Laser Source Modeling in WaveTrain

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March 5, 2008

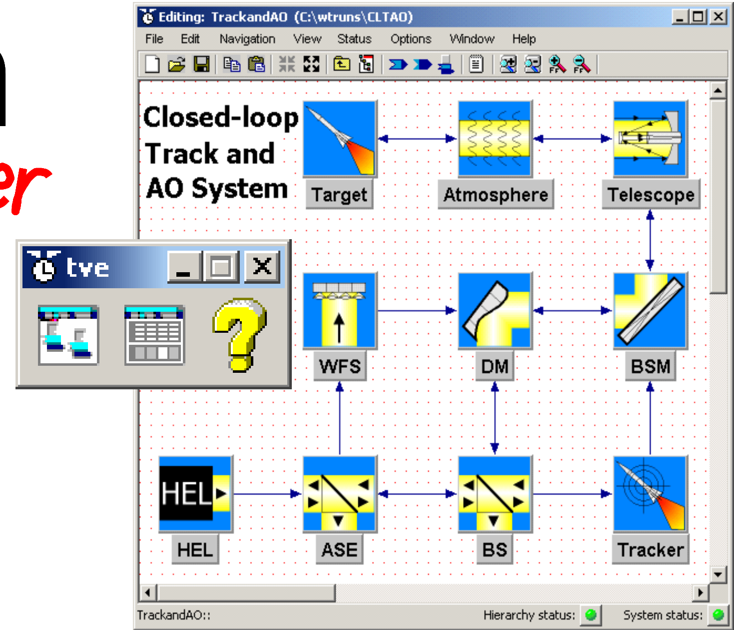
Outline

- Short overview of WaveTrain
- Laser Resonator Modeling
  - Introduction & Theoretical Foundations
  - ResonatorSource Component
  - SimpleSaturableGain Component
- Examples
  - Stable Resonator without Gain
  - Stable Resonator with Gain
  - Unstable Laser Resonator

Introduction to WaveTrain

WaveTrain

wave optics made ~~easy~~ ier

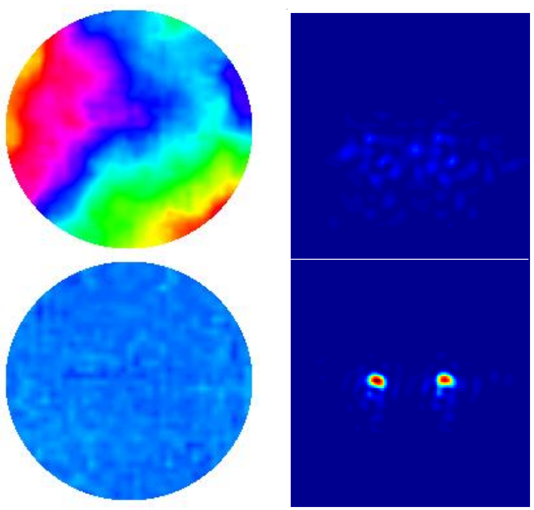


The Challenge of Wave Optics Simulation

Wave optics simulation is a crucial technology for the design and development for advanced optical systems. Until now it has been the sole province of a handful of specialists because the available codes were extraordinarily complicated, difficult to use, and they often required supercomputing resources.

Without Adaptive Optics

With Adaptive Optics



Phase **Image**

The Solution is WaveTrain

WaveTrain puts the power of wave optics simulation on your PC. Through an intuitive connect-the-blocks visual programming environment in which you can assemble beam lines, control loops, and complete system models, including closed-loop adaptive optics (AO) systems.

MZA Associates Corporation

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What is WaveTrain?

- WaveTrain is a systems modeling and simulation tool that performs detailed physical simulations of complex closed-loop optical systems.
  - Supports arbitrarily complex sequential optical path modeling.
  - Adaptive optics controls including wavefront sensors and deformable mirrors.
  - Propagation through the atmosphere and other random media (e.g. aero-optics).
  - Continuous and discrete controls systems.
- WaveTrain is designed for ease of use, so that it can be used by a broad technical user community.
  - Plug-n-play block diagram editing and parameter specification.
  - Provides extensive features for a broad spectrum of users, from the occasional model "runner", to the simple model "builder", to sophisticated model "builders" and subsystem programmers.
- WaveTrain is designed to be reconfigurable, so that it can be used to model a wide variety of optical systems and experiments.
  - Users build-up models from a library of available components.
  - Programmers add their own components programming in C++, C, Matlab m-file, and Fortran.
  - Not limited to a particular propagation algorithm or phase screen implementation.
- WaveTrain provides wave optics and system simulation techniques in a true modern object-oriented programming (OOP) paradigm.
  - WaveTrain is not a graphical user interface (GUI) layered on top of a legacy wave-optics code.
  - WaveTrain is a bottoms up implementation of the fundamental features of composition-based simulation with emphasis on the modeling of optical systems.

