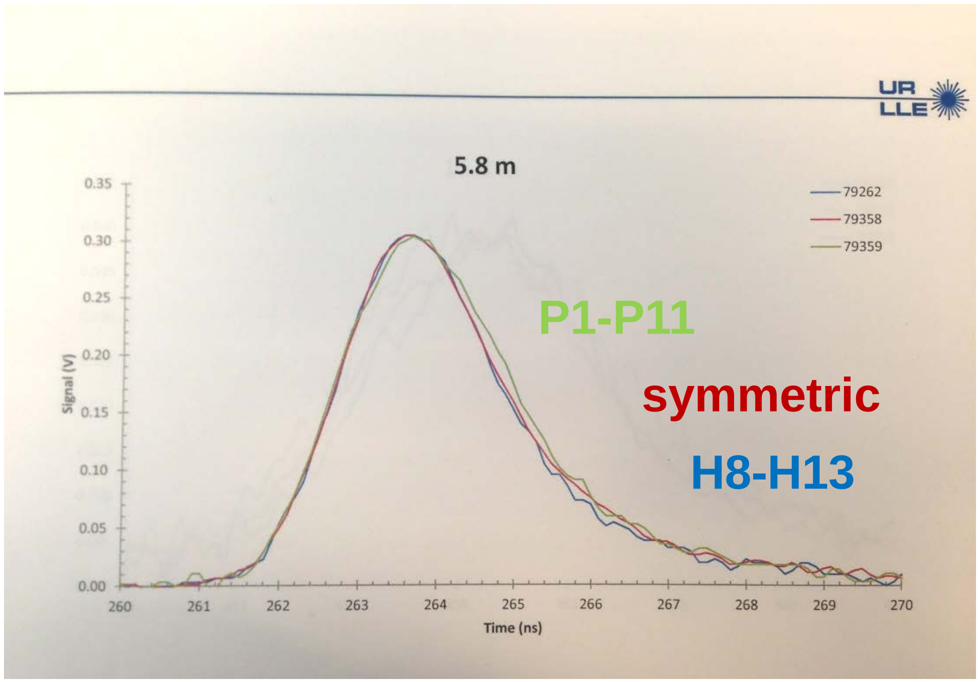
The measured DT/DD yield ratio is high relative to expected given the known D:T fuel isotope ratio; the discrepancy is consistent with LANL Sept 2013 results

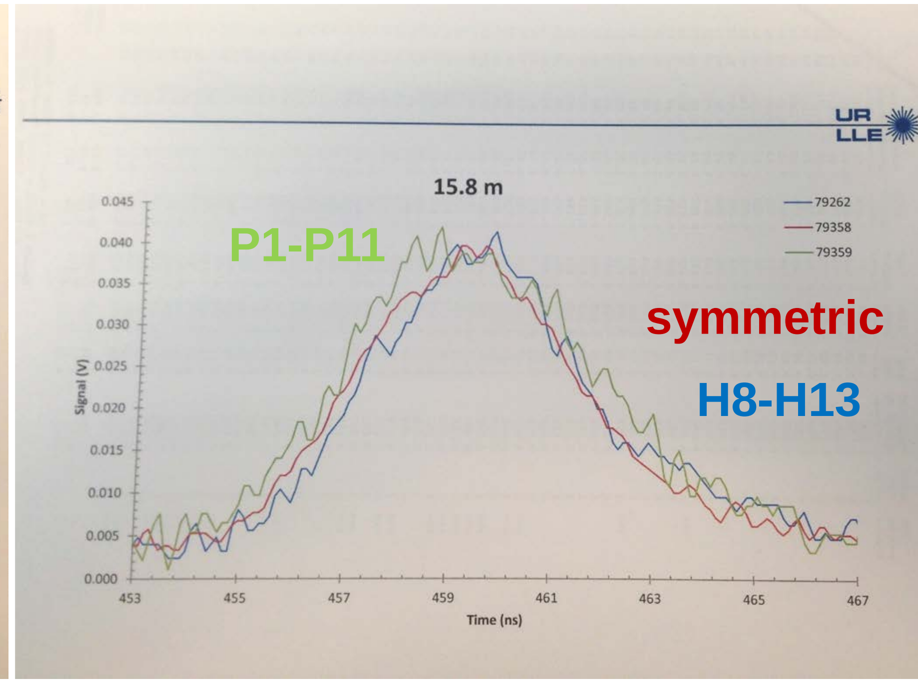




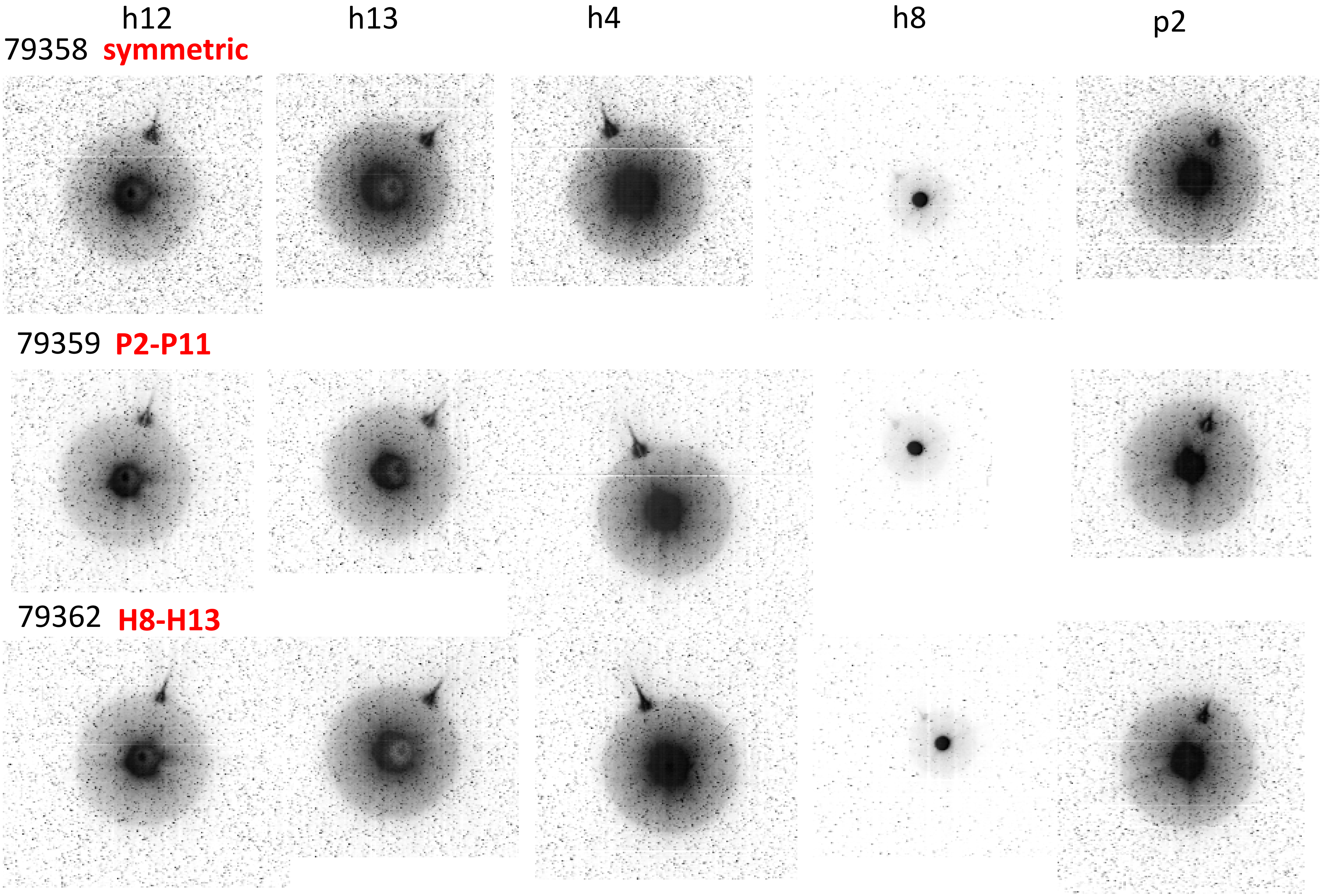
Plot by Yongho Kim
Sept 4-5, 2013 CH shell experiments
Fills for these were done at LLNL

