3D Laser Pulse Shaping for the Cornell ERL Photoinjector

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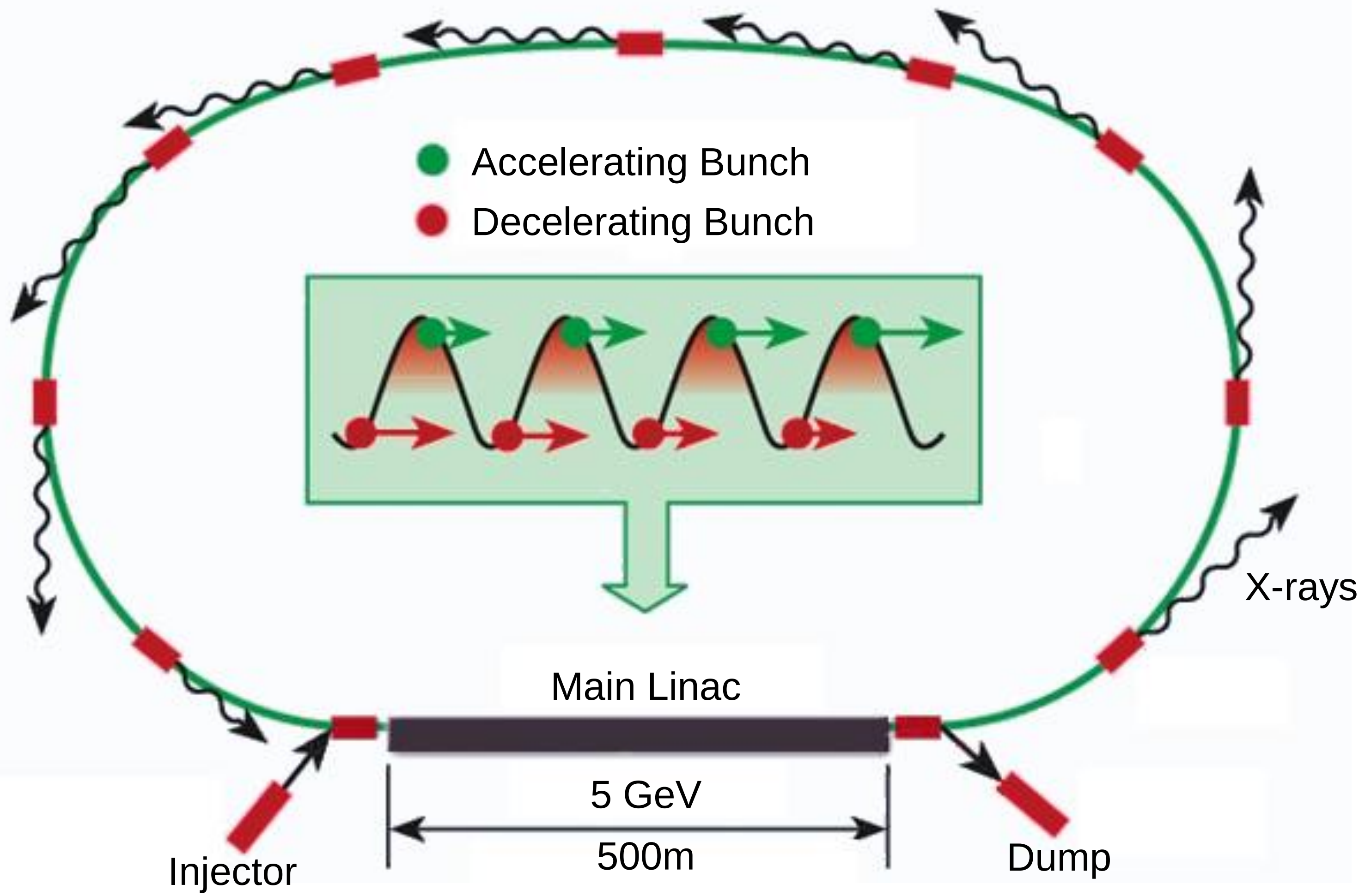
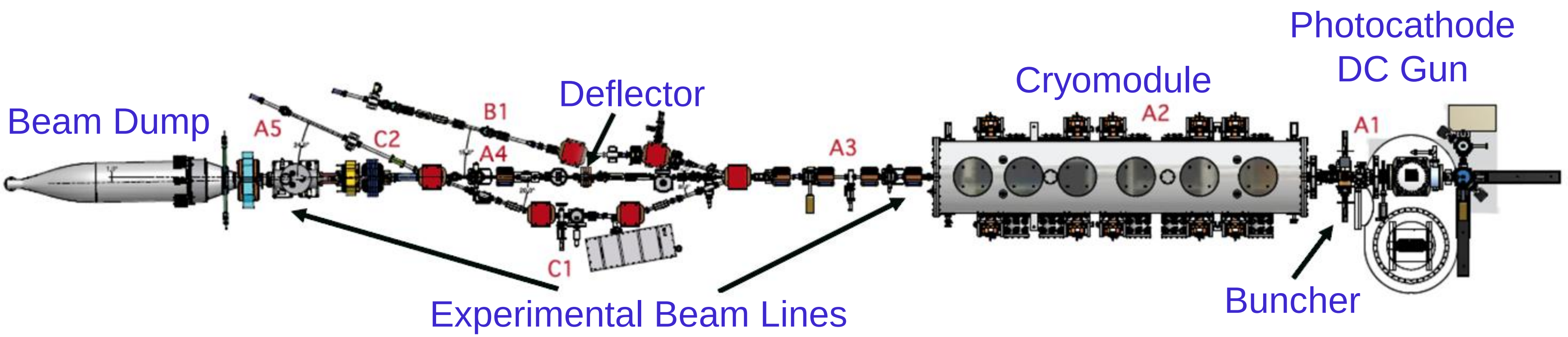
Energy Recovery Linac (ERL)



- Synchrotron radiation x-ray source
- Energy recovered from decelerated electron bunches
- Beam quality is set by source

http://webbuild.knu.ac.kr/~accelerator/BPM.htm

ERL Photoinjector

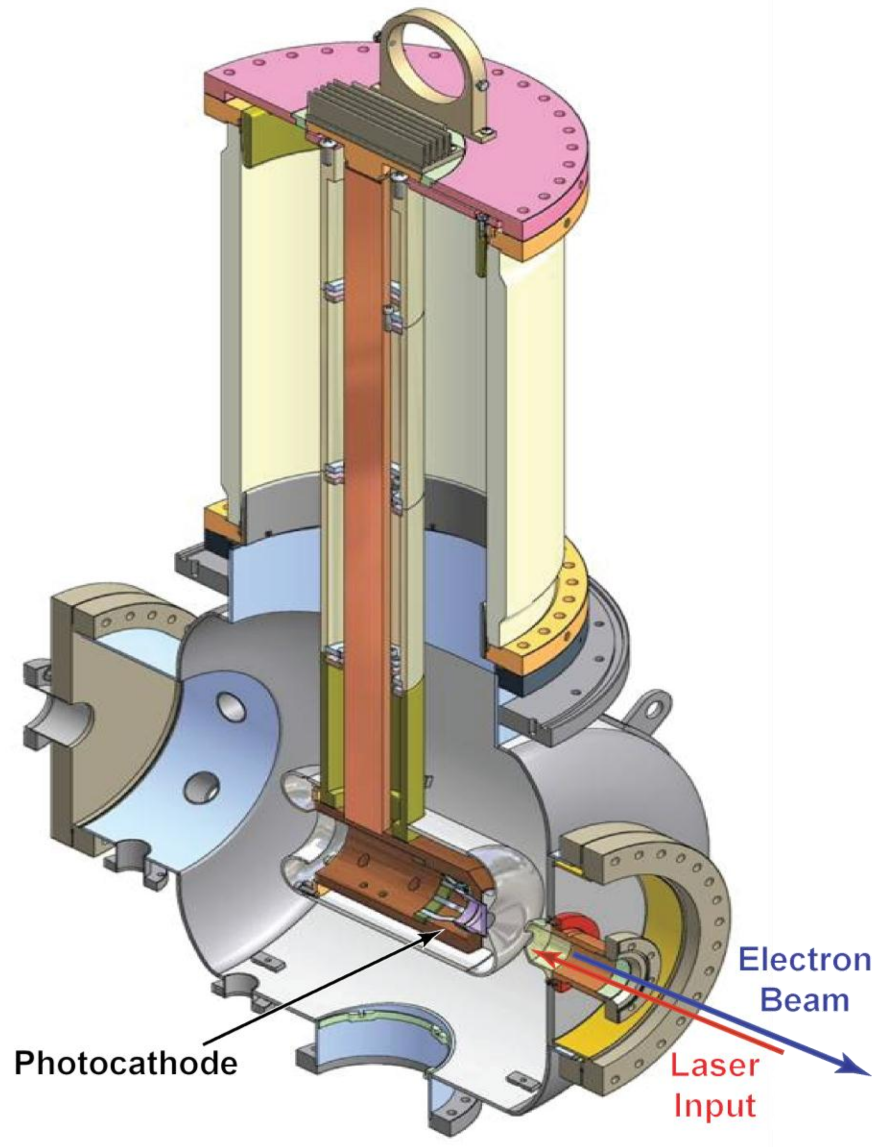


- Provides high energy, low emittance electron bunches to the accelerator
- Beam quality is set by the source

http://srf2009.bessy.de/talks/moobau04_talk.pdf

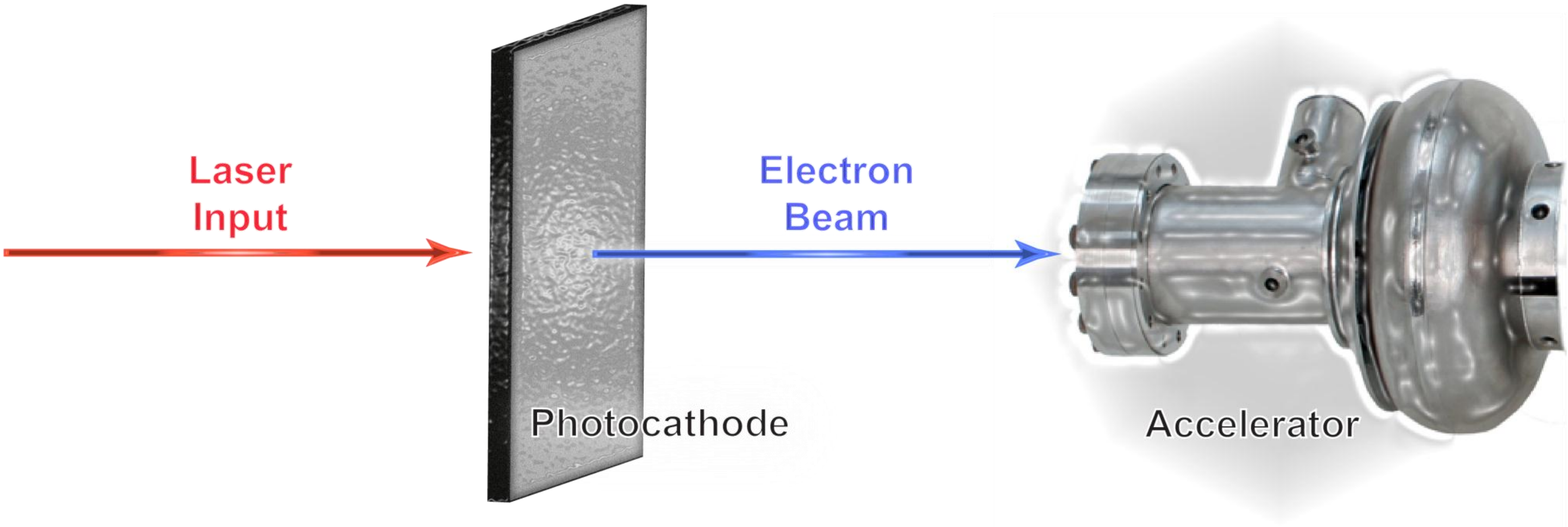
ERL Electron Gun

- High voltage DC electron gun
- Contains photocathode
- Emits electron bunches
- Beam quality is set by the source



http://erl.chess.cornell.edu/papers/2008/First Tests of the Cornell University ERL Injector,.pdf

