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Title: Review of high convergence implosion experiments with single and double shell targets

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Los Alamos
NATIONAL LABORATORY

Summary

Promising Results have been achieved with NIF-analog double shell capsule experiments at Omega

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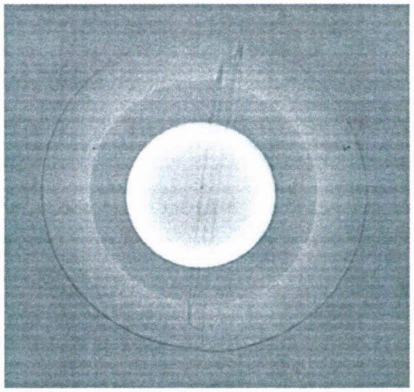
- Experiments have been been performed in recent years at the Omega laser studying double shell capsules as an alternative, non cryogenic, path towards ignition at NIF.
- Double shell capsules designed to mitigate the Au M-band radiation asymmetries, were experimentally found to perform well in **both spherical and cylindrical hohlraums**, **achieving near 1-D (~90%) clean calculated yield** at convergence comparable to that required for NIF ignition[1].
- Near-term plans include directly driven double shell experiments at Omega, which eliminates Au M-band radiation as a yield degradation mechanism.



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[1] Phys. Rev. Lett., 84,5153,May,2000

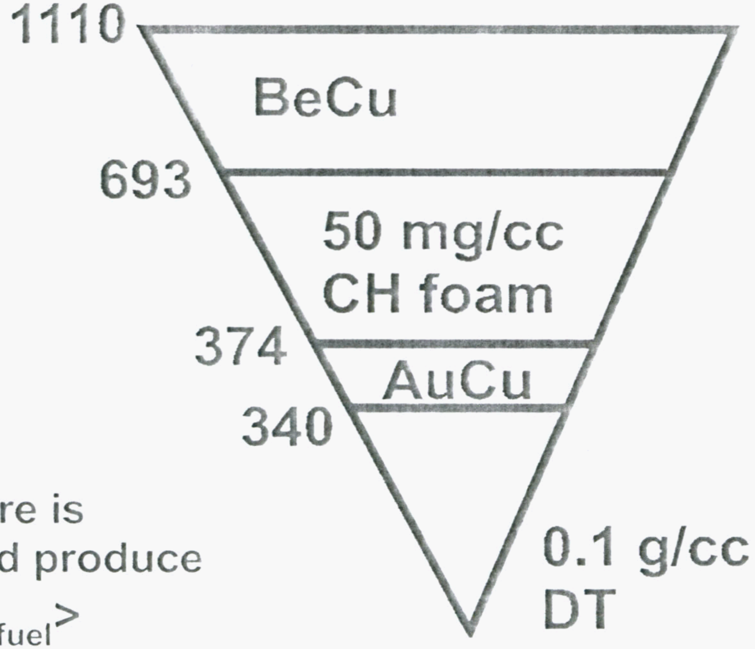
A non-cryogenic double shell target design may be an alternative for NIF ignition

- Simple 6 ns square pulse at 300 TW is adequate for ignition
- CR 32 at 0.1 g/cc DT gas fill produces 2.6 MJ from 1.8 MJ input
- Room temperature operation

Note: convergence ratio (CR) as used here is defined as what a ρR measurement would produce

$CR = OD_{\text{ablator}} (t=0) / <OD_{\text{burning fuel}}>$

NIF double shell (CR 32)



Analogs of this design have been tested at NOVA and Omega

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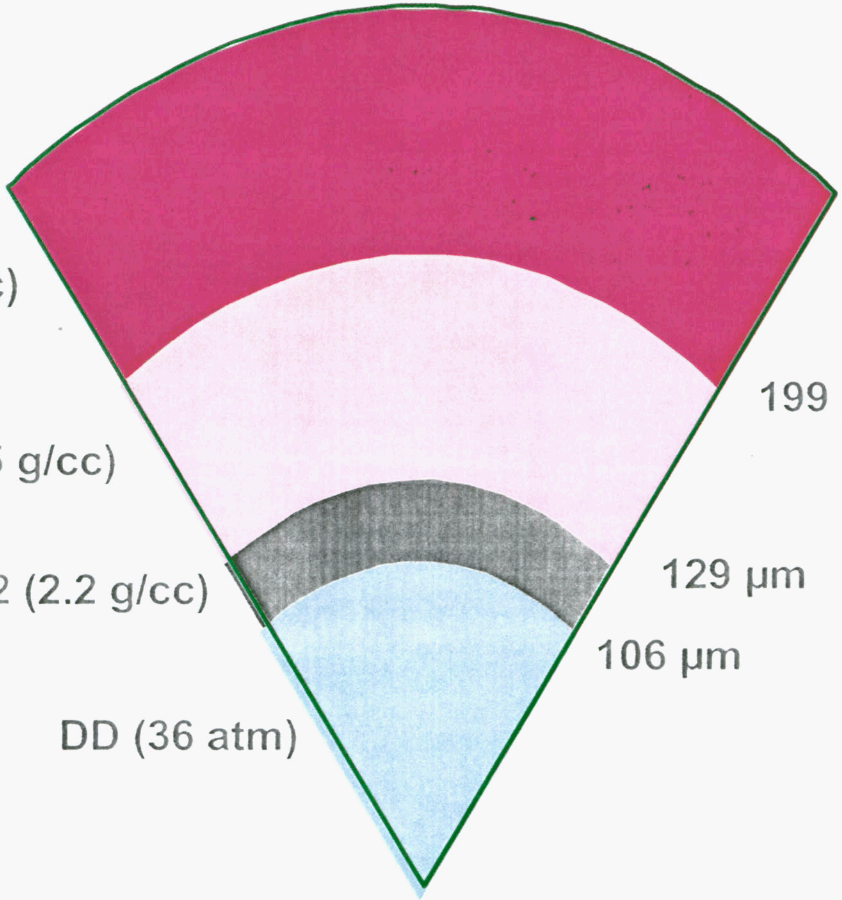
The NIF analog double shell target has an inner glass shell, a vacuum or foam interspace, and a solid CH ablator

This was called the "standard" double shell design used for Omega and Nova laser experiments



CH (1.04 g/cc)

CH (0.05 g/cc)

SiO2 (2.2 g/cc)

DD (36 atm)

275 µm

199 µm

129 µm

106 µm

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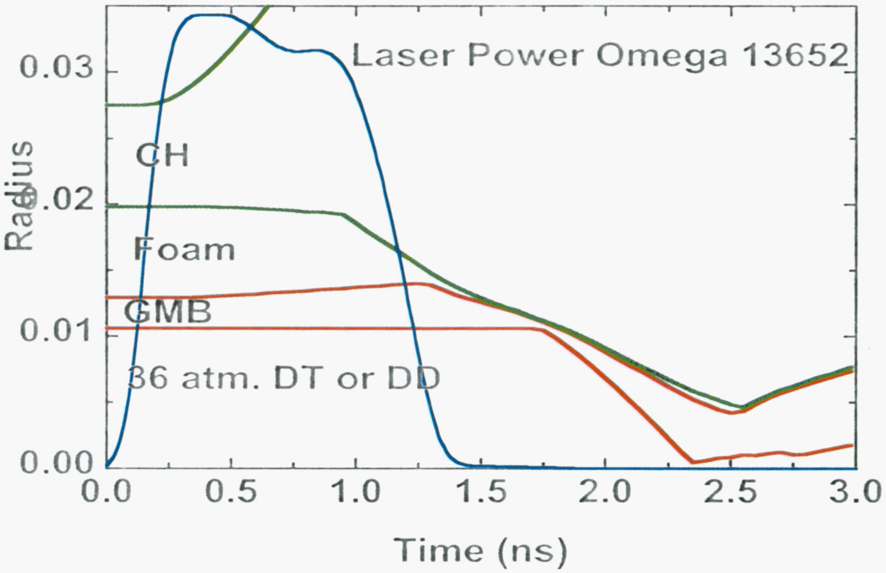
HYADES 1D calculations show some general implosion characteristics for the "standard" double shell design

- Bangtime around 2.3 ns
- Ablator - GMB collision time ~1.3 ns, << bangtime
- Some decompression of the GMB due to M band x-ray penetration through the ablator
- Velocity multiplication of order 1.3
  - ratio of the maximum velocity of the peak density layer in the GMB to that in the ablator



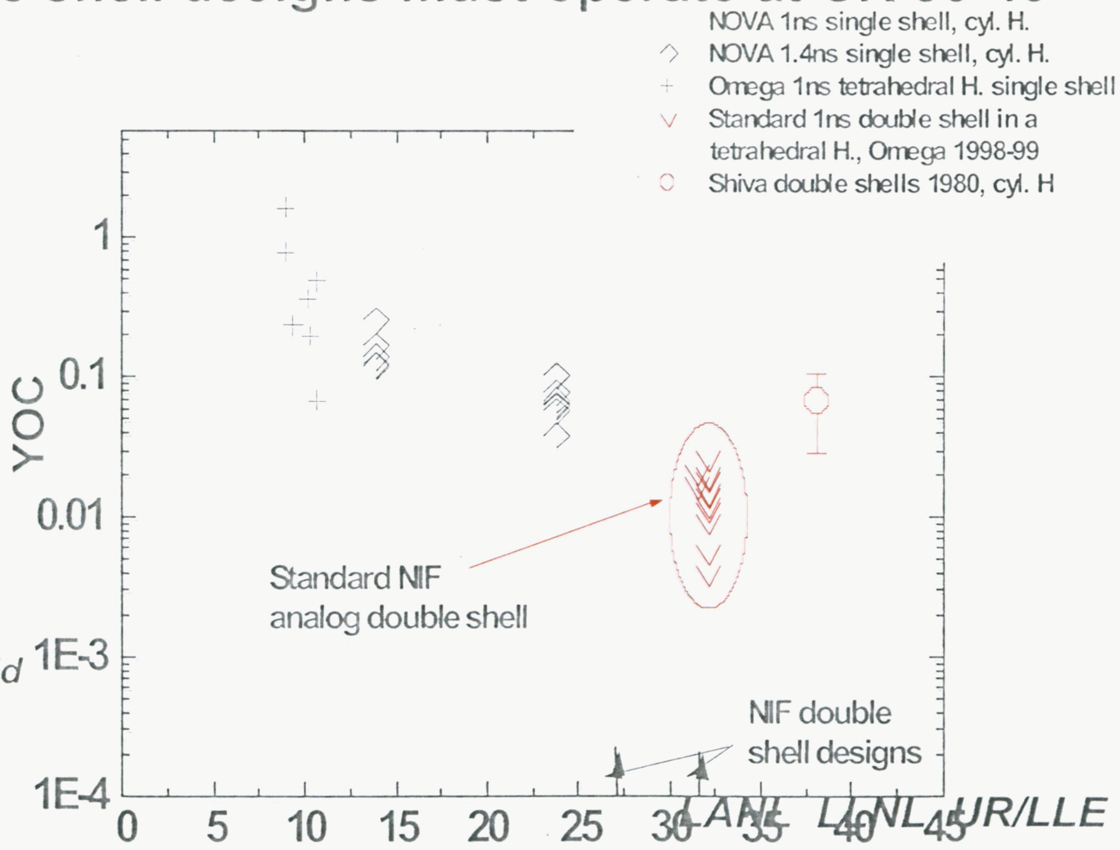
This calculation is for the thick Glass+foam+CH ablator (standard) double shell used exclusively prior to March 1999, which performed poorly

Initial experiments using double shell targets showed no performance improvement over single shell designs

- Historically all ICF targets (ID and DD drive) have performed poorly at high convergence, for unknown reasons
- NIF single and double shell designs must operate at CR 30-40

Double shell designs have been studied since 1980 in ICF, but have performed poorly, with neutron yields <10% of 1D or 2D calculations.

YOC is fraction of 1-D calculated yield



Standard NIF analog double shell

NIF double shell designs

So double shell targets were not in favor until very recently in this program ...

But of course they failed because ...

- Shiva double shell shots 1980, YOC < 10% @ CR = 38
  - but Shiva was an early glass laser with poor beam characteristics, and the codes were not very refined
- 4 NOVA shots 3-4/98 with DT, YOC ~1% @ CR = 37
  - but NOVA at that time had poor beam balance and poor thermal drive symmetry

Hey guys, what now?

- 5 Omega double shells in tetrahedral hohlraums (9/98) with good thermal symmetry, with DD and DT, YOC 0.7-1.3% @ CR = 32
  - OOPS, this one has much better thermal symmetry due to spherical hohlraum and 60 beams and better codes ...

The question was why was the behavior so bad: maybe it was Au M-band radiation that was NOT symmetric in the Nova/NIF cylindrical hohlraum and worse in Omega tetrahedral hohlraum due to 60 beams clustered at the 4 LEH ...

To remove sensitivity to asymmetric Au M-band from the laser spots, two general approaches may be used

- ***Suppressed M-band (CH:Br) design*** reduces this potential source of degradation incident on the inner capsule
  - bromine doped ablator reduces M-band to 15% of undoped level
- ***Reduced M-band absorption* (imaging) *design*** reduces the response of the inner capsule to this potential source of degradation
  - 80% of inner capsule glass replaced with CH
  - reduced shell ρR allows x-ray imaging of the core
  - New variants allowed ρR measurements and removed all glass from the inner core

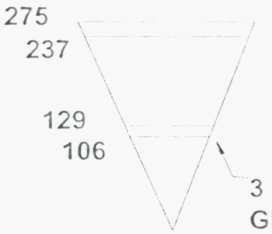
If asymmetric M-band from the laser spots is the culprit, let's design targets that are less susceptible to it

Reduced M-band absorption (imaging)
CR 27-37 (31-12 atm DD or DT)

Type A thick ablator imaging capsule

3 um wall GMB + 19 um GDP

Type B thin ablator imaging capsule



3 um wall GMB + 19 um GDP

Reduced M-band absorption (imaging)
Low mass, high velocity, increased yield variant (18 atm DD)

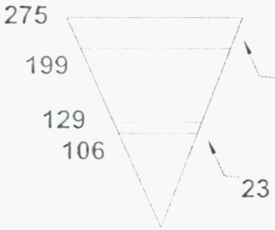
The terms Imaging and reduced M-band absorption will be used interchangeably from here on

Reduced M-band absorption (pure CH)
NO MORE SiO_2

Type C thick ablator, pure CH inner imaging capsule

23 um wall single shell CH, with PVA gas barrier

Type D brominated ablator standard capusle



C8H8.06Br0.194

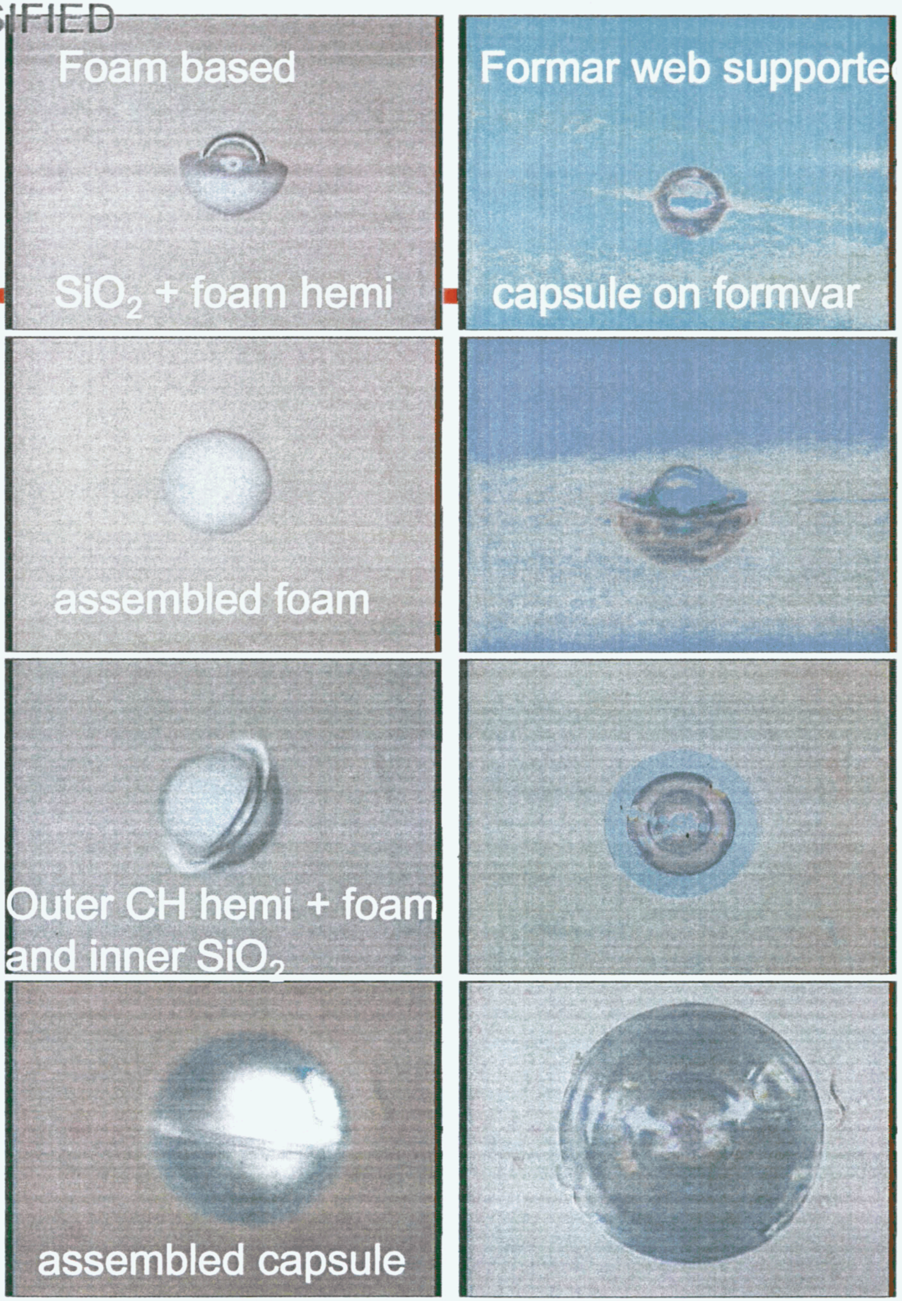
23 um wall GMB

Suppressed M-band CH:Br
CR 32 (24 atm DT)