Jim Knauer's 3dp2 diamond detectors show a hint of difference going in the right direction (analysis pending)





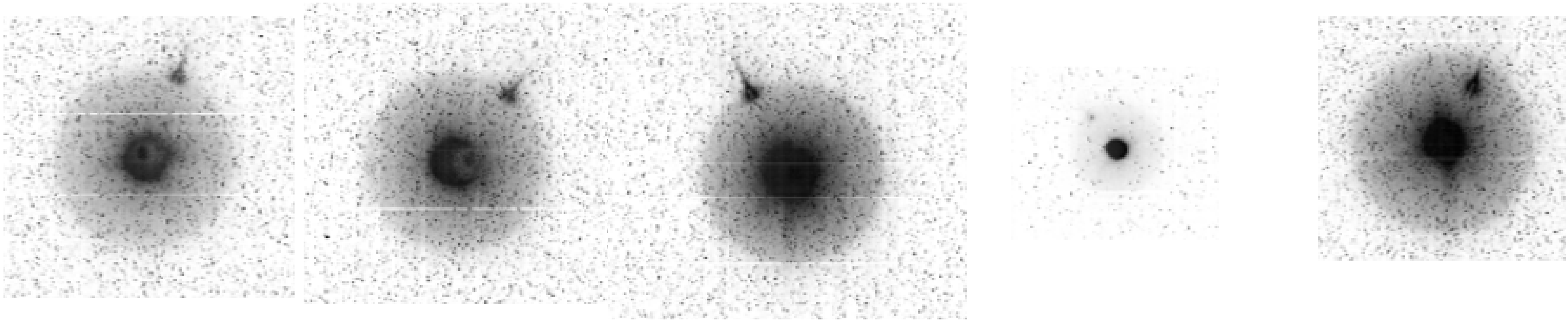
x-ray pinhole cameras



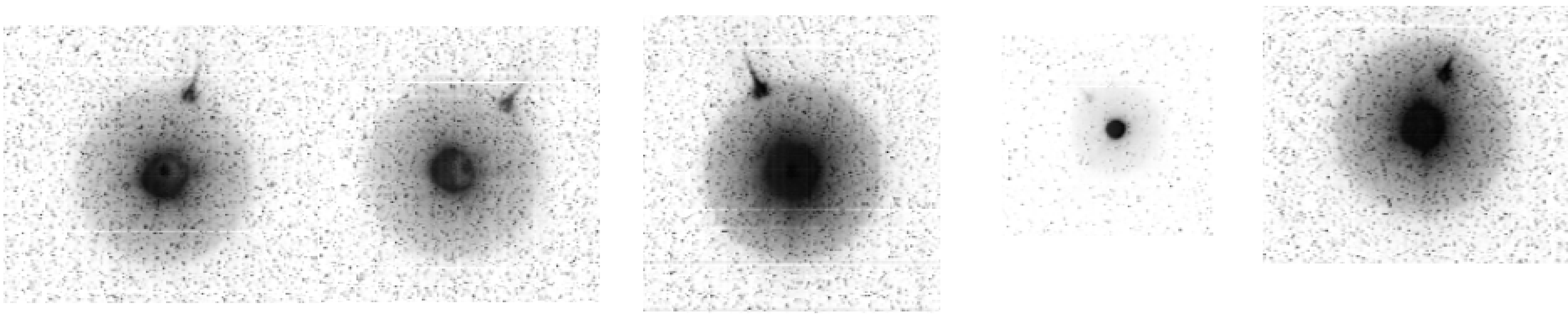
x-ray pinhole cameras

h12 h13 h4 h8 p2

79363 **P2-P11**



79364 **H8-H13**

