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Tradeoffs of efficiency and symmetry control for z-pinch driven ICF hohlraums

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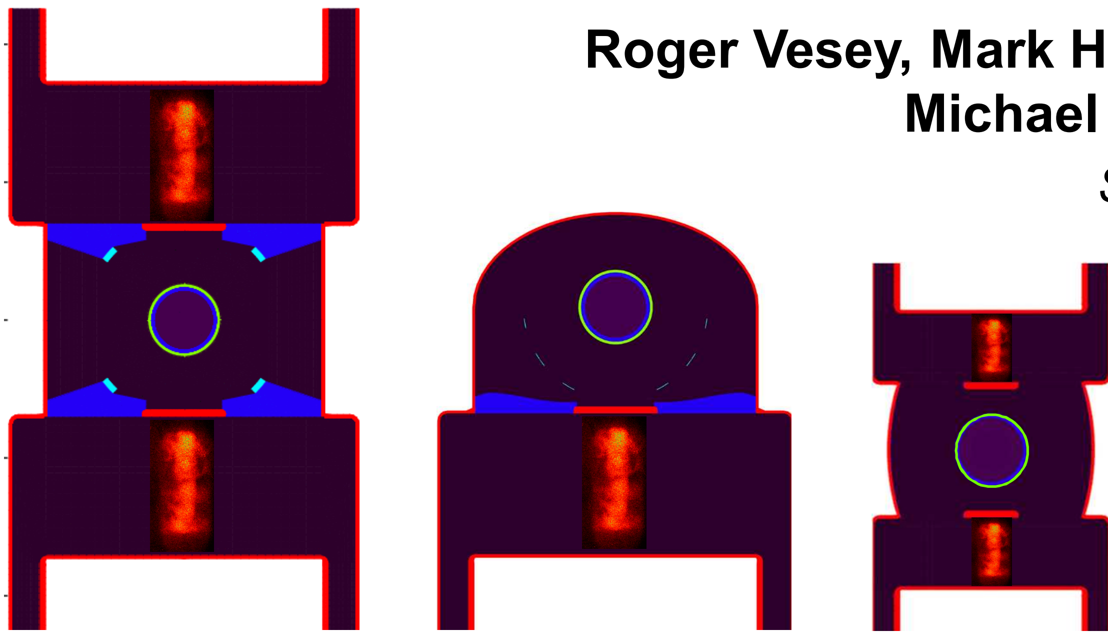

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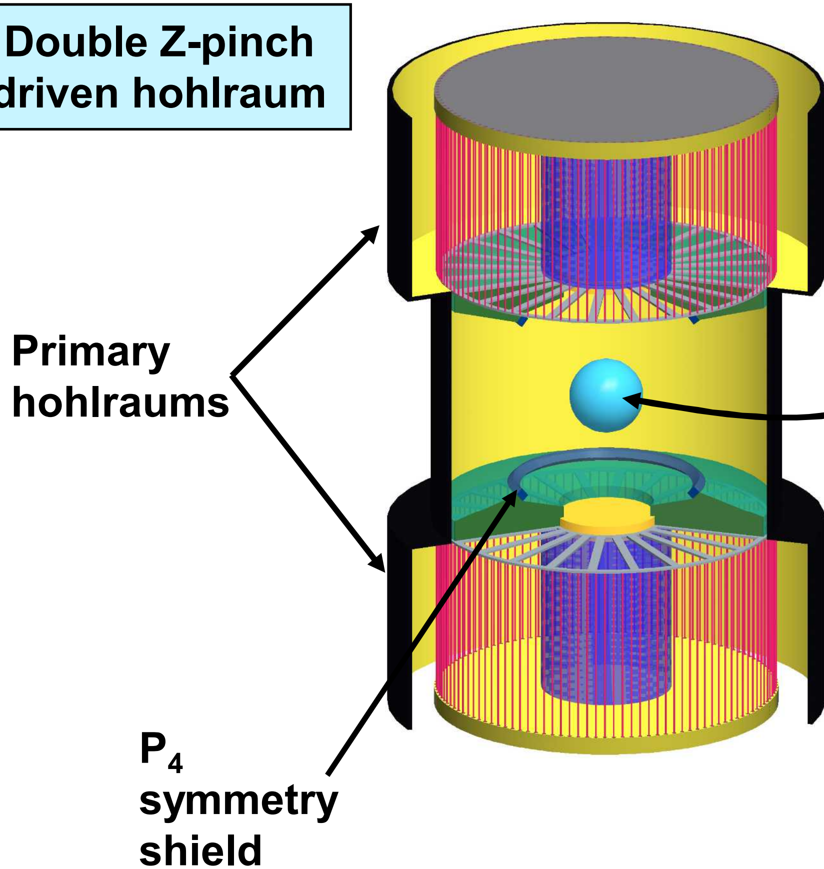
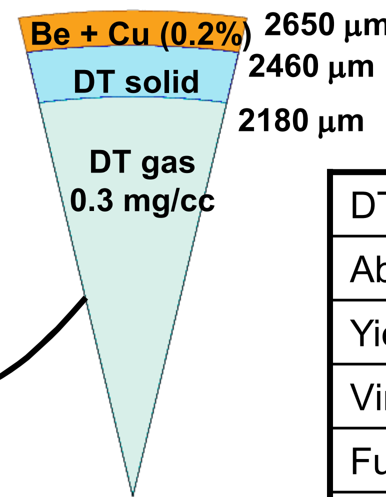
A reference design for a z-pinch driven high yield system has been recently published[1]

Double Z-pinch driven hohlraum





Capsule

DT fuel mass (mg)	**4.74**
Absorbed energy (MJ)	**1.2**
Yield (MJ)	**520**
Vimp (cm/μs)	**26.0**
Fuel KE margin	**29%**
Hot spot CR	**34**

Total source x-ray energy 19 MJ
Hohlraum efficiency = 6 %
Accelerator stored energy ~ 400 MJ