So let's see what a double shell target actually looks like

- The inner DT or DD gas is held in a small capsule inside a bigger capsule separated from it by vacuum or a low density foam
- Shots with either foam or vacuum looked the same in early work, so we use foam exclusively

Kudos to Target Fab Team !!
Led by A. Nobile and R. Day at LANL



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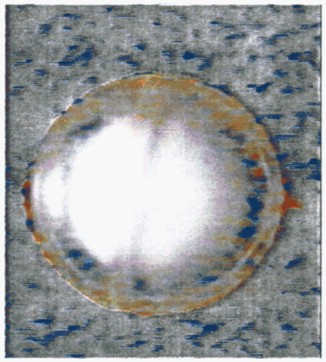
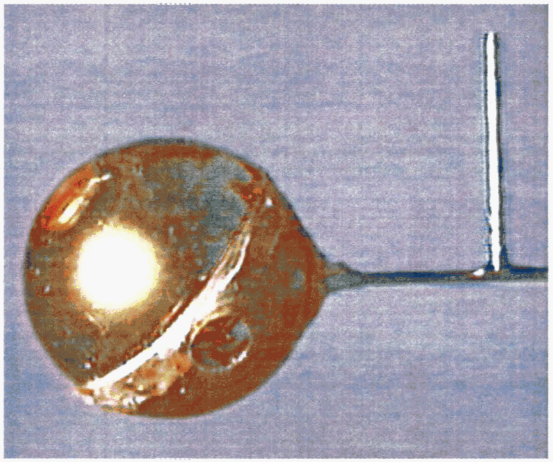
These double shell capsules are enclosed in thin wall tetrahedral or NOVA/NIF style hohlraums

Outer hemisphere seam is often visible in optical photos

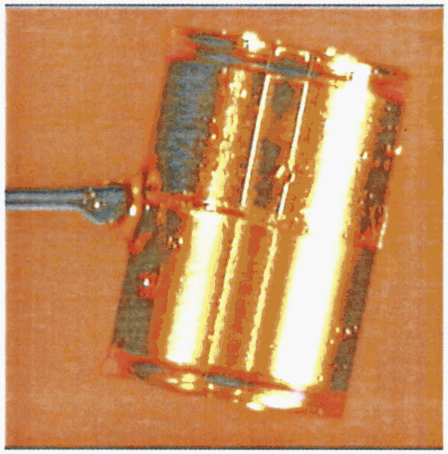


Tetrahedral hohlraum double shell targets

2.8 mm ID thin wall tetrahedral hohlraum

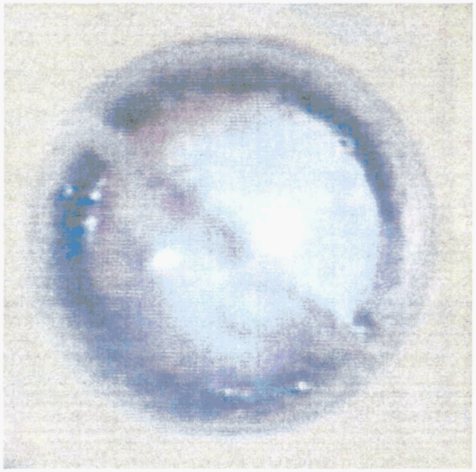


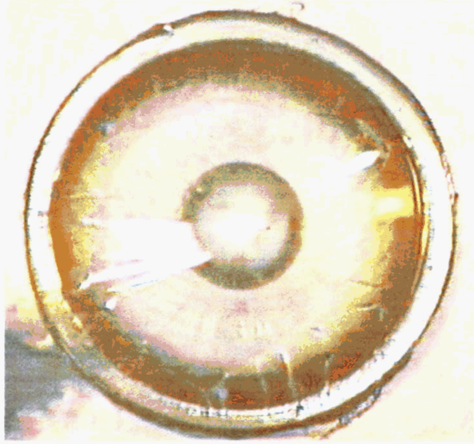
NOVA/NIF style hohlraum double shell targets



Standard 550 ∝m OD double shell capsules are used in both hohlraums

Target capsules were visibly flawless in almost all cases for the final Nov. 2000 campaign in NOVA/NIF hohlraums





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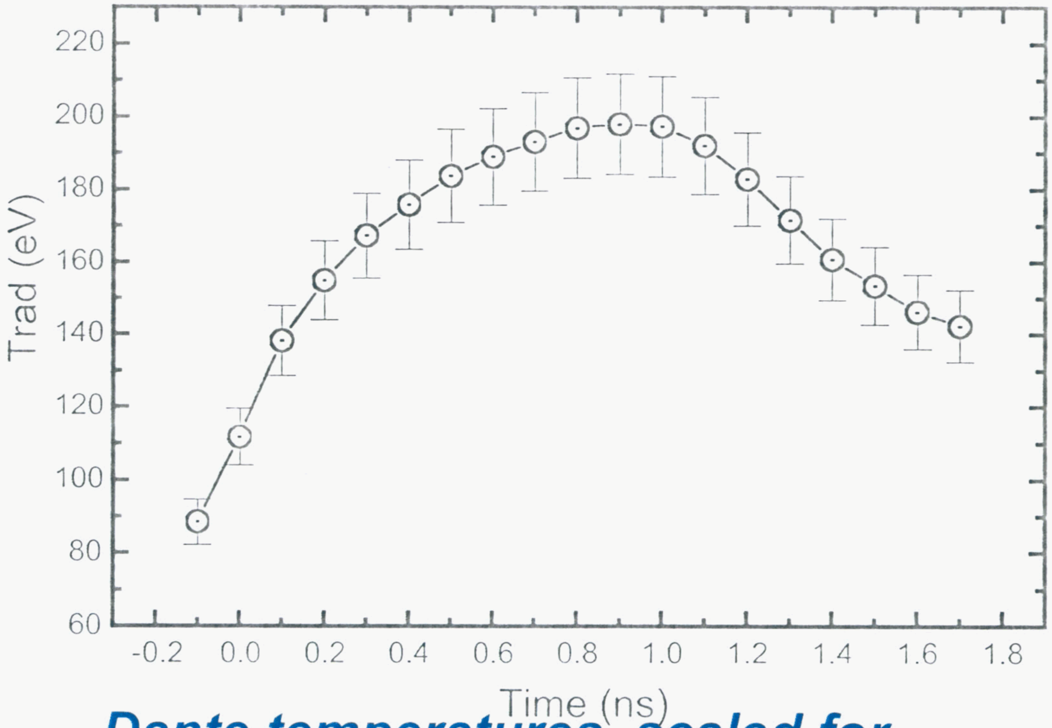
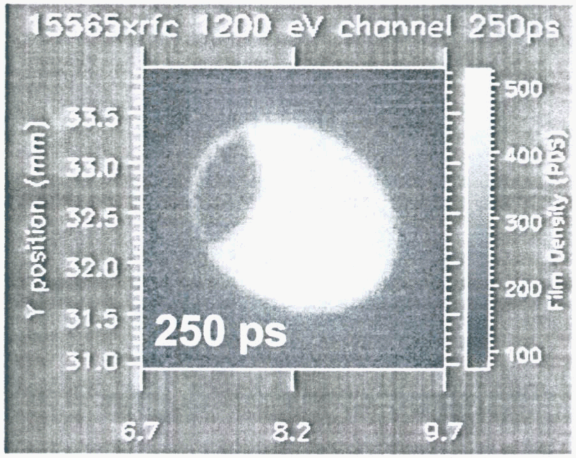
Diagnostics used in the Omega shots emphasize neutron production and core shape

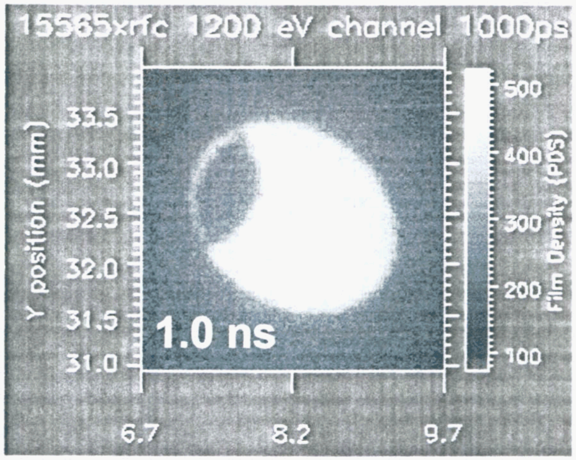
- Omega neutron suite (NTD, scintillators, Medusa, Cu activation for DT targets
  - Fuel ρR was obtained, albeit with large error bars, on 6 shots
- Los Alamos neutron bang time detector
  - Data was obtained on the majority of shots and is under analysis
- Static pinhole camera - transverse core imaging
- Gated imager - transverse core imaging
- Gated imager - axial core imaging
- DANTE - drive history on all shots
- backscatter calorimetry, beam power history

Earlier NOVA data emphasized the same diagnostics with the exception of imaging

Omega produces a 200 eV Plankian drive + an extra 7% M band, with little hole closure during the 1 ns pulse, using tetrahedral hohlraums. Cylindrical hohlraums are a bit hotter.







Dante temperatures, scaled for delivered energy on each shot, are used to calculate the burn average CR

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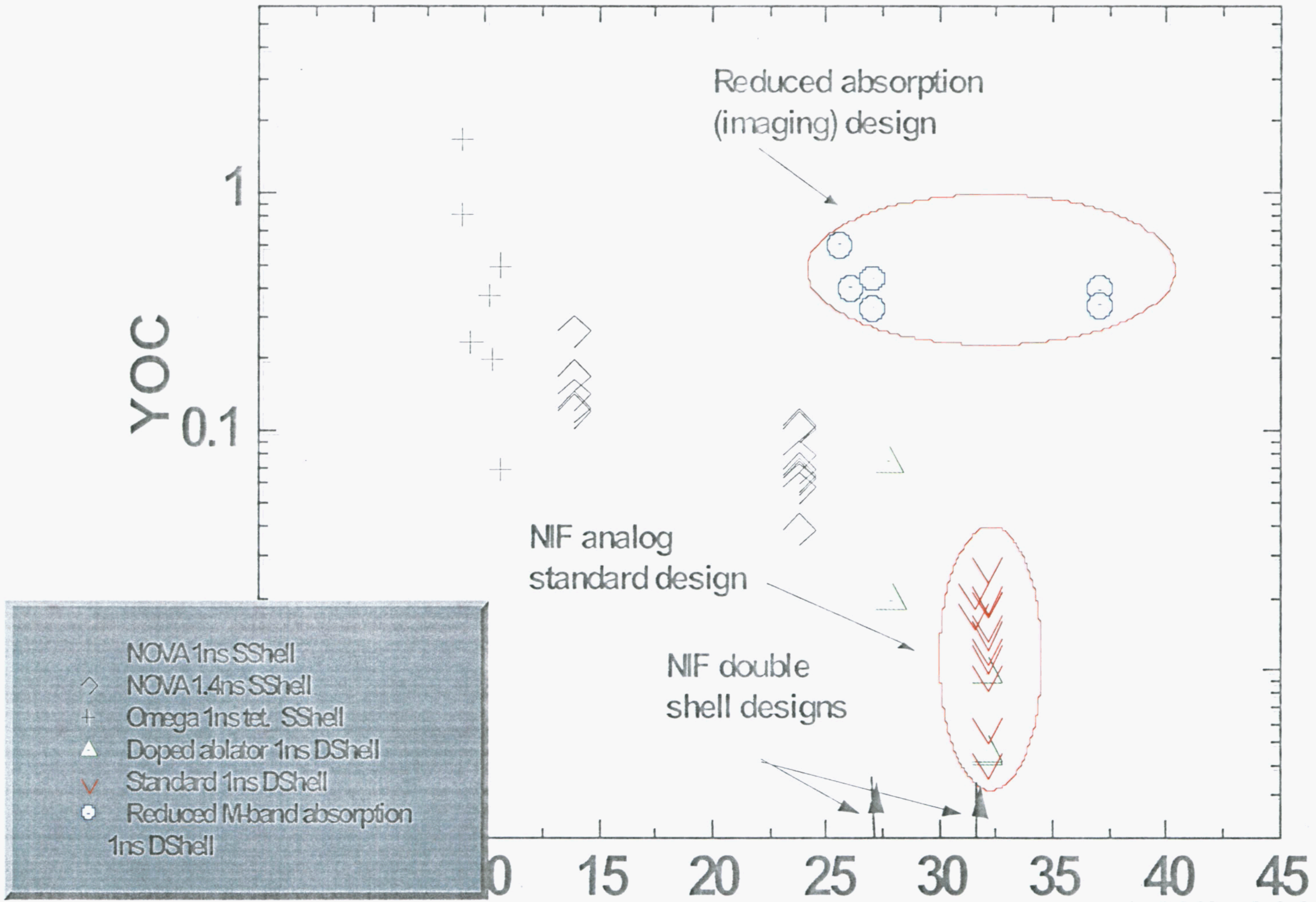
Success, at last!