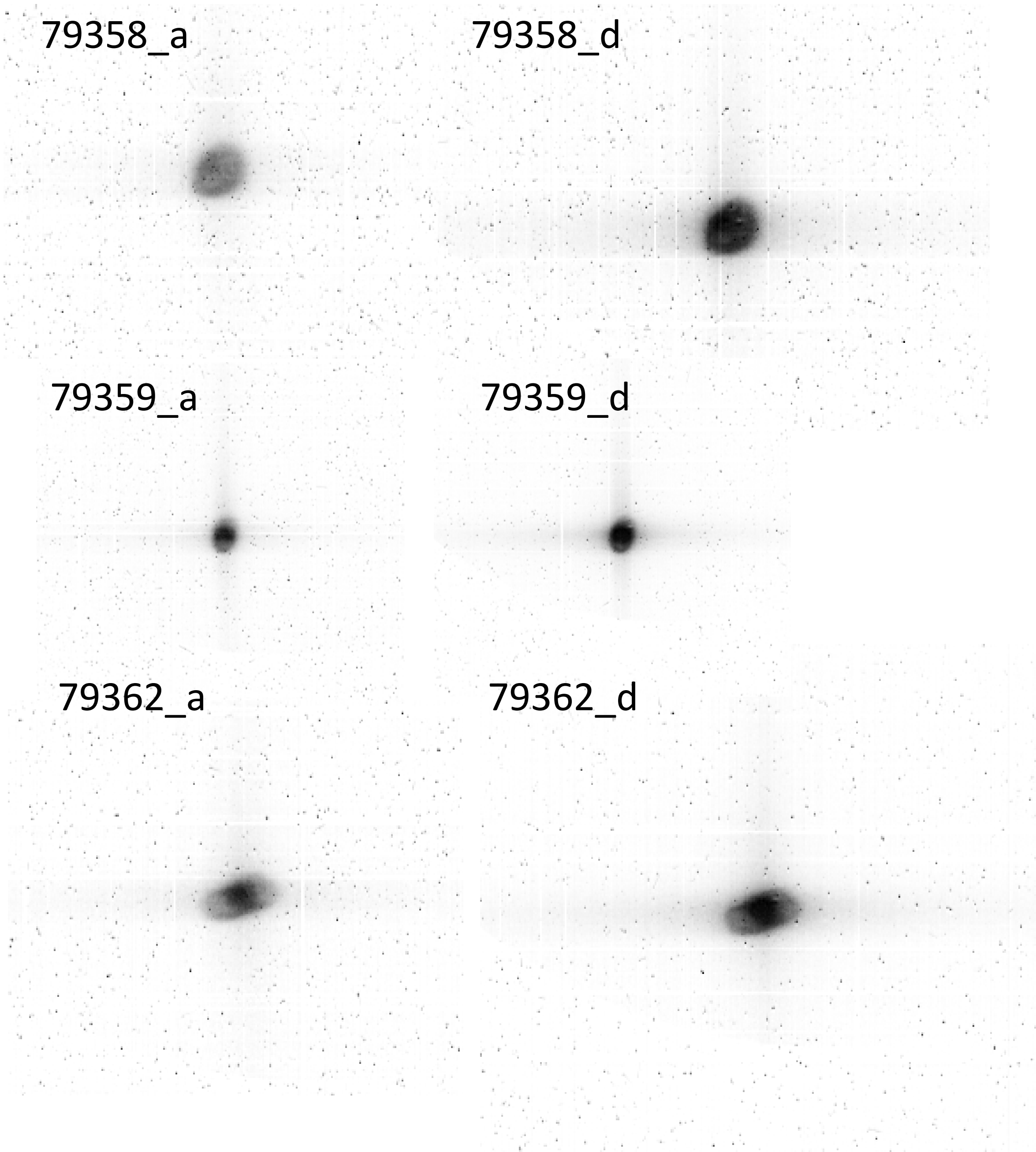


GMXI

symmetric

P2-P11

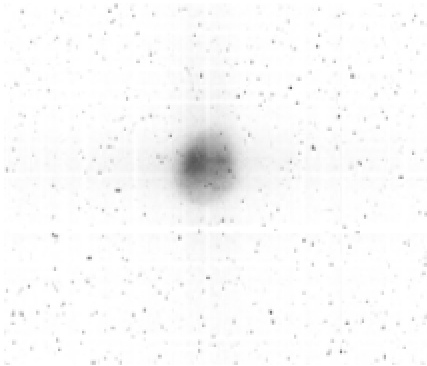
H8-H13



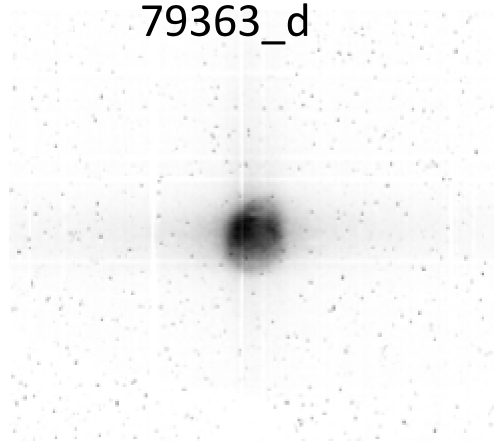
GMXI

P2-P11

79363_a

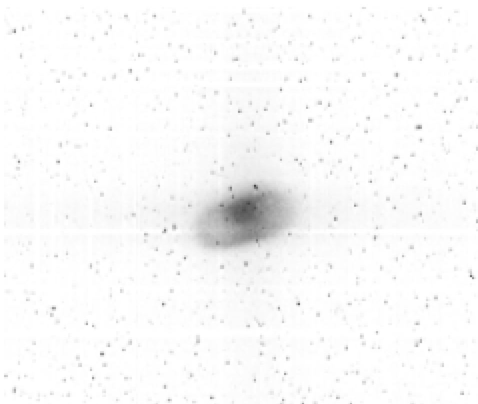


79363_d

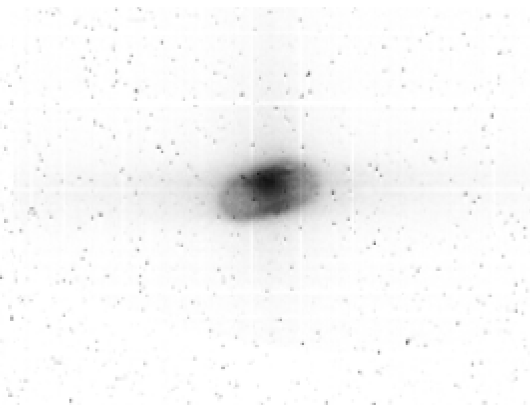


H8-H13

