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

Core x-ray image: Strong P2 asymmetry
Experiment

KBFRAMED @ 1032 ps

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

nTOF Tion: No apparent asymmetry

<table>
<thead>
<tr>
<th>Time</th>
<th>Experiment</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>12mtof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.8mtof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0mcvd</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

**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 15.8m nTOF LOS, minimize for 12m nTOF LOS
• Asymmetry 2 was designed to flip asymmetry 1 to maximize the observable differences
Outline

- Setup

- Results
  - nTOF Tion
  - X-ray measurements (KBRA MeD, SFC3)
  - Yield
  - Bang time/burn duration (NTD)

- Interpretation/simulations (work in progress!)
No significant $T_{\text{ion}}$ asymmetry was seen for any of the three drive schemes
$T_{\text{ion}}$ 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 $T_{\text{ion}}$ enhancement in the 15.8m line-of-sight relative to symmetric – this goes in the right direction.

Results

<table>
<thead>
<tr>
<th>Apparent DT $T_{\text{ion}}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>79358 (symmetric)</td>
</tr>
<tr>
<td>79359 (P2-P11)</td>
</tr>
<tr>
<td>79363 (P2-P11)</td>
</tr>
<tr>
<td>Simulated (P2-P11)</td>
</tr>
</tbody>
</table>

Expect enhancement
The H8-H13 asymmetry shows a $T_{\text{ion}}$ 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: $2\sigma$ variation for warm implosions is $\sim 7\%$:

2015 room-temperature targets

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Average Tion (keV)</th>
<th>Dev. from average:</th>
<th>Shot Type</th>
<th>$\chi^2_{\text{red}}$ (symm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5mcvd</td>
<td>12mntof</td>
<td>15.8mntof</td>
</tr>
<tr>
<td>79358</td>
<td>5.62</td>
<td>1.9%</td>
<td>-3.7%</td>
<td>3.2%</td>
</tr>
<tr>
<td>79359</td>
<td>5.79</td>
<td>5.3%</td>
<td>-2.4%</td>
<td>-1.7%</td>
</tr>
<tr>
<td>79362</td>
<td>5.94</td>
<td>5.9%</td>
<td>-8.4%</td>
<td>4.7%</td>
</tr>
<tr>
<td>79363</td>
<td>5.78</td>
<td>4.4%</td>
<td>-1.5%</td>
<td>-2.0%</td>
</tr>
<tr>
<td>79364</td>
<td>5.91</td>
<td>4.7%</td>
<td>-2.4%</td>
<td>-1.3%</td>
</tr>
</tbody>
</table>
While no clear asymmetry is seen in the Tion data, clear asymmetry signatures are seen in x-ray images.

**KBFRAMED** 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

<table>
<thead>
<tr>
<th>Shot</th>
<th>Asymmetry</th>
<th>Symmetry</th>
<th>t (ns)</th>
<th>PSF Smoothed Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>79358</td>
<td>Symmetric</td>
<td></td>
<td>1.032</td>
<td>![Image]</td>
</tr>
<tr>
<td>79359</td>
<td>P2-P11</td>
<td></td>
<td>1.032</td>
<td>![Image]</td>
</tr>
<tr>
<td>79362</td>
<td>H8-H13</td>
<td></td>
<td>1.032</td>
<td>![Image]</td>
</tr>
<tr>
<td>79363</td>
<td>P2-P11</td>
<td></td>
<td>0.993</td>
<td>![Image]</td>
</tr>
<tr>
<td>79364</td>
<td>H8-H13</td>
<td></td>
<td></td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Analysis pending

"As round as it gets" fit semi major axis direction 31.4 degrees, which is within alignment uncertainty of the direction of P2. 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.

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.
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

Results

- 79358 (symmetric)
- 79362 (H8-H13)
- 79363 (P2-P11)
- 79364 (H8-H13)
Bang times/burn durations were measured with cryo NTD and came in very similar for all implosion types.

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 → cooling of the fuel before the asymmetry develops → 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

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**

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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.

**Interpretation**

Without radiation cooling in the CH

With radiation cooling in the CH

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

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

Simulation, no radiation loss

Simulation, with radiation loss

TIM2 framing camera measurement (should see 98% of the P2-P11 asymmetry)
The measured difference in yield between symmetric and asymmetric implosions is smaller than predicted.

