NIF Hohlraum Experiments at Room Temperature, a.k.a. “Warm Shots”

Anomalous Absorption Meeting
11 July 2013

D. J. Strozzi, D. E. Hinkel, J. E. Ralph, T. Ma,
D. A. Callahan, J. L. Kline, J. D. Moody, O. Jones, J. R. Rygg

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

Why warm instead of cryogenic (cryo)?

Physics:

- San Ramon 2012 workshop: hotter hohlraum plasma could reduce inner-beam SRS
- Hohlraum gas fill affects laser propagation: higher Z absorbs more via inverse bremsstrahlung
- Only H, He, and some Ne gas fills don't freeze in cryo conditions
- Warm shots allow range of gas fills, e.g. hydrocarbons

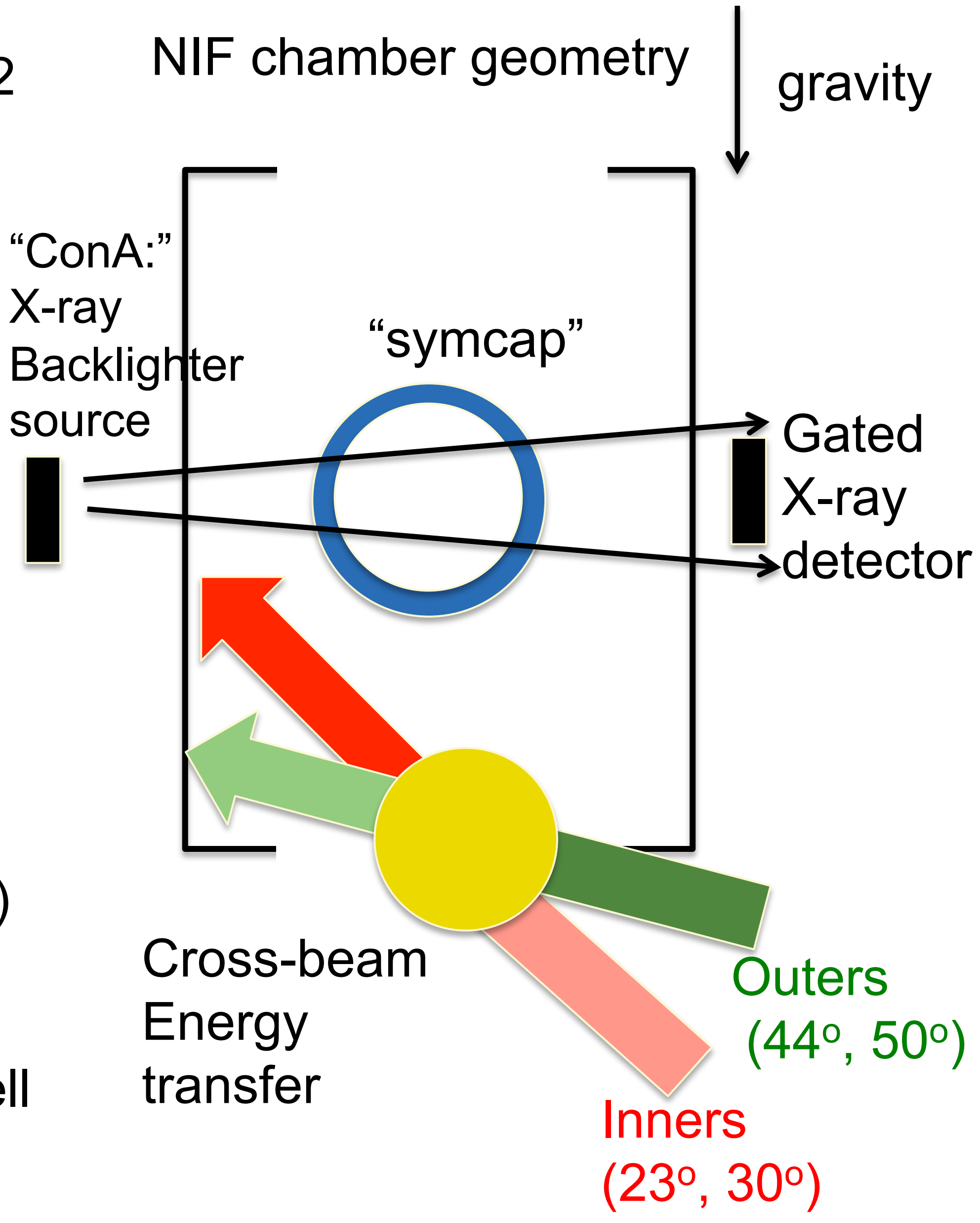
Practical: more shots

- Warm shots easier to field, shorter shot cycle
- Cheaper targets – no cryo hardware

Fielding warm shots

- Hohlraum fill gas: warm shots have 0.82 mg/cc neopentane (C_5H_{12})
  - Same initial electron density as standard cryo fill 0.96 mg/cc He
  - Windows can't hold same He density warm

- Capsule fill gas: propane (C_3H_8), or deuterated (C_3D_8) for neutrons
  - H, He diffuse through plastic at room temperature
  - Could Al-coat capsule, or continuously pump gas (T. Parham)
  - Other ablators (Be, B_4C, diamond) may not leak
  - More radiation, cooler hot spot, shell emission in x-ray images



We have (almost*) successfully commissioned the NIF warm hohlraum platform

2009: first two symcaps!
- Less inner SRS, more outer SBS, less pancaked at same $\Delta\lambda$ than cryo

2012-2013 symcaps: walked up in energy/power: avoid laser SBS damage
N121226: 821 kJ, 292 TW, $\Delta\lambda$ = 1.5 Å (low transfer)
  Comparable inner SRS and outer SBS power
  Delivered inner / total power ~ 1/3 -> large pancake
N130125: higher power: 946 kJ, 368 TW
  $\Delta\lambda$ = 3.5 Å: round hotspot! This $\Delta\lambda$ used subsequently
N130217: extend peak power: 1.26 MJ, 362 TW
  up-down asymmetry (potential alignment issues)
N130405: repeat 130217, first C_3D_8 capsule fill, round hotspot

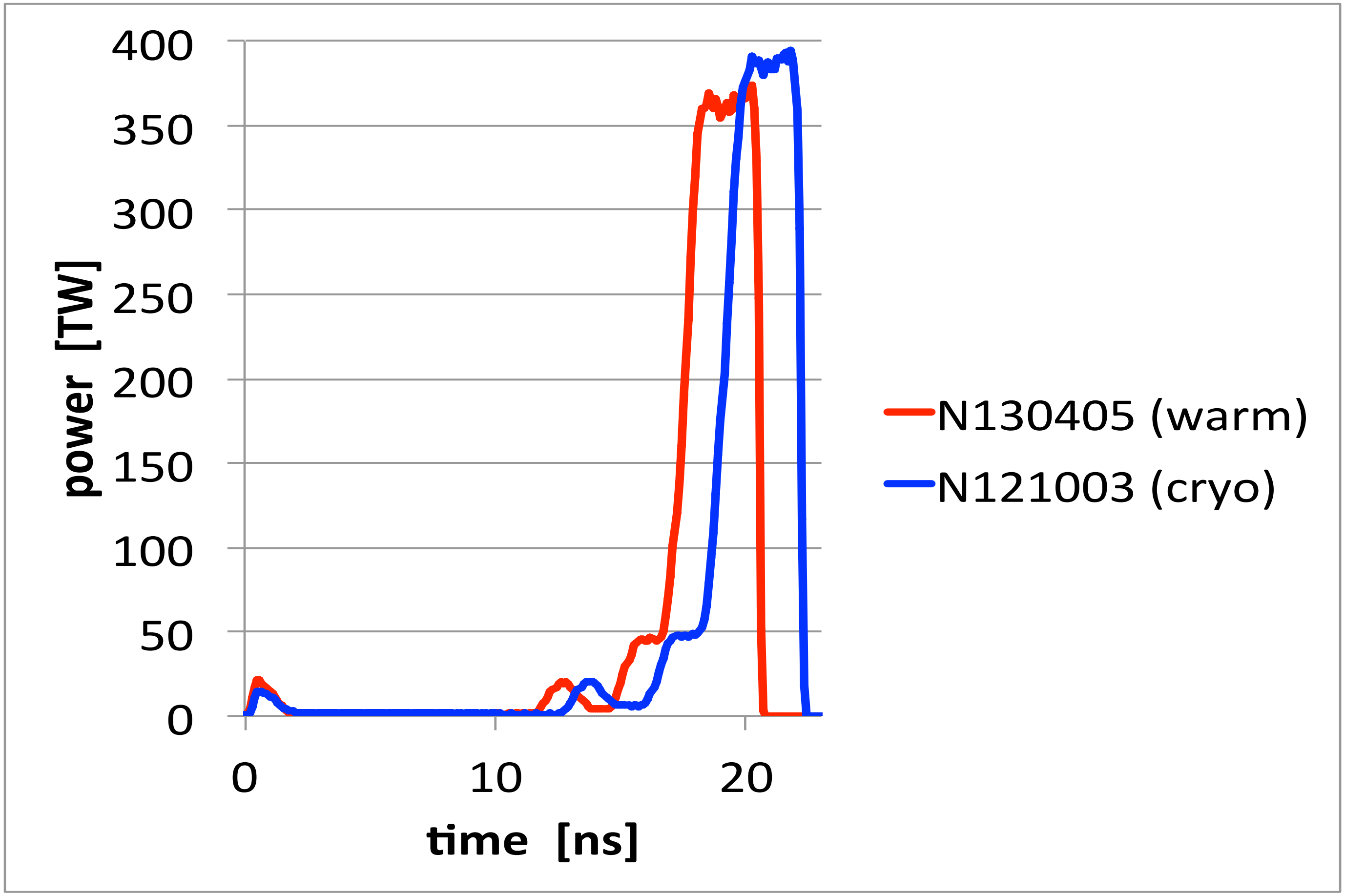
2013 2D ConA's:
N130509: -300 um hohlraum: large in-flight diamond (P_4>0)
N130627: +700 um: reduced in-flight P_4
  0.5x capsule fill pressure to reduce self-emission in ConA images

* Warm keyhole shot would verify shock strengths and timings (H. Robey)

Warm shot performance different from cryo

- Backscatter: Warms have less inner-beam SRS, more outer-beam SBS
- P_2 shape: Warm hotspots are close to round with less cross-beam energy transfer
- The P_4 question: warm in-flight diamond shape, square hotspot
  - Lengthening hohlraum reduces in-flight diamond – both warm and cryo
  - Cryo shots have diamond in-flight and hotspot
  - Hydra simulations: both warm and cryo diamond in-flight, square hotspot
- Nuclear:
  - Deuterated propane C_3D_8 -> up to 2.6E11 neutrons
  - T_{ion} up to 1.7 keV

Warm laser pulse similar to cryo: picket higher by ~20% to burn through higher Z hohlraum gas