Seek robust designs with higher efficiency

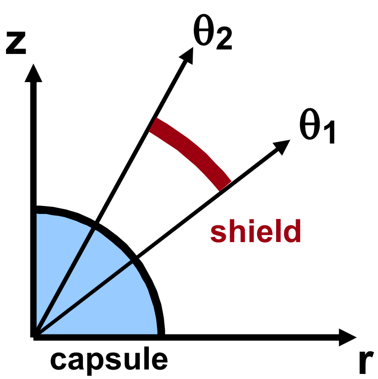
[1] R. A. Vesey, M. C. Herrmann, R. W. Lemke, *et al.*, *Phys. Plasmas* **14**, 056302 (2007)

Mode-selective shields are an important part of the double z-pinch high yield target design

Control the Legendre mode content of transmission past the shield

Specify positive P_4 content to counteract inherent $-P_4$ flux in hohlraum

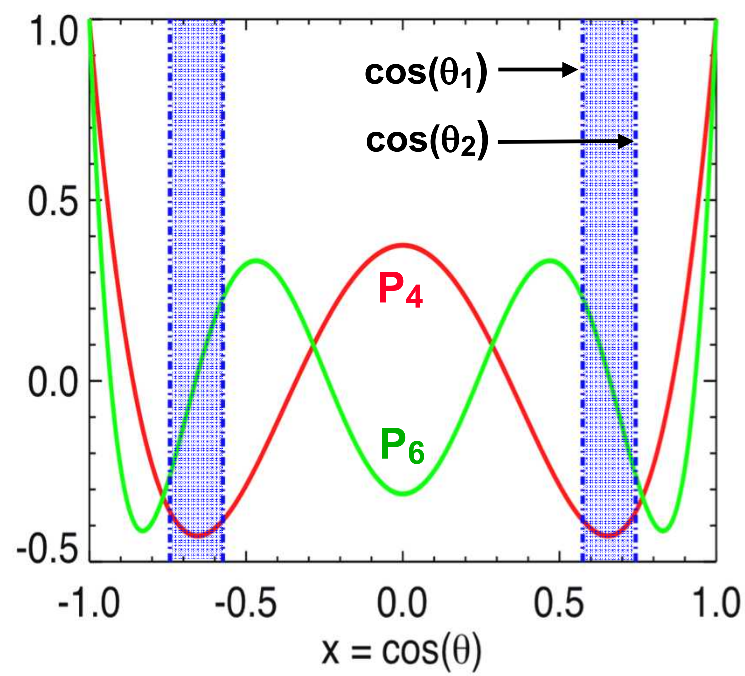
Specify zero P_6 content



$$x = \cos(\theta)$$

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

$$a_{4,shield} = \frac{9}{2} \int_{-1}^{1} T(x) P_4(x)\,dx > 0$$



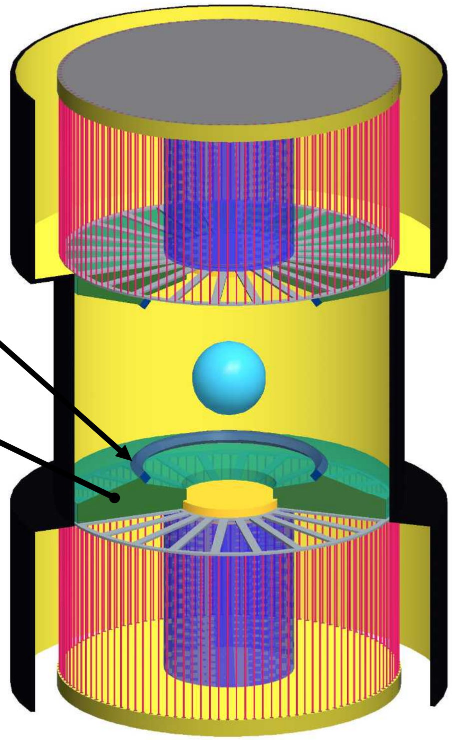
Family of (θ_1,θ_2) solutions with P_4 effect $\propto \Delta\theta$

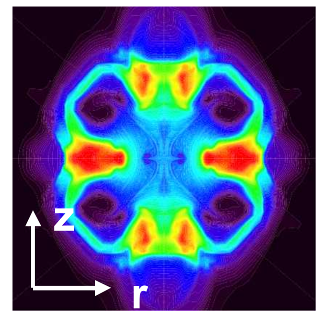
Mode-selective shields provided adequate symmetry control for 2D ignition & burn

Mode-selective shields minimize P_4 without enhancing P_6 or P_8

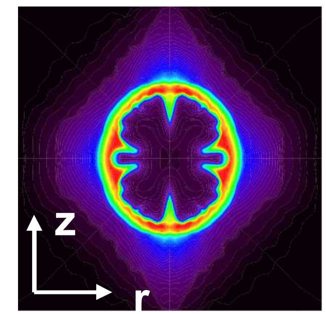
P_4 symmetry shield
4.4° range
0.2 g/cc CH_2 (3% Ge)

