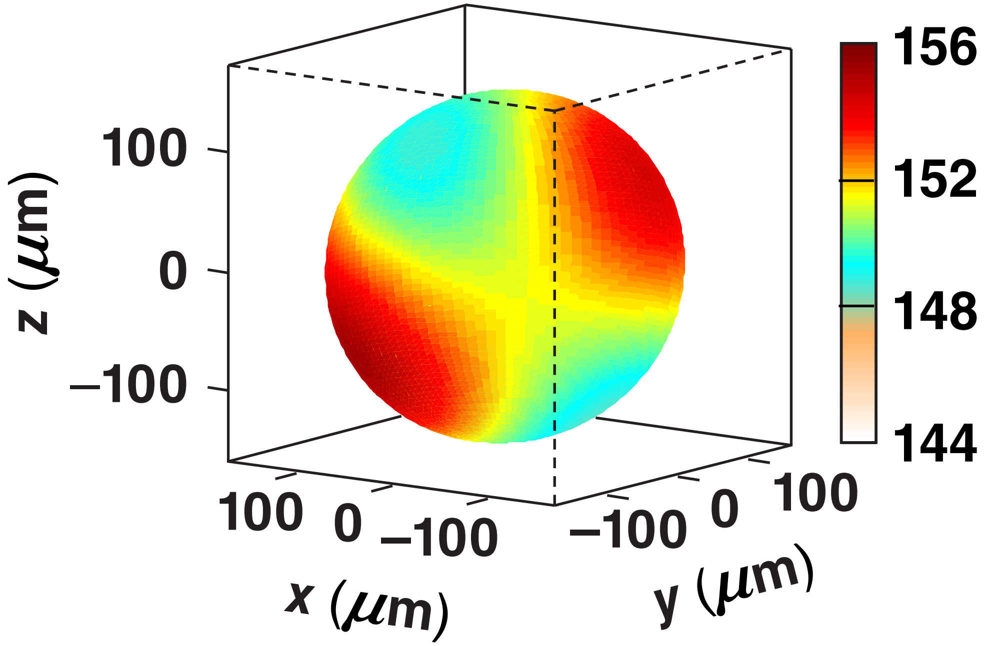
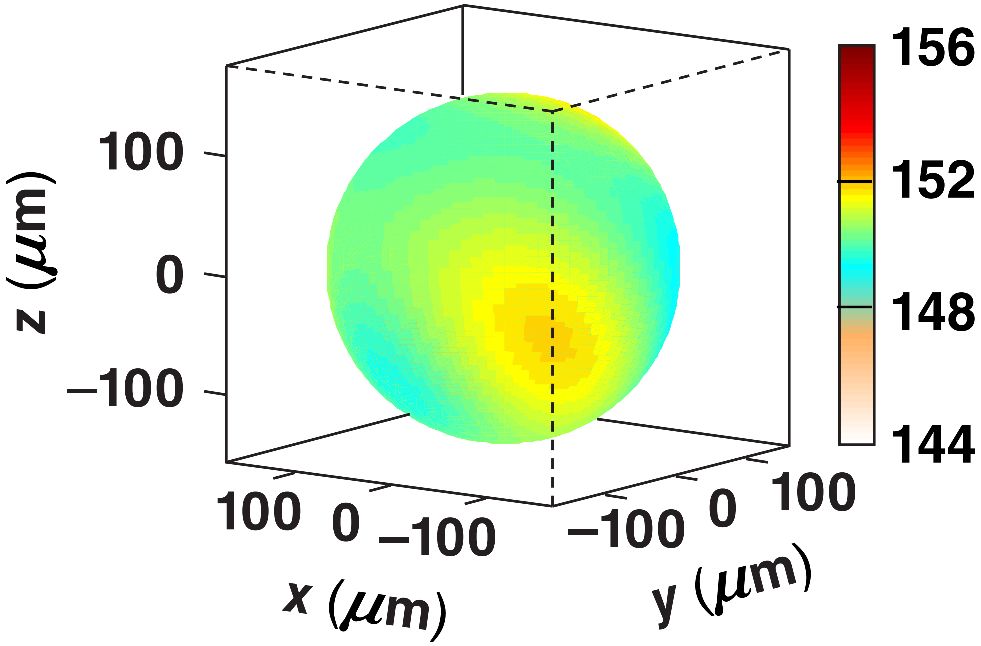
Subpercent Scale Control of 3-D Modes 1, 2, and 3 of Targets Imploded in Direct-Drive Configuration on OMEGA

Nominal balance



3.5-μm rms

After correction



1-μm rms

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Summary

Improved drive symmetry has been demonstrated on OMEGA

- In a series of direct-drive implosions, multiple self-emission x-ray images were used to tomographically measure their 3-D modes 1, 2, and 3 at a convergence ratio of ~3
- The target modes were shown to vary linearly with the laser modes from approximately constant static modes
- This demonstrated that the target modes can be mitigated by adjusting the laser beam-energy balance to compensate the static modes

This method was applied to low-adiabat shots and made it possible to reduce the low-mode nonuniformities from 3.5 μm to 1 μm.

E26763

Collaborators

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University of Rochester
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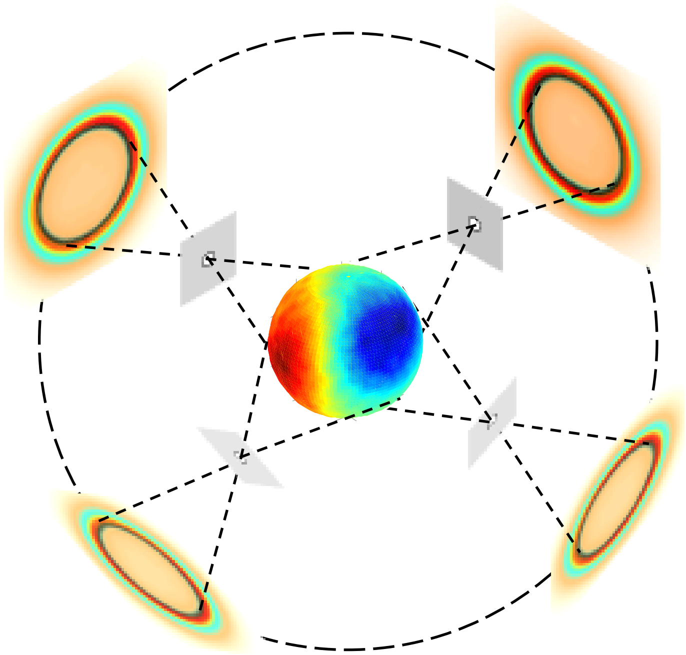
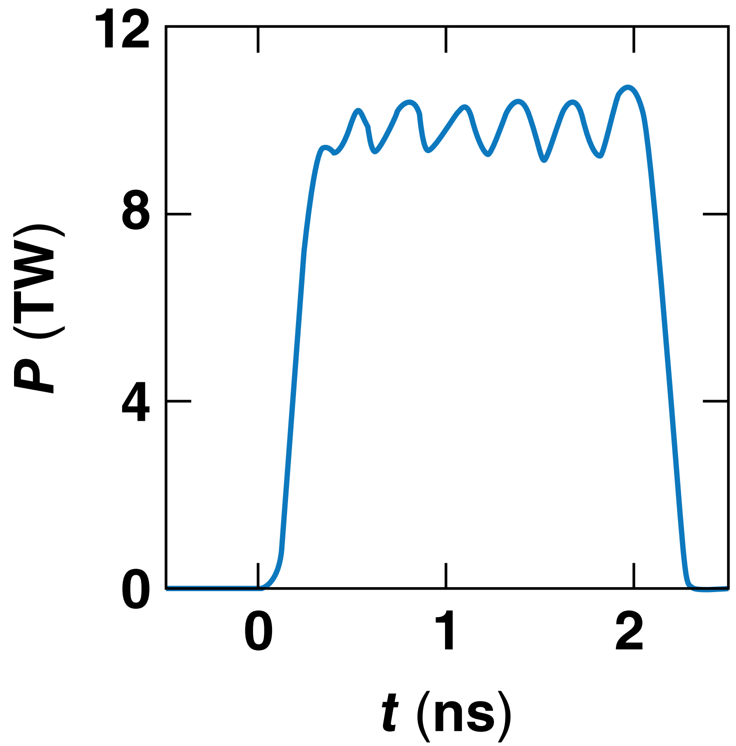
Self-emission shadowgraphy* from multiple lines of sight was used to tomographically measure the 3-D modes $\ell = 1$, $\ell = 2$, and $\ell = 3$ of targets imploded on OMEGA



Synchronized observation $\langle R \rangle = 150\ \mu m$



Each camera measures the projected ablation-front surface along the line of sight of the diagnostic.

$$R(\theta,\phi) = \sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, r_\ell^m Y_\ell^m(\theta,\phi)\ ^{**}$$

*D. T. Michel *et al.*, Rev. Sci. Instrum. 83, 10E530 (2012); D. T. Michel *et al.*, High Power Laser Sci. Eng. 3, e19 (2015).

