Time-dependent radiation drive asymmetry compensation of inertial fusion capsules by ablator doping

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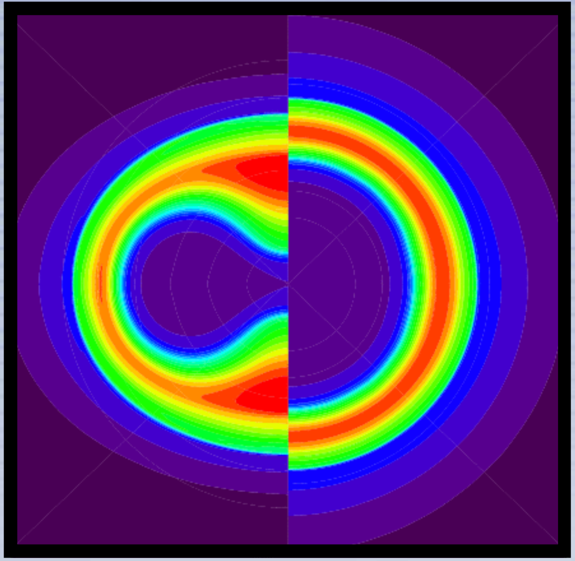

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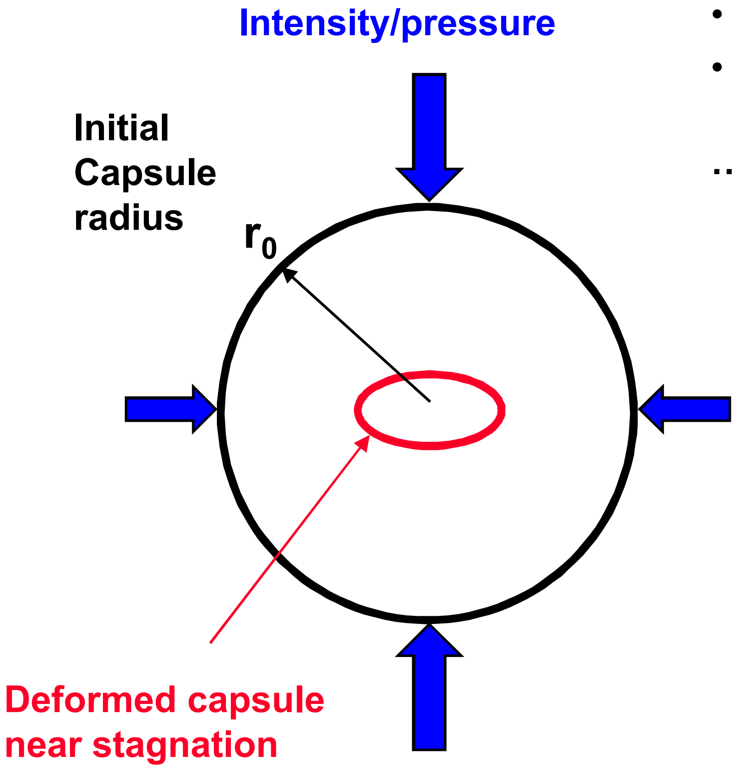
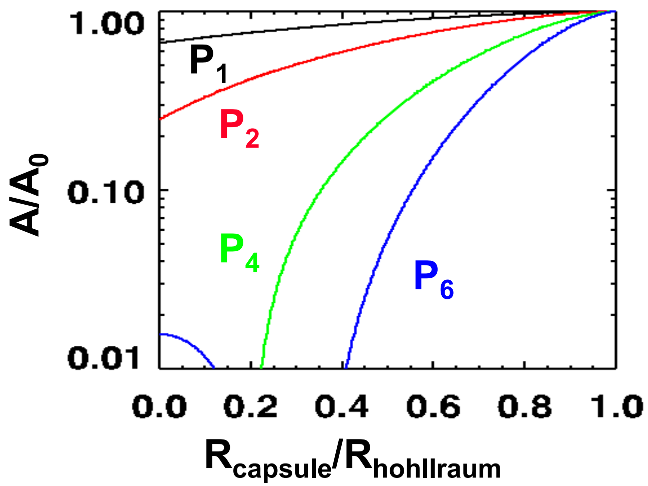
Inertial Fusion Capsules require a high degree of drive symmetry: low order modes most challenging