Tamping foam
5 mg/cc CH_2





No structures
P_4 = -3.3%
Yield = 0.040 MJ

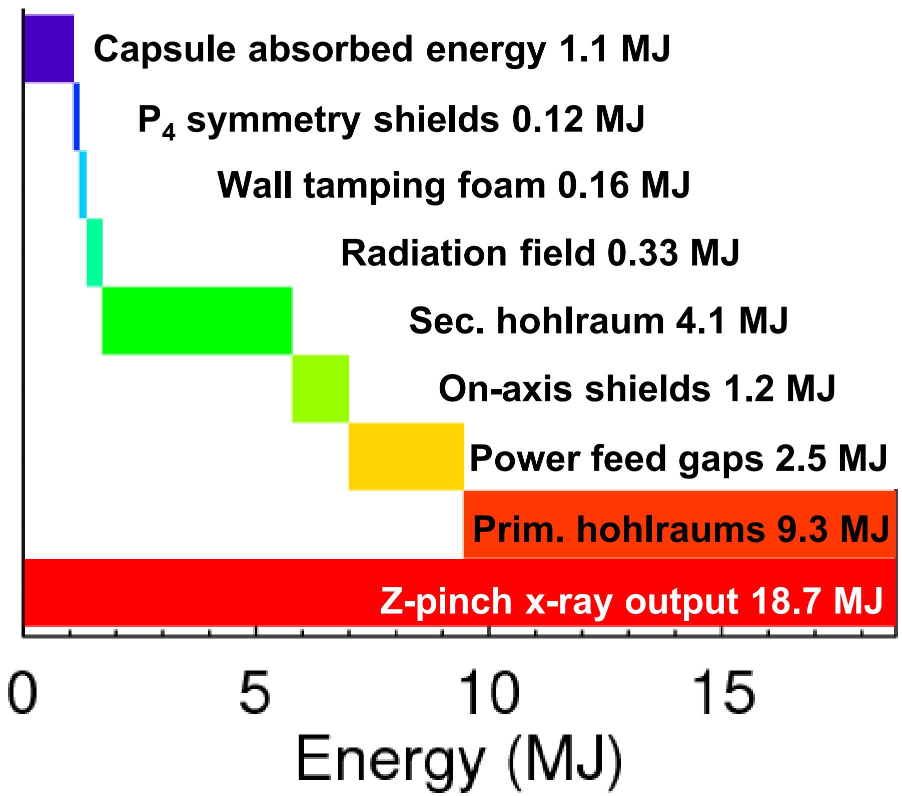


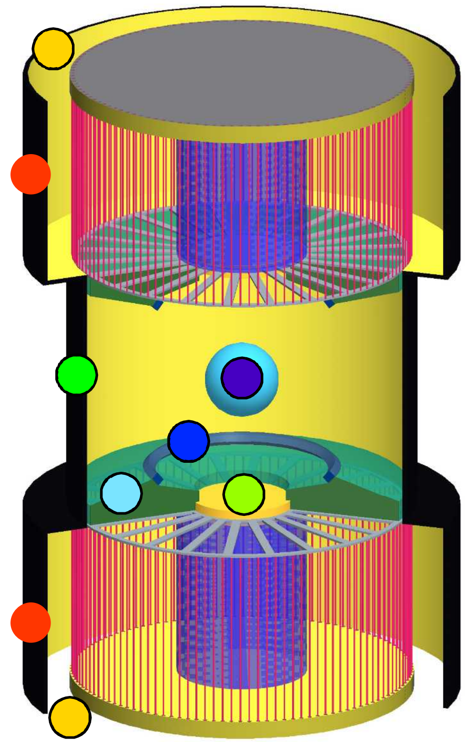
With P_4 shield
P_4 = -0.5%
Yield = 470 MJ

Result can be generalized to N shields to control 2N modes *in principle*

Energy balance for 2-sided design is dominated by energy absorbed by the primary hohlraum walls

Energy balance at time of peak fuel KE





Hohlraum efficiency $= \frac{1.1\ \text{MJ}}{18.7\ \text{MJ}} =$ **5.9%**

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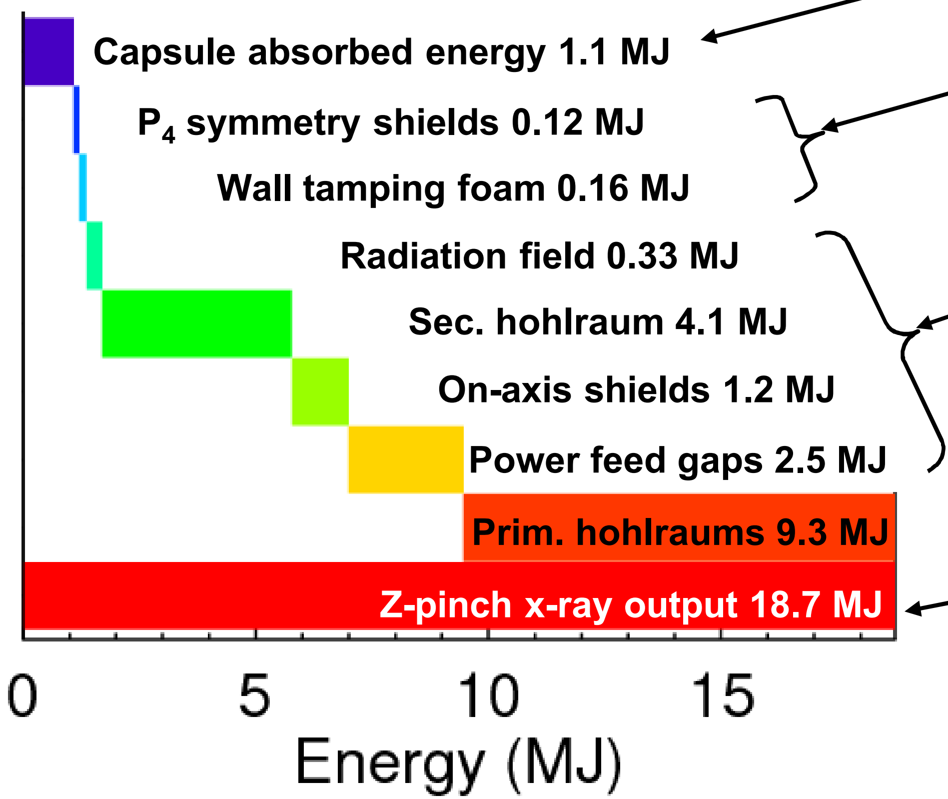
Energy balance for 2-sided design is dominated by energy absorbed by the primary hohlraum walls

Energy balance at time of peak fuel KE



Remains fixed for fixed capsule

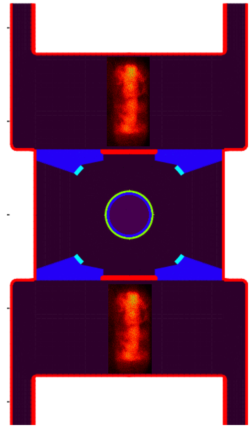
Expect these to increase to provide symmetry control in compact hohlraums

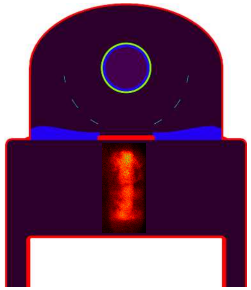
These terms will decrease with decreasing wall area & gap size

Design hohlraums that require lower x-ray source energy

One way to reduce the hohlraum area is to eliminate one of the primary hohlraums !