** Y_ℓ^m are the tesseral spherical harmonics, E. T. Whittaker and G. N. Watson, *A Course of Modern Analysis* (Cambridge University Press, 1927), p. 392; $R(\theta, \phi)$ is normalized in percent ($r_0^0 = 100\%$).

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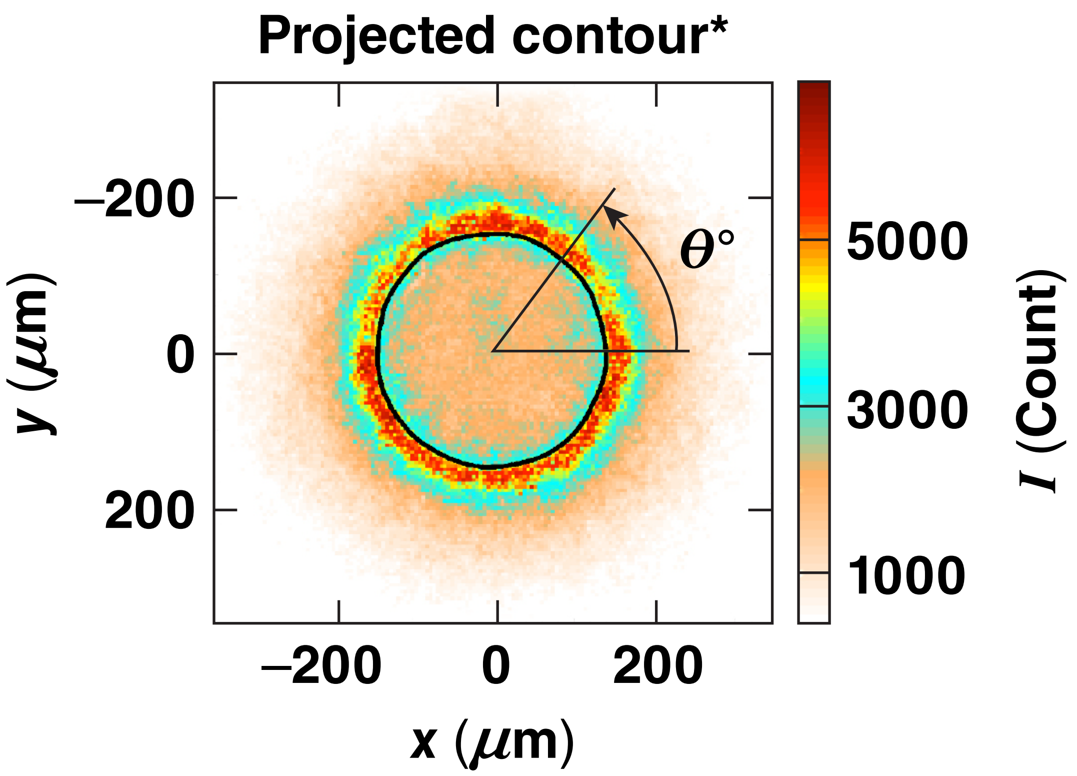
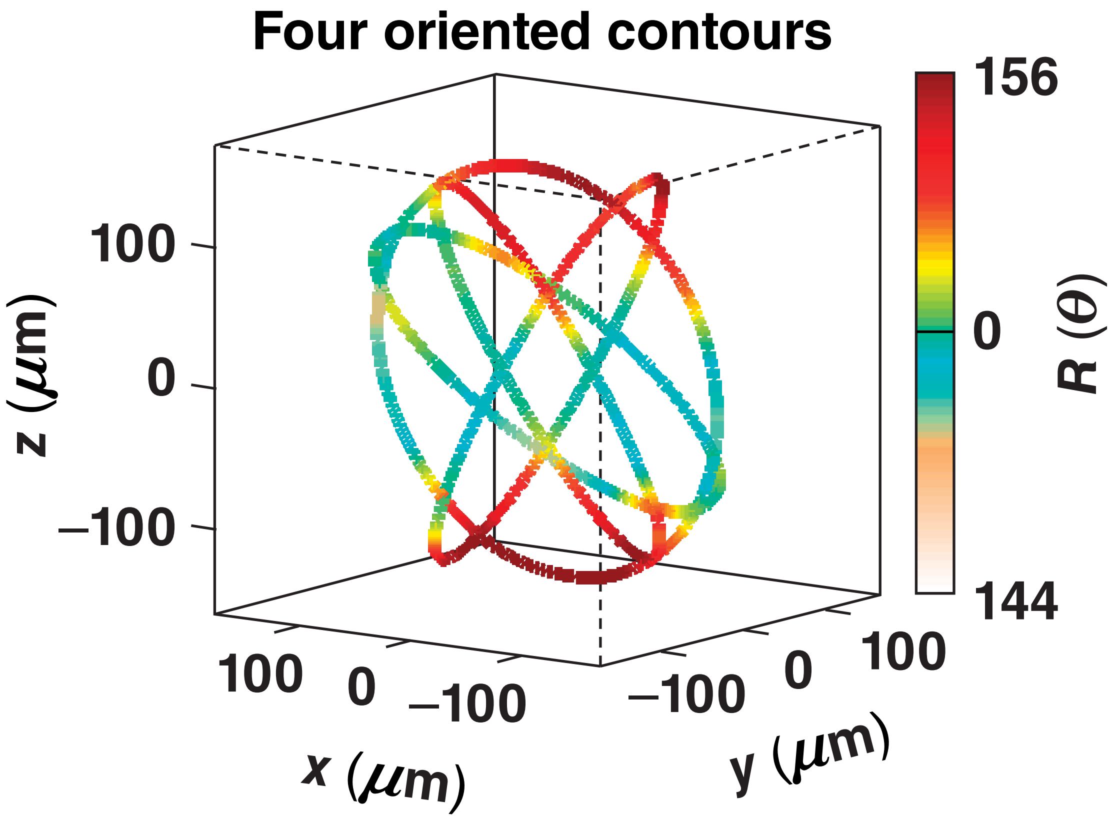
On each camera, the angular variation of the projected ablation contour $R(\theta)$ was determined for an averaged radius of 150 μm

