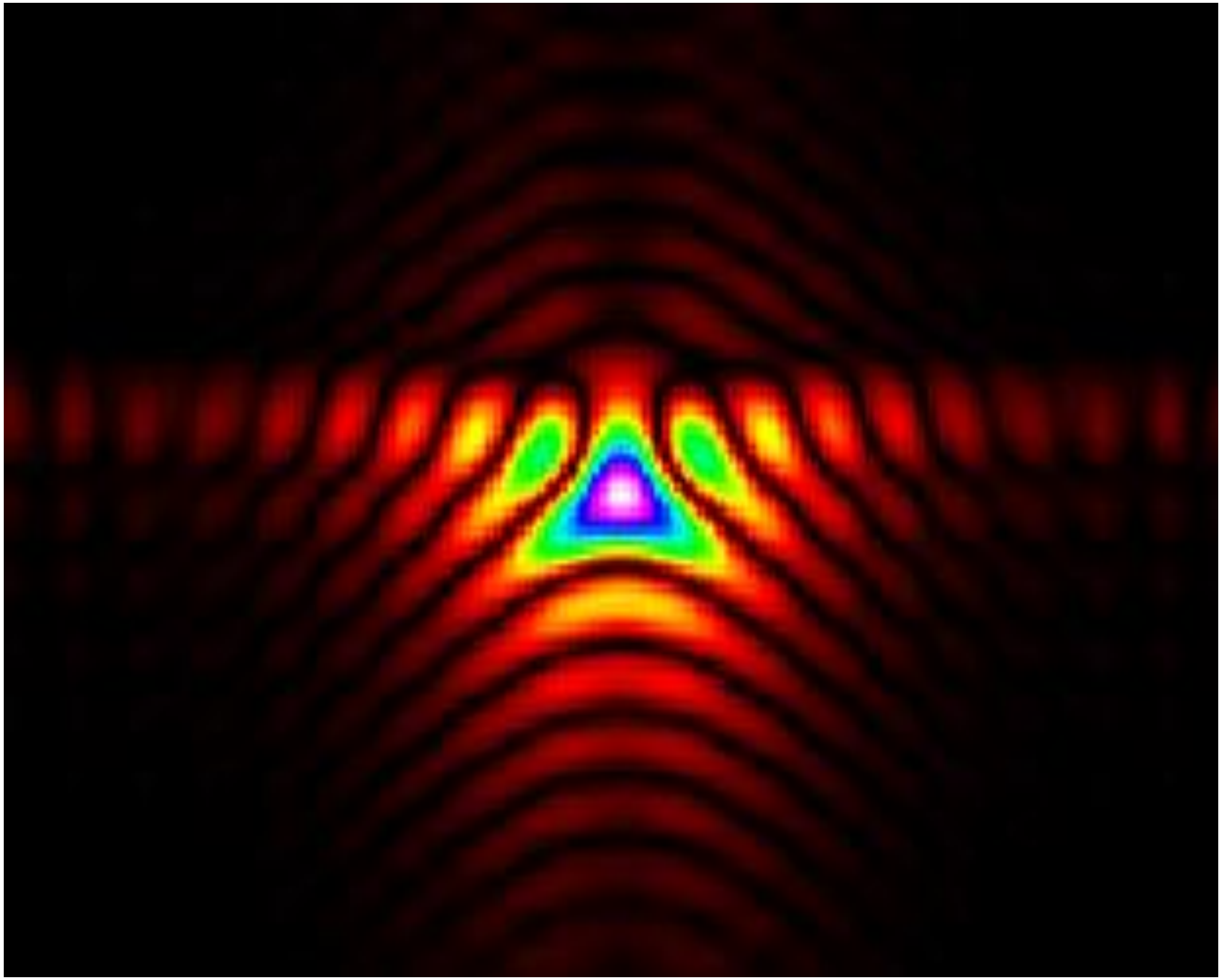
Laser Beam Diagnostic Sensors Modeled in WaveTrain



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DEPS
March 5, 2008

WaveTrain
wave optics made easy/ier

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A necessary disclaimer…

- **We are not trying to advocate a particular beam quality measurement technique.**

- **Presented here are two beam quality measures that we have implemented in WaveTrain**

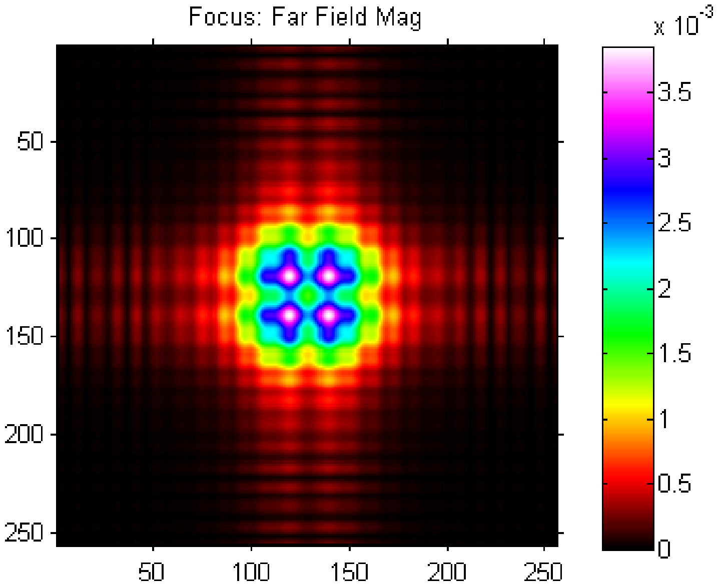
- **We intend to demonstrate WaveTrain’s flexibility while implementing two specific beam quality measures**

Beam Quality is a metric commonly used to quantify the performance of a laser system

Often thought of as "How well can this beam be focused?"

A beam with high quality will diverge much slower than a beam with low quality

DE weapons applications require high beam quality to deliver maximum power to the target



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Selection of a particular beam quality measure depends on the application requirements

Even within an established technique, variations exist on how certain parameters are computed

Metric	Parameter	Variations
M^2	Beam Width	• Width at first nulls • Variance of intensity profile • Width at 1/e or 1/e^2 intensity • D86 (86% Total Energy) • Width of fitted Gaussian • 2σ (ISO 11146 standard)
Power on Target	Mask Definition	• Rectangular or Circular • Size / Diameter

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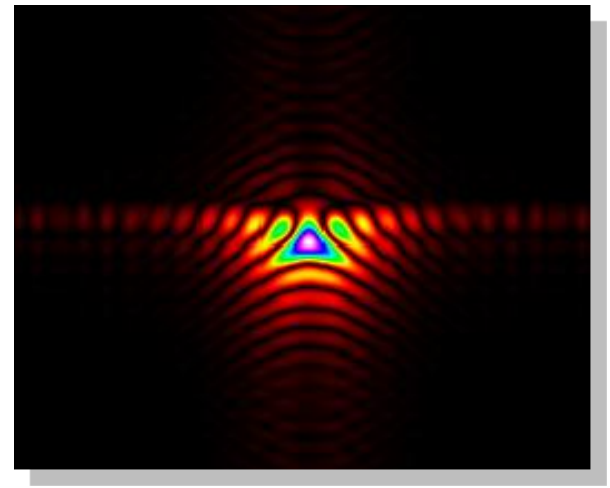
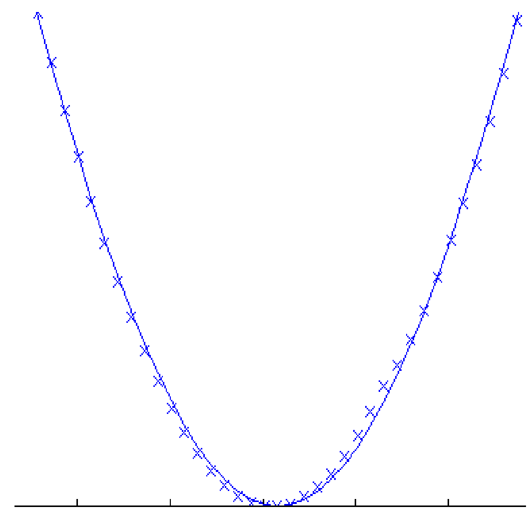
This presentation is an introduction to WaveTrain's beam quality meters



Power-on-Target Meter

- Definition & Computation
- WaveTrain Implementation

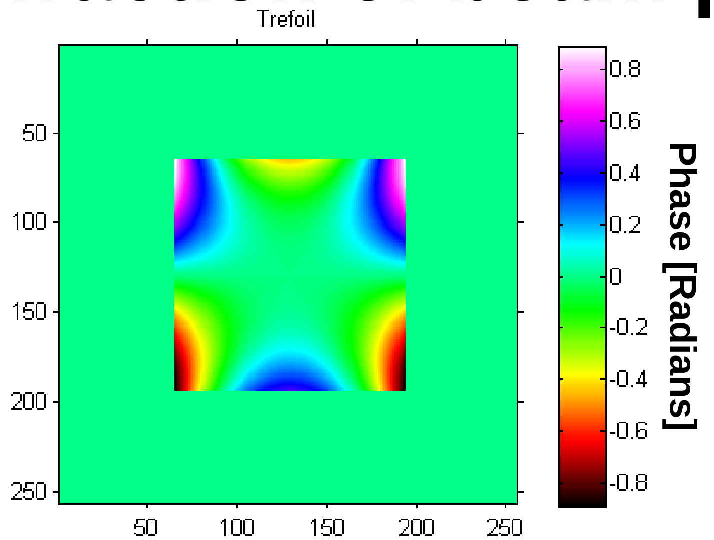


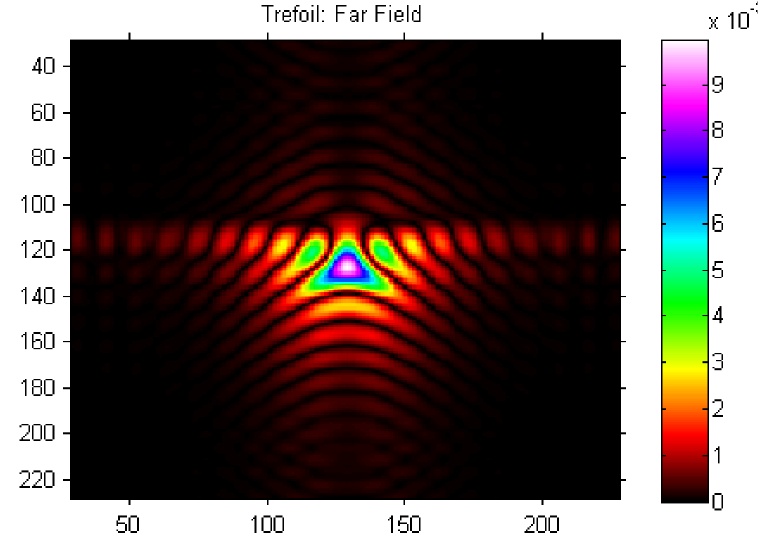
M-squared Beam Quality

- Definition & Computation
- WaveTrain Implementation

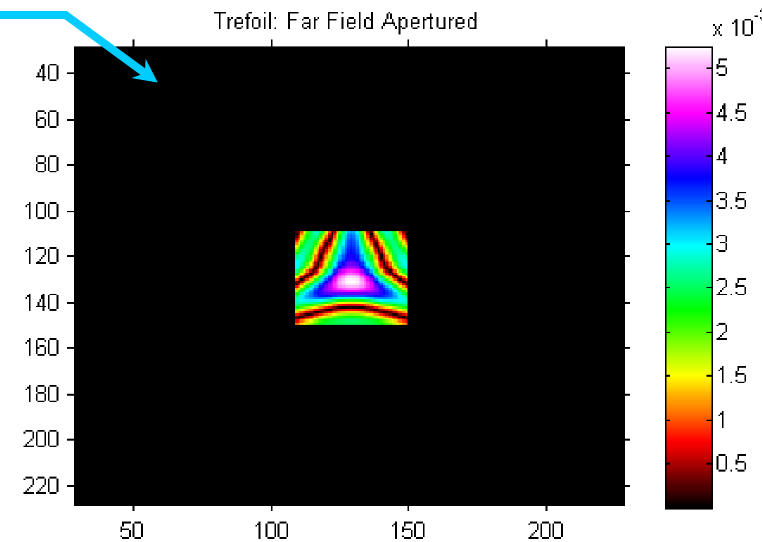
Power on Target Meter

Power on target can be defined in terms of the fraction of beam power in a region