- Ablation pressure is nearly proportional to radiation Intensity: ($P_{abl} \sim I^{0.9}$) => $\delta r \sim r_0 \delta I/I$
- Assuming $\delta r < r_f/2$: => $\delta I/I < 1/(2C_r)$
- High convergence ratios needed to keep the drive energy practical, $E \sim 1/Cr^6$

…Cr~35 is typical => $\delta I/I \sim 1.5\%$





•High modes are effectively smoothed with a modest ratio of $R_{capsule}/R_{hohlraum}$

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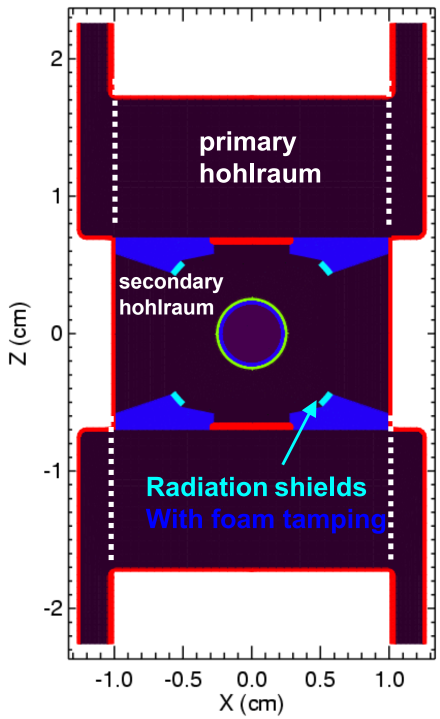
The attainment of adequate symmetry is a challenge for all radiation driven ICF approaches

- P_2, P_4, and P_6 are controlled by accurately locating laser focal spots into multiple rings within the hohlraum
- Modified laser pointing could improve LPI but effect symmetry
- Shorter and/or smaller hohlraums could improve efficiency but increase asymmetry



•Vacuum Z-pinch hohlraums require radiation shields

•One sided drive would improve efficiency

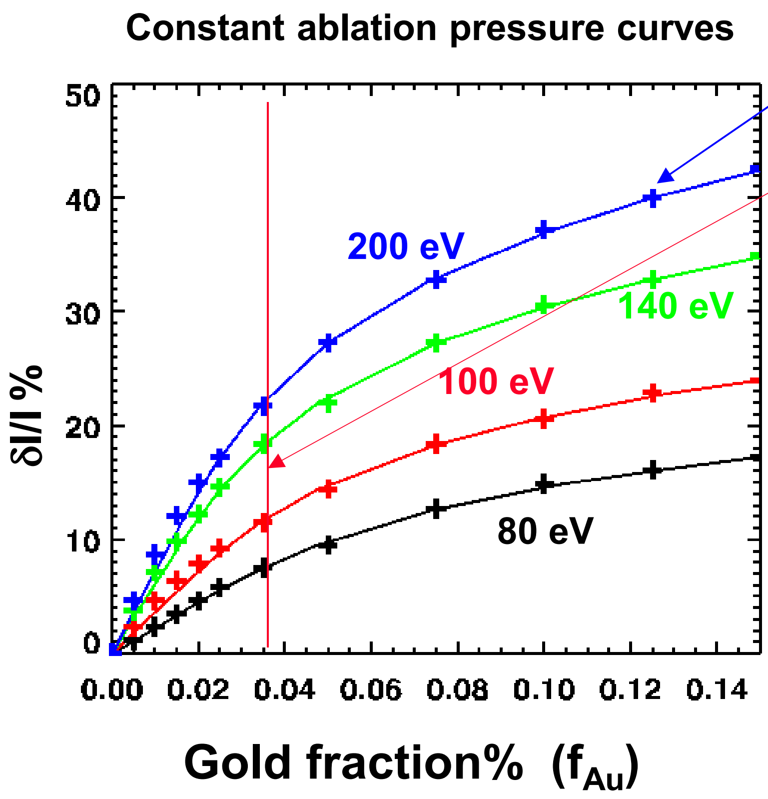
•Distributed ion deposition in heavy ion targets have problems with P_4