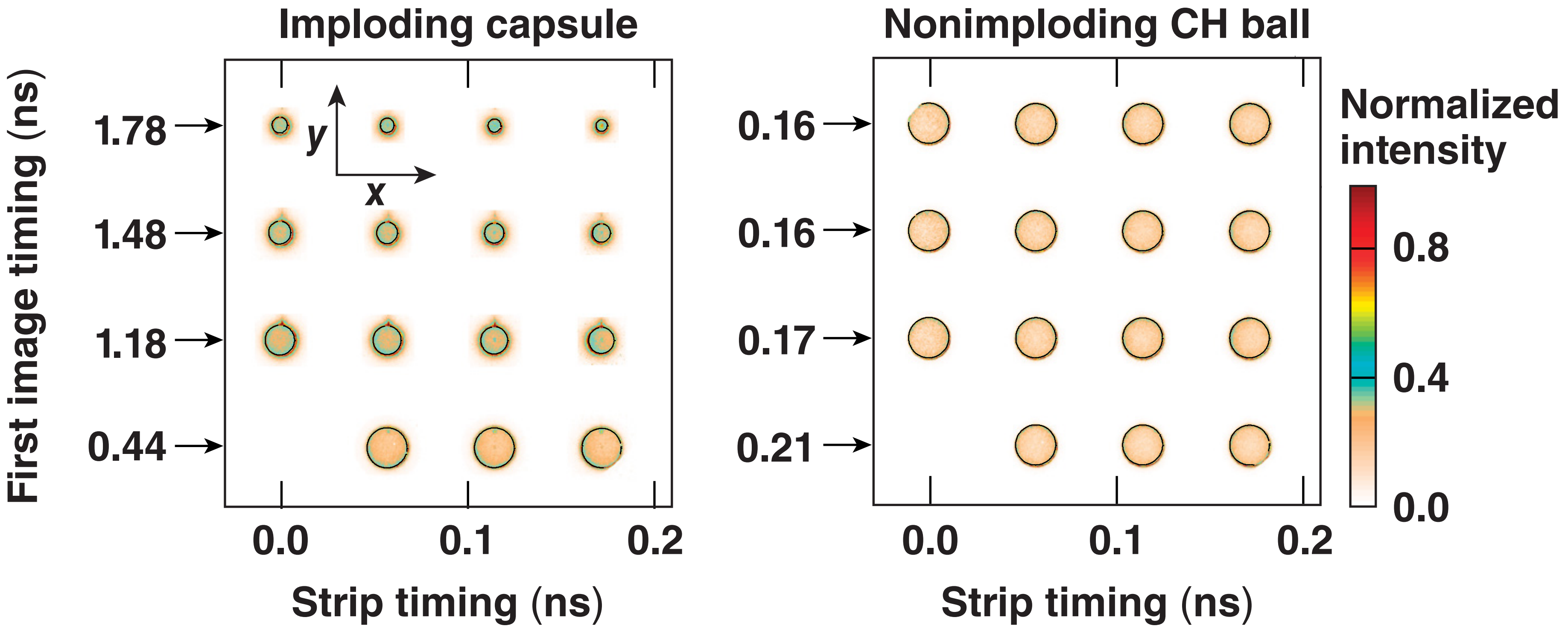


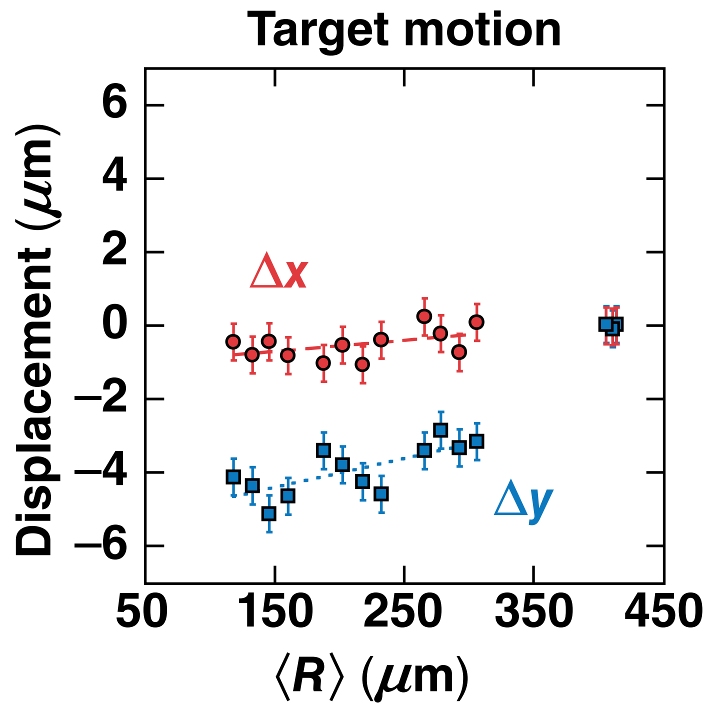


The 3-D shape of the target was obtained by orienting the four contours perpendicular to the camera axis.

*$\delta[\Delta R(\theta)]$ = ±0.7 μm, resulting in $\delta[\Delta R(\theta)]_{150}$ = ±0.4 μm at the 90th percentile of the student's t distribution.

The target motion was obtained by comparing the positions of the contours centers with the corresponding contour centers measured on a nonimploding solid CH ball shot





The target motion at 150 μm was obtained using linear fits.*

*$\delta(\Delta R_{center}) = \pm 1.3$ μm, resulting, in $\delta[(\Delta R_{center})_{150}] = \pm 0.6$ μm at the 90th percentile of the student's *t* distribution

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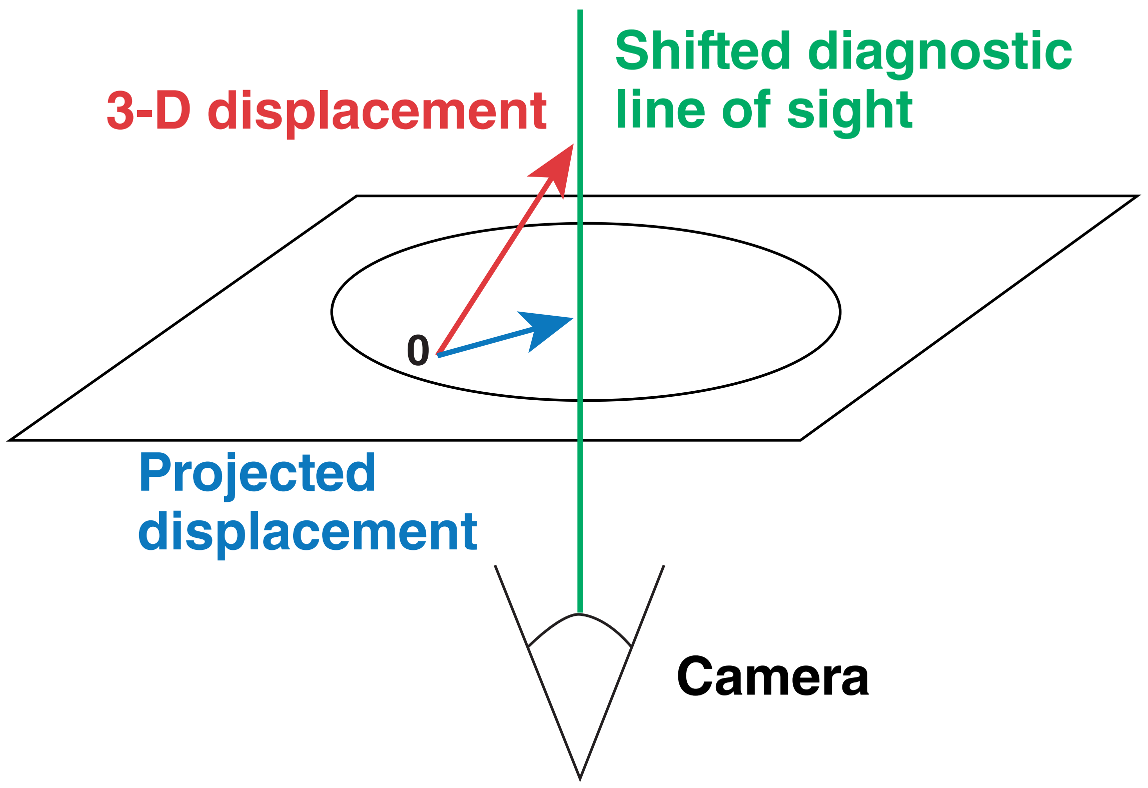
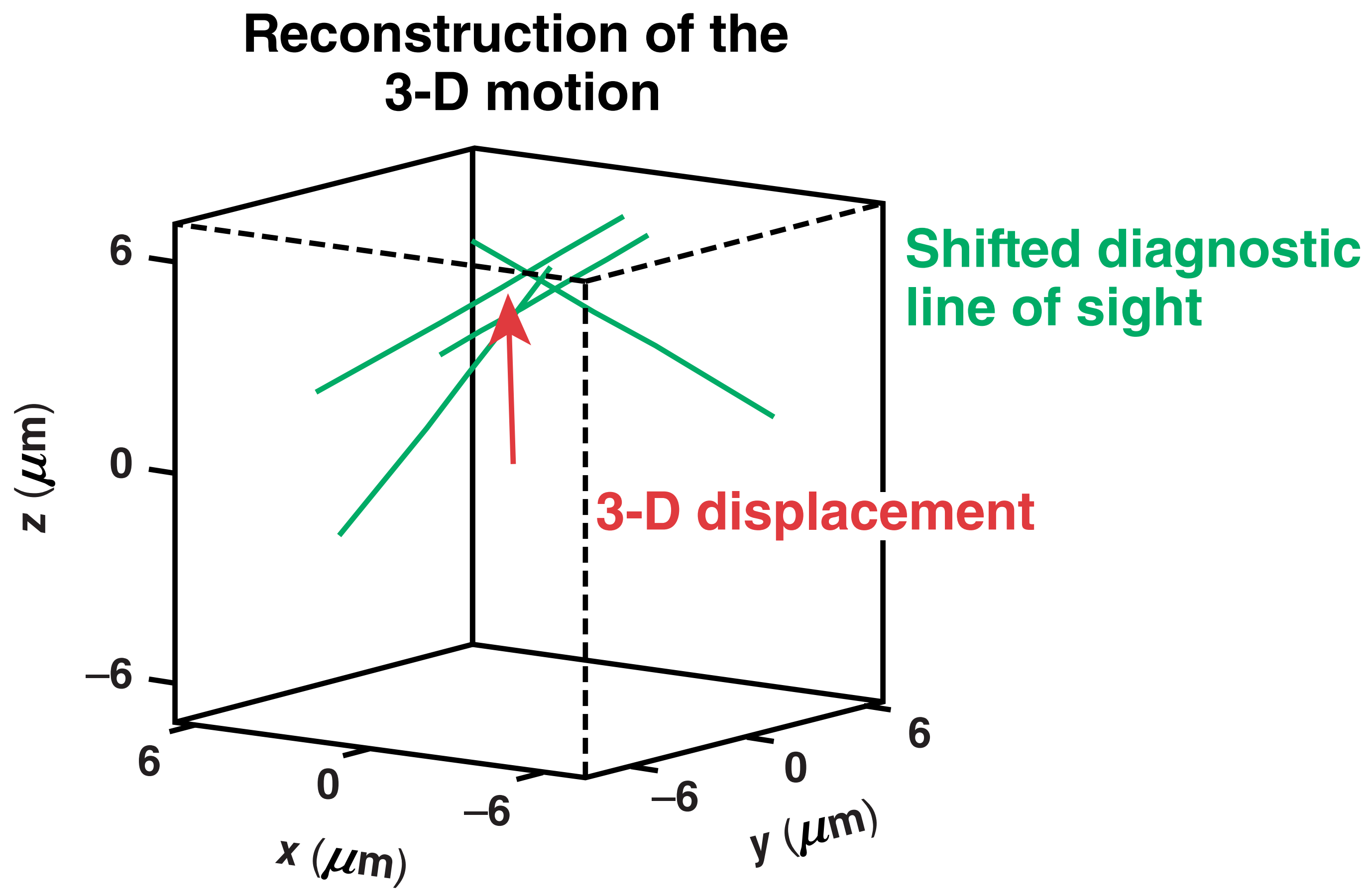
The 3-D target displacement is located at the intersection of the four lines defined by the camera axis, translated by the measured projected target motions