Project Overview



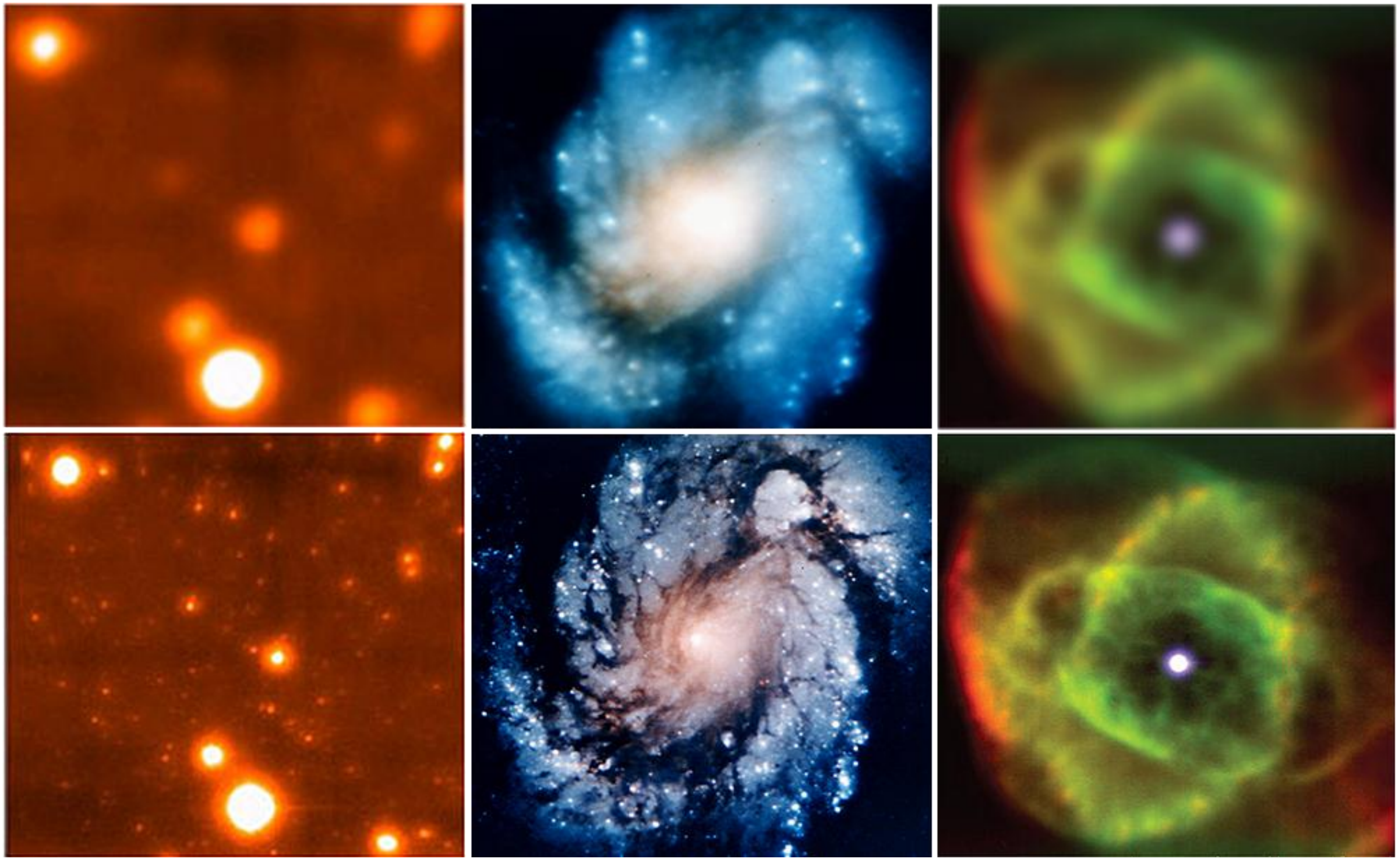
- Laser pulse strikes cathode, emitting electron bunch
- Electron bunch is injected into accelerator
- Laser pulse shape determines electron bunch shape
- This is the source!

Cavity: http://newsline.linearcollider.org/images/2010/20100617_dc_1.jpg

Project Goals (1): Clean Up Laser Pulse

Before

After



Project Goal:

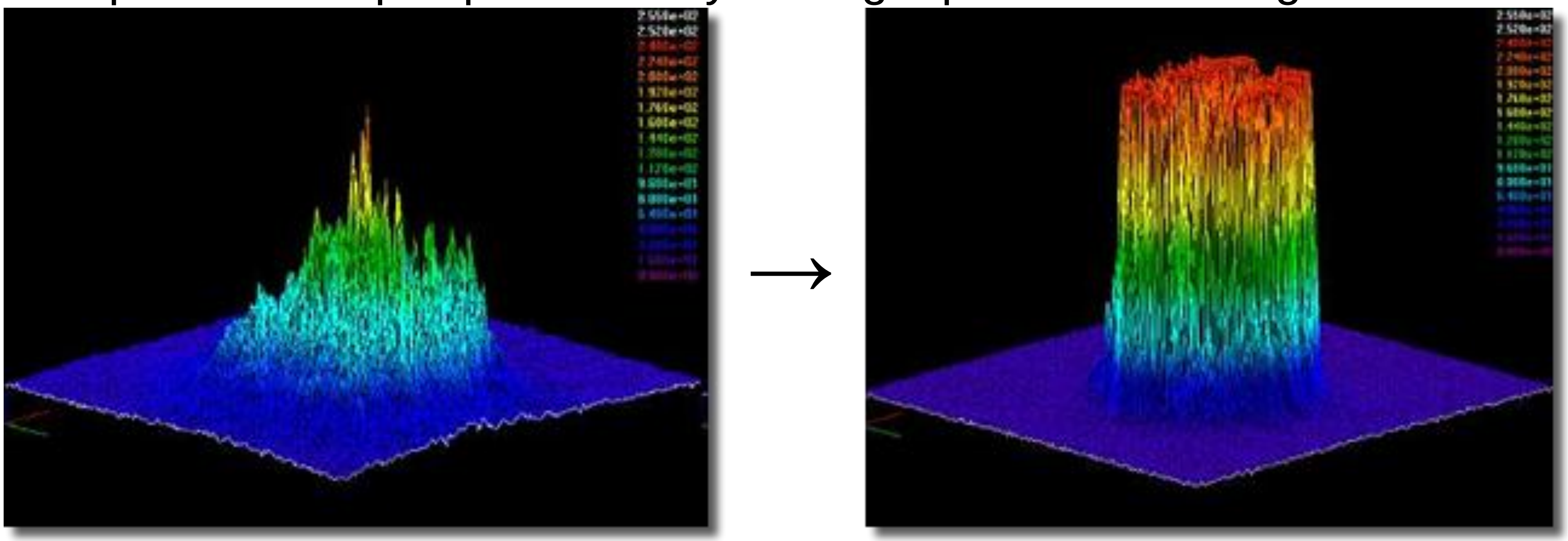
Clean Up Beam

- Remove aberrations from wavefront

Middle: http://dayton.hq.nasa.gov/IMAGES/LARGE/GPN-2002-000064.jpg
Ends: http://www.techshout.com/science/2007/05/sharpest-ever-space-images-captured-with-the-lucky-camera/

Project Goals (2): Shape laser pulse

- A beam of arbitrary shape can be created by adding an appropriate phase and passing the beam through a Fourier transforming lens
- Example: A flat-top is produced by adding a phase to the original waveform



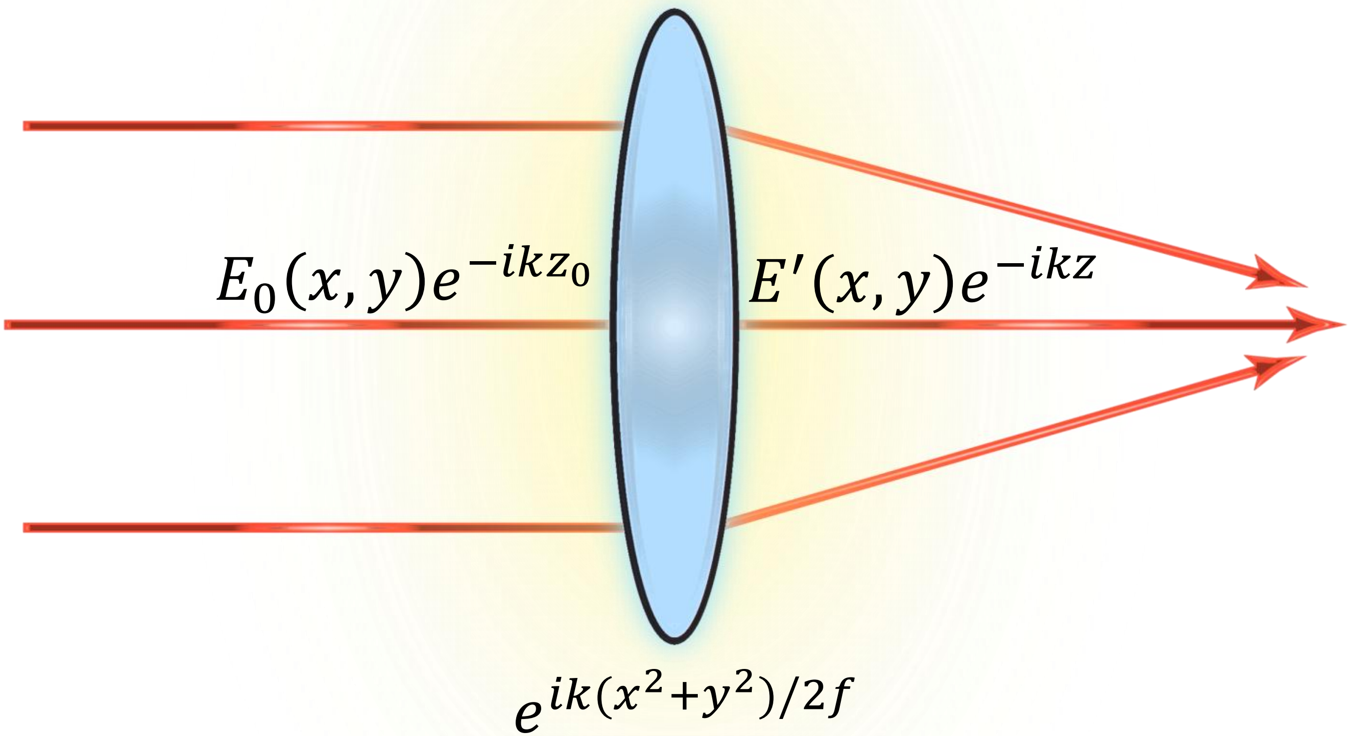
Project Goal:

Shape Beam

- Produce beam of arbitrary shape

http://www.spring8.or.jp/en/facilities/accelerators/upgrading/project/rf_gun/fig_e/laser_shaping.jpg