•External shims can correct early P_4 asymmetries

D.A. Callahan et al. Plasma Phys. Contrl. Fusion 47, B379(2005)

•In depth variable doping could correct much larger asymmetries, which can have nearly arbitrary time-dependence

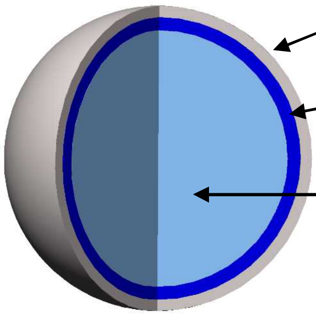
Gold doping of beryllium ablators can compensate for radiation temperature variations



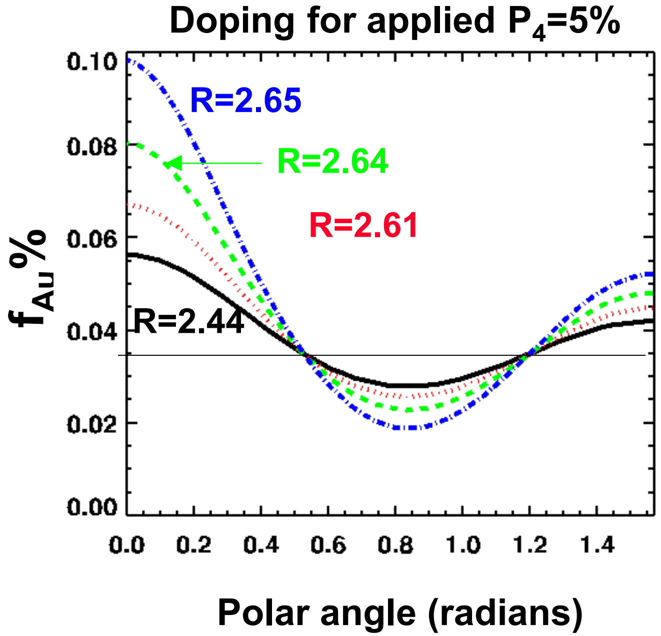
- Lasnex simulations determine ablation pressure reduction as a function of f_{au} at fixed T_{rad}.
- $P_{abl} \sim T_{rad}^{3.5}$ used to determine $\delta I/I = F(f_{AU})$ to yield ablation pressure of pure Be
- A median pressure operating point is obtained with a constant $f_{Au} = 0.035$
- 1-D simulations used to locate the ablation front depth as a function of time
- A polynomial expression (curves), which fits the Lasnex results over the range $80 < T_{rad} < 240$, determines gold dopant fraction for the $\delta I/I$ expected at the time the ablation front reaches each depth within the ablator for a particular time-dependent radiation asymmetry

Baseline z-pinch driven capsule with Cu-doped beryllium was modified for symmetry doping

In-flight aspect ratio	35
Implosion velocity	26 cm/μs
Convergence ratio	35
Total ρr	3.1 g/cm^2
Absorbed energy	1.2 MJ
Yield	500 MJ



0.2% Cu replaced with 0.035% Au, ablator thickened by 10%, and T_{rad} increase by 4%



Optimum doping fraction depends on both polar angle and depth even for a constant applied asymmetry

Copper or Gold replace beryllium atoms without deforming the lattice for doping fractions < 1%