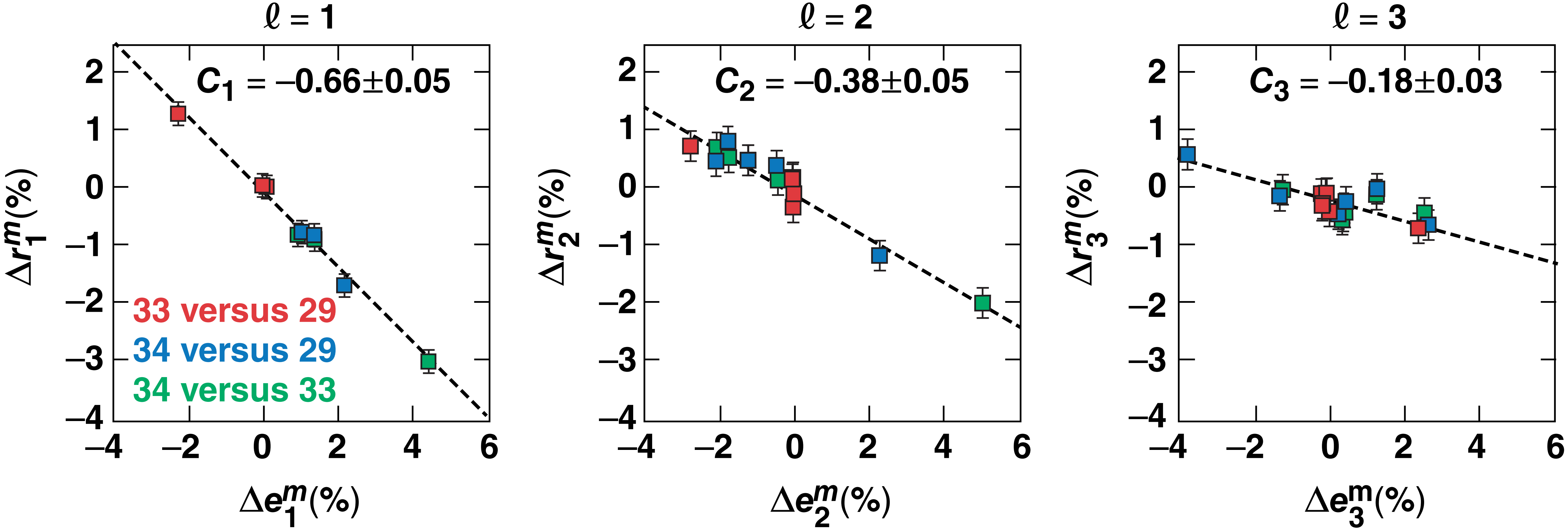




E26766

For each mode ℓ, a linear evolution of the target modes (Δr_ℓ^m) with the laser beam-energy balance (Δe_ℓ^m) was measured

$C_\ell = \Delta r_\ell^m (150\ \mu m)/\Delta e_\ell^m$



The reduction of C_ℓ with ℓ was explained by the individual beam shape that modifies the laser illumination nonuniformity compared to the laser beam-energy balance.

*The laser modes are obtained by minimizing $\sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, e_\ell^m Y_\ell^m (\theta_b, \phi_b) - E_b,$ where is E_b, is the beam energy normalized to the averaged beam energy.

E26768

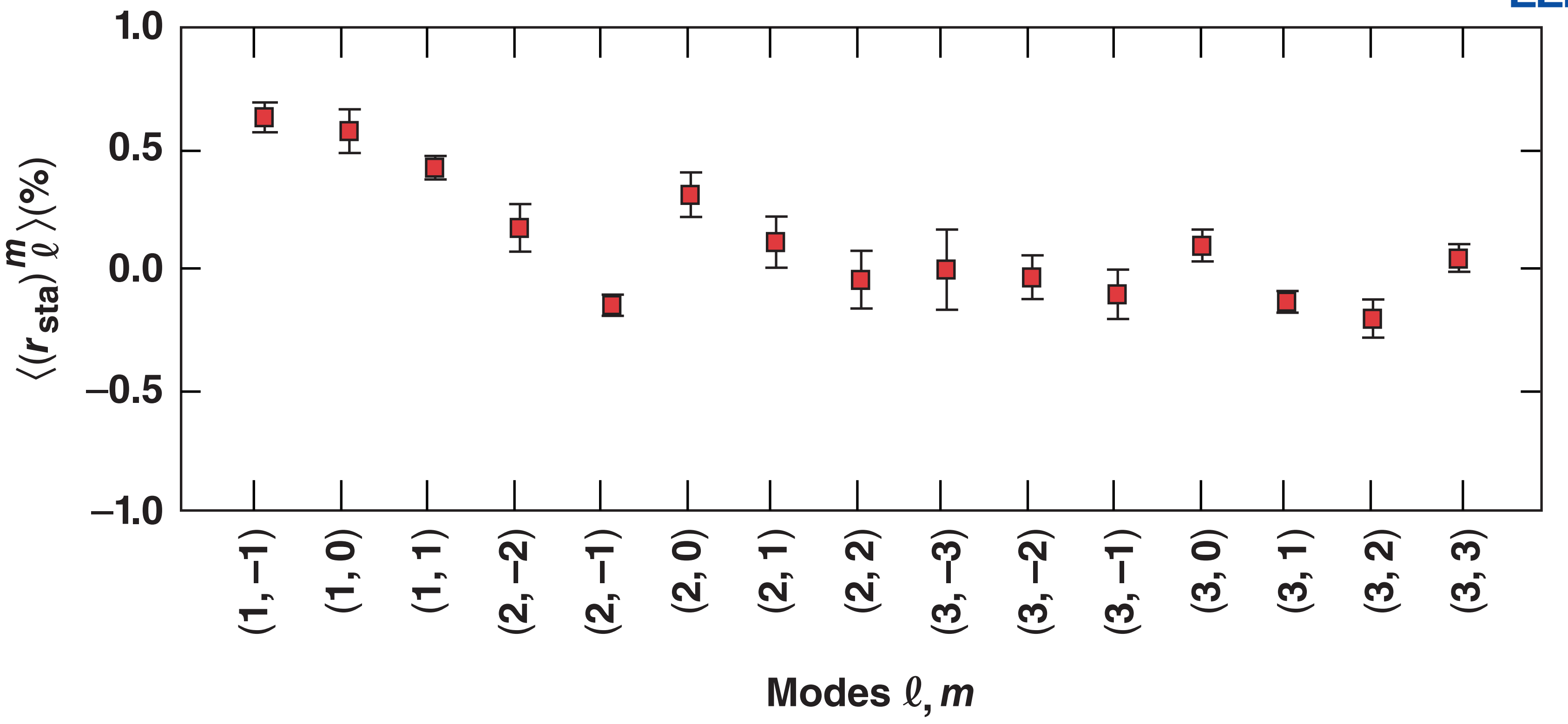
The linear variations show that the target modes are the result of two components: a part that varies linearly with the laser modes and a static part

The static modes are given by

$$\left\langle (r_{\text{sta}})_\ell^m \right\rangle_{\text{shots}} = \left\langle r_\ell^m - C_\ell e_\ell^m \right\rangle_{\text{shots}}$$

The optimized beam energy balance is given by

$$(e_{\text{opt}})_\ell^m = -\frac{\left\langle (r_{\text{sta}})_\ell^m \right\rangle_{\text{shots}}}{C_\ell}$$