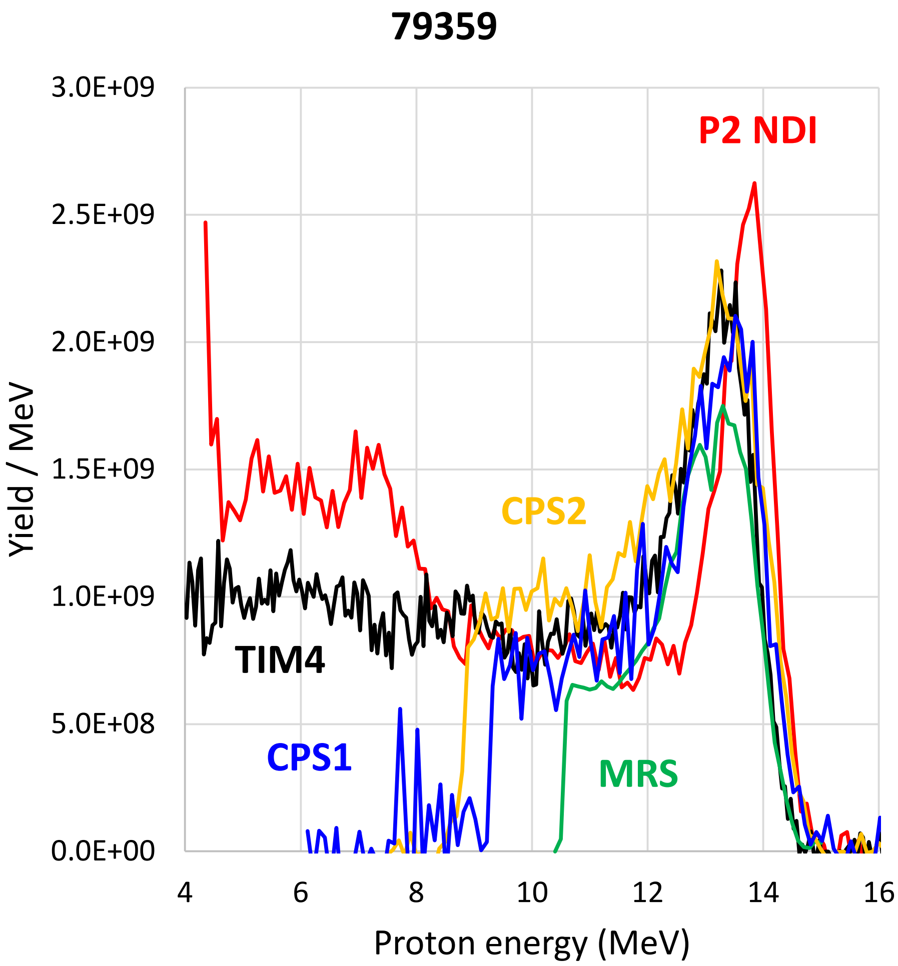
79364_a

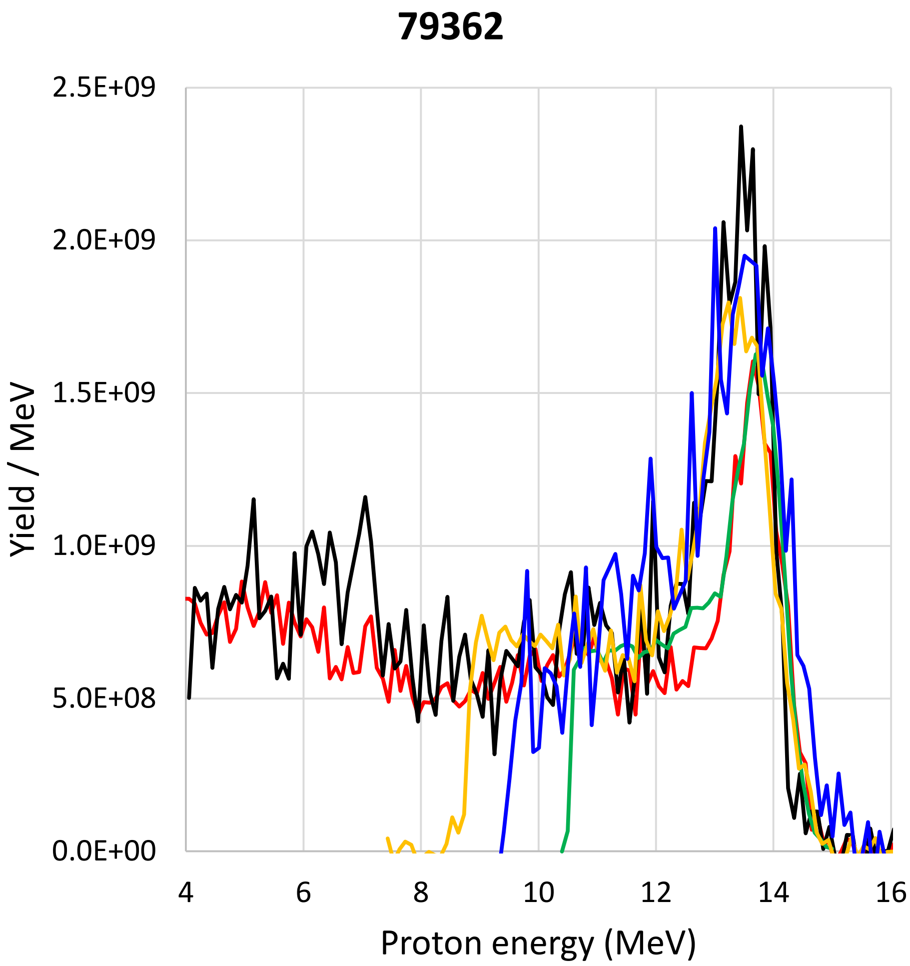


79364_d



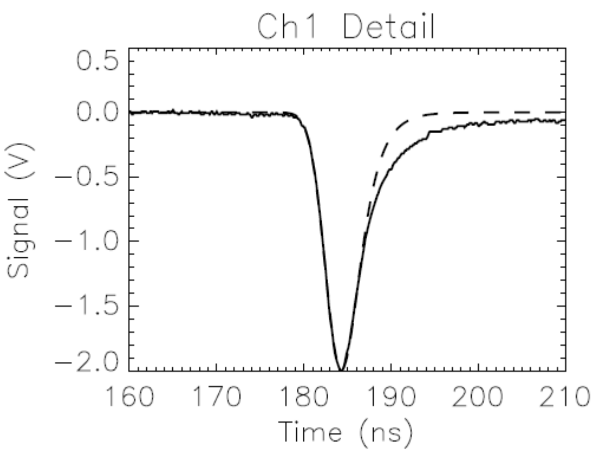
No significant ρR asymmetries are observed outside of error bars on 79359 and 79362 (only two shots analyzed so far)





Tion data for shot 79358 (symmetric)