Far Field Mask



$$BQ = \frac{P_{\mathrm{Target}}}{P_{\mathrm{Total}}}$$

P_{Target} : Power in masked far field

P_{Total} : Total Power

The mask opening can be defined in terms of the diffraction limited spot size

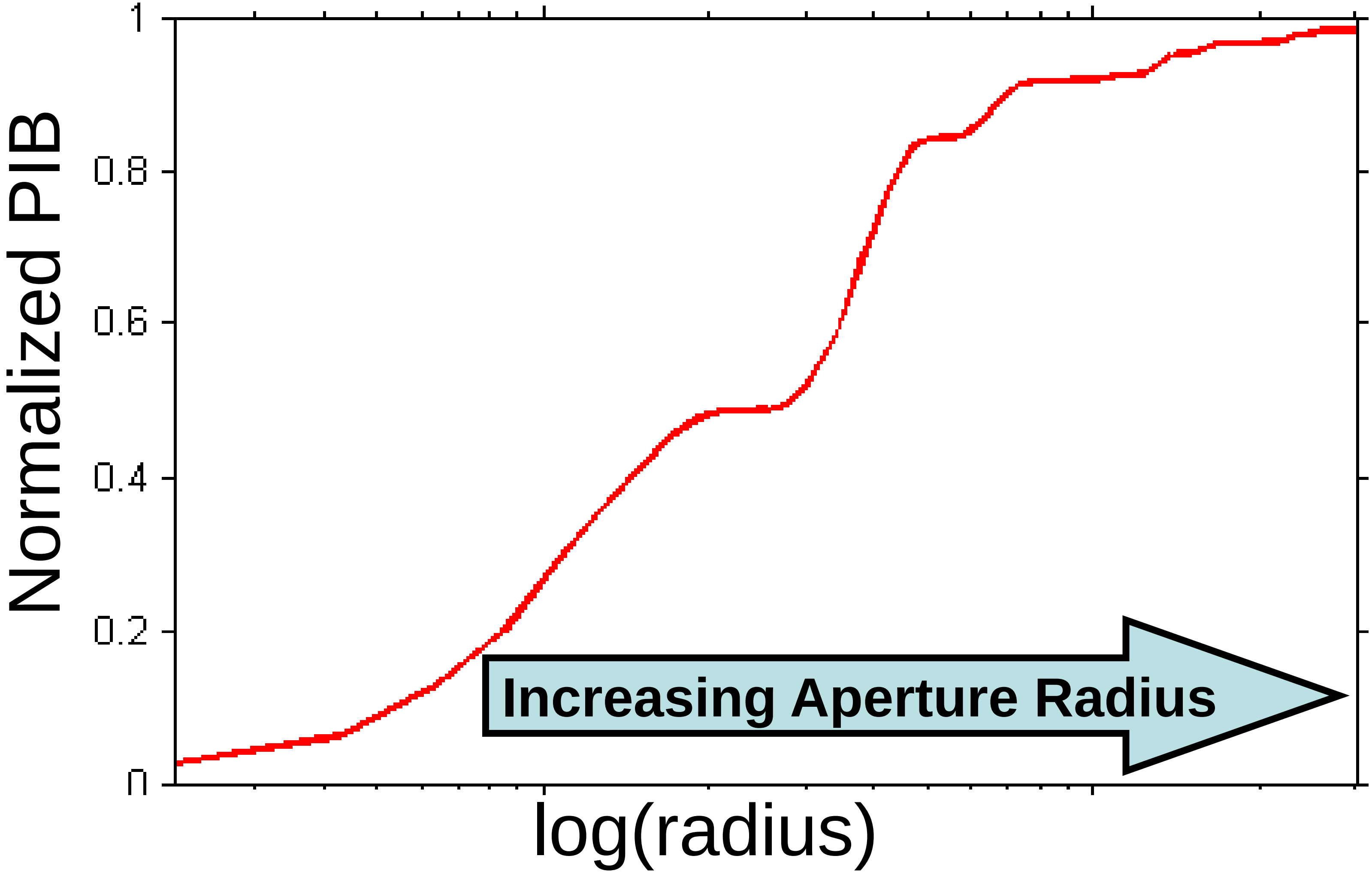
Circular Mask

$$D_{DL} = \frac{2.44 f\lambda}{d}$$

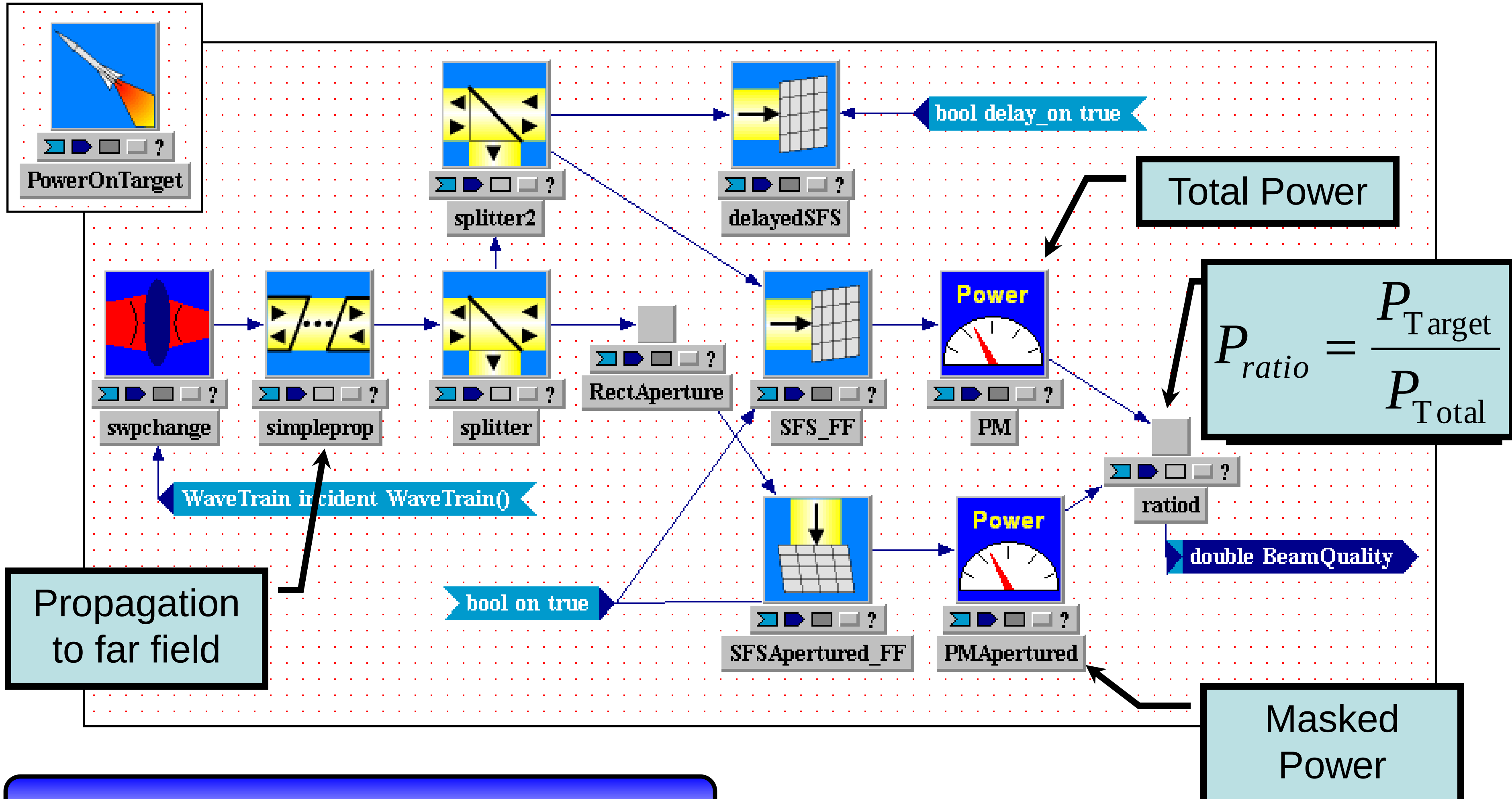
Rectangular Mask

$$D_{DL} = \frac{2.0 f\lambda}{d}$$

A power-in-the-bucket plot can be generated by varying the mask diameter

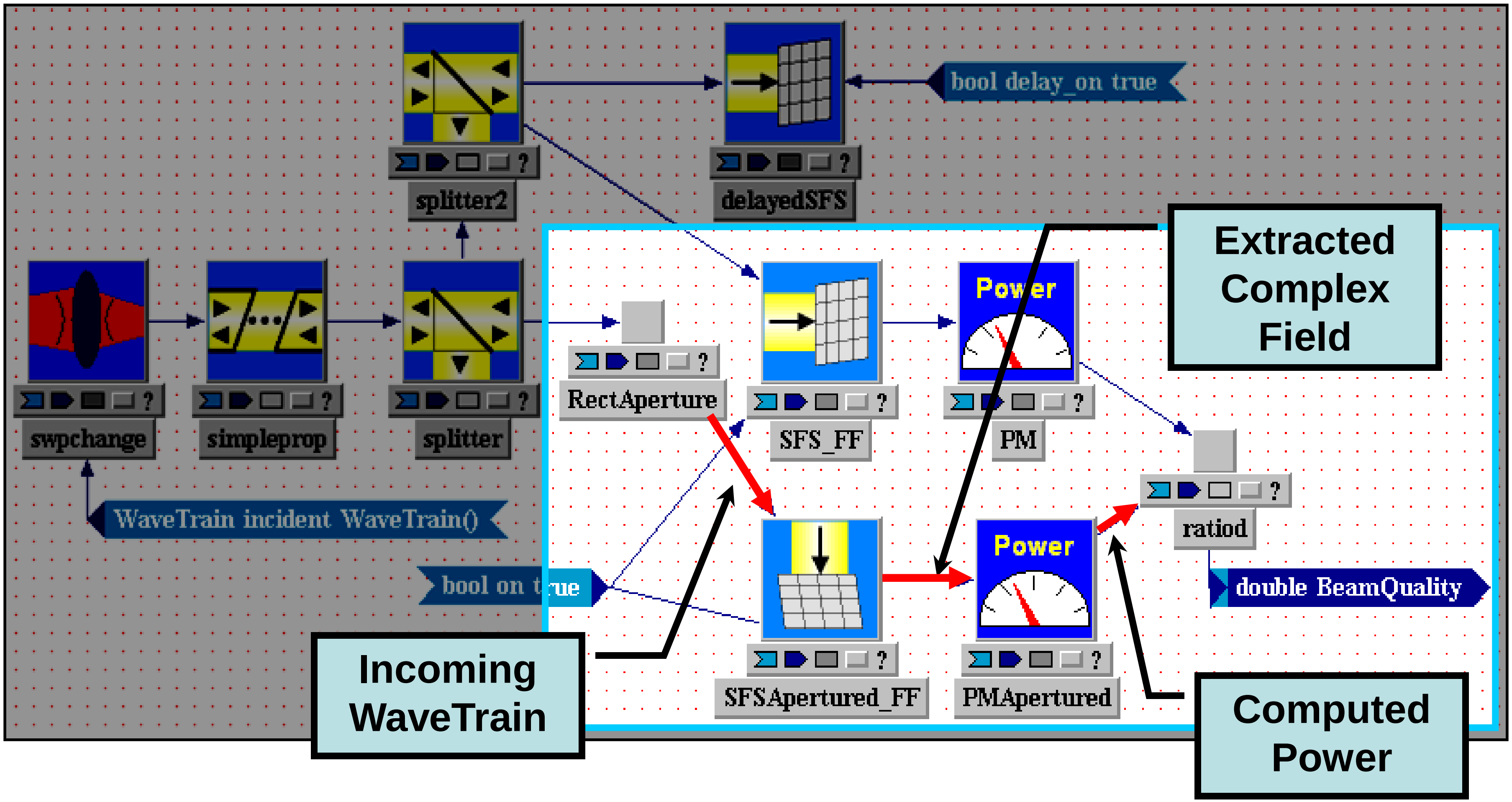


WaveTrain's Power-on-Target Meter was implemented with existing subsystems



WaveTrain Implementation

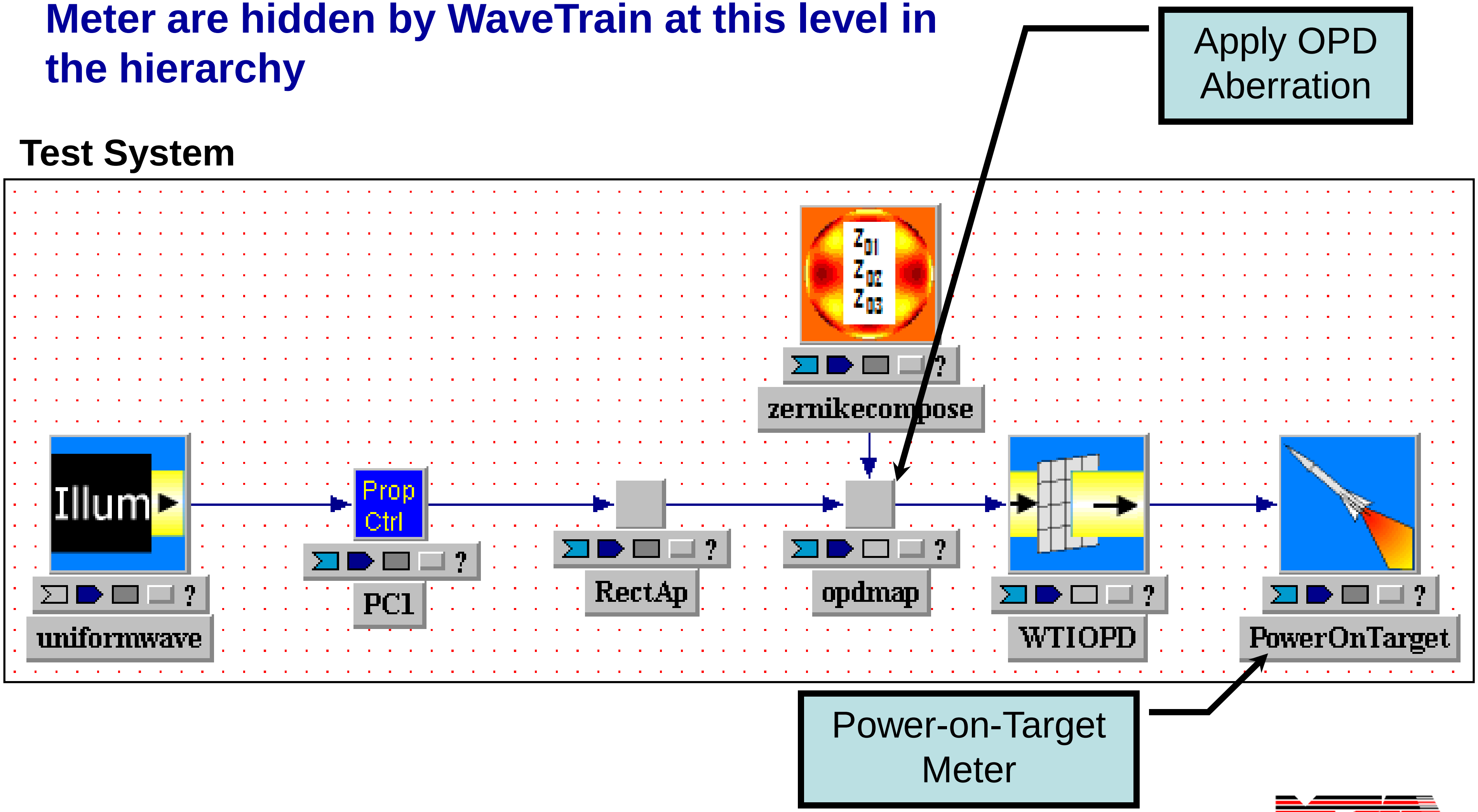
The WaveTrain PowerMeter and SimpleFieldSensor work together to compute the power of a WaveTrain



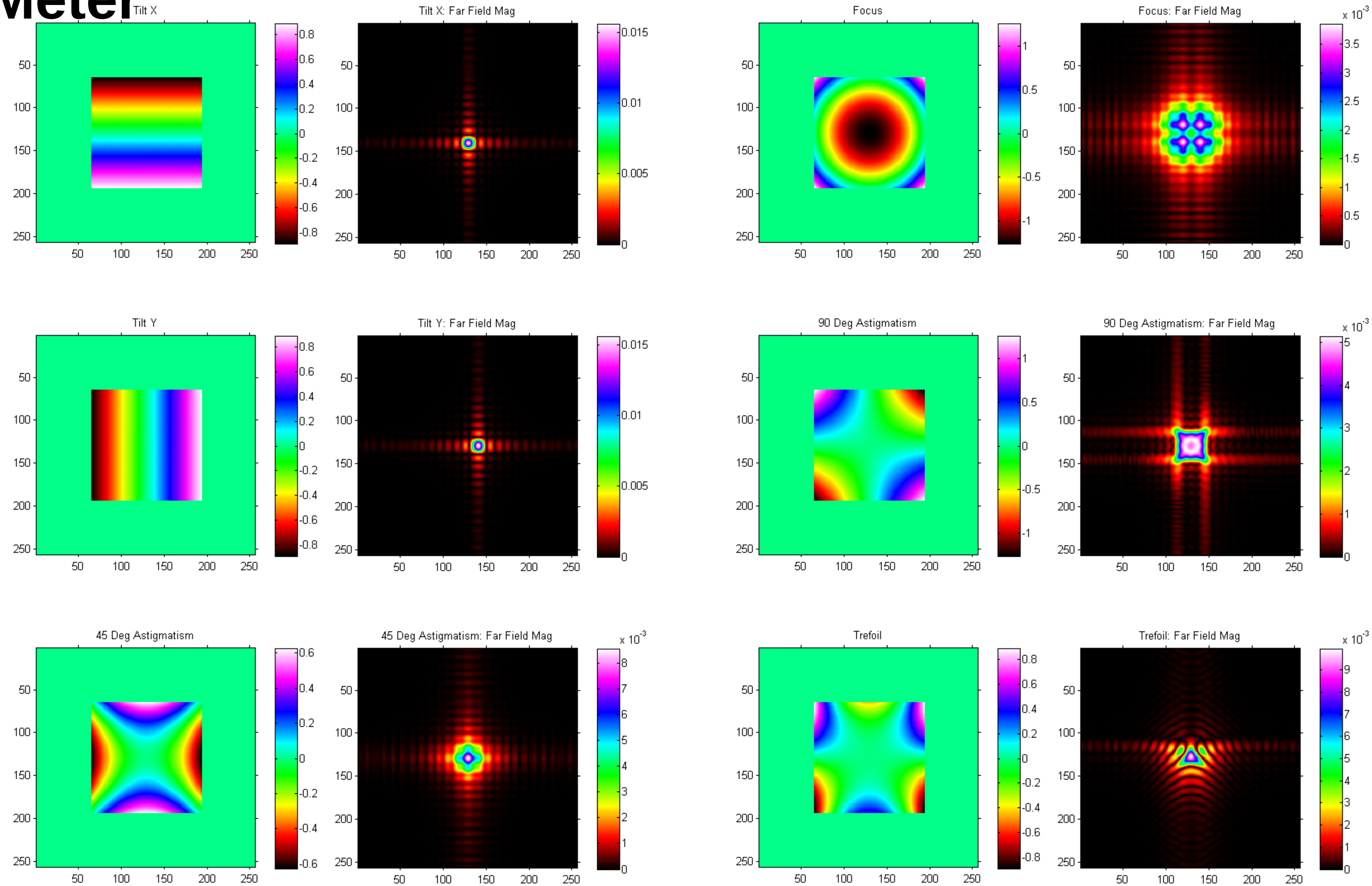
Any WaveTrain simulation can use the Power-on-Target Meter

Implementation details of the Power-on-Target Meter are hidden by WaveTrain at this level in the hierarchy

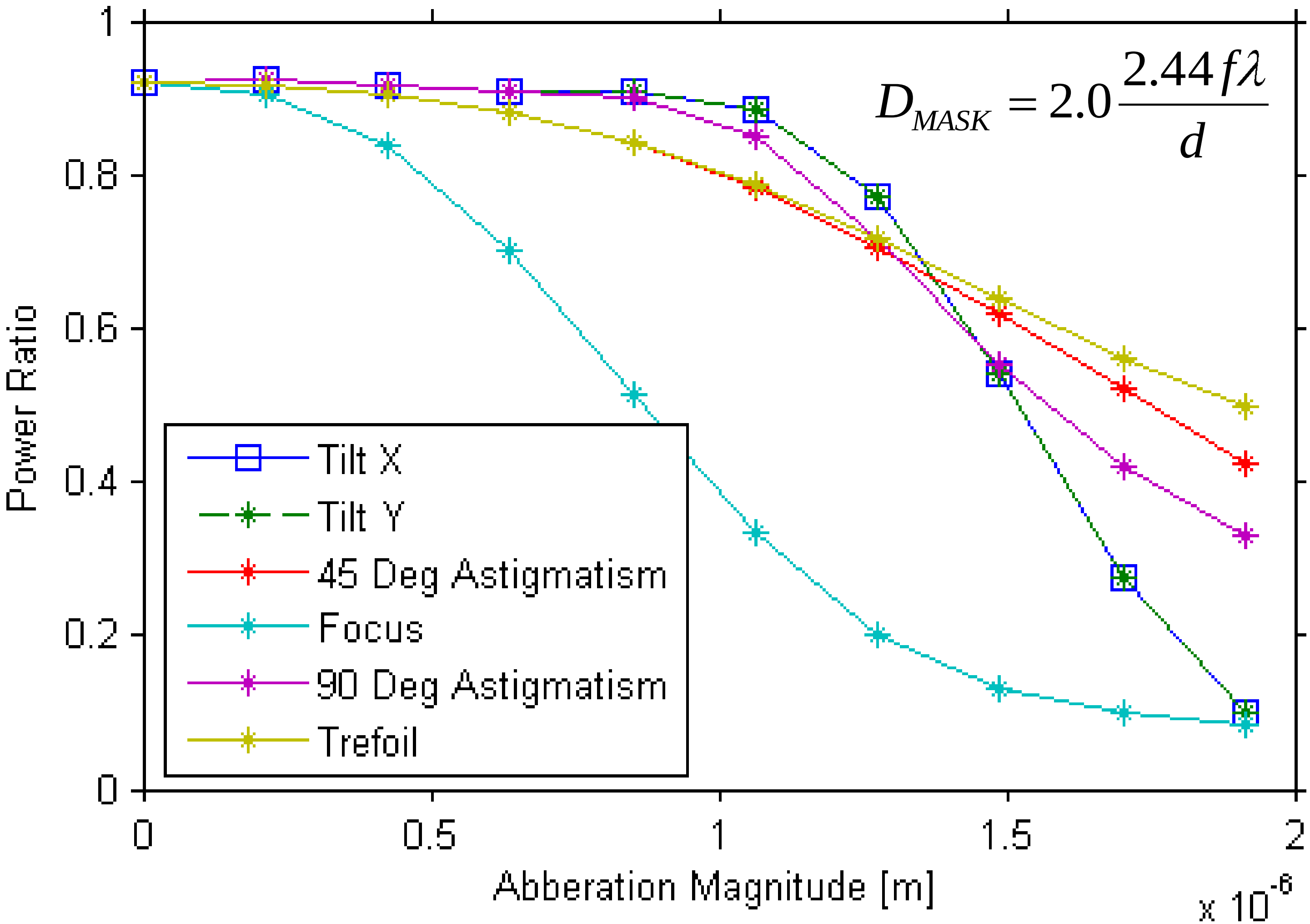
Test System



Aberrations applied to field to test Power-On-Target Meter



TDL beam quality decreases with increasing aberration magnitude



$$D_{MASK} = 2.0\frac{2.44 f\lambda}{d}$$

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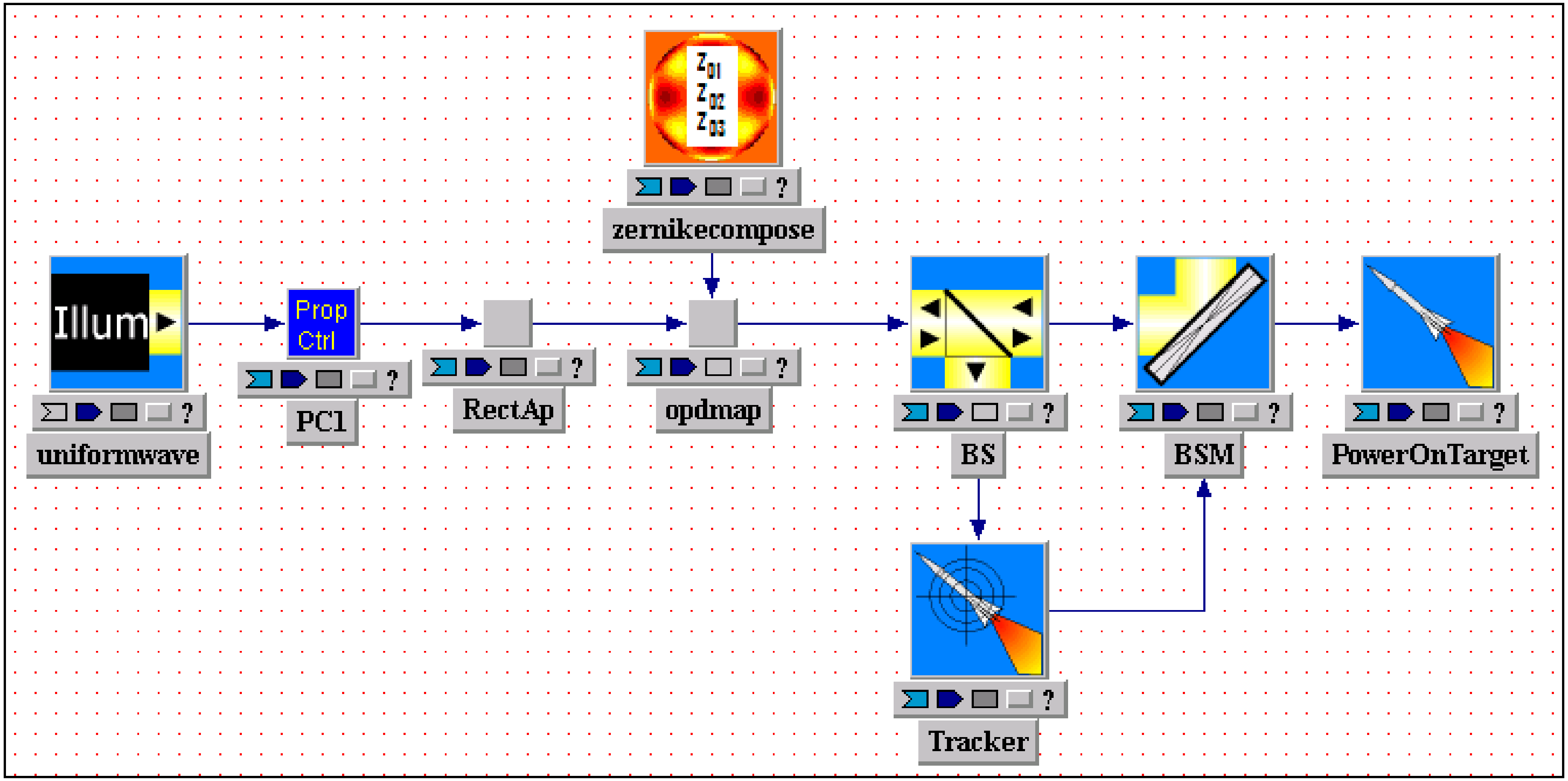
The effect of tilt can be removed with a tracking loop



M-squared Beam Quality Meter

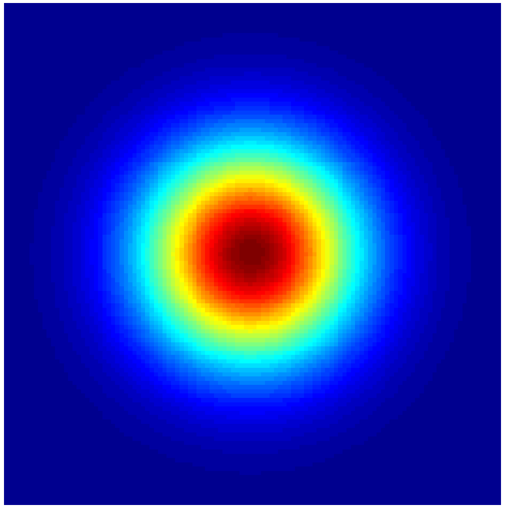
M-squared is a commonly employed measure of beam quality

M^2 was developed by Tony Siegman and Steve Townsend as a method of characterizing laser beams

