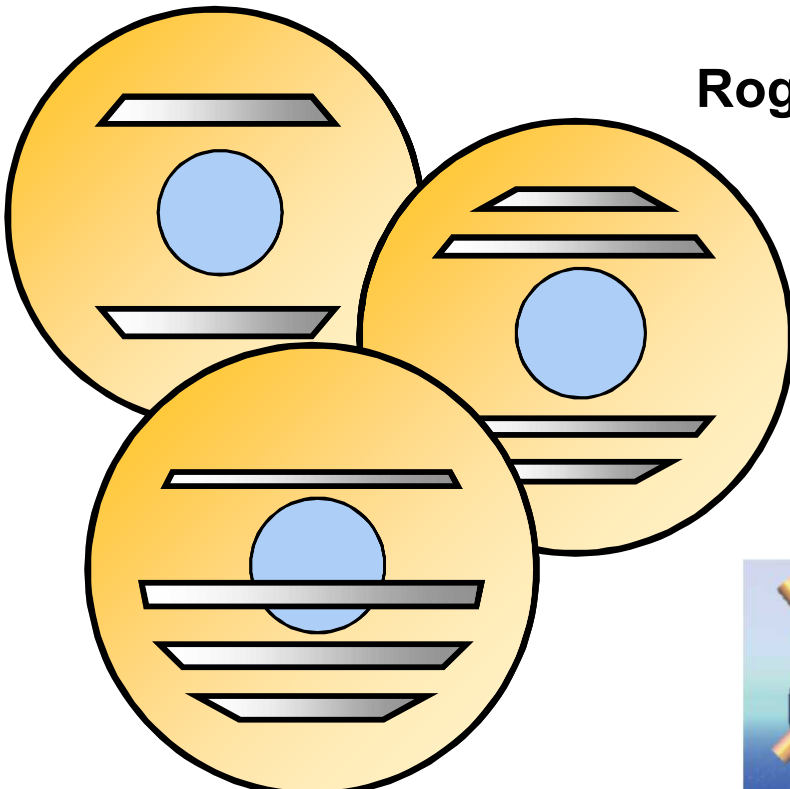
SAND2007-6007C

Mode-selective shields as a target design technique for radiation symmetry control in hohlraums



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Albuquerque, NM, USA

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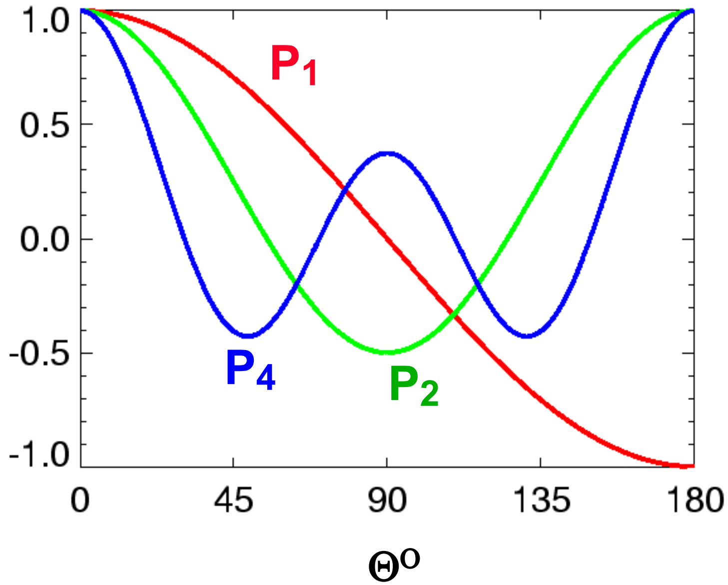
Radiation symmetry control techniques are crucial for indirect drive inertial fusion target designs

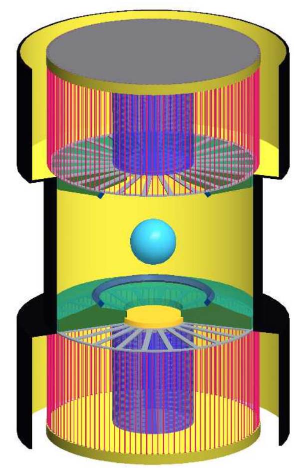
Flux in 2D axisymmetric – Legendre modes :

$$f(\theta) = \sum_n a_n P_n(\cos\theta)$$



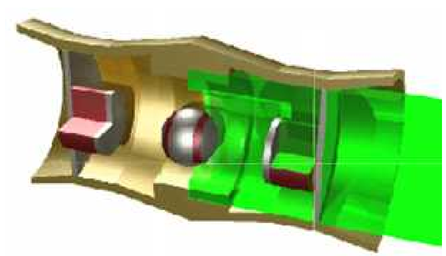
NIF hohlraum

multiple beam cones
beam power phasing
gas/foam fill
LEH shields



Double z-pinch driven hohlraum

hohlraum geometry
burn-through layers
shields

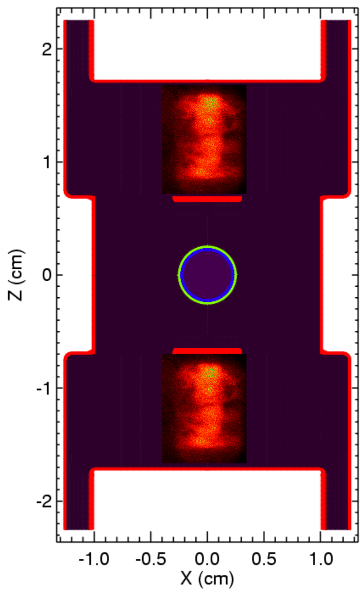


heavy ion hohlraum

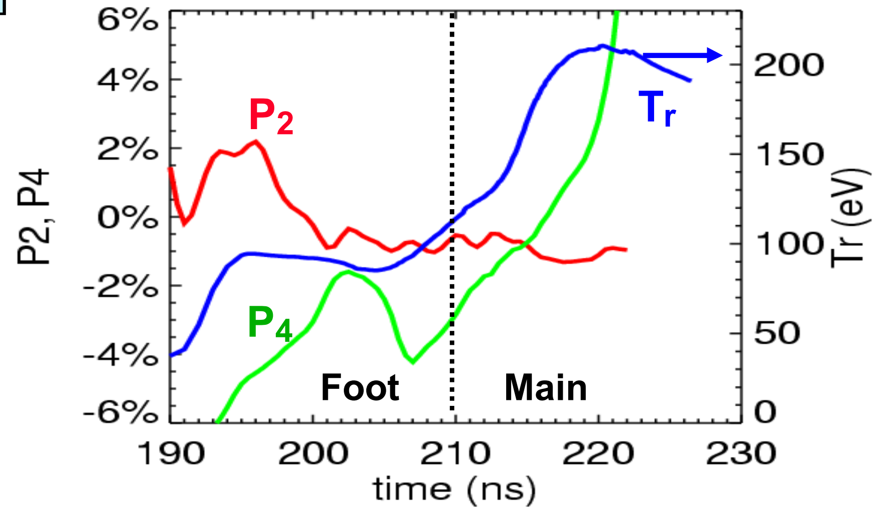
beam pointing and range
tailored convertors
capsule shims