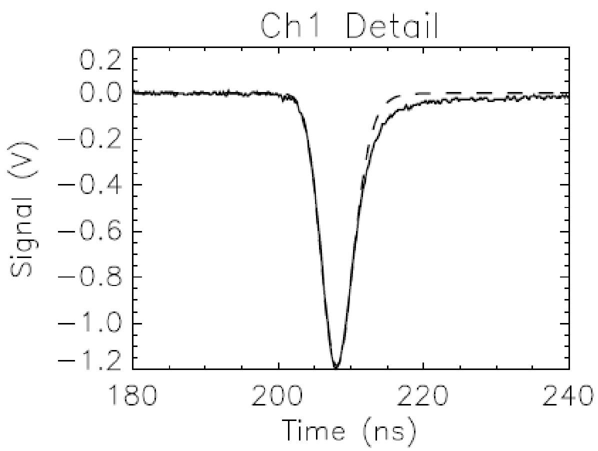
12mnTOF



Signal	Rise	Fall	FWHM	Time
−5.85	1.59	1.80	4.70	183.103

Chi = 0.27 Response = 0.75 ns
T_i = 5.84 Charge1 = 210.45pC

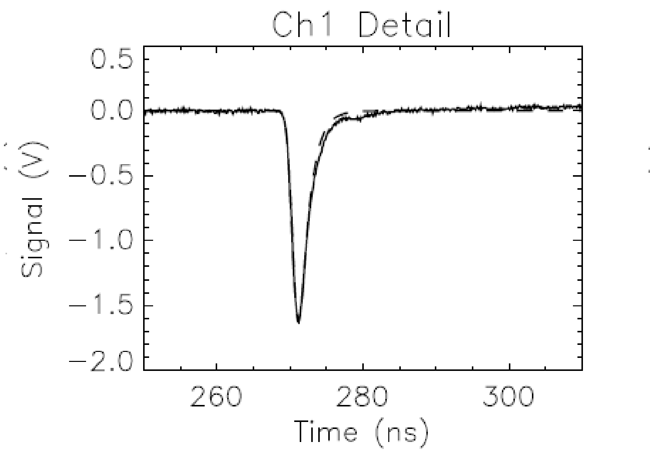
15.8mnTOF



Signal	Rise	Fall	FWHM	Time
−4.82	1.94	1.40	5.10	206.966

Chi = 0.27 Response = 0.75 ns
T_i = 5.45 Charge1 = 134.96pC

5mcvd

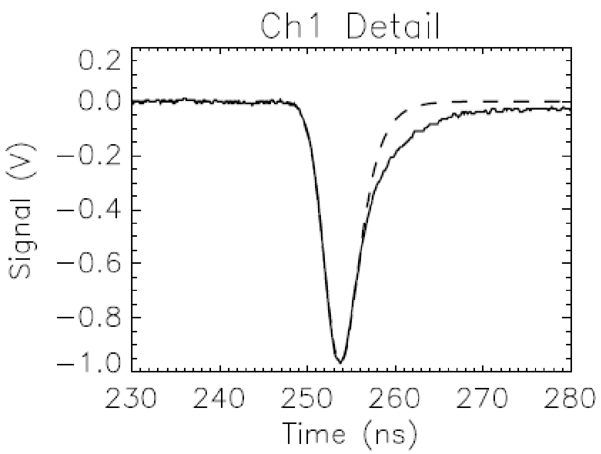


Signal	Rise	Fall	FWHM	Time
−3.40	0.66	1.33	2.30	270.483

Chi = 0.12 Response = 0.60 ns
T_i = 5.52 Charge1 = 90.54pC

Tion data for shot 79359 (P2-P11)

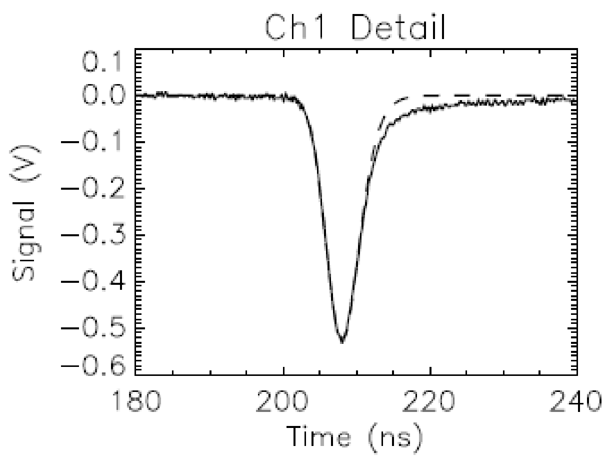
12mnTOF



Signal	Rise	Fall	FWHM	Time
−2.85	1.60	1.80	4.90	252.547

Chi = 0.34 Response = 0.75 ns
T_i = 5.93 Charge1 = 102.76p

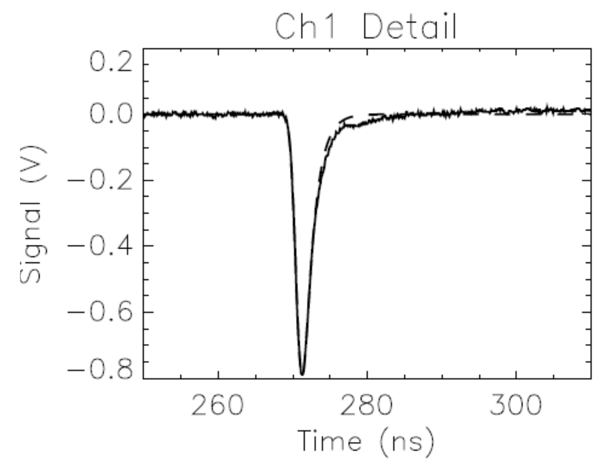
15.8mnTOF



Signal	Rise	Fall	FWHM	Time
−2.19	2.02	1.40	5.30	206.949

Chi = 0.31 Response = 0.75 ns
T_i = 5.89 Charge1 = 61.38pC

5mcvd

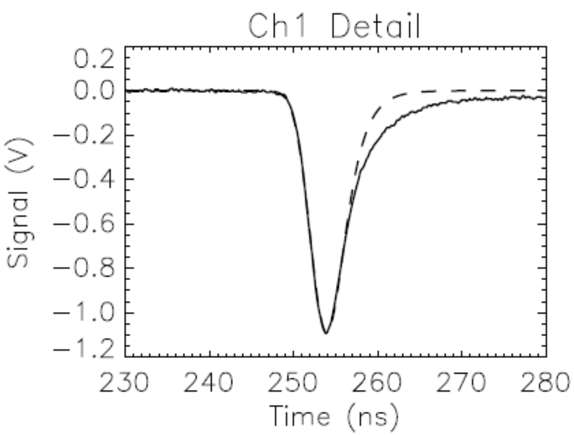


Signal	Rise	Fall	FWHM	Time
−1.66	0.66	1.33	2.30	270.563

Chi = 0.11 Response = 0.60 ns
T_i = 5.50 Charge1 = 44.26pC

Tion data for shot 79362 (H8-H13)

