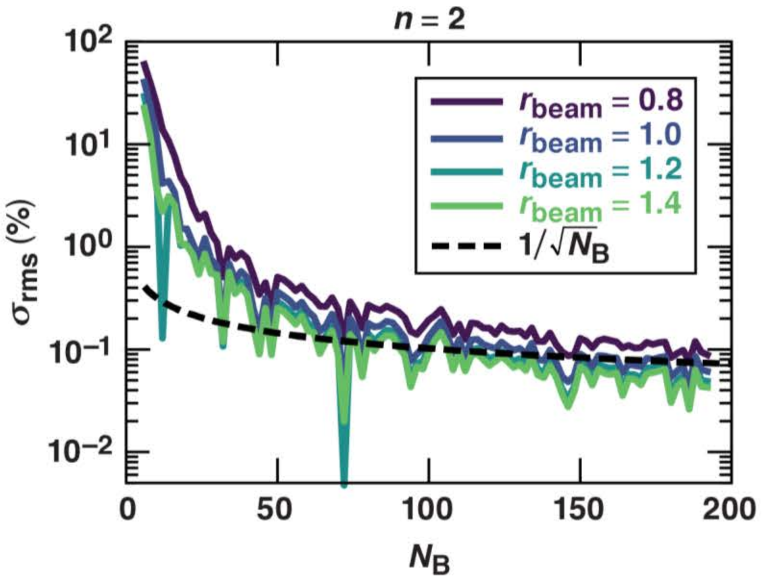
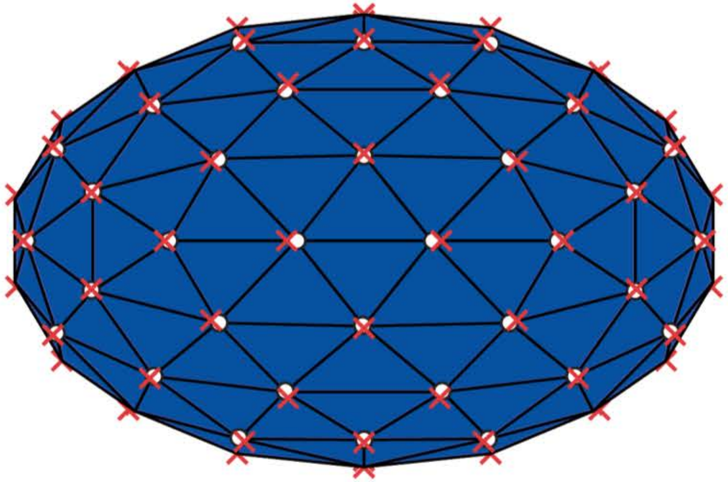
Optimization of Beam-Port Configurations to Minimize Low-Mode Perturbations in High-Yield Inertial Confinement Fusion Targets

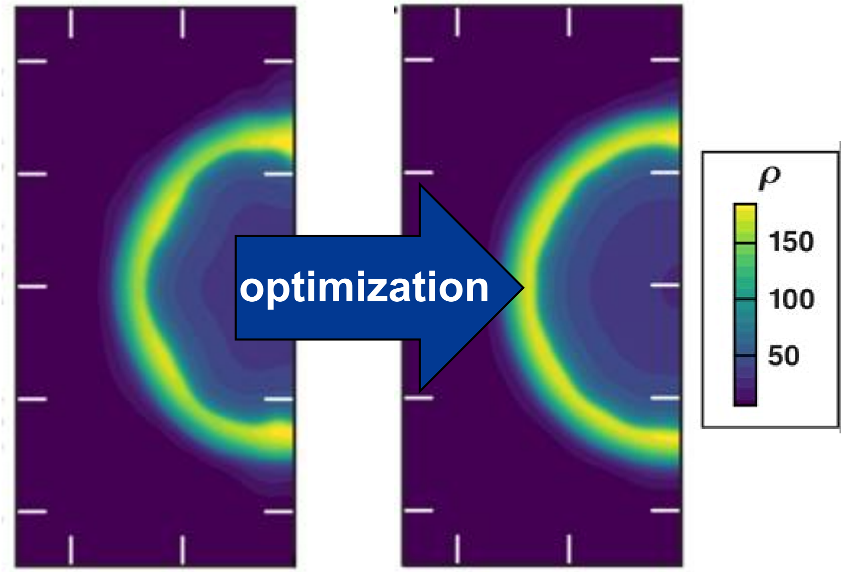
Perturbation scaling with beam number



92-beam configuration



2D DRACO simulations at t_{bang} - 20 ps



W. Trickey
University of Rochester
Laboratory for Laser Energetics

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wtri@lle.rochester.edu

Summary

Candidate beam configurations can be found through charged-particle simulations initialized with icosahedral symmetry and tested in DRACO

- **High-yield ICF targets require good symmetry and minimization of low-mode perturbations**
- **Beam-port geometry is one major contributor to low-mode shell asymmetries**
- **The best candidate configurations are based on icosahedrons with charged-particle optimization**
- **Multidimensional radiation-hydrodynamics simulations are underway, 2D (DRACO) and 3D (ASTER)***

ICF: inertial confinement fusion
* I. V. Igumenshchev *et al*., NO04.00015, this conference.

Collaborators

V. N. Goncharov, E. M. Campbell, T. J. B. Collins, M. J. Rosenberg, N. Shaffer, W. Theobald, R. C. Shah, A. Shvydky, and I. V. Igumenshchev
Laboratory for Laser Energetics
University of Rochester

A. Colaïtis
Centre Lasers Intenses et Applications
University of Bordeaux

S. Atzeni and L. Savino
Università di Roma, “La Sapienza”

High-yield targets require good shell stability, in particular the dynamic shell has long periods of hydrodynamic implosion/expansion

- High-yield design
  - requires low shell asymmetry

Wetted DT Foam

Adiabat – 1.4

IFAR - 13

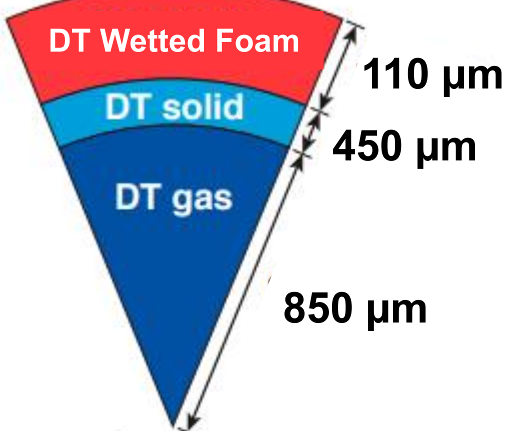
CR – 22

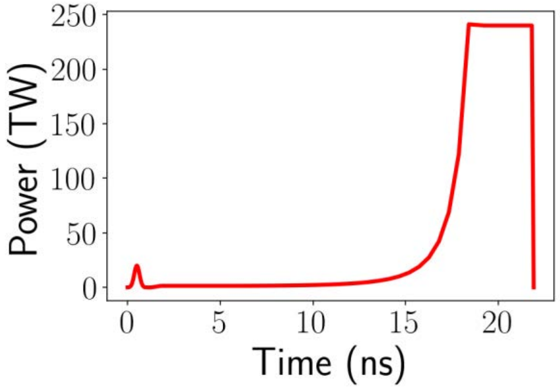
v_{imp} – 264 km/s

E_{Laser} – 1.10 MJ

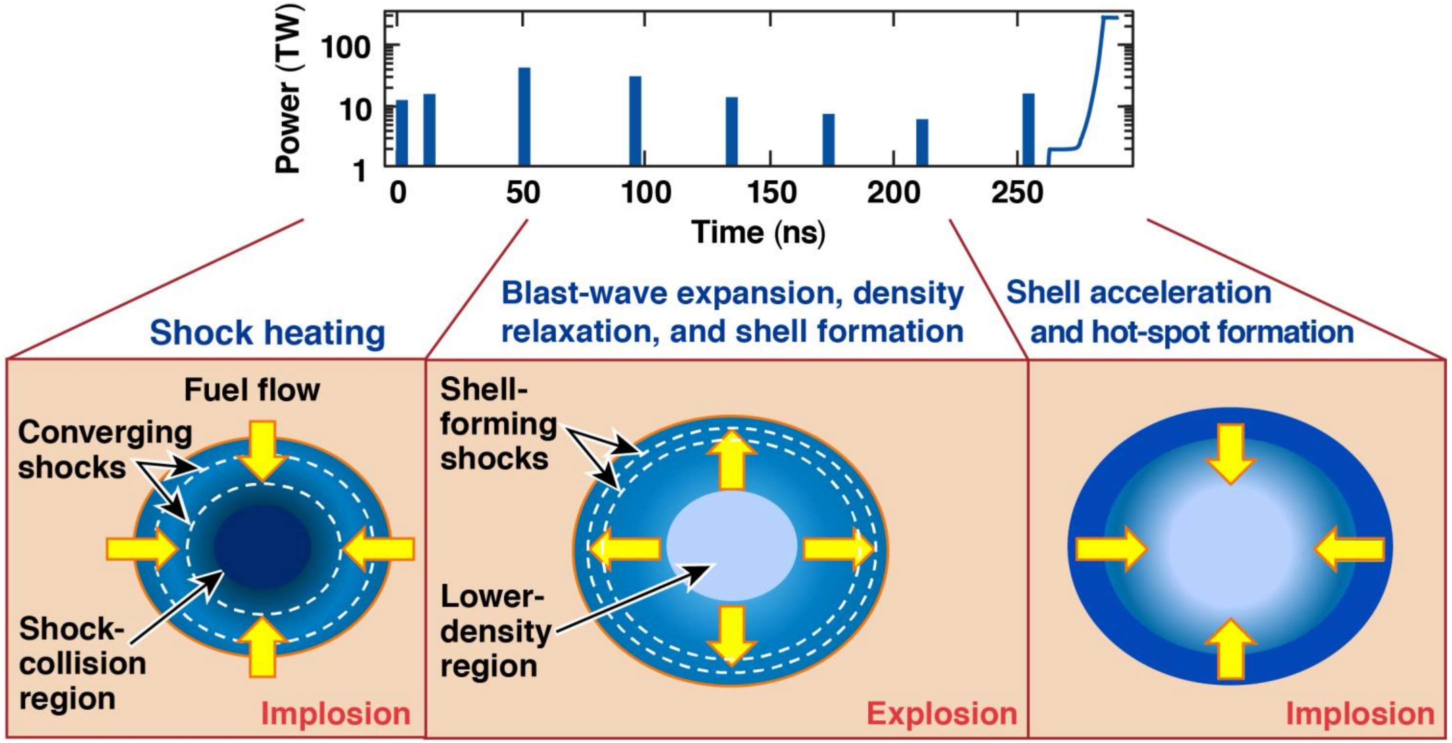
E_{yield} – 145 MJ

Gain – 132





- Dynamic shell target*
  - several stages of hydrodynamic implosion/expansion to consider for stability