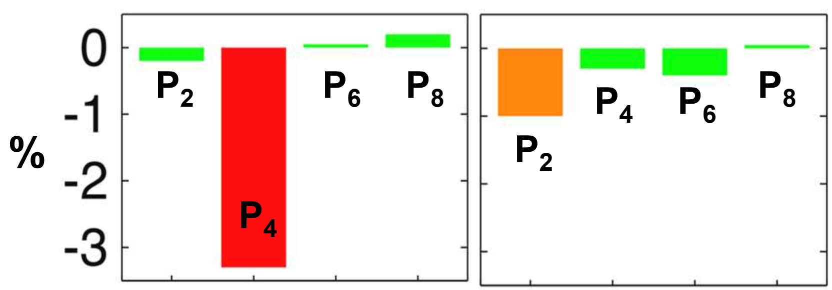
The problem of specifically controlling P_4 asymmetry arose in a recent high yield target design study

Double z-pinch driven hohlraum

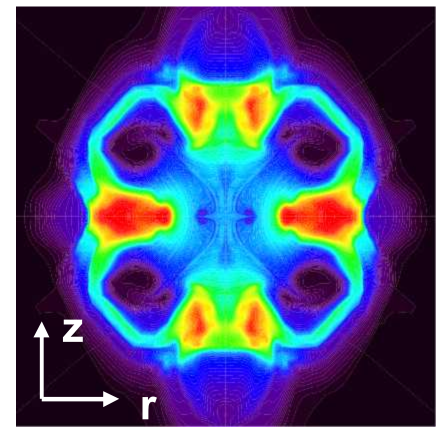


Ablation pressure asymmetry





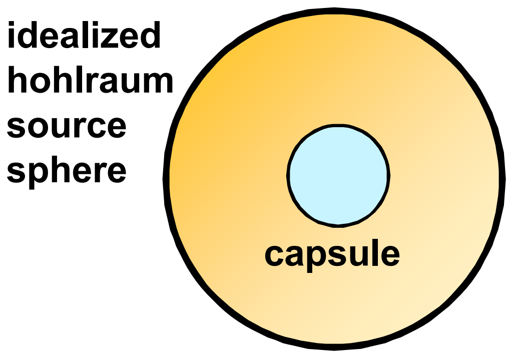
Fuel density contours at peak convergence



Yield = 0.040 MJ

The problem of specifically minimizing P_4 without significantly enhancing P_6 and P_8 was solved using mode-selective symmetry shields

Geometric averaging at the capsule reduces the effects of source flux asymmetry

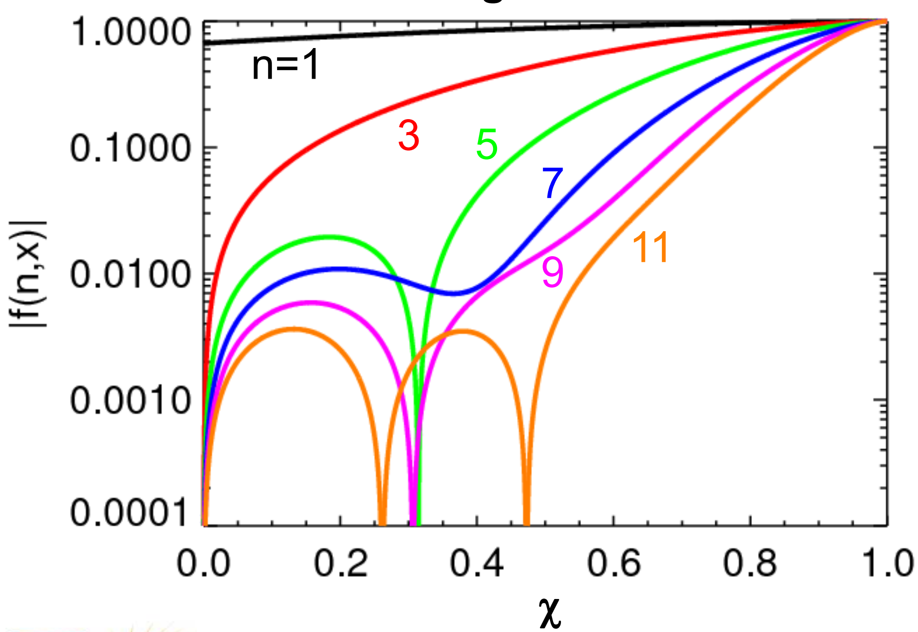


A. Caruso and C. Strangio, *Japanese J. Appl. Phys.* **30**, 1095 (1991)
M. Murakami and K. Nishihara, *Japanese J. Appl. Phys.* **25**, 242 (1986)

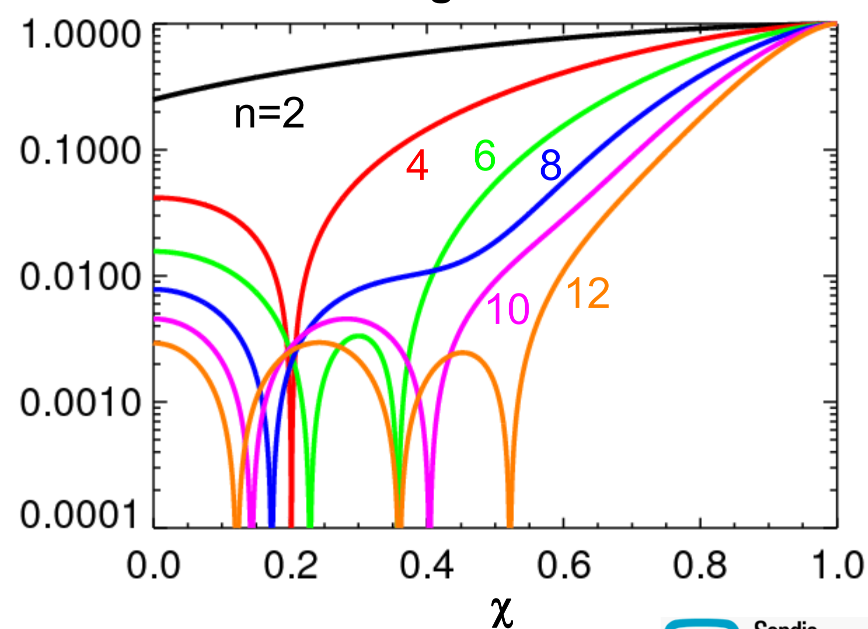
Geometric averaging factor for mode n :

$$\chi \equiv \frac{R_{caps}}{R_{hohl}} \qquad \frac{a_{n,caps}}{a_{n,source}} = f(n,\chi) = 2\int_{\chi}^{1} \frac{(u-\chi)(1-\chi u)}{(1-2\chi u+\chi^{2})^{2}} P_n(u)\,du$$

Odd Legendre modes



Even Legendre modes



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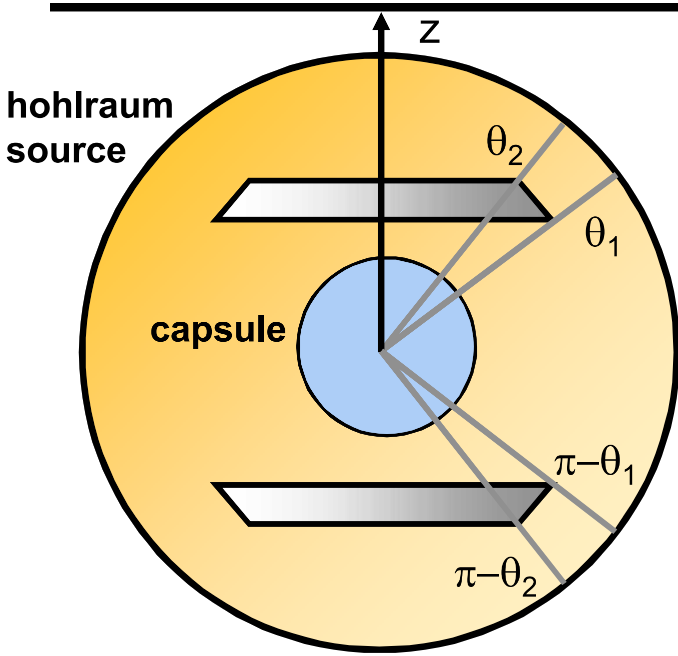
Consider adding absorbing shields placed between the hohlraum "source" and the capsule



Ring shields shown for even mode tuning, symmetric above/below capsule equator

$x = \cos(\theta)$ $\quad T(x)$ **is x-ray transmission**

$$a^*_{n,shield} = \frac{2n+1}{2}\int_{-1}^{1} T(x)P_n(x)dx$$

$$a_{0,shield} = \frac{1}{2}\int_{-1}^{1} T(x)dx \qquad a_{n,shield} \equiv \frac{a^*_{n,shield}}{a_{0,shield}}$$

For a ***uniform source***:

(a) Effect of shield on capsule flux asymmetry $a_{n,caps}$ is independent of the actual source sphere radius.