WaveTrain Modeling References

General

find these at www.mza.com

- Extending the Hierarchical Block Diagram Paradigm for Modeling and Development of Large-Scale Systems, Comp. Sim. Conf., 1997
- WaveTrain: A User-Friendly Wave Optics Propagation Code, SPIE, 1999.
- WaveTrain Hands-On Workshop, 1999-present, MZA presentation.
- Introduction to Beam Control, 2003, MZA presentation.
- Choosing Mesh Spacings and Mesh Dimensions for Wave Optics Simulation, 2007, SPIE.
- Determining Wave-Optics Mesh Parameters for Complex Optical Systems, 2007, SPIE.

Short Courses and Tutorials

DEPS 2004 – Modeling and Simulation of Beam Control Systems

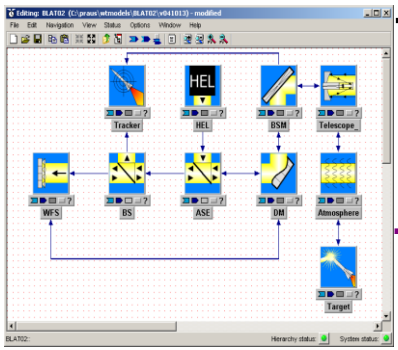
DEPS 2005 – Modeling and Simulation using WaveTrain

DEPS 2006 – Introduction to tempus

DEPS 2007 – Analysis of Optical Systems using Scaling and Wave-Optics Models

WaveTrain Process Flow

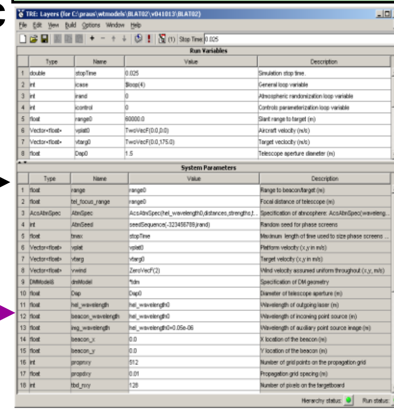
system editor



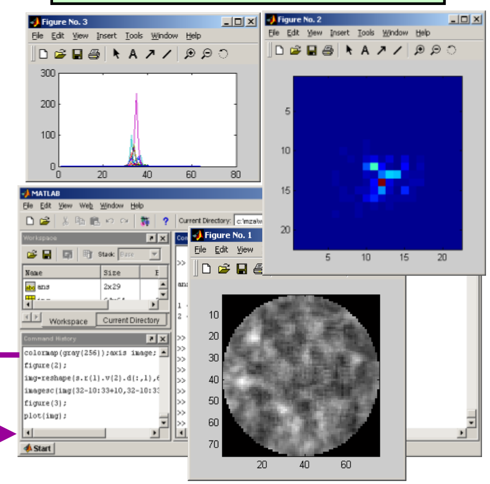
- Construct & modify tempus Systems
- Create Atomic System templates