TC15894

CR: convergence ratio

IFAR: in-flight aspect ratio

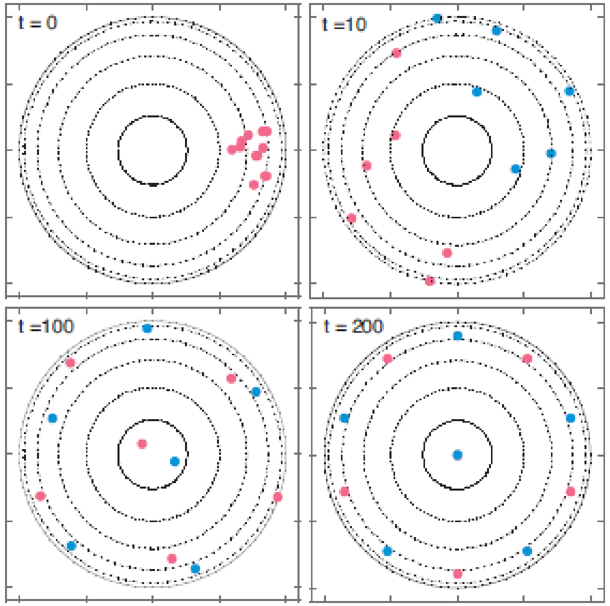
* V. N. Goncharov et al., NO04.00012, this conference

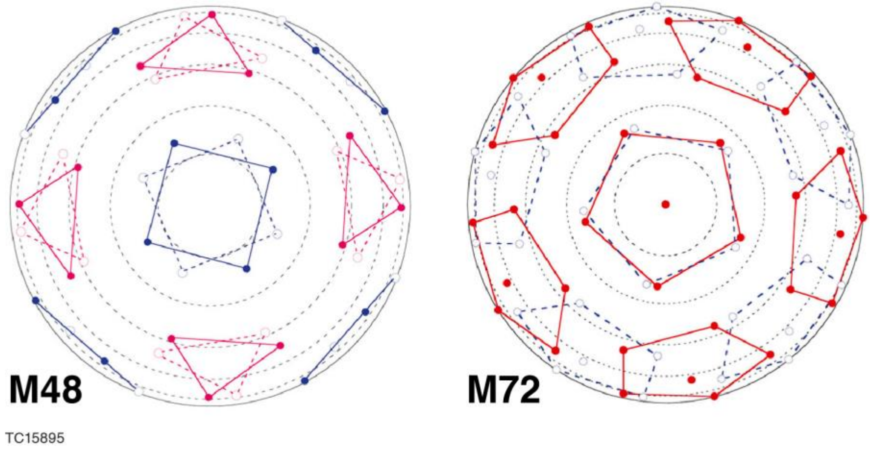
Optimization of irradiation uniformity is well studied; a charged-particle optimization technique has been shown to work

- **Beam-ports modelled as charged particles fixed to the surface of a sphere**
- **Historically referred to as the Thomson Problem****
- **Many other techniques exist for beam-port optimization†, ‡**

$$F_i = \sum_{j=1(j\neq i)}^{N_B} A\frac{\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j}{\left|\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j\right|^3} - B\frac{d\hat{\boldsymbol{r}}_{\boldsymbol{i}}}{dt}$$

$$E_p = \frac{1}{2}\sum_{i=1}^{N_B}\sum_{j=1(j\neq i)}^{N_B}\frac{1}{\left|\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j\right|}$$





Figures from Murakami *et al*. *

* M. Murakami et al., Phys. Plasmas 17, 082702 (2010)
** J.J. Thomson F.R.S. (1904) XXIV, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 7:39, 237-265
† S. Skupsky et al., Journal of Applied Physics 66, 3456 (1989)
‡ C. Tian etl al., Opt. Express 23, 12362-12372 (2015)

Low-mode perturbations scale as $N_B^{1/2}$ with a number of dips at specific N_B's

- An analytic laser-absorption model* used to find Legendre mode contributions
- σ_{rms} is the sum of all mode contributions

$$\sigma_{rms} = \left[\sum_{\ell=1}^{\infty} \frac{a_l^2}{2\ell+1} G_\ell^2\right]^{1/2}$$

Beam factor

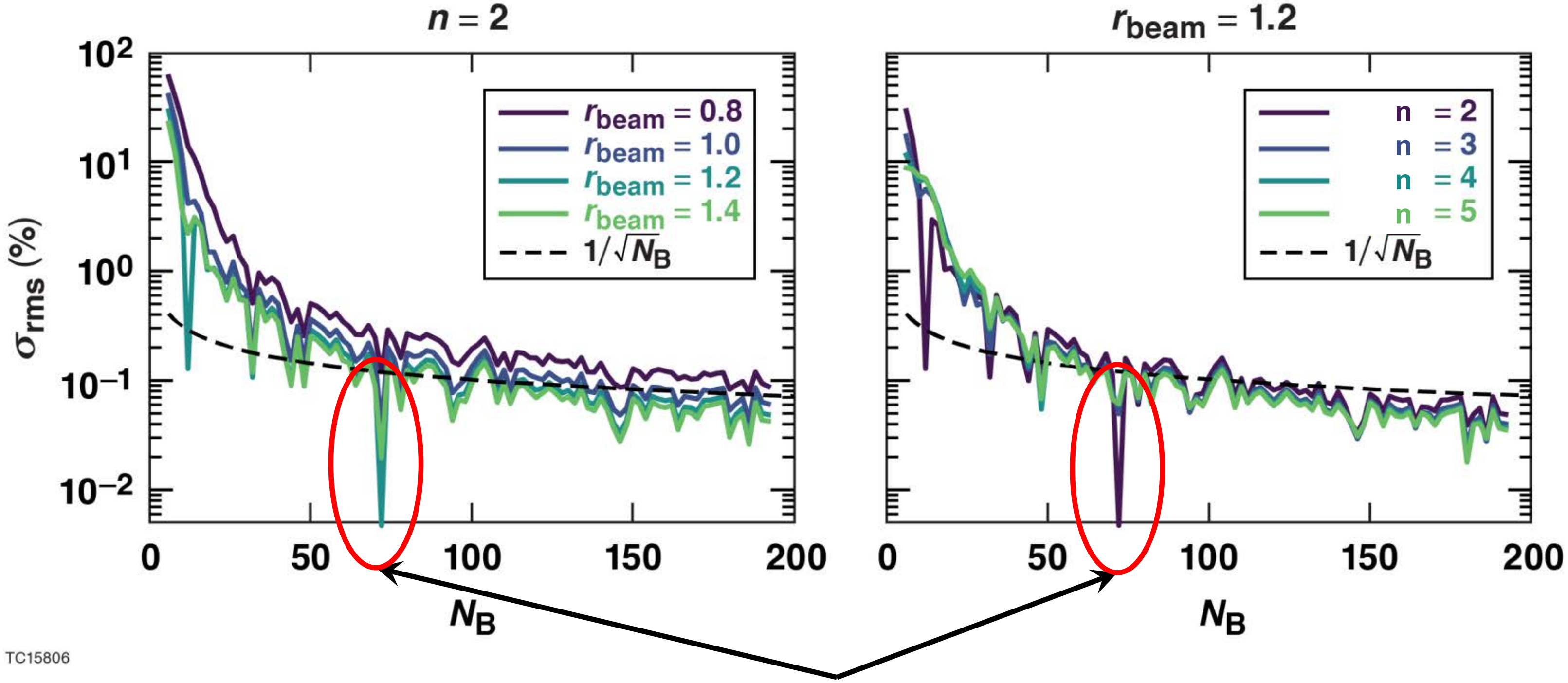
$$a_l = \frac{2l+1}{2}\int_{-1}^{1} I_a(\theta) P_l(\cos\theta)\, d(\cos\theta)$$

Geometric factor

$$G_l = \left[\sum_{j=1}^{N_B}\sum_{k=1}^{N_B} \frac{P_l(\Omega_j \cdot \Omega_k) I_j I_k}{I_T^2}\right] / N_B$$

r_{beam} – r at 95% integrated beam energy

$$I(r) = I_0\, exp - \left(\frac{r}{r_{beam}}\right)^n$$



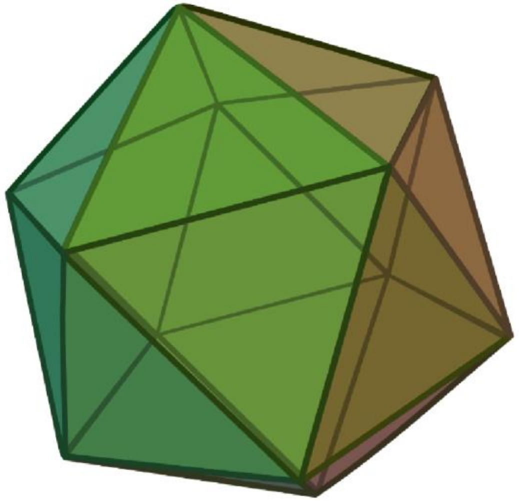
TC15806

Significant drop in σ_{rms} observed at $N_B = 72$

* M. Murakami et al., Phys. Plasmas 17, 082702 (2010)

The highest-performing beam-port configurations share icosahedral symmetry

- Class of geometric shapes with icosahedral symmetry
- Formed by subdividing triangular faces and projecting vertices onto the surface of a sphere



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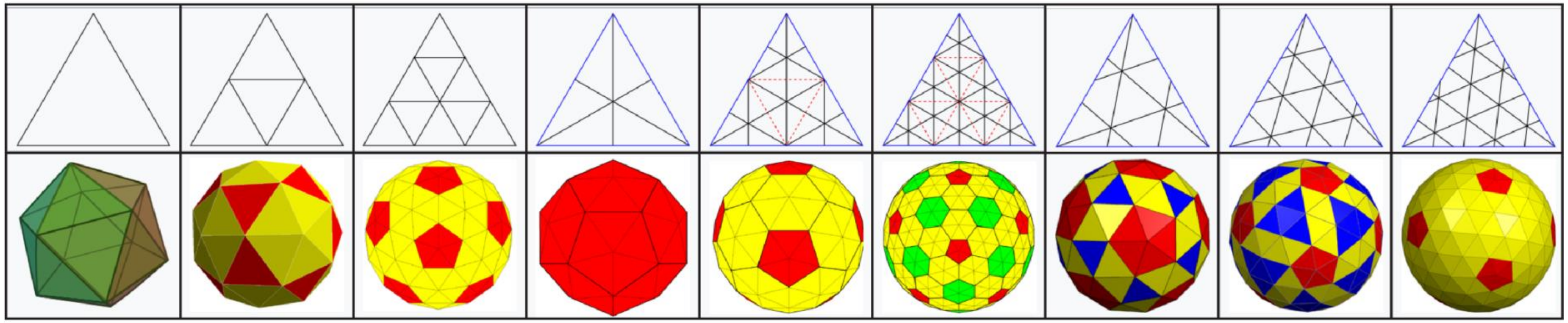