(b) Mode coefficient $a_{n,caps}$ is exactly given by: $a_{n,caps} = a_{n,shield} f(n, R_{caps}/R_{shld})$

With a *non-uniform source*, analytic arguments are useful but not sufficient

We use analytic arguments, viewfactor calculations, and rad-hydro simulations to optimize shields

1. Use the Legendre mode content of the shield transmission as design parameters $a_{n,shield}$

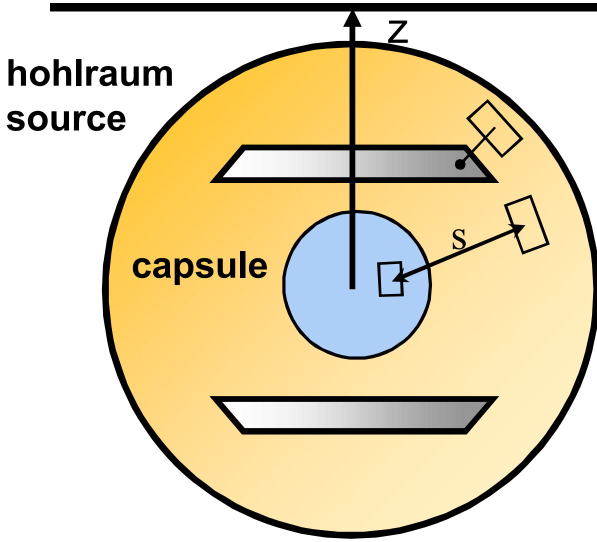
2. Solve for shield solutions θ_1, θ_2, etc. that provide the desired mode content

3. Include shields in static 2D **viewfactor** calculations to evaluate effectiveness

   (a) Scan shield solutions to map out sensitivity
   (b) Powell optimization:
      Design parameters: shield mode content $a_{n,shield}$
      Function call: viewfactor calculation
      Minimize: capsule flux asymmetry mode content $a_{n,caps}$

4. Use 2D **LASNEX** rad-hydro simulations to evaluate shield performance including time-dependent ablation and radiation burnthrough effects

2D viewfactor and rad-hydro simulations provide successively more realistic hohlraum models



2D axisymmetric viewfactor code:

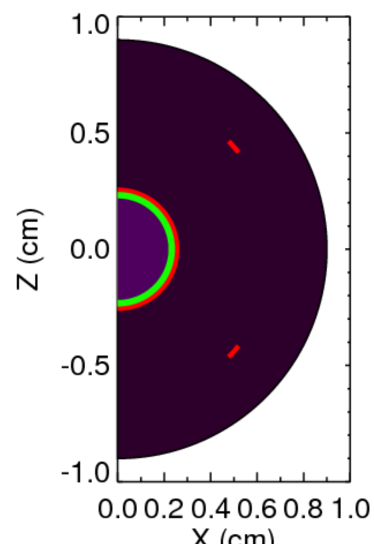
Discretize system into surface elements
Calculate flux transfer among all elements using differential form factor approximation

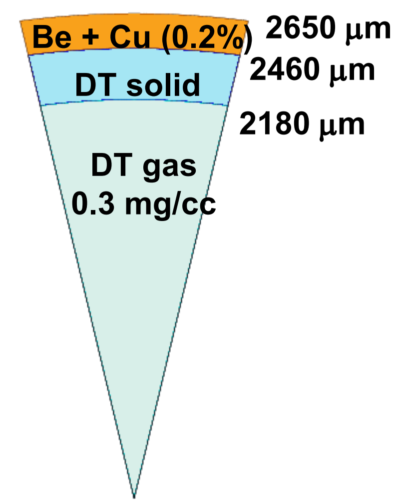
$$dF_{dA_1 \rightarrow dA_2} = \frac{\cos\theta_1 \cos\theta_2}{\pi s^2} V_{1\rightarrow 2} dA_2$$

Lambertian (diffuse) emission assumed
Include 3D occlusion by ring shields $V_{1\rightarrow 2}$
Resulting matrix equation links 2D ring elements

LASNEX 2D axisymmetric radiation-hydrodynamics simulations:

Includes multi-group radiation transport
Includes capsule and shield rad-hydro effects such as ablation, plasma expansion, and radiation burnthrough
Examples in this poster use a 500 MJ capsule from a recent ICF target design study[1]

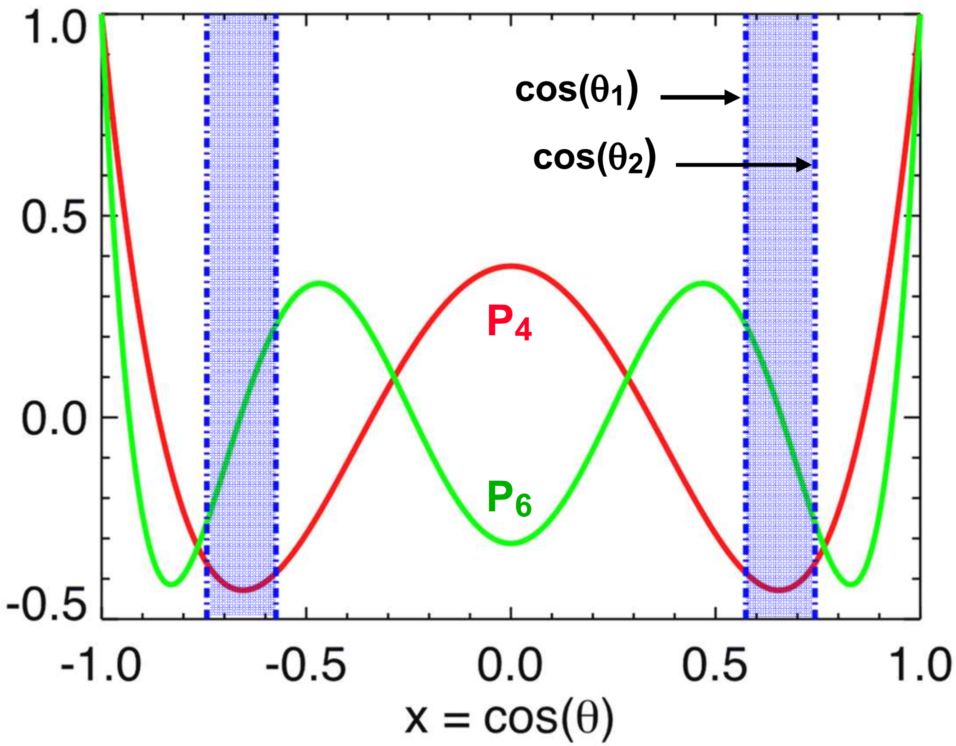




[1] R. A. Vesey, M. C. Herrmann, R. W. Lemke, *et al.*, *Phys. Plasmas* **14**, 056302 (2007)