… density = $n_{lattice}[(1-f_{Au})M_{Be}+f_{Au}M_{Au}]$

…a large gold doping fraction (0.1%) causes a small density increase of 2.1%

Studies indicate error tolerance for doping ~ 25%

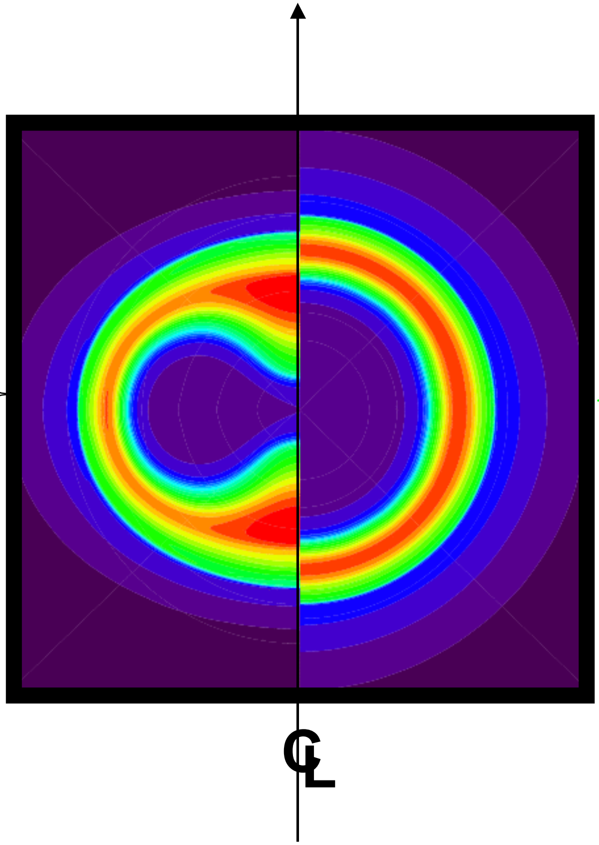
Fuel density contours at ignition show the dramatic effect of doping with $P_2 = 1.9\%$

No variable doping

Variably doped

Uncorrected capsule is near failure threshold.

…A polar jet quenches ignition at $P_2 = 2.0\%$



Corrected capsule is spherically symmetric

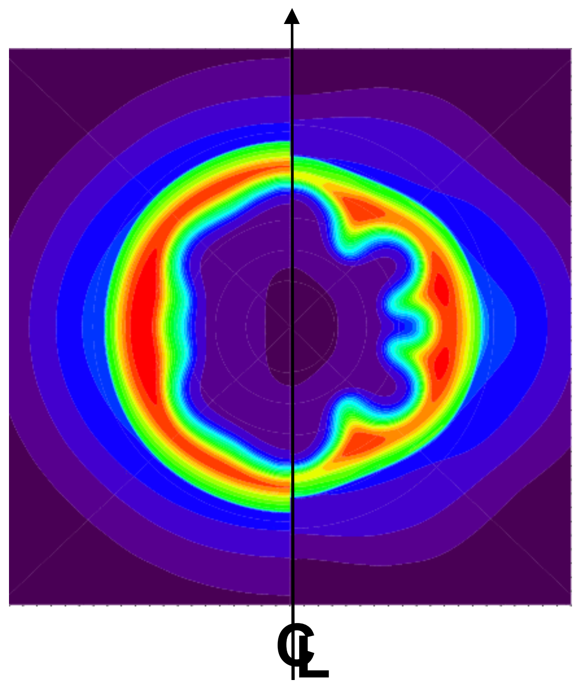
…much higher radiation asymmetries can be tolerated

Large applied P_2 asymmetry requires higher order doping corrections

- P_4 corrections remove the P_4 distortion at large applied P_2

Applied P_2=12%

Small P_6 distortion is evident



Applied P_2=20%

Large P_6 distortion

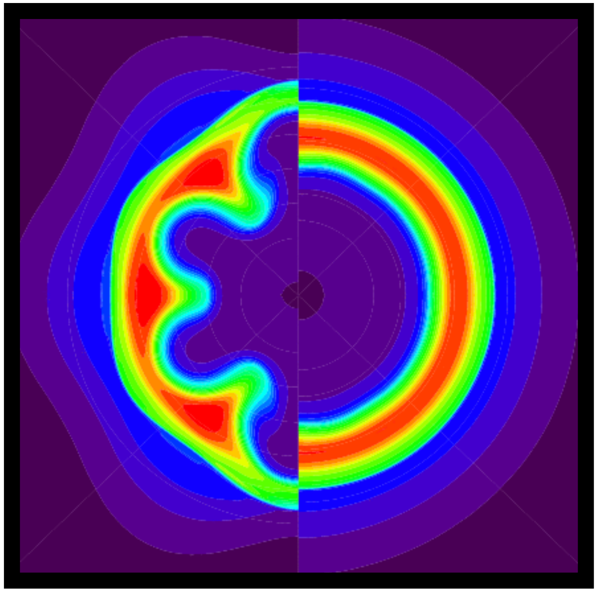
…corrections could extend results

Despite imperfections in doping algorithm, the maximum acceptable P_2 has been increase by a factor of 10!