Near 1D performance (YOC~1) at high convergence was seen the first time the imaging capsule was used (Oct. 1999)

- The first two series of shots that removed M-band asymmetry sensitivity used tetrahedral hohlraums (Oct. 1999 and March 2000)
- The historically poor "standard" thick GMB inner capsule double shell still failed as always before so the design change was assumed to be the cause of the improved performance for the reduced absorption (imaging) capsule
- The suppressed M-band design failed to give significant yield, and has not yet done well for unknown reasons
- Both the "standard" double shell capsule and the suppressed M-band capsule were DT filled, so there is still a concern that DT fills might be the culprit
  - post shot tests of remaining DT filled capsules indicate that gas was present

The initial imaging target performance in tetrahedral hohlraums exceeded that of all other ICF targets at CR ~38



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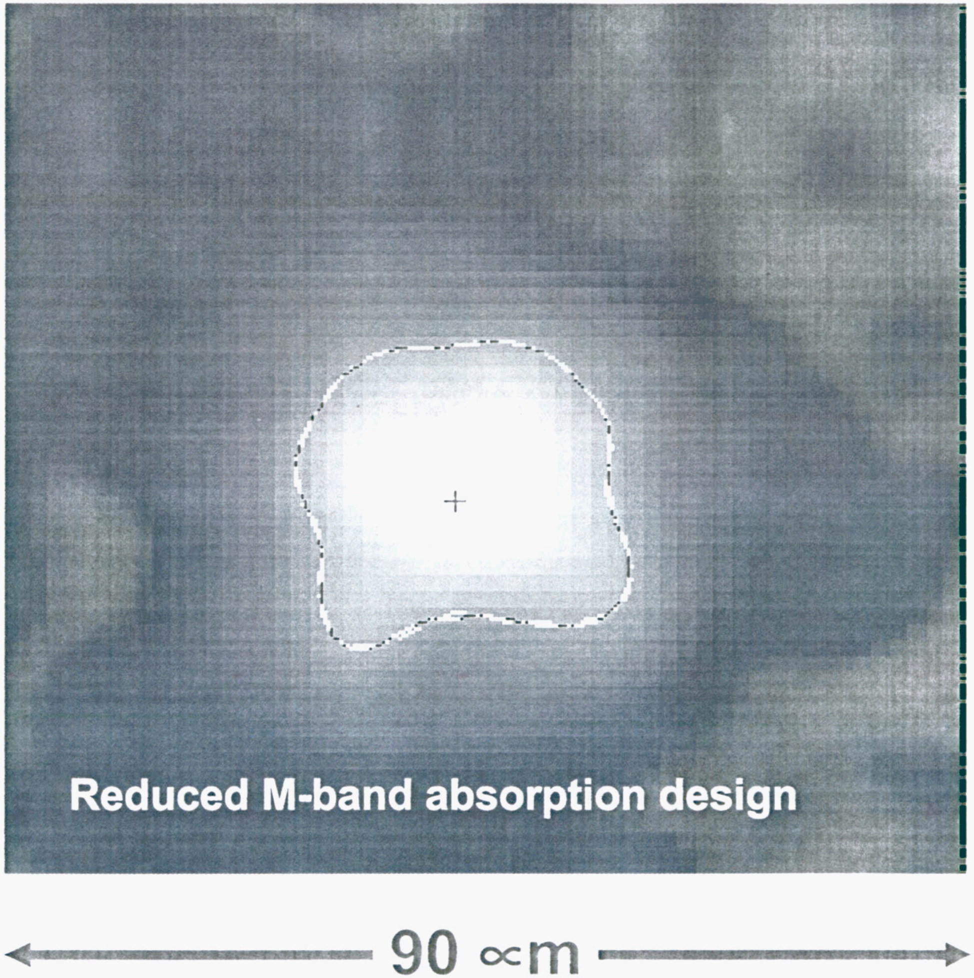
The core x-ray image at peak compression shows a mean diameter of 32 ∝m and an eccentricity of 0.96 (tetrahedral hohlraum, March 2000)



A post-processed 1D hydro simulation of this shot produces an x-ray image prediction of 32 ∝m FWHM, in excellent agreement with the observed size.

Gated x-ray framing camera image of a reduced absorption double shell at peak compression, with an 80 ps frame time and 7-8 ∝m resolution

The reduced M-band designs seem to work in tetrahedral hohlraums, but so what ...

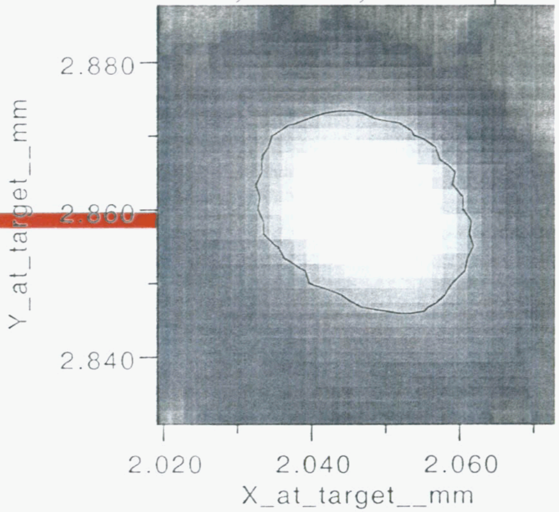
- NIF will use a cylindrical hohlraum with 4 beam cones
- Thermal symmetry will vary much more as a function of time for a NIF hohlraum than this tetrahedral one
- M-band asymmetry will be different and there will be a significantly different percentage of LEH loss area

So let's see if the hohlraum shape even matters, since clearly the standard double shell failed miserably in both the NOVA and Omega hohlraums, but this new design seems to work in tetrahedral hohlraums that do not currently apply to NIF ...

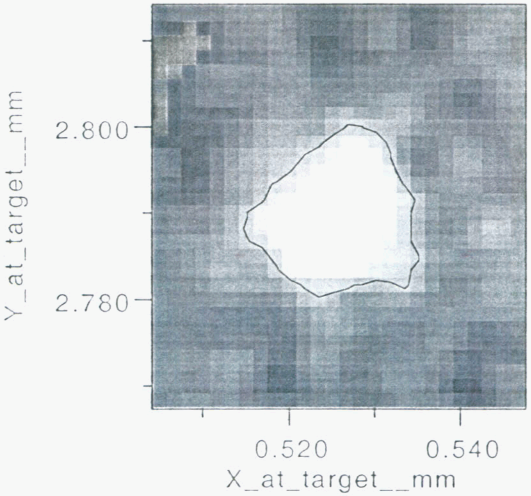
The most recent (Nov. 2000) results at Omega, using cylindrical hohlraums, produced mostly symmetric implosion images, except for the brominated ablator target

Images have been converted to exposure using Henke film calibration, images have been smoothed, contours shown are 50% contour in exposure. **Smallest measured core diameter implies CR of about 28.** With 5μm pinholes, the pinhole camera had a resolution of about 7 μm.

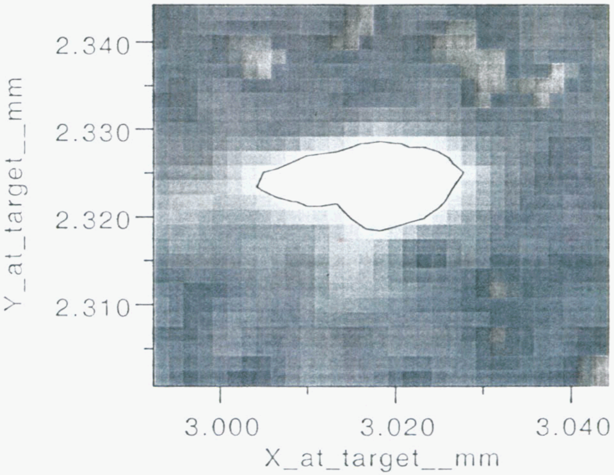
21698, imaging capsule, thin ablator, e=0.90, D=27.5μm



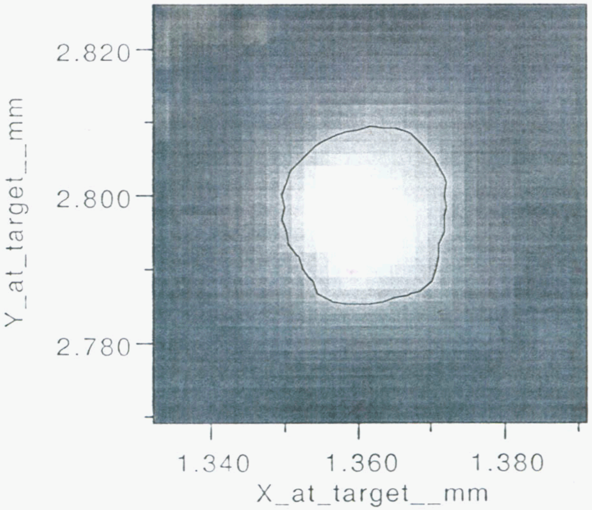
21695, Pure CH inner capsule e=0.9, D=19μm



21689, CH(Br) ablator, e=0.45, D=22μm x 10μm



21685, imaging capsule, thick ablator, e=1.04, D=22.5μm



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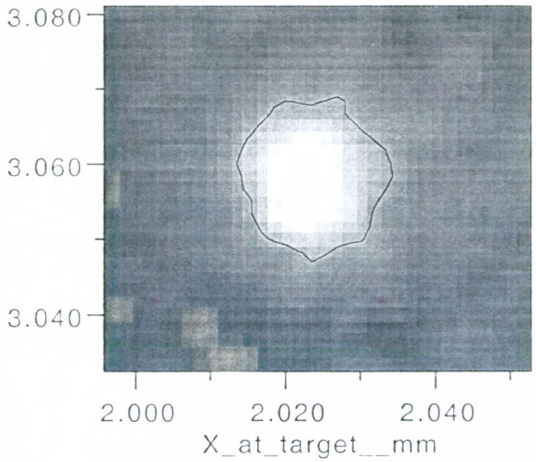
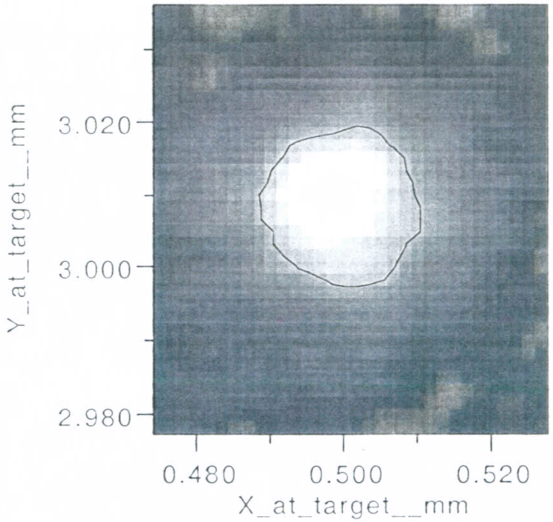
DT filled targets, while having yields in some question, gave core images similar to DD capsules

The three images are part of the DT convergence scan, with fill pressures ranging from 12 atm DT to 31 atm DT. The **smallest measured core diameter implies CR of about 30**. With 5μm pinholes, the pinhole camera had a resolution of about 7 μm.

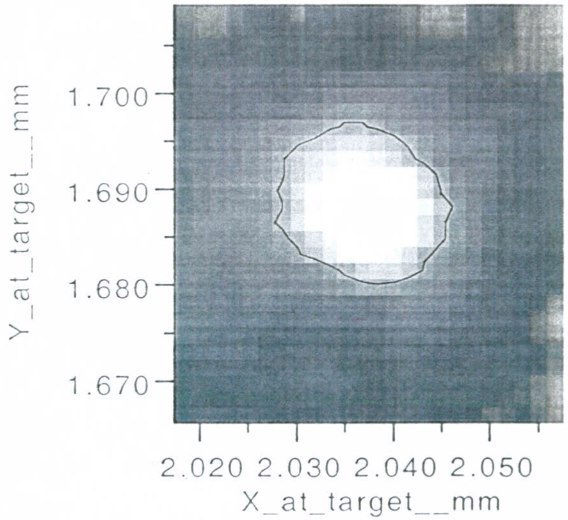
21703, e=1.1, D=19.5μm
12 atm. DT fill



21700, e=0.98, D=21.3μm
18 atm DT fill

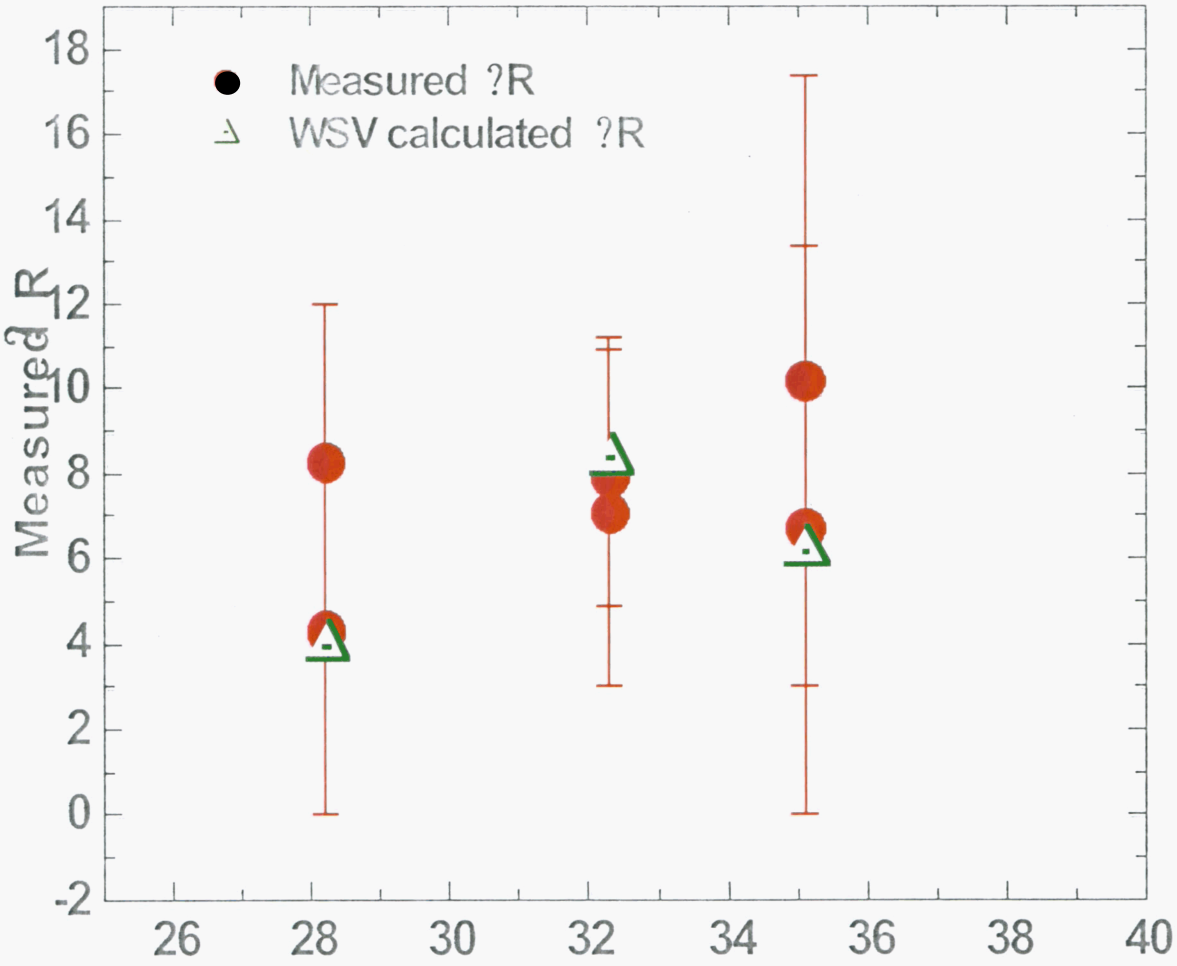


21707, e=1.0, D=18μm
31 atm DT fill



The compressed core image is a combination of emission from DT gas and inner glass shell

ρR measurement was obtained by Medusa, albeit with large error bars, in cylindrical hohlraums (Nov. 2000)



good agreement of ρR with 1D calculations

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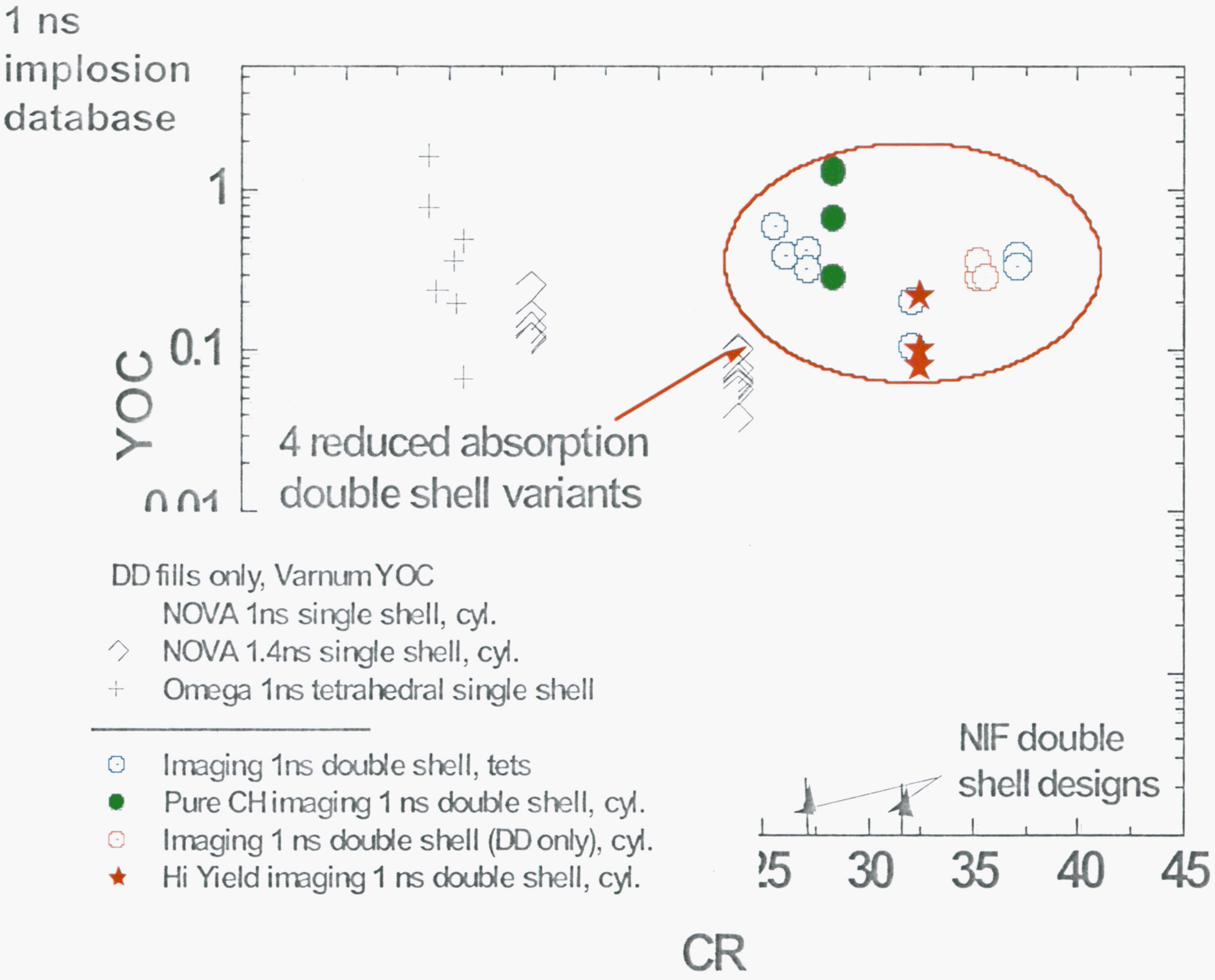
The imaging target concept gives near 1-D yield at convergence ratios up to 38 in either hohlraum type



DT shots, which also have high YOC at CR > 25, have been removed from this plot because the results are still in dispute. The "standard" and brominated low YOC DT data have also been removed for clarity.