M^2 describes a beam in terms of its deviation from its fundamental TEM_{00} mode (Gaussian)

A standard method for computing M^2 is defined in ISO 11146

$M^2 = 1.0$



ISO standard 11146 defines beam width in terms of the beam second moment

Second Central Moment

$$\sigma_x^2 = \frac{\iint (x - x_0)^2 I(x,y)\,dx\,dy}{\iint I(x,y)\,dx\,dy}$$

$$\sigma_y^2 = \frac{\iint (y - y_0)^2 I(x,y)\,dx\,dy}{\iint I(x,y)\,dx\,dy}$$

where

$(x_0, y_0) =$ Beam Center

$I(x,y) =$ Irradiance Profile

Beam Width

$$w_x \equiv 2\sigma_x$$

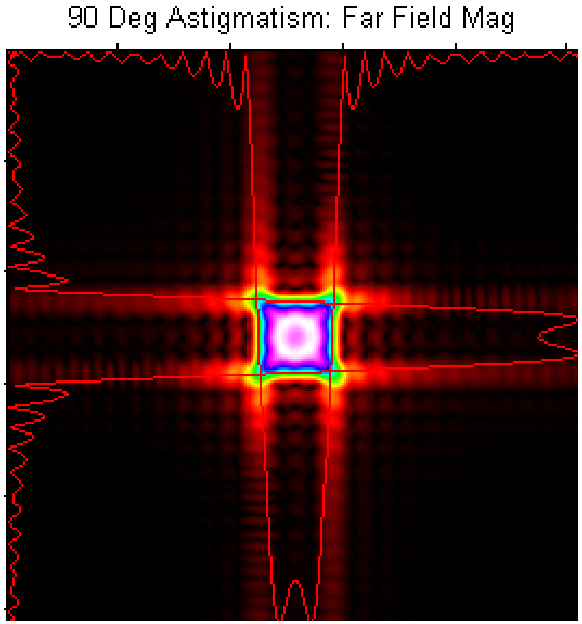
$$w_y \equiv 2\sigma_y$$

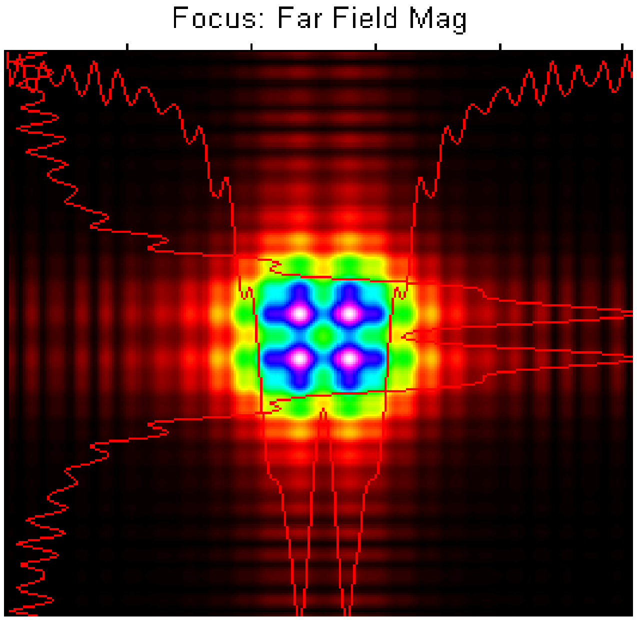
The beam center (x_0,y_0) is the first moment of the beam (centroid)

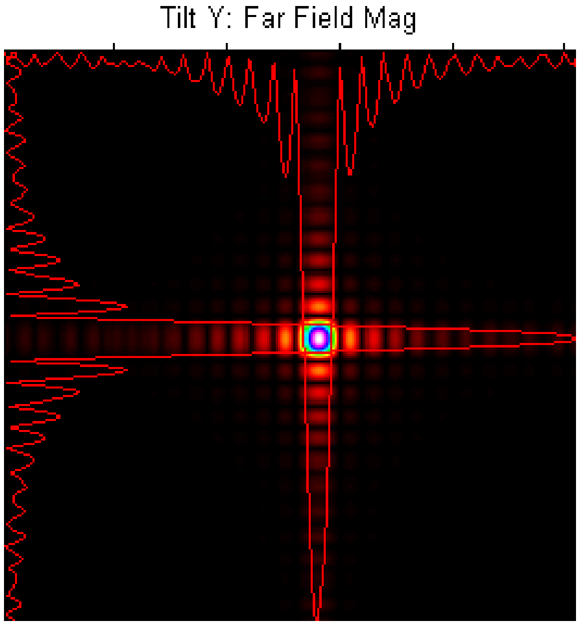
Defining beam width measure is very important

Beam Width

- Width at first nulls
- Variance of intensity profile
- Width at 1/*e* or 1/*e*^{2} intensity
- D86 (86% Total Energy)
- Width of fitted Gaussian
- 2σ (ISO 11146 standard)







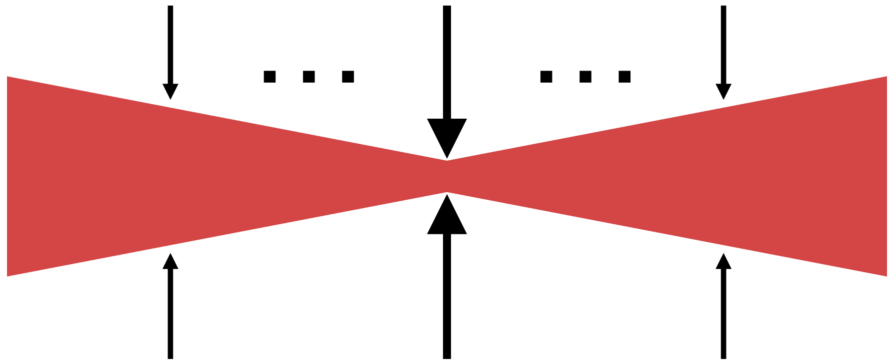
Top level description of M-squared algorithm

1. Measure the width of the beam near the beam waist in several locations to estimate the waist location.

2. Measure the beam width at several locations further away from the waist to characterize the divergence of the beam.

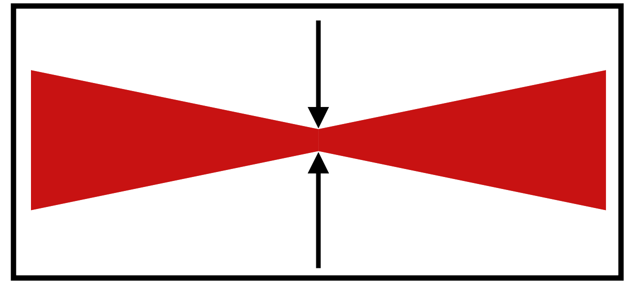
3. Fit the resulting measurements with a quadratic.

4. Extract beam quality from fitted coefficients



M-squared algorithm

1 Find the approximate location of the beam waist

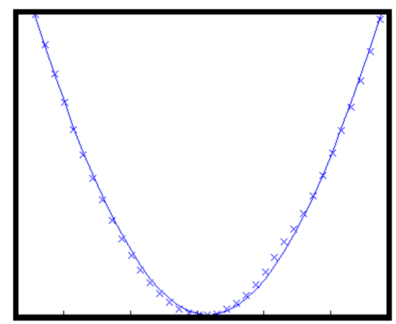


2 Propagate to N points distributed evenly around the beam waist location and measure the beam width at each point

$$w_x \equiv 2\sigma_x$$

$$w_y \equiv 2\sigma_y$$

3 Fit the resulting beam width measurements to a parabola and extract the beam quality



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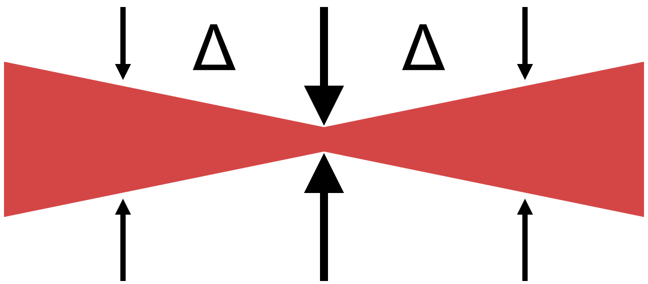
Step 1

Find the approximate location of the beam waist



$$\Delta = 0.1\frac{\pi \overline{w}^2}{\lambda}$$

$$\overline{w} = \frac{w_x + w_y}{2}$$

Propagate Δ on either side of current beam location

↓

Fit the average beam size squared versus propagation distance to a parabola and find the minimum

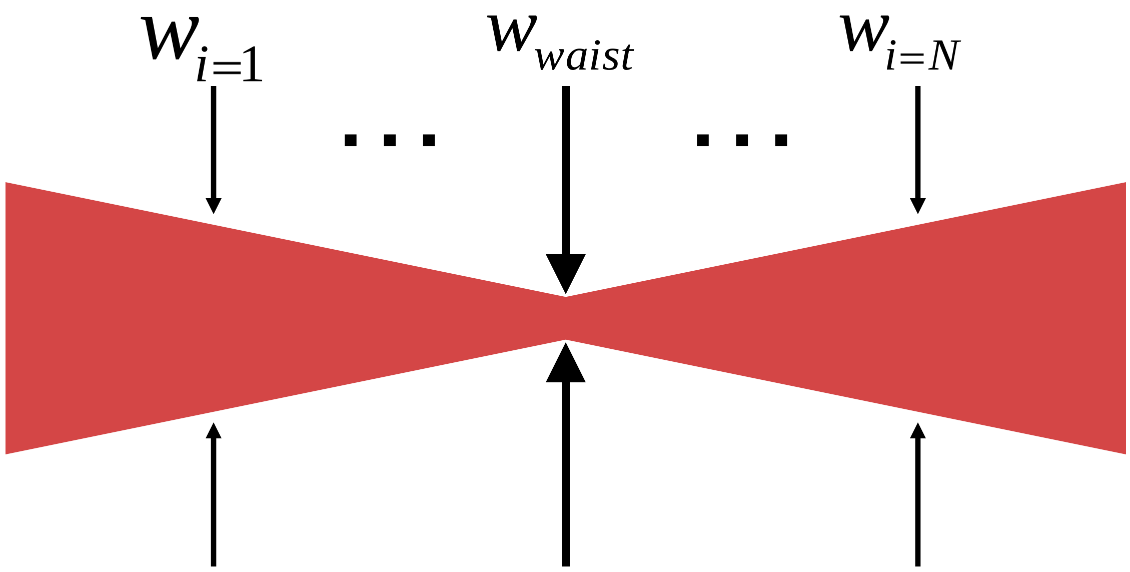
↓

Repeat M times to approximate beam waist location

Step 2

Propagate to N points distributed evenly around the beam waist location and measure the beam width at each point

This step is characterizing the beam divergence



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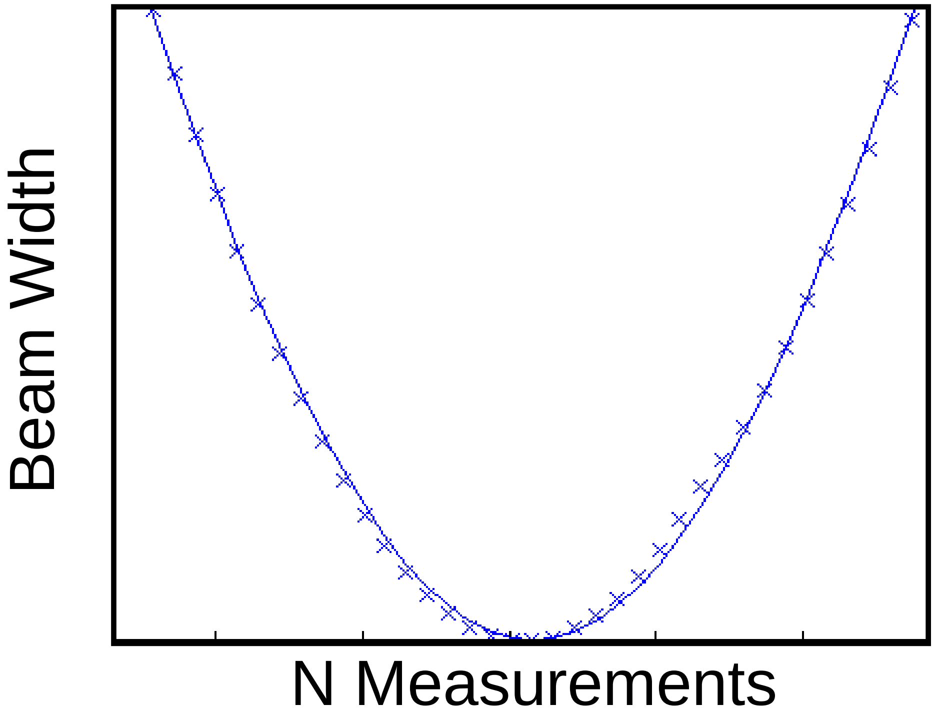
Step 3

Fit the resulting beam width measurements to a parabola and extract the beam quality



$$f(x) = ax^2 + bx + c$$

Find a least squares solution for (a, b, c) using SVD

Step 3

Fit the resulting beam width measurements to a parabola and extract the beam quality

$$w^2 = w_0^2 + \left(\frac{M^2\lambda}{\pi w_0}\right)^2 (z - z_0)^2$$

Equation relating beam waist width/location, and M-squared

$$w^2 = \left(\frac{M^2\lambda}{\pi w_0}\right)^2 z^2 + \left(-2z_0\left(\frac{M^2\lambda}{\pi w_0}\right)^2\right) z + \left(\left(\frac{M^2\lambda}{\pi w_0}\right)^2 z_0^2 + w_0^2\right)$$

$$a = \left(\frac{M^2\lambda}{\pi w_0}\right)^2, b = \left(-2z_0\left(\frac{M^2\lambda}{\pi w_0}\right)^2\right), c = \left(\left(\frac{M^2\lambda}{\pi w_0}\right)^2 z_0^2 + w_0^2\right)$$

$$\Bigg\} \; ax^2 + bx + c$$

$$z_0 = \frac{-b}{2a}, w_0 = \sqrt{c - \frac{b^2}{4a}}, M^2 = \frac{\pi}{2\lambda}\sqrt{4ac - b^2}$$

Solve for beam waist width/location and M-squared in terms of a, b, and c

z_0 = location of beam waist

w_0 = beam width at beam waist

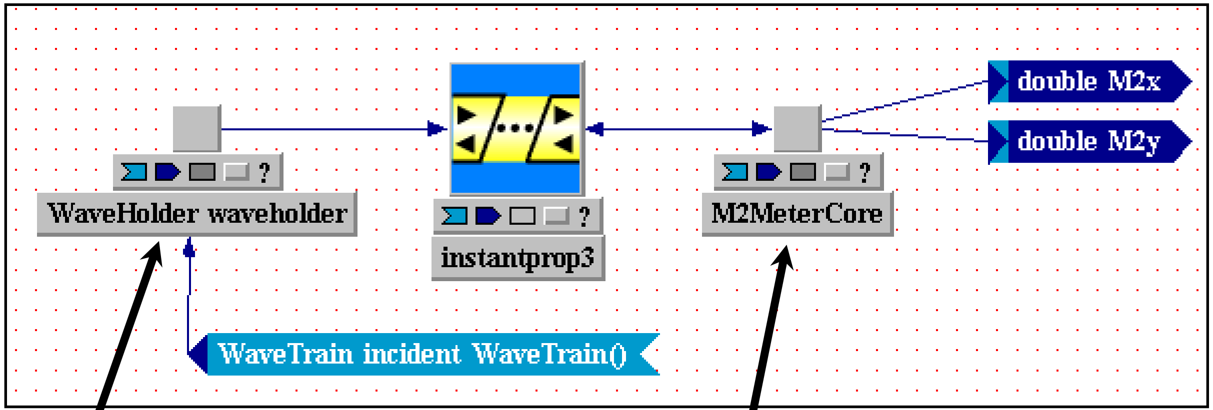
M^2 = beam quality

A. E. Siegman, *"How to (Maybe) Measure Laser Beam Quality," Tutorial presentation at the Optical Society of America Annual Meeting, Long Beach, California, October 1997.*

The core functionality of the WaveTrain M-squared meter is implemented as a C++ class, M2MeterCore

WaveTrain has a highly extensible architecture.

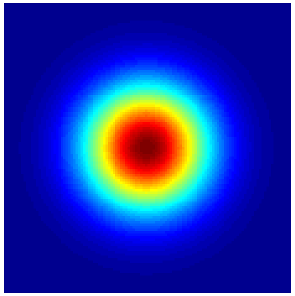
SVD least squares matrix inversion accomplished using Boost C++ Library

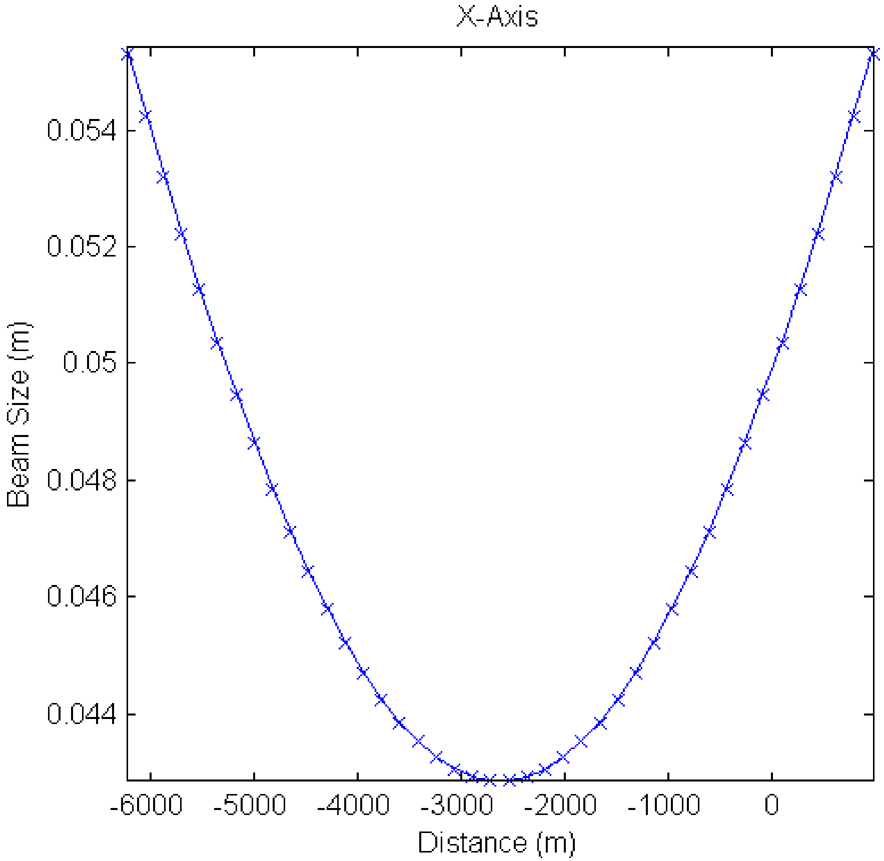


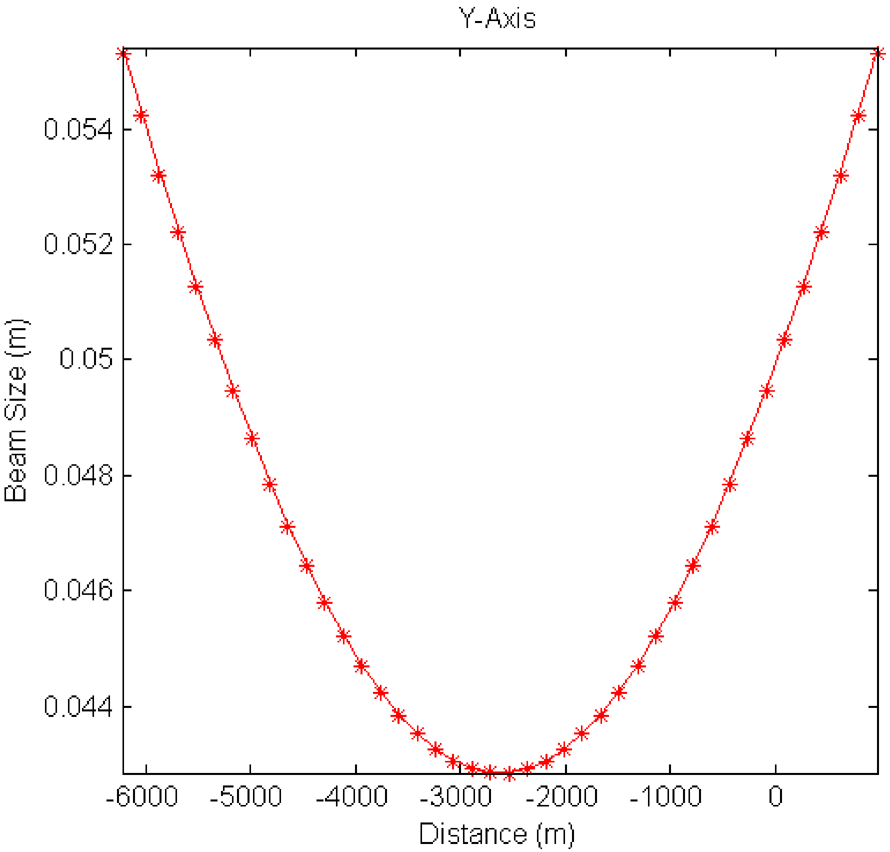
Stores state of WaveTrain to prevent computation of multiple propagations