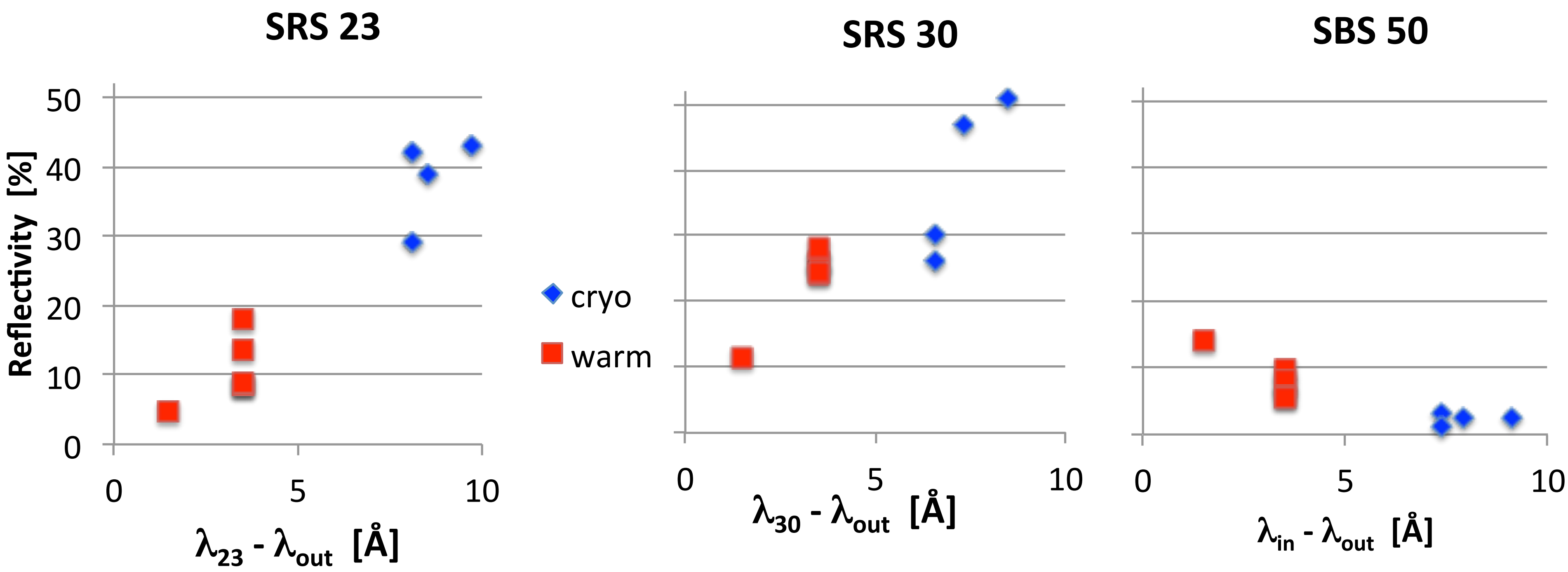


- First two shots used lower peak power or duration – avoid backscatter laser damage
- Warm trough shorter due to starting from a different comparison shot

BACKSCATTER

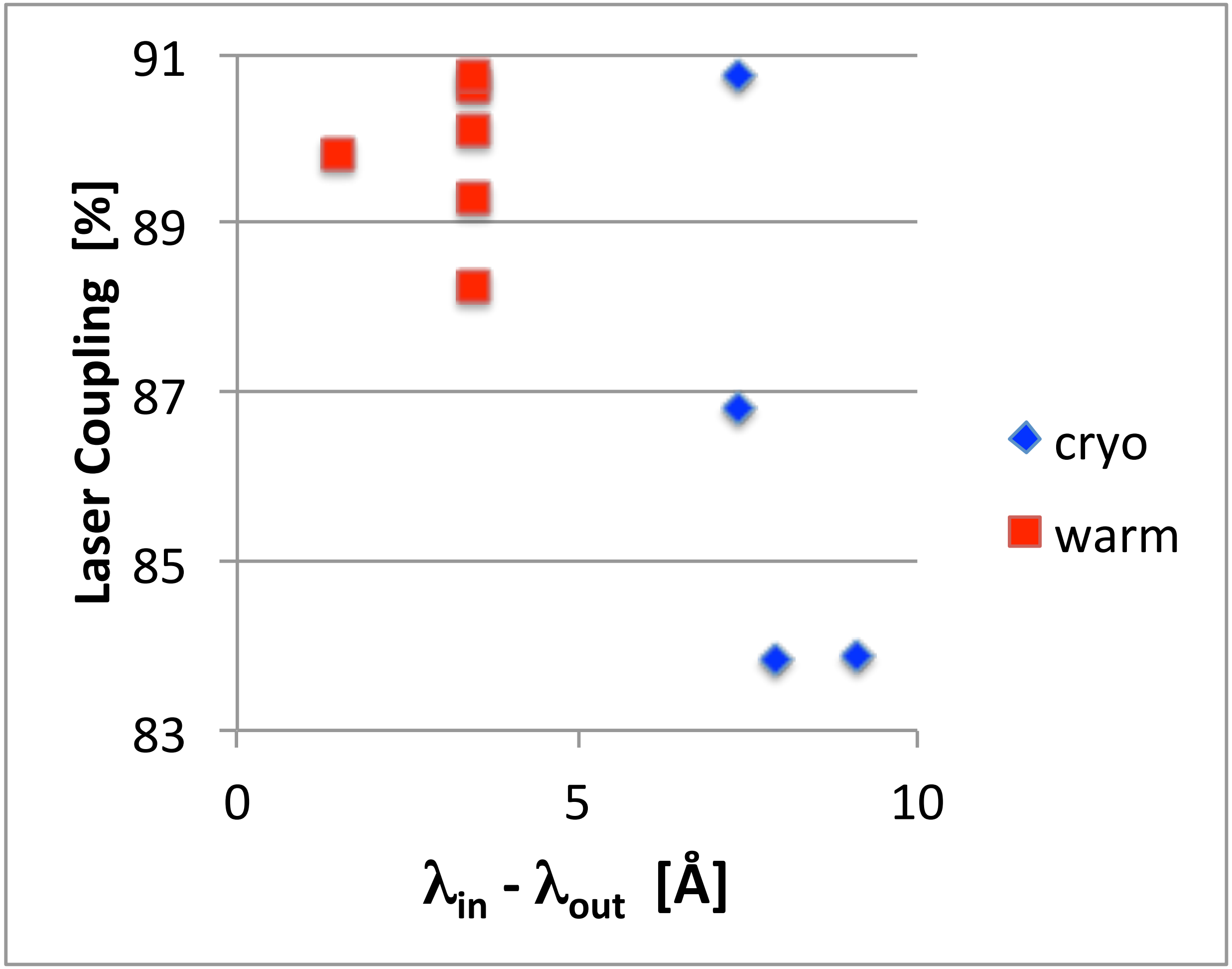
Warm shots have less inner SRS, more outer SBS, than cryos

- Difference partly (entirely?) due to less Δλ in warms
- 2009: similar changes just due to hohlraum gas composition: same pulse, same Δλ, just changed gas fill



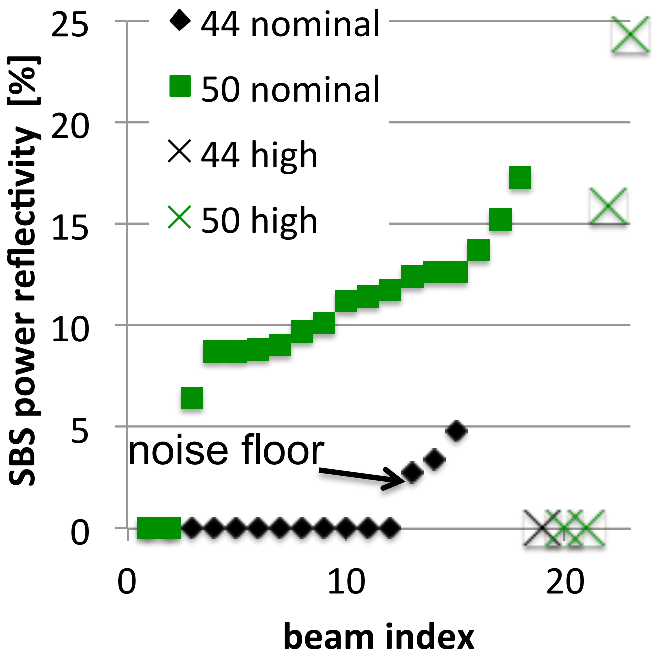
Warm shots have more laser coupling than cryos