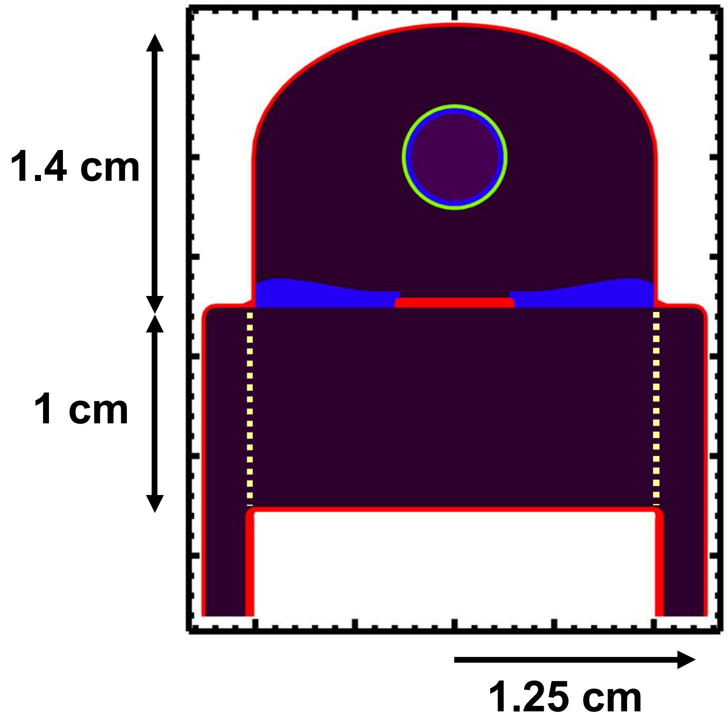
	2-sided	1-sided	Area factor
Primary hohlraum	25.52 cm^2	12.76 cm^2	0.5
Secondary hohlraum	8.86 cm^2	9.64 cm^2	1.09
On-axis shields	1.14 cm^2	0.57 cm^2	0.5
A-K gap (trunc.)	3.54 cm^2	1.77 cm^2	0.5
Total wall area	39.1 cm^2	24.7cm^2	0.63

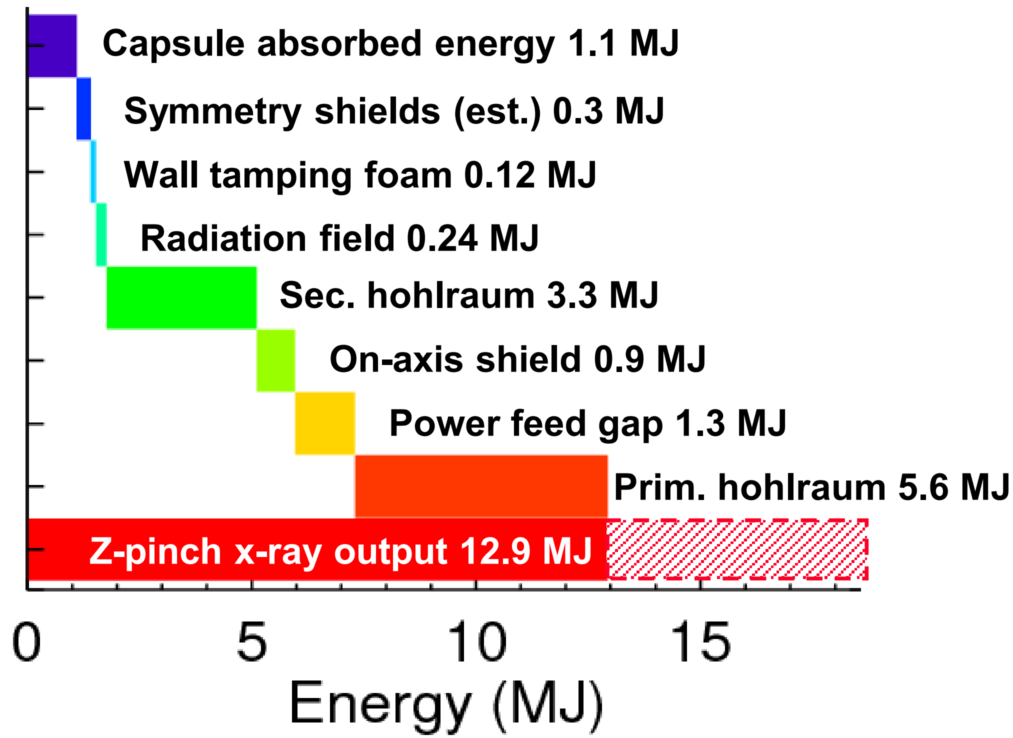




Also eliminates imbalance & mistiming concerns of 2-pinch systems

1-sided configuration requires 30% less source x-ray energy compared to 2-sided





But...

P_1 = 20% to 25 %
P_3 = -4% to -8%

presenting a challenge for symmetry control

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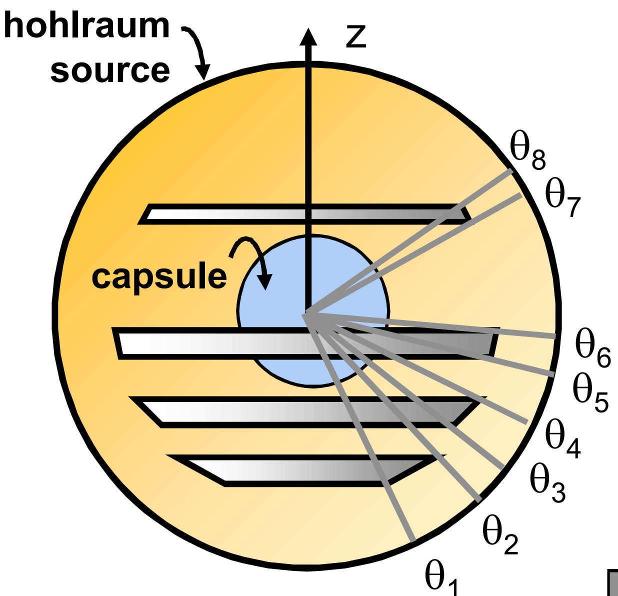
Multi-dimensional optimization of shields to counteract P_1, P_3, and P_4