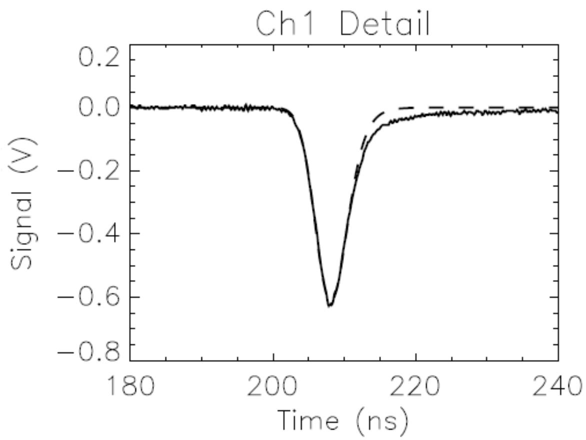
12mnTOF



Signal	Rise	Fall	FWHM	Time
−3.30	1.67	1.80	5.00	252.700

Chi = 0.34 Response = 0.75 ns
T_i = 6.48 Charge1 = 118.88pC

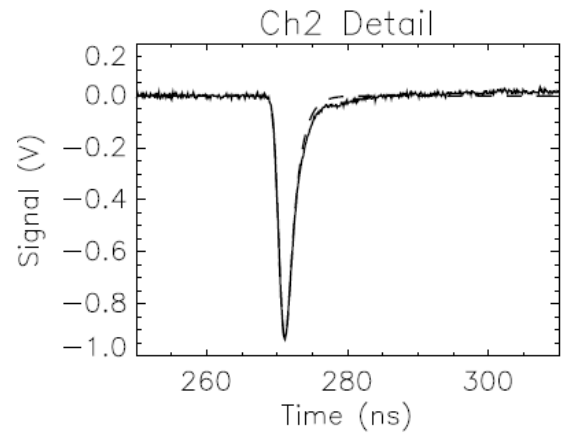
15.8mnTOF



Signal	Rise	Fall	FWHM	Time
−2.53	1.98	1.40	5.20	206.995

Chi = 0.35 Response = 0.75 ns
T_i = 5.67 Charge1 = 70.98pC

5mcvd

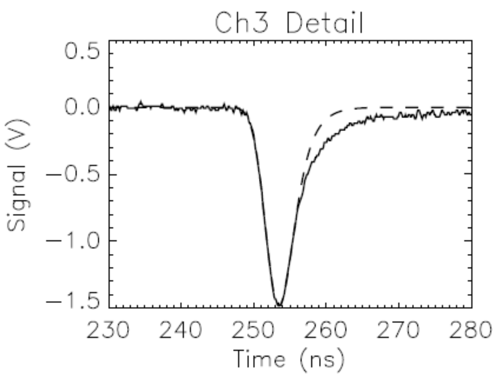


Signal	Rise	Fall	FWHM	Time
−1.97	0.67	1.33	2.30	270.391

Chi = 0.15 Response = 0.60 ns
T_i = 5.61 Charge2 = 52.29pC

Tion data for shot 79363 (P2-P11)

12mnTOF

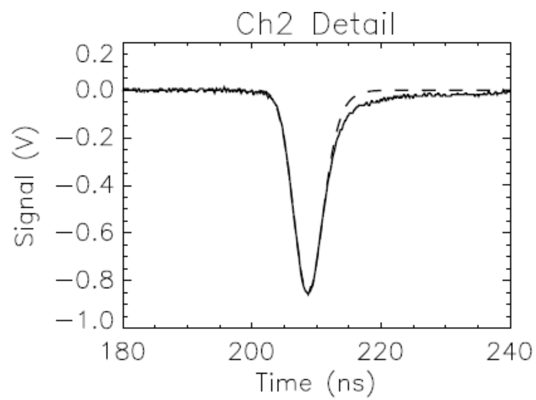


Signal	Rise	Fall	FWHM	Time
−4.36	1.59	1.80	4.80	252.272

Chi = 0.26 Response = 0.75 ns

T_i = 5.87 Charge2 = 157.09pC

15.8mnTOF

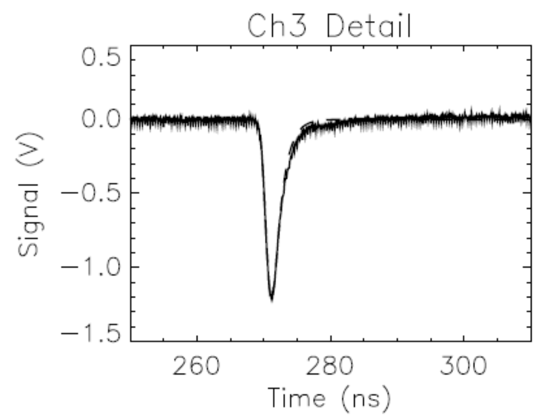


Signal	Rise	Fall	FWHM	Time
−3.58	2.02	1.40	5.40	207.558

Chi = 0.20 Response = 0.75 ns

T_i = 5.90 Charge2 = 100.34pC

5mcvd



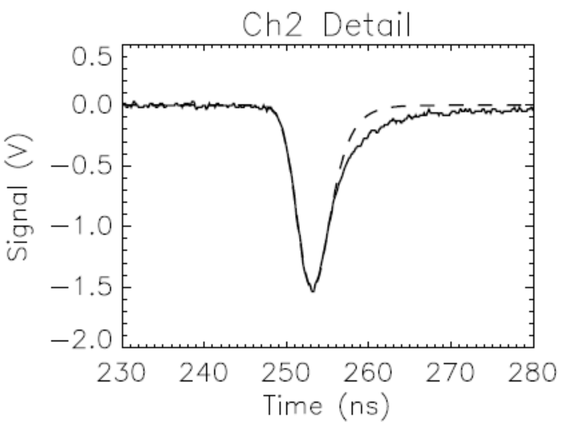
Signal	Rise	Fall	FWHM	Time
−2.55	0.66	1.33	2.40	270.474