M-squared computation in a custom atomic WaveTrain component

Gaussian Beam Test

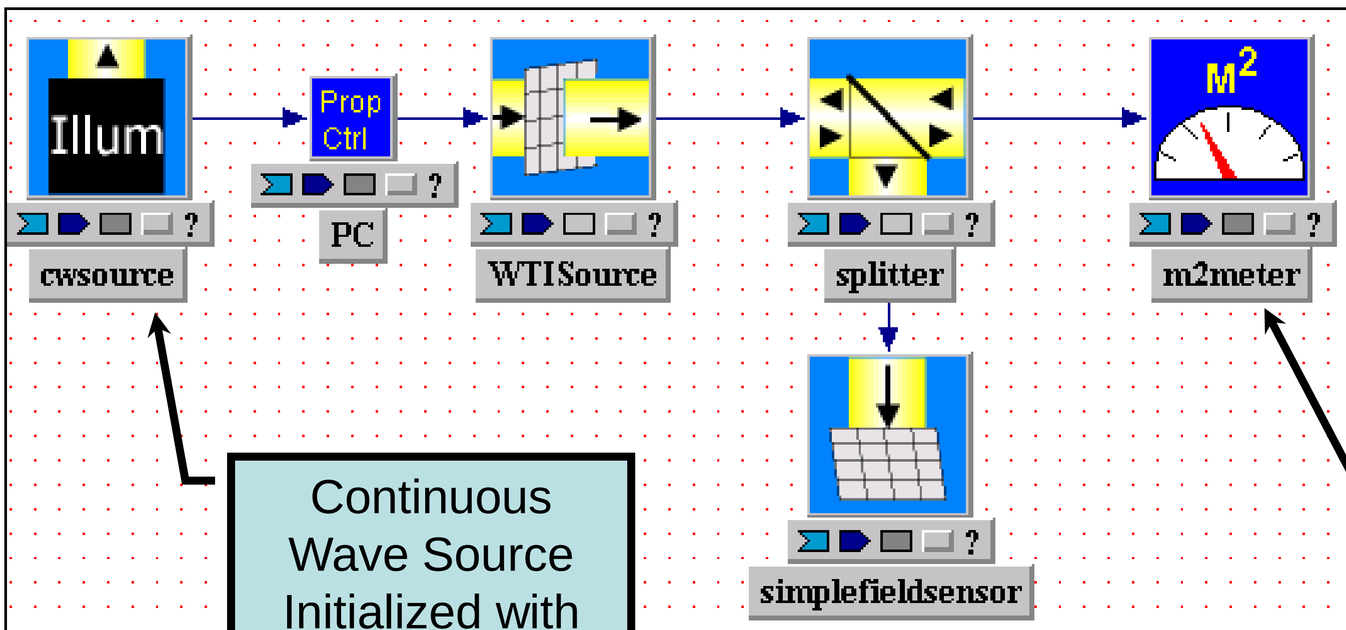


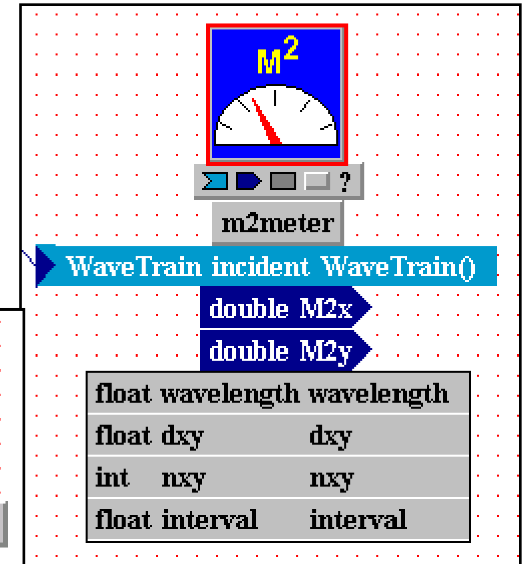




M^2=(1,1) z0=(-2627.27,-2627.27) w0=(0.0428461,0.0428461)

Any WaveTrain simulation can use the M^2 beam quality meter





Continuous Wave Source Initialized with Matlab Data File

M-squared Beam Quality Meter

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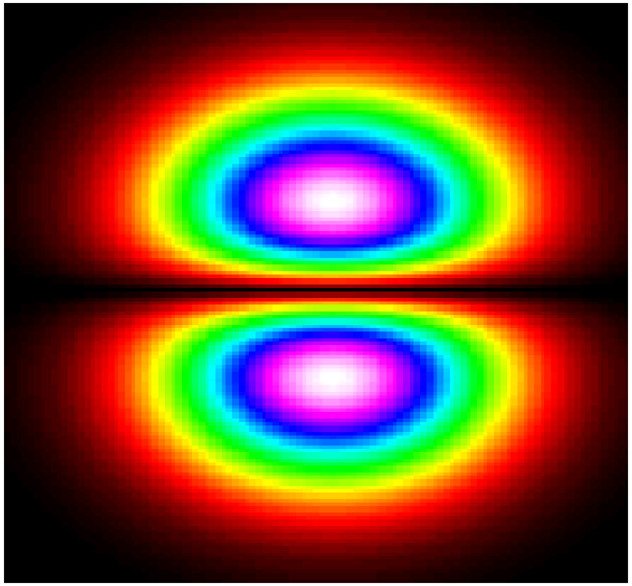
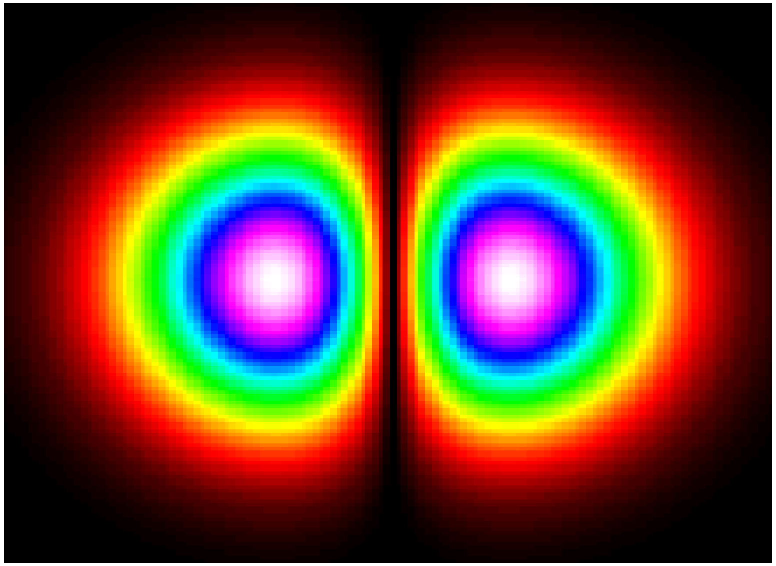
Define source beam shape in terms of Hermite-Gaussian Modes to test M-squared BQ Meter



TEM_{01}



TEM_{10}

The effect of the Hermite-Gaussian modes on M-squared beam quality is easily computed

M-squared values for Hermite-Gaussian modes increase according to the following equations

$$M_X^2 = 2n + 1$$

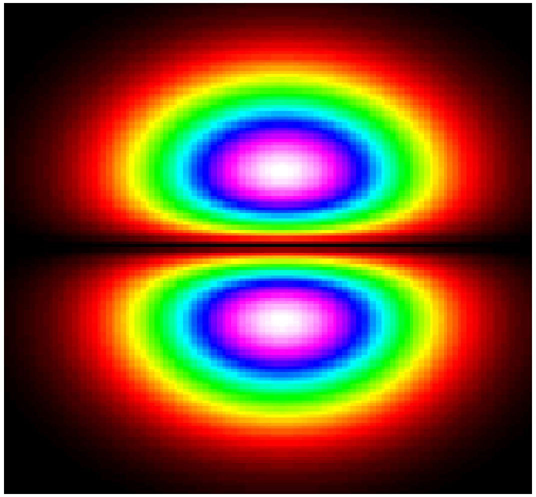
$$M_Y^2 = 2m + 1$$

$$TEM_{nm}$$

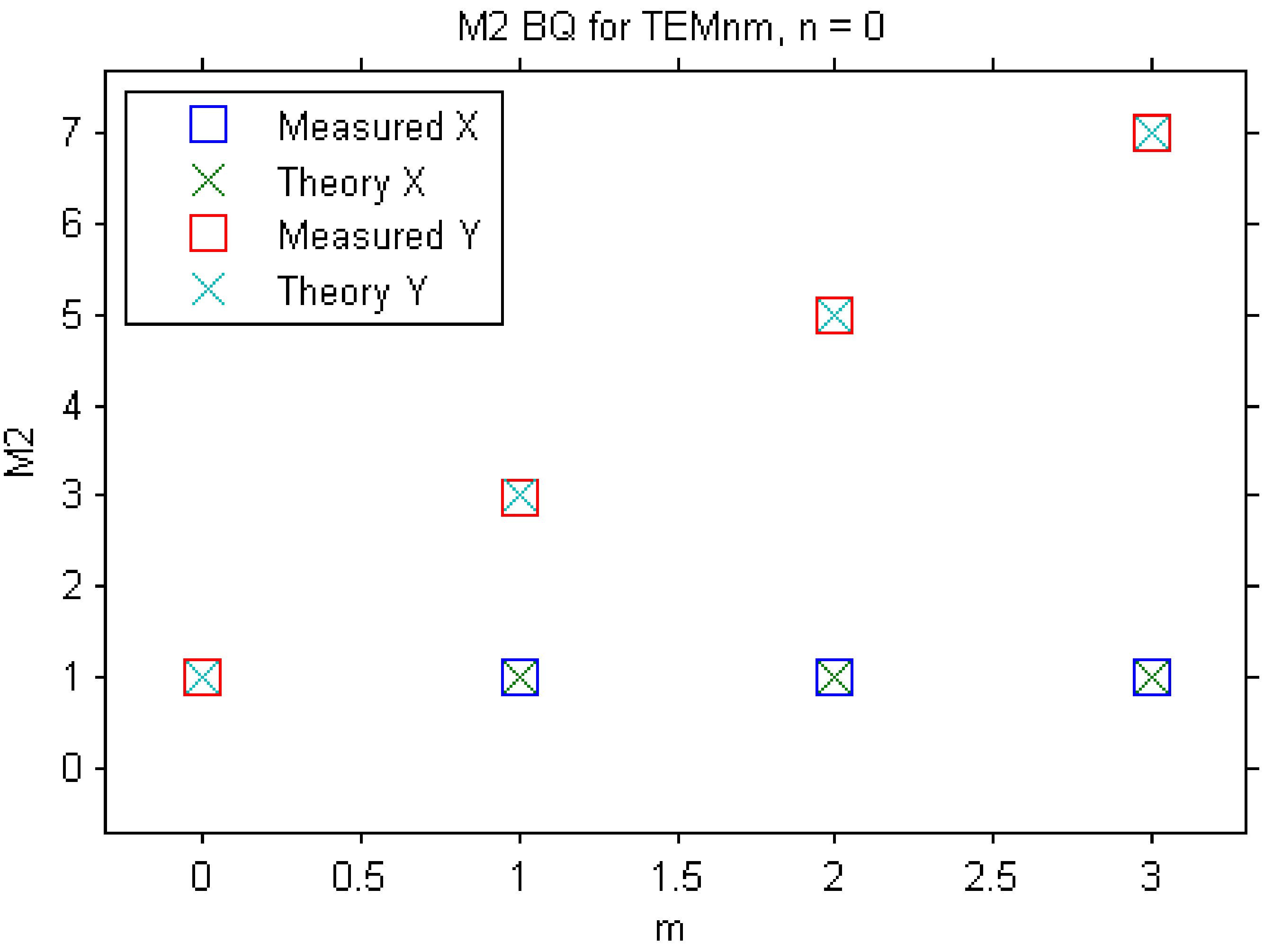
Using these equations, we can predict the values of M-squared in the x and y directions for any Hermite-Gaussian mode

A. E. Siegman, Steven W. Townsend, "Output Beam Propagation and Beam Quality from a Multimode Stable-Cavity Laser," IEEE JOURNAL OF QUANTUM ELECTRONICS. VOL. 29. NO. 4. APRIL 1993

M-Squared Beam Quality for TEM_{0m}



n = 0, m = 1



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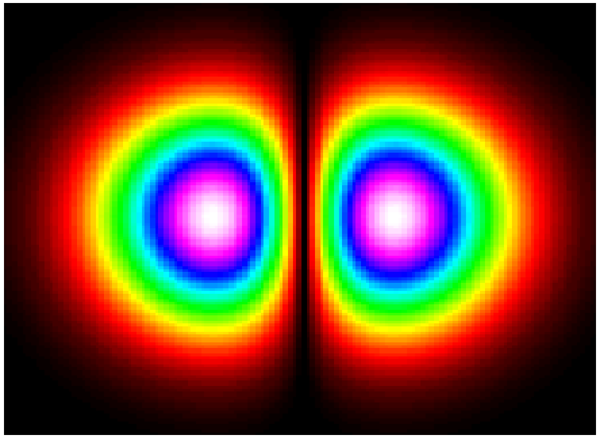
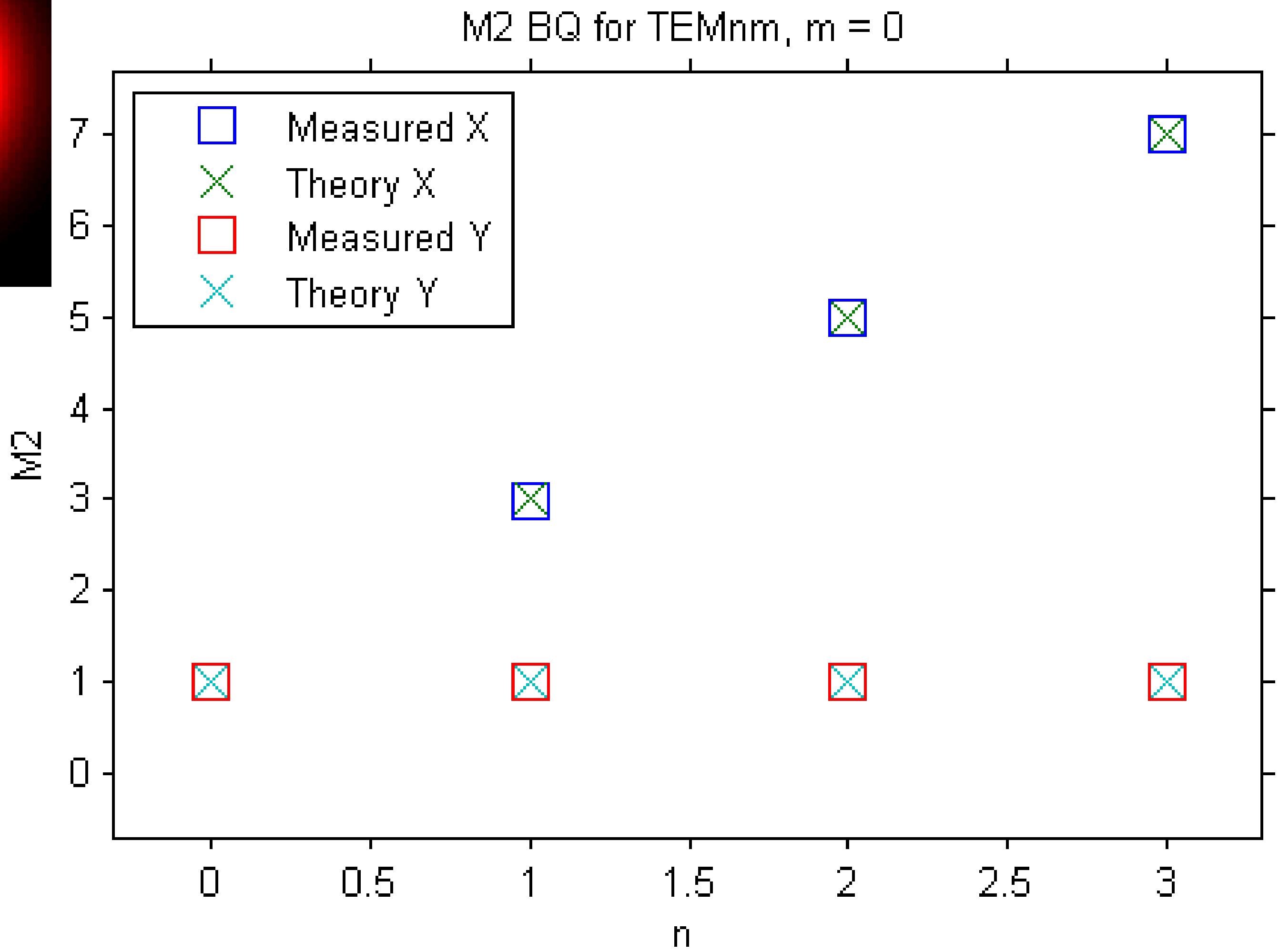
M-Squared Beam Quality for TEM_{0m}



n = 1, m = 0



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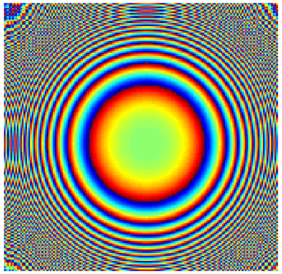
Future Work

- Continue anchoring efforts
- Evaluate performance with more complex laser resonator models

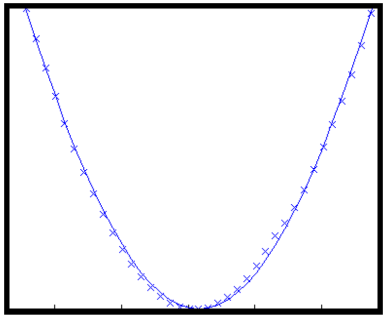
Acknowledgements

- **Funding for this work**
  - LADERA Contract from AFRL
- **Special Thanks**
  - Morris Maynard (MZA)
  - Robert Praus (MZA)

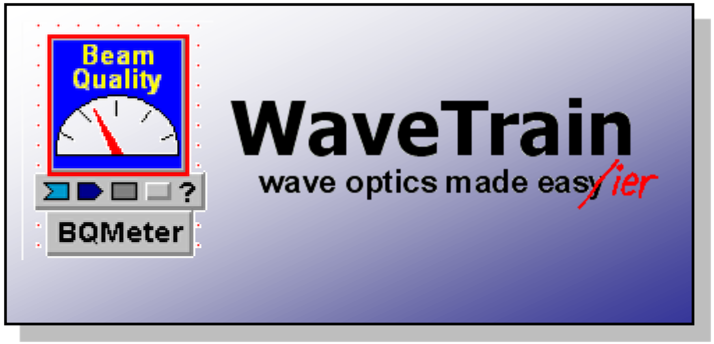
Conclusions

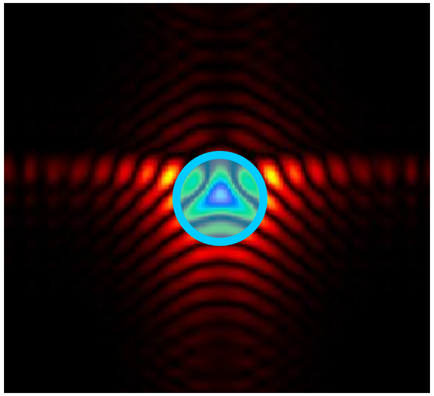


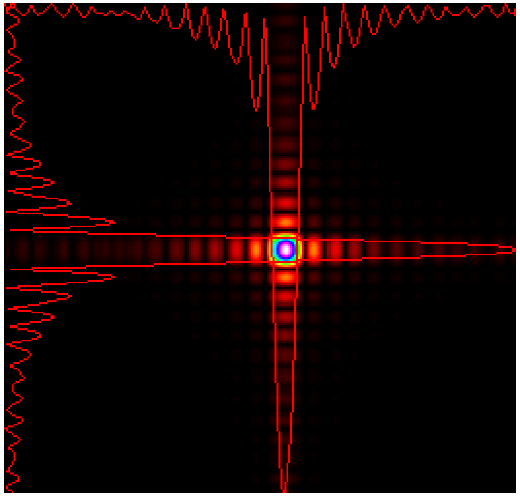
Never assume that different beam quality values are comparable unless the measurement method is well defined



WaveTrain's flexible architecture allows the designer to choose an appropriate beam quality metric







Questions?