Coupling = incident - backscattered

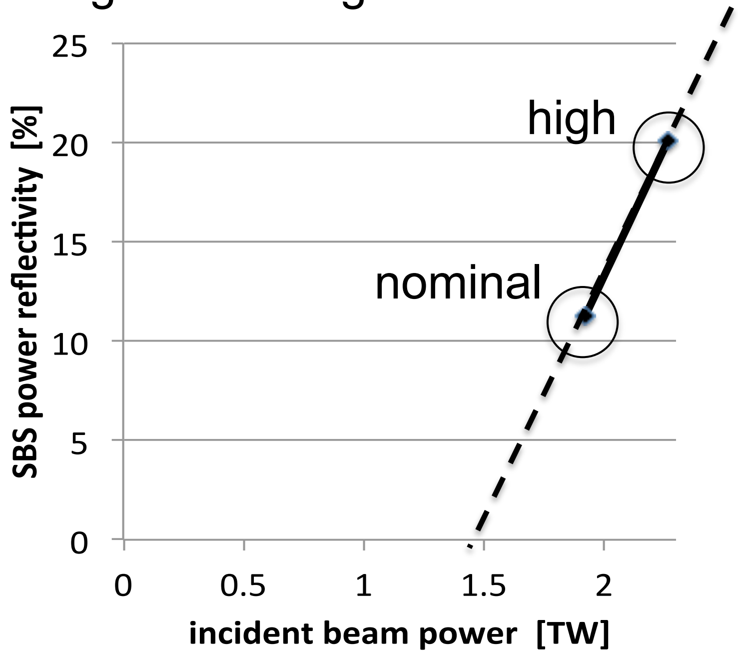


Outer beam SBS: DrD sensors show more on cone 50 than 44, and give power scaling

N130125:
970 kJ shot



"Tang curve:" avg. nonzero 50's

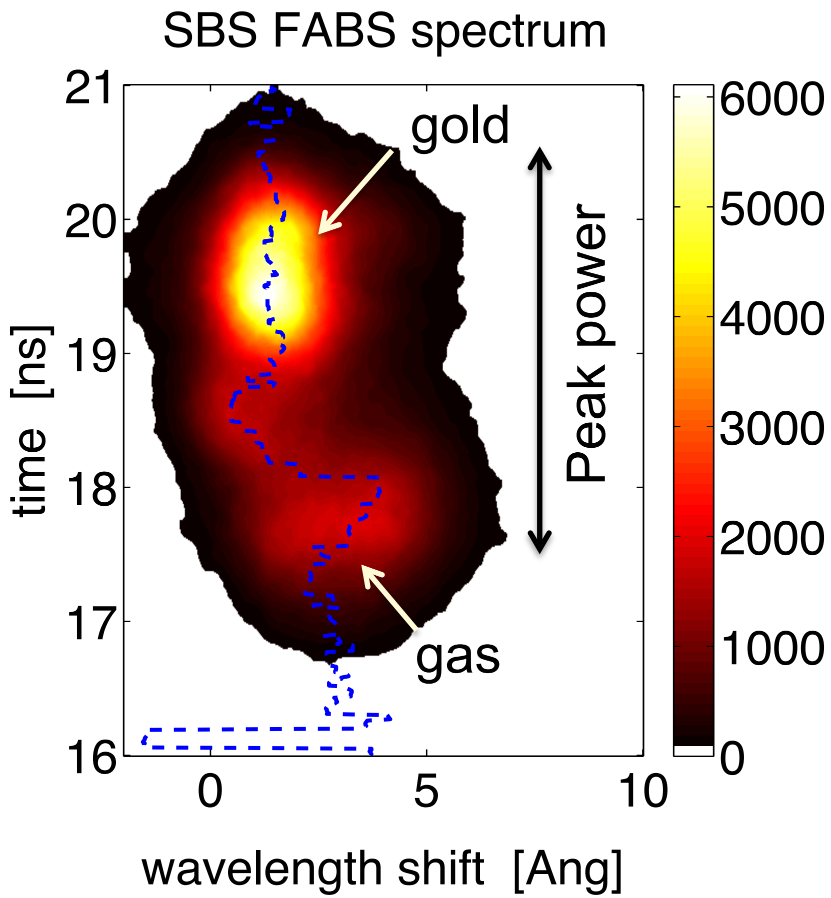


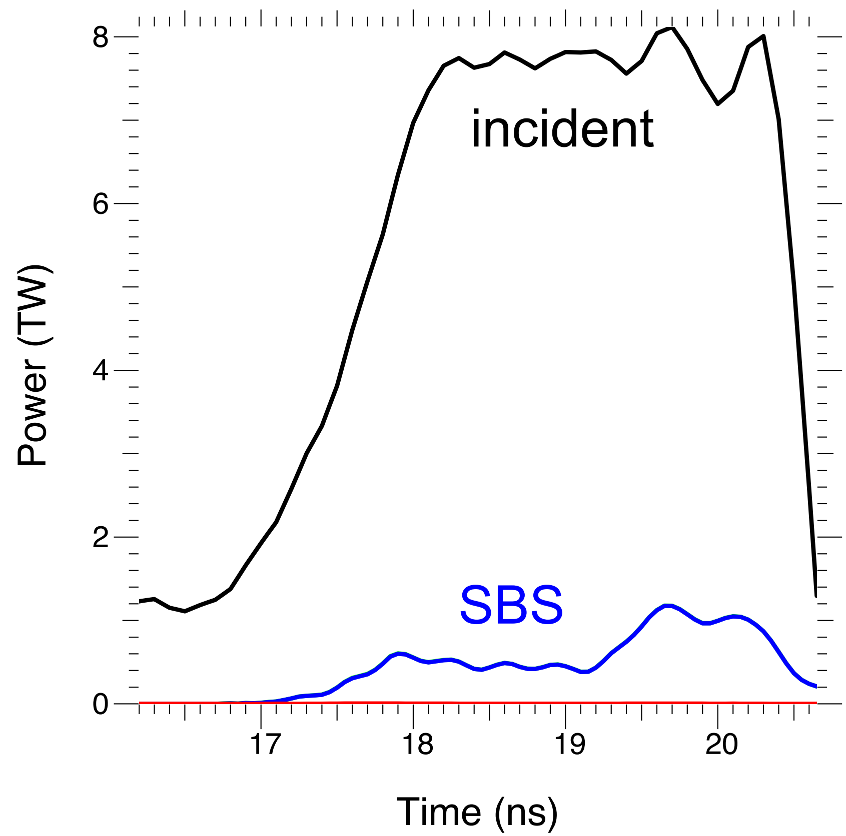
- DrD = drive diagnostic sensor - at least one beam in each quad
  - 3ω power history - forward and backward (separated in time)
- N130125: one quad on each cone had 18% higher power: power scaling on one shot!

- Why more SBS on 50's than 44's?
  - 50 focal spot smaller -> higher intensity
  - Cross-beam energy transfer calculations: post-transfer power on 50's > 44's
  - Could be pure intensity scaling; plasma conditions may also play role

SBS on 50° outer cone

N130405:
1.3 MJ shot

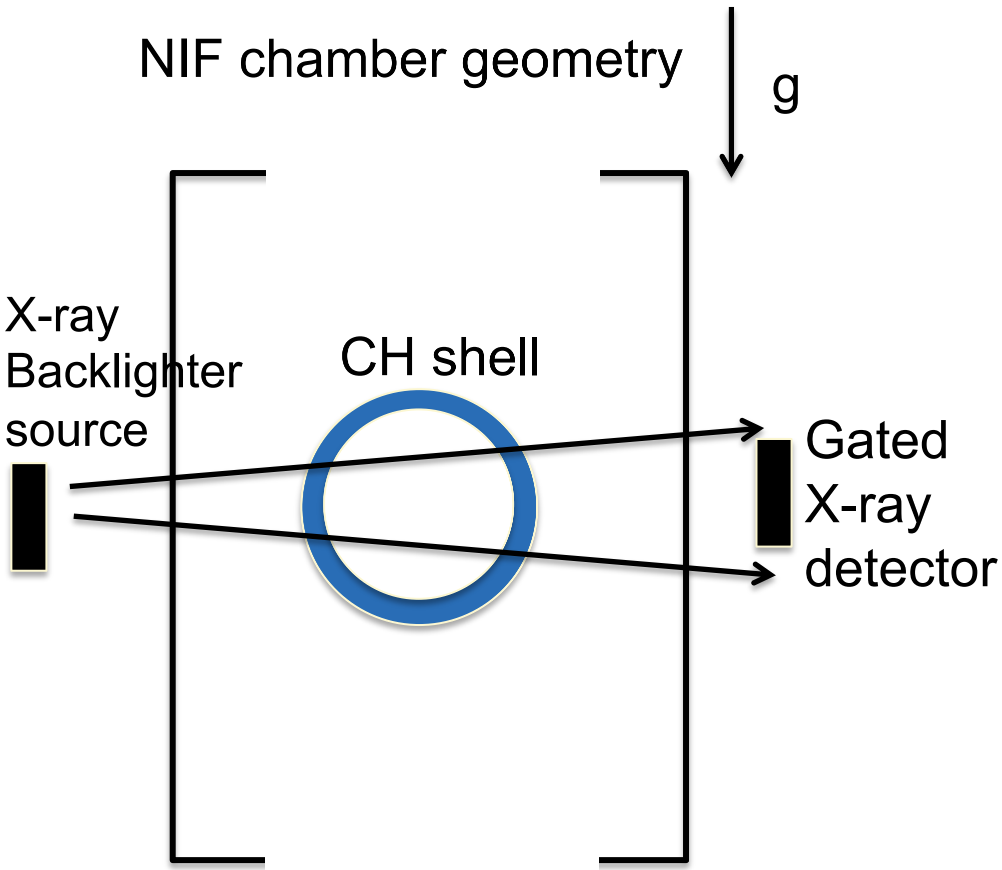




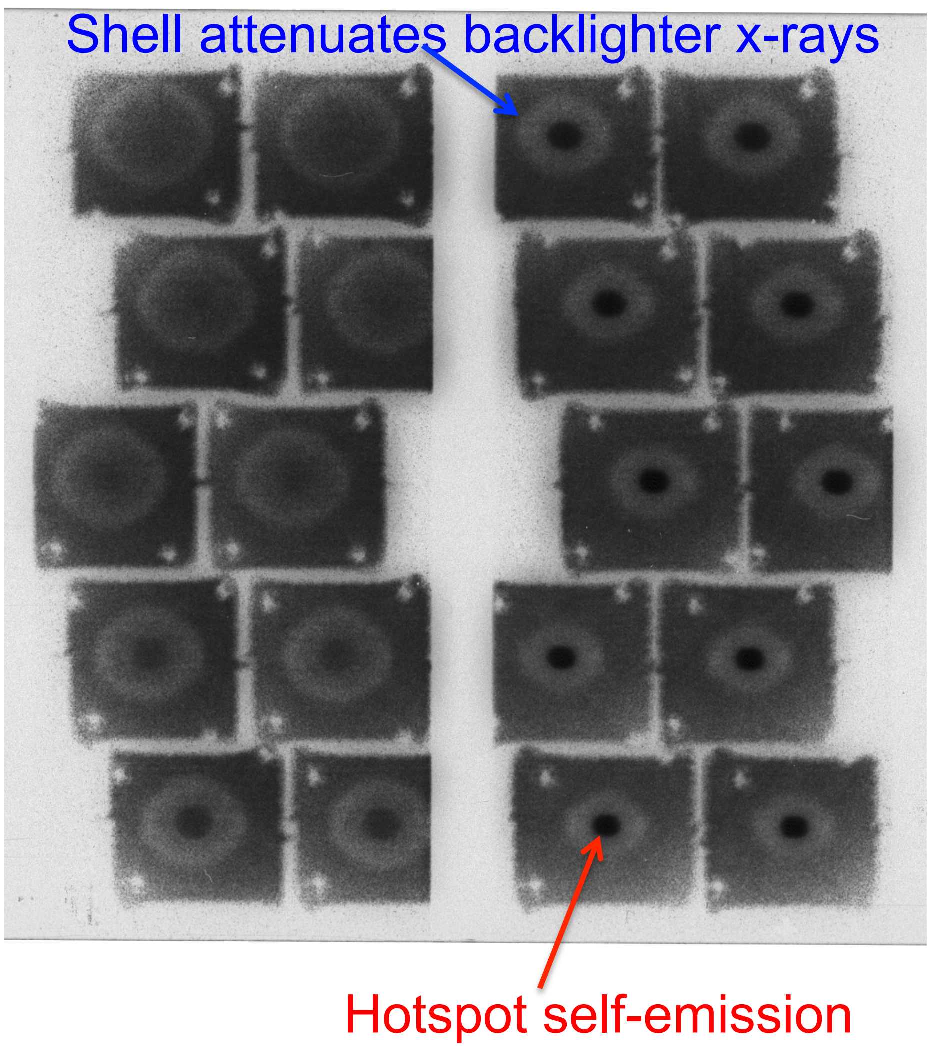
- Cryo shots show some outer SBS late in time, esp. for longer pulses or high power
- Warm platform good for studying outer SBS and mitigation – cheaper, reproducible

IN-FLIGHT SHELL SHAPE

Convergent ablator "ConA" shots: backlit radiographs of shell in-flight (before hotspot formation)



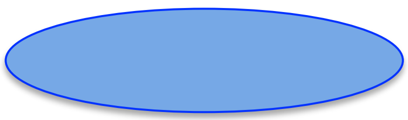
N130627 (warm 2D ConA)



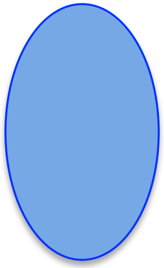
Implosion symmetry expressed with Legendre modes, mut be controlled for ICF to work

NIF chamber geometry | g

P_2 mode: determined by final (post-transfer, post-backscatter) laser cone fraction