Interpretation

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?

<table>
<thead>
<tr>
<th>Shot</th>
<th>Glue spot diameter [um]</th>
<th>length [um]</th>
<th>stalk length [um]</th>
</tr>
</thead>
<tbody>
<tr>
<td>79358</td>
<td>77.05</td>
<td>98.12</td>
<td>1063.75</td>
</tr>
<tr>
<td>79359</td>
<td>83.15</td>
<td>97.56</td>
<td>993.35</td>
</tr>
<tr>
<td>79362</td>
<td>61.53</td>
<td>85.37</td>
<td>1018.29</td>
</tr>
<tr>
<td>79363</td>
<td>56.54</td>
<td>80.93</td>
<td>973.39</td>
</tr>
<tr>
<td>79364</td>
<td>61.53</td>
<td>79.82</td>
<td>888.58</td>
</tr>
</tbody>
</table>

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

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

B. Haines, IFSA 2015
Simulations give a burn history similar to cryo-NTD measured

Notes:
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 $T_{\text{ion}}$ measurements – is there a P1?
  • $\rho R$ asymmetry measurements from D$_3$He 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 $\rho R$ asymmetries are observed outside of error bars on 79359 and 79362 (only two shots analyzed so far)
Observed energy differences correspond to $\rho R$ differences of $\sim 35-48 \text{ mg/cm}^2$ (not considering error bars), with the thinnest spot being in the P2 LOS.
Puzzle: Line-of-sight variations in OMEGA $T_{\text{ion}}$ measurements are substantially larger than LOS variations in NIF $T_{\text{ion}}$ measurements.

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.

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

H12 h13 h4 h8 p2

79358 symmetric

P2-P11

79359

H8-H13

79362
x-ray pinhole cameras

h12  h13  h4  h8  p2

79363  P2-P11

79364  H8-H13
symmetric

P2-P11

H8-H13
No significant $\rho R$ asymmetries are observed outside of error bars on 79359 and 79362 (only two shots analyzed so far)

<table>
<thead>
<tr>
<th>Proton energy (MeV)</th>
<th>Yield / MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>6</td>
<td>5.0E+08</td>
</tr>
<tr>
<td>8</td>
<td>1.0E+09</td>
</tr>
<tr>
<td>10</td>
<td>1.5E+09</td>
</tr>
<tr>
<td>12</td>
<td>2.0E+09</td>
</tr>
<tr>
<td>14</td>
<td>2.5E+09</td>
</tr>
<tr>
<td>16</td>
<td>3.0E+09</td>
</tr>
</tbody>
</table>

**Results**

- **79359**
  - TIM4
  - CPS1
  - CPS2
  - P2 NDI

- **79362**
  - TIM4
  - CPS1
  - CPS2
  - MRS
Tidion data for shot 79358 (symmetric)

- **12mnTOF**
  - Signal: $-5.85$
  - Rise: $1.59$
  - Fall: $1.80$
  - FWHM: $4.70$
  - Time: $183.103$
  - Chi: $0.27$
  - Response: $0.75$ ns
  - $T_i = 5.84$, Charge1 = $210.45pC$

- **15.8mnTOF**
  - Signal: $-4.82$
  - Rise: $1.94$
  - Fall: $1.40$
  - FWHM: $5.10$
  - Time: $206.966$
  - Chi: $0.27$
  - Response: $0.75$ ns
  - $T_i = 5.45$, Charge1 = $134.96pC$

- **5mcvd**
  - Signal: $-3.40$
  - Rise: $0.66$
  - Fall: $1.33$
  - FWHM: $2.30$
  - Time: $270.483$
  - Chi: $0.12$
  - Response: $0.60$ ns
  - $T_i = 5.52$, Charge1 = $90.54pC$
Tien data for shot 79359 (P2-P11)

12mnTOF

Ch1 Detail

Time (ns)

Signal (V)

Signal Rise Fall FWHM Time
-2.85 1.60 1.80 4.90 252.54

Chi = 0.34 Response = 0.75 ns

T_i = 5.93 Charge1 = 102.76 pC

15.8mnTOF

Ch1 Detail

Time (ns)

Signal (V)

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 = 61.38 pC

5mcvd

Ch1 Detail

Time (ns)

Signal (V)

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 = 44.26 pC
Tion data for shot 79362 (H8-H13)