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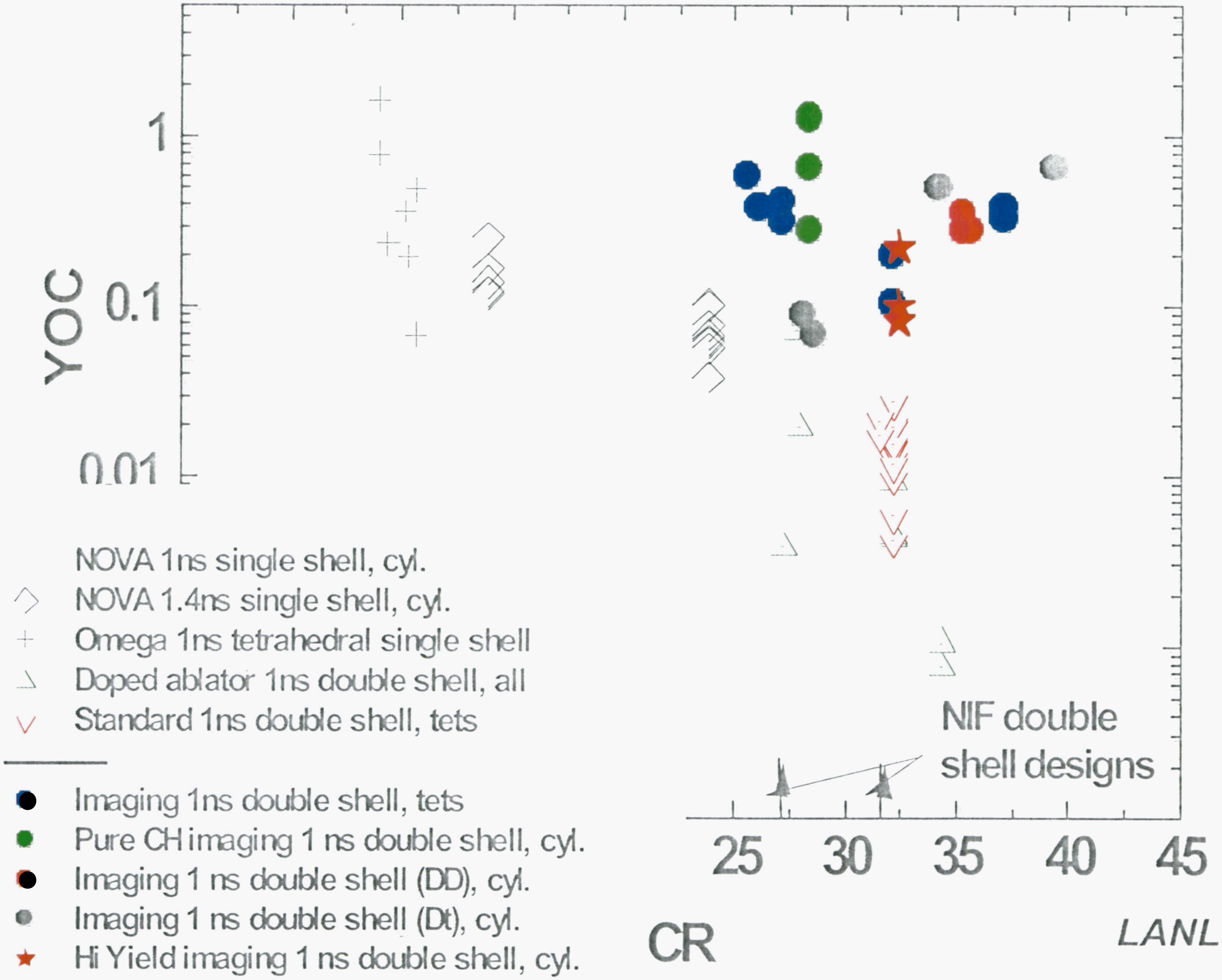
Imaging deuterium filled double shell targets worked well in recent Omega experiments with cylindrical hohlraums

- DD imaging capsules had YOC 35-45%, similar to tet results
- DD pure CH imaging capsules had a big spread from 19-95%
- DT filled Brominated CH capsules failed again
- DT imaging capsules had erratic YOC, with highest at 72% @ CR = 37 and the lowest at 1% @ CR = 26; DT fills are under investigation.
- Fuel ρR obtained on 6 of 15 shots, and agrees with simulations.
- Bangtime obtained on 13 shots with NTD, Tion obtained on 2 shots.
- Static core images obtained on most shots, with the core appearing round except for the Brominated CH capsules

All shots taken together, regardless of defects or gas fill, suggest a very robust system for “imaging” double shell designs



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Conclusions: indirect drive double shell results

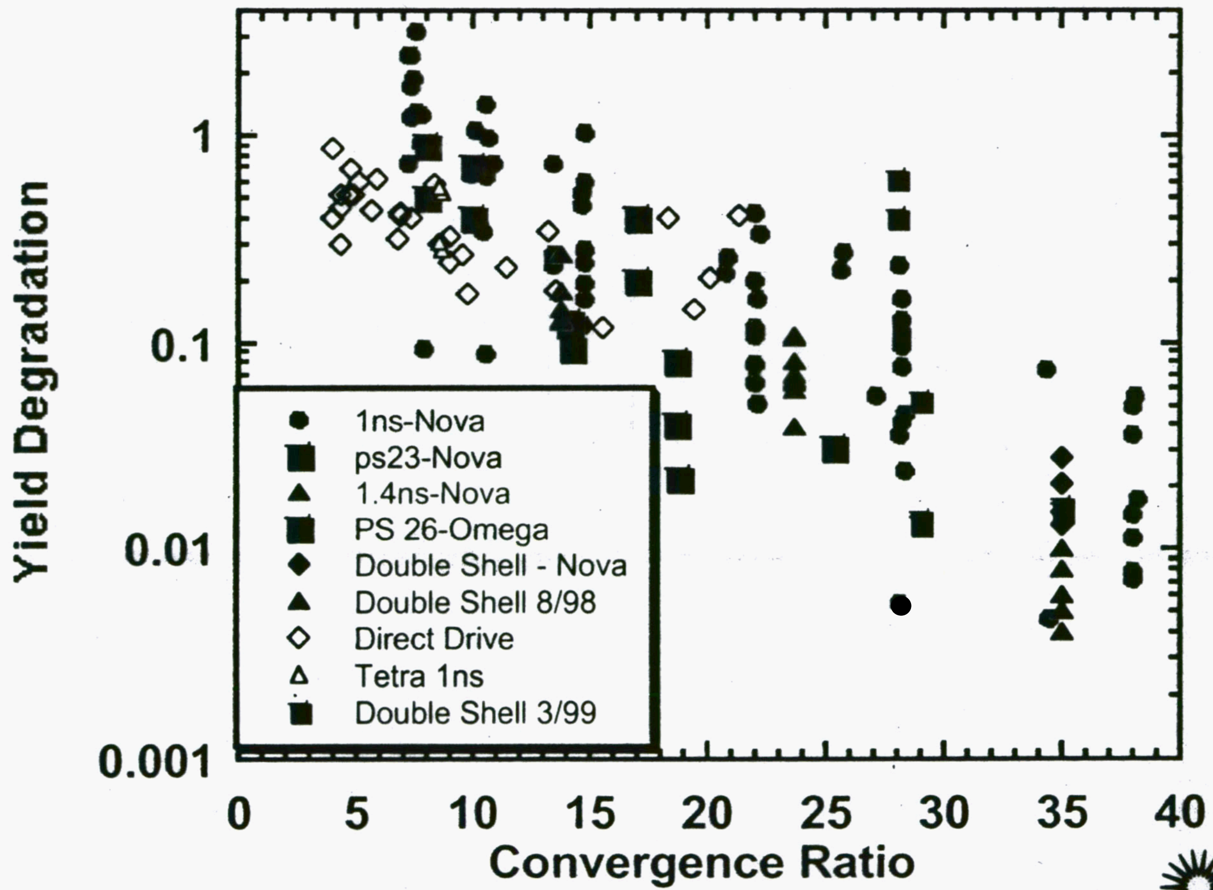
- Imaging designs that reduce the sensitivity to any Au M-band asymmetry operate at YOC up to 1 for CR up to 38 with D_2
- Imaging designs work well in both spherical and cylindrical hohlraums, so thermal asymmetry must not be the dominant degradation mechanism for the "standard" double shell
- Imaging implosions appear spherical in both hohlraum types, both in static and gated x-ray images
- DT filled imaging implosions have given high YOC (up to 70%) but have also given poor YOC for the same designs, for unknown reasons
- Additional Omega experiments to study M-band induced asymmetries are planned for FY02

Near term future plans

- Direct drive double shell implosions will be done in Sept. 2001 at Omega
  - this further examines the M-band as the culprit in degrading the "standard" historically poor double shell design
    - Direct Drive eliminates the Au wall completely
    - 1D calculations suggest higher, more easily measurable yields and ρR

    … so the "standard" and all other double shell target designs should produce near clean yield
  - a competing theory for the degradation of the "standard" double shell based on diffusive mix is not sensitive to the change to direct drive so if mix is the culprit the "standard" target should fail as always

Historic yield over clean calculated yield (YOC) has shown a fall off with convergence ratio



Explantions have included:

- **mix due to growth of surface roughness**
- **flux assymetry on the capsule**

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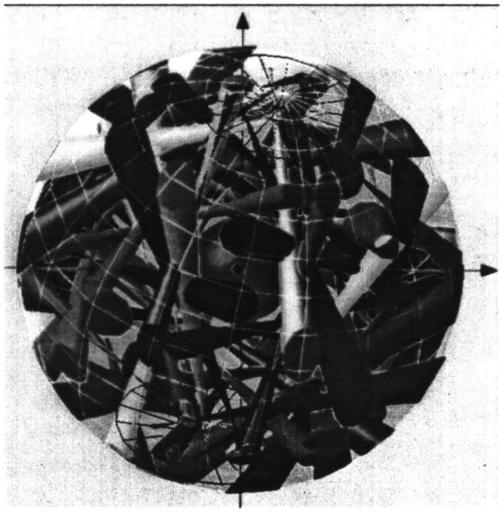
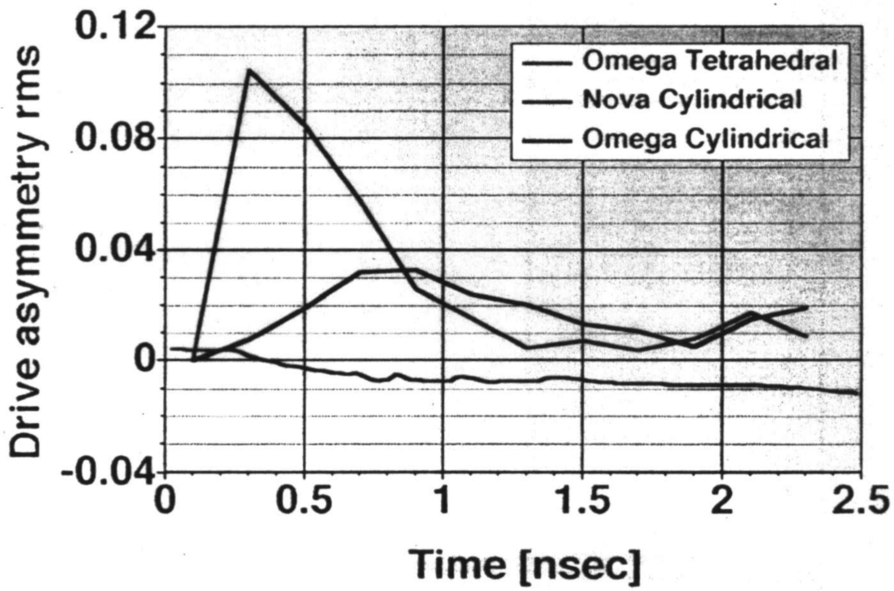
To address the importance of symmetry in yield degradation, we set out to perform implosion experiments in a very symmetric environment





View factor calculations (Pollaine and others) indicated that tetrahedral hohlraums could produce very good time dependent flux symmetry.

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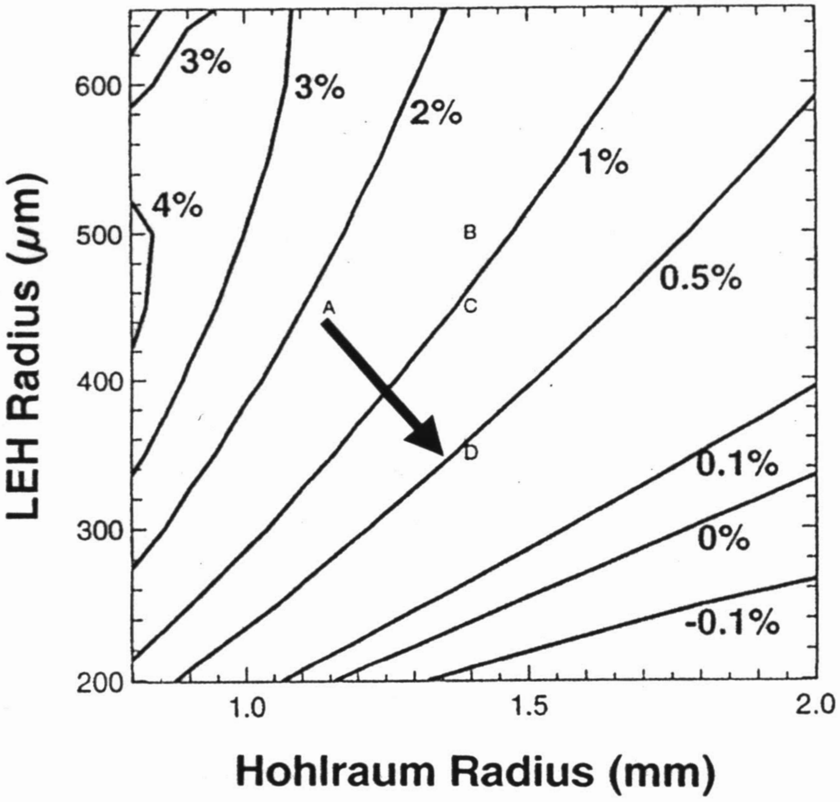
View factor calculations by Pollaine suggested that a larger radius and smaller LEH could improve symmetry



The larger hohlraum and a desire to use shaped pulses caused a large drop in the x-ray drive available for driving a capsule.