runset editor

- Create test cases
- Devise parametric studies

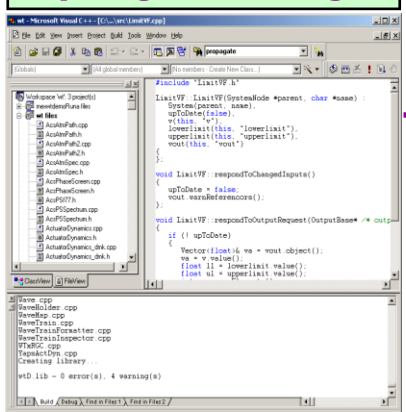


analysis



- Visualize and analyze results

programming



- Write Atomic Systems
- Debug applications

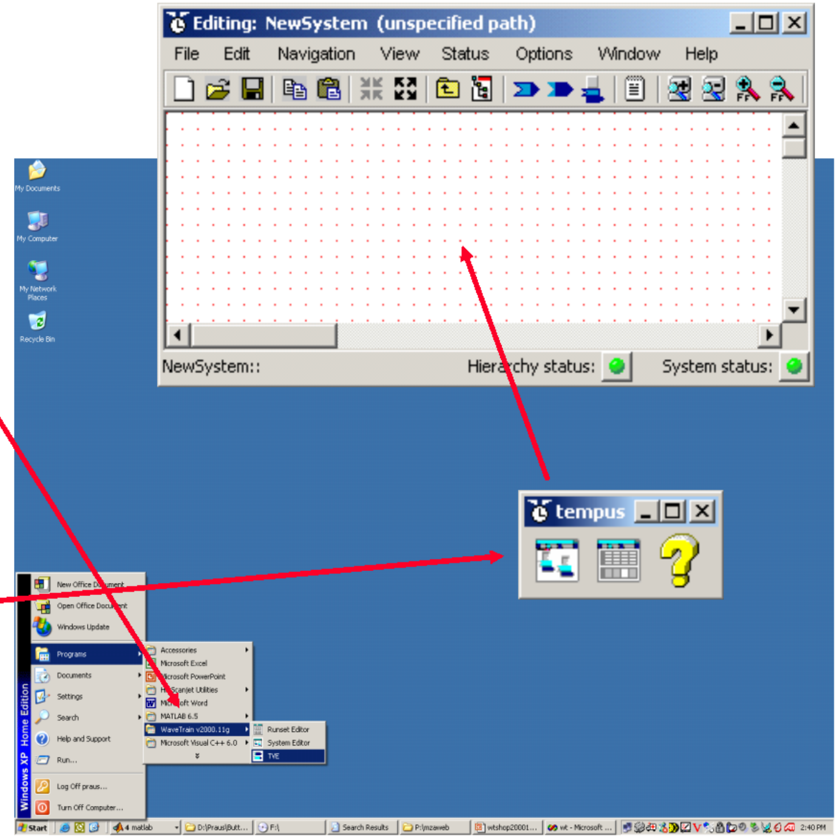
The process supports WaveTrain System development, debugging, and analysis

Starting the WaveTrain GUI (tve)…

- WaveTrain is built atop tempus, a general-purpose simulation tool. In tempus, a system model is defined in terms of its interface (inputs, outputs, and parameters), its subsystems, and the connections between them. Each system model is mapped into a portable C++ class via automatic source code generation.

- To begin, start the GUI by selecting WaveTrain v2000.11 TVE under the Windows Start-Programs menu (possibly nested in a program group). This will bring up the tempus top-level window. Alternatively you can open System Editor or Runset Editor (TRE) by selecting the corresponding item in the WaveTrain program group.

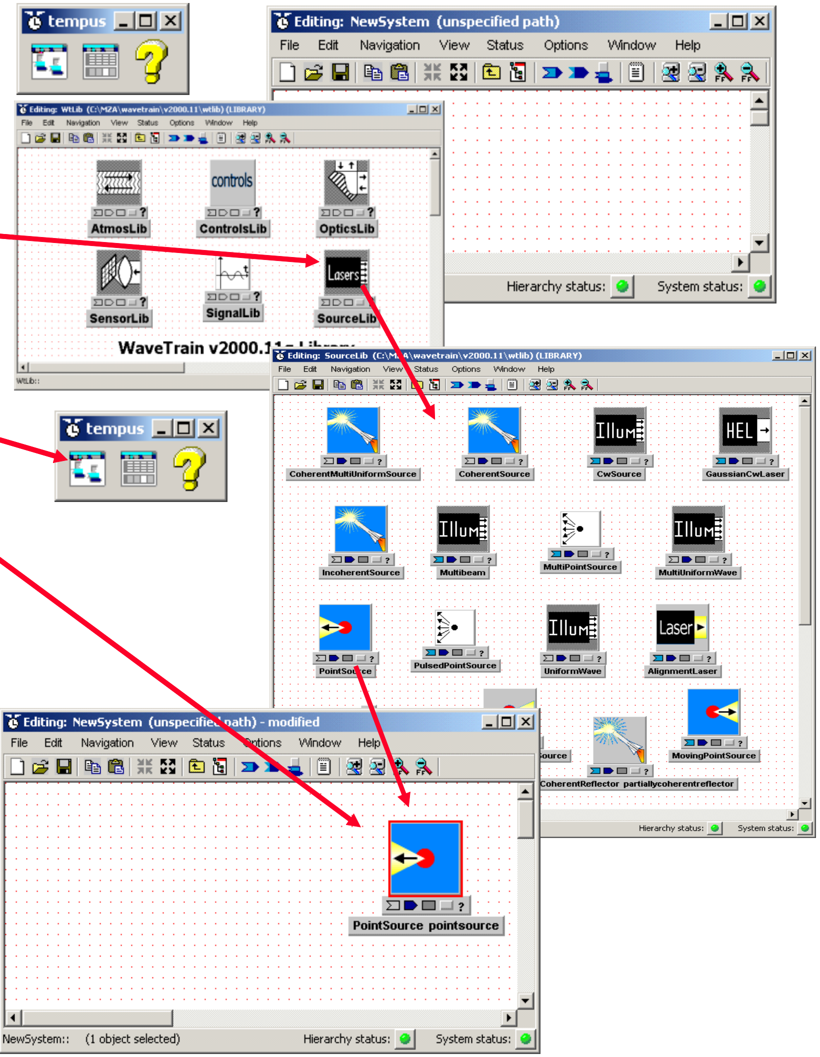
- Click on  which will bring up the System Edit Window (skip this step if you started System Editor directly). When System Editor window comes up it already has a new system model, called “NewSystem”, loaded by default.