Use simpler sphere-in-sphere model problem

Hohlraum source asymmetry applied in P_1, P_3, P_4 :

At capsule, P_1 = 25%, P_3 = -8%, P_4 = -2%

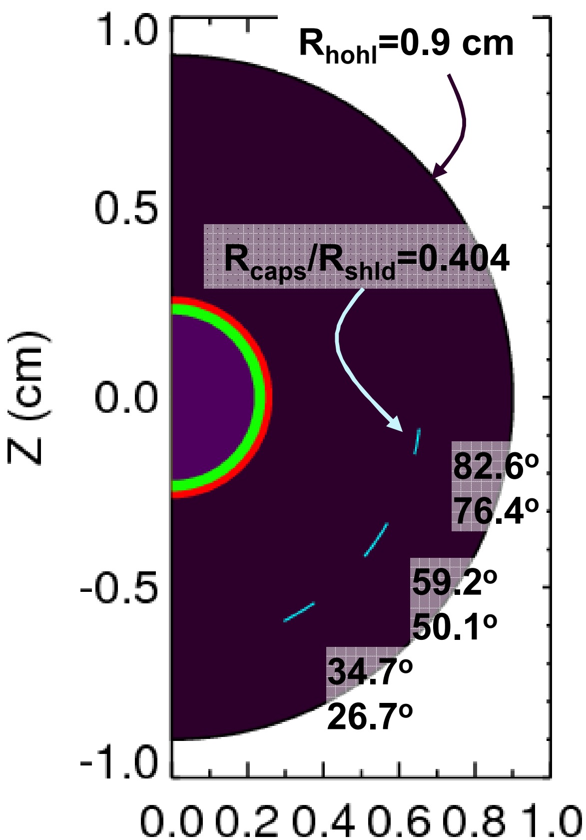
Optimization procedure:

Shield Legendre mode content $a_{n,shield}$ are parameters
8 equations for θ_n , n = 1, 2, 3, ..., 8
Call viewfactor routine to calculate flux to capsule
Evaluate mode content in flux at capsule, $a_{n,caps}$

Seek $|a_{n,caps}| < 0.1\%$ for n=1 to 8

The viewfactor optimization predicts 3 shields can reduce $P_1 \rightarrow P_{10}$ to less than 1%

Model problem



Viewfactor result: static flux asymmetry

Mode	$a_{n,caps}$
1	-0.05 %
2	-0.05 %
3	-0.002 %
4	0.05 %
5	0.04 %
6	0.05 %
7	0.02 %
8	-0.03 %
9	0.05 %
10	0.07 %

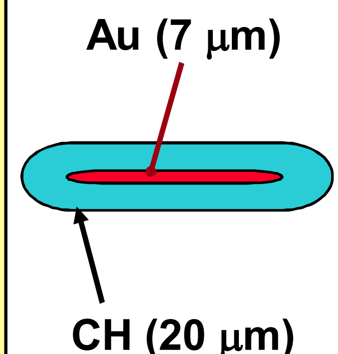
25 %

-8 %

-2 %

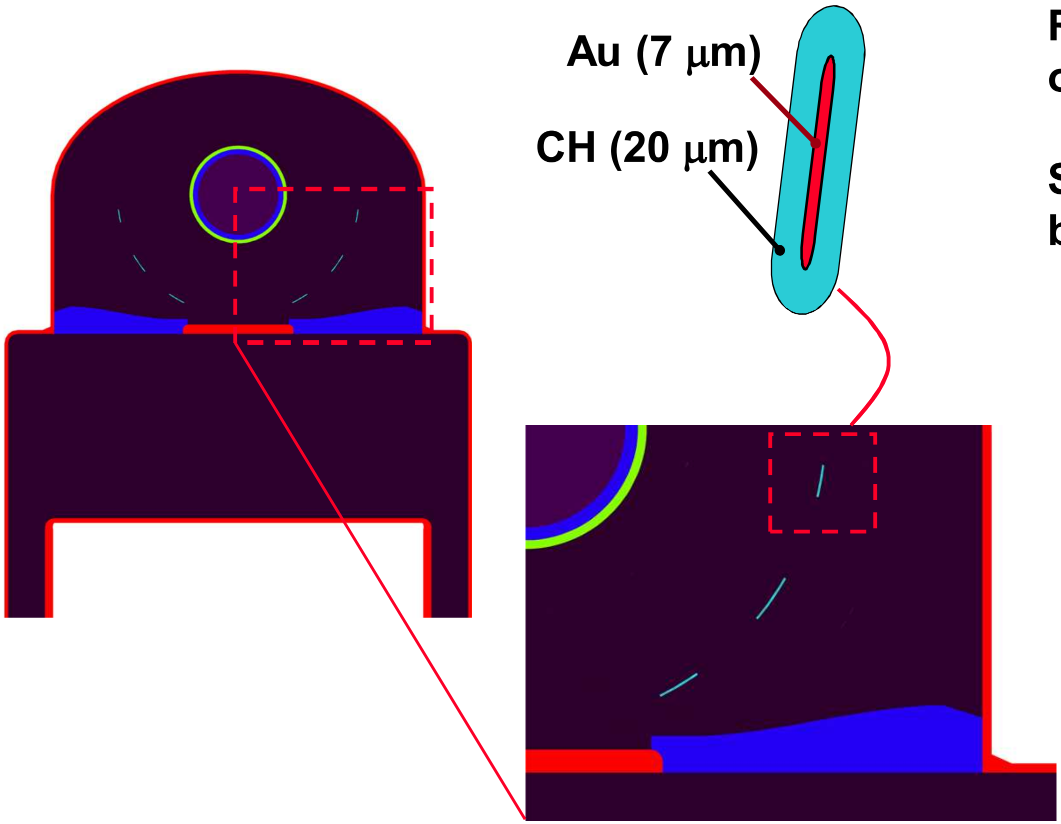
2D LASNEX result: ablation pressure asymmetry during foot

Mode	$a_{n,pressure}$
1	-0.74 %
2	-0.05 %
3	-0.64 %
4	-0.73 %
5	0.08 %
6	0.29 %
7	0.01 %
8	-0.06 %



Shields absorb 0.31 MJ

2D LASNEX hohlraum simulations test shield performance in the hohlraum environment



Resolving ablation and expansion of shields is a challenge

Simulations are still in progress, but look promising...