Single shield allows solutions with zero P_6 content, but with desired P_4 content

Ring shield considered as a mask on the hohlraum sky



For ***purely absorbing*** shields, satisfying zero P_6 content of the shield transmission:

$$a_{6,shield} = \frac{\frac{13}{2}\int_{-1}^{1} T(x)P_6(x)dx}{\frac{1}{2}\int_{-1}^{1} T(x)dx} = 0$$

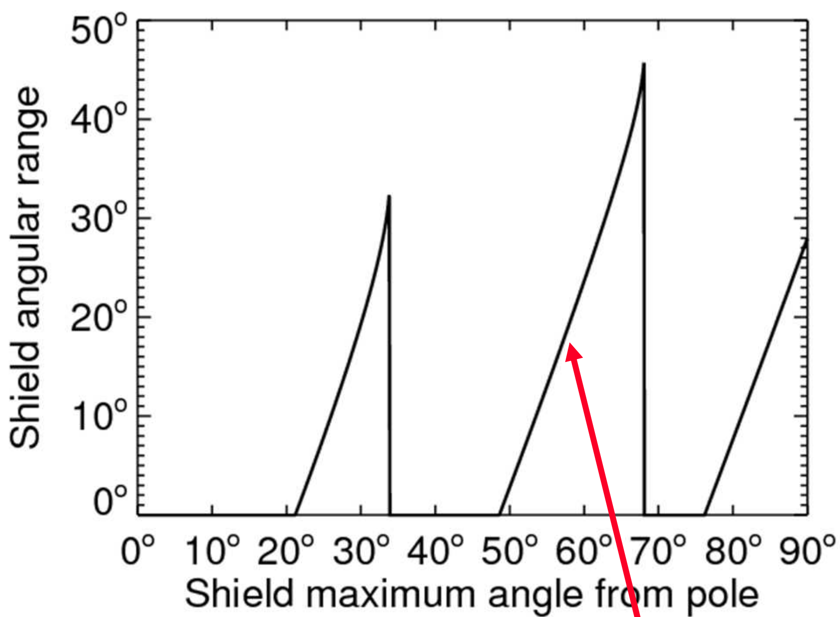
reduces to solving (given θ_1) for θ_2 that satisfies:

$$\int_{\cos(\theta_1)}^{\cos(\theta_2)} P_6(x)\,dx = 0$$

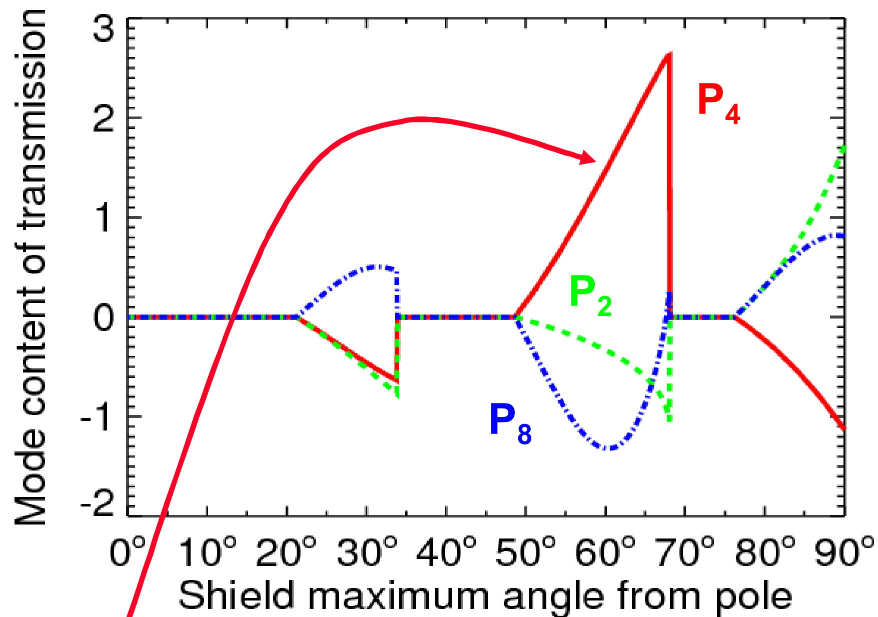
Solve for family of shield solutions, then test them in 2D viewfactor and radiation-hydrodynamics simulations

Shield solutions should allow a wide range of P_4 tuning while providing zero P_6 content

Family of zero P_6 shield solutions ($\Delta\theta$ vs. θ_1)



Mode content of shield transmission for family of zero P_6 solutions



Solutions in this region should be useful in counteracting negative P_4 content of flux

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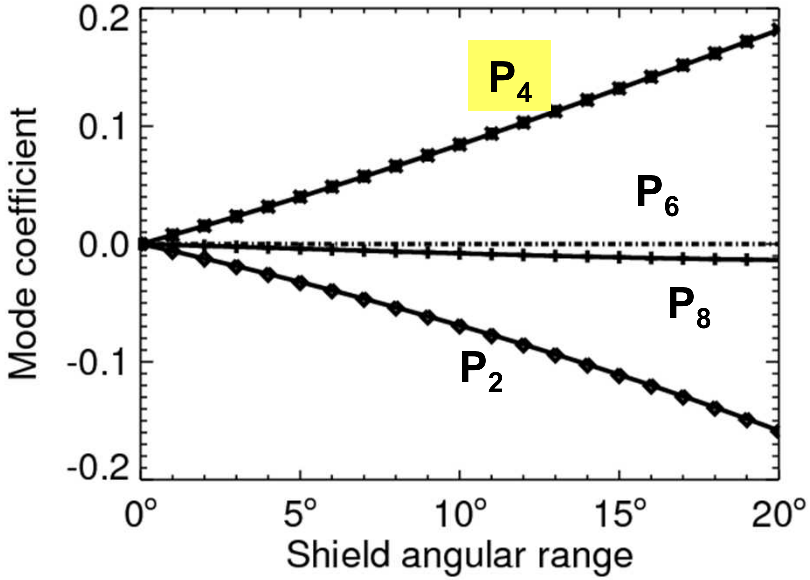
Viewfactor calculations confirm the shields behave as expected with a uniform source

Viewfactor calculations with *uniform source flux* (only P_0 term)

R_{hohl} = 10 mm, R_{caps} = 2.5 mm, R_{caps}/R_{shld} = 0.404

Shield solutions chosen from the region with $a_{4,shield} > 0$

Mode content of capsule flux asymmetry $a_{n,caps}$ vs. shield $\Delta\theta$



Solid lines are viewfactor results

Symbols are given by:

$$a_{n,caps} = a_{n,shield} f(n, R_{caps}/R_{shld})$$

Numerical $a_{6,caps}$ and $a_{10,caps} < 5\times10^{-5}$

$a_{6,caps} = 0$ because $a_{6,shield} = 0$

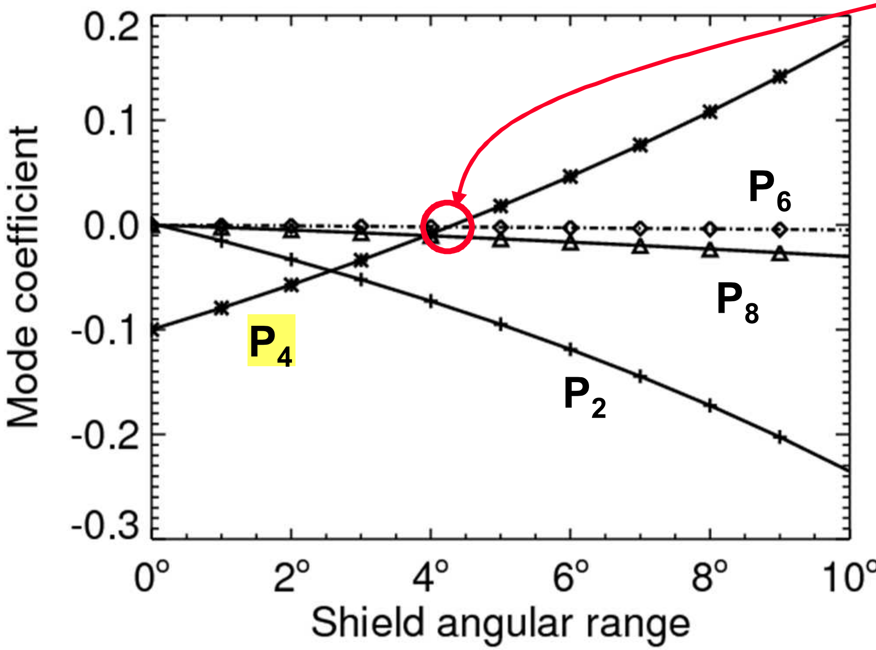
$a_{10,caps} = 0$ because $f(10,0.404)=0$

This is a useful starting point to optimize shields for non-uniform source...

The simple solutions with a uniform source are still effective even with a significant P_4 source asymmetry

Include the family of shield solutions in a set of viewfactor calculations, with source asymmetry chosen to give uncorrected $a_{4,caps} = -0.10$

Capsule flux asymmetry modes vs. shield angular range



P_4 curve crosses zero for $\Delta\theta = 4.3^o$:

$a_{6,caps} = -1.95\times10^{-3}$
$a_{8,caps} = -0.011$
$a_{10,caps} = 9.7\times10^{-5}$

Solving for new shield with $a_{6,shield} > 0$ can improve this result.
e.g. $a_{6,shield} = 0.0195$ solution gives:

$a_{6,caps} = 1.30\times10^{-5}$ **(100x reduction)**
$a_{8,caps} = -0.012$
$a_{10,caps} = -9.0\times10^{-5}$

Suggests iteratively optimizing shields parametrized by their mode content

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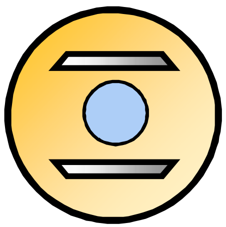
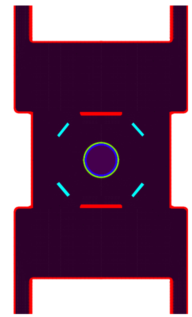
2D LASNEX rad-hydro simulations in hohlraums confirm the performance of practical shield materials

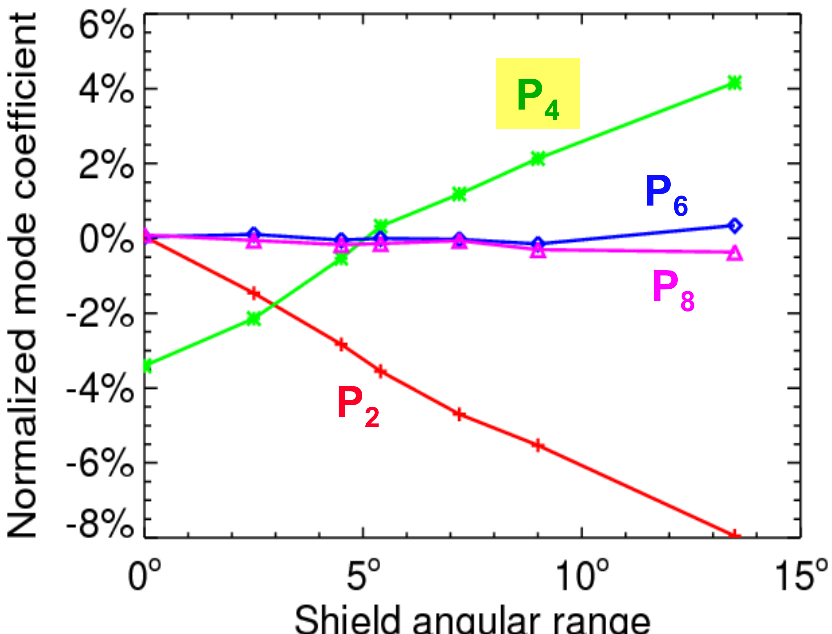
Cases include 500 MJ capsule with 3-step drive pulse, shield ablation and burnthrough
Capsule ablation pressure Legendre modes are plotted, time-averaged over foot pulse

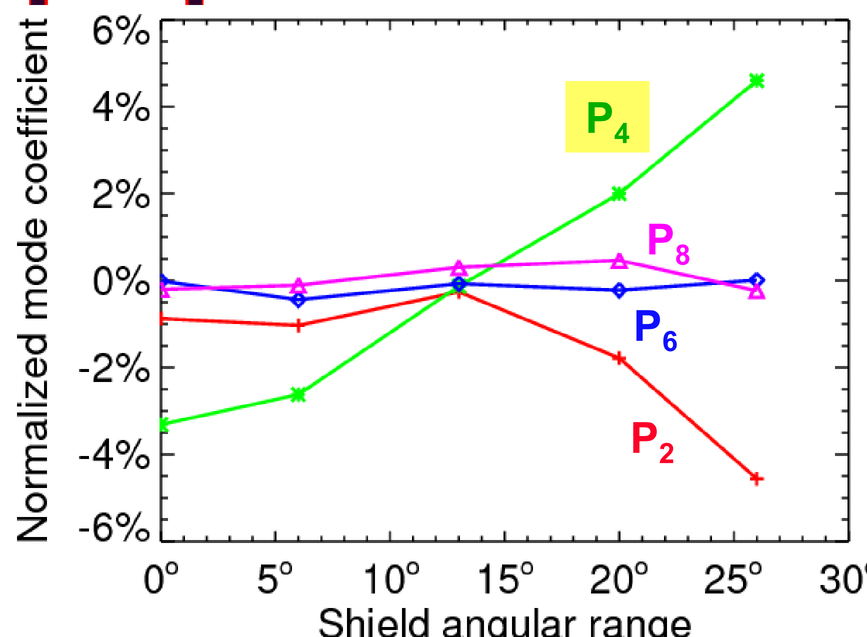


Sphere-in-sphere
uncorrected flux P_4 = -4%
shields 200 mg/cc Ge-doped CH_2



Double z-pinch hohlraum
moving x-ray source
wall ablation & motion
time-dependent wall albedo
shields 100 mg/cc Ge-doped CH_2





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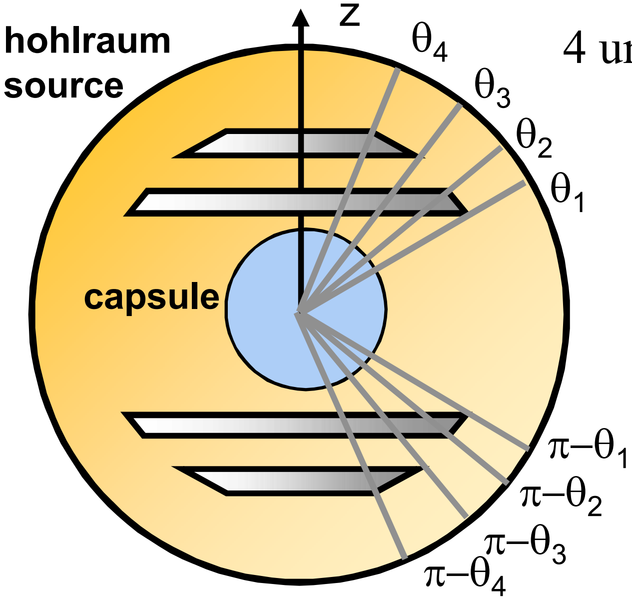
With 2 shields above/below equator, it is possible to simultaneously tune P_2, P_4, P_6, and P_8