WaveTrain includes a graphical user interface which is used to construct models by establishing relationships (connections) between the dynamic "Inputs" and "Outputs" of fundamental building blocks.

Copying from the component library…

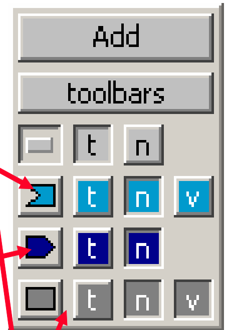
- On your screen you should now have the tempus top-level window and two System Edit Windows, one for WtLib, one for NewSystem, as shown in the upper right.
- Double-click on SourceLib to “descend” into it. Click on PointSource to select it, then use Ctrl-C to copy it into the paste buffer.
- Click on the NewSystem window, then use Crtl-v to paste a PointSource, which will appear in the upper left. Move it to the upper right by clicking on it, holding the button down, moving the mouse to the desired spot, then releasing it.
- Click on the WtLib window, then double-click on white space to ascend back to the top of the library.



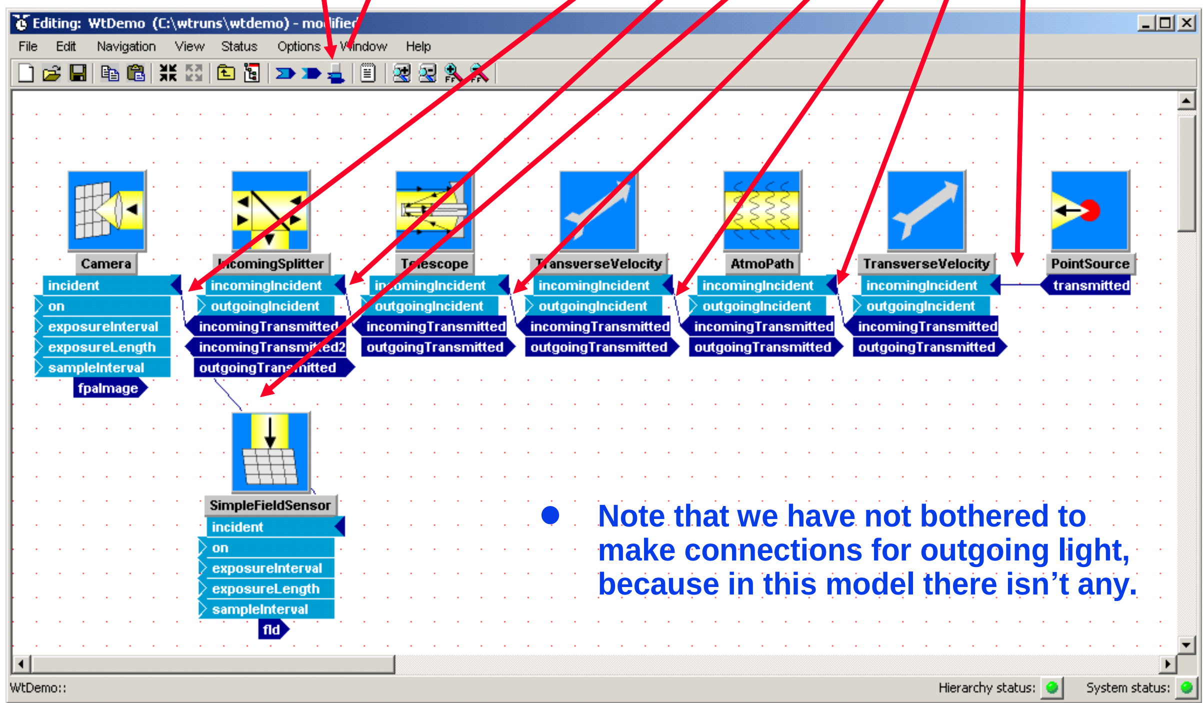
First, you have to copy modules from the WaveTrain component library.