Fourier Optics

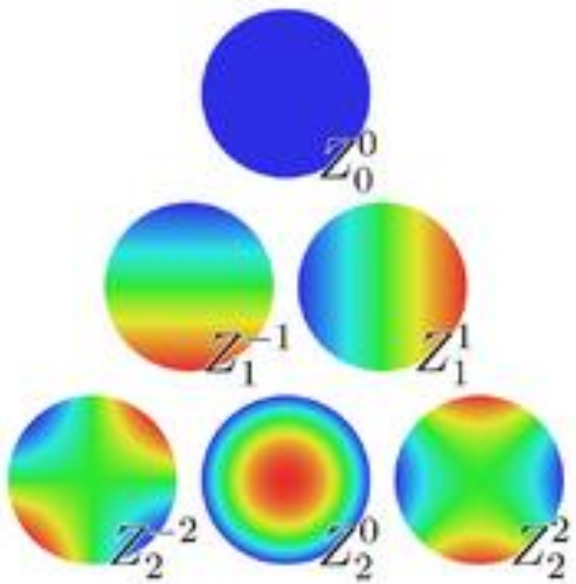


- Geometric optics describes beam size
- Fourier optics describe phase propagation
- Considers waves in the spatial frequency domain
- A lens is a Fourier transformer

Optical Aberrations (1)

- Zernike Polynomials are used to describe optical aberrations
- Orthogonal set of polynomials used in optics

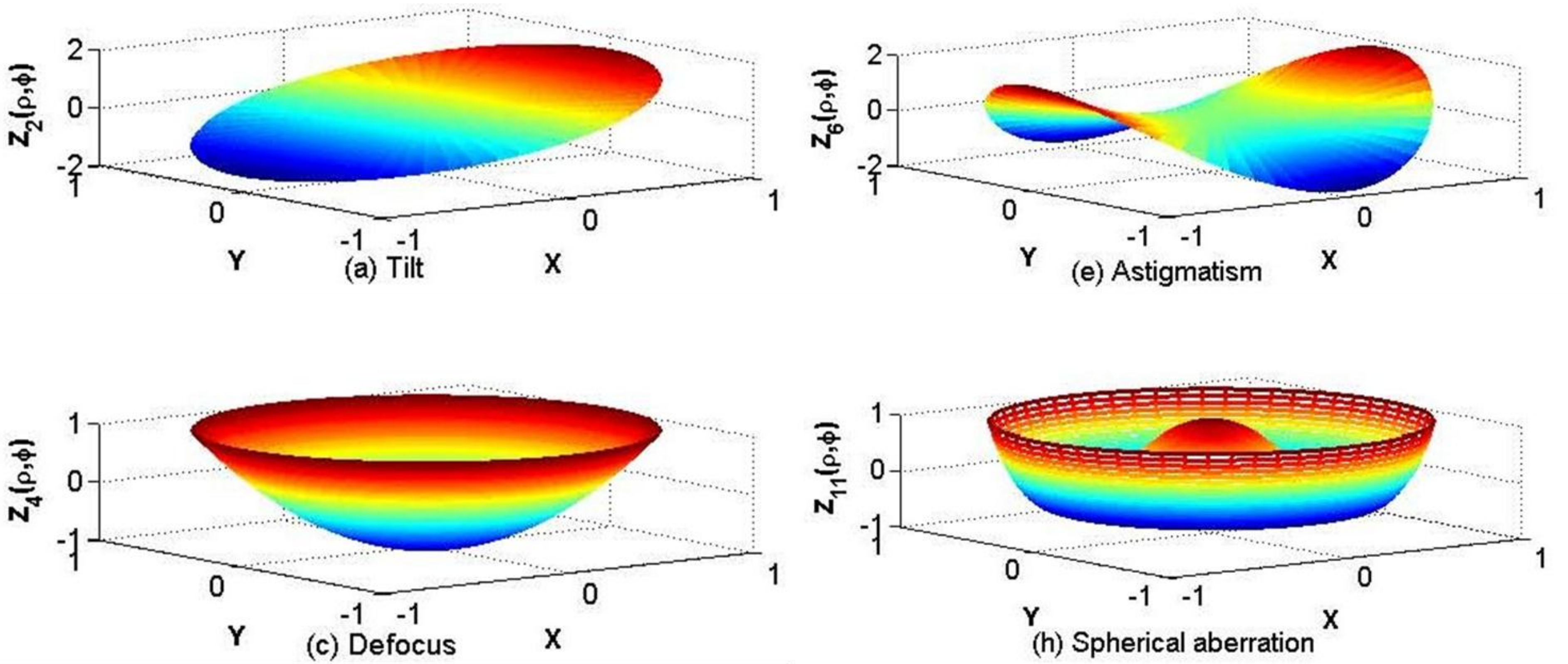
$$Z_{mn}(\rho,\varphi) = \quad R_{mn}(\rho)Cos(m\varphi)$$
$$Z_{mn}(\rho,\varphi) = -R_{mn}(\rho)Sin(m\varphi)$$



http://upload.wikimedia.org/wikipedia/commons/thumb/3/3d/Zernike_polynomials2.png/360px-Zernike_polynomials2.png

Optical Aberrations (2)

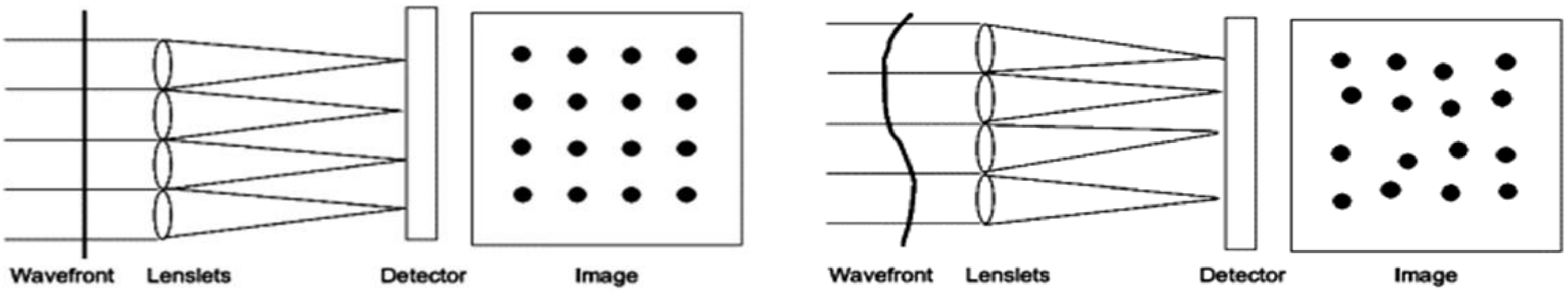
- Any phase can be written as a weighted sum of Zernike polynomials



http://cictr.ee.psu.edu/research/pcs/Zernike%20polynnomials.jpg

Shack Hartman Apparatus

- Measures the phase of the wavefront



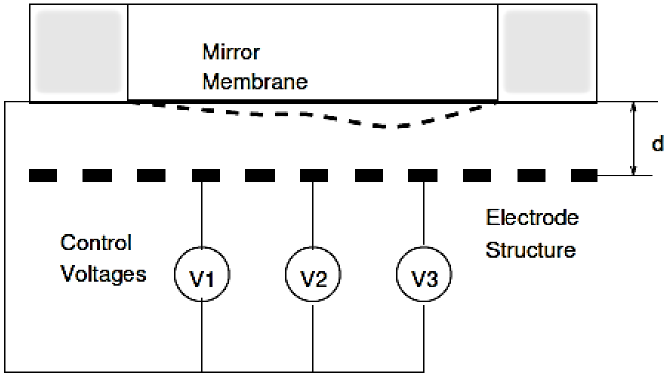
- Non-flat wavefronts produce shifted spot patterns on the sensor
- Reconstructs wavefront by analyzing how much each point is shifted

http://www.sciencedirect.com/science/article/pii/S0168900205006686

Micromachined Membrane Deformable Mirror (MMDM)

- Shapes the wavefront

Image of MMDM

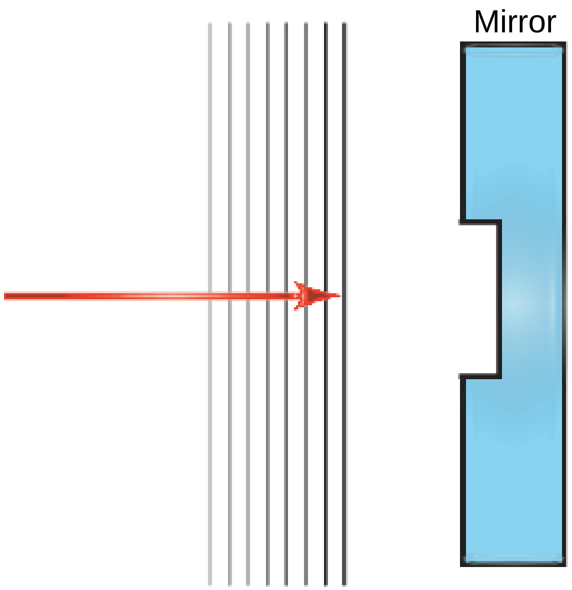


MMDM Schematic

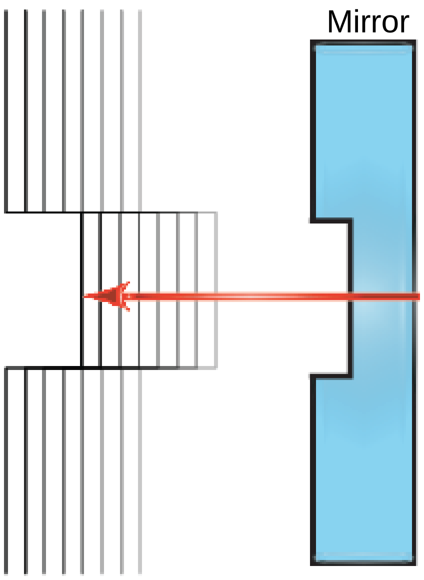
- Mirror changes phase of incoming laser beam
- Applying voltage to actuators deforms mirror membrane
- Shape of added phase corresponds to shape of mirror

Left: http://www.okotech.com/15-mm-37-ch-qoko-mirrorq
Right: http://www.okotech.com/images/pdfs/catwww3.pdf

Laser Shaping (2)



Incoming Plane Wave

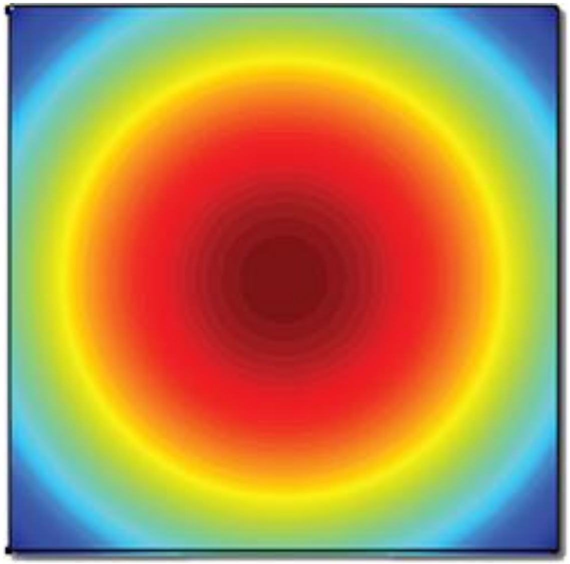


Reflected Wave

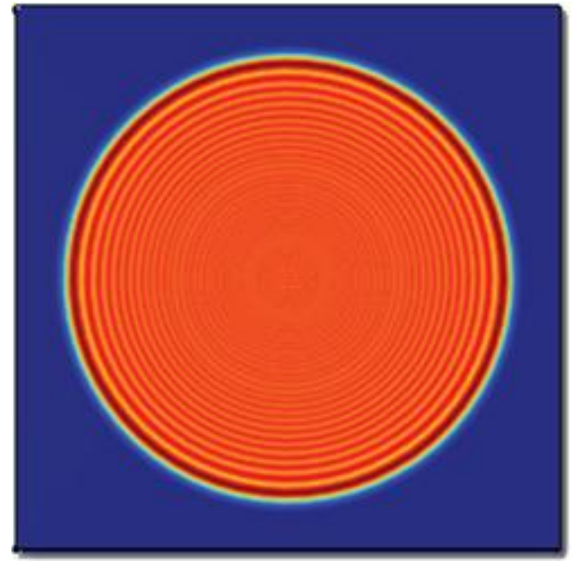
- Mirror shape corresponds to phase shape