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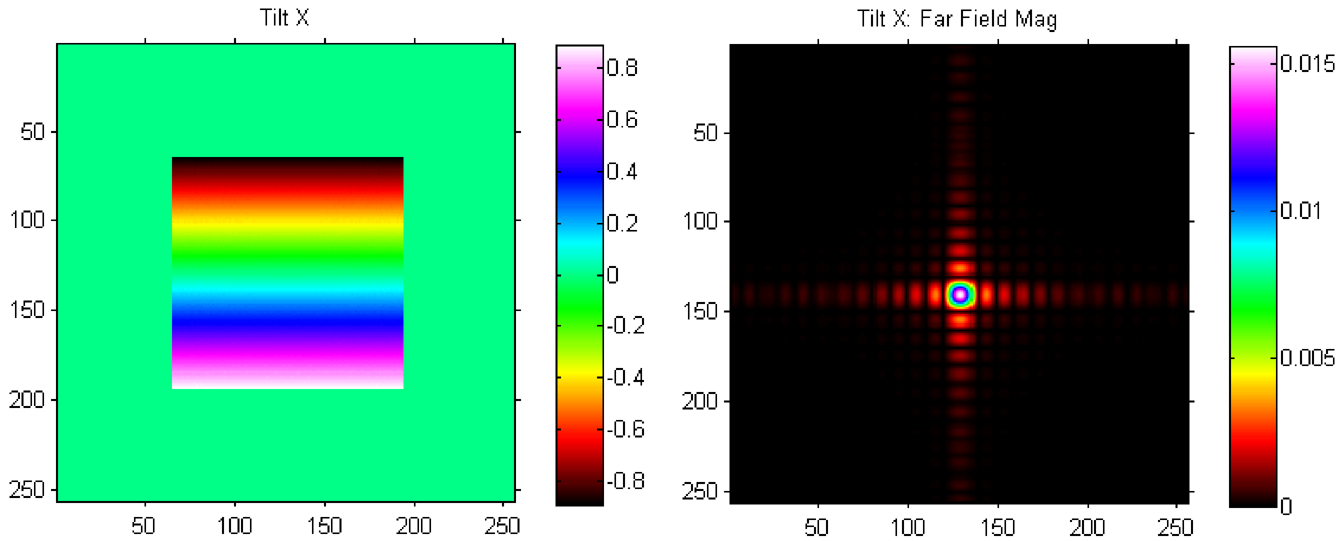
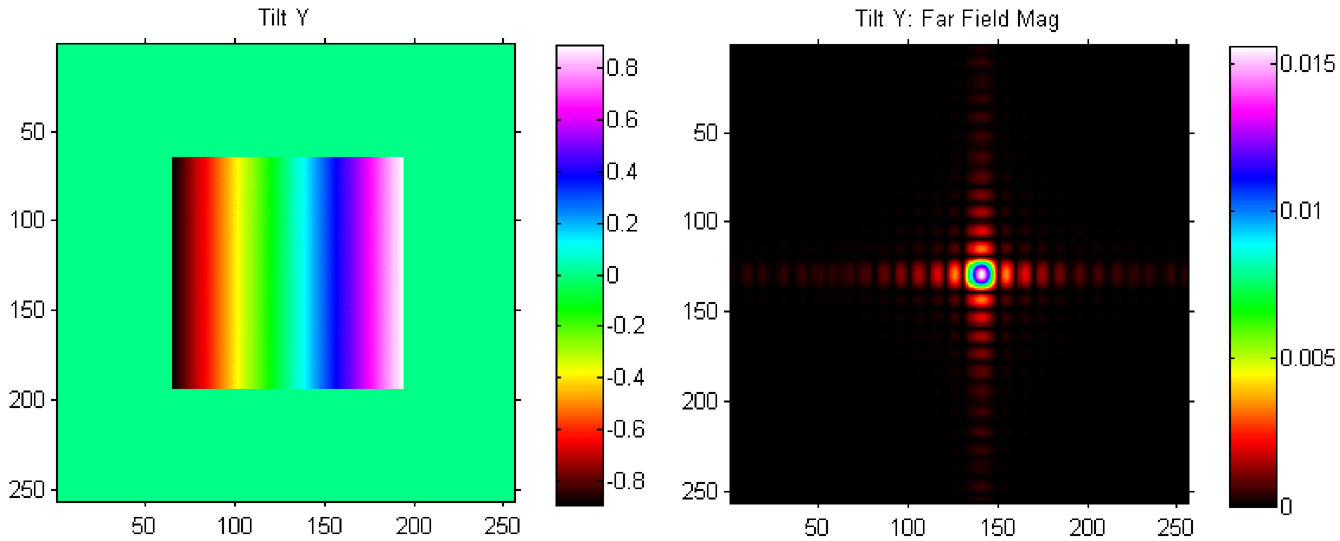
Backup Slides

Tilt X



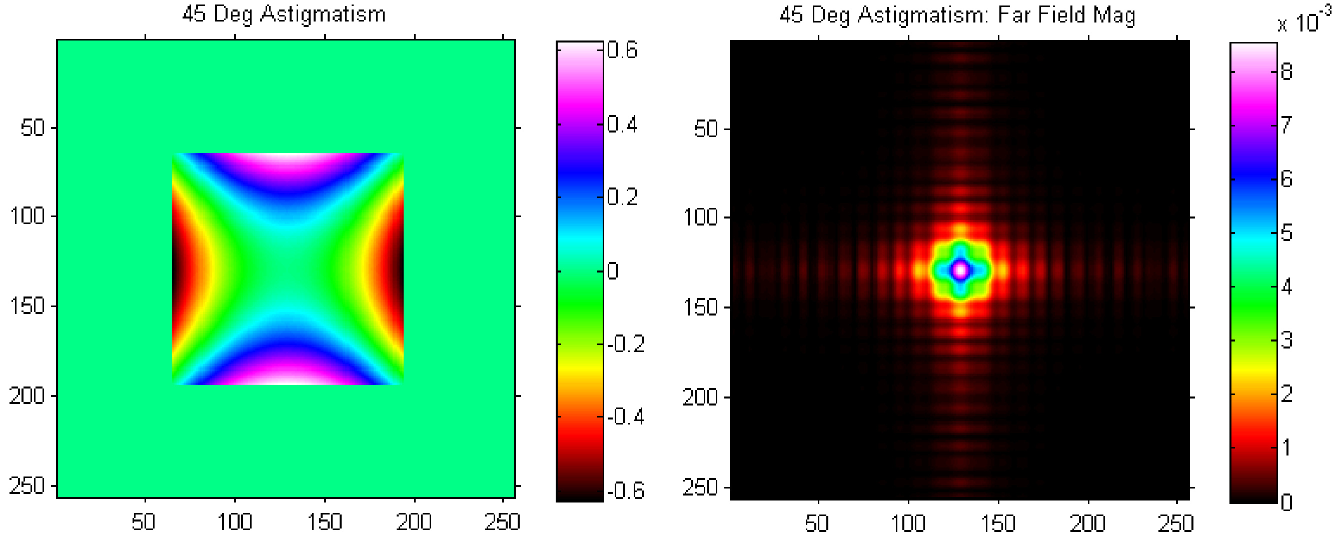
Tilt X
50
100
150
200
250
50
100
150
200
250
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Tilt X: Far Field Mag
50
100
150
200
250
50
100
150
200
250
0.015
0.01
0.005
0

Tilt Y

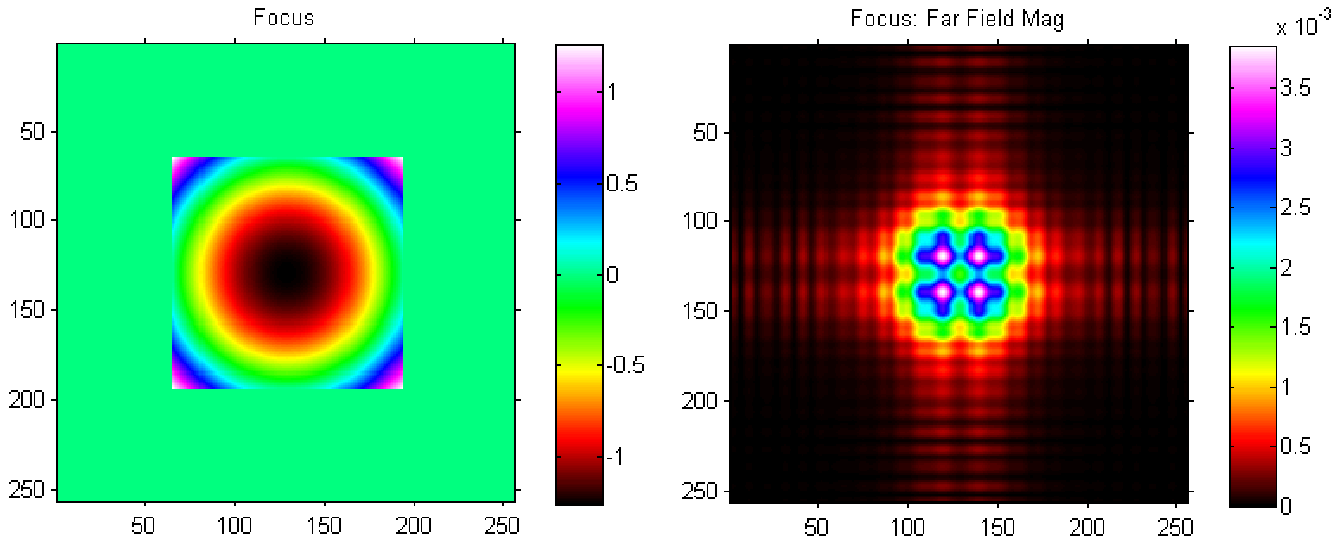


Tilt Y
50
100
150
200
250
50
100
150
200
250
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Tilt Y: Far Field Mag
50
100
150
200
250
50
100
150
200
250
0.015
0.01
0.005
0

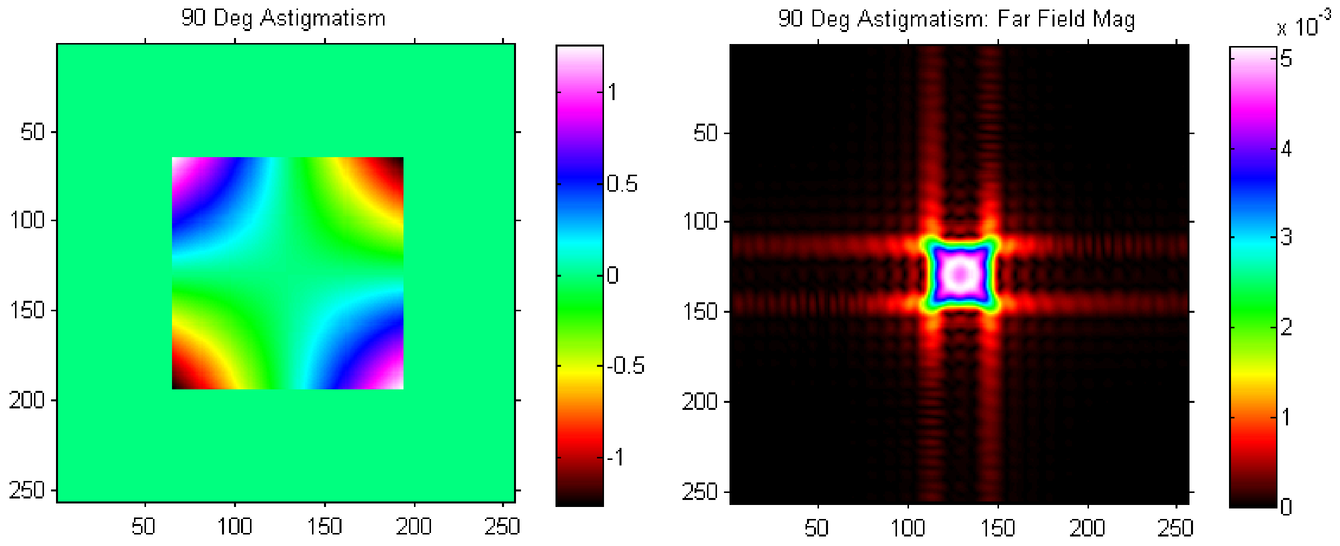
45 Deg Astigmatism



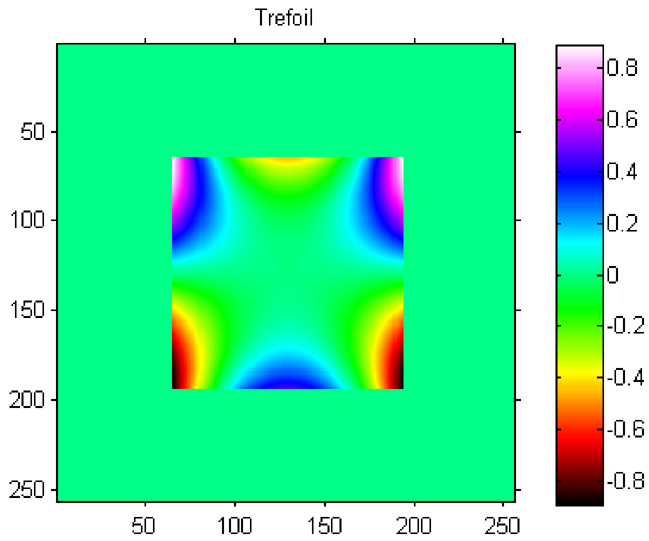
Focus


Focus
Focus: Far Field Mag
x 10^-3
50
100
150
200
250
1
0.5
0
-0.5
-1
3.5
3
2.5
2
1.5
1
0.5
0

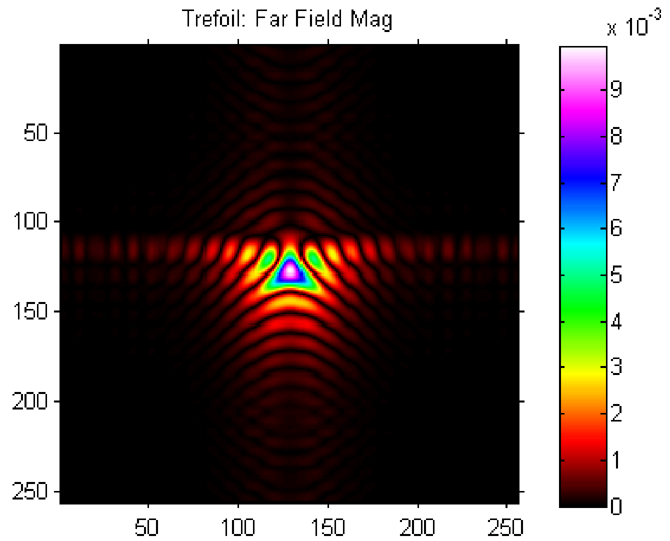
90 Deg Astigmatism



Trefoil



Trefoil
50
100
150
200
250
50
100
150
200
250
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8



Trefoil: Far Field Mag
x 10^-3
50
100
150
200
250
50
100
150
200
250
9
8
7
6
5
4
3
2
1
0