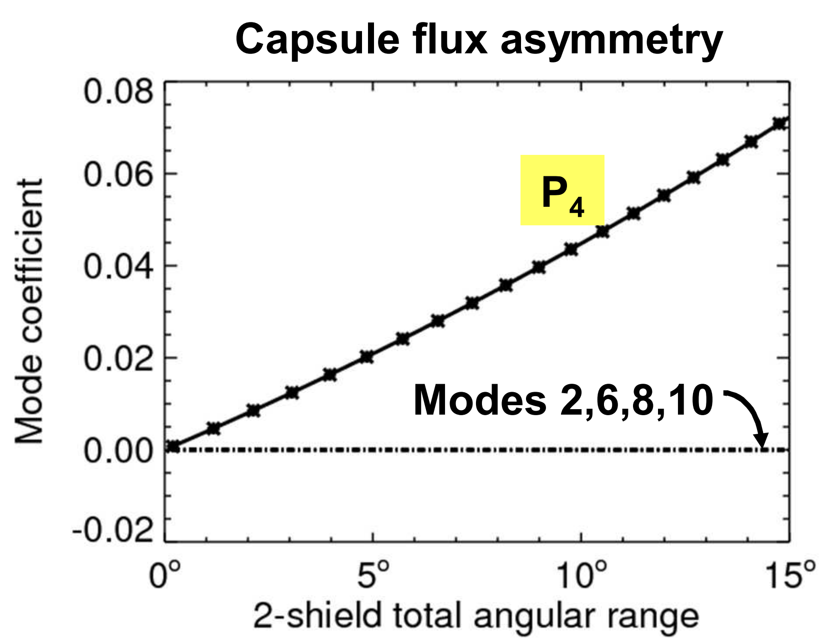
4 unknowns → 4 equations for $a_{n,shield}$, n=2, 4, 6, 8

$$a_{n,shield} = \frac{-(2n+1)\left[\int_{x_1}^{x_2} P_n(x)dx + \int_{x_3}^{x_4} P_n(x)dx\right]}{1 + x_1 - x_2 + x_3 - x_4}$$

for perfectly absorbing shields

Find family of solutions with $a_{4,shield} > 0$ and $a_{n,shield}=0$ for n=2, 6, 8

Capsule asymmetry from viewfactor tests with ***uniform source***, $R_{caps}/R_{shld}=0.404$



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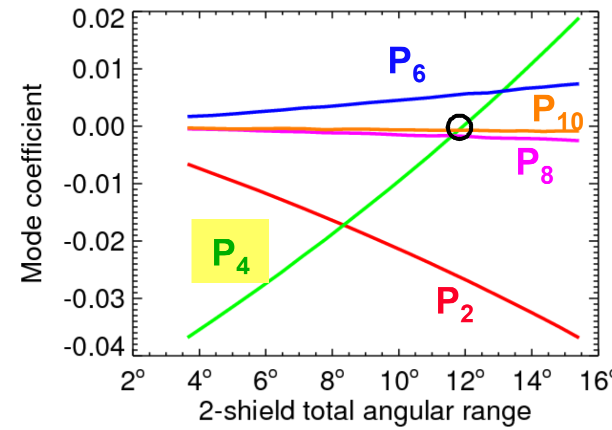
The uniform source solution provides a starting point for optimization in the case of a non-uniform source

Source asymmetry chosen to give $\mathbf{a_{4,caps}}$ **= -0.05**, but use uniform source shield solutions

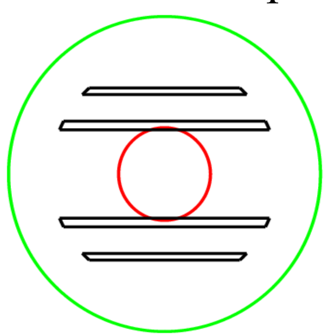
(1) Scan $\Delta\theta$, find where the calculated $a_{4,caps} = 0$

$a_{2,caps} = -0.027$
$a_{4,caps} = 0.0$
$a_{6,caps} = 0.0056$
$a_{8,caps} = -0.0017$
$a_{10,caps} = -6.9\times10^{-4}$



(2) Use as initial point for ***Powell optimization***, calling viewfactor code as a function, with the goal of finding shields that give $|a_{n,caps}| < 10^{-3}$ for n = 2, 4, 6, 8, and 10

Successful result has shields spanning [41.46°, 46.25°] and [62.57°, 67.33°] from polar axis:

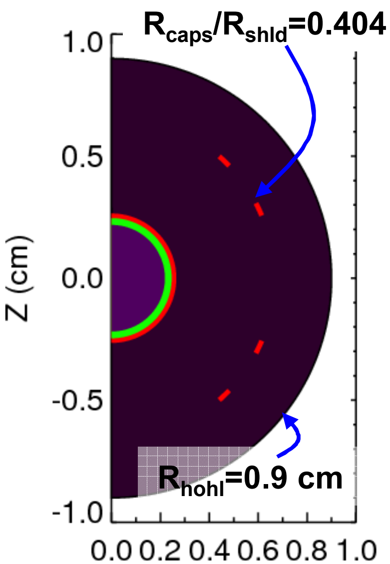


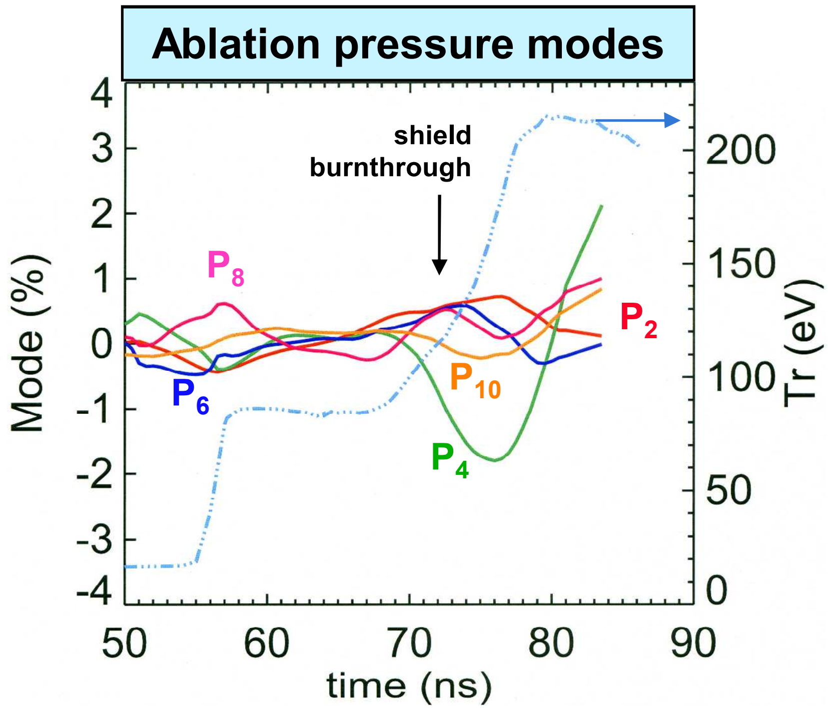
$a_{2,caps} = -1.1\times10^{-4}$
$a_{4,caps} = -1.9\times10^{-4}$
$a_{6,caps} = 3.6\times10^{-4}$
$a_{8,caps} = -4.0\times10^{-5}$
$a_{10,caps} = -6.4\times10^{-4}$

Test these optimized shields in LASNEX...