Chi = 0.96 Response = 0.60 ns

T_i = 5.54 Charge2 = 67.83pC

Tion data for shot 79364 (H8-H13)

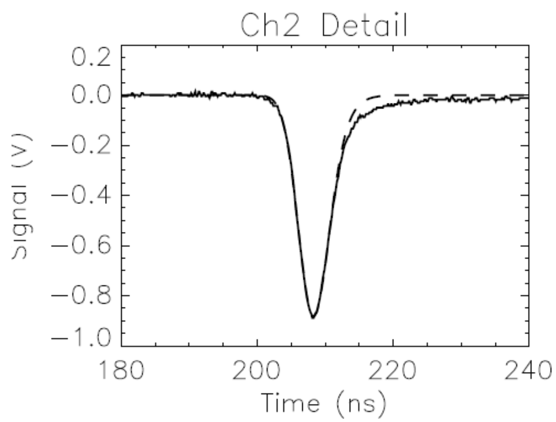
12mnTOF



Signal	Rise	Fall	FWHM	Time
−4.51	1.62	1.80	4.80	251.940

Chi = 0.35 Response = 0.75 ns
T_i = 6.06 Charge2 = 162.52pC

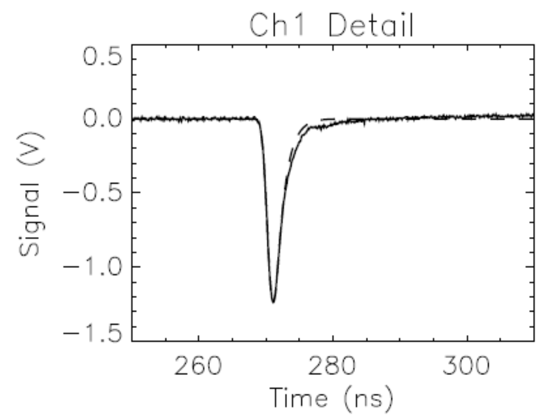
15.8mnTOF



Signal	Rise	Fall	FWHM	Time
−3.72	2.03	1.40	5.40	207.189

Chi = 0.24 Response = 0.75 ns
T_i = 5.99 Charge2 = 104.12pC

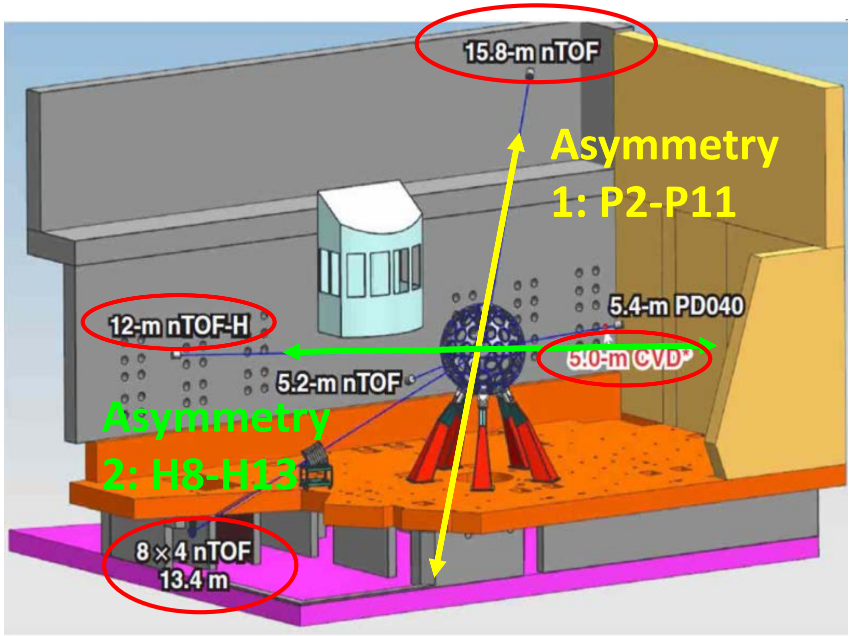
5mcvd



Signal	Rise	Fall	FWHM	Time
−2.62	0.67	1.33	2.40	270.404

Chi = 0.12 Response = 0.60 ns
T_i = 5.65 Charge1 = 69.67pC

Pre-shot simulations predicted a 2 keV min-max T_{ion} asymmetry between the 15.8mntof, 12mntof and 5mcvd lines-of-sight; measured Tions were isotropic



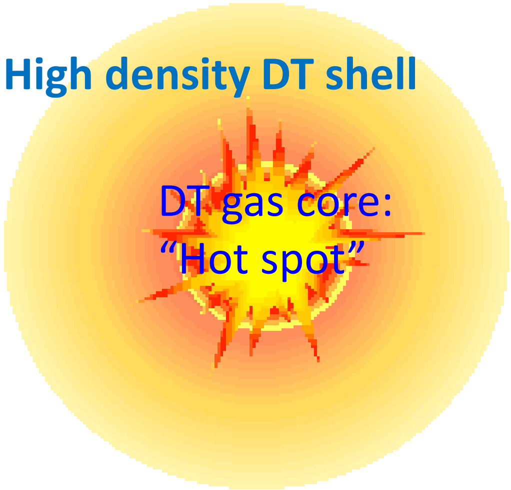
Result from the P2-P11 asymmetry 1 shots:

	DT Tion (keV)		
LOS	Simulated	79359	79363
no flow	4.14	-	-
15mntof	**6.94**	**5.89**	**5.90**
5mcvd	4.92	5.50	5.54
12mntof	**4.86**	**5.93**	**5.87**

Burn-averaged "T_{ion}" inferred from the width of the neutron spectrum includes contributions from thermal T_{ion} and any flows

$$\text{Apparent } T_{ion}\text{ DT} = T_{thermal}\text{ DT} + (m_n + m_\alpha)\cdot\sigma_v^2$$

$$\text{Apparent } T_{ion}\text{ DD} = T_{thermal}\text{ DD} + (m_n + m_{3He})\cdot\sigma_v^2$$



- Uniform (radial or turbulent) velocity would result in *isotropic* T_{ion} measurements
- Non-uniform velocity would result in *anisotropic* T_{ion} measurement