Connecting the components…

- **Click the toolbar button with image of the subsystem.** A small menu will pop up.
- **Select the button with a light blue "receptor" shape**, also shown depressed at right. This will display all subsystem inputs. The window should now appear as shown in the upper right.
- **Select the button with a dark blue arrowhead**, shown depressed at right. This should cause all subsystem outputs (dark blue arrows attached to the bottom of each subsystem) to be displayed. If it does not work, click on white space and try again.



- **Connect outputs to inputs as shown**, by clicking on the pointed tip of each output, and dragging it to the receptor of the appropriate input.

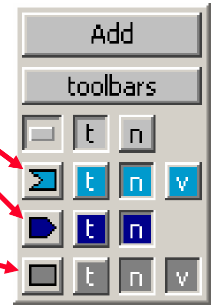


- Note that we have not bothered to make connections for outgoing light, because in this model there isn't any.

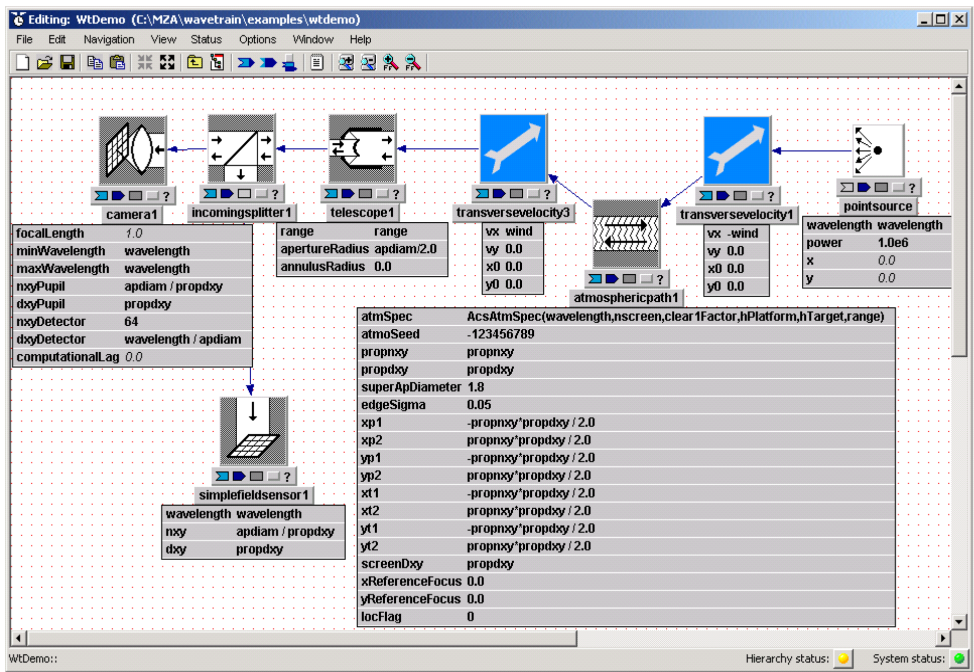
Then you have to connect the components.

Specifying parameter values…

- Undisplay the subsystem inputs and outputs. The window should now look as shown in the upper right.
- Click on the button with the medium gray rectangle (lower left corner of the menu), which will display the subsystem parameters, as shown at the lower right