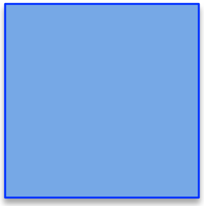


$P_2 < 0$: pancake*: outers too strong

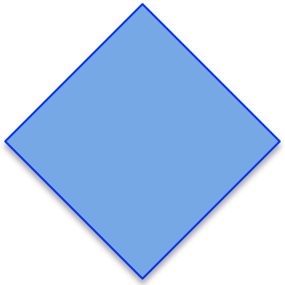


$P_2 > 0$: Sausage: inners too strong

P_4 mode: determined by geometry: hohlraum length, beam pointing



$P_4 < 0$: square: corners out



$P_4 > 0$: diamond: corners in

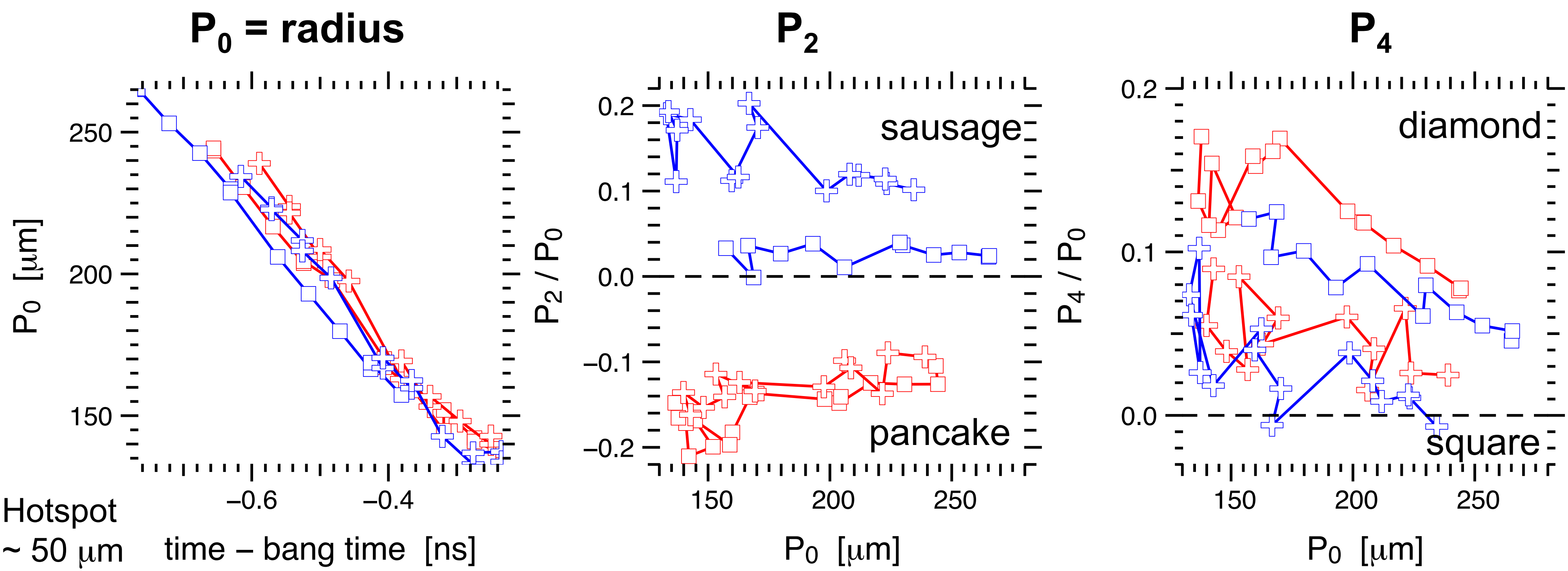
*Oblate, prolate are ancient Etruscan for pancake, sausage

NIF

In-flight shape (ConA): warms are more pancaked ($P_2<0$), slightly more diamond ($P_4>0$) than cryo

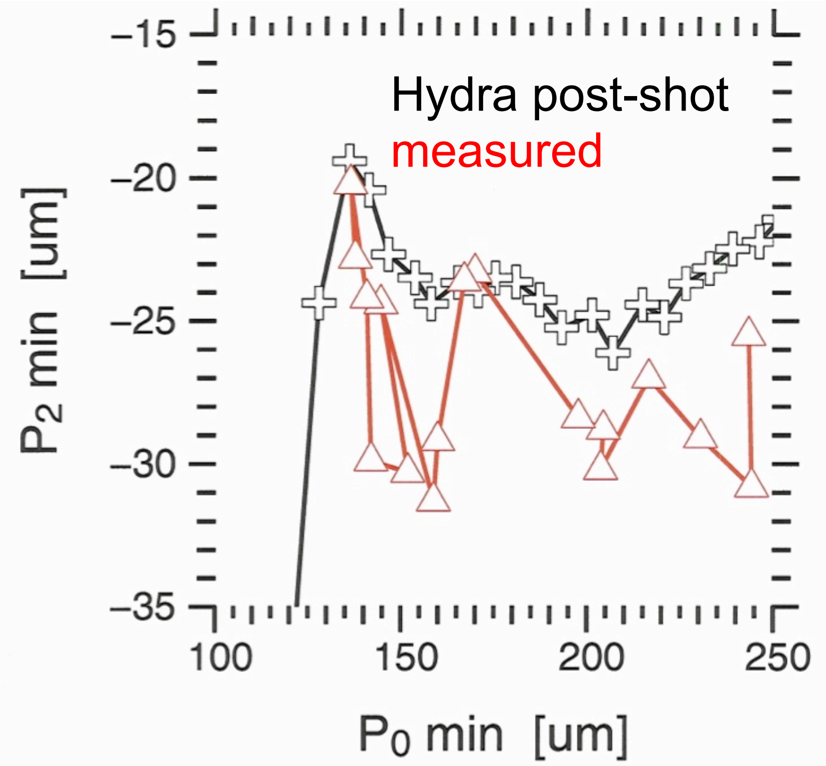
Red: warm
Blue: cryo
□: L_{hohl} -300 μm
✚: L_{hohl} +700 μm

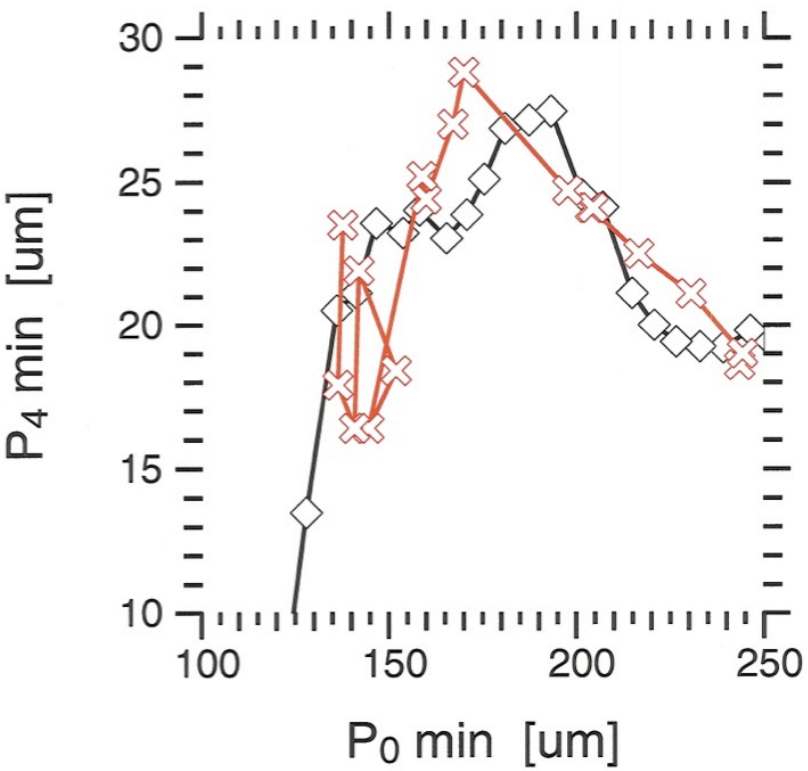
□: N121219: cryo -300 μm
✚: N130211: cryo +700 μm
□: N130509: warm -300 μm
✚: N130627: warm +700 μm



- Longer hohlraum reduces P_4 in both warms and cryos – as Hydra predicts
- Program has adopted +700 μm as standard hohlraum

N130509: warm 2D ConA, L_{hohl} -300 um: Hydra and data agree on P_4, so-so on P_2

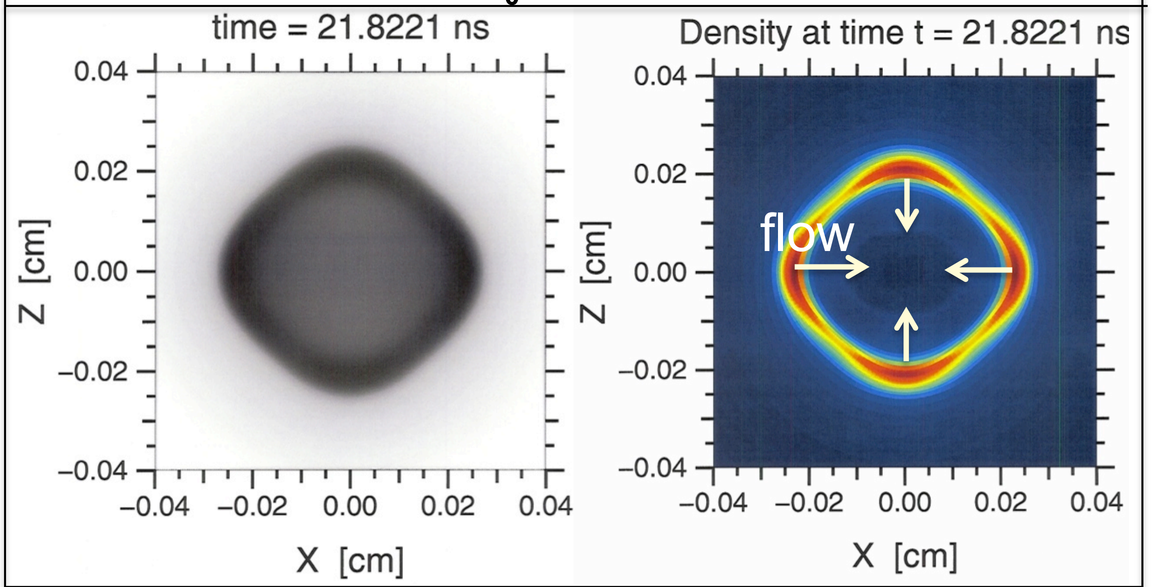




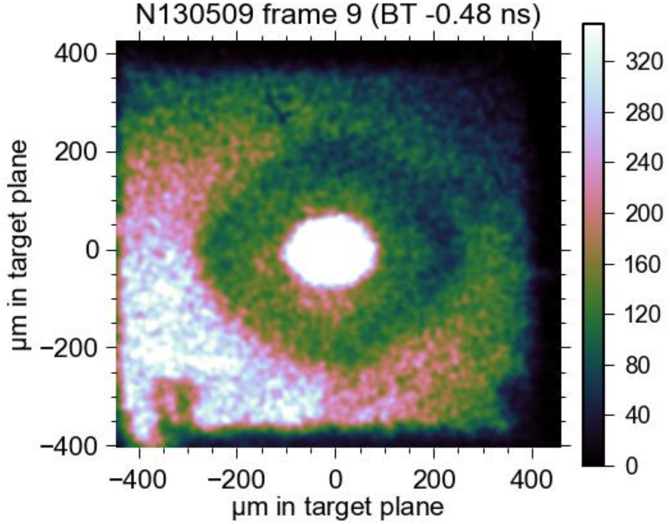
- Hydra P_2 controlled by $\delta n/n$ saturation clamp in cross-beam energy transfer. Lower value would agree better with data.
- Inline Hydra model, including ion heating, under investigation. [P. Michel et al., PRL 2012]