Two Classes
- Face-centered points: N_B = 20, 60, 80, 140, 180…
- Vertex-centered points: N_B = 12, 32, 42, 72, 92, 122, 132, 172…

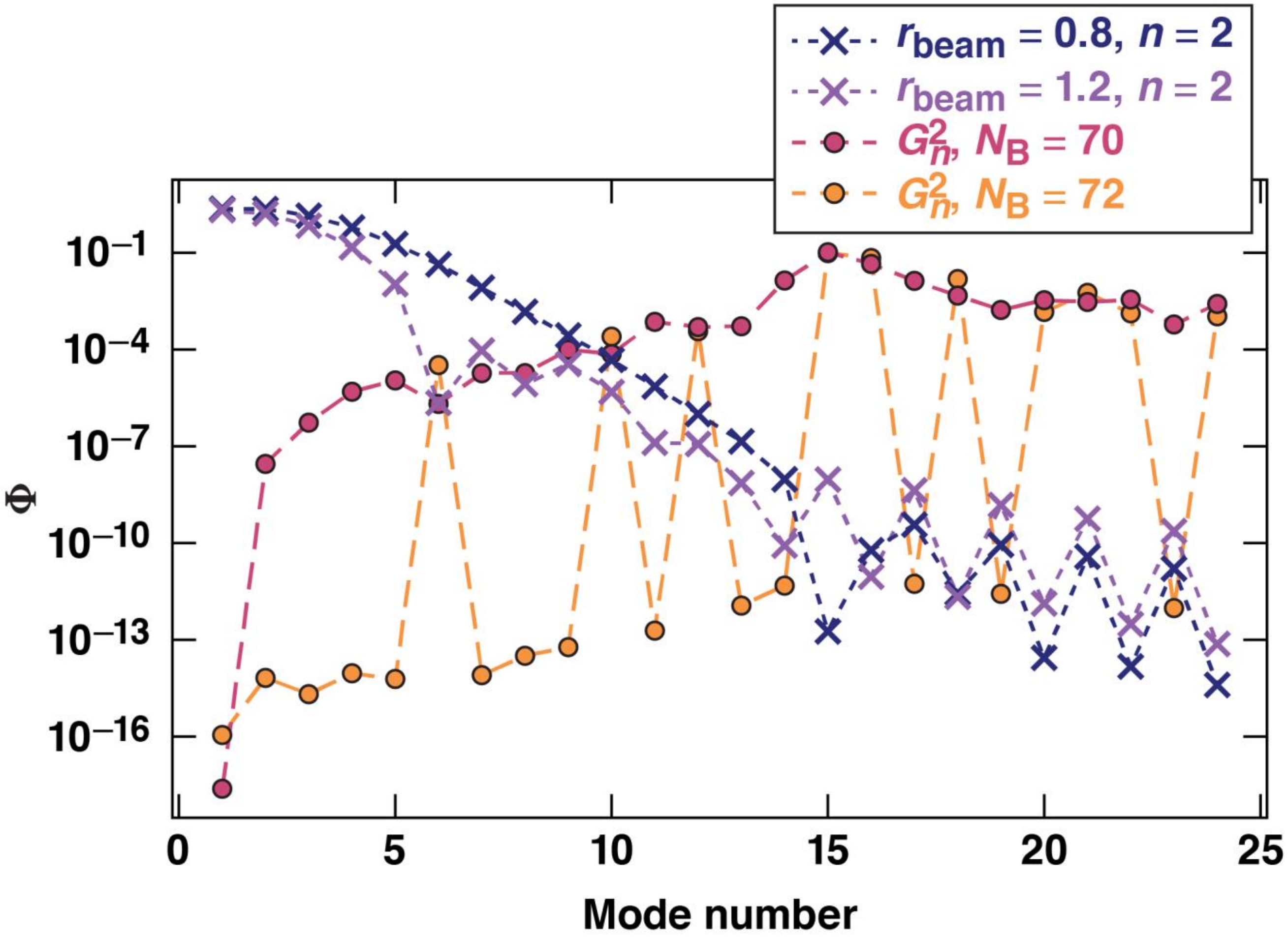
Images accessed from https://en.wikipedia.org/wiki/Geodesic_polyhedron (10/11/21)

The high performance of icosahedral configurations comes from the suppression of the $\ell = 6$ Legendre mode

- **Typical charged-particle configurations have small contributions from many modes**
- **Dip in the single beam factor at $\ell = 6$ significantly reduces σ_{rms}**
- **Decaying single-beam factor means higher modes are less important**

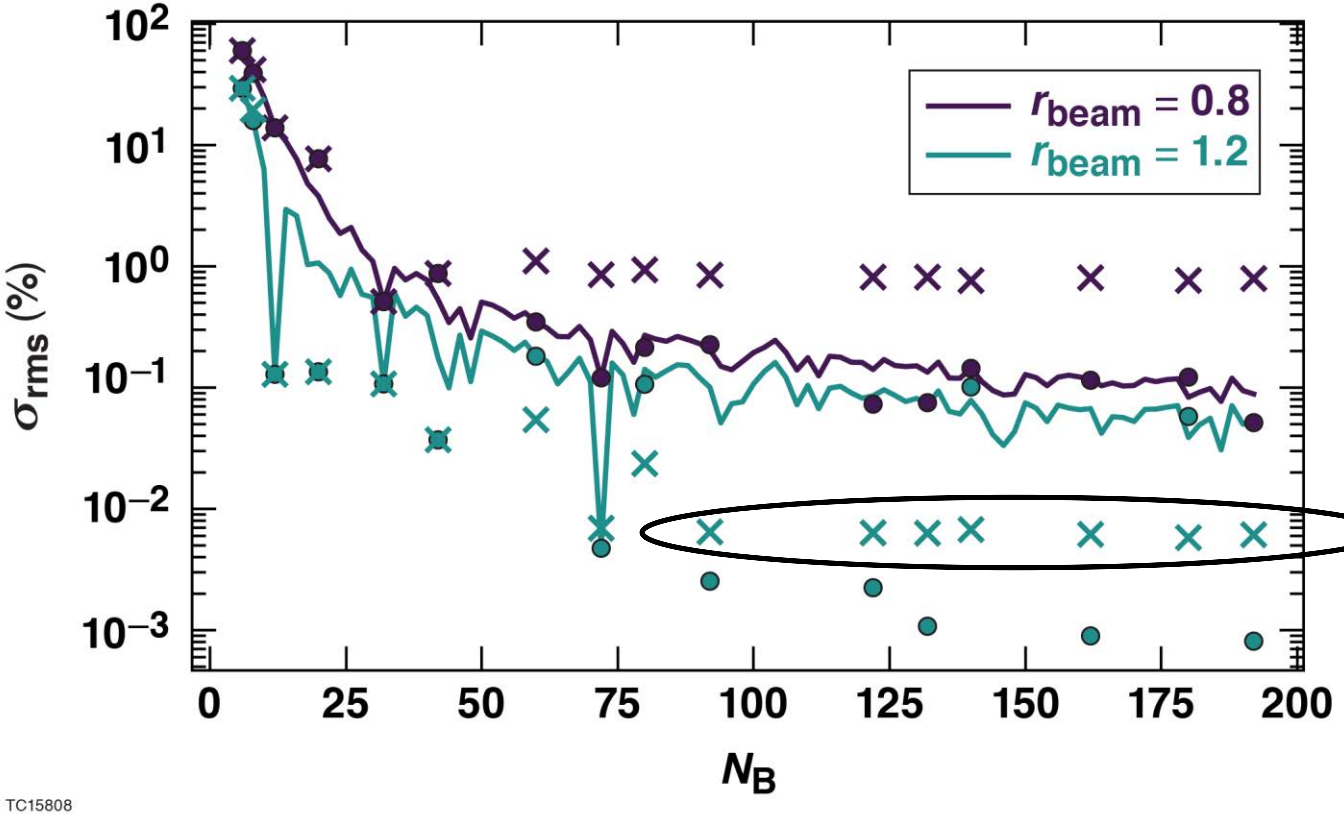
$$\sigma_{\text{rms}} = \left[\sum_{n=1}^{\infty} \underbrace{\frac{a_n^2}{2n+1}}_{\text{Beam factor}} \underbrace{G_n^2}_{\text{Geometric factor}}\right]^{1/2}$$

Beam factor **Geometric factor**



TC15807c

Geodesic icosahedral configurations show much lower σ_{rms} than the random charged-particle configurations



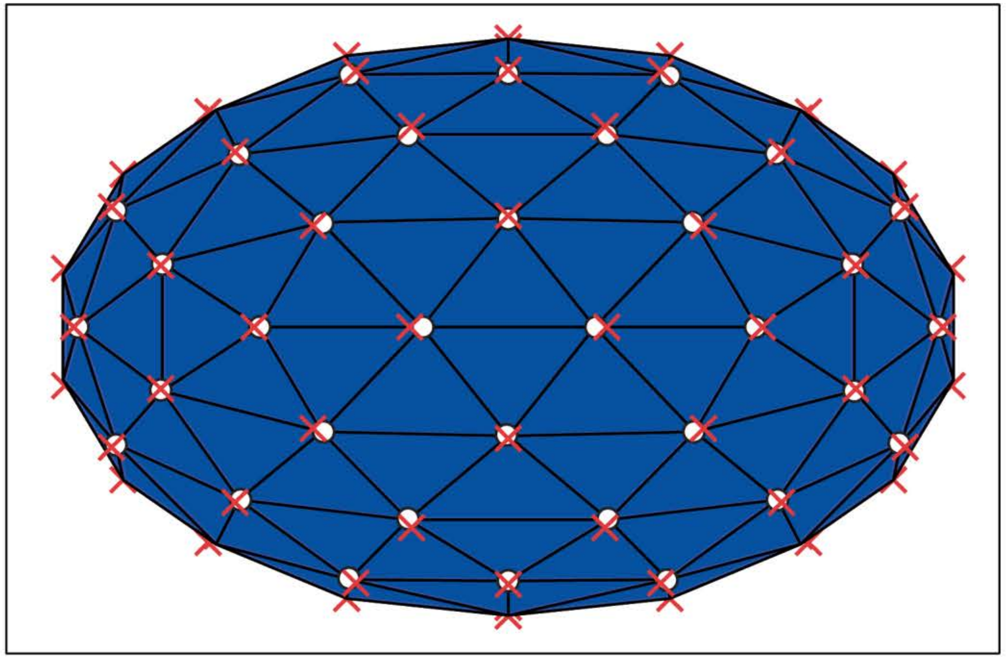
TC15808

$$\sigma_{rms} = \left[\sum_{n=1}^{\infty} \frac{a_n^2}{2n+1} G_n^2\right]^{1/2}$$