Example: Shaping the Laser Pulse

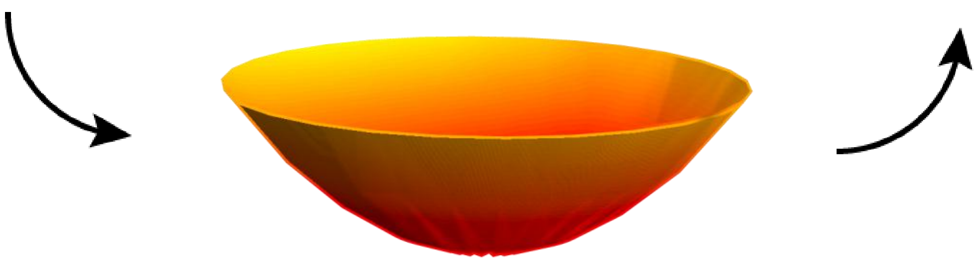
- MMDM can be used to change the intensity of the beam
  - Add phase with MMDM
  - Use lens to Fourier transform beam



Gaussian Beam



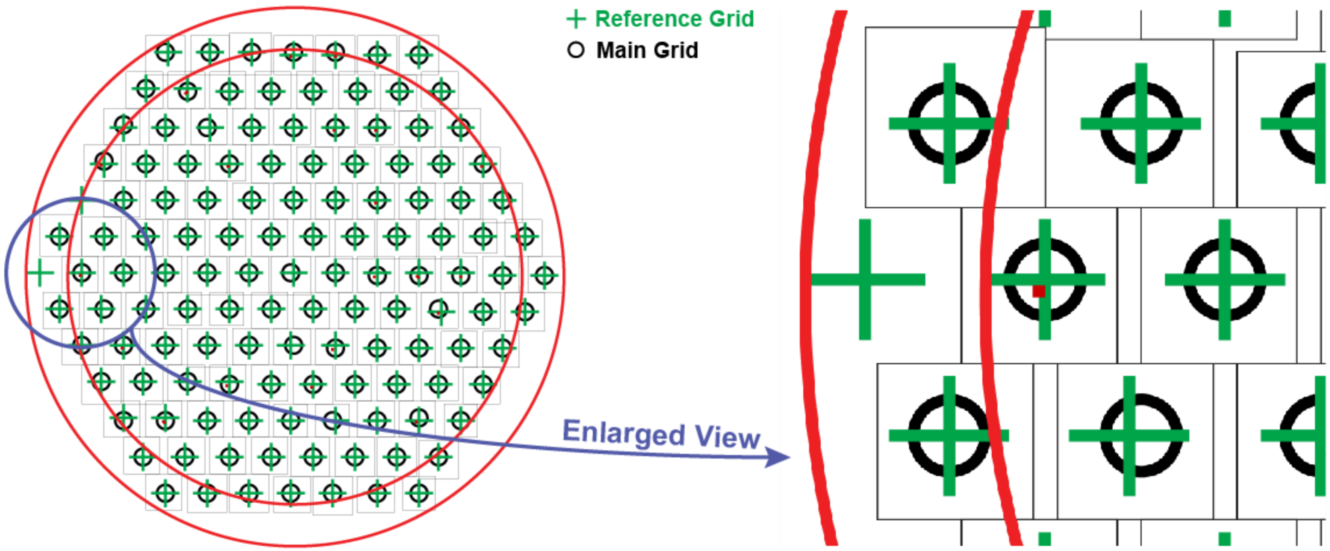
Flat-Top Beam



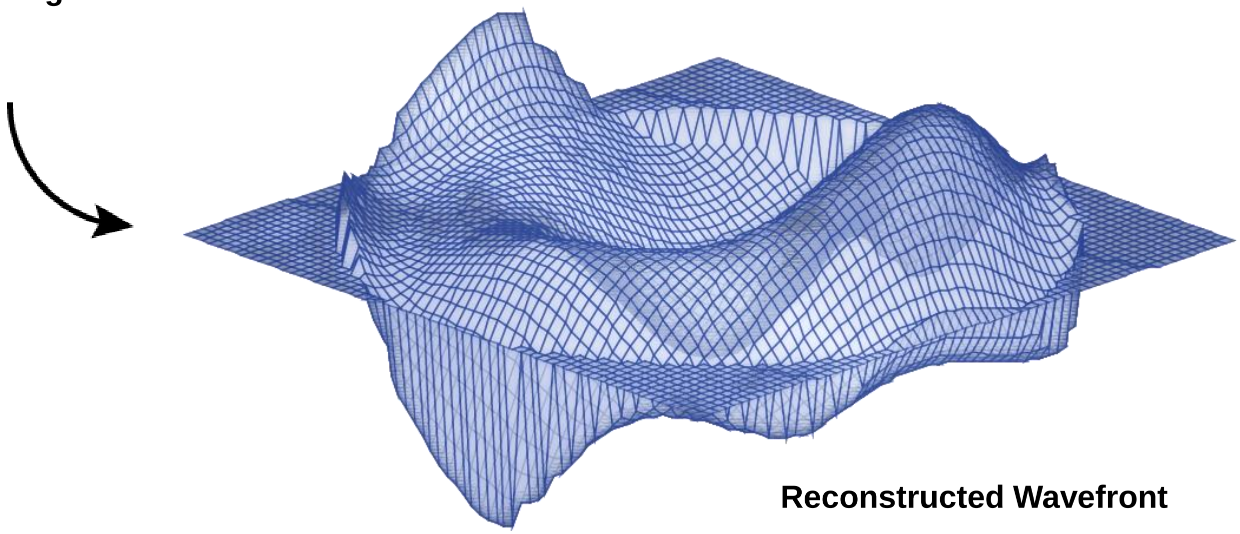
+ Phase
+ Fourier Transform

Frontsurfer Software (1)

- Reconstructs phase using wavefront sensor

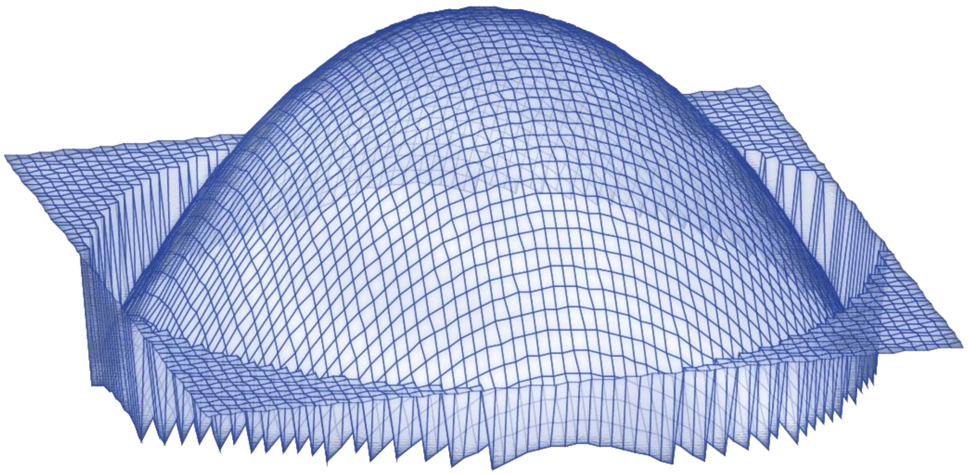


Hartmannogram



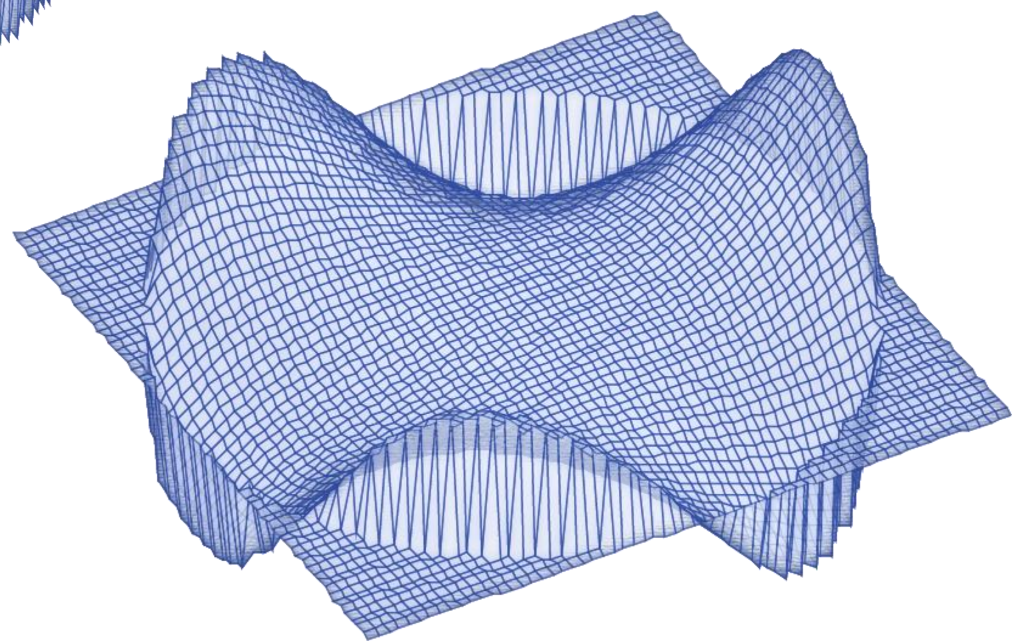
Reconstructed Wavefront

Frontsurfer Software (2)