Aggressive symmetry control enables z-pinch hohlraum designs with higher efficiency

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

1-sided drive reduces the total source energy requirement by 30% but introduces odd Legendre mode asymmetry with $P_1 > 20\%$

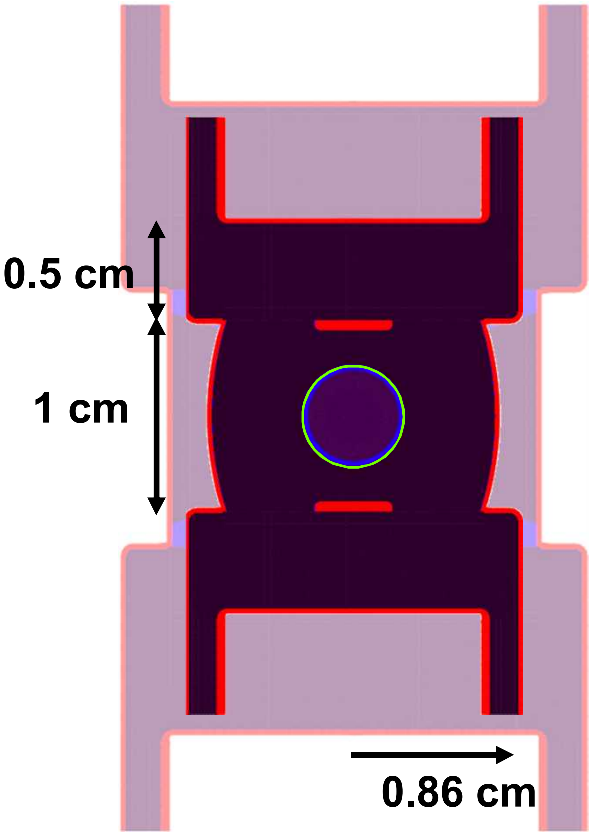
Viewfactor-optimized shields can reduce instantaneous P_1 through P_{10} to $< 0.1\%$, confirmed by LASNEX rad-hydro simulations

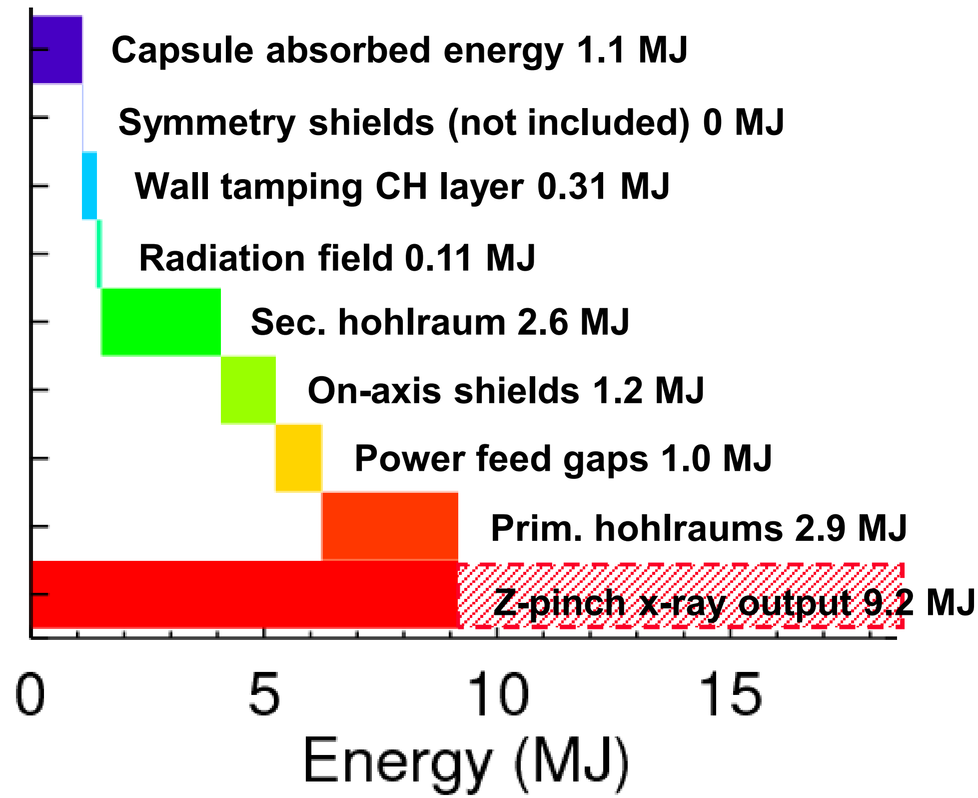
These shields show the potential of controlling large odd mode asymmetry in full 2D LASNEX hohlraum+capsule simulations of 1-sided drive

Compact x-ray sources will allow even larger gains in efficiency

extras

2-sided configuration based on compact x-ray sources lowers the required x-ray energy





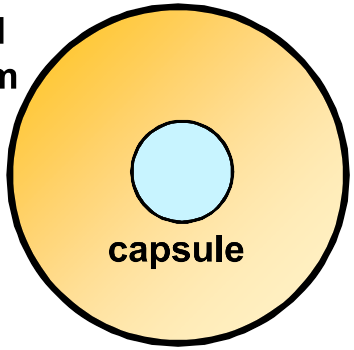
Short rise-time compact cylindrical wire arrays or foils
Planar wire arrays (Kantsyrev et al.)
Radial wire arrays (Bland et al.)
Axially-zippering foils (Hammer APS 2000)