Geodesic icosahedral configurations

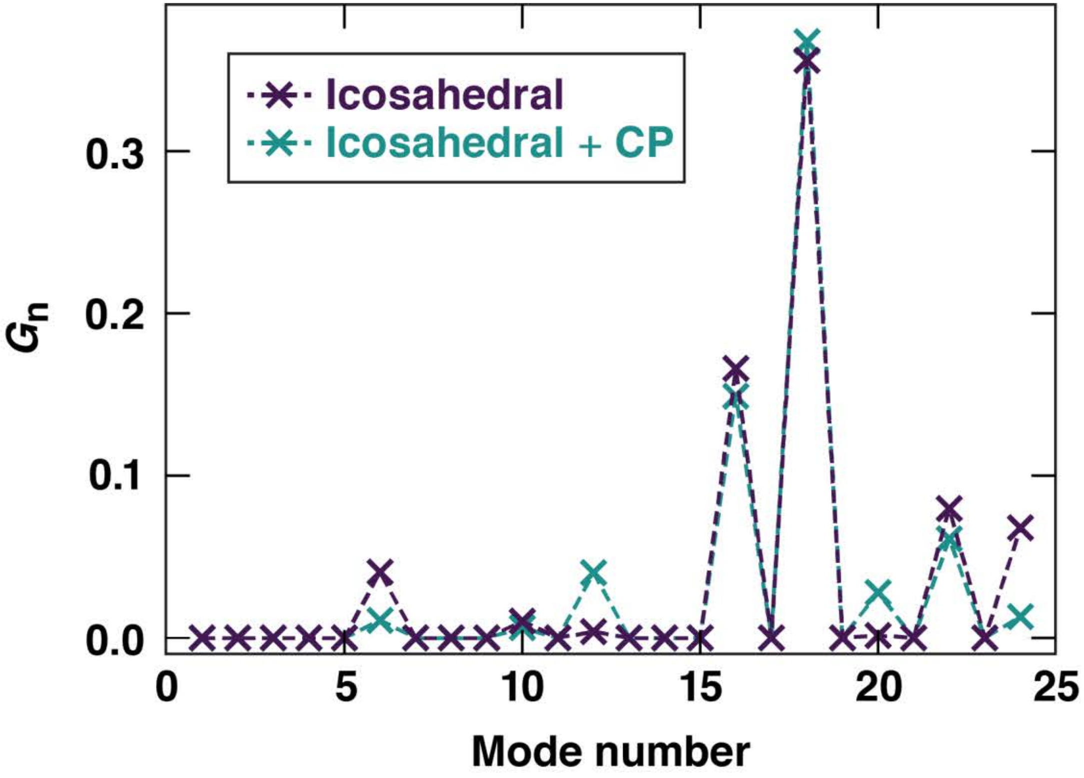
Geodesic icosahedral configurations are further improved with charged-particle optimization

92-beam configuration with charged-particle distortion

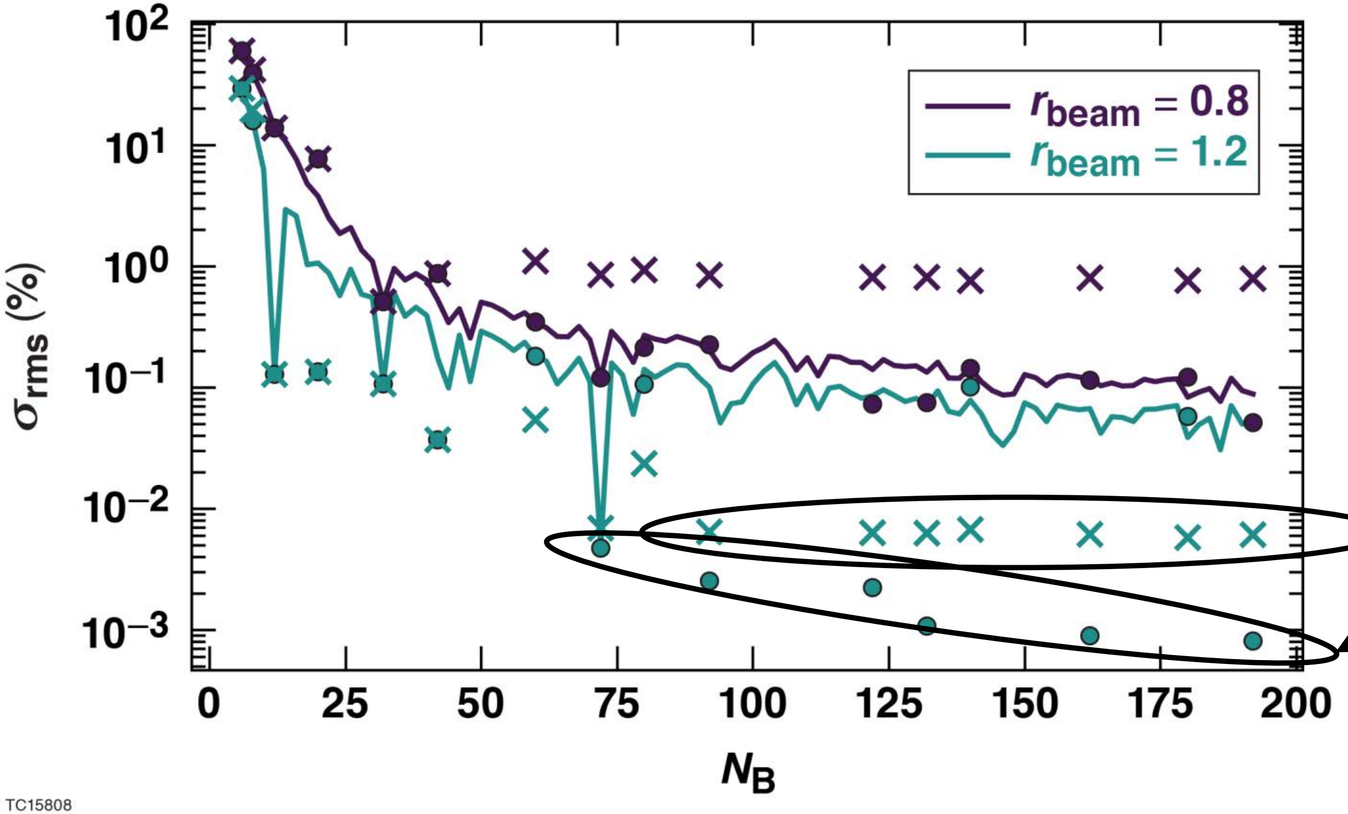


TC15809

Changes to the spectral structure of the modes



Geodesic icosahedral configurations with charged particle optimization show highest performance



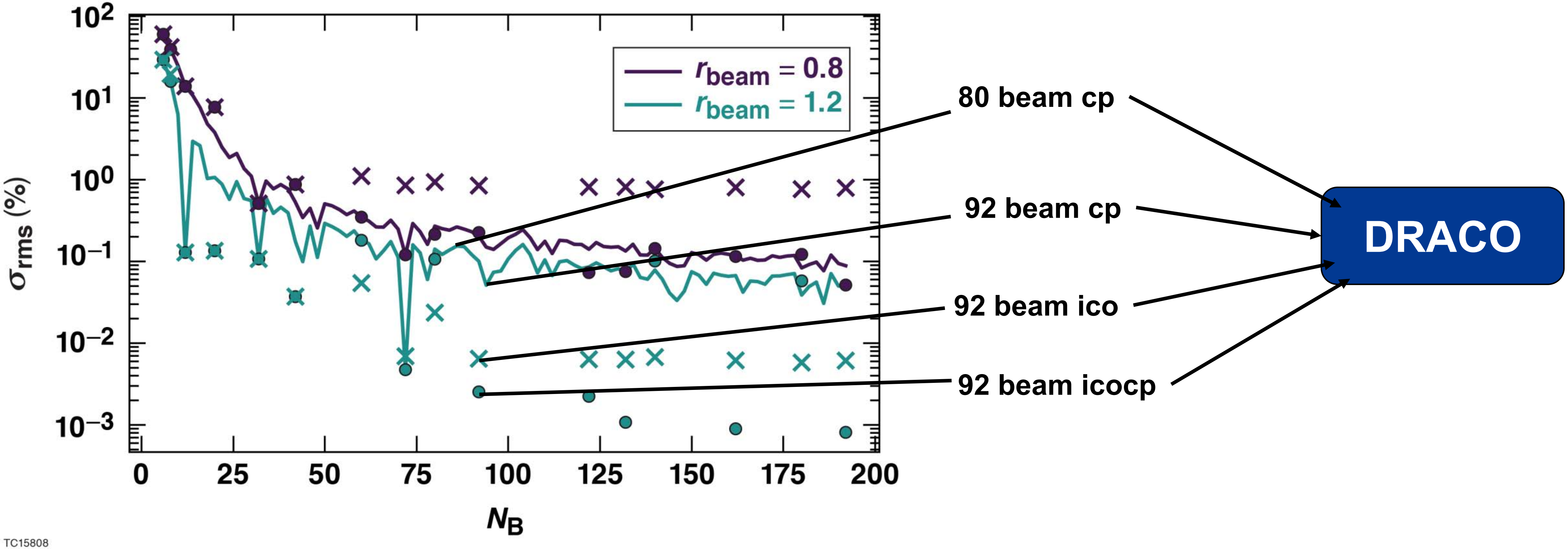
TC15808

$$\sigma_{rms} = \left[\sum_{n=1}^{\infty} \frac{a_n^2}{2n+1} G_n^2\right]^{1/2}$$