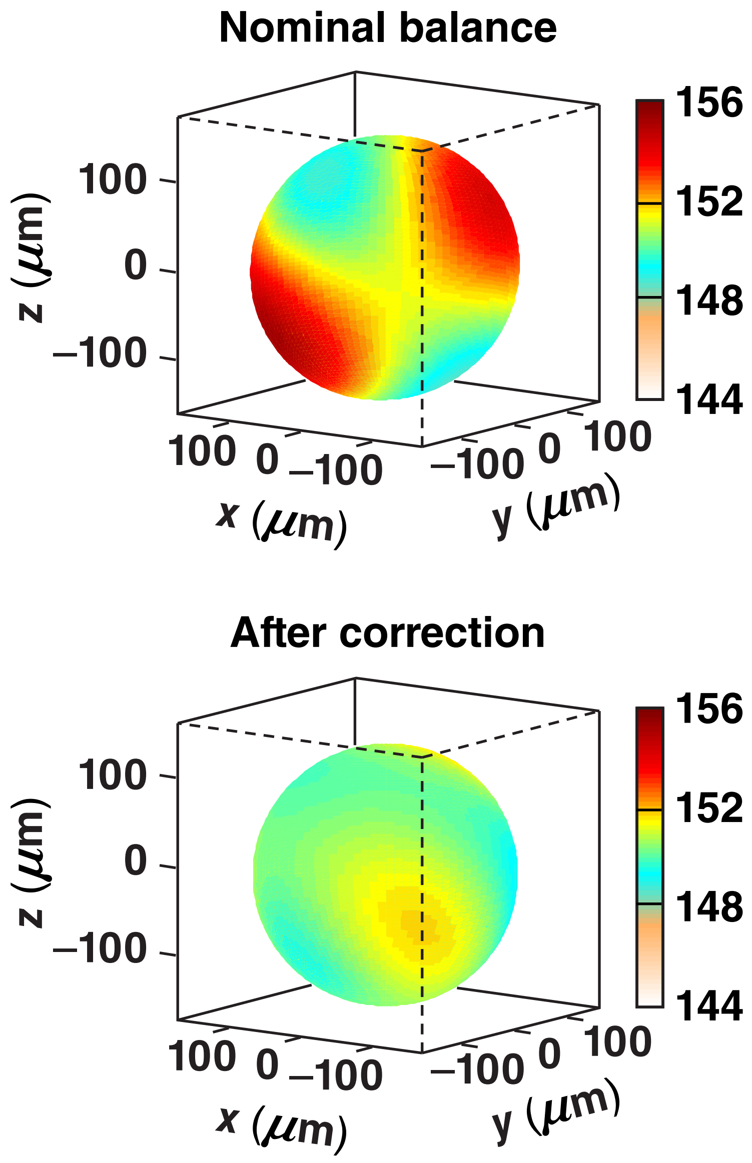


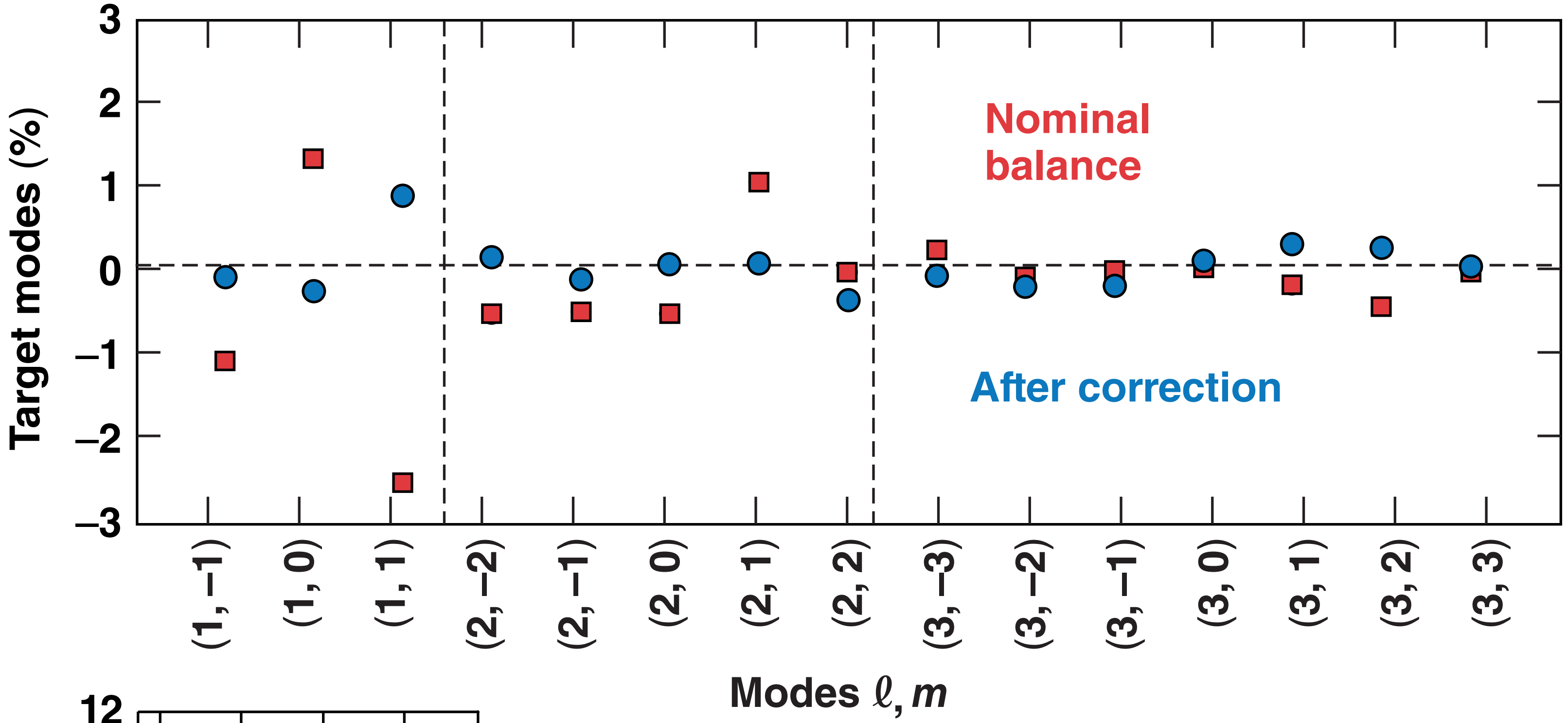
This demonstrates that the target modes can be mitigated by adjusting the laser modes to compensate the static modes.

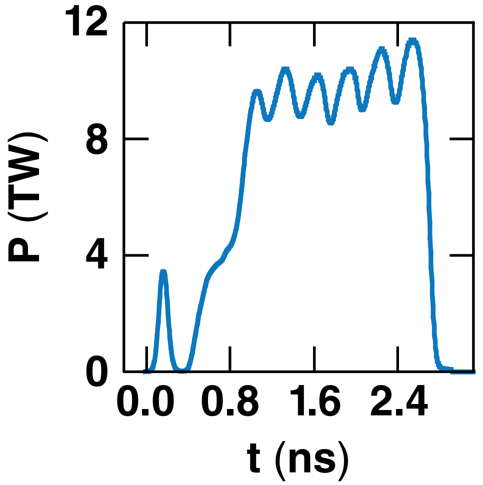
D. T. Michel *et al.*, "Subpercent-Scale Control of 3-D Modes 1, 2, and 3 in Direct-Drive Configuration on OMEGA," submitted to Physical Review Letters.

E26769

This method was successfully applied to mitigate the target nonuniformities on a low-adiabat warm implosion







The correction made it possible to reduce the standard deviation of the target modes 1, 2, and 3 from ~3.5 μm to ~1 μm.

E26770

Improved drive symmetry has been demonstrated on OMEGA

- In a series of direct-drive implosions, multiple self-emission x-ray images were used to tomographically measure their 3-D modes 1, 2, and 3 at a convergence ratio of ~3
- The target modes were shown to vary linearly with the laser modes from approximately constant static modes
- This demonstrated that the target modes can be mitigated by adjusting the laser beam-energy balance to compensate the static modes

This method was applied to low-adiabat shots and made it possible to reduce the low-mode nonuniformities from 3.5 μm to 1 μm.

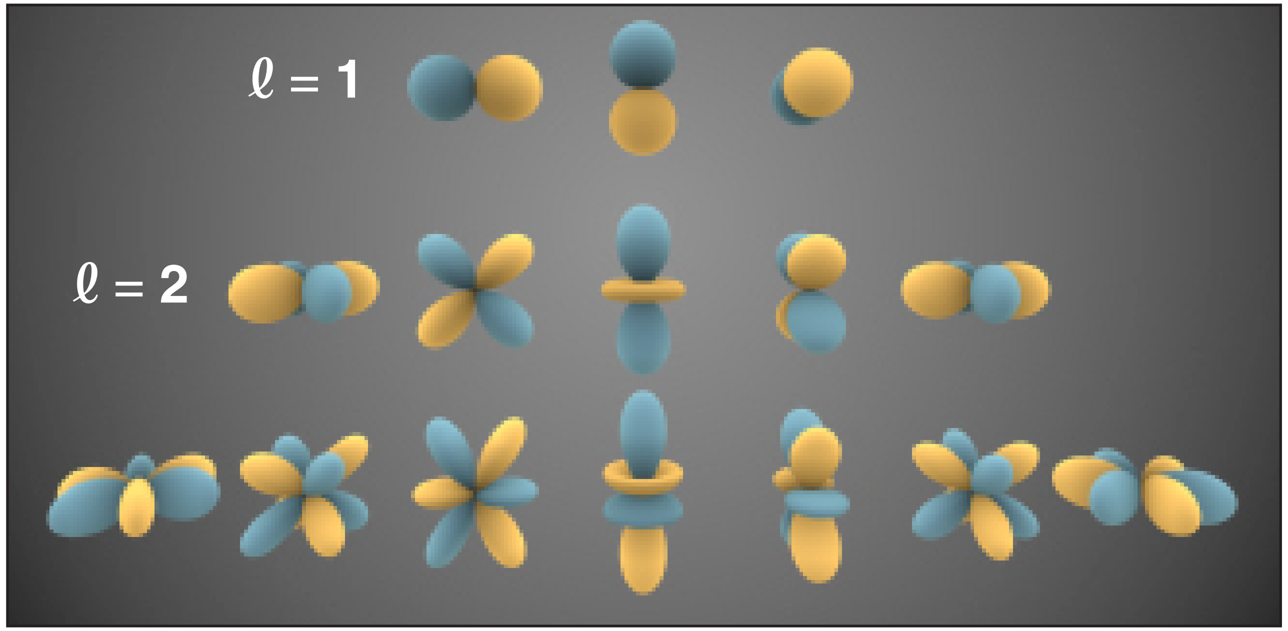
Over three shots, the beam-energy balance was changed to modify their modes $\ell = 1$, $\ell = 2$, $\ell = 3$, and for $m = 0$