Variable doping is effective for higher radiation asymmetry modes, e.g. P_6=0.49%

No variable doping

Uncorrected capsule is at the threshold for failure which occurs at P_6=0.5%



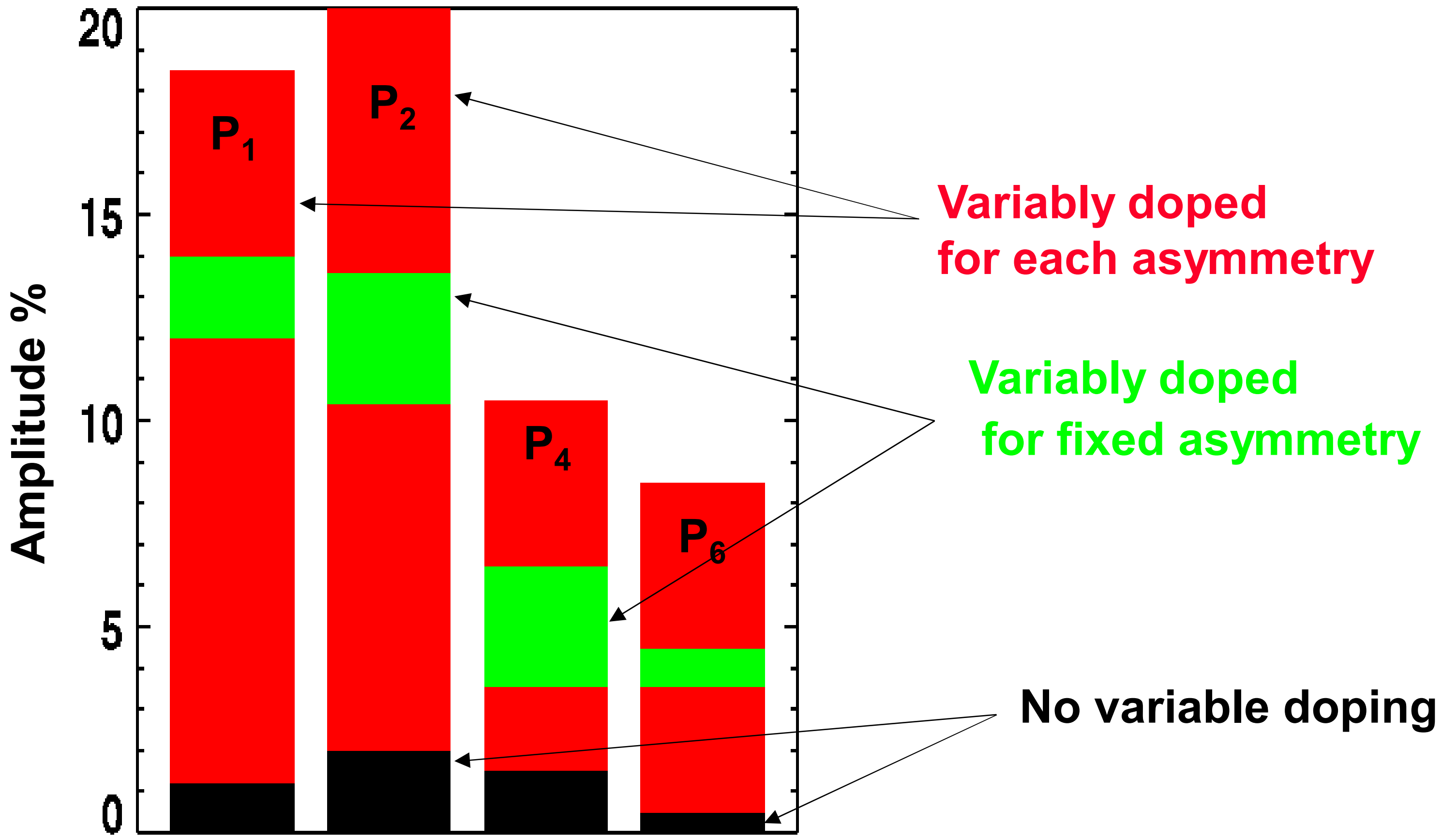
Variable doping

The compressed fuel of the variably doped capsule is nearly spherical

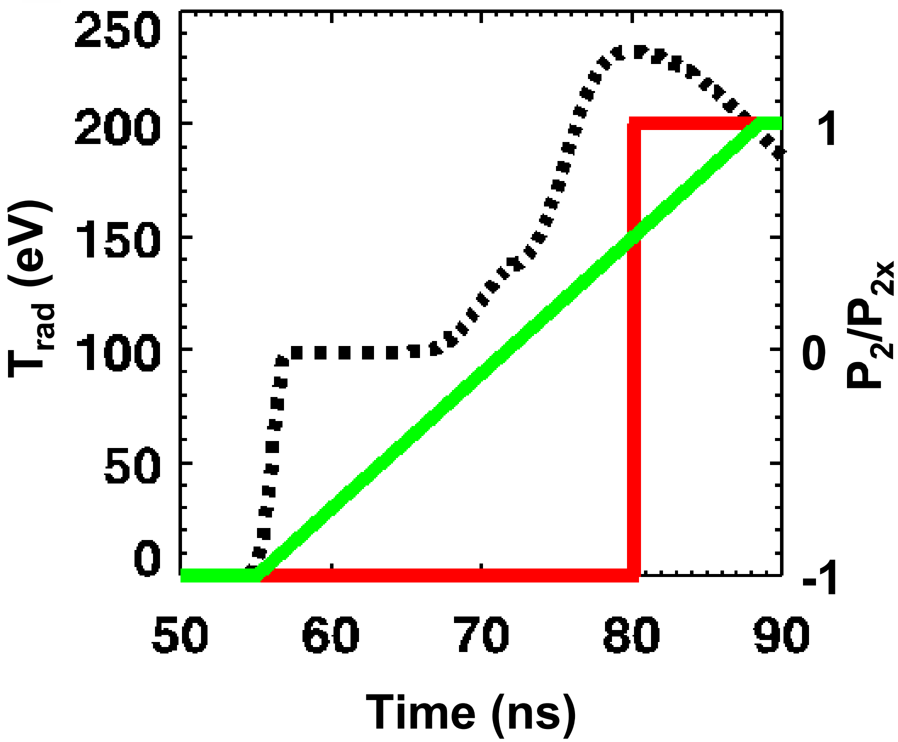
…doping can compensate for much higher values of P_6

Variable doping mitigates radiation asymmetries for important modes

Tolerated range of asymmetries (positive or negative)



Variable doping can compensate for time-dependent asymmetries



Step function:

…without doping P_{2x}<5.7%

…with correction P_{2x}<17.5%

Ramp function:

…without doping P_{2x}<2.3%

…with correction P_{2x}<17%

Doping in the ablated plasma effects radiation transport

…$P_n(t)$ cannot be simply related to a single layer in the ablator

…Doping algorithm needs further work to obtain optimum results

Future work includes:

- Design a variably doped capsule for a NIF hohlraum which has relaxed constraints on laser pointing or geometry and consequently does not have adequate symmetry
- study the effect of variable doping on capsule stability
- develop fabrication techniques
- improve the doping algorithm particularly for time-dependent asymmetries

Despite added complexity, there could be significant advantages to multiple dopants

- A single dopant causes a variation in the ablator density

… density = $n_{lattice}[(1-f_d)M_{Be}+f_dM_d]$

- Density variations could possibly make the capsules more susceptible to Rayleigh-Taylor Instability.

…Not expected, but stability studies are planned.

- Radial tailoring of the ablator density could increase capsule robustness to the RT instability

…S. W. Haan *et al*. Phys. Plasmas, 12, 056316 (2005)

…two or more dopants are required

Two dopants can produce a variable opacity without changing the density

- Copper and gold replace beryllium atoms without deforming the lattice for doping fractions < 1%

…F. Aldinger and G. Petzow in *Beryllium Sci. Tech* Vol I Plenum Press, New York, 1979)

… density = $n_{lattice}[\ (1-f_{Cu}-f_{Au})M_{Be}+f_{Cu}M_{Cu}+f_{Au}M_{Au}\ ]$

- The density is independent of dopant fractions if $f_{Au} = 0.29(f_{Cu0}-f_{Cu})$