P_4 = -15% to -20 %
P_6 = -2%

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)

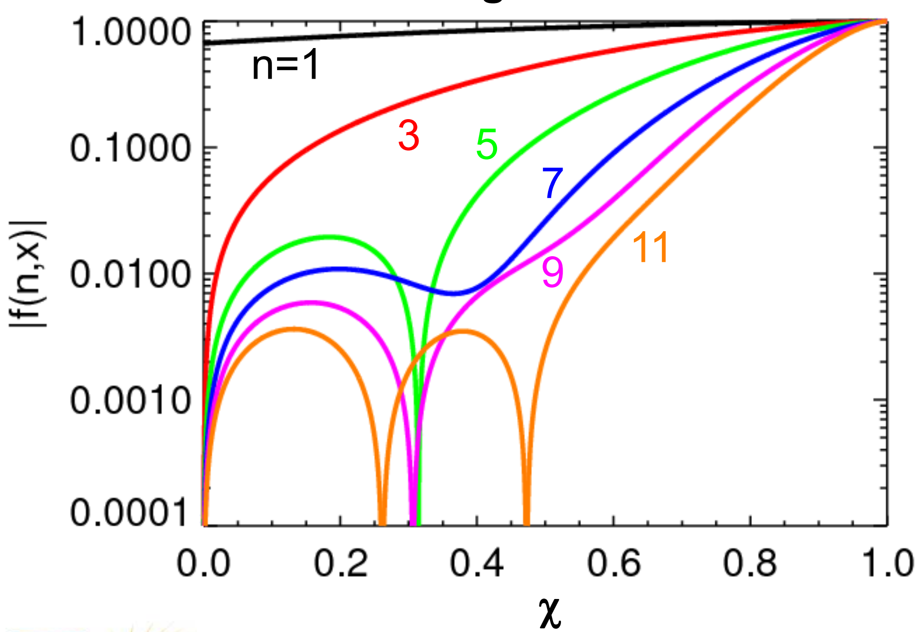
idealized hohlraum source sphere



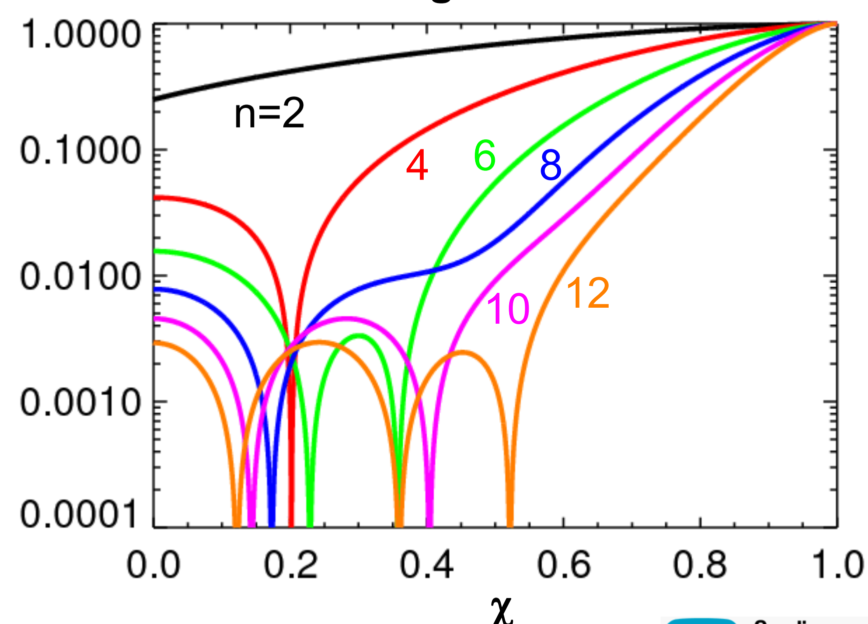
Geometric averaging factor for mode n :

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

Odd Legendre modes



Even Legendre modes

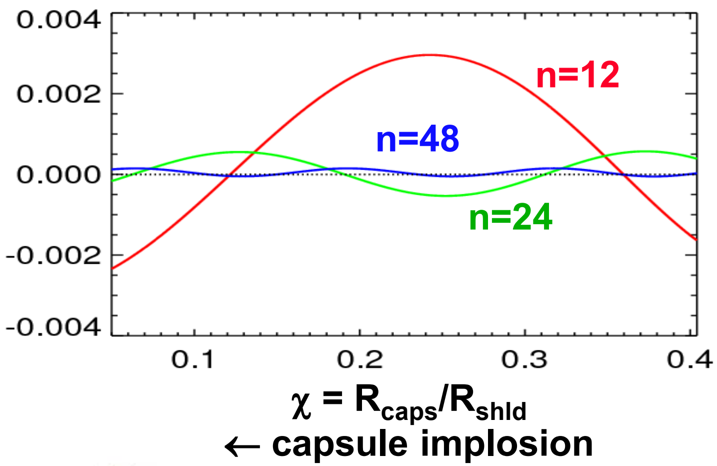


Geometric averaging reduces the effects of the inherent high-mode content of the shields