UR LLE

$$\bar{E}(\theta_b, \phi_b) = \sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, e_\ell^m Y_\ell^m(\theta_b, \phi_b)\ ^*$$

Shots	Δ	Δ	Δ
84633 versus 84629	–2.2	–2.6	2.4
84634 versus 84629	2.2	2.2	–3.5

$\ell = 3$



$$C_\ell = \Delta r_\ell^m (150\ \mu m) / \Delta e_\ell^m$$

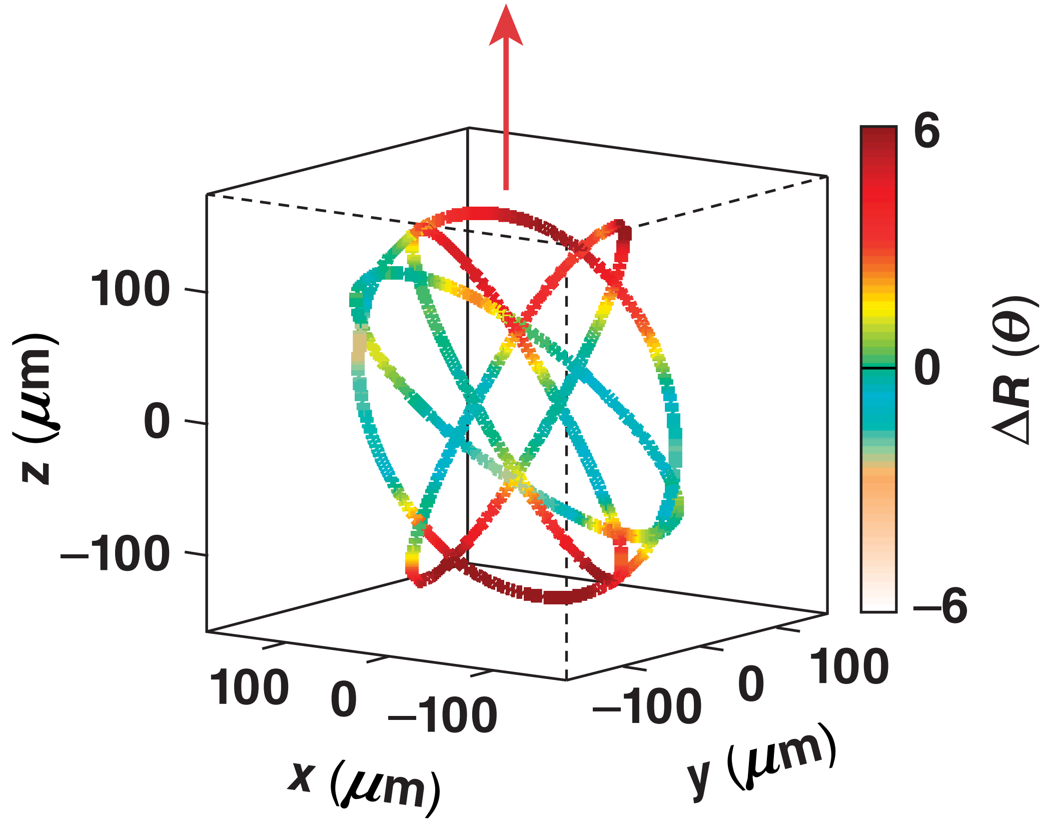
The low-mode coupling coefficients were determined by measuring the variation of the target modes (Δr_ℓ^m) as a function of the laser beam-energy balance (Δe_ℓ^m).

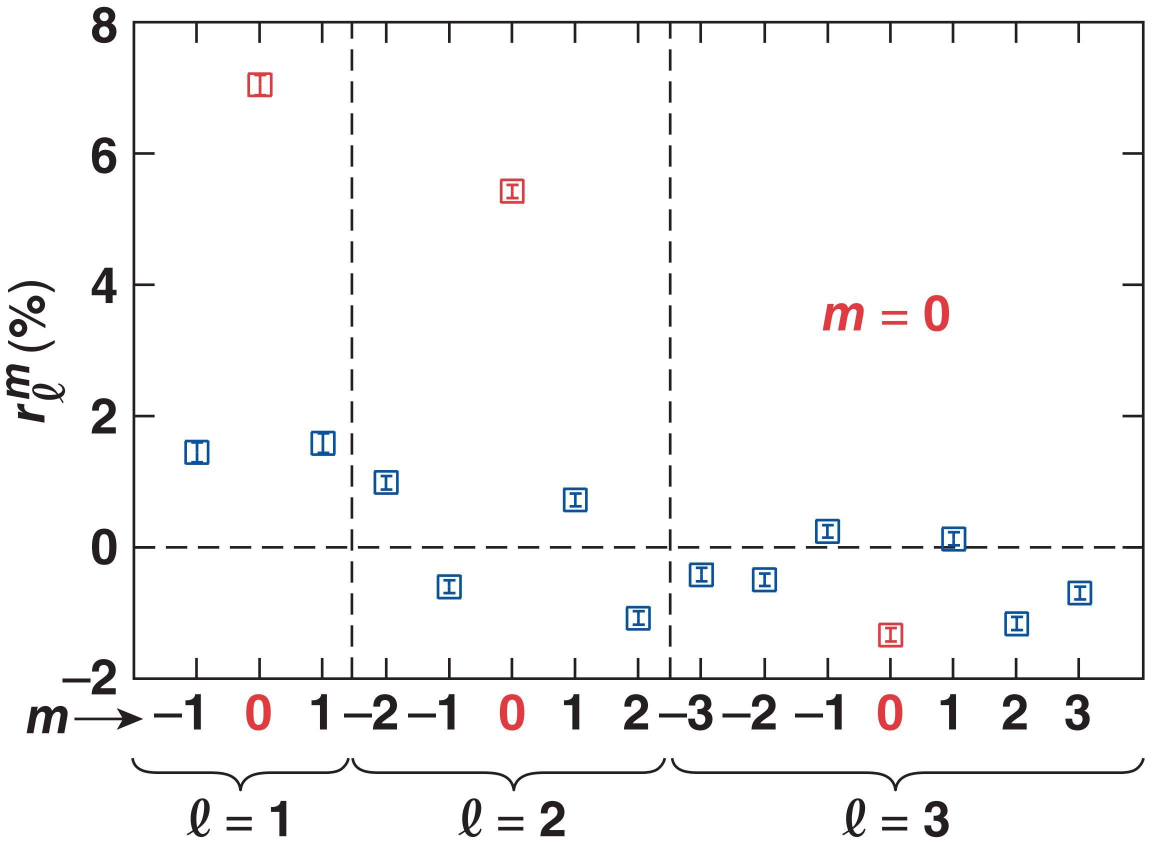
**The modes are obtained by minimizing $\sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, e_\ell^m Y_\ell^m(\theta_b, \phi_b) - \bar{E}_b$, where $\bar{E}_b$ is normalized to the averaged beam energy.

E26771

The target modes were obtained by decomposing the four contours translated by the target displacement over spherical harmonics

$$\overline{R}(\theta_c, \phi_c) = \sum_{\ell=0}^{3} \sum_{m=0}^{3} r_\ell^m Y_\ell^m(\theta_c, \phi_c)$$





Errors of $\delta(r_1^m) = \pm0.15\%$, $\delta(r_2^m) = \pm0.1\%$, and $\delta(r_3^m) = \pm0.1\%$ were obtained by simulating the errors in $[\Delta R(\theta)]_{150}$ and $[\Delta R_{center}]_{150}$.