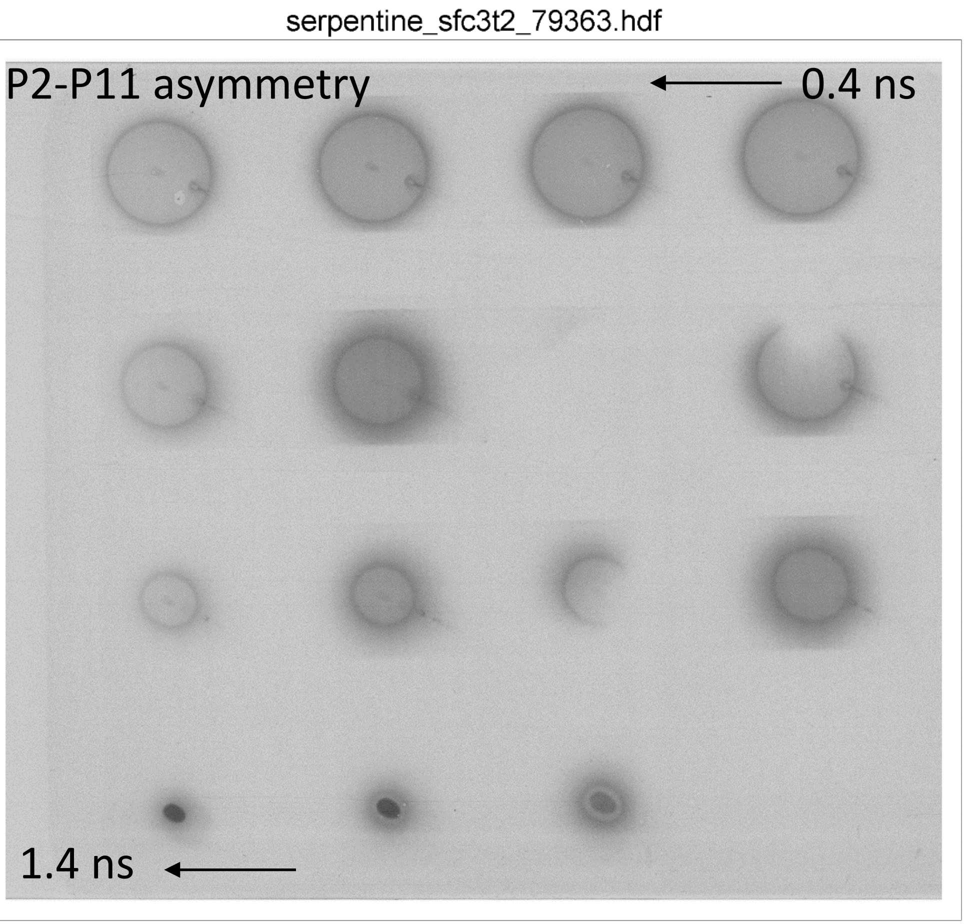
*T.J. Murphy, Phys.Plasmas **21**, 072701 (2014)*
*B. Appelbe and J. Chittenden, PPCF **53**, 045002 (2011)*

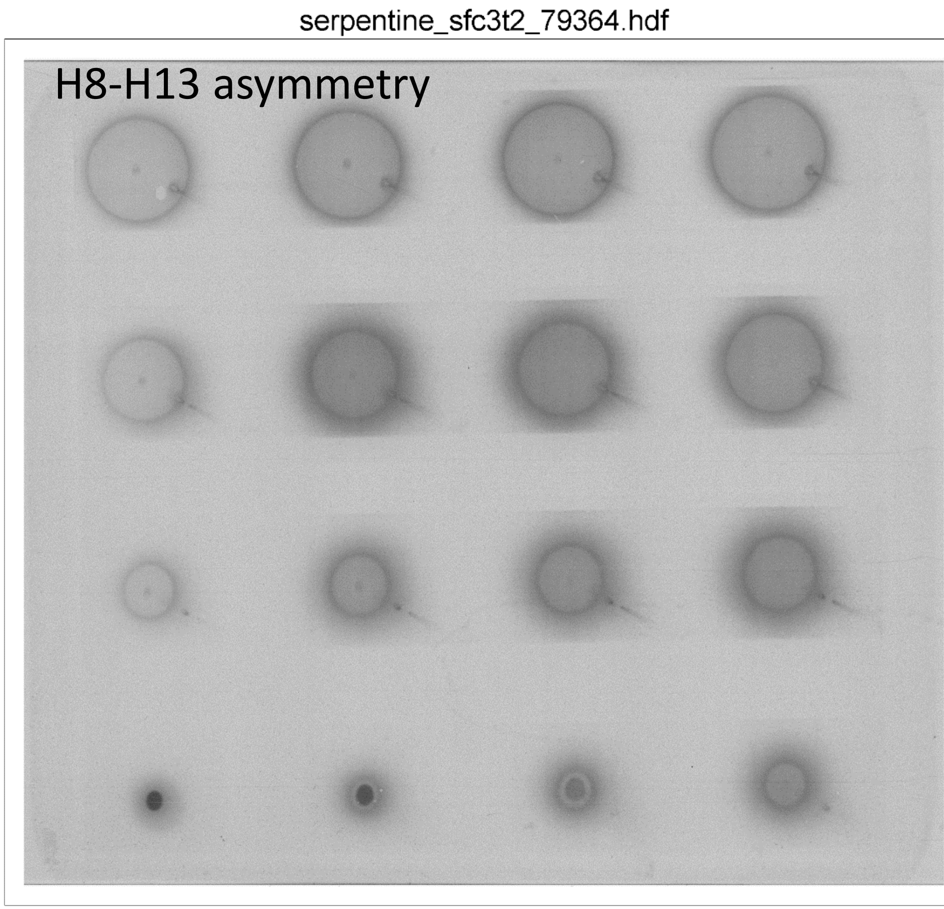
No significant T_{ion} asymmetry was seen for any of the three drive schemes

Shot	Drive type	5.0mcvd	15.8mntof	12mntof
79358	Symmetric	5.52	5.45	5.84
79359	P2-P11 asymmetry	5.50	5.89	5.93
79362	H8-H13 asymmetry	5.61	5.67	6.48
79363	P2-P11 asymmetry	5.54	5.90	5.87
79364	H8-H13 asymmetry	5.65	5.99	6.06

Simulation prediction for symmetric implosions: 5.5 keV including fluid velocity broadening, 5.23 keV without flow

Good SFC3 images were obtained on the last two shots





- SFC3 was fielded in TIM2, 79° away from the P2-P11 axis and 42° away from the H8-H13 axis
- We do not have good data on the symmetric shot due to a setup mistake

Start time: t_0 + 0.4 ns, time delay for each strip 0, 0.25, 0.5 and 0.75 ns