Initial Shape

Zero Actuator Voltage

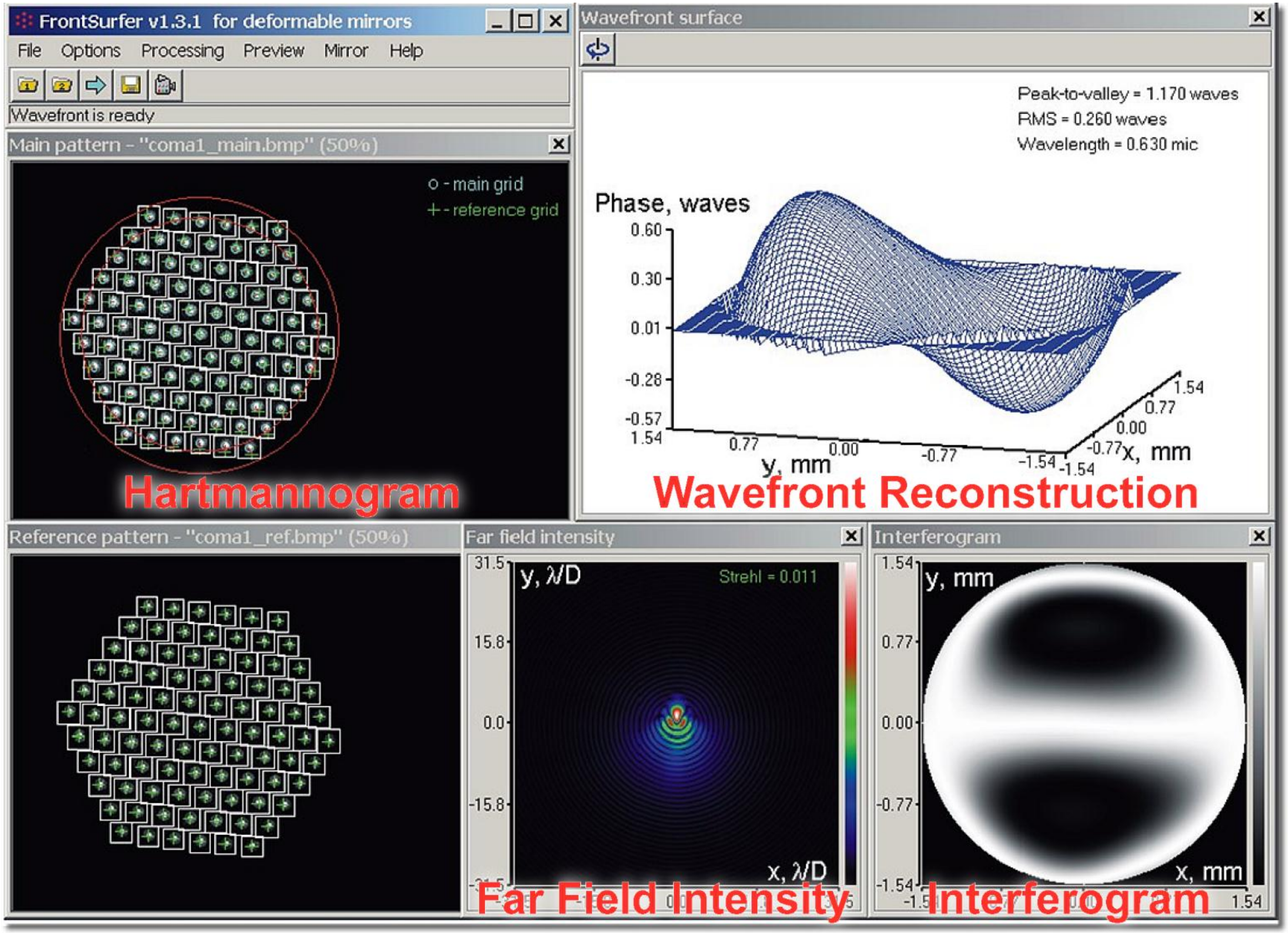


Target Function

Astigmatism

- Adjusts MMDM actuator voltages to produce target function

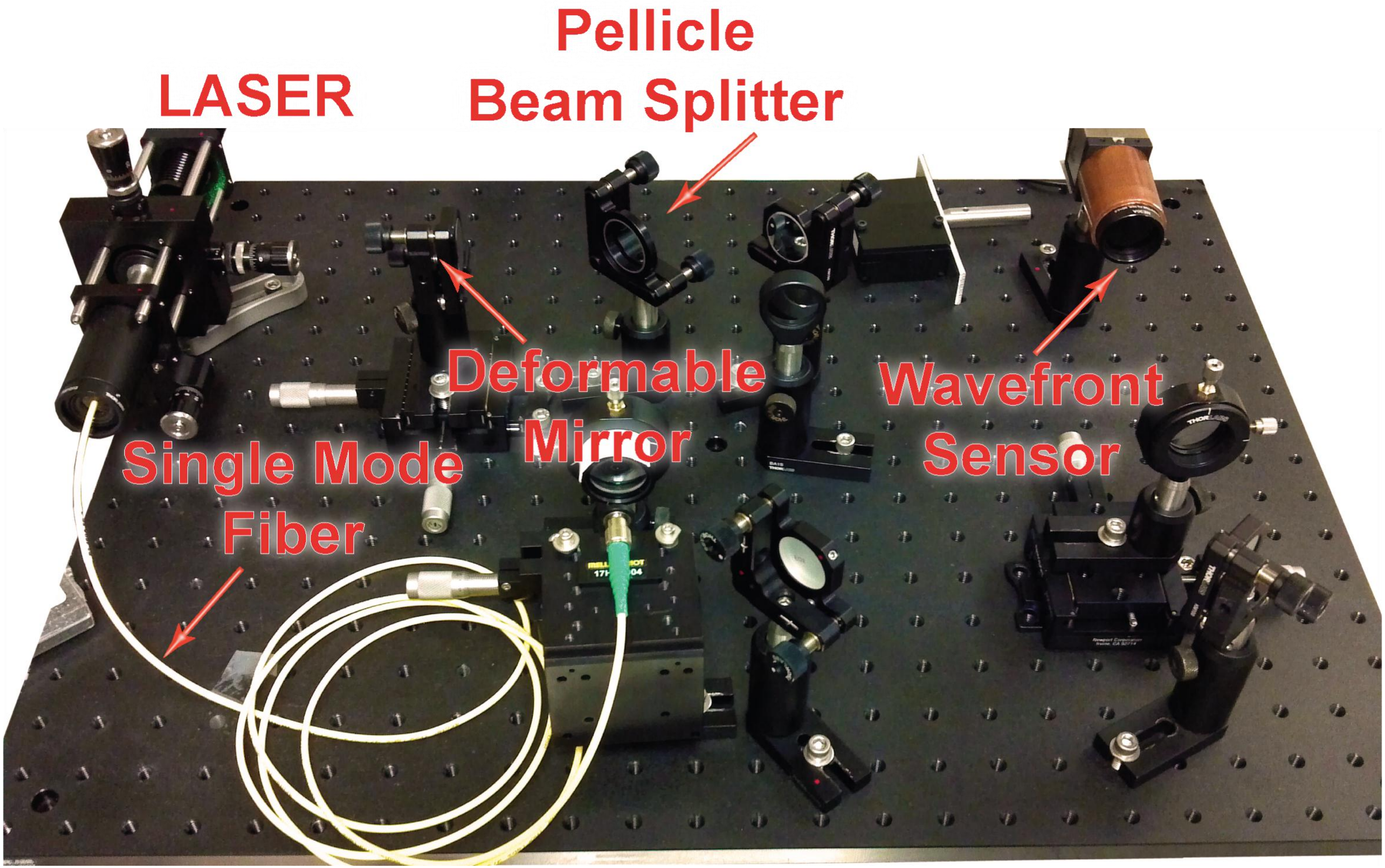
Frontsurfer Software (3)