E26772

The decrease of C_ℓ with ℓ was a result of the beam profiles that modify the amplitude of the laser modes on target*

- The laser modes are described by minimizing $(\partial A/\partial e_1^m = 0)$: $A = \sum_{b=1}^{60}\left[\sum_{\ell=0}^{\infty}\sum_{m=-1}^{\ell'}\sqrt{4\pi}\, e_\ell^m Y_\ell^m(\theta_b,\varphi_b) - \bar{E}_b\right]^2$
- This results in

$$\sum_{b=1}^{60}\left[\bar{E}_b Y_\ell^m(\theta_b,\phi_b)\right] = \sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\sqrt{4\pi}\, e_\ell^m \sum_{b=1}^{60}\left[Y_\ell^m(\theta_b,\phi_b) Y_{\ell'}^{m'}(\theta_b,\phi_b)\right]$$

$$\approx \sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\sqrt{4\pi}\, e_\ell^m (60/4\pi)\int_\Omega\left[Y_\ell^m(\theta_b,\phi_b) Y_{\ell'}^{m'}(\theta_b,\phi_b)\right] \approx \sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\sqrt{4\pi}\, e_\ell^m (60/4\pi)\delta_{\ell\ell'}\delta_{mm'} \approx \sqrt{4\pi}\, e_\ell^m (60/4\pi)$$

- The mode decomposition of a single beam energy per solid angle on target is given by

$$\tilde{E}_b(\theta,\phi) = \bar{E}_b \sum_{\ell'=0}^{\infty}\frac{2\ell+1}{4\pi} a_\ell P_\ell(\cos\gamma) = \bar{E}_b \sum_{\ell=0}^{\infty} a_\ell \sum_{m'=-\ell'}^{\infty} Y_\ell^m(\theta_b,\phi_b) Y_\ell^m(\theta,\phi)$$

- The mode decomposition of the total energy per solid angle on target is given by

$$\tilde{E}_{tot}(\theta,\phi) = \frac{60}{4\pi}\sum_{b=1}^{60}\tilde{E}_{tot}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell'}\sqrt{4\pi}\,\tilde{e}_\ell^m Y_\ell^m(\theta,\phi) \text{ with: } \tilde{e}_\ell^m = \frac{a_\ell}{\sqrt{4\pi}}\frac{4\pi}{60}\sum_{b=1}^{60}\bar{E}_b Y_\ell^m(\theta_b,\phi_b) = a_\ell e_\ell^m,$$

where $a_\ell = 2\pi\int_{-1}^{1}\bar{E}_b(\theta,\phi)P_\ell(\cos\gamma)\,d(\cos\gamma)$ are normalized to have $e_0^0 = 100\%$

E26773

*S. Skupsky and K. Lee, J. Appl. Phys. 54, 3662 (1983).

The decrease of C_ℓ with ℓ was a result of the beam profiles that modify the amplitude of the laser modes on target*

- The modes of the laser beam energy balance are described by minimizing

$$A = \sum_{b=1}^{60} \left[\sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, e_\ell^m Y_\ell^m (\theta_b, \phi_b) - \bar{E}_b \right]^2$$

- Accounting for the beam profile, the mode decomposition of the total energy per solid angle on target is given by

$$E_{tot}(\theta, \phi) = \sum_{\ell=0}^{3} \sum_{m=-1}^{\ell} \sqrt{4\pi}\, e_\ell^m Y_\ell^m (\theta, \phi)$$

with $\tilde{e}_\ell^m = a_\ell$, where $a_\ell = 2\pi \int_{-1}^{1} \bar{E}_b(\theta, \phi) P_\ell(\cos\gamma)\, d(\cos\gamma)$

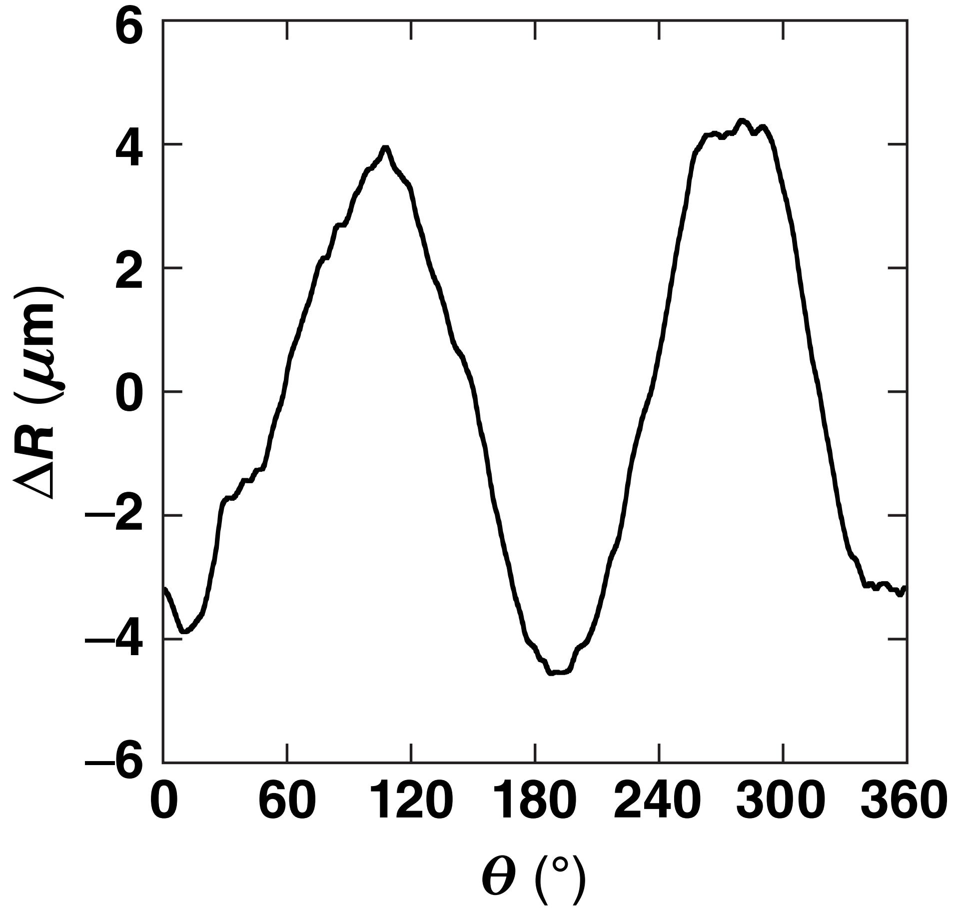
a_1	0.79
a_2	0.47
a_3	0.20

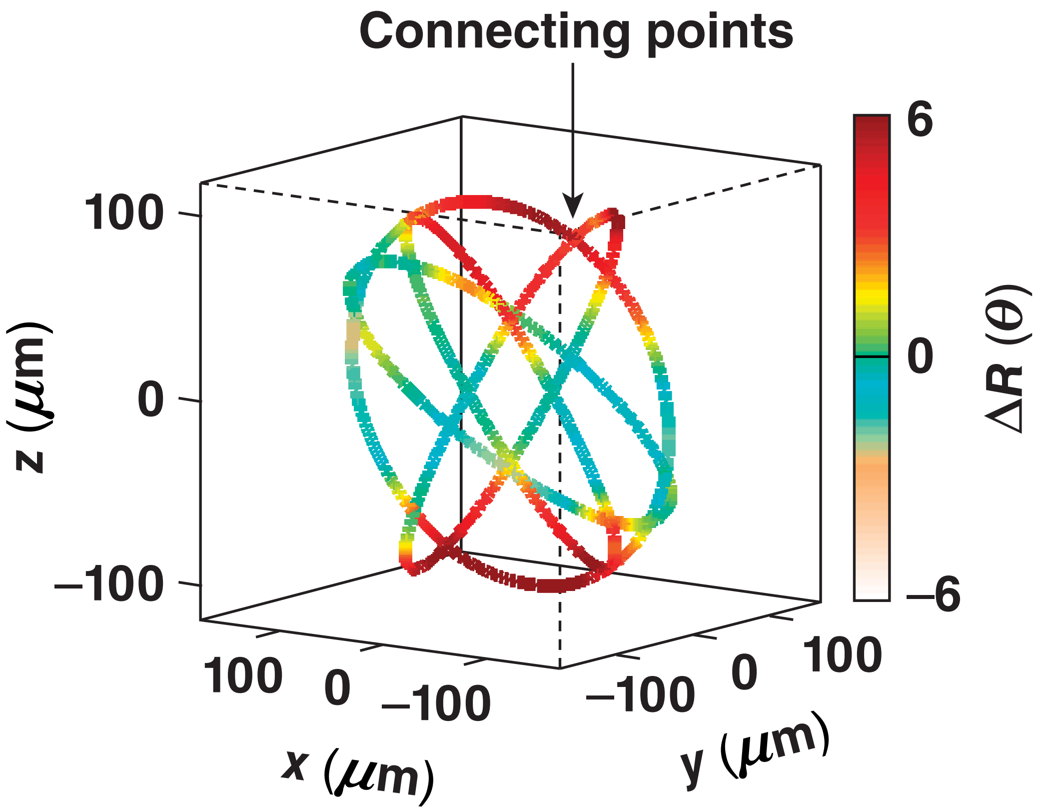
A constant coupling of the modes of the target irradiation pattern to the target modes is obtained of $C_\ell / a_\ell = -0.85 \pm 0.07$.