LASNEX simulations confirm the performance of optimized double-ring shields in minimizing $P_{2,4,6,8}$

Viewfactor-optimized shields are included as 200 μm thick, 1.85 g/cc Be rings





Interval time-averaged ablation pressure modes

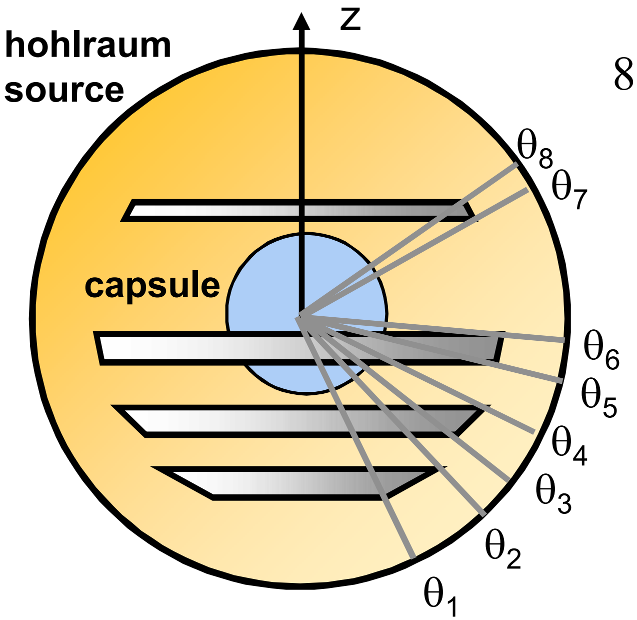
	Foot	Main
$\langle P_2 \rangle$	0.18 %	0.45 %
$\langle P_4 \rangle$	-0.02%	-0.84 %
$\langle P_6 \rangle$	0.15%	-0.06 %
$\langle P_8 \rangle$	0.09%	0.38 %
$\langle P_{10} \rangle$	0.16%	0.04%

Be or Ge-doped CH_2 foam shields remain optically thick through foot pulse

Once shields become optically thin, capsule sees uncorrected P_4, but geometric averaging causes $a_{4,caps}$ to move in positive direction as R_{caps} decreases

Adequate resolution of shield ablation allows optimization of shield materials

With a set of 4 independent shields, it is possible to simultaneously tune modes P_1 through P_8



8 unknowns → 8 equations for $a_{n,shield}$, n = 1, 2, 3, ..., 8

For 4 perfectly absorbing shields,

$$a_{n,shield} = \frac{-\frac{(2n+1)}{2}\sum_{i=1}^{4}\left[\int_{x_{2i-1}}^{x_{2i}} P_n(x)dx\right]}{1-\frac{1}{2}\sum_{i=1}^{4}[x_{2i}-x_{2i-1}]}$$

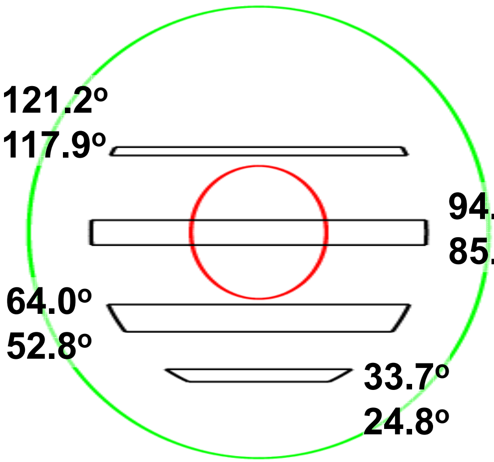
As before, the approach is to use $a_{n,shield}$ as design parameters and optimize to minimize $a_{n,caps}$ mode content of the flux incident on the capsule

Optimized shields show potential to symmetrize a highly non-uniform hohlraum source

Use viewfactor code to optimize shields with strongly non-uniform source:

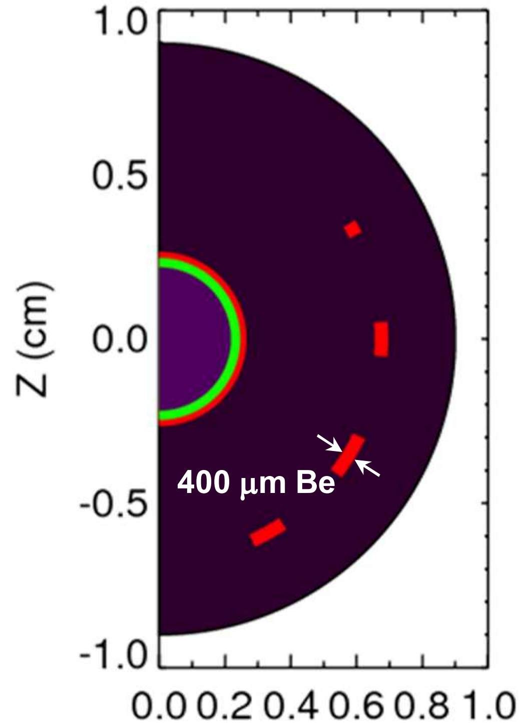
$a_{1,caps} = 0.25$ $a_{3,caps} = -0.08$ $a_{4,caps} = -0.02$

Viewfactor optimized shields give low $a_{n,caps}$ for n=1...8



n	$a_{n,caps}$
1	3.5×10^{-4}
2	-6.3×10^{-4}
3	4.2×10^{-4}
4	-3.4×10^{-3}
5	-8.9×10^{-3}
6	-4.5×10^{-3}
7	-1.4×10^{-3}
8	3.7×10^{-3}

2D LASNEX simulations are in progress:



Geometric averaging reduces the effects of the inherent high-mode content of the shields

Shield content in high modes is low

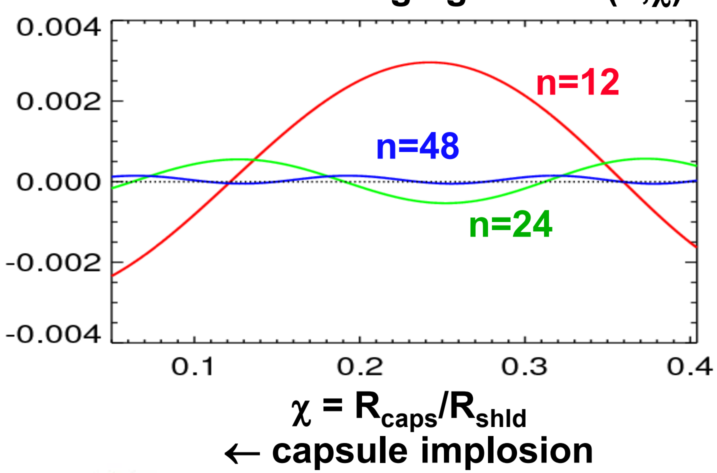
Geometric averaging between shield and capsule provides greater reduction as mode number increases, leading to $a_{n,caps} \ll a_{n,shield}$