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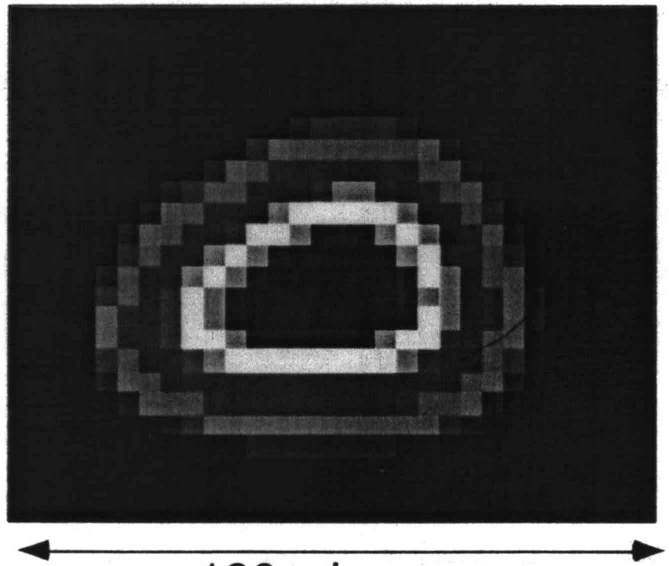
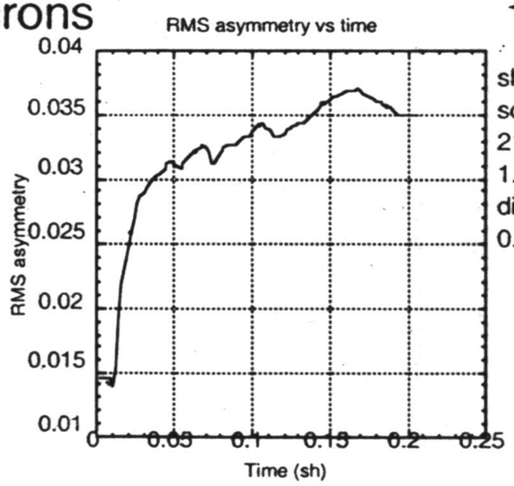
We can control the flux asymmetry in tetrahedral hohlraums

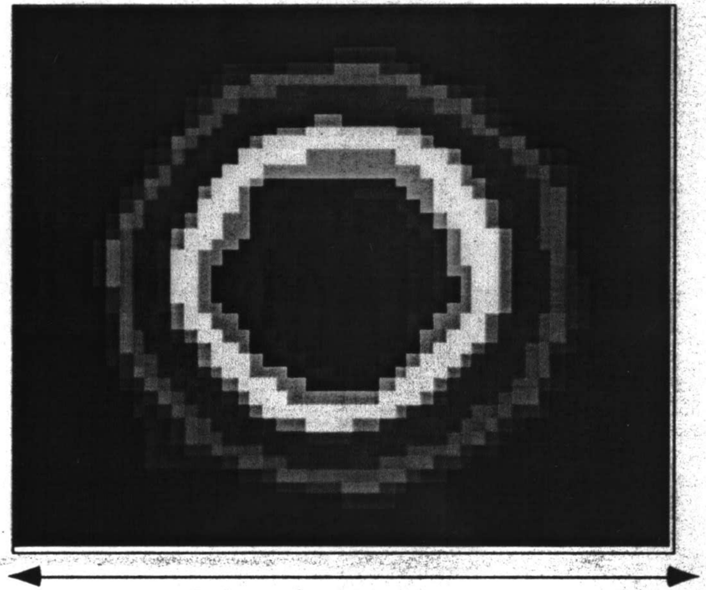
Omega experiments in March and August 1997 show that tetrahedral hohlraums are an alternative to cylindrical



120 microns

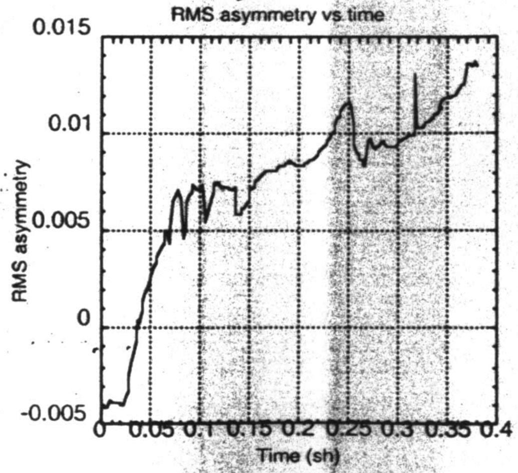
shot 9018 (march 1997)
scale 1 tetrahedral, 450 leh
31.6 kJ laser energy, 1ns square pulse
5.5E8 neutron yield
distortion=1.16
3.6%rms Y32 flux asymmetry





80 microns

shot 10354 (august 1997)
scale 1.2 tetrahedral, 350 leh
21.8 kJ laser energy, ps22 laser pulse
1.2E8 neutron yield
distortion=1.01
0.8%rms Y32 flux asymmetry



Comparison with detailed modeling is necessary for ultimate applications

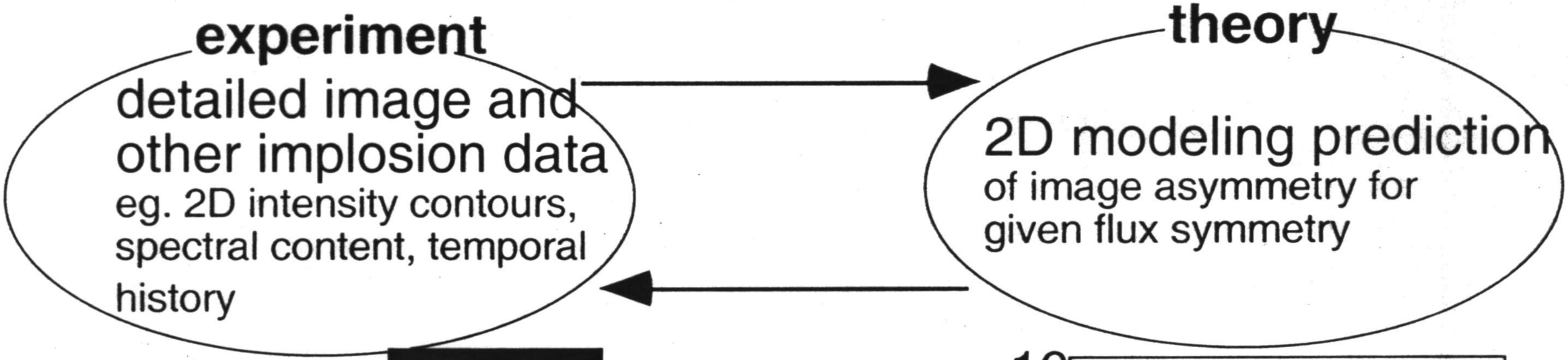
- **2D radiation hydrodynamic codes** - attempt to solve the complete integrated problem with laser deposition , hydrodynamic motion, radiation transport
  - implosion hydrodynamics are treated in Lagrangian mode
  - absorption - inv bremsstrahlung , resonance absorption for optical ; opacity tables for x-rays
  - thermal transport - typically flux limited diffusion
  - rad. transport - multigroup flux limited diffusion is one possibility
  - detailed radiation physics (diagnostics)
    - average ionization state calculated in line with hydro
    - some detailed ionization and excitation physics can be calculated in line but more typically "post process" output files of temp. density etc.

- view factor codes can treat the problem in 3D but do not include accurate laser deposition or hydrodynamics

  does include changing albedo factors recalculated to account for heating

  realistic radiation transfer (but does not allow for absorption of plasma filling the hohlraum)

Detailed comparison of experiment is made with radiation hydrodynamic modeling



experiment

detailed image and other implosion data

eg. 2D intensity contours, spectral content, temporal history

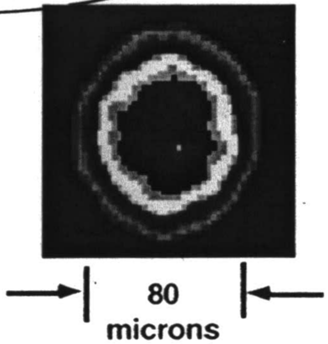
theory

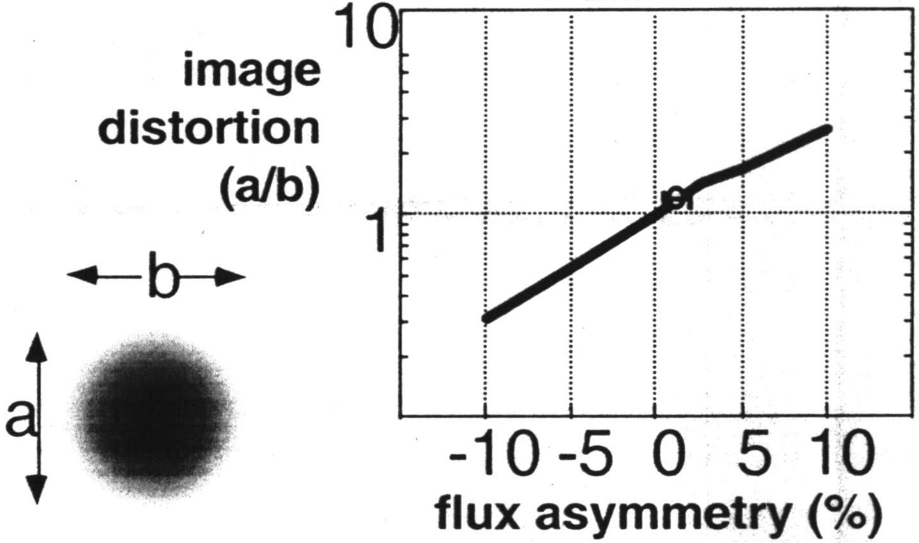
2D modeling prediction

of image asymmetry for given flux symmetry

a/b~1.05

convergence ratio ~ 7



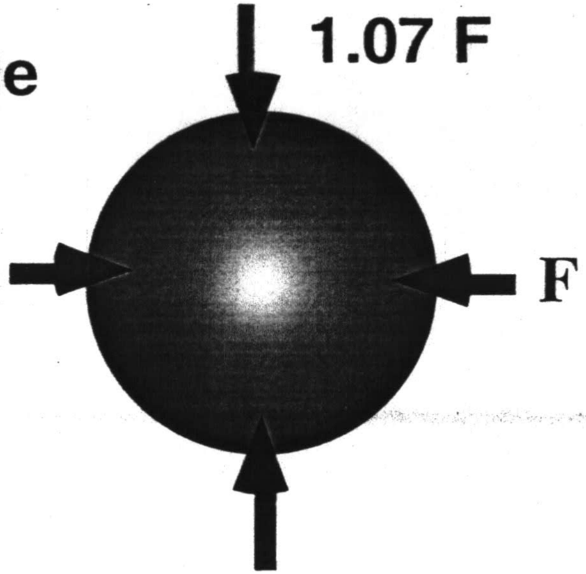


7 % flux asymmetry gives a 2:1 image distortion

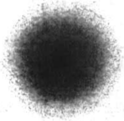
The shape of the imploded core amplifies the flux asymmetry on the capsule

$$\frac{\Delta r}{r_{final}} \cong \frac{r_0}{r_{final}} \frac{\Delta v}{v} = C_r \frac{\Delta v}{v} \quad ; \quad v_{implosion} \propto T_r^{1.5}$$

consider the example of a 7% flux asymmetry



for $C_r \sim 10$



compressed core

7% Flux → 1.75% T_R → 2.5 % velocity → 2:1 distortion

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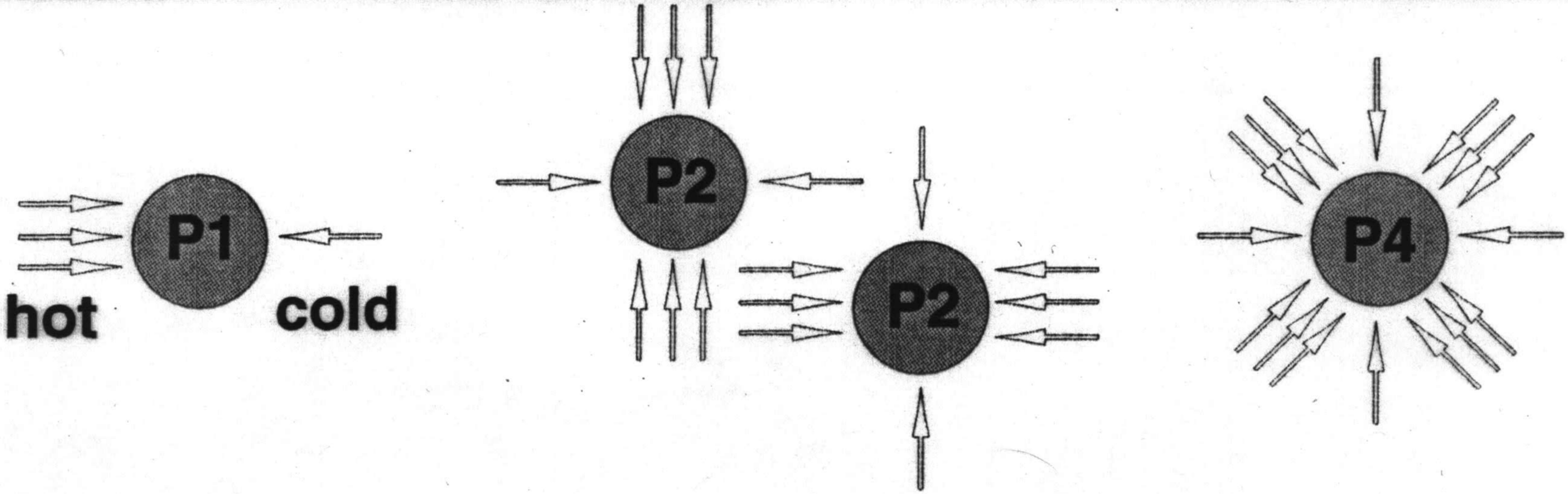
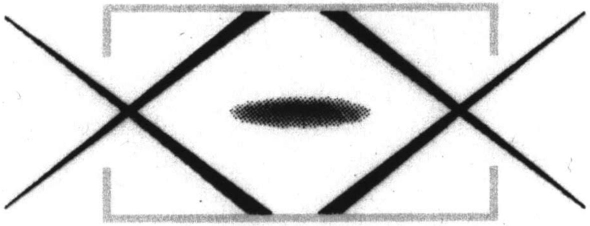
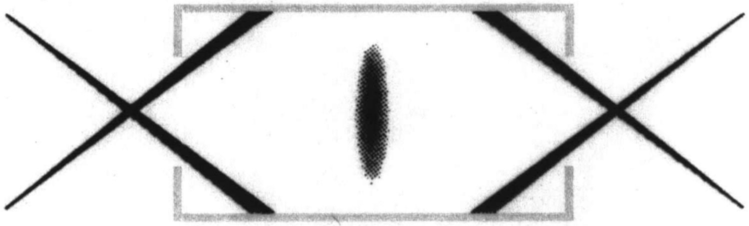
Symmetry is analyzed in terms of Legendre Polynomials



- *P2 mode is typically the largest mode in a cylindrical hohlraum configuration*
- *Pointing scans involve moving the beams inwards or outwards*

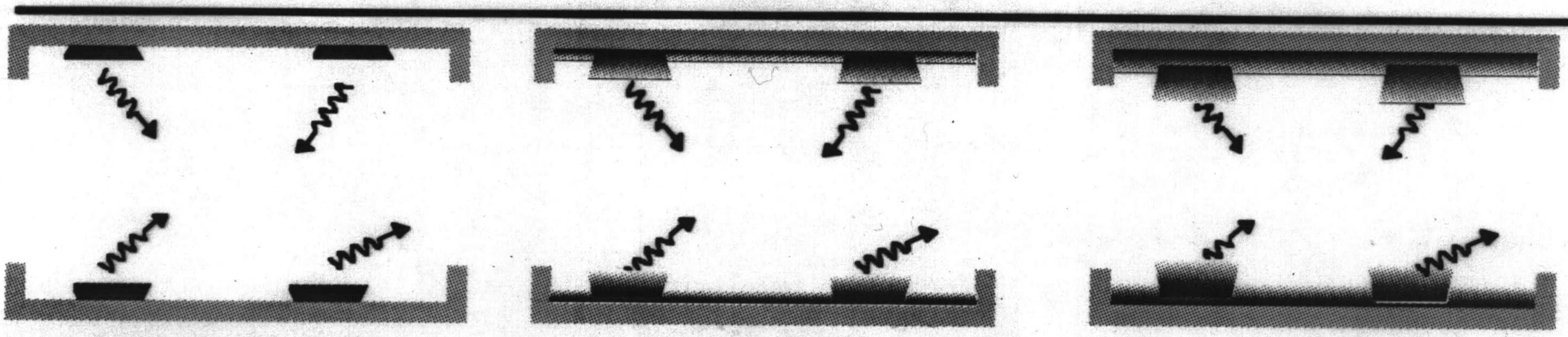


Inward pointing
equator-hot
"sausage"



Outward pointing
pole-hot
"pancake"