2X DL Aperture

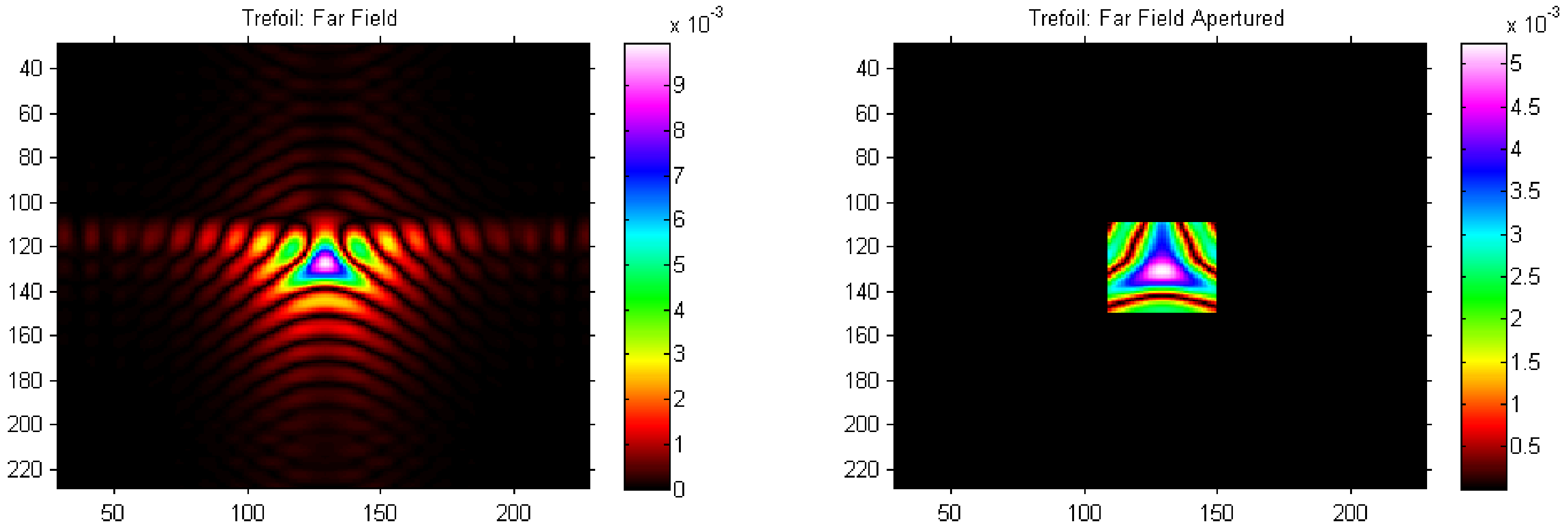


Figure 1

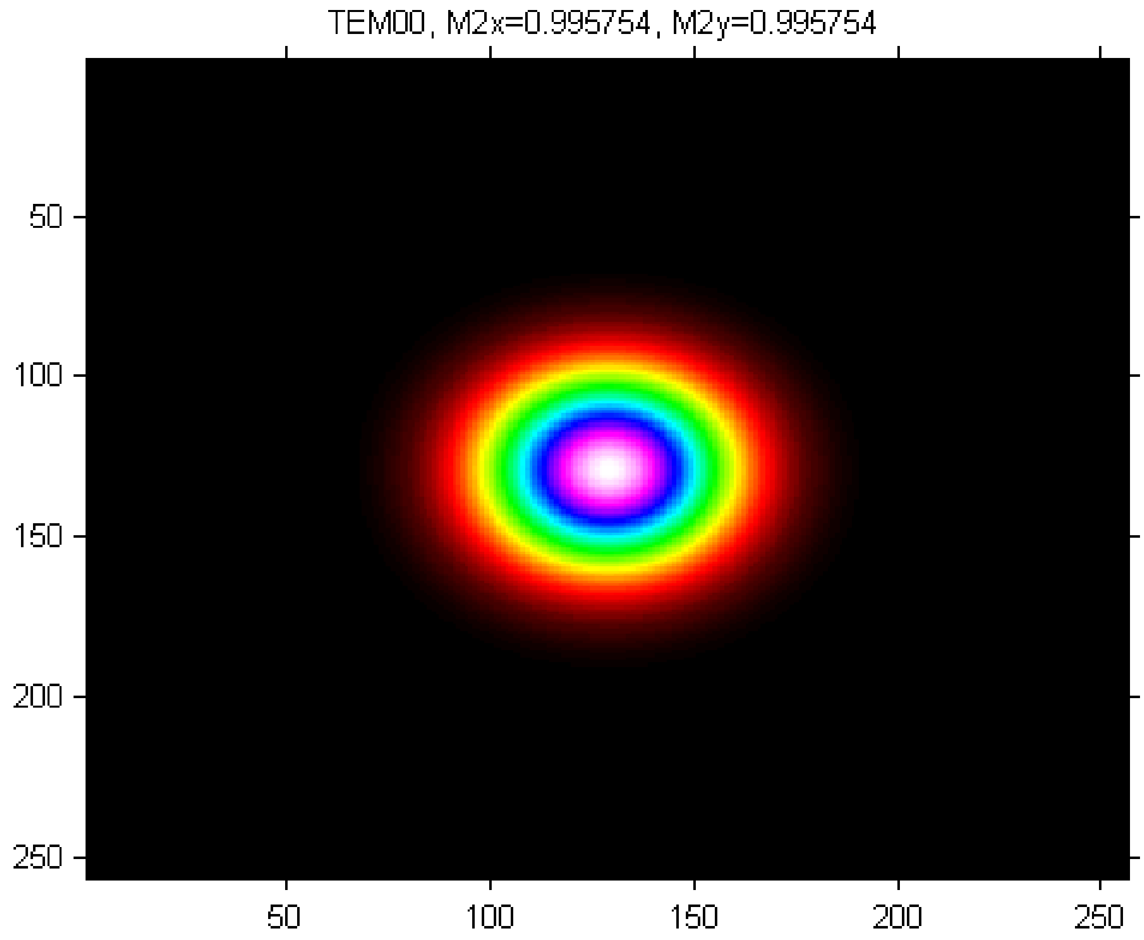


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Figure 1

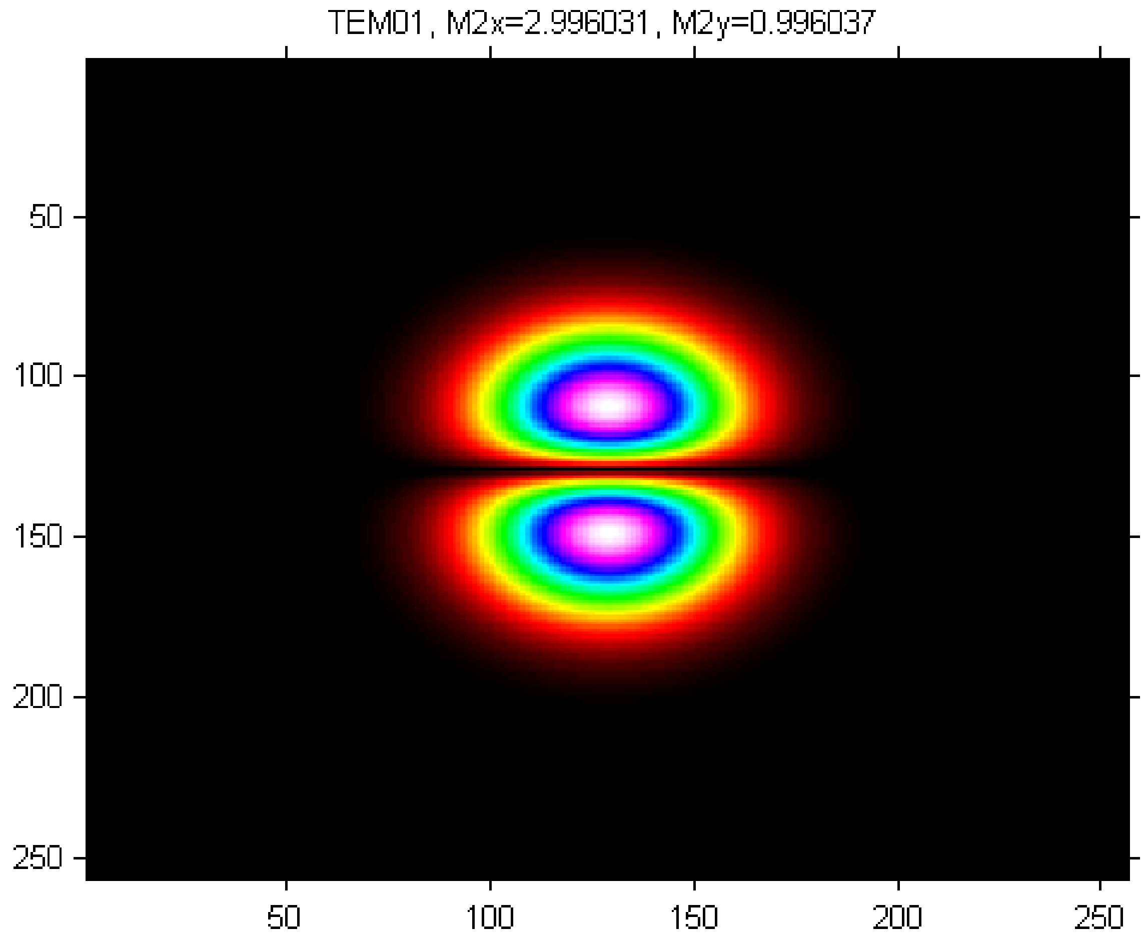
TEM01, M2x=2.996031, M2y=0.996037
50
100
150
200
250
50
100
150
200
250

Figure 1

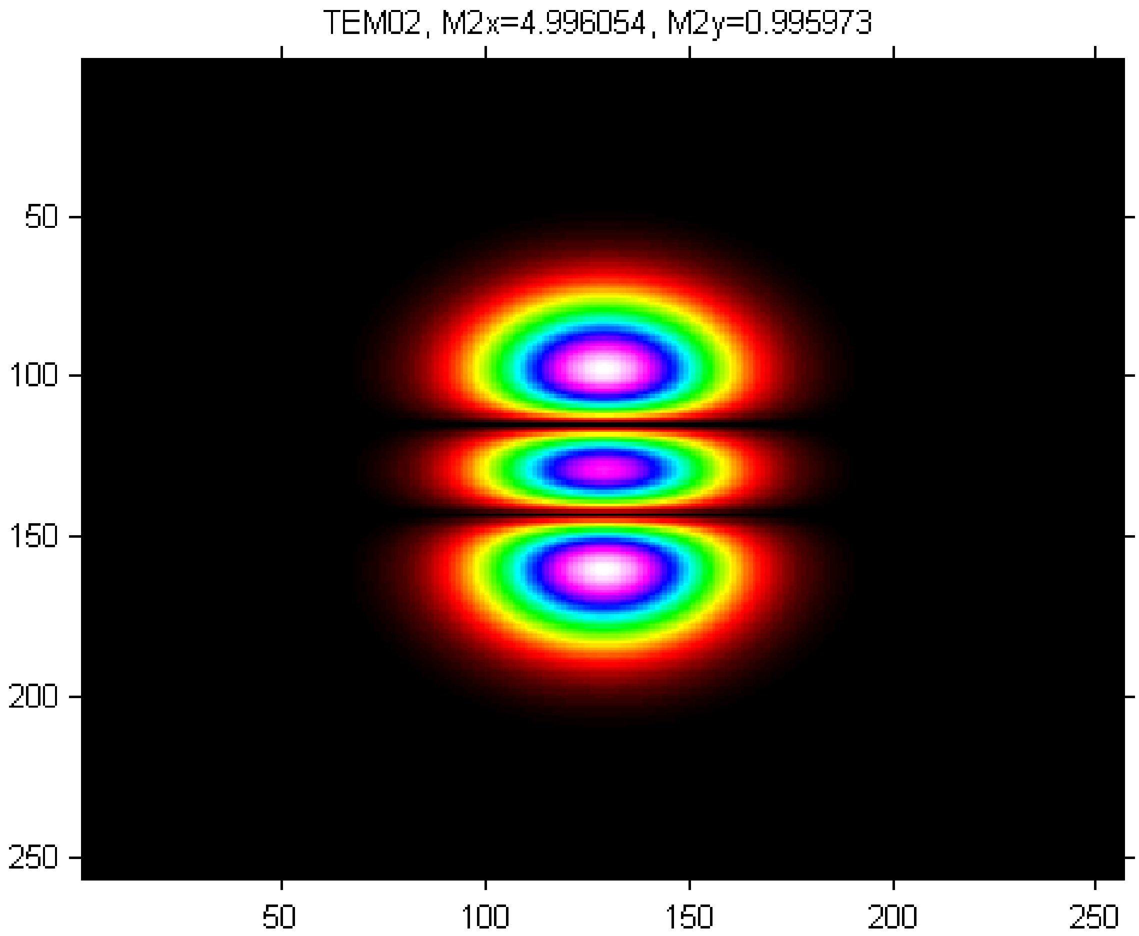
TEM02, M2x=4.996054, M2y=0.995973
50
100
150
200
250
50
100
150
200
250

Figure 1

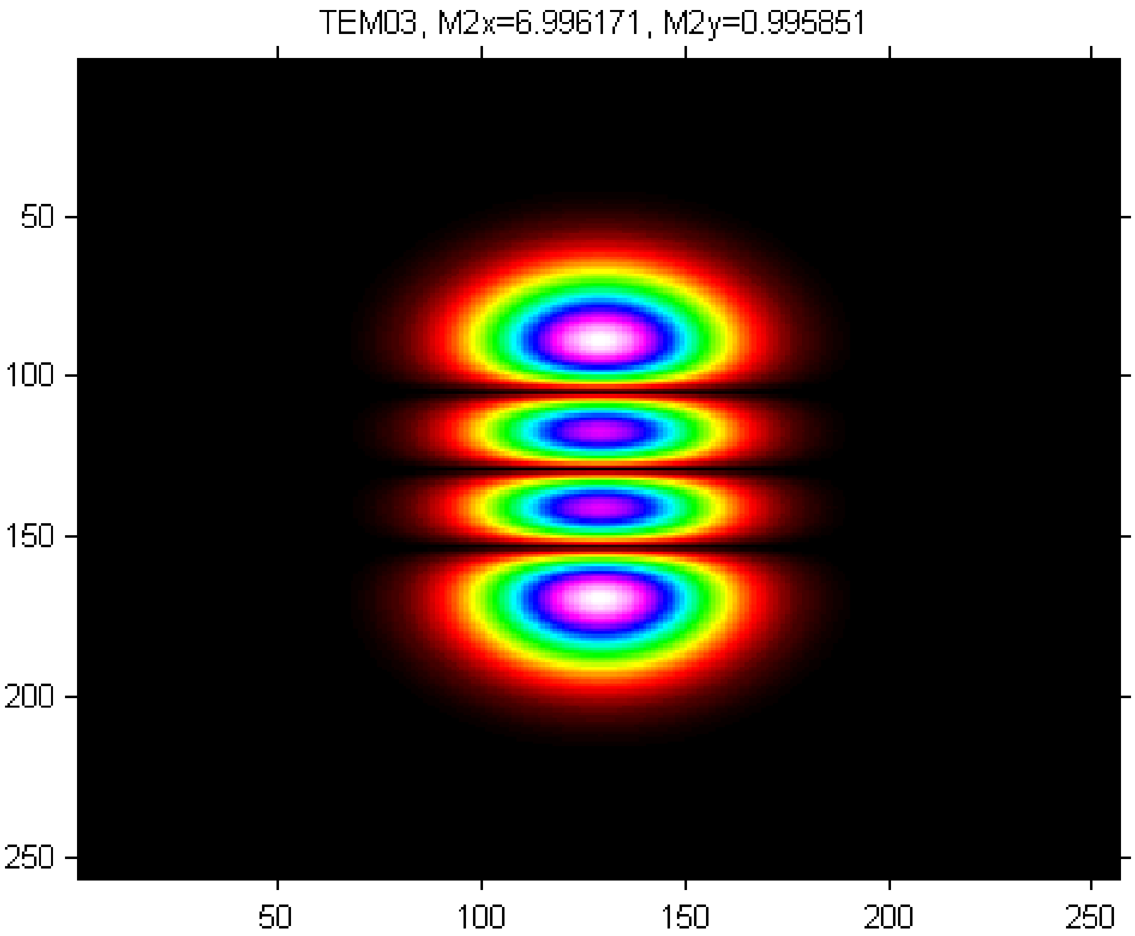
TEM03, M2x=6.996171, M2y=0.995851
50
100
150
200
250
50
100
150
200
250

Figure 1

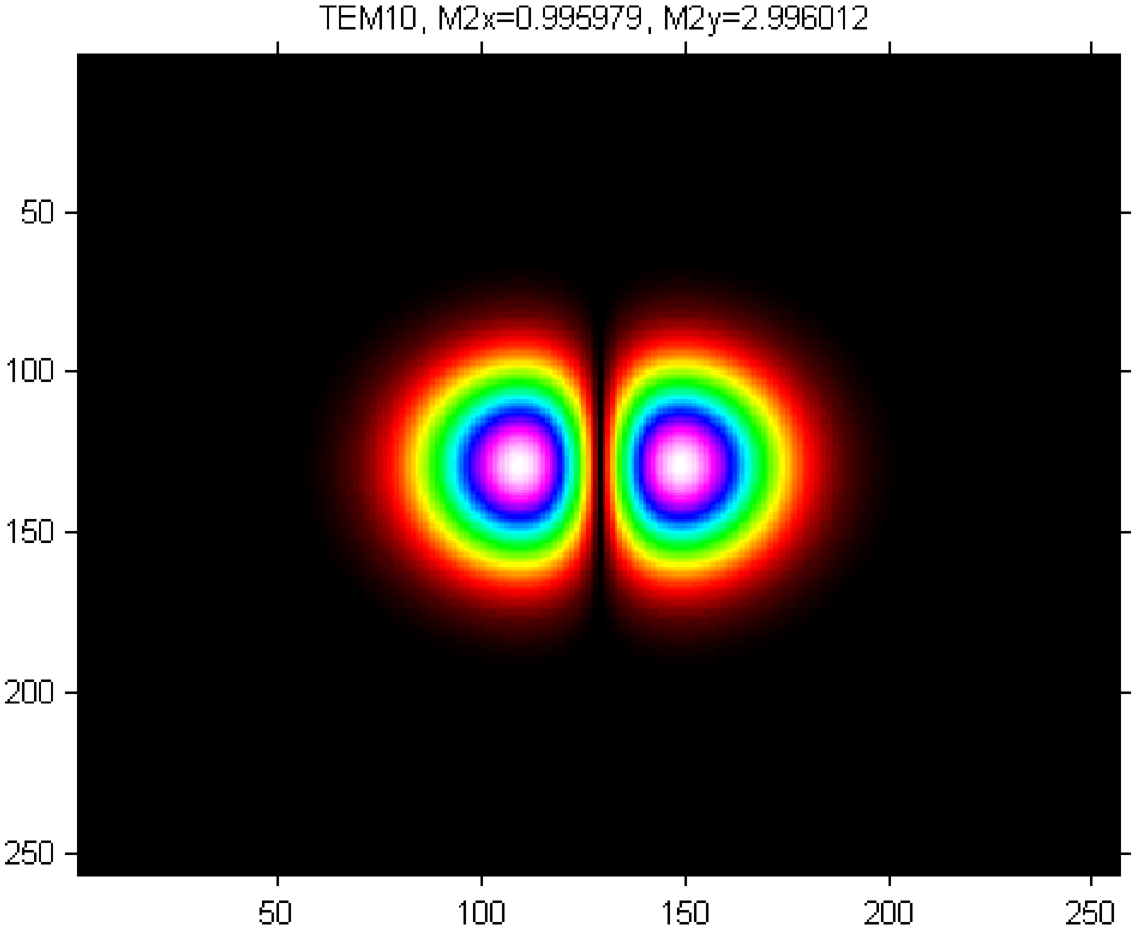
TEM10, M2x=0.995979, M2y=2.996012
50
100
150
200
250
50
100
150
200
250

Figure 1

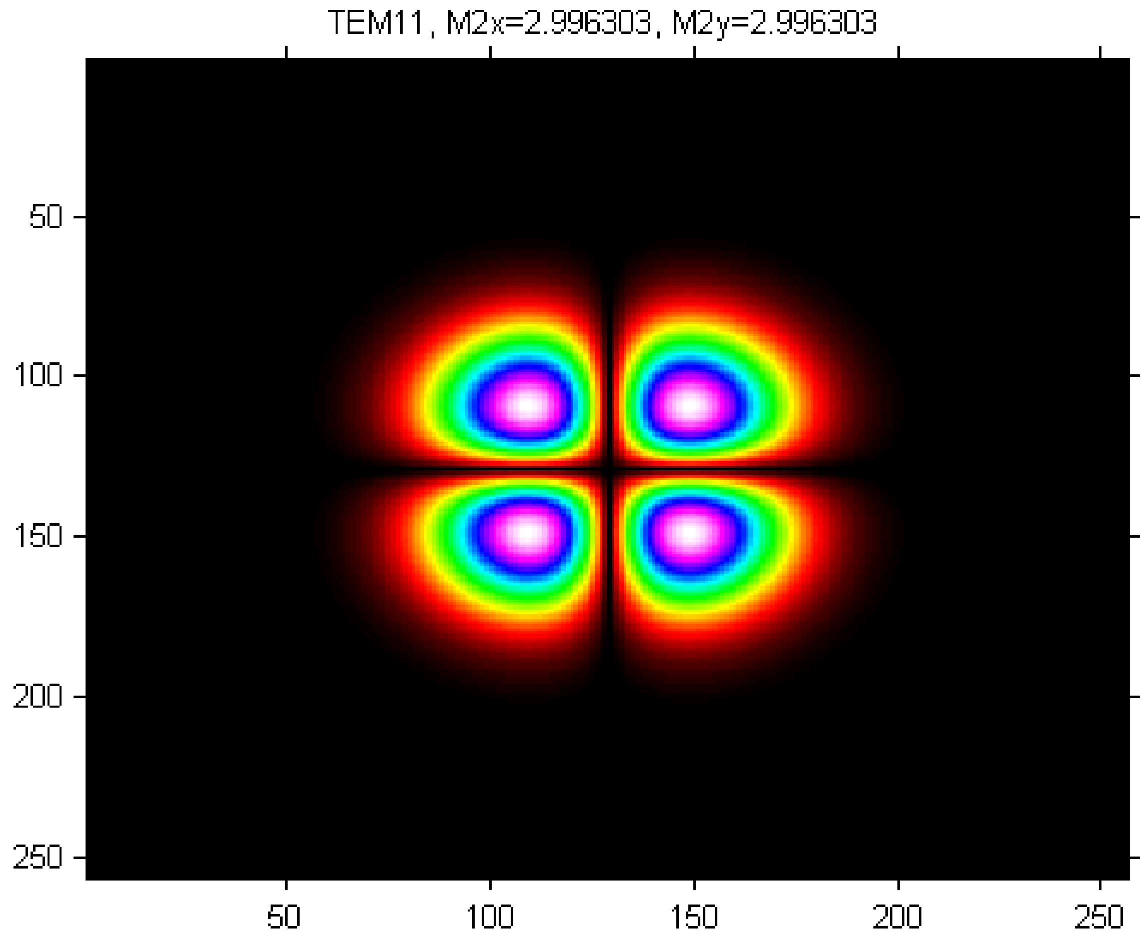

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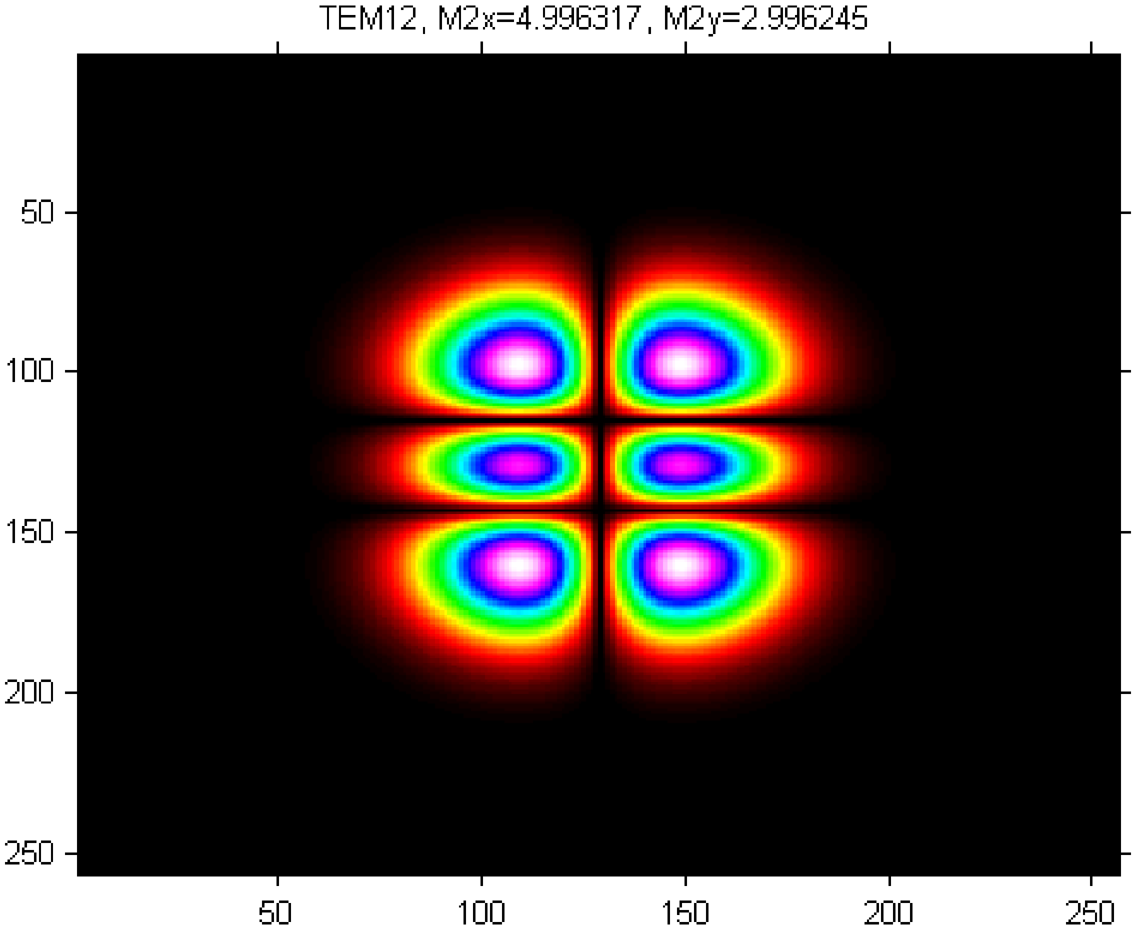
Figure 1