N130509: simulations show diamond P_4 in shell density, which leads to square hotspot

Post-shot image and density
P_0 = 200 um



Measured data:
P_0 limb min = 197 um

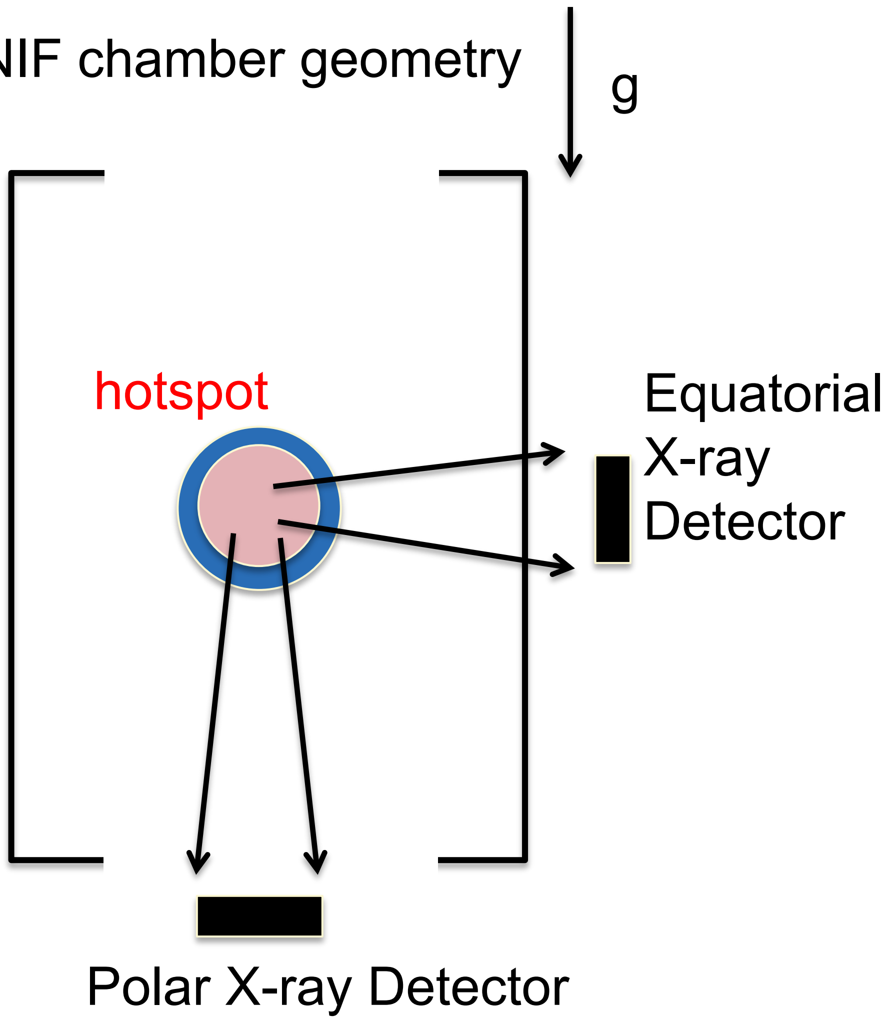


In-flight density nodes plow in material, making a square hotspot

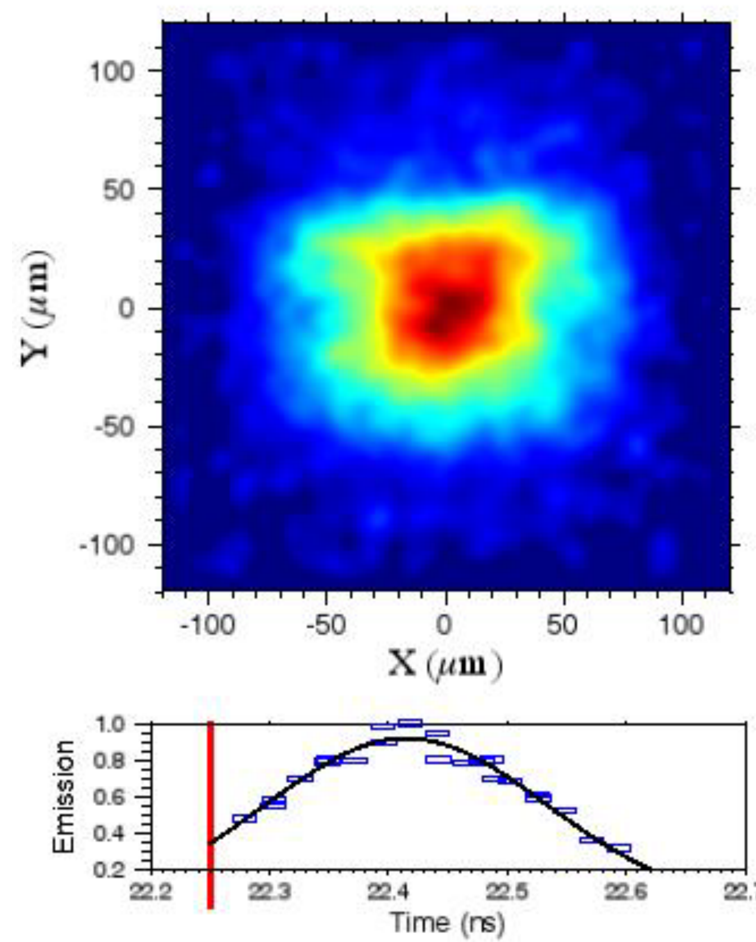
HOTSPOT SHAPE: THE P_4 QUESTION

Gated x-ray movies of hotspot emission give equatorial and polar shape

NIF chamber geometry

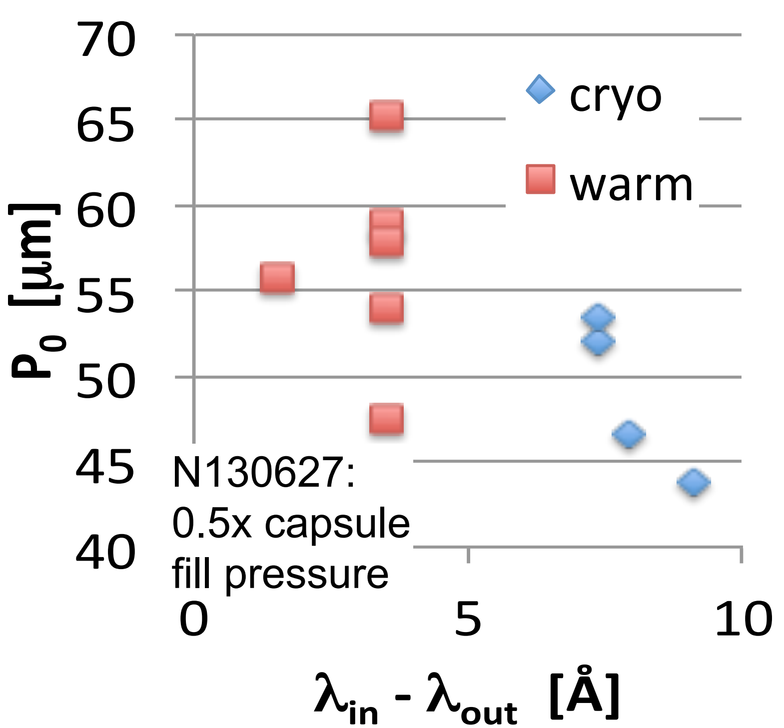


Movie of N130405 equatorial GXD images

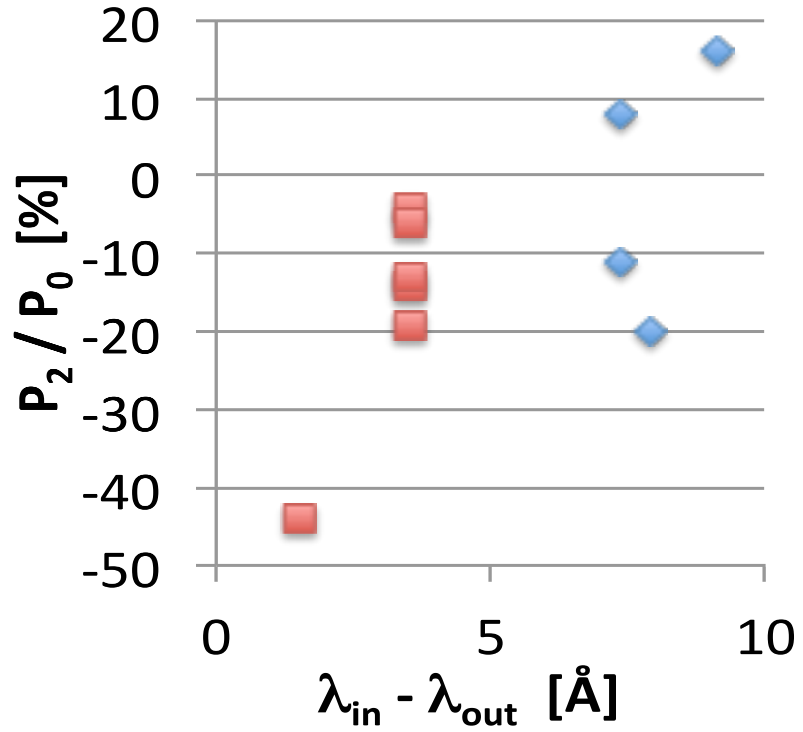


Hotspot equatorial x-ray images: warm and cryo

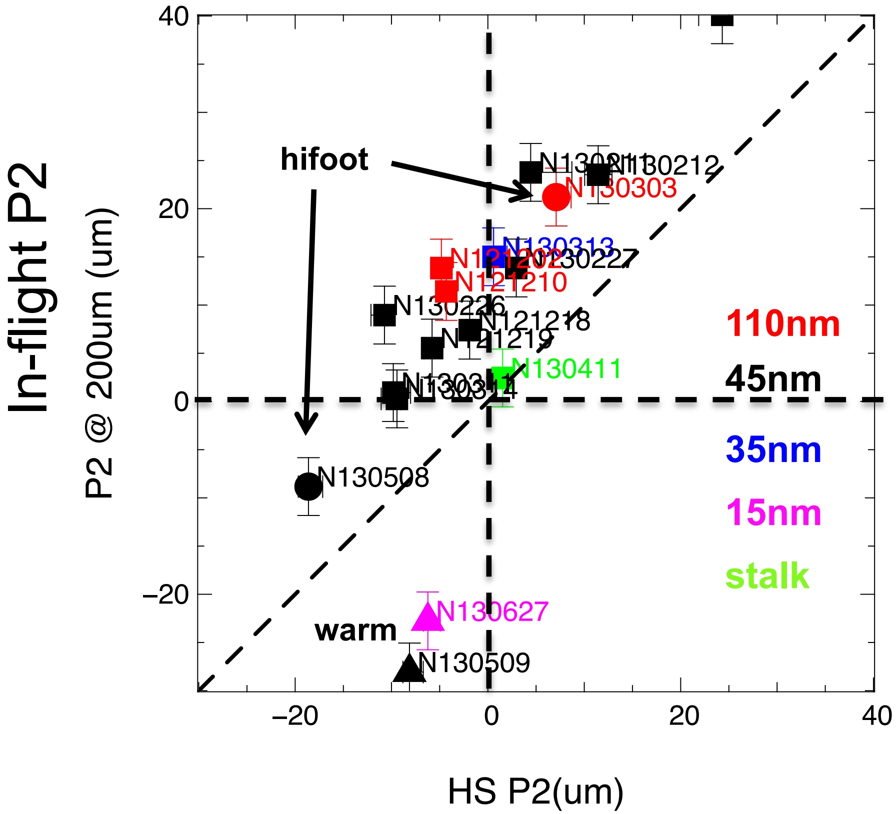
Warm radius slightly larger: cooler hotspot, shell emission?