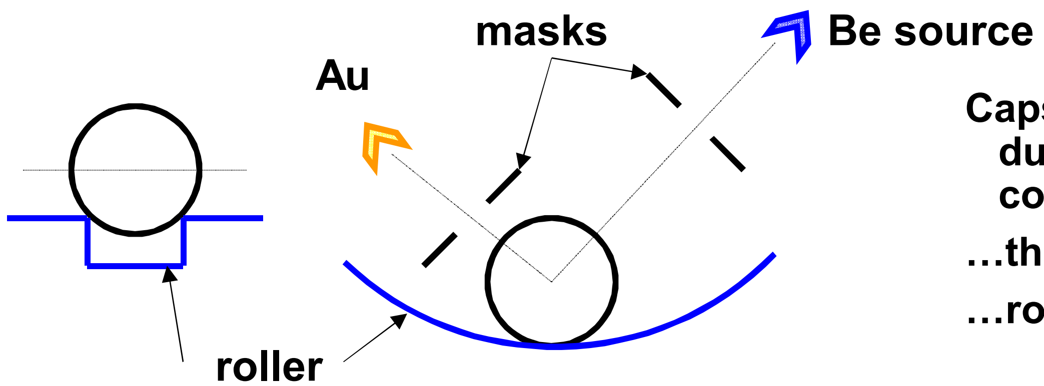
…density = $1.85[\ 1+6.05f_{Cu0}\ ]$ g/cc

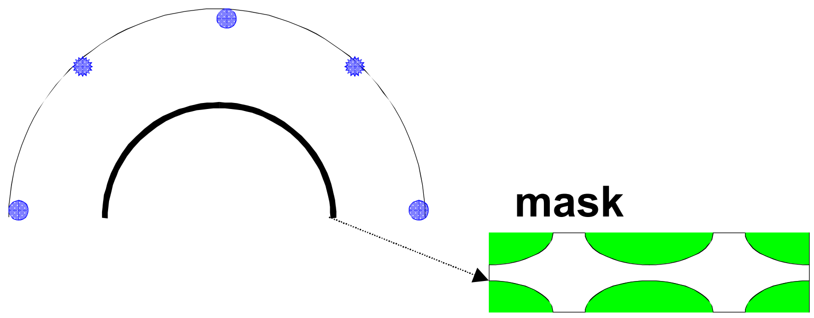
…radial tailoring of f_{Cu0} results in radial density tailoring

- The opacity of gold is much larger than for copper so the opacity is an increasing function of f_{Au}

- Many other ablator materials and dopant combinations are possible!

Capsule fabrication techniques need to be developed to allow variable doping





Capsule should rotate on axis during coating (no bounce coating)

…this has been done on spindle

…roll coating may be preferable

Symmetry of the beryllium and profile of the dopant determined by

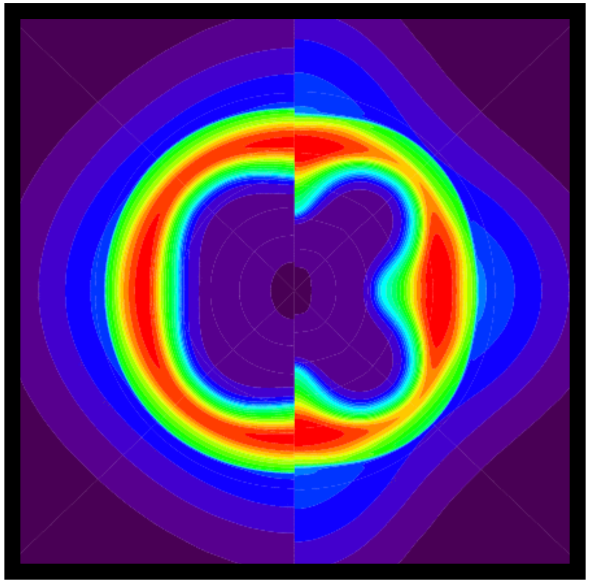
…masking

…and/or movement of the sources

Mode mixing occurs in capsules doped for large amplitude radiation asymmetries

$P_2 = 6\%$

Small P_4 distortion is evident



$P_2 = 12.0\%$

Significant P_4 distortion is evident

Mode mixing probably occurs due to errors in the doping algorithm

…suggests higher order corrections