Geodesic icosahedral configurations

Geodesic icosahedral + charged-particle configurations

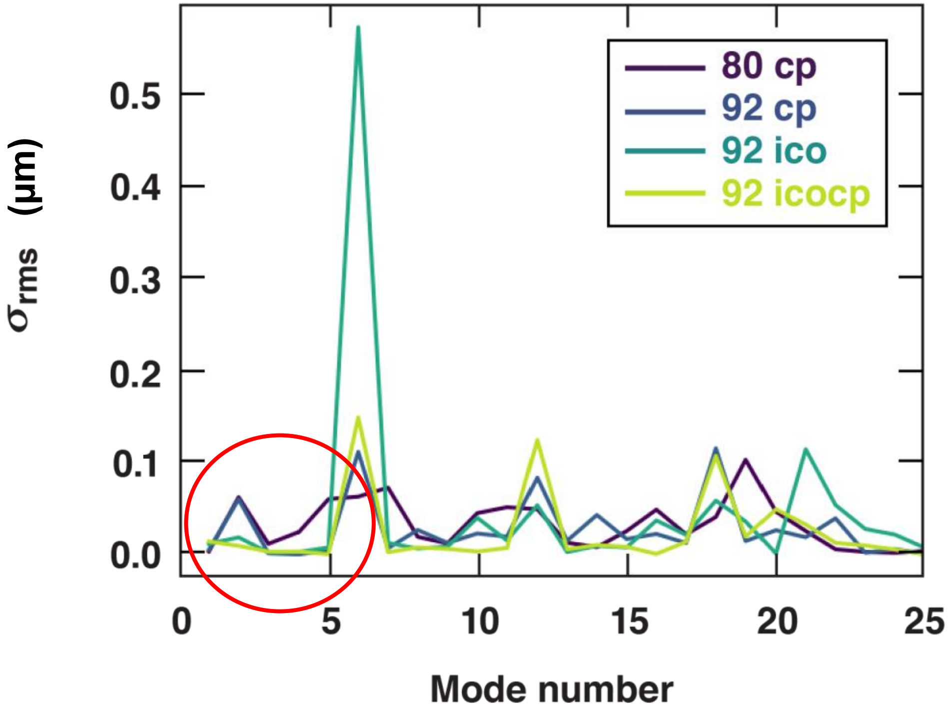
The analytic laser deposition model is not sufficient, 2D radiation hydrodynamics modelling was carried out with DRACO for 4 configurations



TC15808

cp: charged particle
ico: icosahedral
Icocp: icosahedral + charged particle

Some of the suppression of the ℓ=6 mode is lost but crucially the contributions from lowest modes is smallest for the icosahedral configurations



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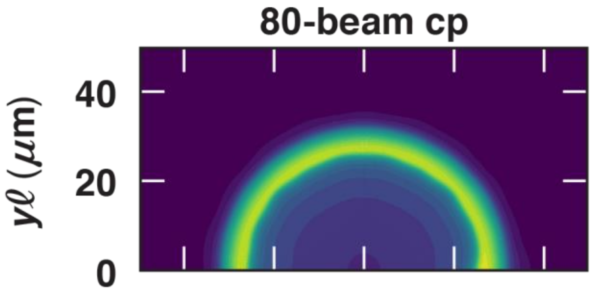
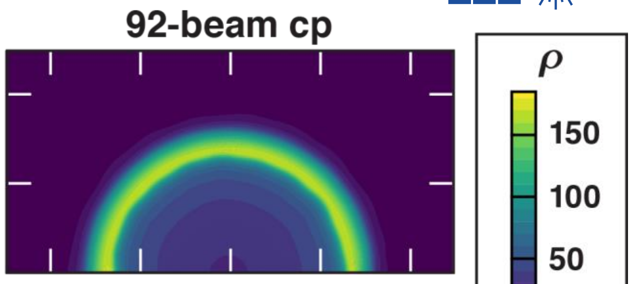
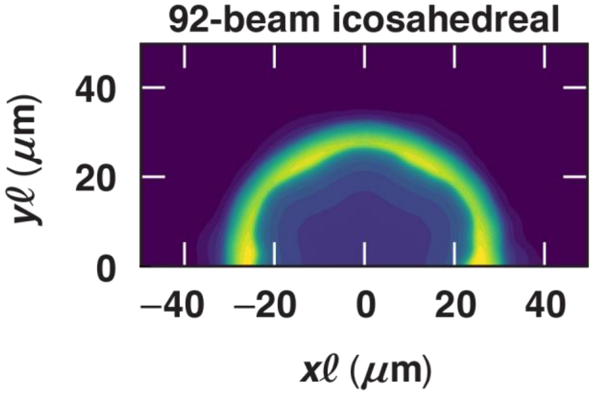


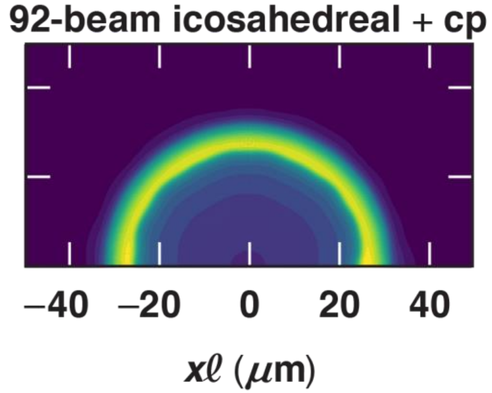
σ_{rms} (μm)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.12	0.09	0.28	0.32



σ_{rms} (μm)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.08	0.16	0.27	0.32



σ_{rms} (μm)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.03	0.86	0.30	0.91



σ_{rms} (μm)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.02	0.22	0.29	0.36

TC15957

Candidate beam configurations can be found through charged-particle simulations initialized with icosahedral symmetry and tested in DRACO

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- Beam-port geometry is one major contributor to low-mode shell asymmetries
- The best candidate configurations are based on icosahedrons with charged-particle optimization
- Multidimensional radiation-hydrodynamics simulations are underway, 2D (DRACO) and 3D (ASTER)*

ICF: inertial confinement fusion
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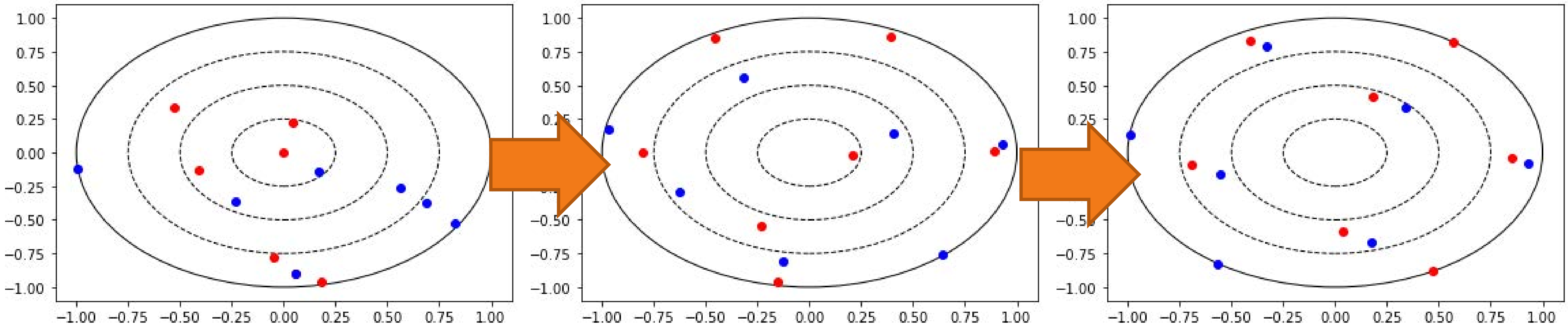
Charged Particle Simulation

- **Calculates Coulomb Force**
- **Updates using suvat eqns**

$$F_i = \sum_{j=1(j\neq i)}^{N_B} A \frac{\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j}{\left|\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j\right|^3} - B\frac{d\hat{\boldsymbol{r}}_{\boldsymbol{i}}}{dt}$$

$$E_p = \frac{1}{2}\sum_{i=1}^{N_B} \sum_{j=1(j\neq i)}^{N_B} \frac{1}{\left|\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j\right|}$$

Convergence: $E_{t+1} - E_{t-1} < 10^{-11}$



Analytic rms non-uniformity model

Single beam factor comes from the beam profile, expanding the irradiation profile along the target surface into Legendre polynomials

$$a_l = \frac{2l+1}{2}\int_{-1}^{1} I_a(\theta)P_l\,(\cos\theta)\,d\,(\cos\theta)$$

Geometric factor comes from the relative pointings and powers of each beam

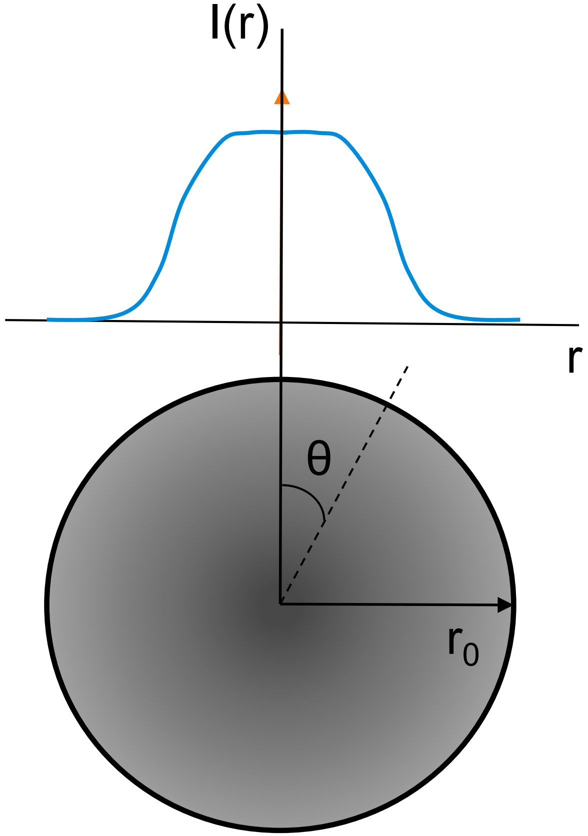
$$G_l = \left[\sum_{j=1}^{N_B}\sum_{k=1}^{N_B}\frac{P_l\left(\mathbf{\Omega}_j\cdot\mathbf{\Omega}_k\right)I_jI_k}{I_T^2}\right]/N_B$$