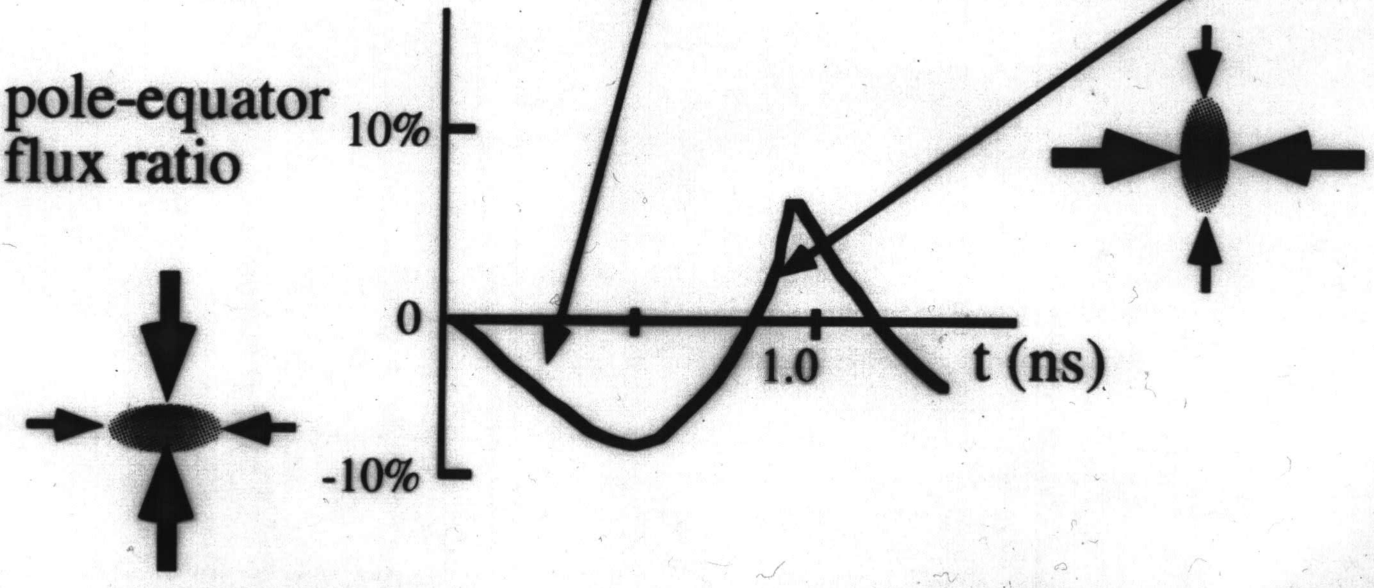
generic picture of time varying symmetry



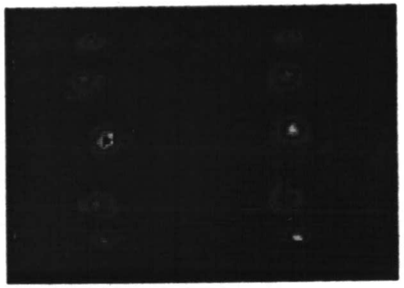
localized energy deposition in laser focal regions

walls heated by x-ray flux and **albedo rises**

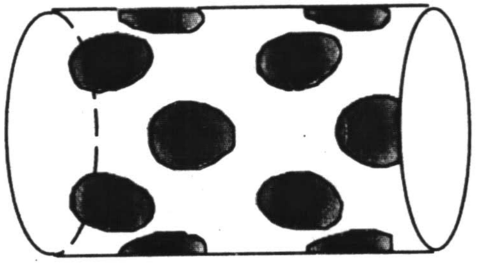
regions of laser absorption and strongest **soft x-ray** emission **move inward**

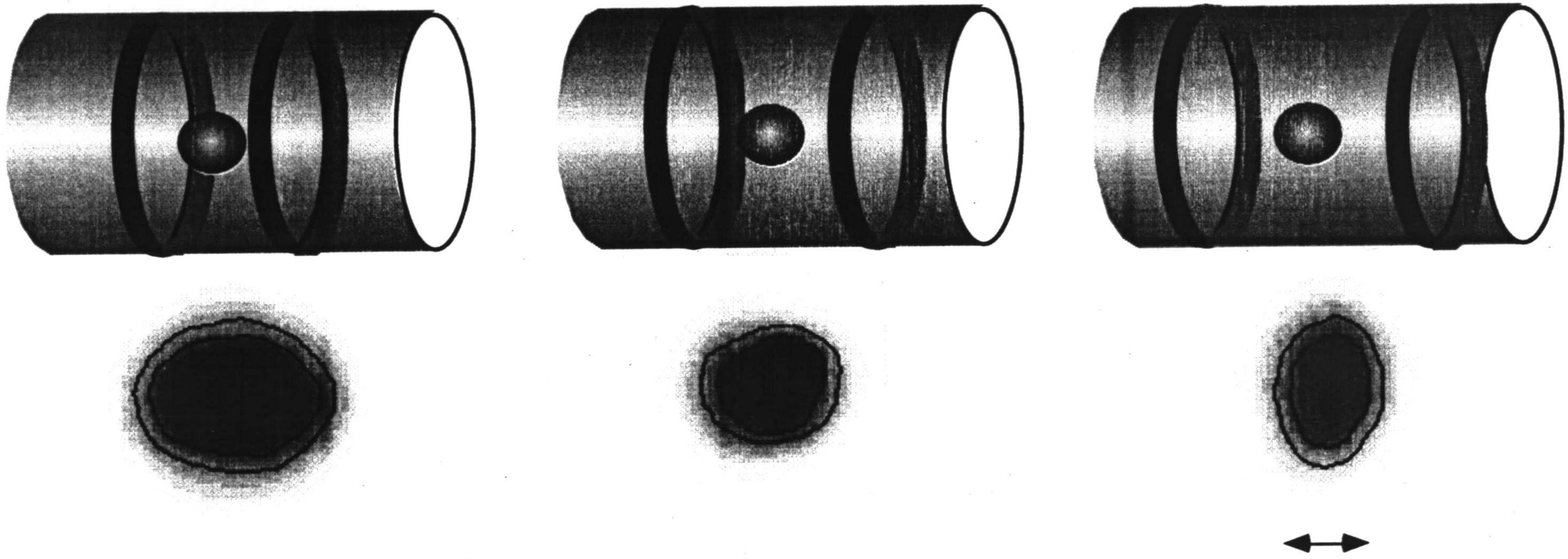


symmetry can be tuned by moving the "rings" of illumination



x-ray image
through
hohlraum
wall

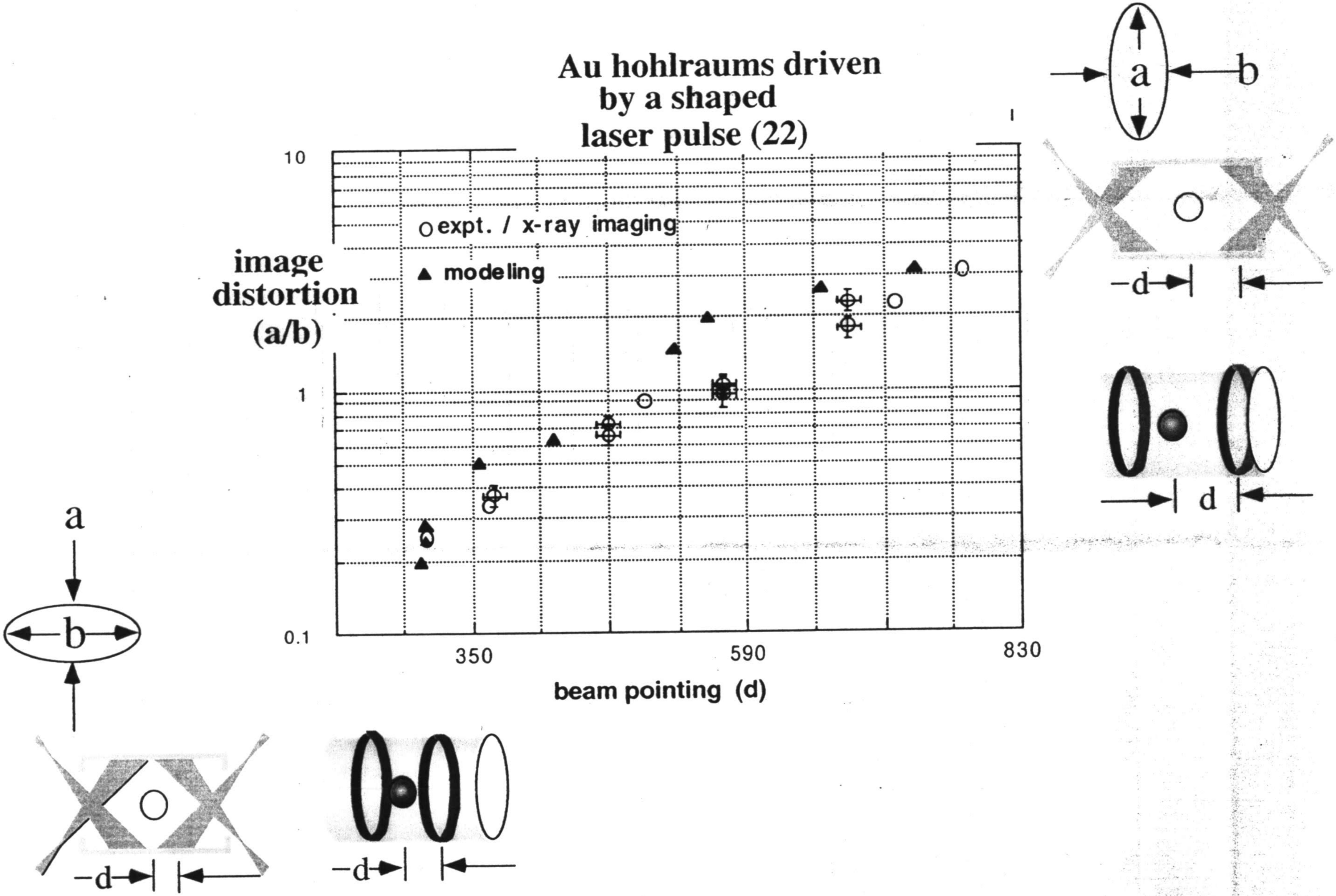




x-ray images of compressed core

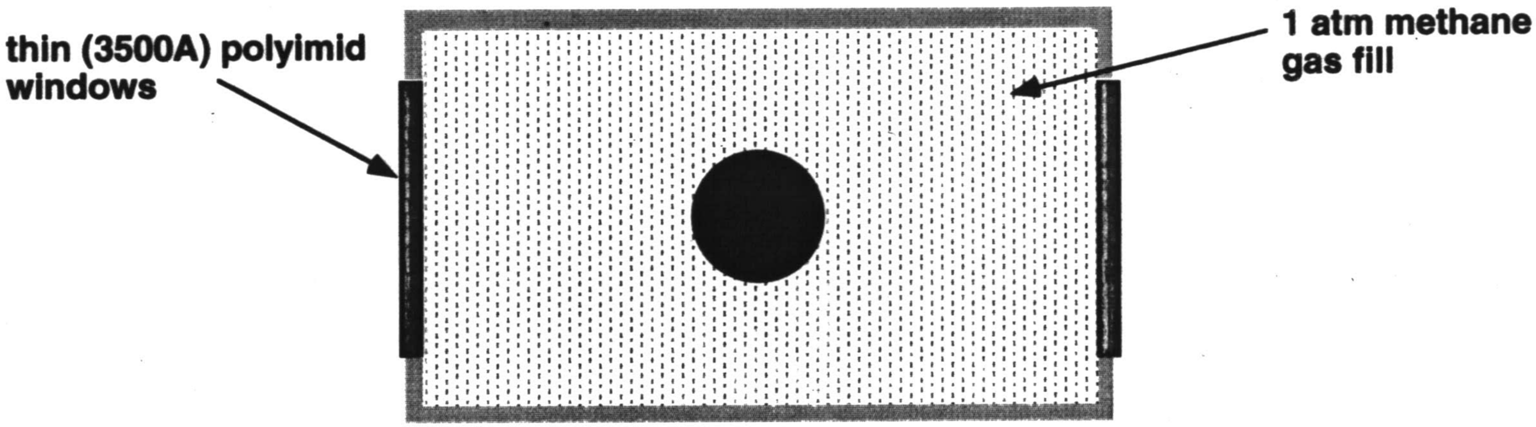
20 microns

Experiments show sensitive tuning of symmetry that agrees with modeling



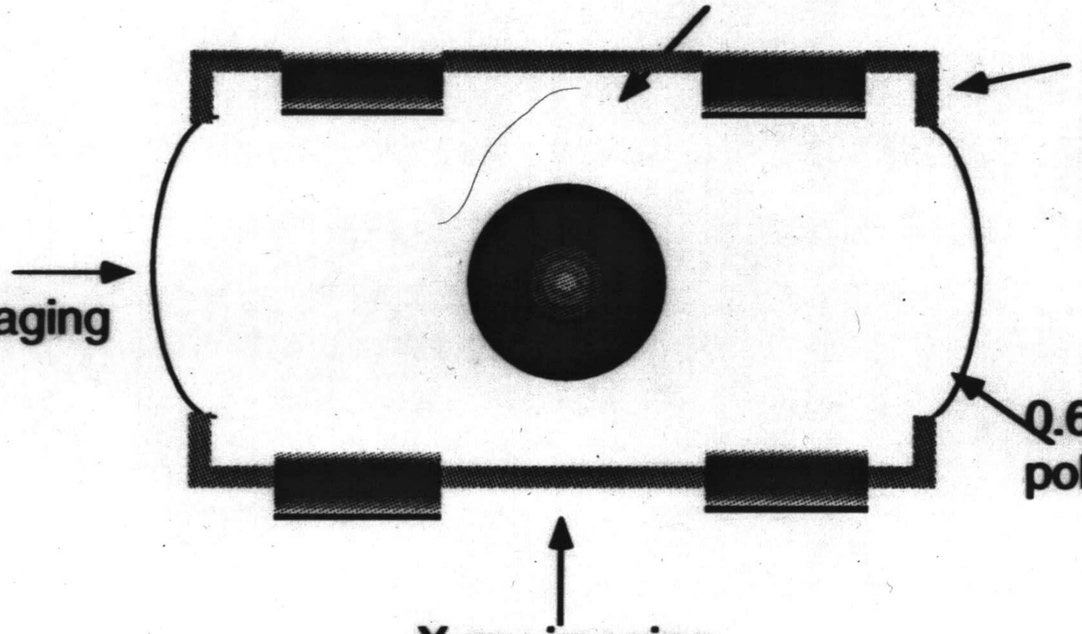
Au hohlraums driven by a shaped laser pulse (22)

Gas-filled hohlraums mimic many of the requirements of NIF hohlraums



- NIF ignition designs require a gas fill to inhibit plasma filling and spot motion
- Symmetry can be measured in conditions close to those predicted for NIF
- Large gas-filled hohlraums have Ne, Te and scale lengths close to those in NIF designs
- Experiments with gas fill can help improve the predictive capability of the modeling codes.