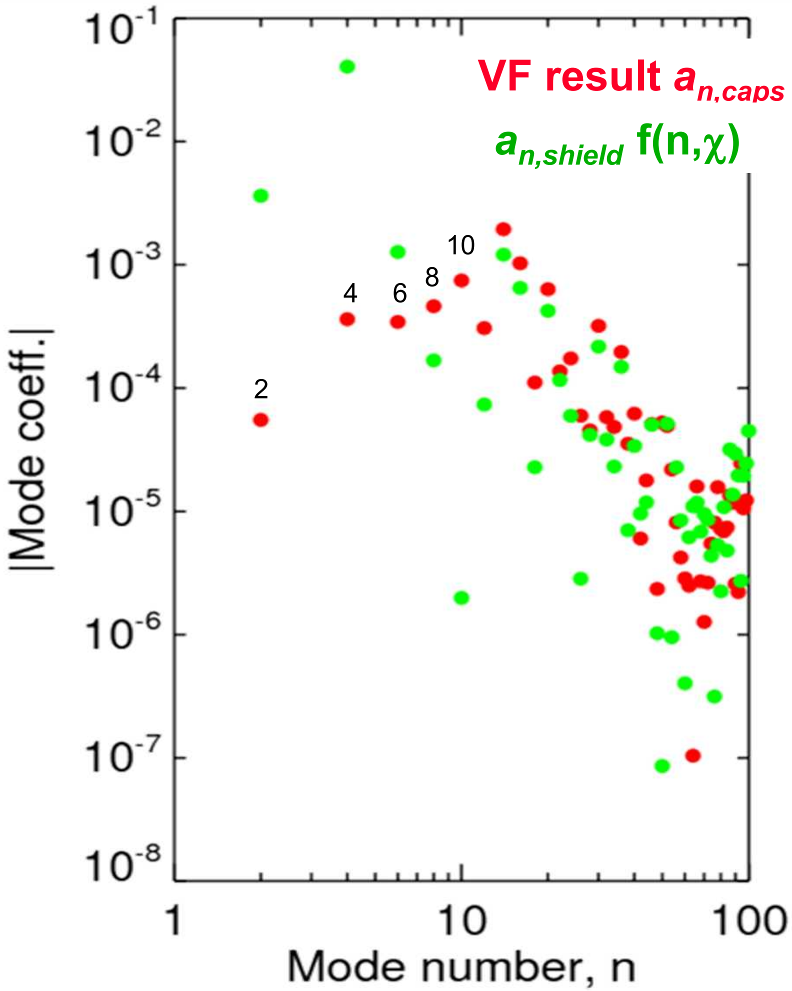
Example: applied asymmetry -5% P_4
Optimized shields minimize $P_{2,4,6,8,10}$
High resolution viewfactor result in red
Estimate $a_{n,shield}$*f(n,R_{caps}/R_{shld}) in green

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,χ)



Simple estimate is good for n>10



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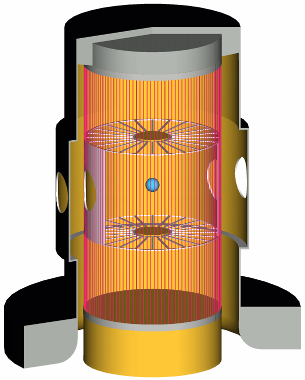
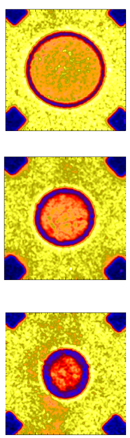
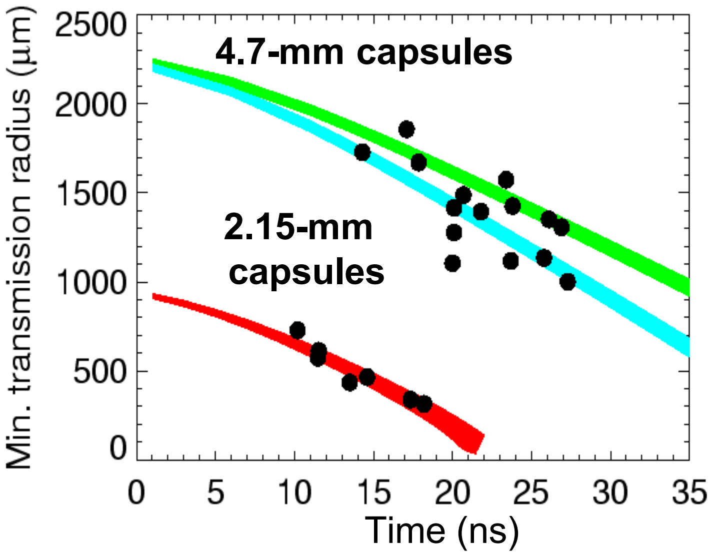
Experiments on Z have validated our 2D LASNEX simulations of hohlraum energetics and symmetry

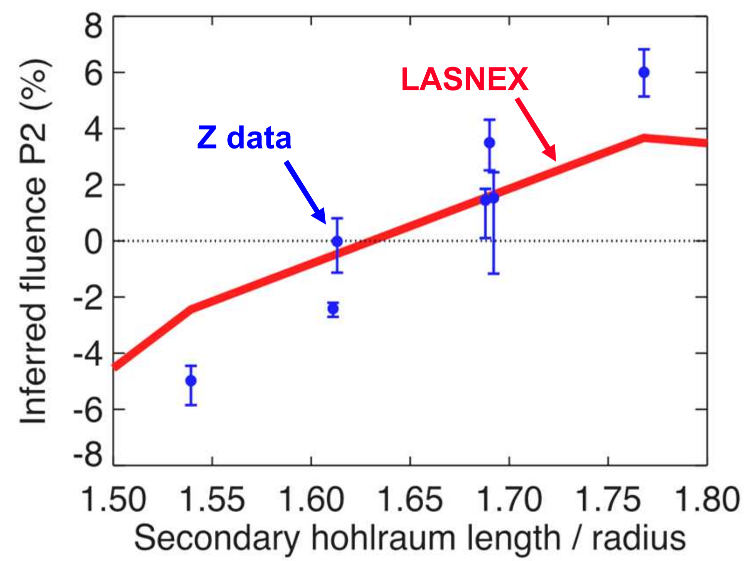




Backlit capsule trajectories confirm hohlraum coupling



P_2 asymmetry can be zeroed with secondary hohlraum length tuning



- **Consistency of z-pinch and hohlraum energetics documented at ± 20% level in flux**
- **Spoke transmission measured to be > 70%**

M. Cuneo et al., *Phys. Plasmas* 2001
G. Bennett et al., *Phys. Plasmas* 2003
R. Vesey et al., *Phys. Plasmas* 2003
R. Vesey et al., *proc. IFSA* 2005