Time-varying R_{caps}/R_{shld}

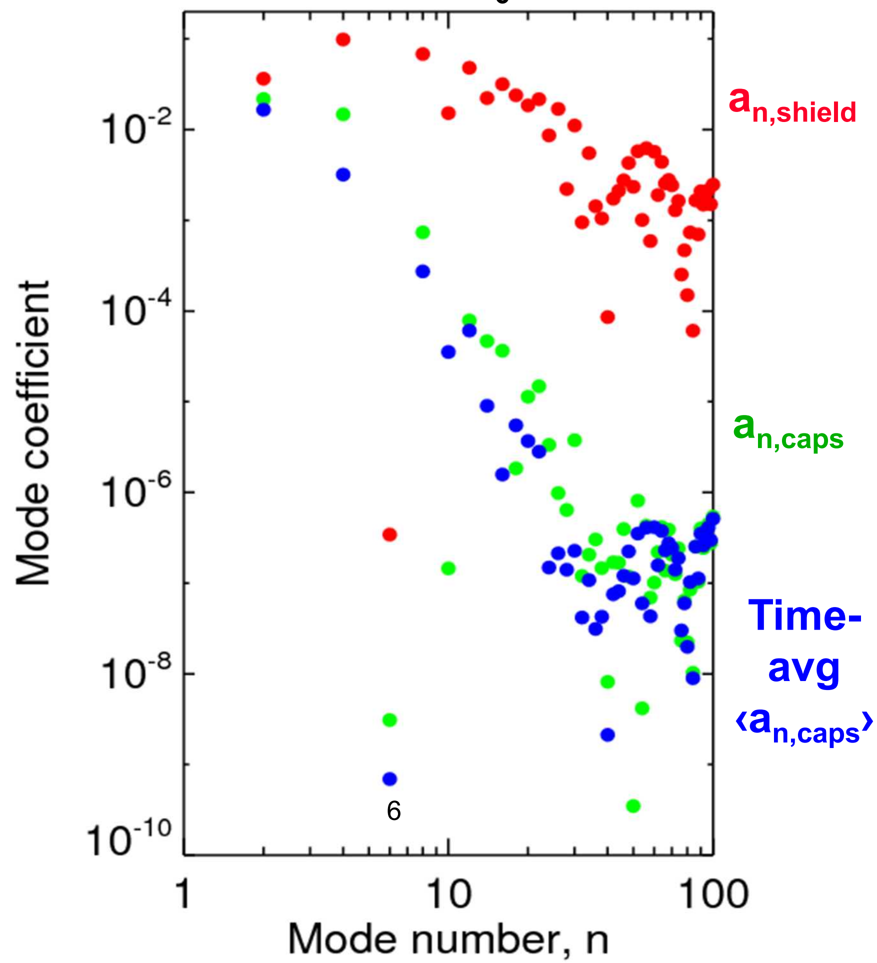
As capsule implodes, χ decreases

Time-averaged geometric averaging reduces average $a_{n,caps}$ for most modes

Geometric averaging factor $f(n,\chi)$



Example: Mode content of 9° "zero P_6" shield



Conclusion: properly designed symmetry shields can allow control of specific modes in the hohlraum

Ideally, shields remove x-ray flux from portions of the hohlraum sky

The polar angular range(s) occupied by the shields are expressed in terms of their Legendre mode content

For the uniform source case, we can exactly represent the corresponding effect on the Legendre mode content of the flux received by the capsule

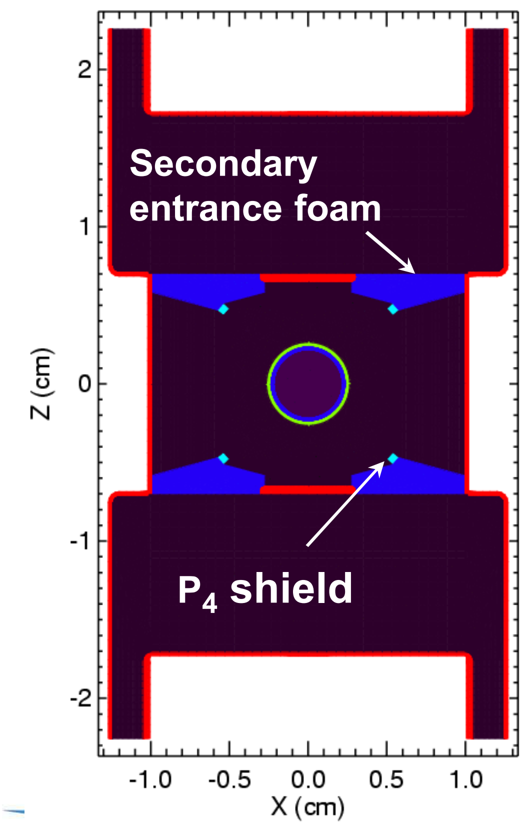
The approach of using the shield Legendre mode content as design parameters within an optimization procedure has been successful in designing:

- "zero P_6" shields to specifically tune P_4
- Double-ring shields per side to specifically tune P_2, P_4, P_6, and P_8
- 4 independent shields to tune P_1 through P_8

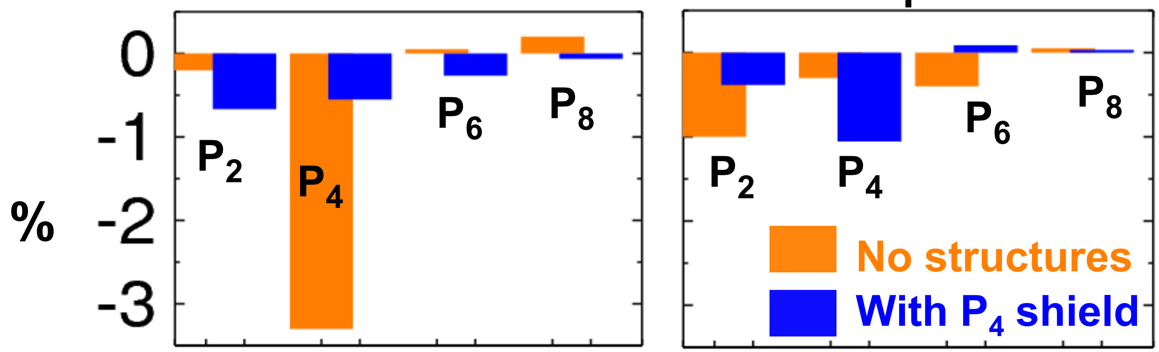
LASNEX radiation-hydrodynamics simulations support the basic design concept and have demonstrated adequate P_4 control for a recent ICF target design study...

"Zero P_6" mode-selective P_4 shields result in full capsule yield in 2D simulations of a z-pinch driven hohlraum

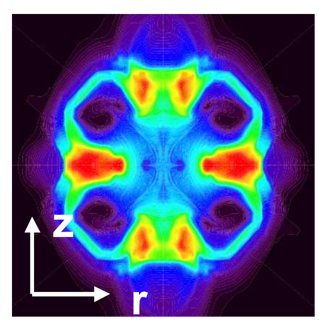
P_4 shield : 4.4° range
200 mg/cc CH_2 (3% Ge)
Secondary entrance foam :
5 mg/cc CH_2



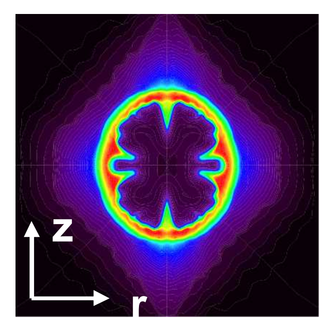
Interval-averaged Legendre coefficients of ablation pressure asymmetry



Fuel density contours near ignition



No structures
Yield = 0.040 MJ



With P_4 shield
Yield = 470 MJ