We have completed a series of experiments to measure symmetry of implosions in gas-filled hohlraums at Nova



time resolved spectrometer

standard hohlraum with
25µm gold wall OR
2µm thick thin wall
hohlraum

axial imaging

0.6µm mylar, 0.1µm or 0.35 µ
polyimide window over 75% LEH

X-ray imaging

- **Diagnostics** include gated and time integrated x-ray imaging, time resolved x-ray spectroscopy, neutron yield and Tion measure.
- **We study symmetry variation** by changing laser pointing and hohlraum length.
- **Gas fill** is varied to study effects of differing gas density

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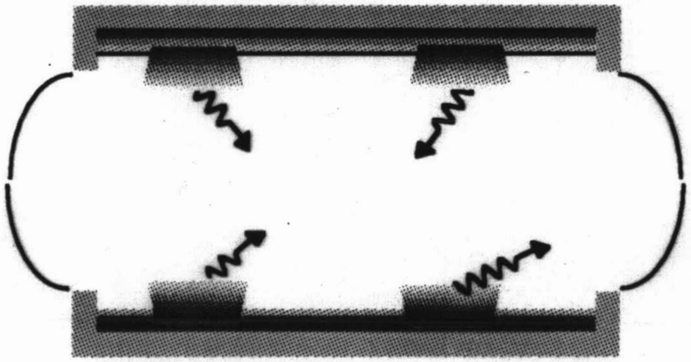
Purpose: To better understand physics issues associated with NIF target design

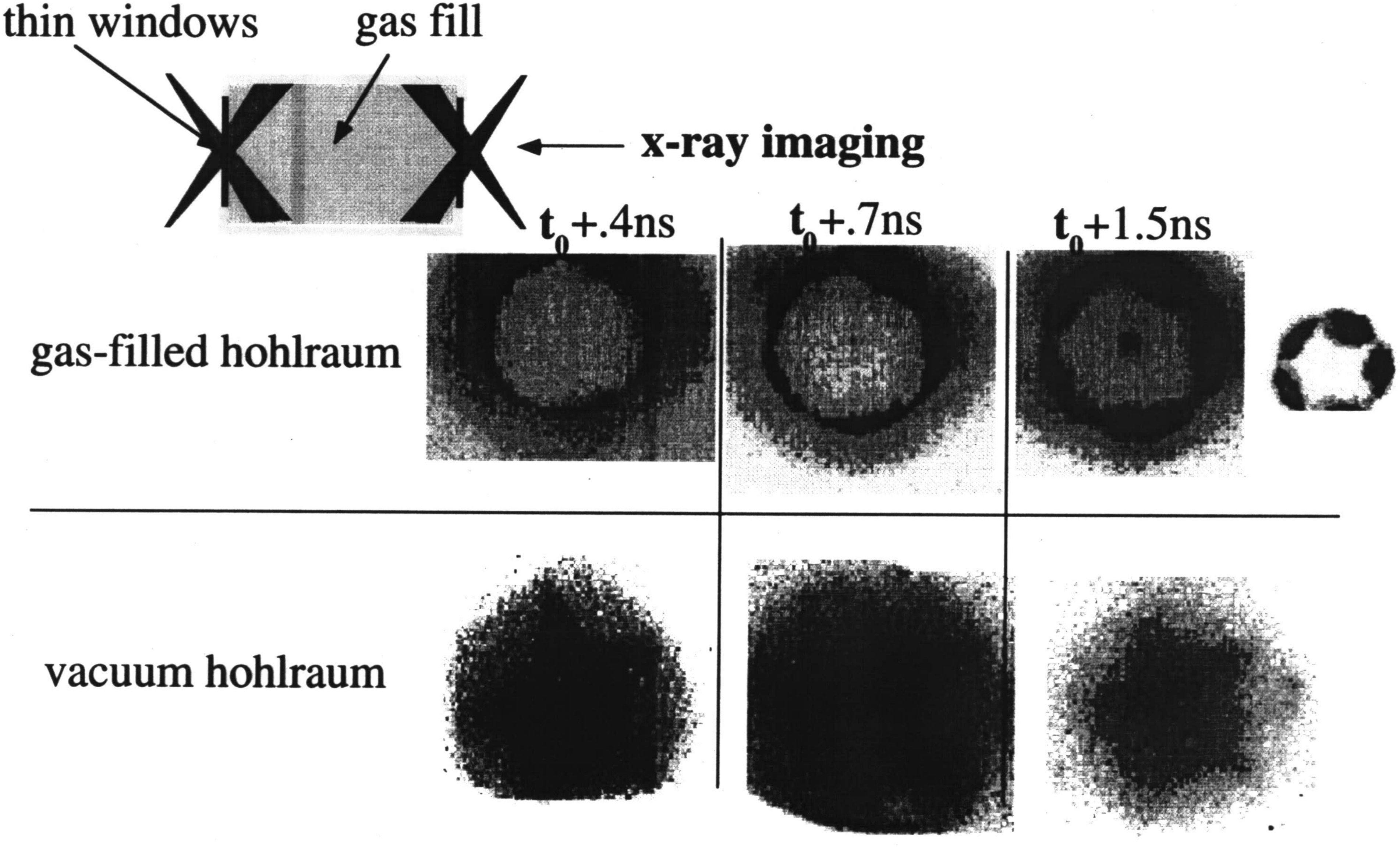
- Understanding **drive symmetry in gas filled hohlraums** is currently of interest because the baseline design of the NIF ignition target **requires** a gas filled hohlraum.

- The purpose of filling the hohlraum with gas is to **tamp the motion of the gold ablating from the walls.**

- To **understand the important physics issues** with gas filled hohlraums and help **develop our modeling codes**.



gas-filled hohlraums have been shown to suppress wall blowoff



thin windows

gas fill

x-ray imaging

t_0+.4ns

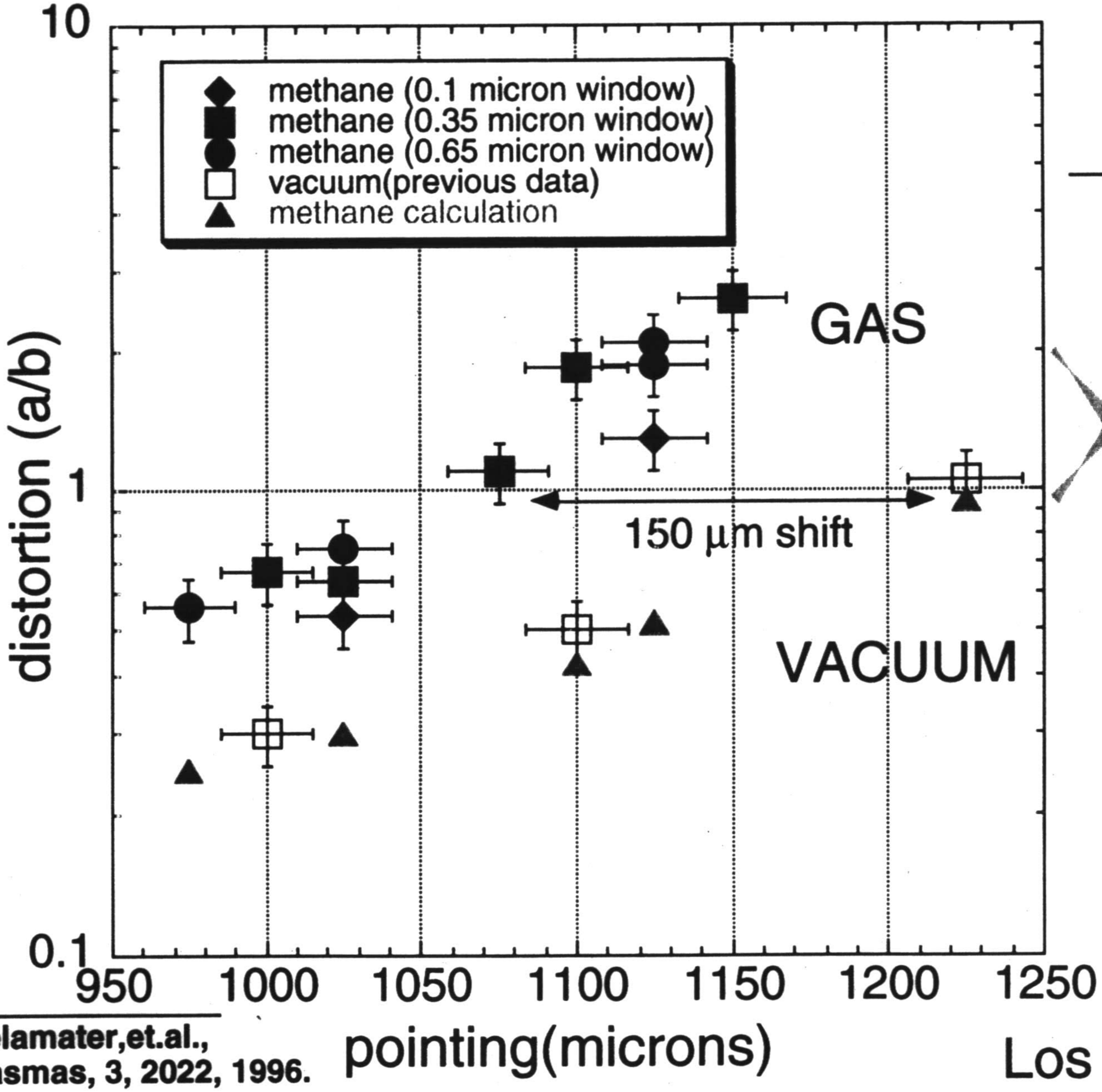
t_0+.7ns

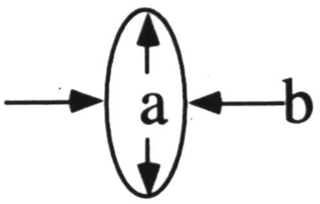
t_0+1.5ns

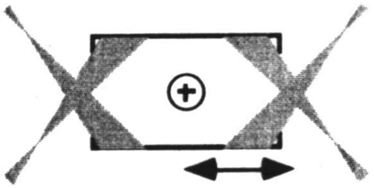
gas-filled hohlraum

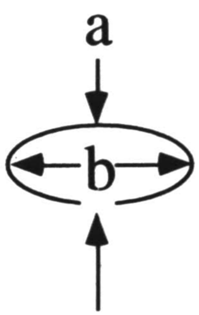
vacuum hohlraum

Pointing scan in methane with **unsmoothed** beams shows a shift of 150µm from previous vacuum data









Reference: Delamater,et.al.,
Physics of Plasmas, 3, 2022, 1996.

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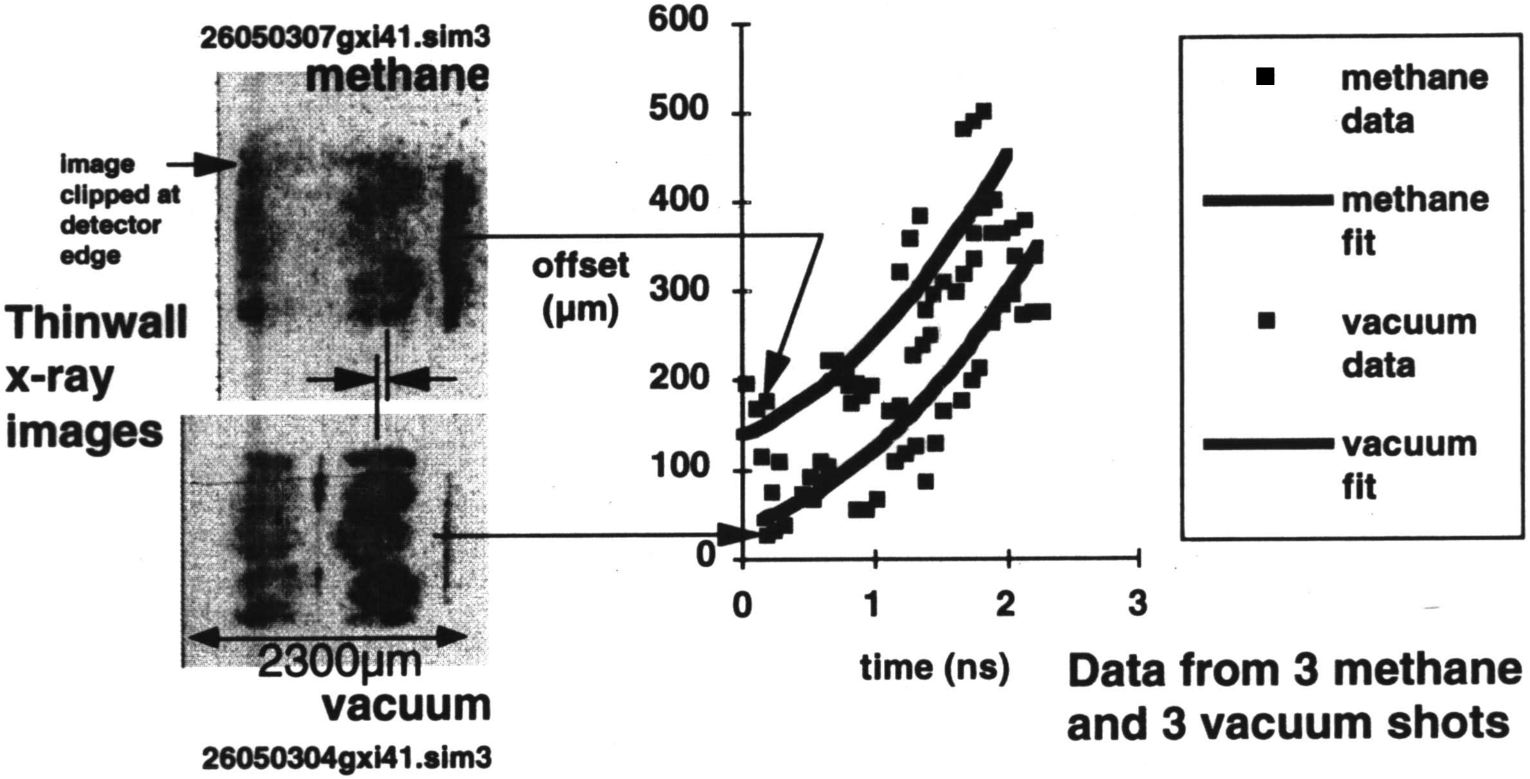
Unsmoothed NOVA beams shift outward 150µm with methane fill



Data from 3 methane and 3 vacuum shots

Reference: N. Delamater, et.al., Physics of Plasmas, 3,2022 (1996)

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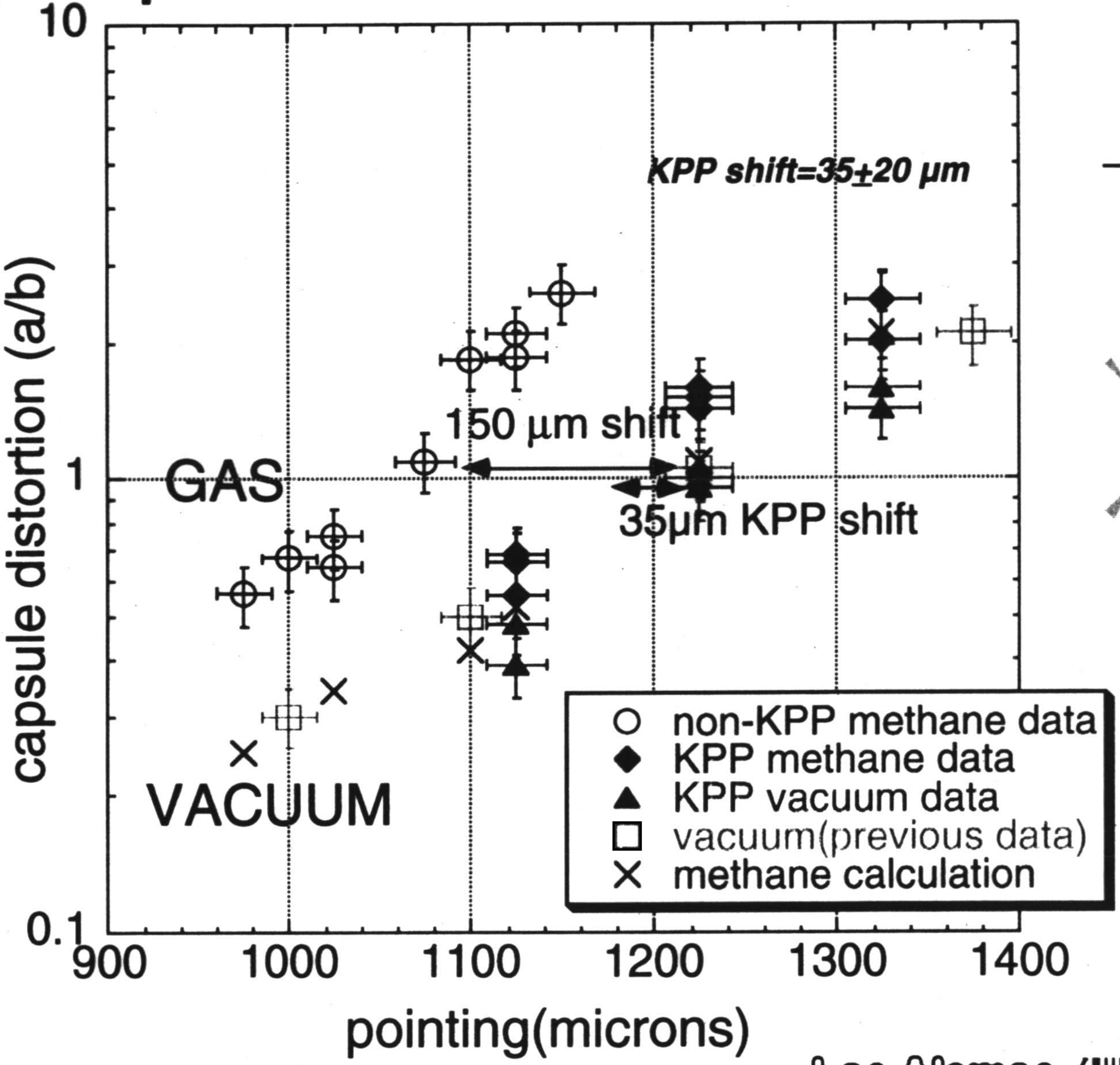
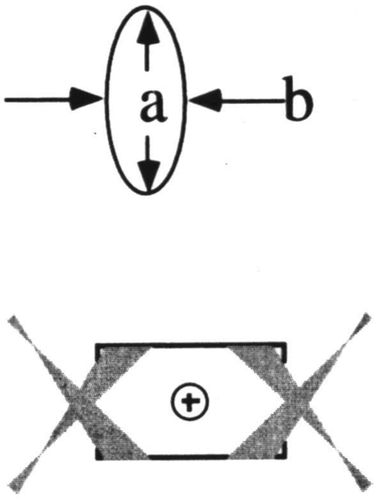
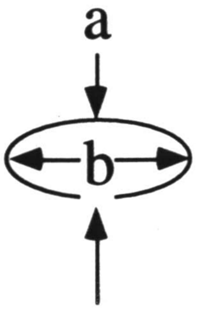
Implosion pointing scan with smooth beams shows only a 35µm shift in methane-filled hohlraums