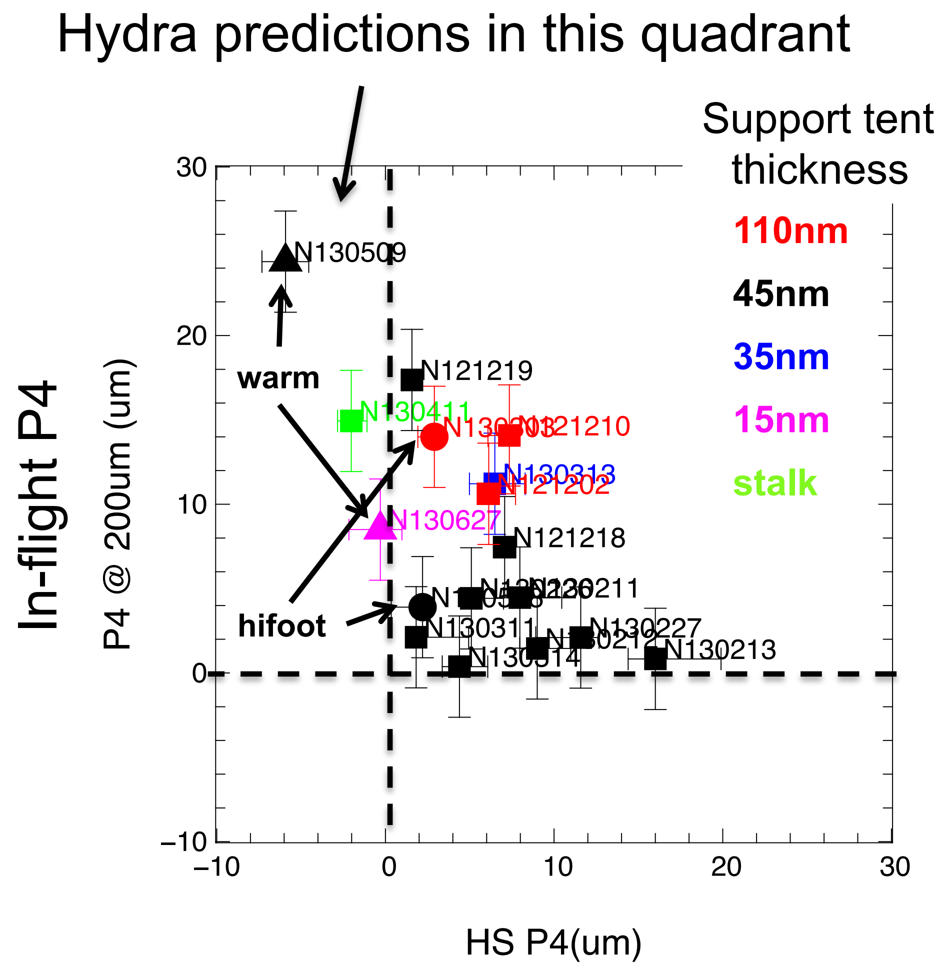
P_2: less transfer makes warms round



While there is a clear correlation between inflight and hot-spot P2 there is not for P4



Hotspot P2



Hotspot P4

Slide courtesy R. Town

Nuclear performance of warm shots is similar to cryos, with cooler hotspots - C_3D_8 fill radiates more

Shot	N130627 2DConA +700 um	N130509 2DConA -300 um	N130405 symcap	N130211 2DconA +700 um	N121219 2DConA -300 um	N120726 symcap	N120705 symcap
E_{las} [MJ]	1.35	1.34	1.27	1.33	1.34	1.37	1.85
T_{ion} DD [keV]	1.7	1.3	1.3	2.1	2.2	2.2	3.4
DD yield [10^{11} n]	2.6	2.0	2.2	2.4	2.0	3.19	5.3
Yield / simulated	135% ! preshot	44%	71%				
Capsule fill pressure	0.5x	1x	1x				
P_0 hotspot	0.82x	57.8 μm					
Capsule fill gas	C_3D_8	C_3D_8	C_3D_8	$D\text{-}^3He$	$D\text{-}^3He$	$D\text{-}^3He$	$D\text{-}^3He$

Good reproducibility!

- Lower capsule pressure increases yield: smaller radius, higher T_{ion}

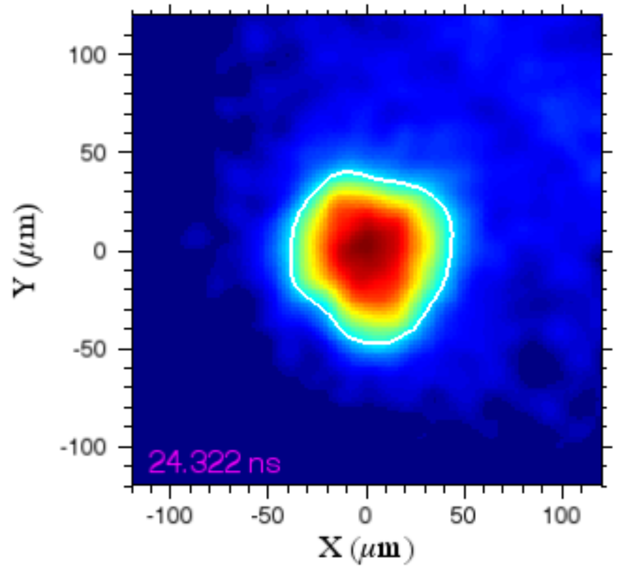
Conclusion: warm hohlraum platform commissioned on NIF, ready for physics studies

- Hydrocarbon hohlraum and capsule fill – unlike H / He for cryo
- P_2 shape: Warm hotspots near round w/ less cross-beam energy transfer
- Backscatter: Warms have less inner-beam SRS, more outer-beam SBS
- The P_4 question: warm in-flight diamond shape, square hotspot
  - Cryo: diamond in-flight and hotspot
  - Hydra: diamond in-flight, square hotspot - warm and cryo
  - Support tent could be playing a role
- Nuclear
  - Deuterated propane: T_{ion} up to 1.7 keV
- Future
- Different hohlraum fill to improve inner beam propagation
- Outer SBS mitigation: Au-Boron wall, split beams in quad
- Capsule spectroscopy - argon, krypton; needs T_e ~ 2 keV (S. Regan)
- Test mix estimates with unknown concentrations (T. Ma)

BACKUP BELOW

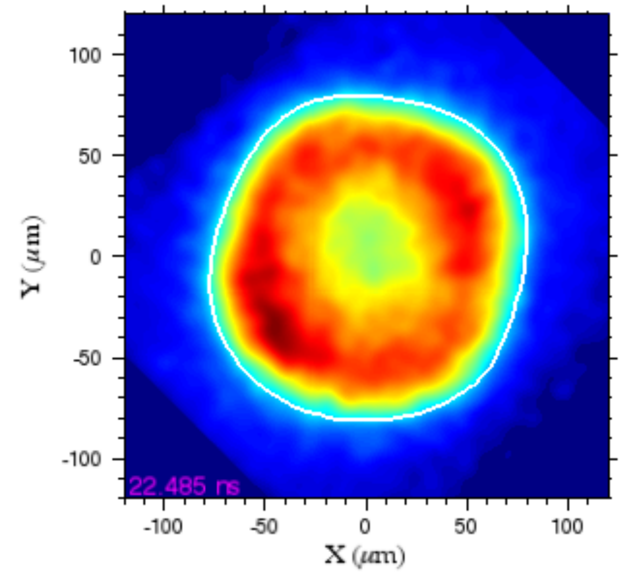
Polar shape: warms much dimmer and larger M_0 vs cryo; "donut" shaped

N120726 – cryo symcap @ bang time



- M0 40.30 μm
- M2/M0 2.26 %
- M4/M0 4%

N130405 (warm symcap) @ bang time



M0:	83 μm
M2/M0:	2.7%
M4/M0:	2.1%

- **Likely due to propane (C_3D_8) capsule fill radiating more and cooling**

Reducing the capsule fill pressure *increased* the yield

Shot	2: N130627 2DConA +700 um	1: N130509 2DConA -300 um
E_{las} [MJ]	1.35	1.34
T_{ion} DD [keV]	1.7 (1.31x)	1.3
$\langle\sigma v\rangle_{DD}$	3.6x	1x
DD yield	1.3x	2.0E11
Yield / simulated	135% preshot	44%
Capsule fill pressure ~ N_i	0.5x	2350 torr
P_0 hotspot	0.82x	57.8 μm
Hotspot pressure = $n_i T_i$	1.22x	1x
Hotspot $n_i \sim N_i / P_0^3$	0.907x	1x

shot 2: lower ion number, hotspot more converged and hotter
Net effect is higher yield

Yield increase estimate:

$$Y \propto \langle \sigma v \rangle * n^2{}_i * \mathrm{Vol}$$

$$\frac{Y_2}{Y_1} = \frac{\langle \sigma v \rangle_2}{\langle \sigma v \rangle_1} * \left[\frac{P_{01}}{P_{02}}\right]^3 * \left[\frac{N_{i2}}{N_{i1}}\right]^2$$