E26774

*S. Skupsky and K. Lee, J. Appl. Phys. 54, 3662 (1983).

The 3-D shape of the target was obtained by orienting each contour perpendicular to the camera axis



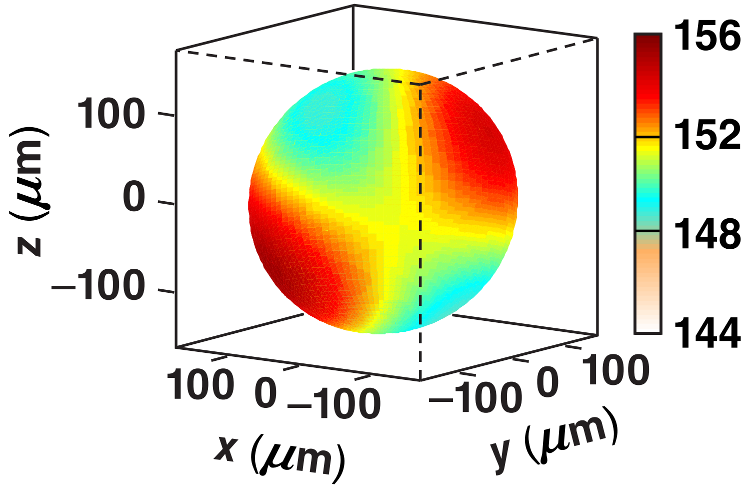


An error of $\delta[\Delta R(\theta)]_{150}$ of 1 μm was evaluated by comparing the contours at the connecting points; this error is comparable to the error of ±0.4 μm estimated previously.

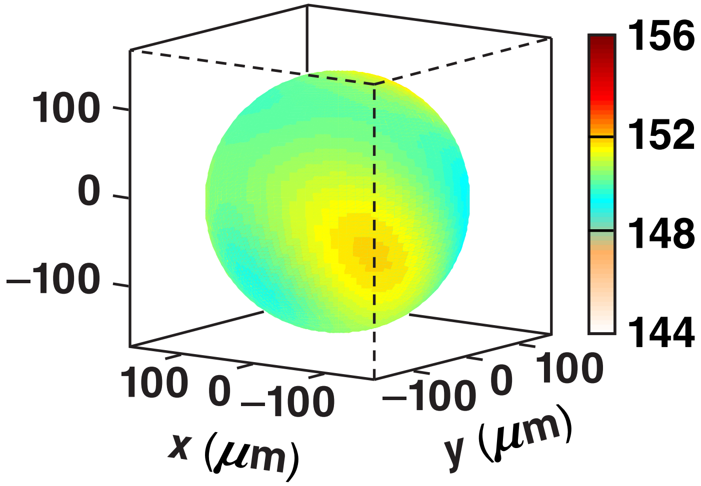
E26775

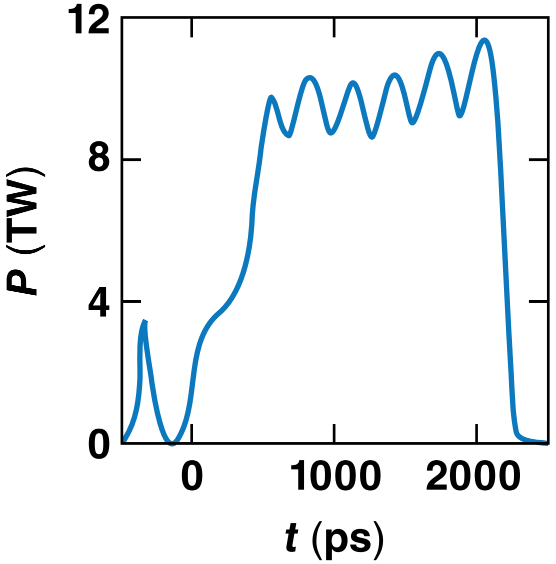
This method was applied to correct the target nonuniformities on a low-adiabat warm implosion

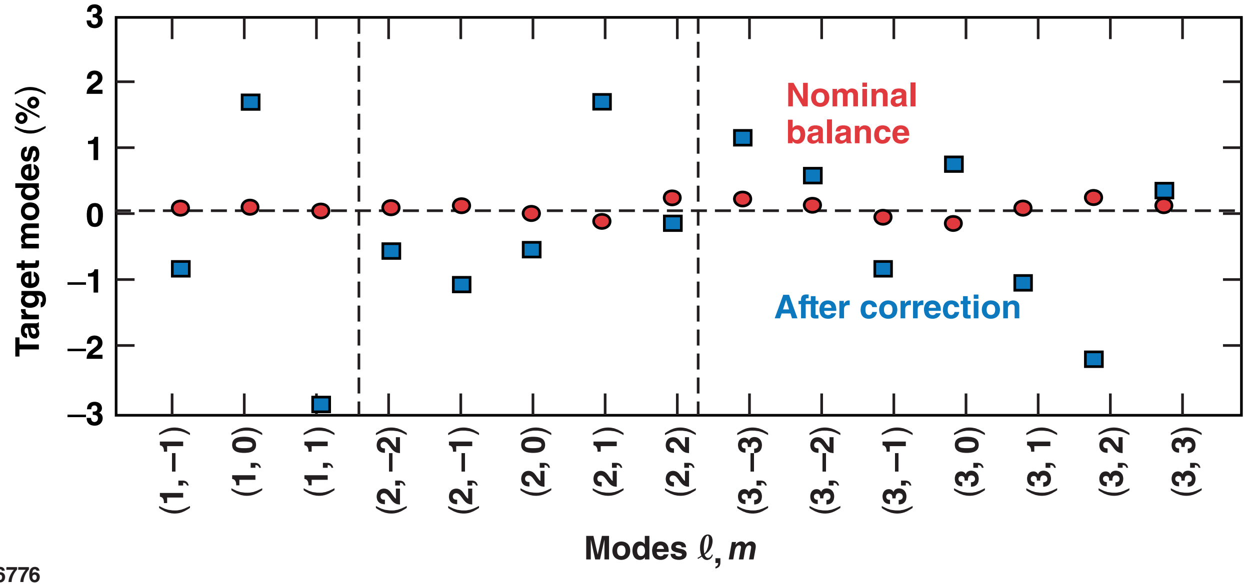
Nominal balance

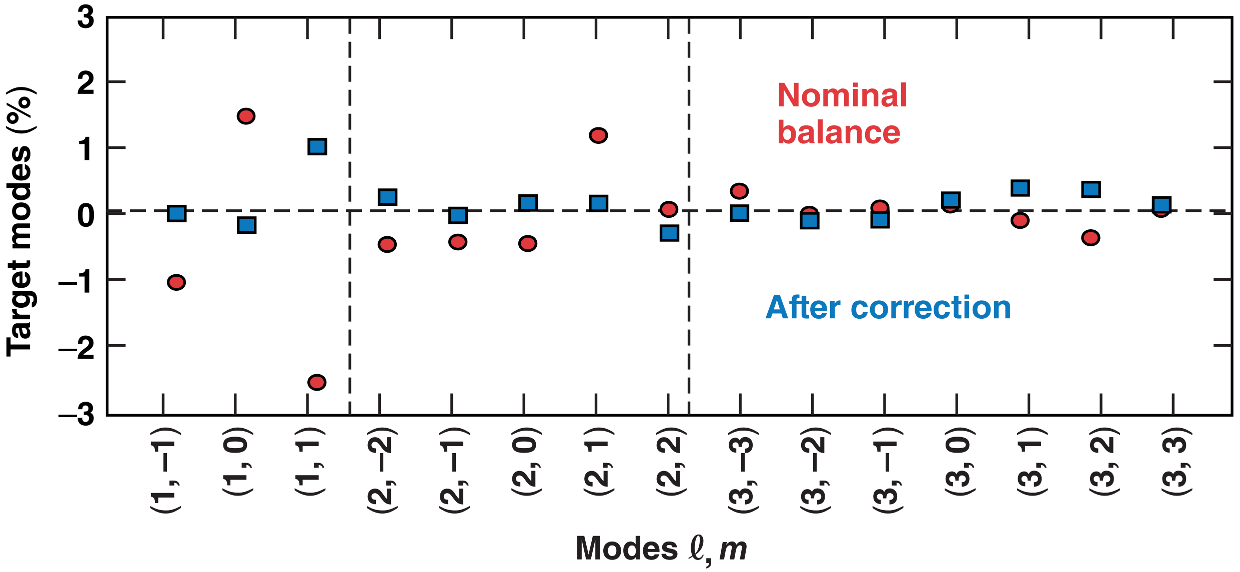


After correction









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