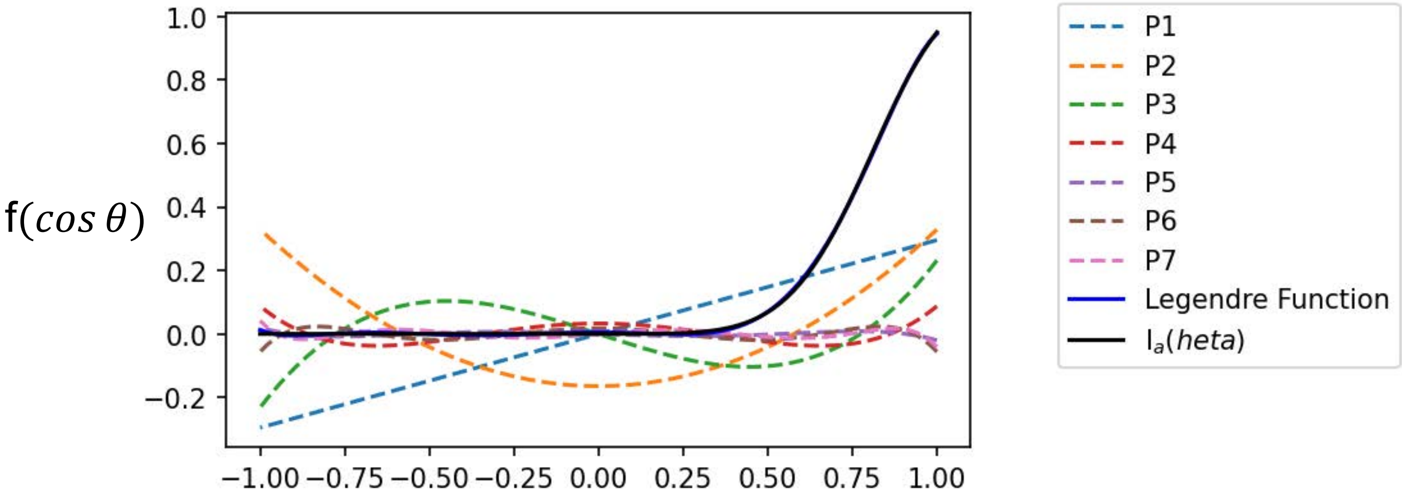
$$\sigma_{rms} = \left[\sum_{l=1}^{\infty}\frac{a_l^2}{2l+1}\left(G_l^2+\frac{\sigma_{sys}^2}{N_B}\right)\right]^{1/2}$$

l - mode number
P_n – Legedre Polynomial
θ – Angle from beam axis

Single beam factor

$$I(r) = I_0 \exp - \left(\frac{r}{r_0 \alpha}\right)^{\beta}$$



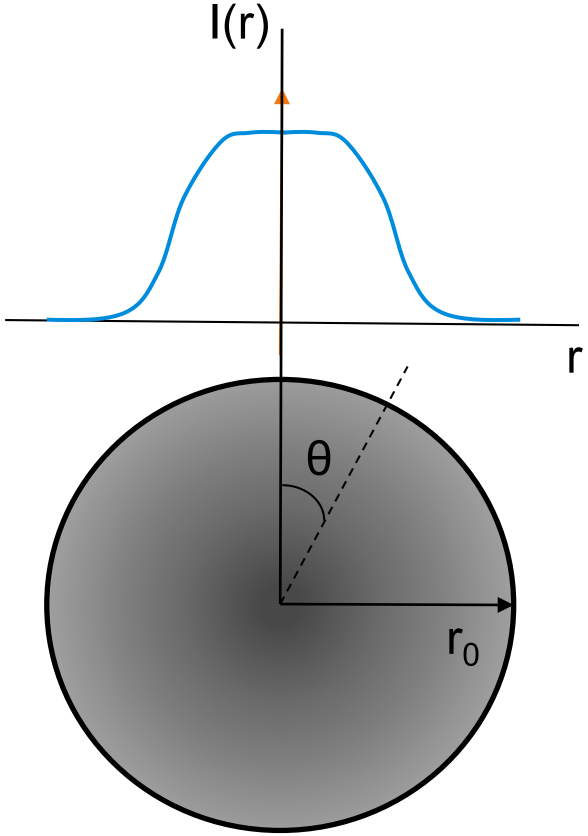


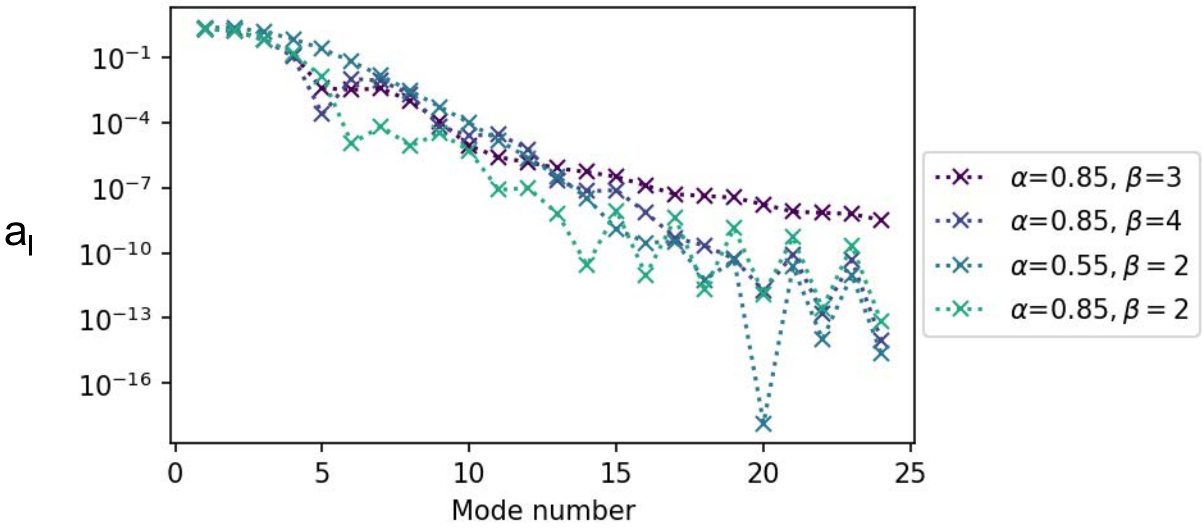
$$I_a(\theta) = I_0\left[1 - (1-\eta)^{\cos^3\theta}\right] \exp\left[-(\sin\theta/\alpha)^{\beta}\right] \cos\theta$$

$$a_l = \frac{2l+1}{2} \int_{-1}^{1} I_a(\theta) P_l(\cos\theta)\, d(\cos\theta)$$

Single beam factor

$$I(r) = I_0 \exp - \left(\frac{r}{r_0 \alpha}\right)^{\beta}$$





$$I_a(\theta) = I_0\left[1 - (1-\eta)^{\cos^3\theta}\right] \exp\left[-(\sin\theta/\alpha)^{\beta}\right] \cos\theta$$

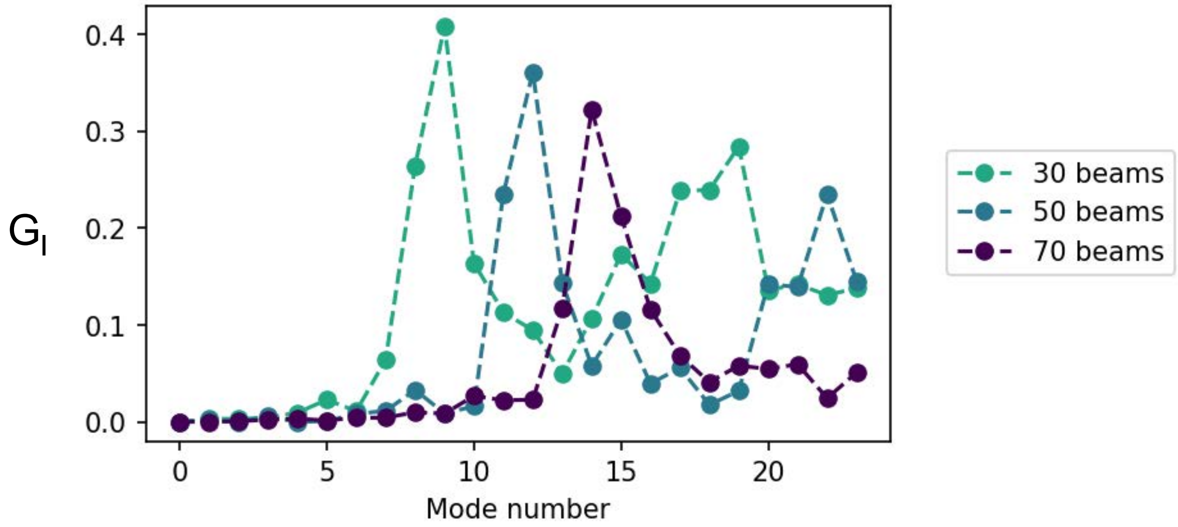
$$a_l = \frac{2l+1}{2} \int_{-1}^{1} I_a(\theta) P_l(\cos\theta)\, d(\cos\theta)$$

Geometric Factor

$$G_l = \left[\sum_{j=1}^{N_B} \sum_{k=1}^{N_B} \frac{P_l(\boldsymbol{\Omega}_j \cdot \boldsymbol{\Omega}_k) I_j I_k}{I_T^2} \right] / N_B$$

$$I_j = I_k, \frac{I_j I_k}{I_T^2} = 1$$

$$P_l(\boldsymbol{\Omega}_j \cdot \boldsymbol{\Omega}_k) = \frac{4\pi}{2l+1} \sum_{m=-l}^{l} Y_{lm}^*(\boldsymbol{\Omega}_j)\, Y_{lm}(\boldsymbol{\Omega}_k)$$

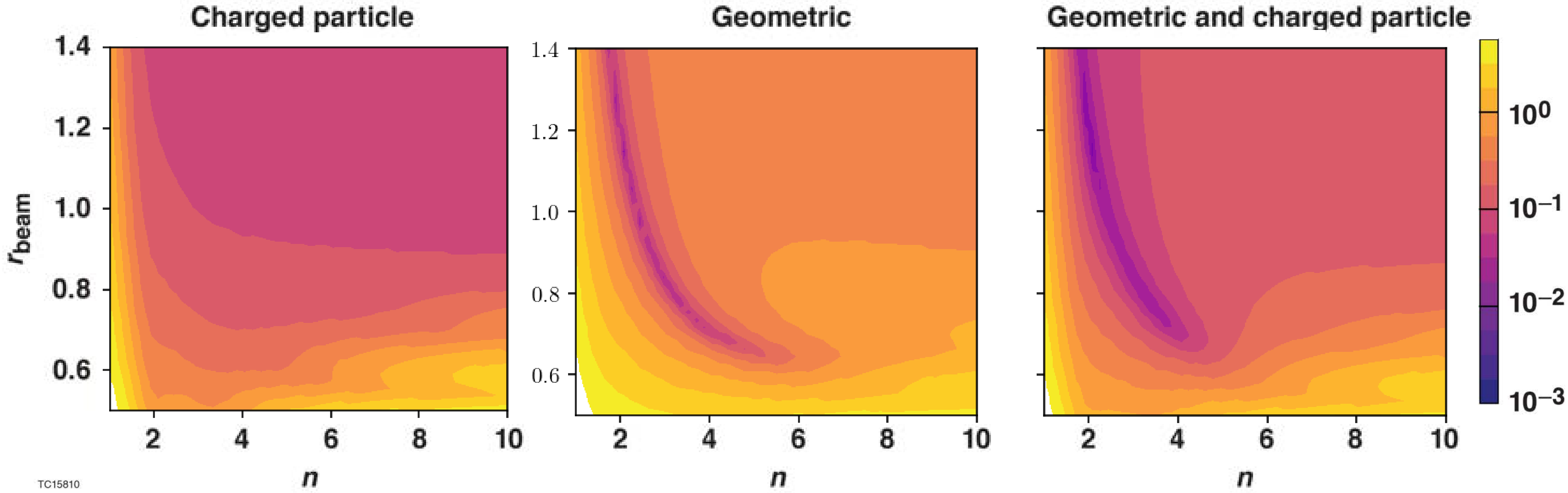


The performance of a beam configuration varies with the Super-Gaussian spot shape parameters