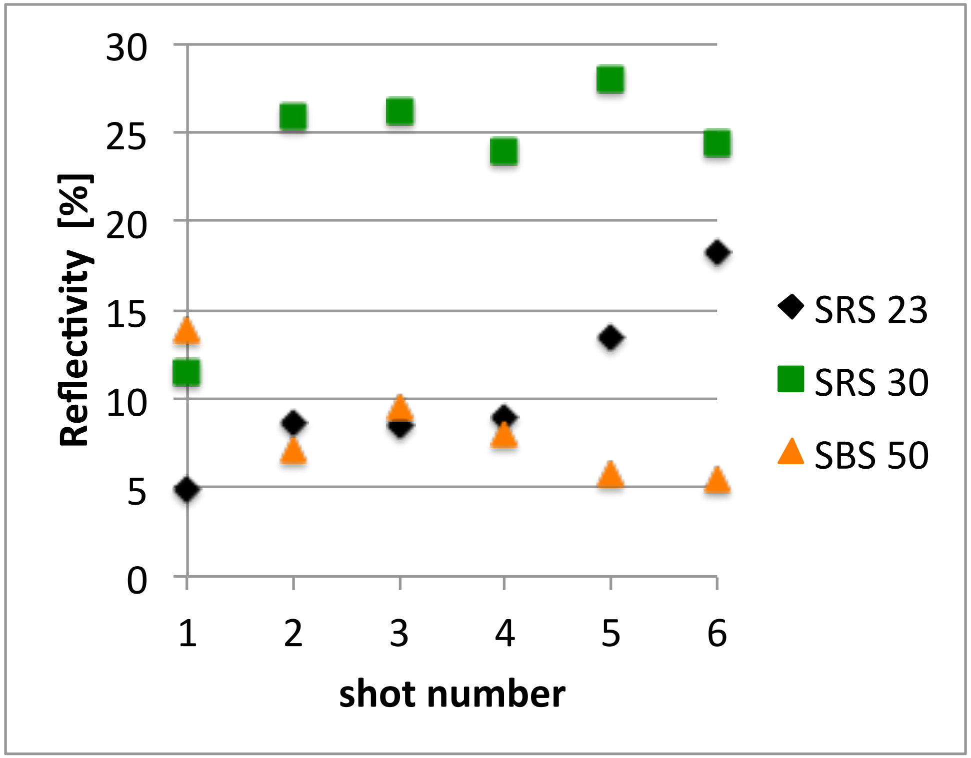
$$\rightarrow \frac{Y_2}{Y_1} = 1.63$$

x=N130509 value

NUCLEAR PERFORMANCE

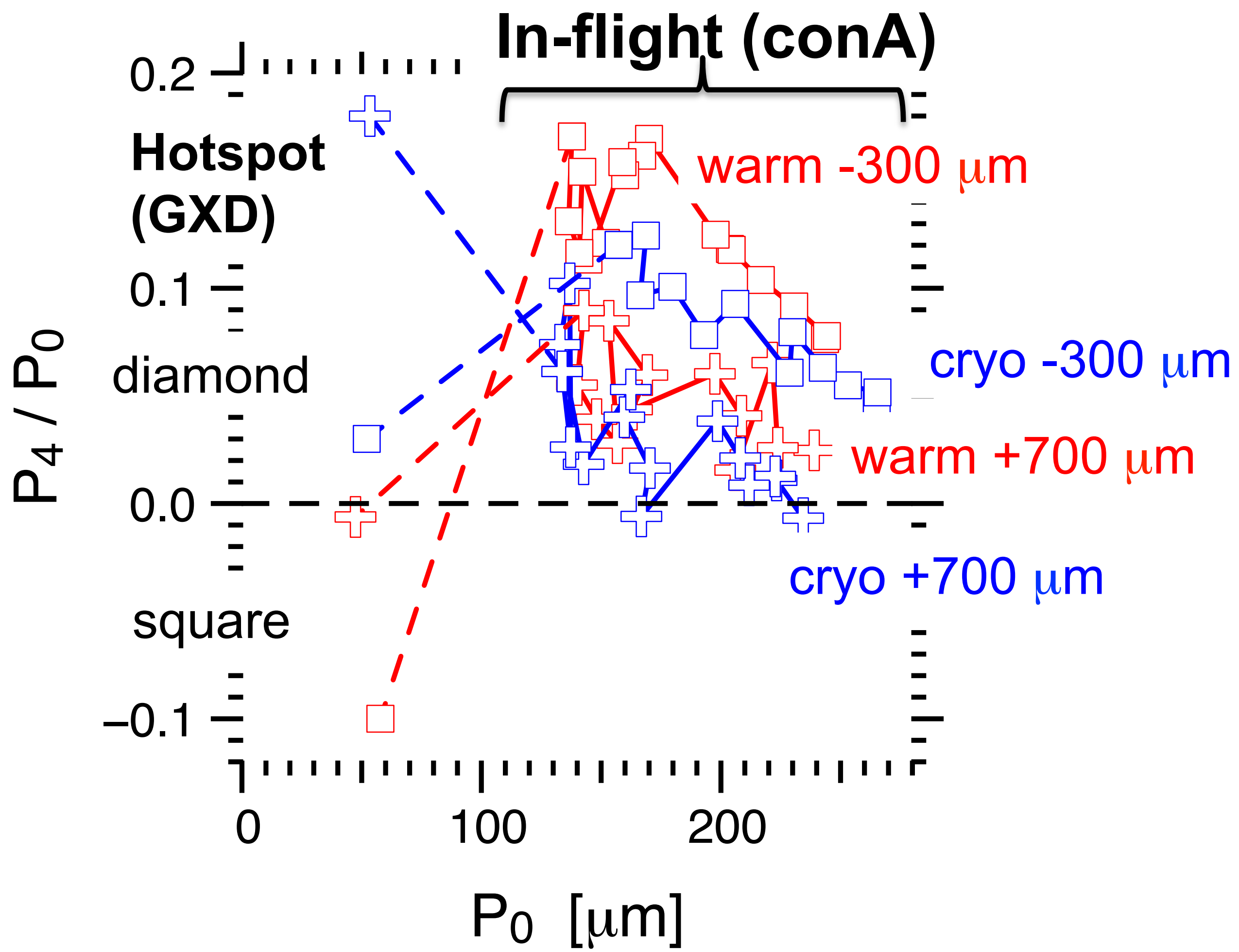
Warm reflectivity

Reflectivity



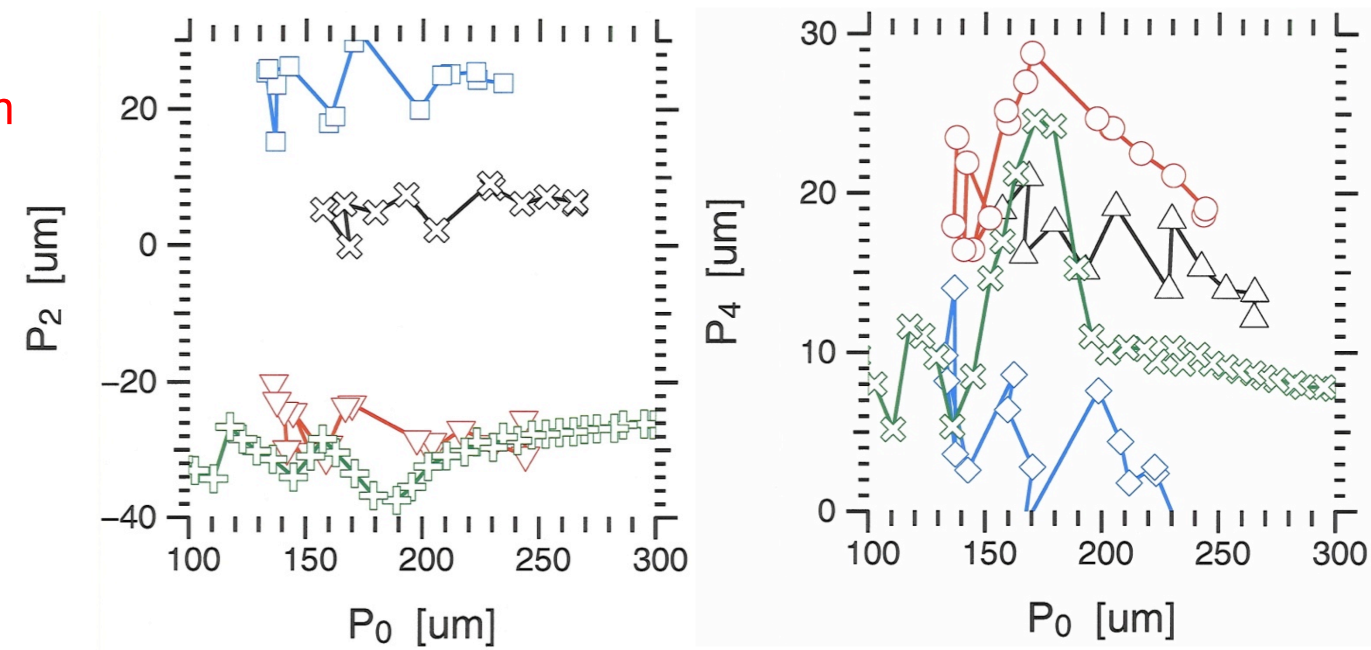
The P_4 question – warms and Hydra agree on in-flight and hotspot P_4, cryos do not

- Warm shots switch from in-flight diamond to hotspot square
- Cryos have diamond in-flight and in hotspot
- Hydra predicts both should behave like warms



Next warm 2D ConA: +700 um hohlraum length: in-flight P_4 should be much less but still > 0

N121219: cryo +300 um
N130211: cryo +700 um
N130509: warm -300 um
Pre-shot warm +700 um



- Warm still calculated to have positive P_4
  - Difference in wall motion / gold bubble (see SXI)?
  - Room for additional re-pointing of outers?

Hydra modeling of warms agrees on bang time and in-flight symmetry

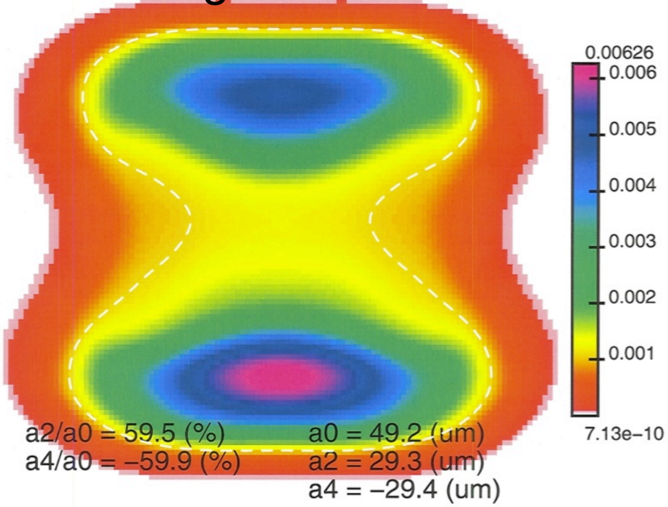
Shot	Hydra pre-shot* Warm +700 um	N130509 Warm 2DConA	Hydra N130509_ps03	N130405 warm symcap	Hydra N130405_ps03
$(\lambda_{23}, \lambda_{30})-\lambda_{out}$ [Å]	3.5, 3.5	Same	Same	Same	Same
Xray BT [ns]	22.57	22.32	Data + 60ps	22.44	Data + 80ps
P0 GXD BT [um]	43.77	57.8 TI	51.8	64.4	49.2
P2/P0 BT [%]	+2.19	-14 TI	+7.8 BT	-6	+60 !!
P4/P0 BT [%]	-12.02	-10 TI	-21.6 BT	-20	-60
DD yield [n]	1.92E11	44% YOS	4.57E11	71% YOS	3.1E11
P2/P0 % @ 200 um	-16.8	-14	-12		
P4/P0 % @ 200 um	+5.18	+11	+12.5		