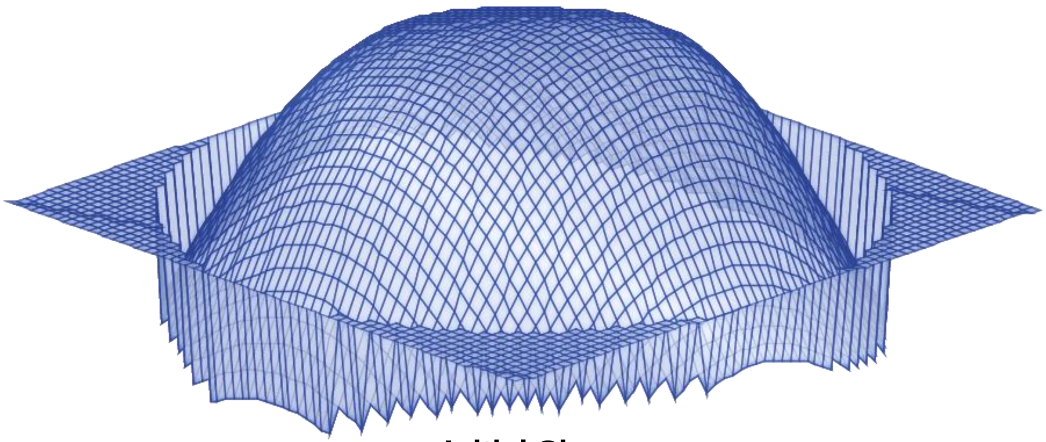
- Frontsurfer software interface

http://www.okotech.com/images/okoimages/fs_screen1big.jpg

Initial Setup

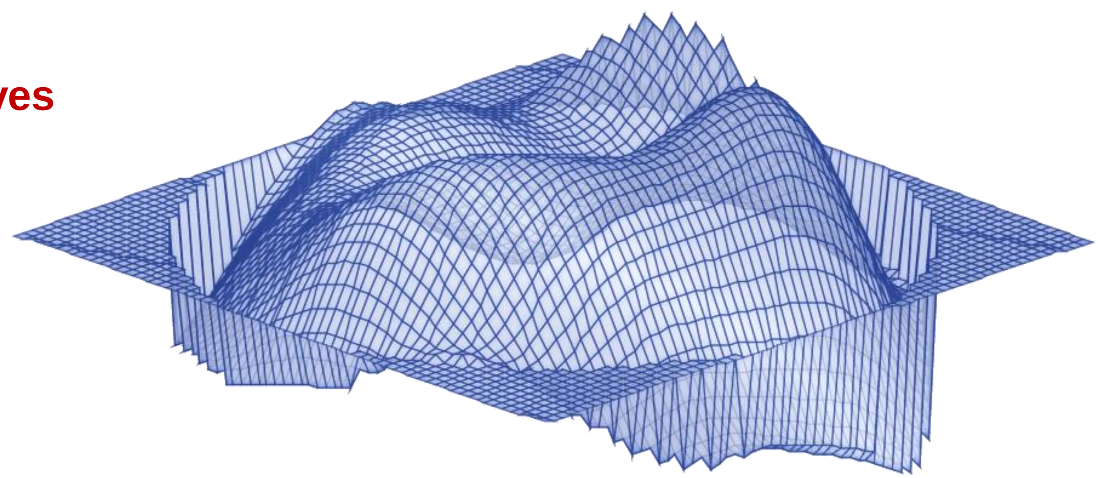


Initial Results



Initial Shape

Peak-to-valley = 1.158 Waves



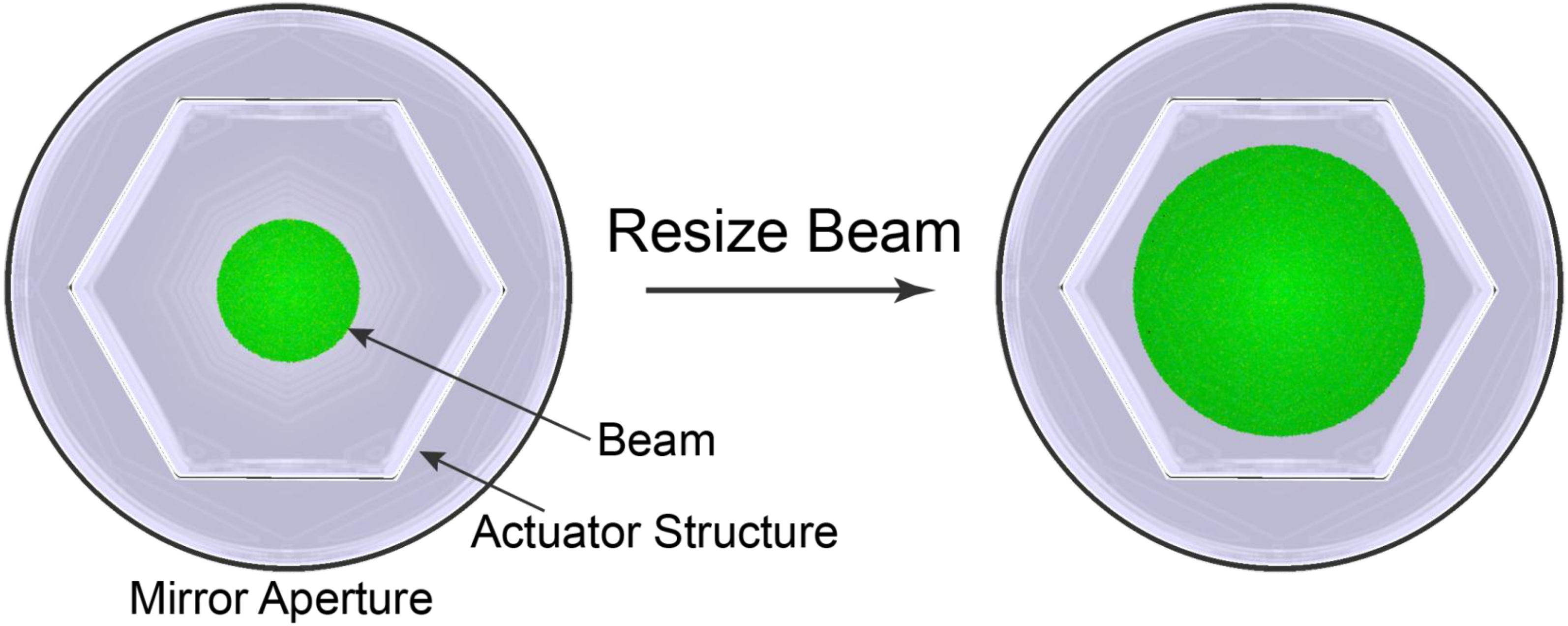
Target Function: Flat Phase

Peak−to−valley = 0.258 waves

- Flattens wave, but not well
  - Peak-to-Valley distance decreased by 80%

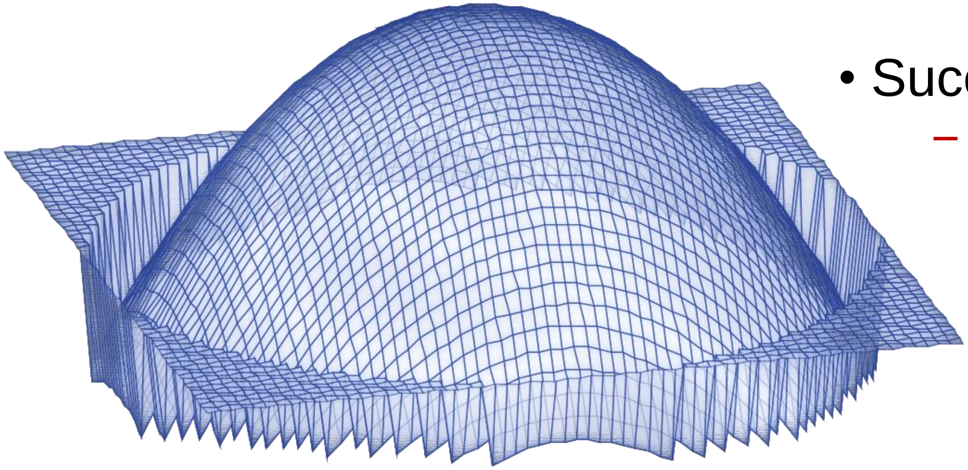
Resize Beam

- Problem: Wrong Size Beam
  - Too few active Zernike modes
  - Beam covers insufficient mirror area
  - Unable to use all actuators effectively
- Solution: Resize Beam
  - Expand beam to cover more mirror surface
  - Resize beam at wavefront sensor



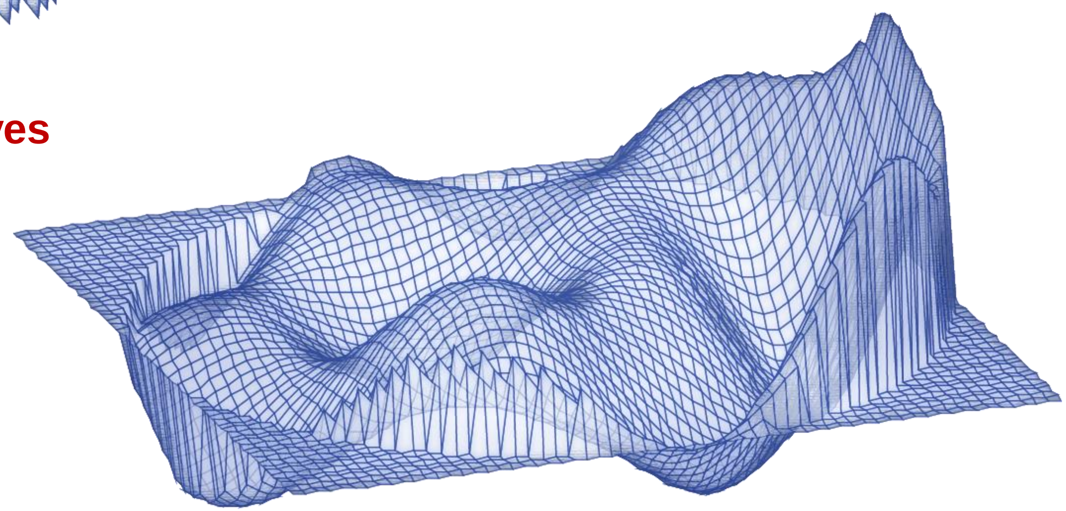
Beam Successfully Flattened

- Successfully flattens wave
  - Peak-to-valley distance decreased by 98.5%



Initial Shape

Peak-to-valley = 5.502 Waves



Target Function: Flat Phase

Peak−to−valley = 0.087 waves

Goal Complete:

✔ Clean Up Beam
- Remove aberrations from wavefront

Turning a Gaussian into a Flat-Top (1)

Next Goal:

Shape Beam

- Produce beam of arbitrary shape

Process:

1. Calculate phase needed to change intensity distribution

$$\varphi(\xi) = \frac{Dk_0}{2f}\int_0^{\xi}\sqrt{1-e^{-s^2}}\,ds$$

$$D = Initial\ Size$$
$$k_0 = \frac{2\pi}{\lambda}$$
$$f = focal\ length$$
$$\mathrm{s} = \frac{\mathrm{r}}{\mathrm{w}}$$

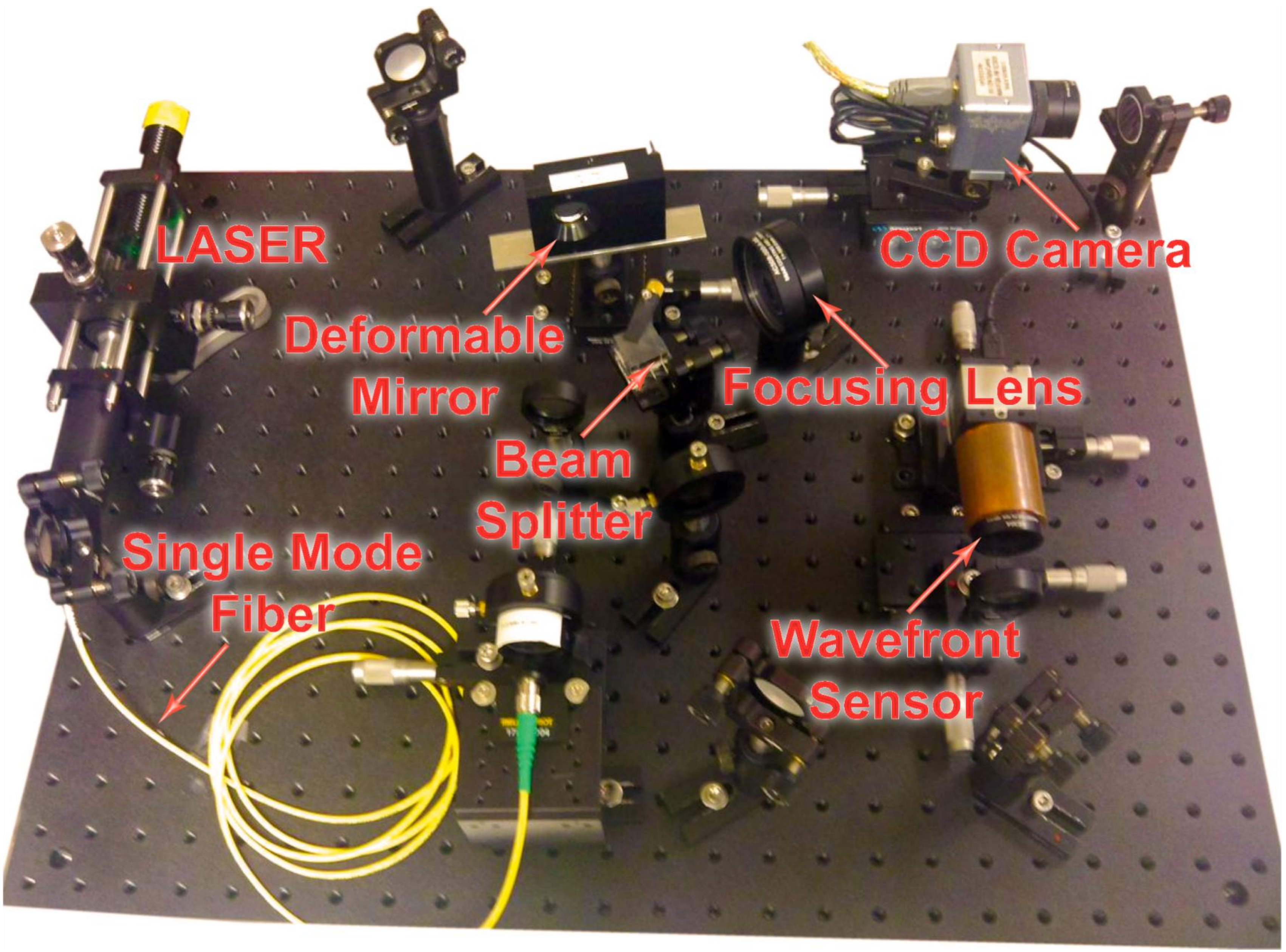
2. Write phase in terms of a weighted sum of Zernike polynomial

$$\varphi = \sum A_{mn}Z_{mn}$$

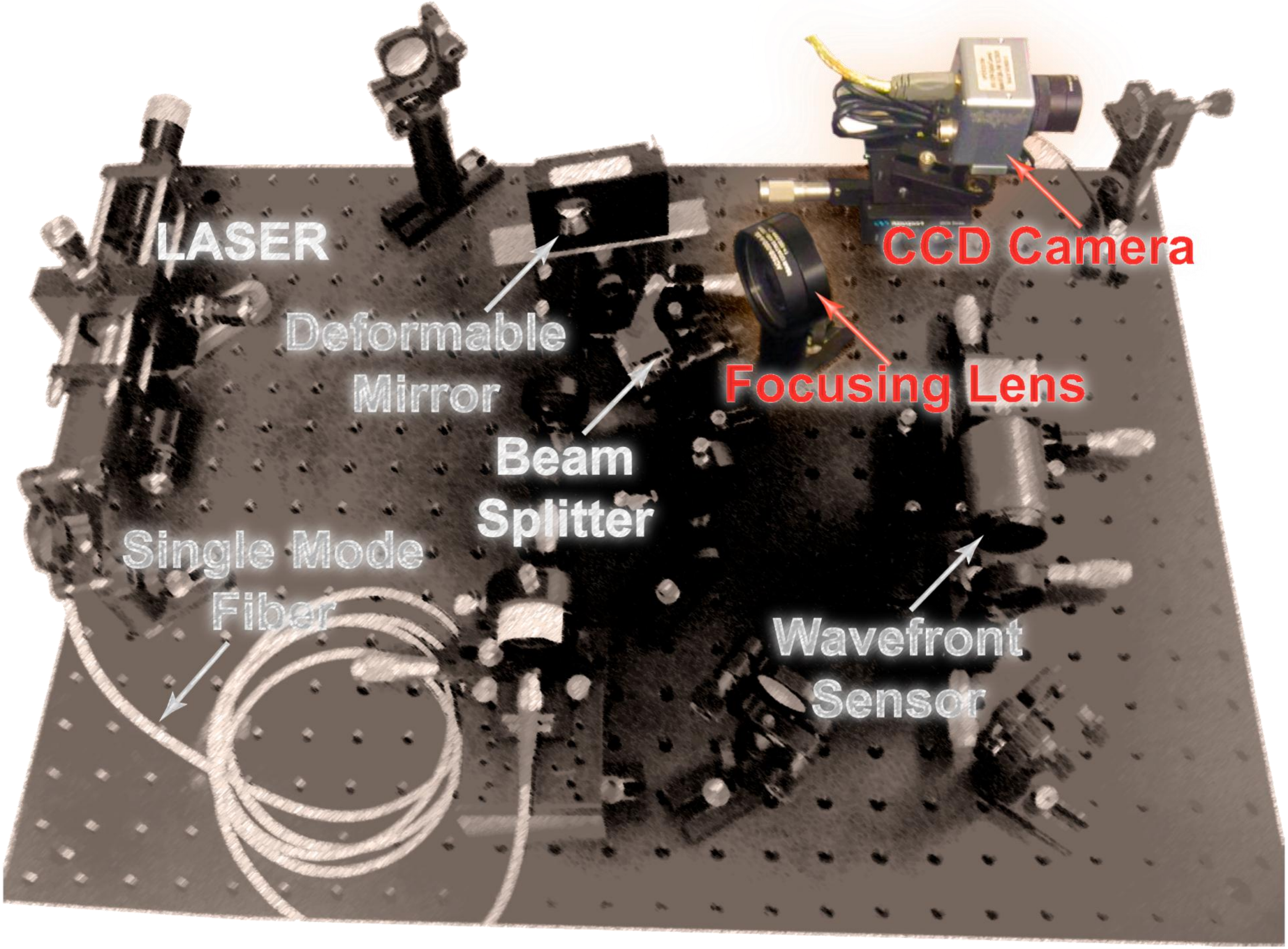
$$A_{mn} = \langle \varphi \mid Z_{mn} \rangle$$