σ_{rms} for N_B = 92

$$I(r) = I_0 \exp - \left(\frac{r}{r_{\text{beam}}}\right)^n$$

r_{beam} – r at 95% integrated beam energy

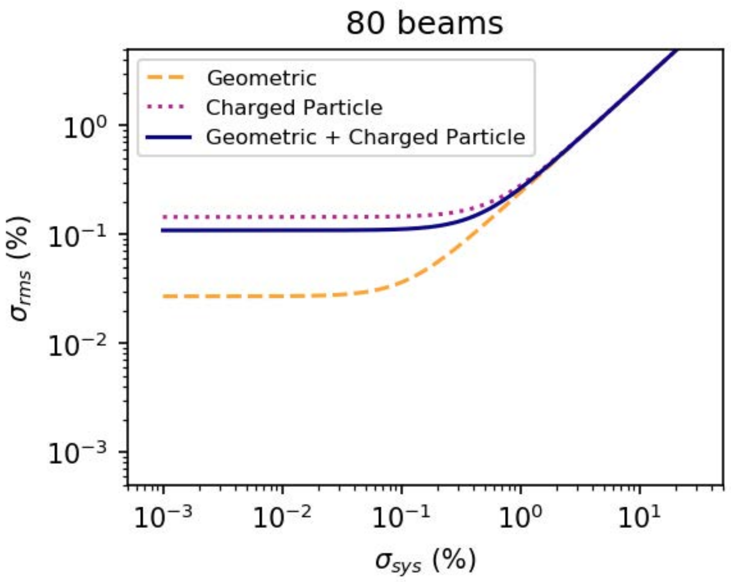


TC15810

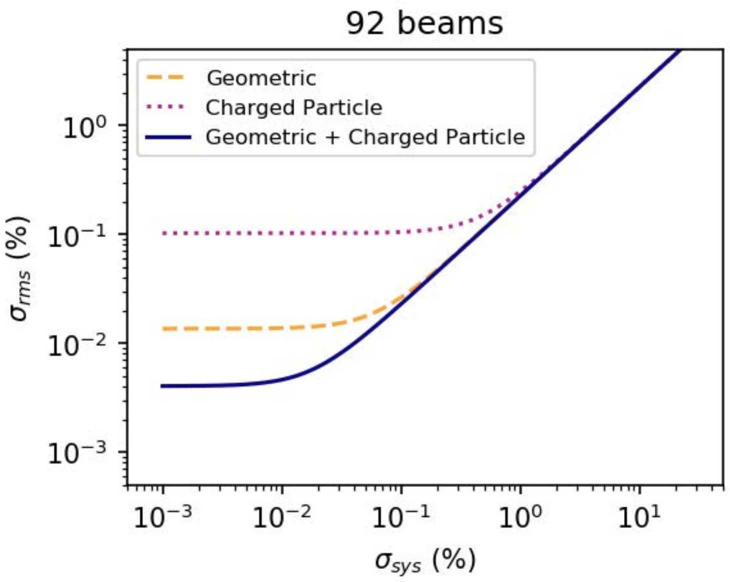
Scaling with σ_{sys}

$$\sigma_{rms} = \left[\sum_{n=l}^{\infty} \frac{a_l^2}{2l+1}\left(G_l^2 + \frac{\sigma_{sys}^2}{N_B}\right)\right]^{\frac{1}{2}}$$

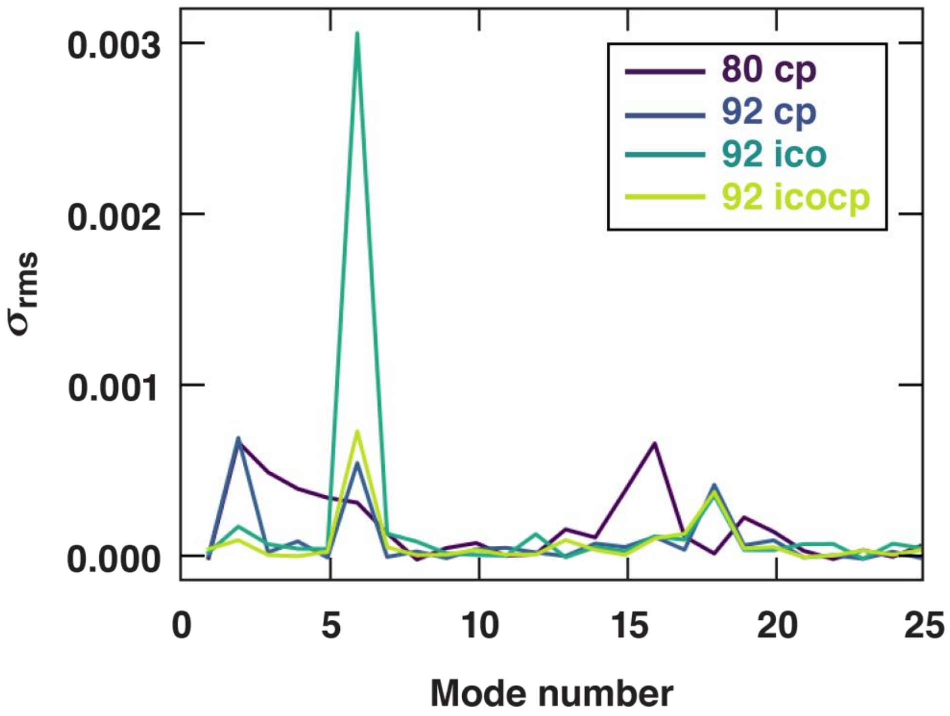
Face Centered

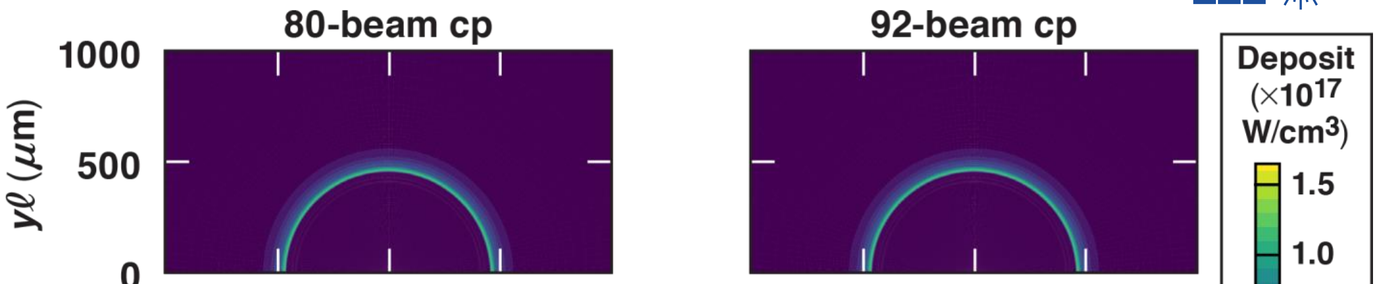


Vertex Centered



Icosahedral with charged particle configurations have the lowest contribution from modes below dominant mode number



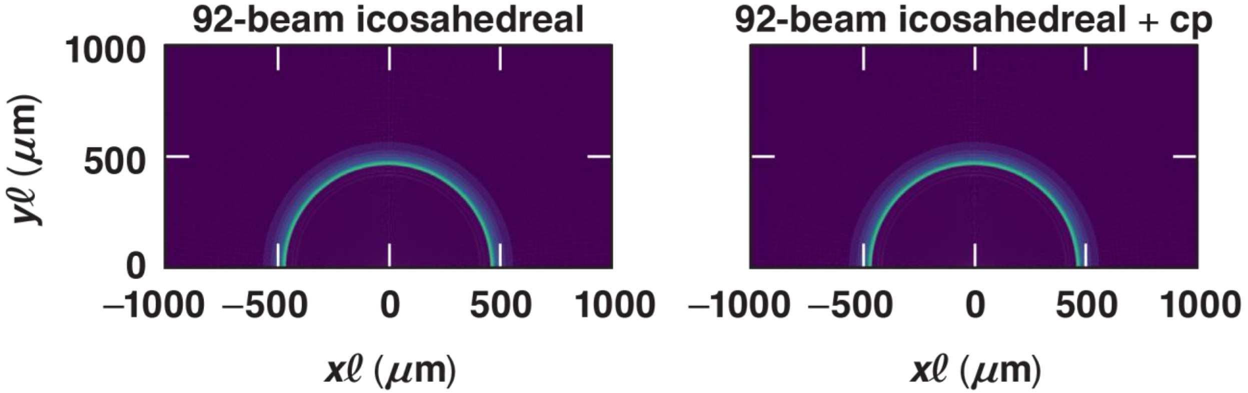


80-beam cp:

σ_{rms} (%)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.10	0.04	0.13	0.17

92-beam cp:

σ_{rms} (%)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.07	0.06	0.08	0.12



92-beam icosahedreal:

σ_{rms} (%)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.02	0.33	0.11	0.35

92-beam icosahedreal + cp:

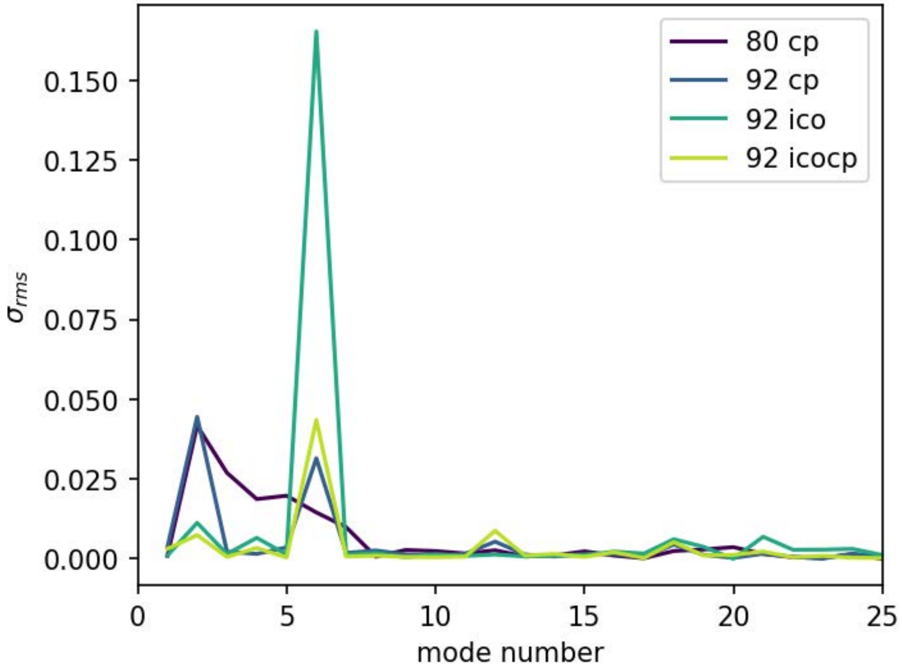
σ_{rms} (μm)			
$\ell < 6$	$\ell = 6$	$\ell > 6$	Total
0.01	0.08	0.11	0.14

cp: charged particle
ico: icosahedral
Icocp: icosahedral + charged particle

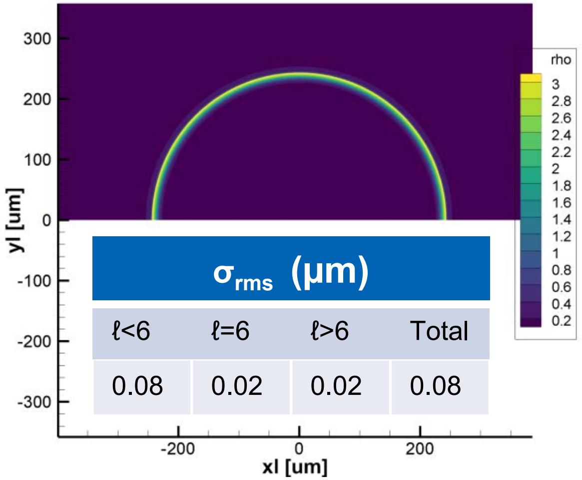
TC15897

wtri@lle.rochester.edu

Mode structure in DRACO Simulations inner shell position at CR=2

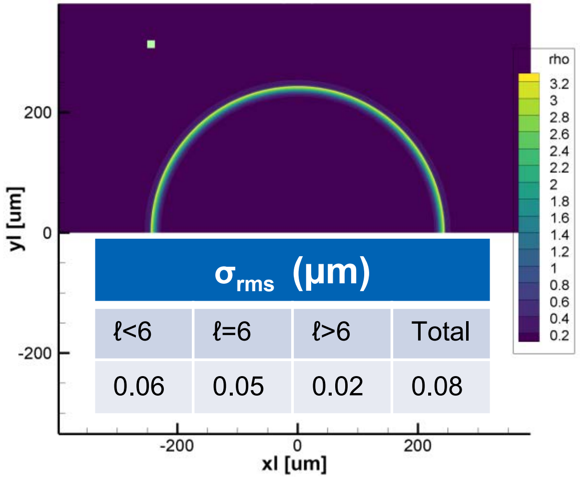


80 beam cp



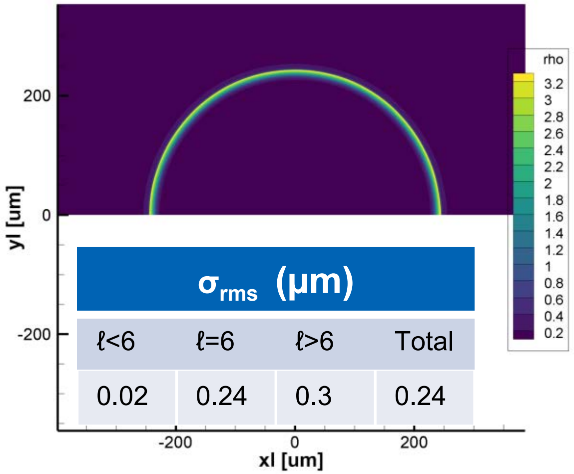
σ_{rms} (µm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.08	0.02	0.02	0.08

92 beam cp



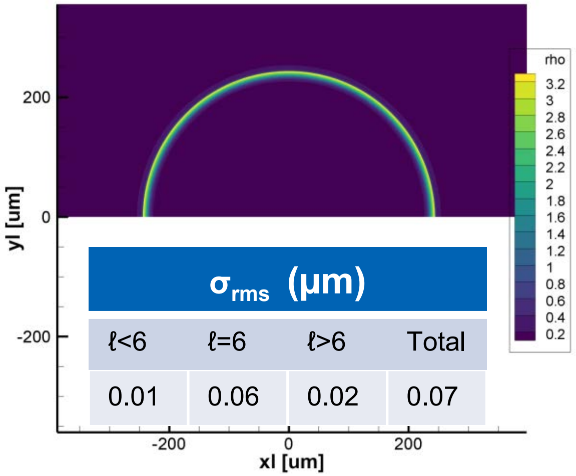
σ_{rms} (µm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.06	0.05	0.02	0.08

92 beam icosahedral



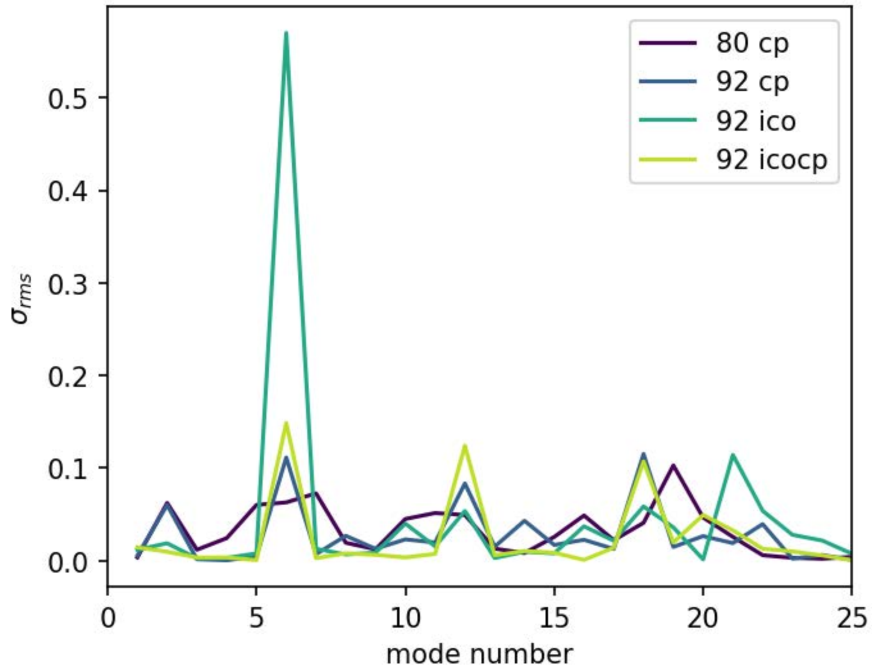
σ_{rms} (µm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.02	0.24	0.3	0.24

92 beam icosahedral+cp

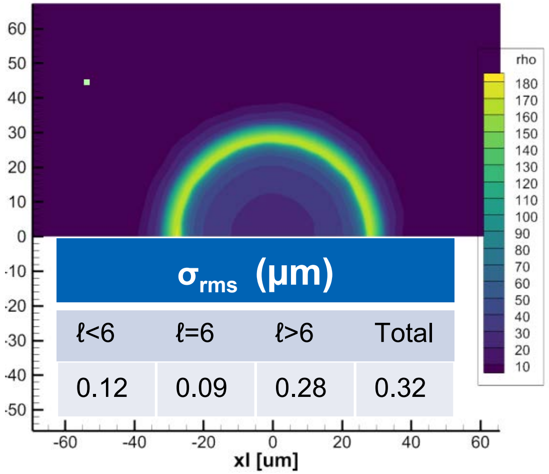


σ_{rms} (µm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.01	0.06	0.02	0.07

Mode structure in DRACO Simulations inner shell position at 2.225ns (bt = 2.45ns)

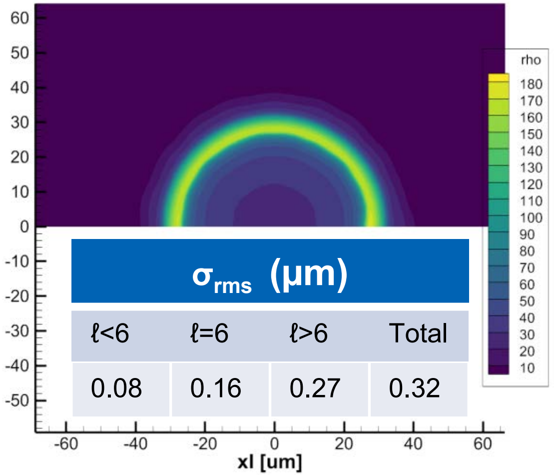


80 beam cp



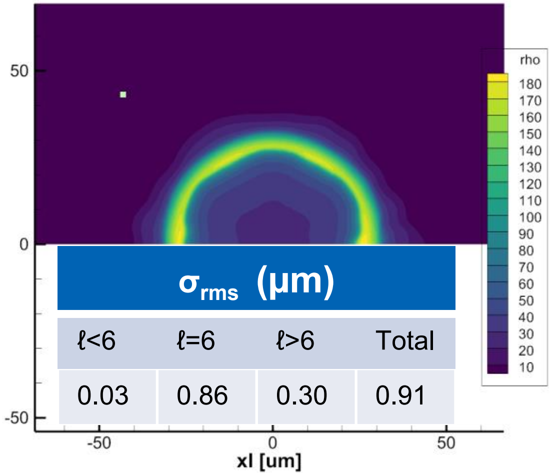
σ_{rms} (μm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.12	0.09	0.28	0.32

92 beam cp



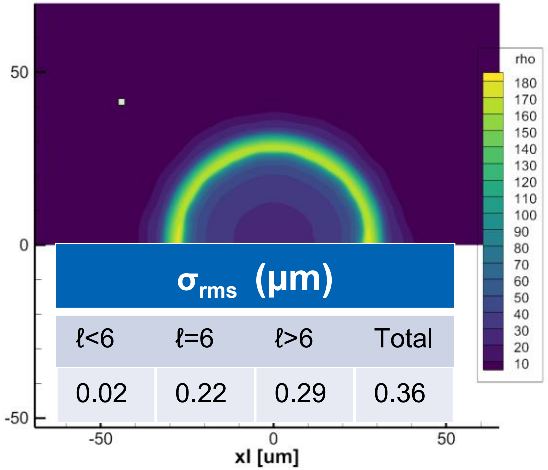
σ_{rms} (μm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.08	0.16	0.27	0.32

92 beam icosahedral



σ_{rms} (μm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.03	0.86	0.30	0.91

92 beam icosahedral+cp



σ_{rms} (μm)			
ℓ<6	ℓ=6	ℓ>6	Total
0.02	0.22	0.29	0.36