TEM12, M2x=4.996317, M2y=2.996245
50
100
150
200
250
50
100
150
200
250

Figure 1

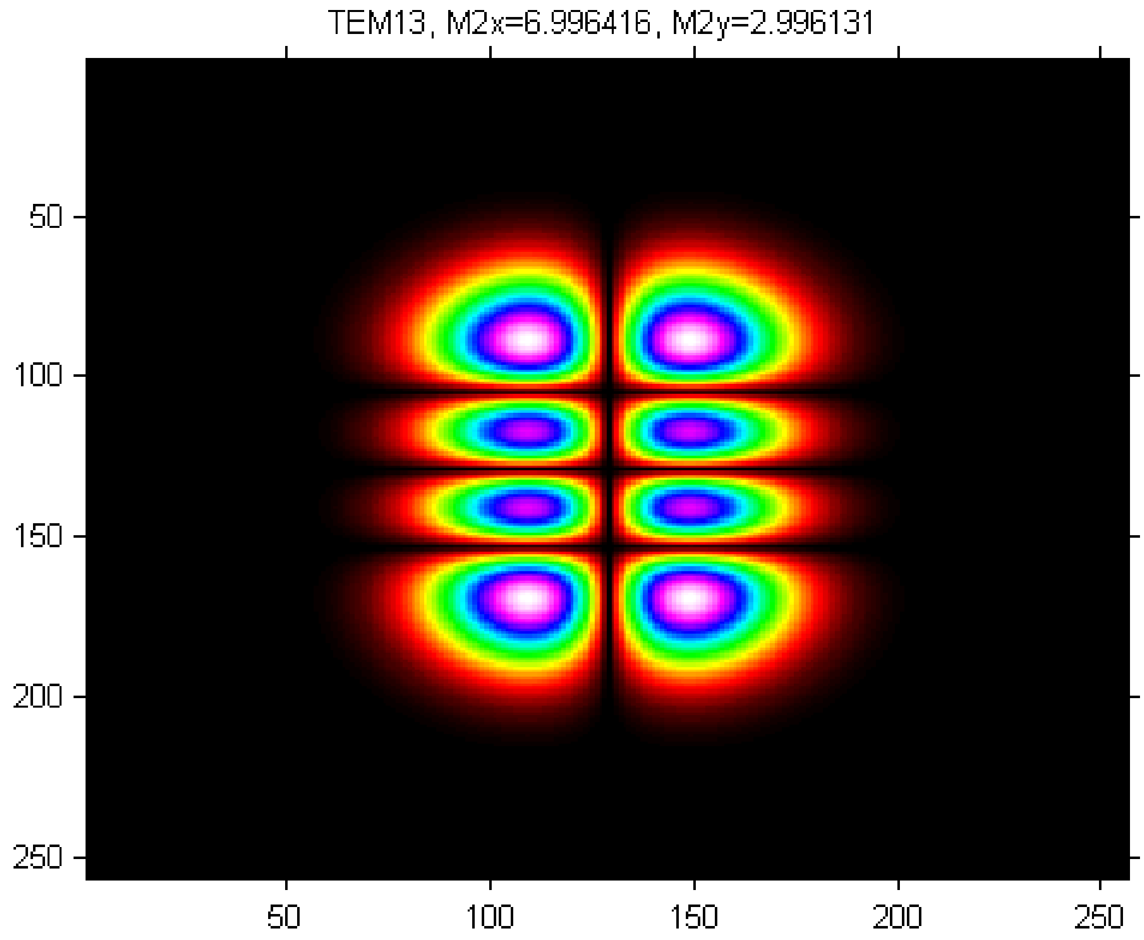

TEM13, M2x=6.996416, M2y=2.996131
50
100
150
200
250
50
100
150
200
250

Figure 1

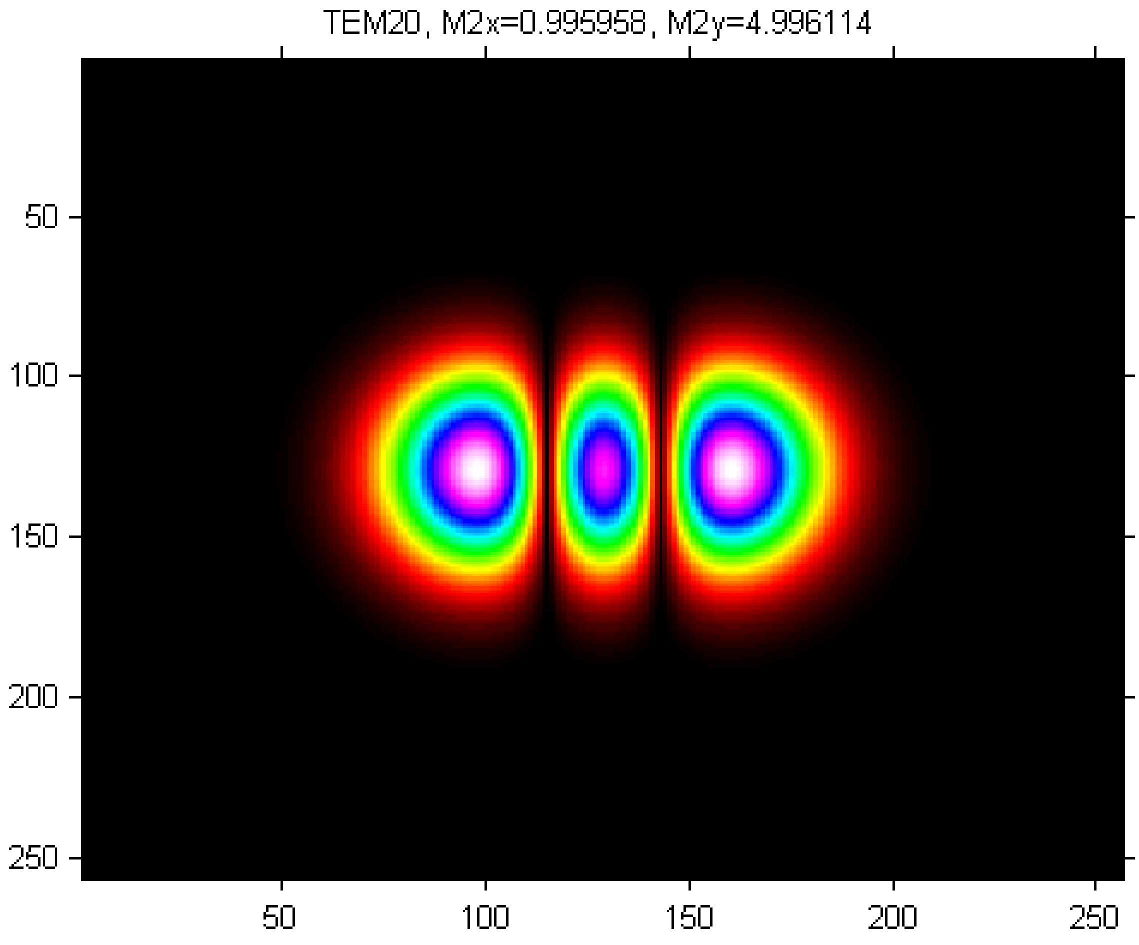

TEM20, M2x=0.995958, M2y=4.996114
50
100
150
200
250
50
100
150
200
250

Figure 1

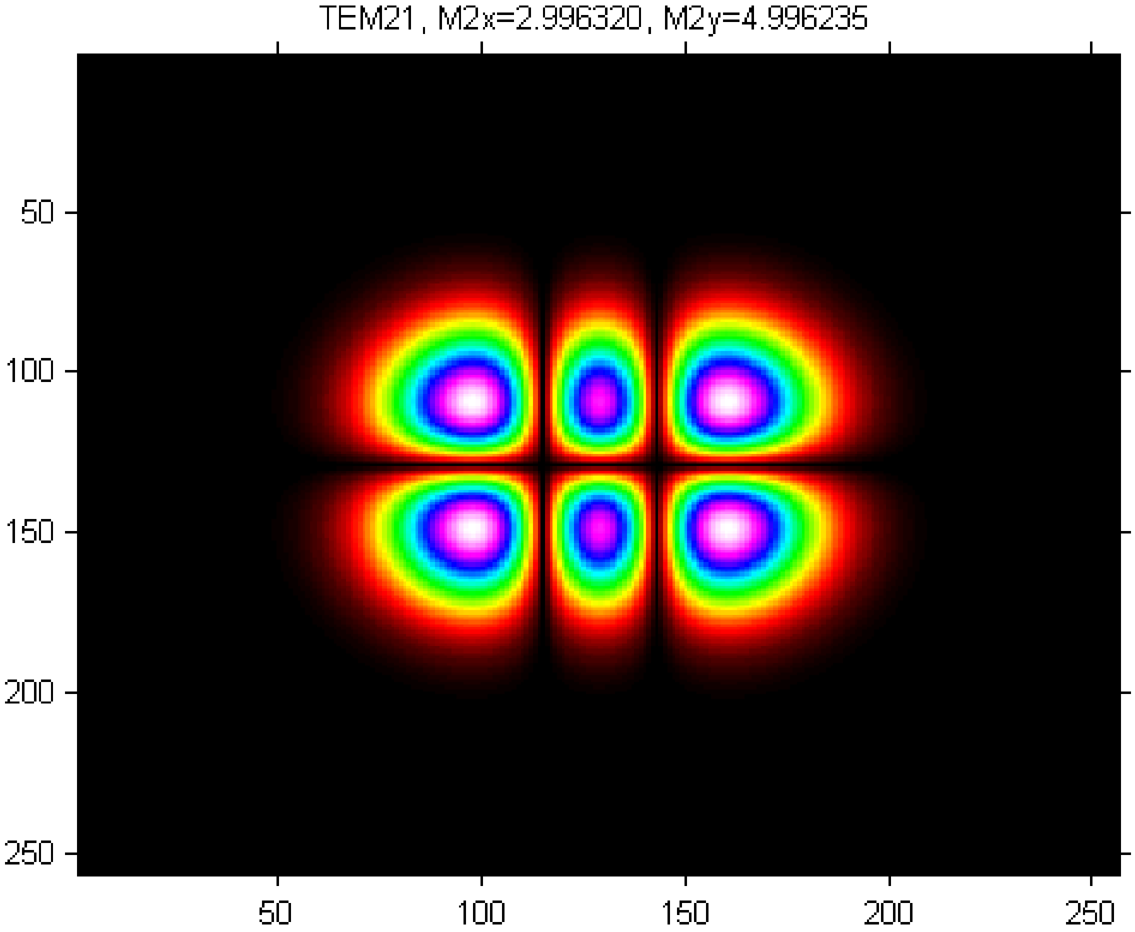

TEM21, M2x=2.996320, M2y=4.996235
50
100
150
200
250
50
100
150
200
250

Figure 1

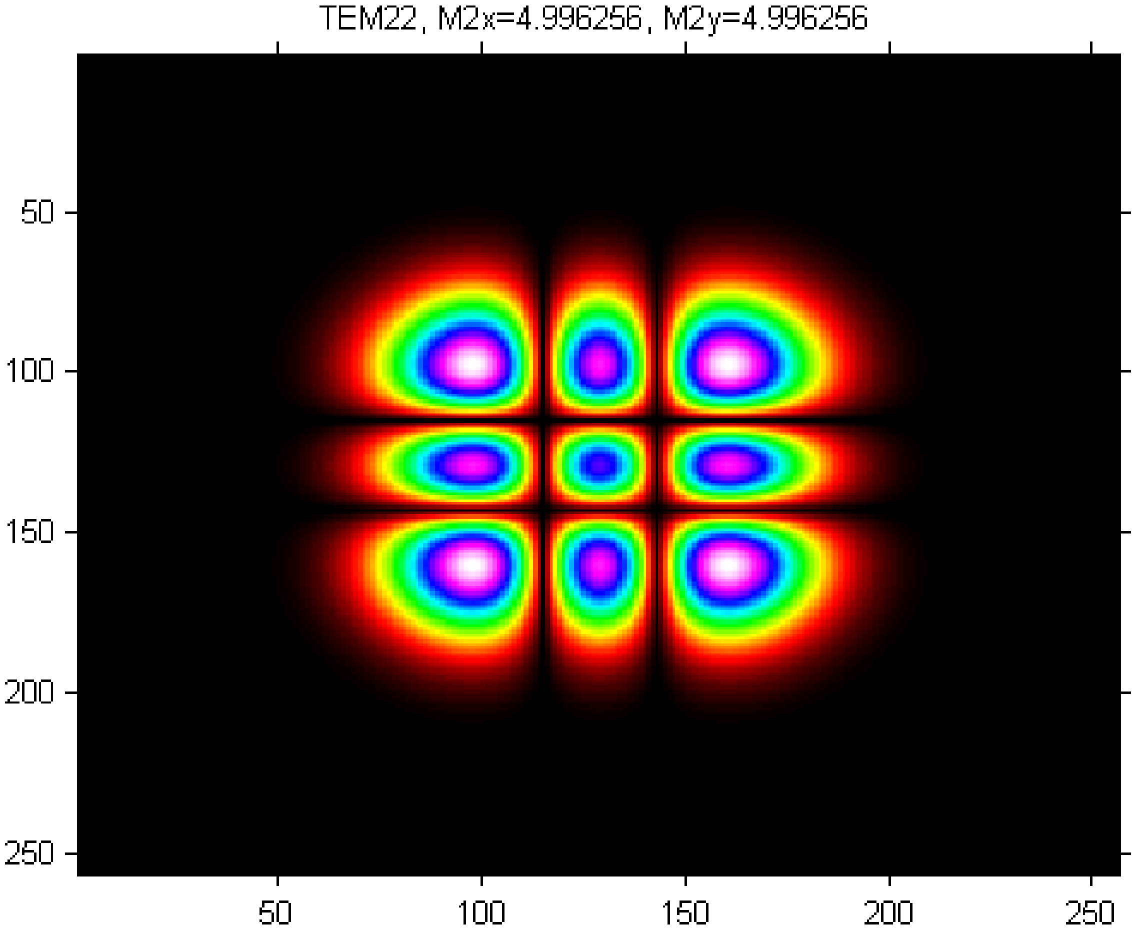

TEM22, M2x=4.996256, M2y=4.996256
50
100
150
200
250
50
100
150
200
250

Figure 1

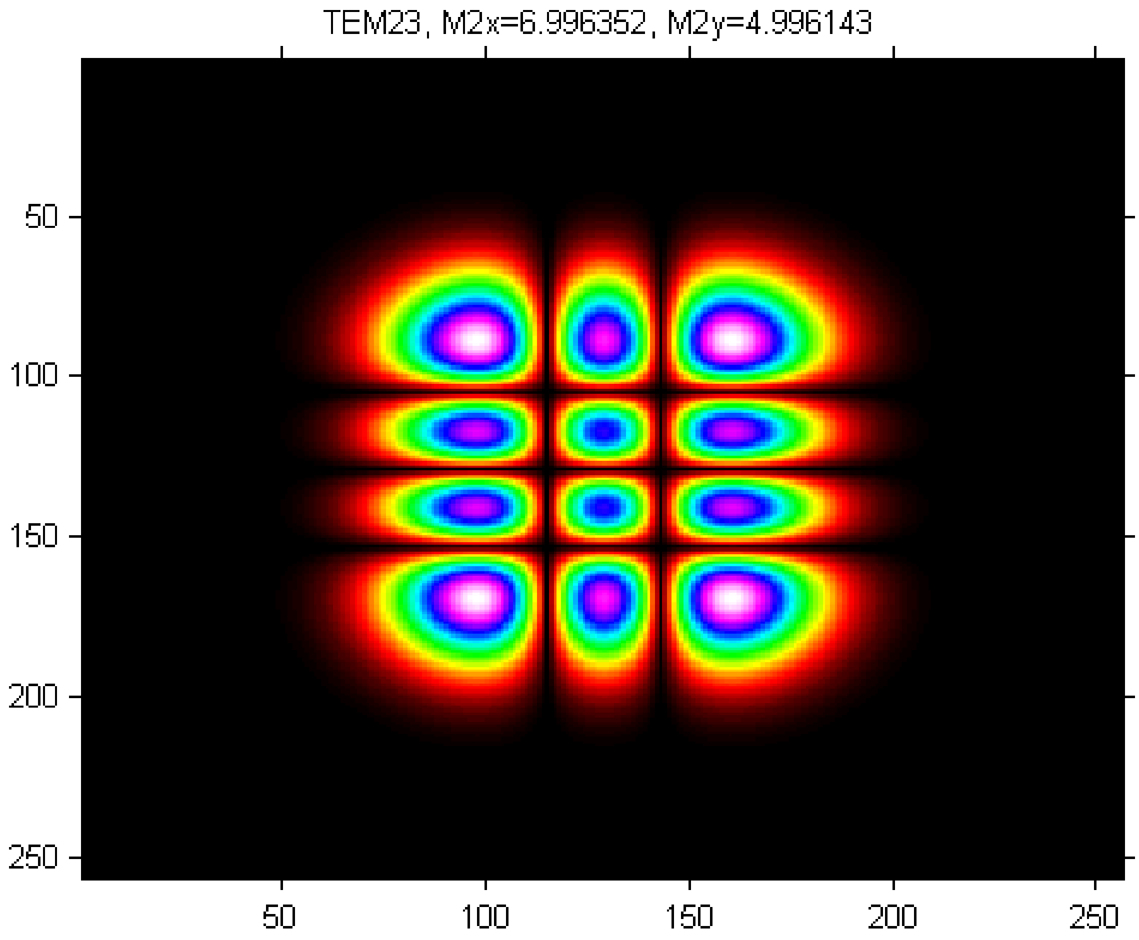
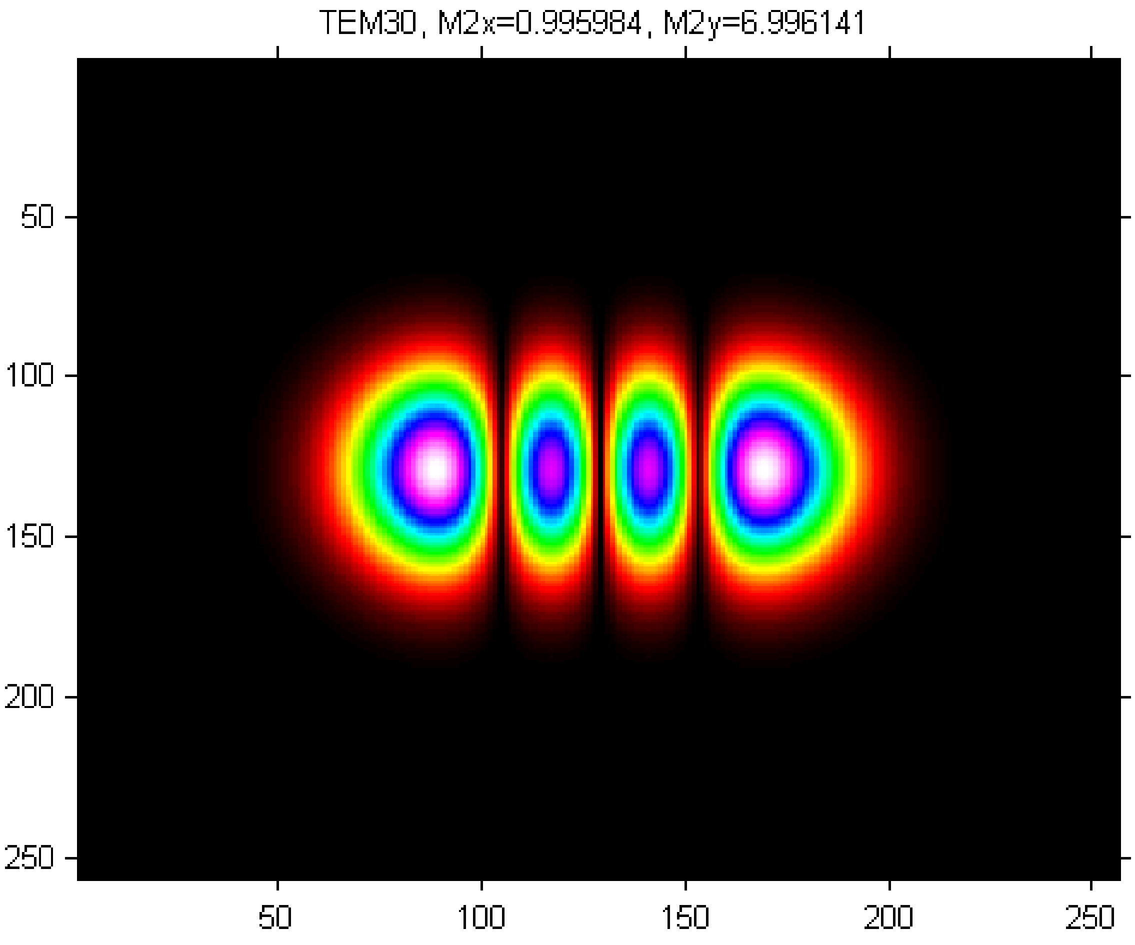