- Hydra predicts both warms and cryos have in-flight diamond and hot-spot square
- Warm shots behave this way
- Cryo shots have both in-flight and hot-spot diamond – disconnect with Hydra

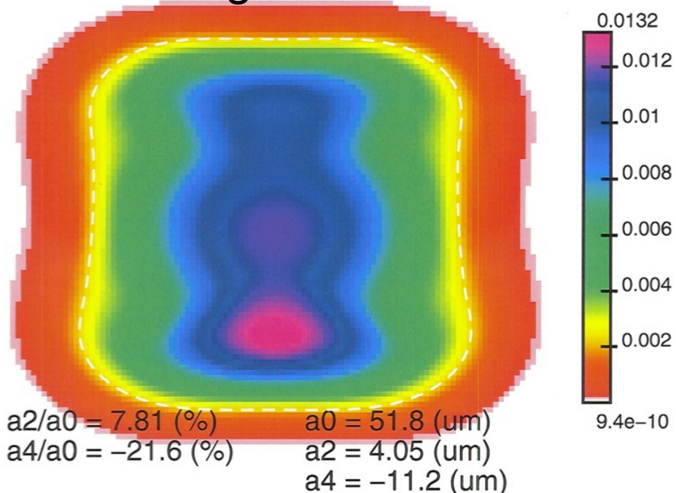
- Warm sims:
  - Time-dependent cryo Oggie multipliers: gives slightly later BT
  - Cross-beam transfer: script w/ dn/n = 6E-4 saturation – lower level would make sim pancaked
  - Working on inline cross-beam and backscatter packages

Warm equatorial self-emission x-ray images

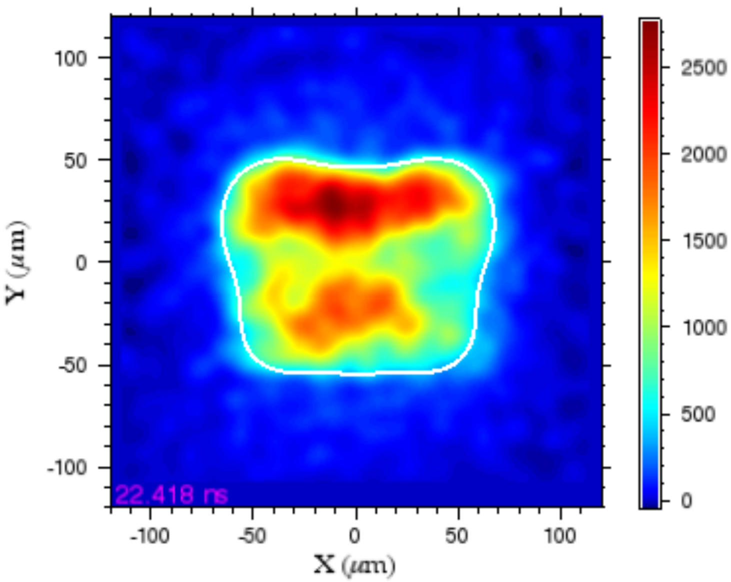
Hydra N130405_ps03
at bang time 22.52 ns



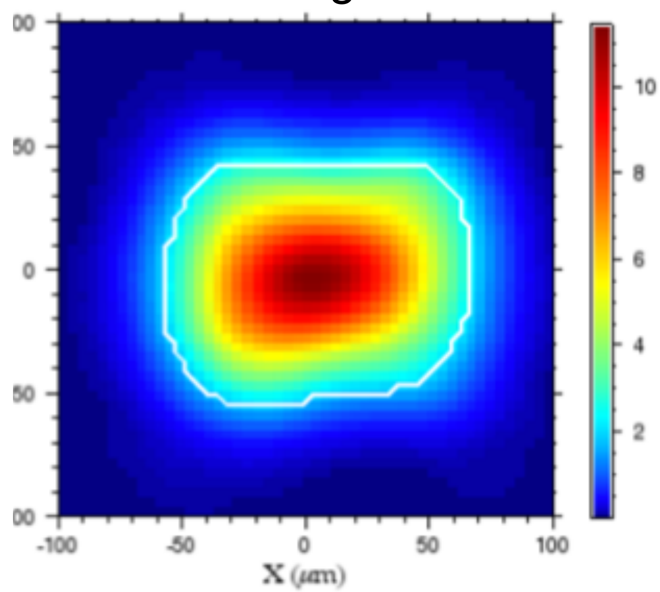
Hydra N130509_ps03
at bang time 22.38 ns



N130405 measured @ bang-time



N130509 (-300 um)
Time-integrated



Warm in-flight diamond ($P_4>0$) switches to hotspot square ($P_4<0$), unlike cryos (stay diamond)

Shot	N130509 Warm 2DConA	N121219 Cryo 2DConA	N130211 Cryo 2DconA	N130405 warm symcap	N120726** Cryo symcap	N120705 Cryo symcap
E_{las} [MJ]	1.34	1.34	1.33	1.27	1.37	1.85
P_{peak} [TW]	379	345	358	367	412	523
$(\lambda_{23}, \lambda_{30})-\lambda_{out}$ [Å]	3.5, 3.5	8.1, 6.6	8.1, 6.6	3.5, 3.5	9.7, 8.5	8.5, 7.3
In-flight shape				n/a to symcaps		
P2/P0 % @ 200 um	-14	+2.7	+12			
P4/P0 % @ 200 um	+11	+8.5	+2.5			
Hotspot shape						
P2/P0 [%]	-14	-11	+7.5	-6	+16	-20
P4/P0 [%]	-10	+3	+15	-20	+3	0

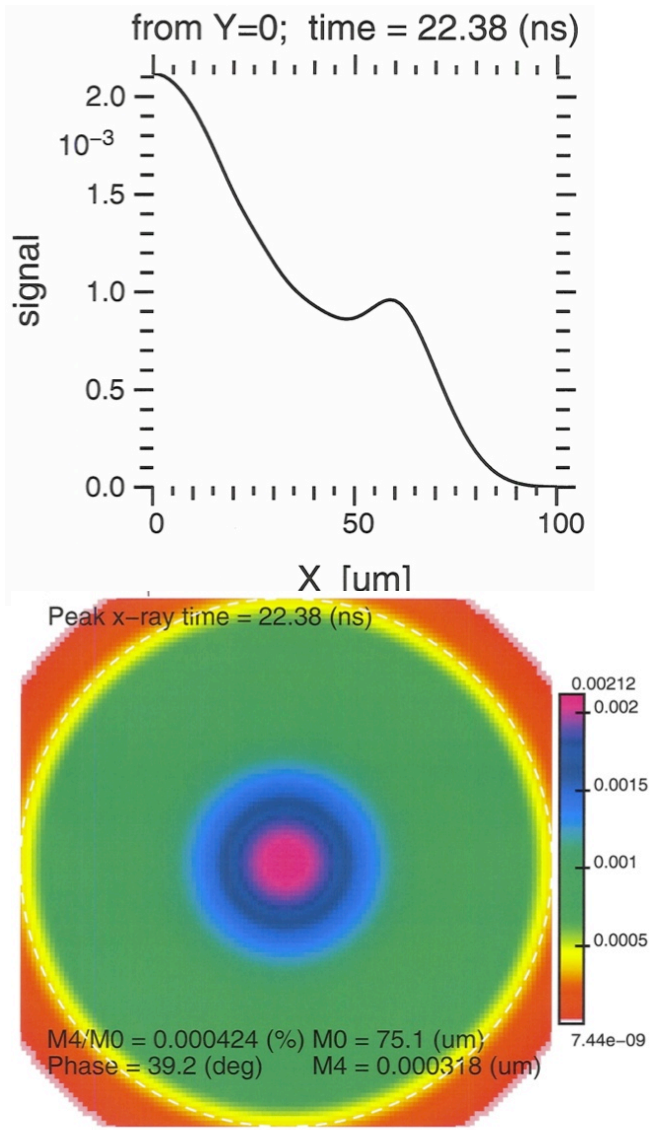
Warm shot hotspots "round" (P_2 small) for less $\Delta\lambda$ than similar to low-foot cryos

Shot	N130509 2DConA	N121219 2DConA	N130211 2DconA	N130405 symcap	N120726** symcap	N120705 symcap
E_{las} [MJ]	1.34	1.34	1.33	1.27	1.37	1.85
P_{peak} [TW]	379	345	358	367	412	523
$(\lambda_{23}, \lambda_{30})-\lambda_{out}$ [Å]	3.5, 3.5	8.1, 6.6	8.1, 6.6	3.5, 3.5	9.7, 8.5	8.5, 7.3
Hohlraum, LEH	Au -300, small	Au -300, small	Au +700, large	Au nom, large	Au nom, large	U nom, small
Hotspot						
Xray BT [ns]	22.32	22.91	22.90	22.44	24.31	23.83
P0 GXD [um]	57.8	52.1	54.9	64.4	43.78	46.56
P2/P0 [%]	-14	-11	+7.5	-6	+16	-20
P4/P0 [%]	-10	+3	+15	-20	+3	0

Warm
cryo

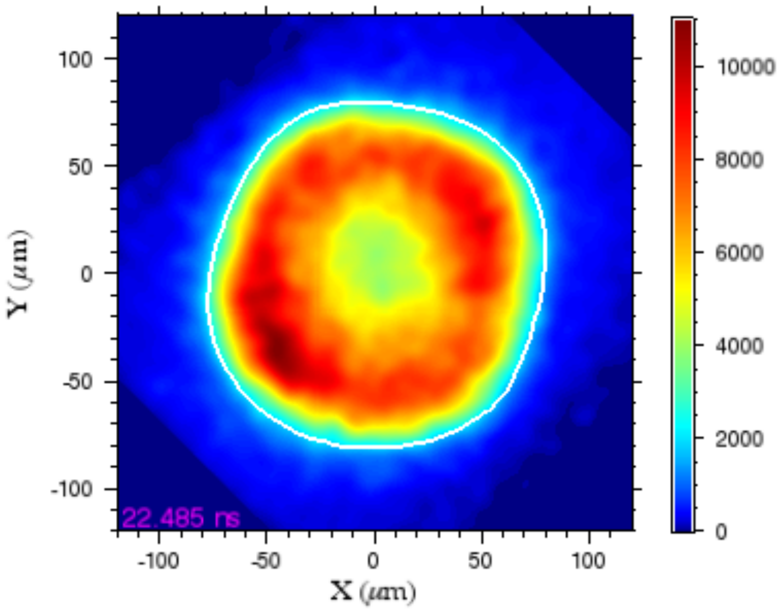
Polar shape in Hydra: large M_0, broad profile but no donut

N130405_ps03 post-shot



N130405: warm symcap

Measurement at bang time




NIF