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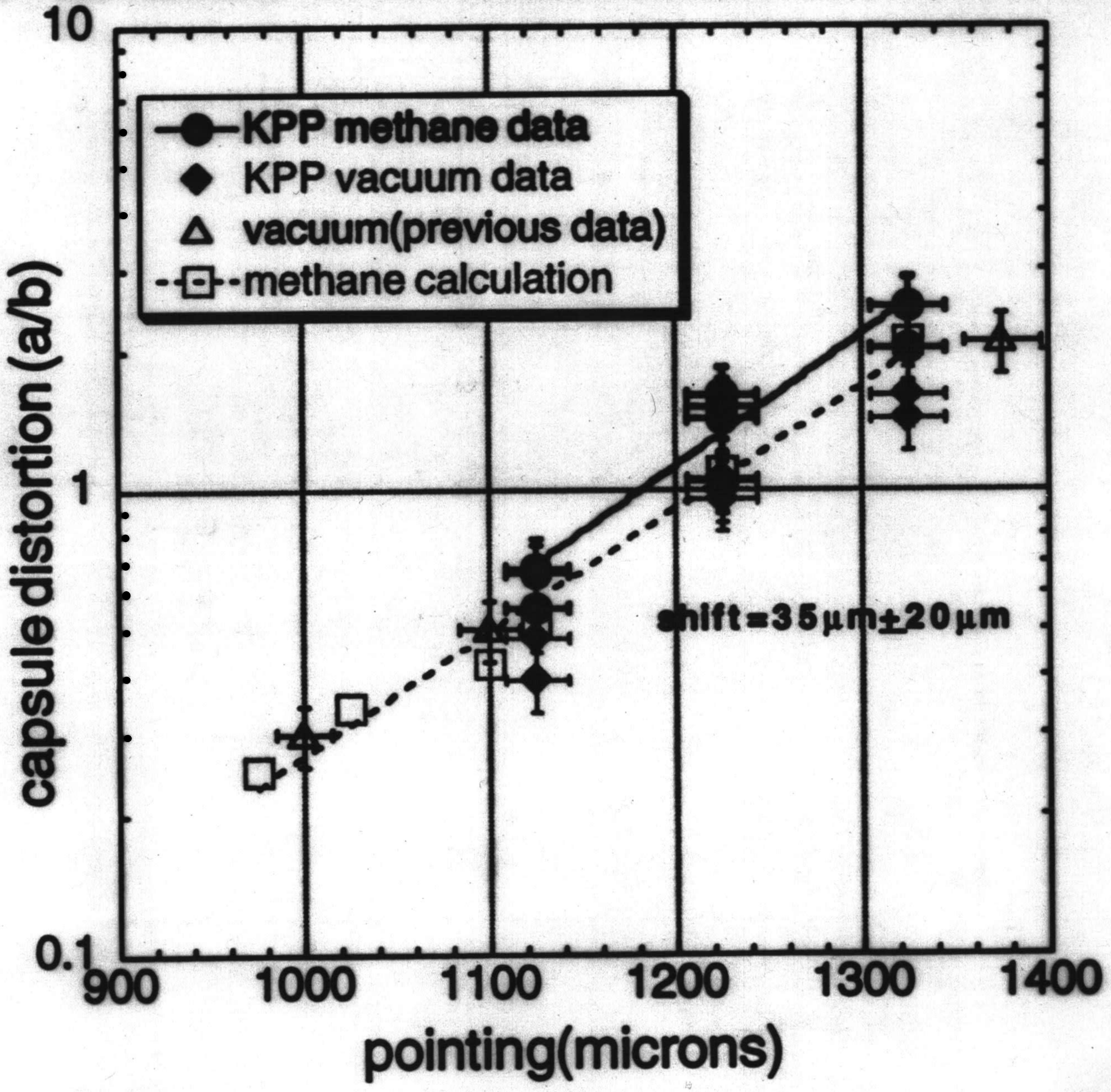
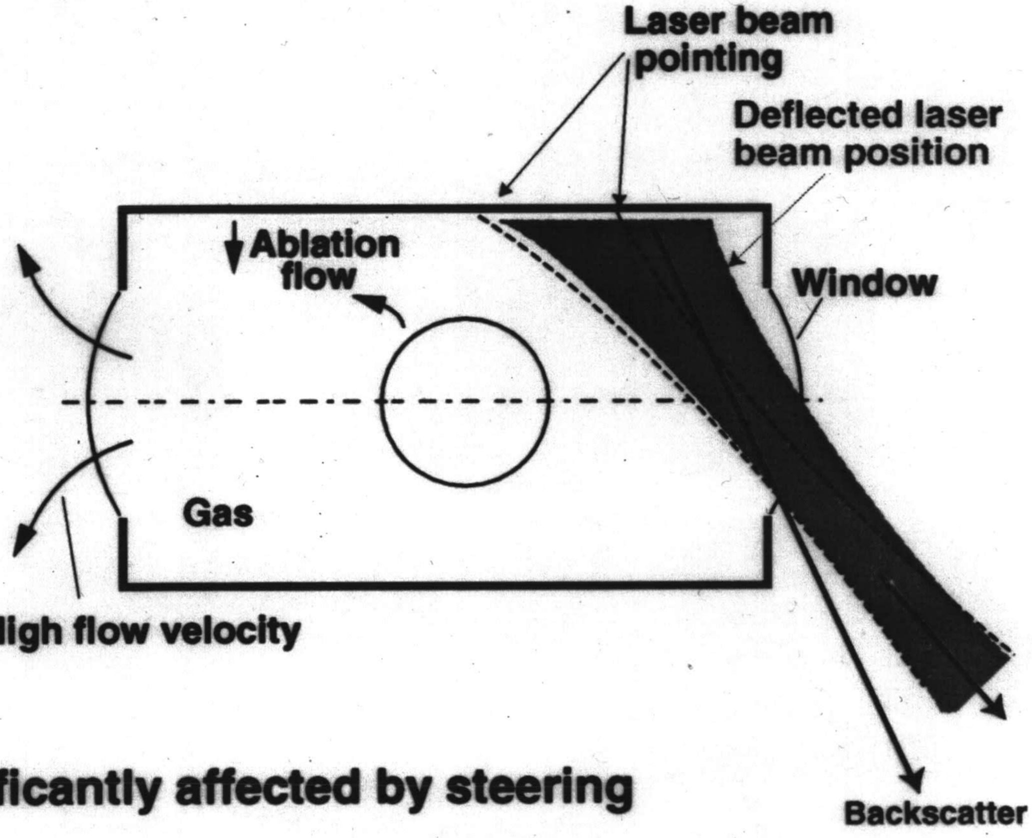
Curve fits of the KPP methane results shows a small residual shift remaining between gas results and calculation



Transverse plasma flow with filamentation can steer the laser beam in the gas filled hohlraum environment

We are formulating a picture of gas-filled hohlraums

- Beam steering has been observed in gas-filled hohlraums
- Beam steering may be explained, in part, by plasma flow bending filaments
- Comprehensive gas-filled hohlraum data base is consistent with beam steering early in time



- Drive symmetry has been significantly affected by steering
- The physics necessary to model these effects is not in LASNEX

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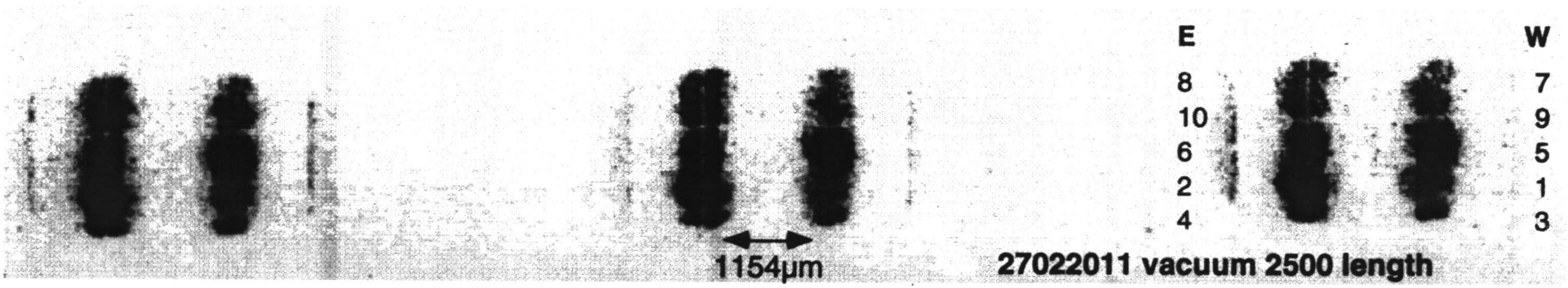
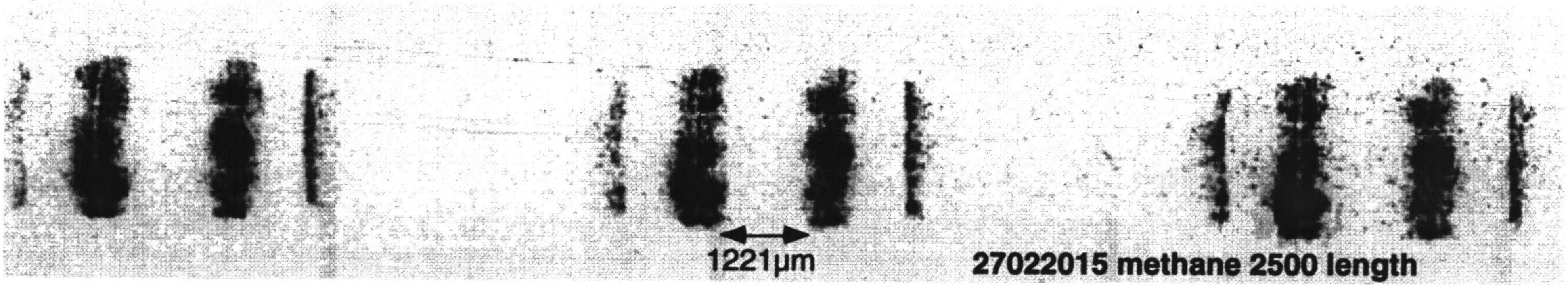
Laser spots at early times appear in similar relative positions on thin wall hohlraums for vacuum or methane fill with 10 KPPs

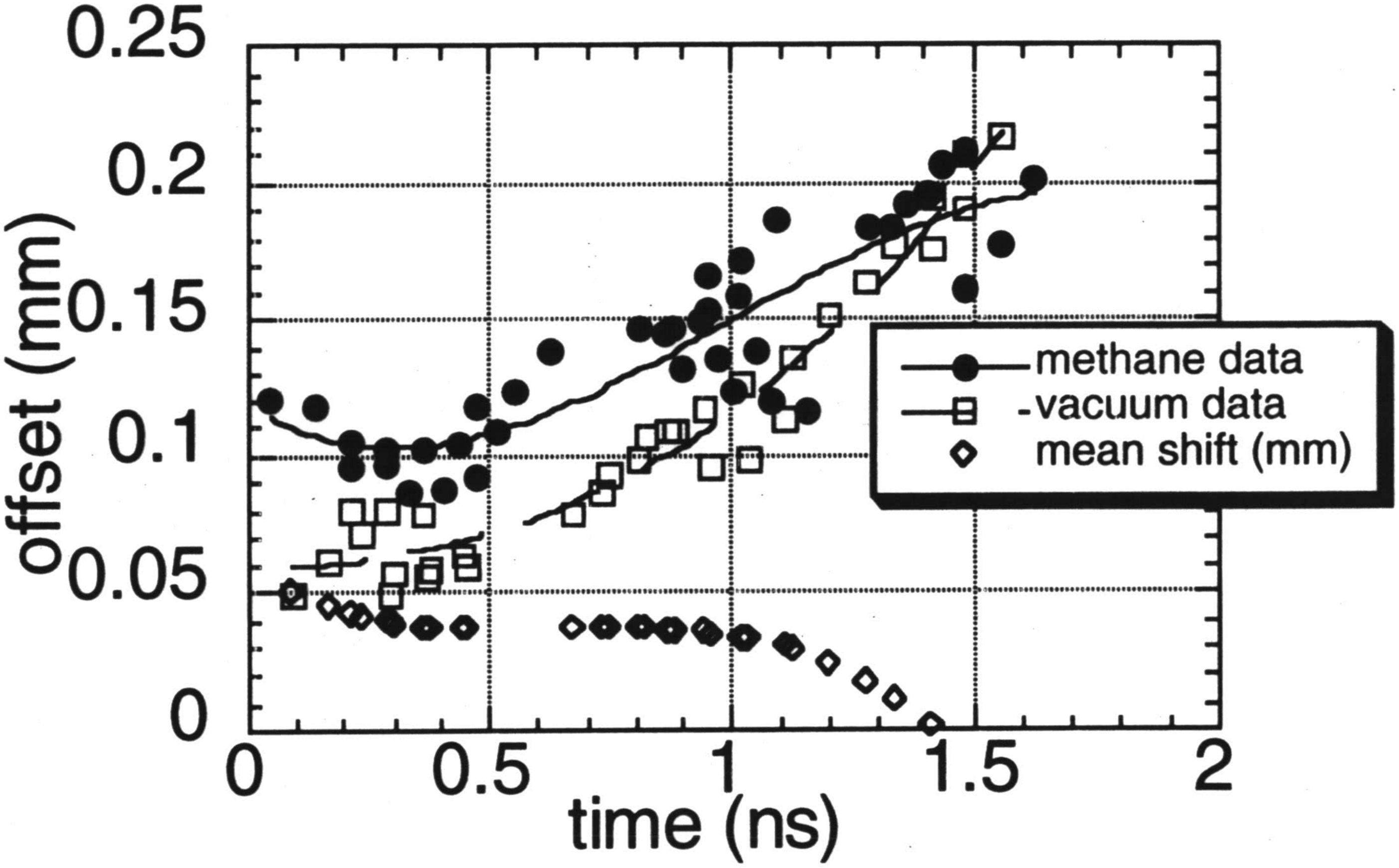




images at times 0.15 - 0.4 ns in each stripline
nominal spot positions are 696μm from ends and 1107μm spot separation

KPPs appear to remove much of early time beam steering but spots appear shifted by about 35 μm outward in gas

Measurement of laser spot positions in thin-wall hohlraums shows a small offset for gas filled hohlraums with smooth beams



A shift of 35 μm is seen during the first nanosecond using KPP smoothed beams for methane-filled hohlraums

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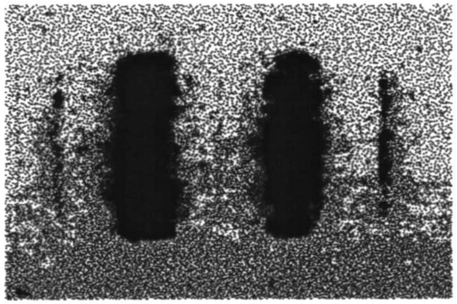
Smooth beams significantly reduce beam steering in gas-filled scale-1 hohlraums at Nova

- ***These results are consistent with the hypothesis that filamentation with plasma flow was the cause of the beam deflection observed previously.***
- *Results from both implosions and imaging of laser spots through thin-walled hohlraums shows that beam steering is **reduced by 4X** from the unsmoothed beam results*
- *Scale-1 gas filled hohlraum experiments with smoothed beams show lower SBS / SRS losses and higher Trad*
- *The initial KPP thinwall shots discovered laser pointing errors affecting shots using precision pointing at Nova. The errors were corrected.*



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