TEM23, M2x=6.996352, M2y=4.996143
50
100
150
200
250
50
100
150
200
250

Figure 1



TEM30, M2x=0.995984, M2y=6.996141
50
100
150
200
250
50
100
150
200
250

Figure 1

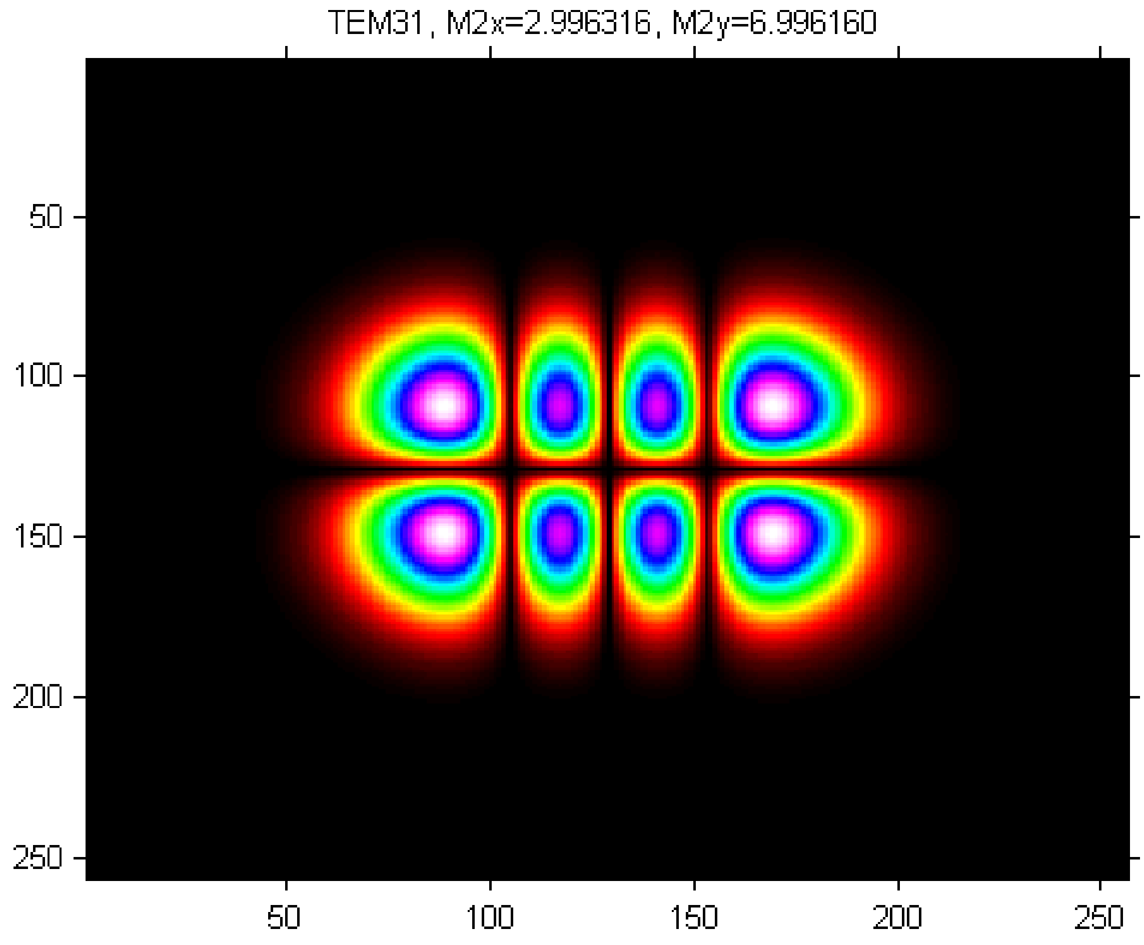

TEM31, M2x=2.996316, M2y=6.996160
50
100
150
200
250
50
100
150
200
250

Figure 1

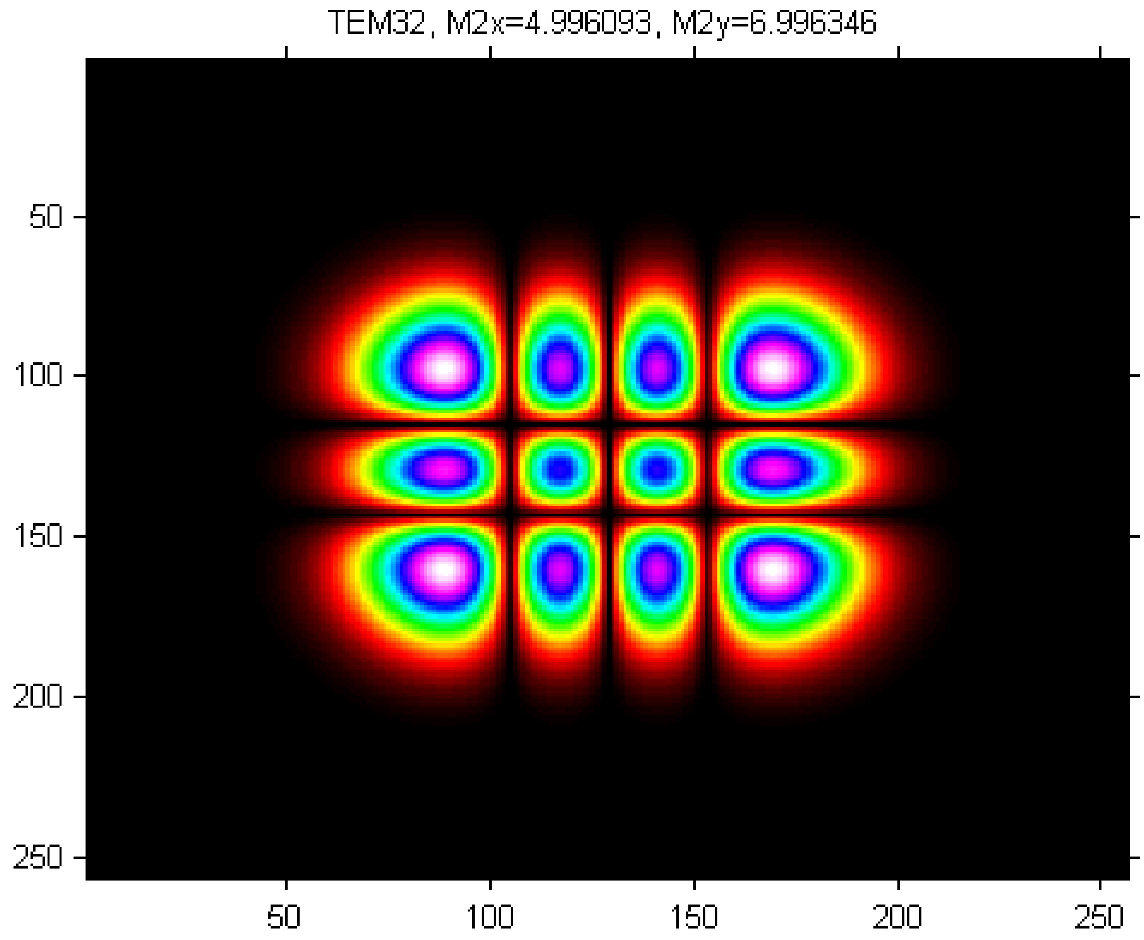

TEM32, M2x=4.996093, M2y=6.996346
50
100
150
200
250
50
100
150
200
250

Figure 1

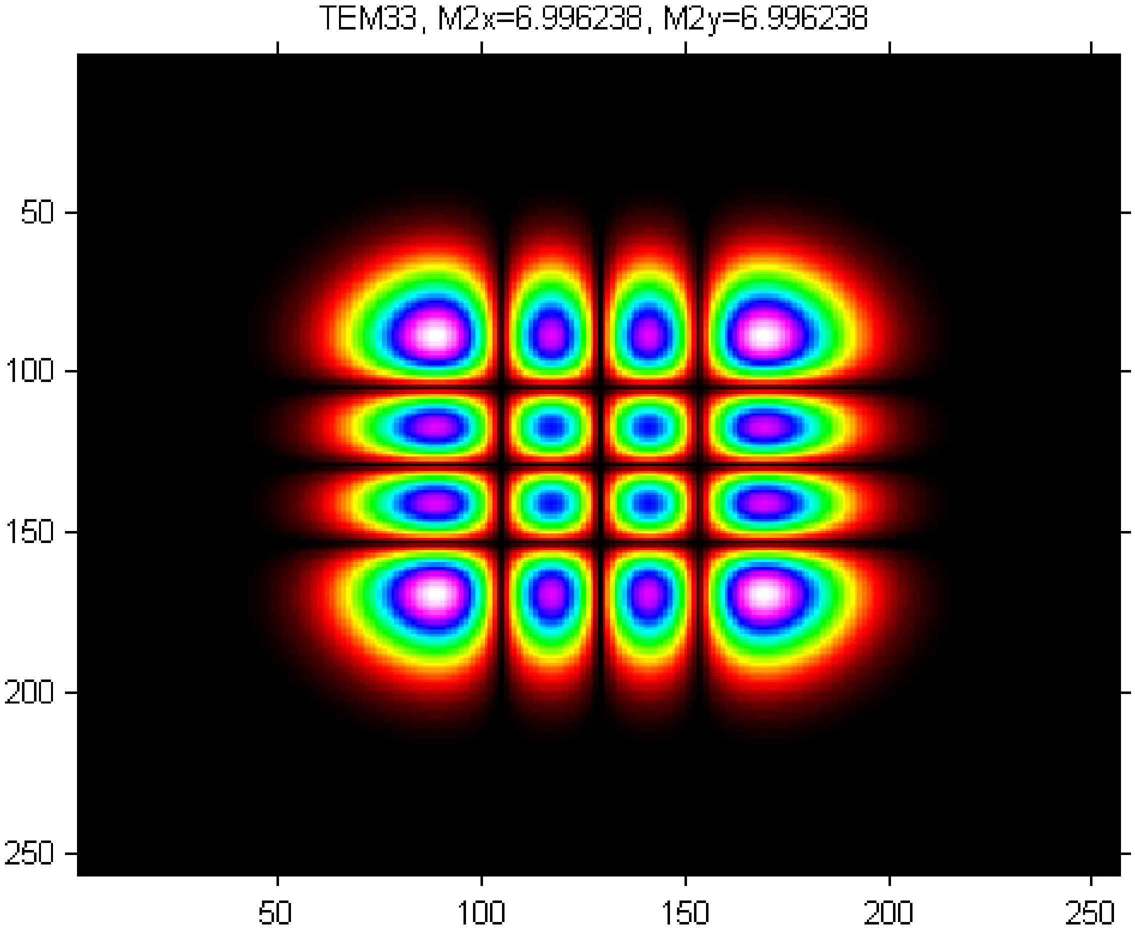

TEM33, M2x=6.996238, M2y=6.996238
50
100
150
200
250
50
100
150
200
250

Figure 2

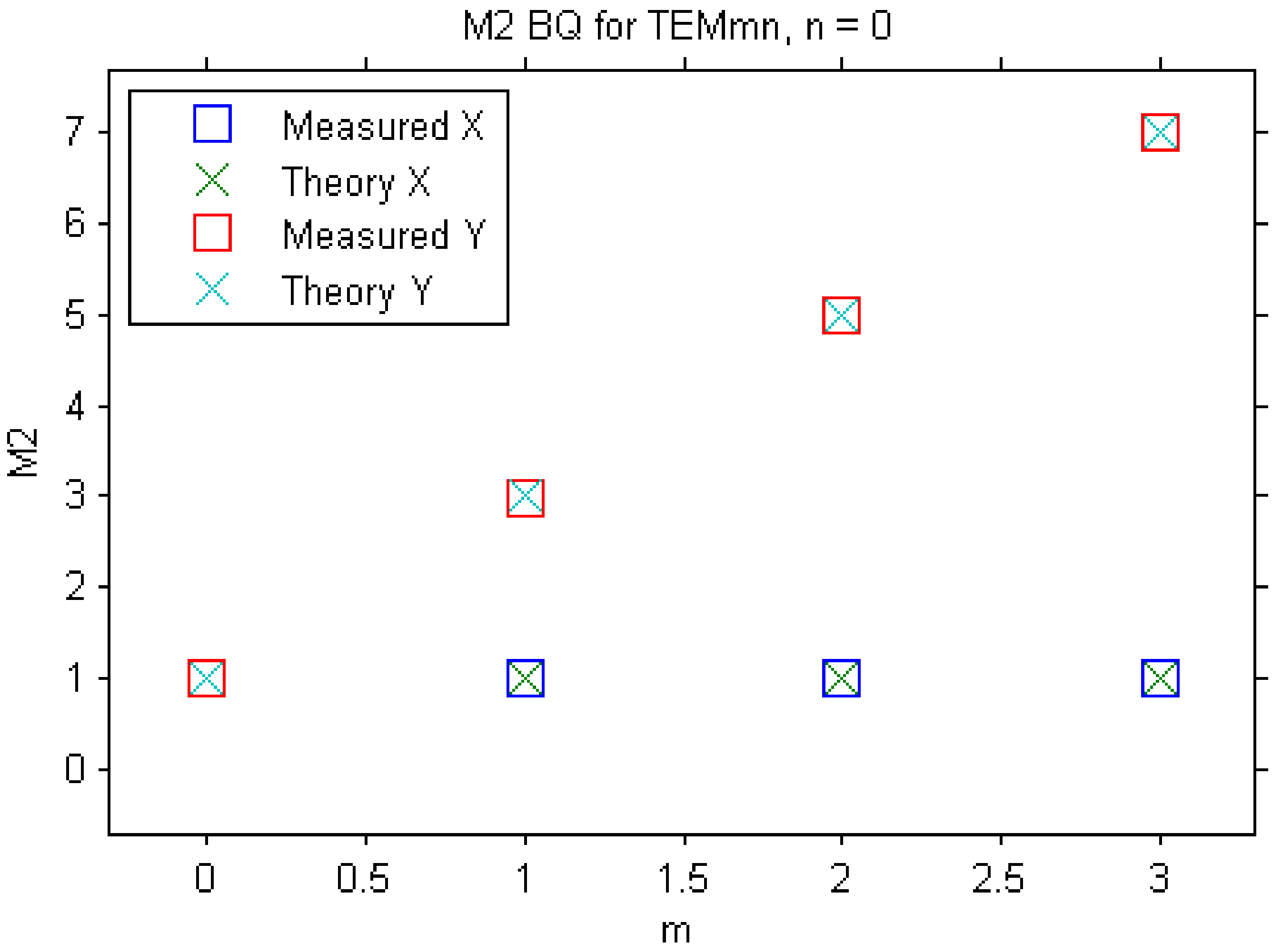


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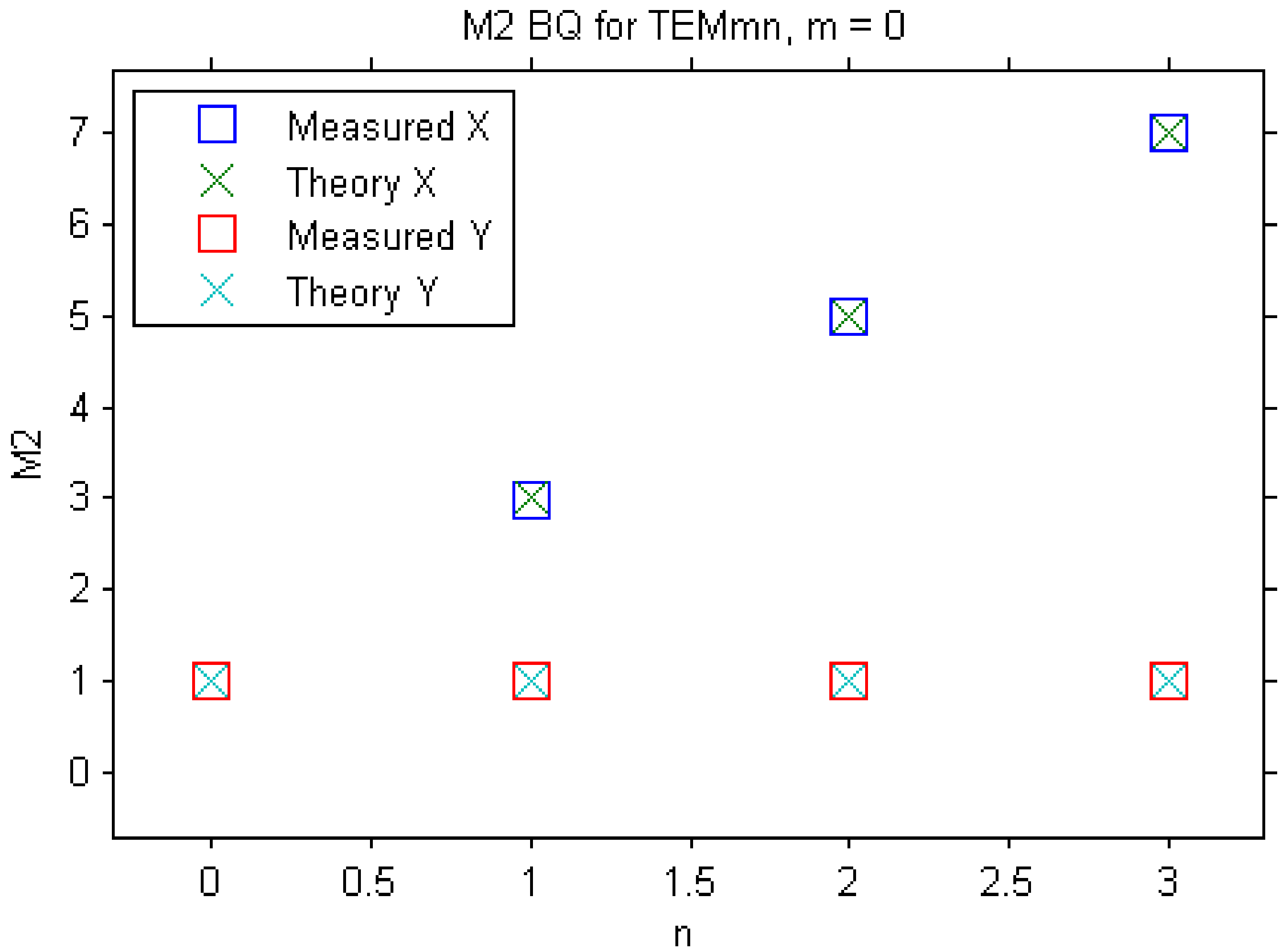
Figure 3


M2 BQ for TEMmn, m = 0
Measured X
Theory X
Measured Y
Theory Y
M2
n
0
1
2
3
4
5
6
7
0
0.5
1
1.5
2
2.5
3