3. Input Zernike coefficients into Frontsurfer software

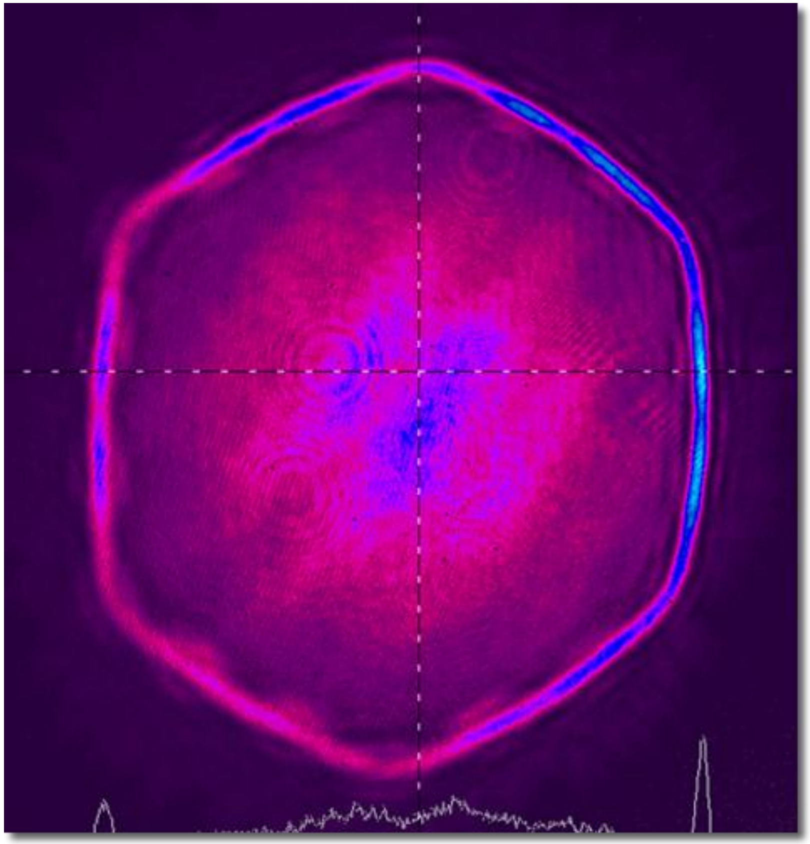
Updated Experimental Setup (1)



Updated Experimental Setup (2)

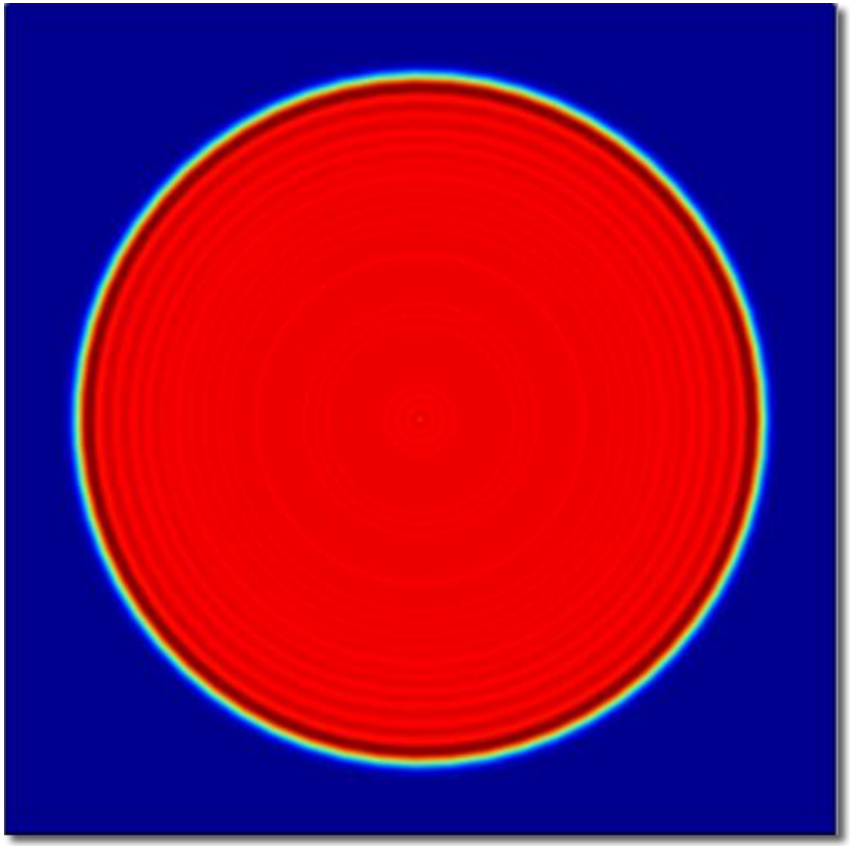


Turning a Gaussian into a Flat-Top (2)



Our Results

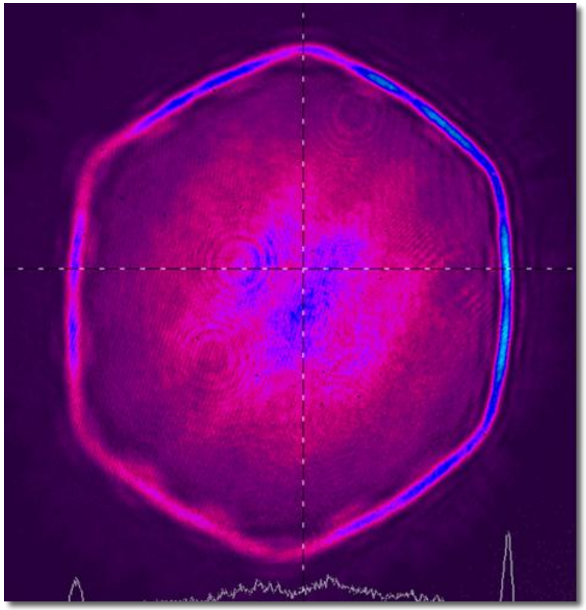
Bright Fringes
Hexagonal Shape



Matlab Results

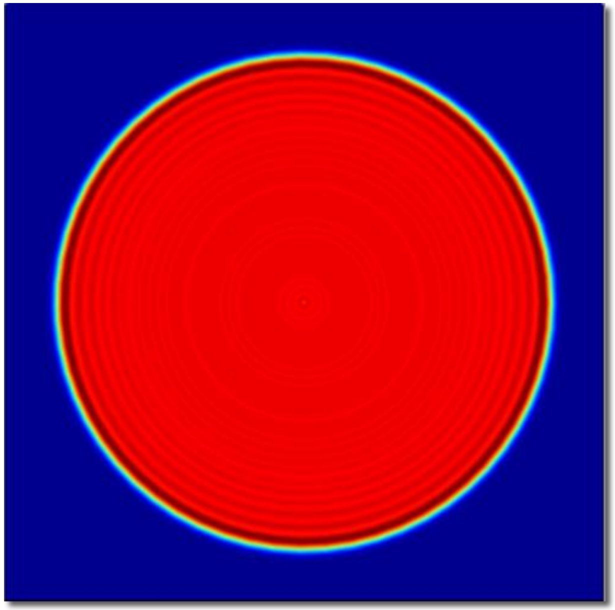
Uniform Intensity
Circular Shape

Wrong initial beam size?



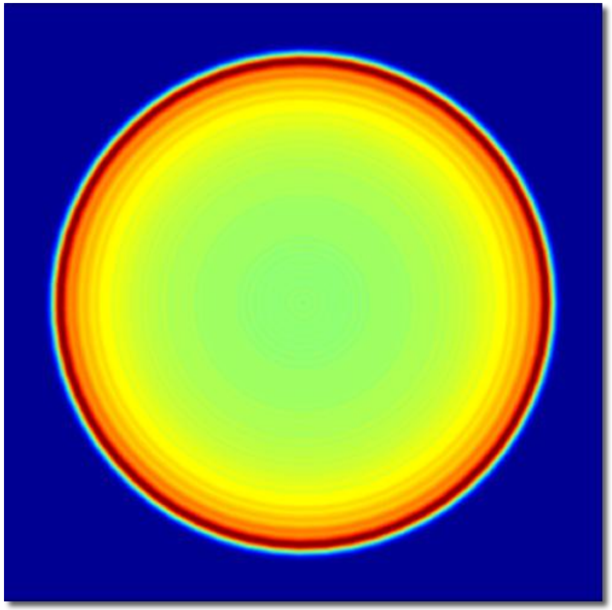
Our Results

7.9mm Beam



Matlab Results

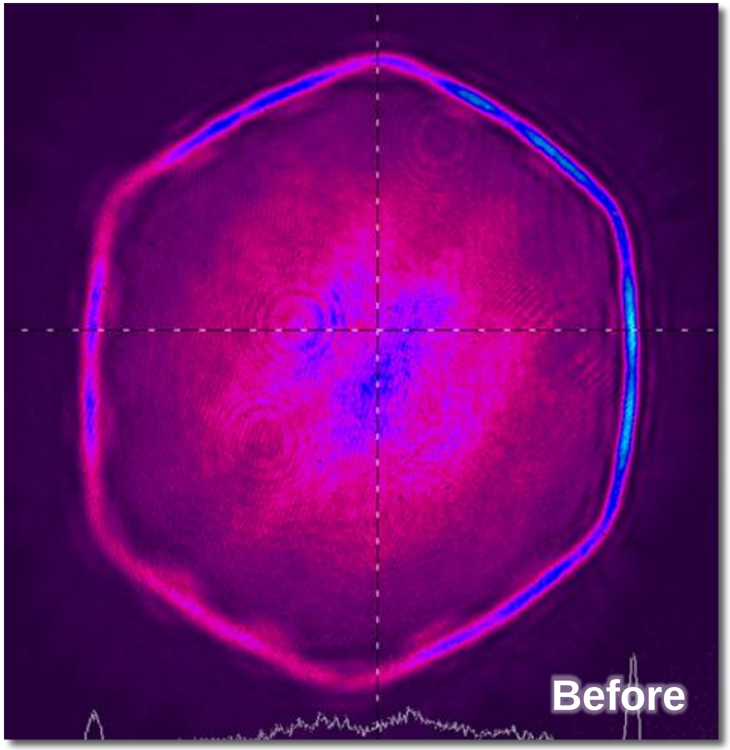
Actual beam
10% larger than beam
used to calculate phase