12mnTOF

Ch1 Detail

Signal Rise Fall FWHM Time
−3.30 1.67 1.80 5.00 252.700

Chi = 0.34  Response = 0.75 ns
T_{ij} = 6.48  Charge1 = 118.88 pC

15.8mnTOF

Ch1 Detail

Signal Rise Fall FWHM Time
−2.53 1.98 1.40 5.20 206.995

Chi = 0.35  Response = 0.75 ns
T_{ij} = 5.67  Charge1 = 70.98 pC

5mcvd

Ch2 Detail

Signal Rise Fall FWHM Time
−1.97 0.67 1.33 2.30 270.391

Chi = 0.15  Response = 0.60 ns
T_{ij} = 5.61  Charge2 = 52.29 pC
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 = 157.09 pC

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 = 100.34 pC

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 = 67.83 pC
Tion data for shot 79364 (H8-H13)

12mnTOF

Ch2 Detail

<table>
<thead>
<tr>
<th>Signal</th>
<th>Rise</th>
<th>Fall</th>
<th>FWHM</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.51</td>
<td>1.62</td>
<td>1.80</td>
<td>4.80</td>
<td>251.940</td>
</tr>
<tr>
<td>Chi</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>T_i</td>
<td>6.06</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Charge2</td>
<td>162.52pC</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

15.8mnTOF

Ch2 Detail

<table>
<thead>
<tr>
<th>Signal</th>
<th>Rise</th>
<th>Fall</th>
<th>FWHM</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.72</td>
<td>2.03</td>
<td>1.40</td>
<td>5.40</td>
<td>207.189</td>
</tr>
<tr>
<td>Chi</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_i</td>
<td>5.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge2</td>
<td>104.12pC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5mcvd

Ch1 Detail

<table>
<thead>
<tr>
<th>Signal</th>
<th>Rise</th>
<th>Fall</th>
<th>FWHM</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.62</td>
<td>0.67</td>
<td>1.33</td>
<td>2.40</td>
<td>270.404</td>
</tr>
<tr>
<td>Chi</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_i</td>
<td>5.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge1</td>
<td>69.67pC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>LOS</th>
<th>DT $T_{ion}$ (keV)</th>
<th>Simulated</th>
<th>79359</th>
<th>79363</th>
</tr>
</thead>
<tbody>
<tr>
<td>no flow</td>
<td></td>
<td>4.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15mntof</td>
<td></td>
<td>6.94</td>
<td>5.89</td>
<td>5.90</td>
</tr>
<tr>
<td>5mcvd</td>
<td></td>
<td>4.92</td>
<td>5.50</td>
<td>5.54</td>
</tr>
<tr>
<td>12mntof</td>
<td></td>
<td>4.86</td>
<td>5.93</td>
<td>5.87</td>
</tr>
</tbody>
</table>
Burn-averaged “$T_{\text{ion}}$” inferred from the width of the neutron spectrum includes contributions from thermal $T_{\text{ion}}$ and any flows

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

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

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

T.J. Murphy, Phys. Plasmas 21, 072701 (2014)
B. Appelbe and J. Chittenden, PPCF 53, 045002 (2011)
No significant $T_{\text{ion}}$ asymmetry was seen for any of the three drive schemes

<table>
<thead>
<tr>
<th>Shot</th>
<th>Drive type</th>
<th>5.0mcvd</th>
<th>15.8mntof</th>
<th>12mntof</th>
</tr>
</thead>
<tbody>
<tr>
<td>79358</td>
<td>Symmetric</td>
<td>5.52</td>
<td>5.45</td>
<td>5.84</td>
</tr>
<tr>
<td>79359</td>
<td>P2-P11 asymmetry</td>
<td>5.50</td>
<td>5.89</td>
<td>5.93</td>
</tr>
<tr>
<td>79362</td>
<td>H8-H13 asymmetry</td>
<td>5.61</td>
<td>5.67</td>
<td>6.48</td>
</tr>
<tr>
<td>79363</td>
<td>P2-P11 asymmetry</td>
<td>5.54</td>
<td>5.90</td>
<td>5.87</td>
</tr>
<tr>
<td>79364</td>
<td>H8-H13 asymmetry</td>
<td>5.65</td>
<td>5.99</td>
<td>6.06</td>
</tr>
</tbody>
</table>

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