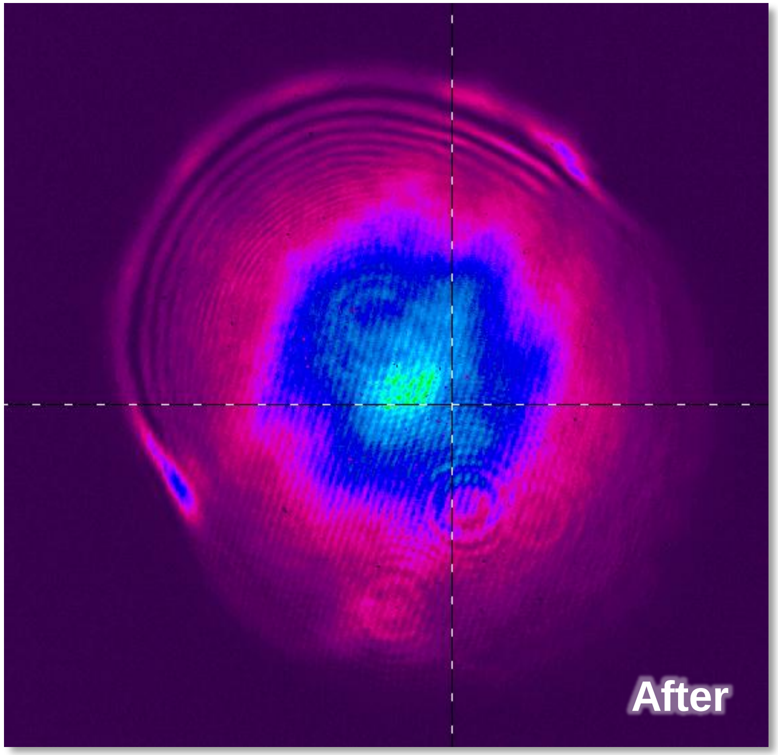
Matlab Results

Actual beam
10% smaller than beam
used to calculate phase

Reduced Beam Diameter to 5mm



Resize



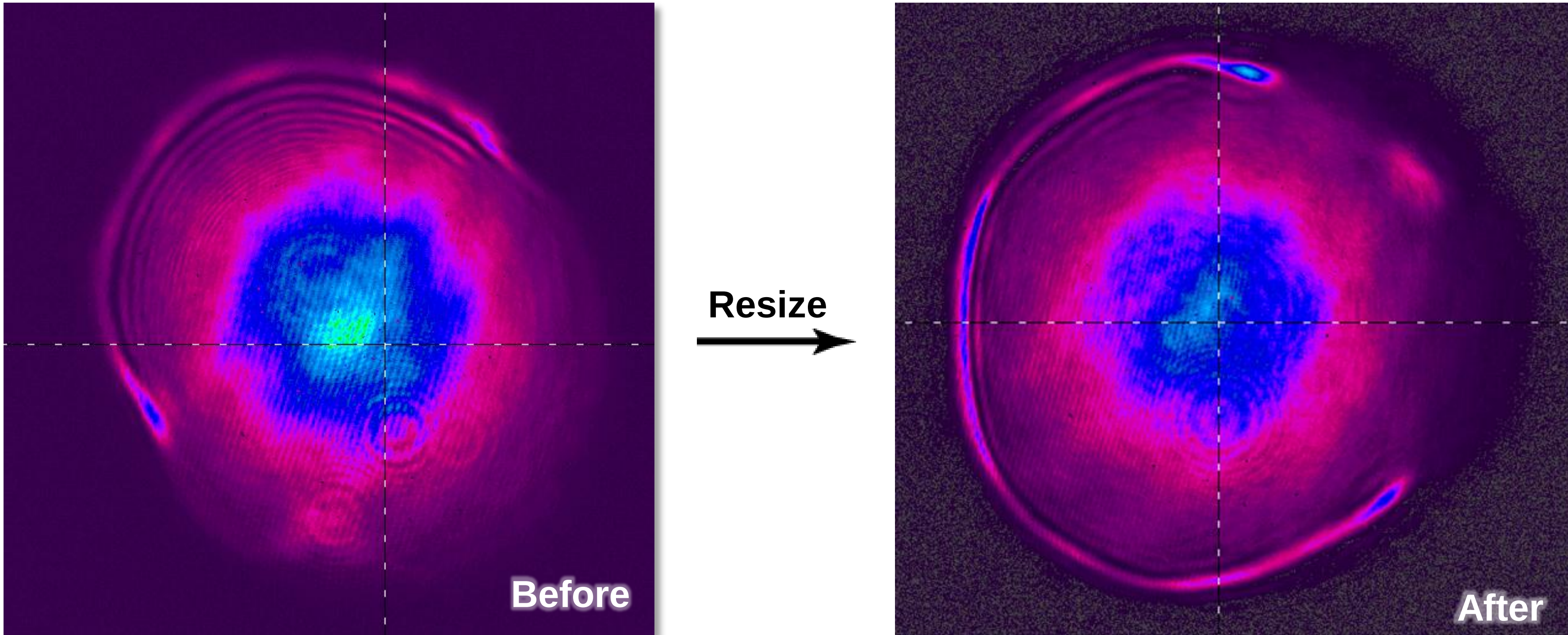
Improvements:

- No Hexagonal Shape
- Bright Fringe Reduced

Shortcomings:

- Not a Flat-Top
- Unable to Produce Target Functions
- Too few active Zernike modes

Resize Beam Diameter to 5.75 mm



Improvements:

- Able to roughly generate target functions
- More active Zernike modes
- More circular shape than 7.9mm beam

Shortcomings:

- Not a Flat-Top
- Larger Bright Fringe than 5mm Beam

Reducing Phase (1)

- Problem:
  - Actuator voltages are maxed out
- Cause:
  - Amplitude of Zernike coefficients are too high
- Next step:
  - Make added phase smaller

$$\varphi(\xi) = \frac{Dk_0}{2f}\int_0^{\xi}\sqrt{1-e^{-s^2}}\,ds$$

$$s = \frac{r}{w}, \qquad w = \text{initial beam size}$$

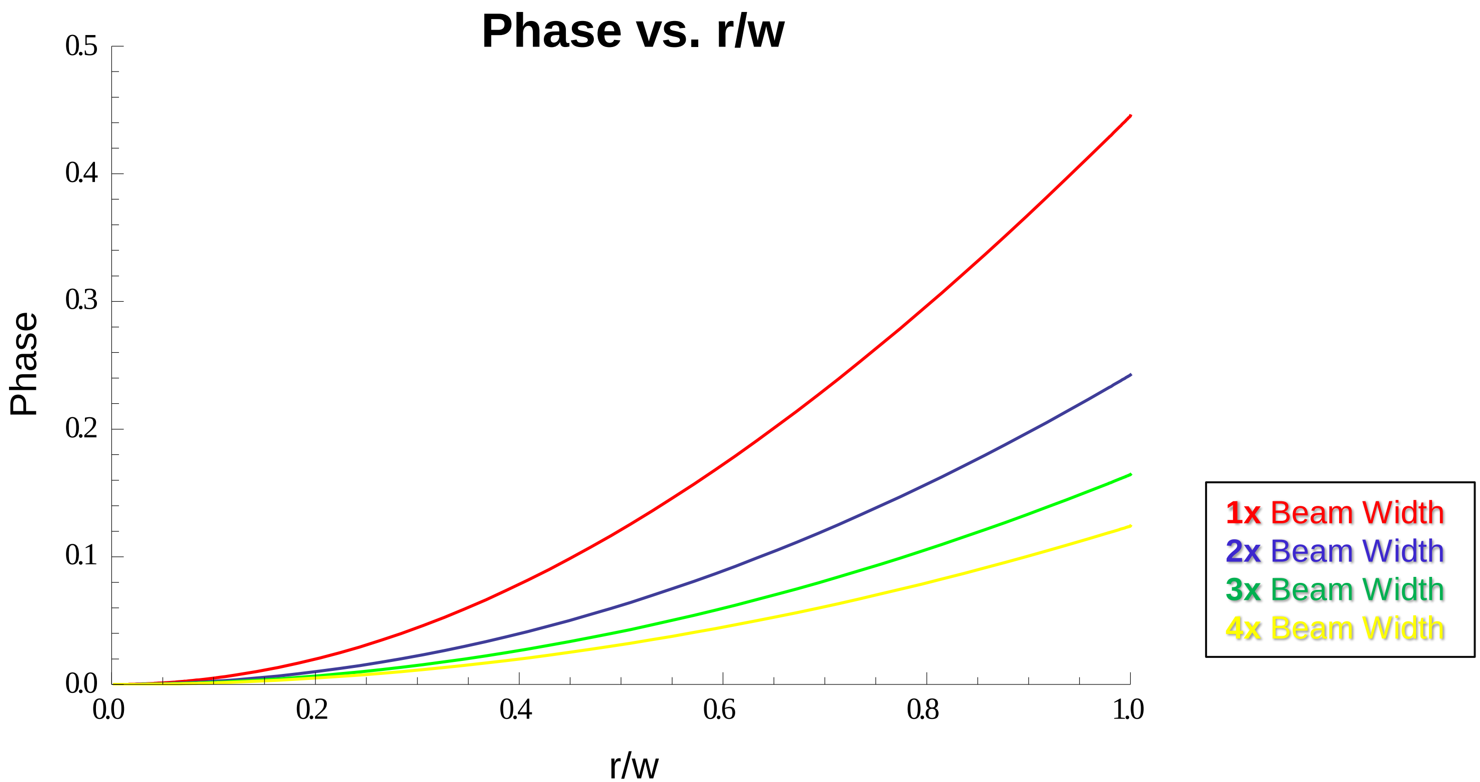
Reducing Phase (2)

- Reduce size of added phase:

$$\varphi(\xi) = \frac{Dk_0}{2f}\int_0^{\xi}\sqrt{1-e^{-s^2}}ds$$

$$s = \frac{r}{w},\ w = Beam\ width$$

- Increasing w decreases φ
  - Even with maximum allowable value of w, Zernike coefficients are too large
- Increasing focal length of focusing lens decreases φ



Conclusions

Project Goals:

Clean Up Beam
- Remove aberrations from wavefront

Shape Beam
- Produce beam of arbitrary shape

Progress So Far:

- Determined phase needed to transform Gaussian into flat-top
- Described phase as weighted sum of Zernike polynomials
- Investigated the effect of changing the beam size
- Identified the problem: Zernike coefficients are too large

Next Step:

- Reduce phase in order to reduce coefficients of Zernike polynomials

References

1. Adaptive Optic Systems. OKOtech Flexible Optical. 6/15/2012.<http://www.okotech. com/ao-systems>
2. Adaptive Optics Guide. OKO Flexible Optical; April 2008 Edition.
3. Dickey, Fred, Holswade, Scott. Laser Beam Shaping: Theory and Techniques. Copyright 2000, Marcel Decker, inc.
4. Wavefront Sensors. OKOtech Flexible Optical. 6/15/2012. <http://www.okotech. com/sensors>
5. Wavefront sensors: Shack-Hartmann. <http://www.ctio.noao..edu/~atokovin/tutorial/part3/wfs.html>