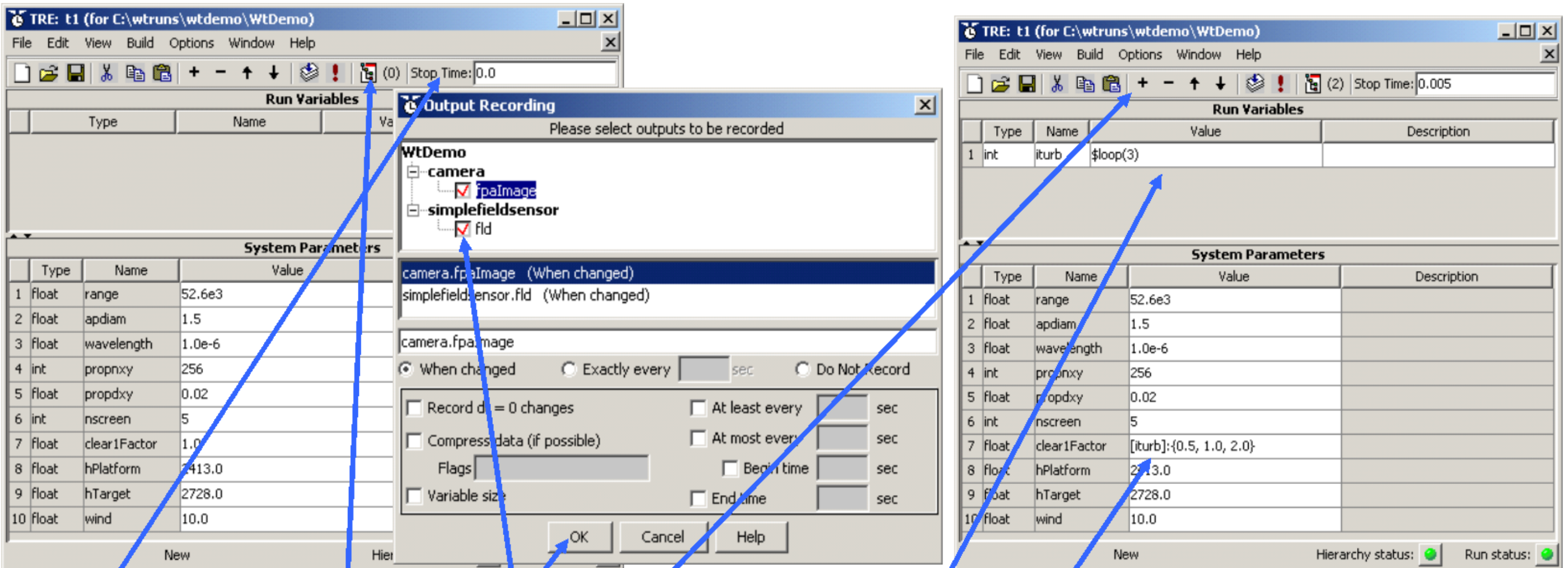


- For each parameter, the parameter name appears to the left, and its "setting expression" appears to the right, if any has been specified.
- Setting expressions are evaluated using the parameters of the containing system, but we have not yet defined any.



Followed by specifying values (and relationships) for parameters.

Creating a "runset"...



- Initially, the Runset will have all system parameters set to the defaults you specified when you built the system. The stop time for each run will be set to zero, and no outputs recording will be set up.
- Set the stop time to 0.005
- Click the button (Recorded Outputs) to display a window for specifying output recording. Click on checkboxes next to each of the two outputs. Click "OK".
- Click the button "+" to create space for one run variable, then enter "int" "iturb" "$loop(3)"; this will create a for-loop, resulting in three separate simulation runs.
- Set clear1Factor to "[iturb]:{0.5,1.0,2.0}"; so its value will change with each loop iteration.

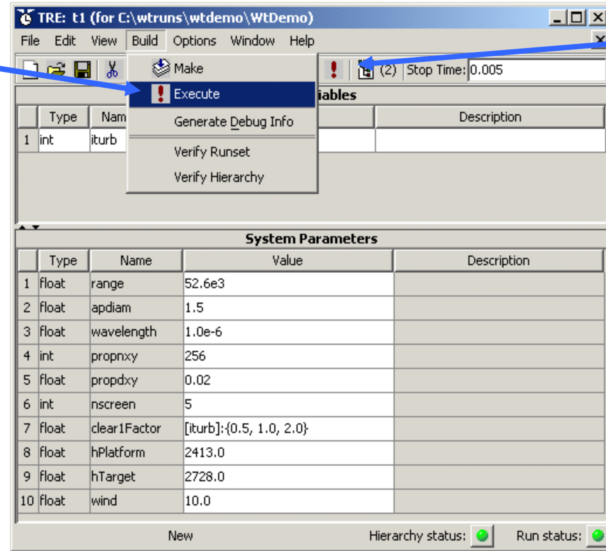
WaveTrain and tempus names are case sensitive!

Create a "runset" which specifies the nature of the study you are to perform.

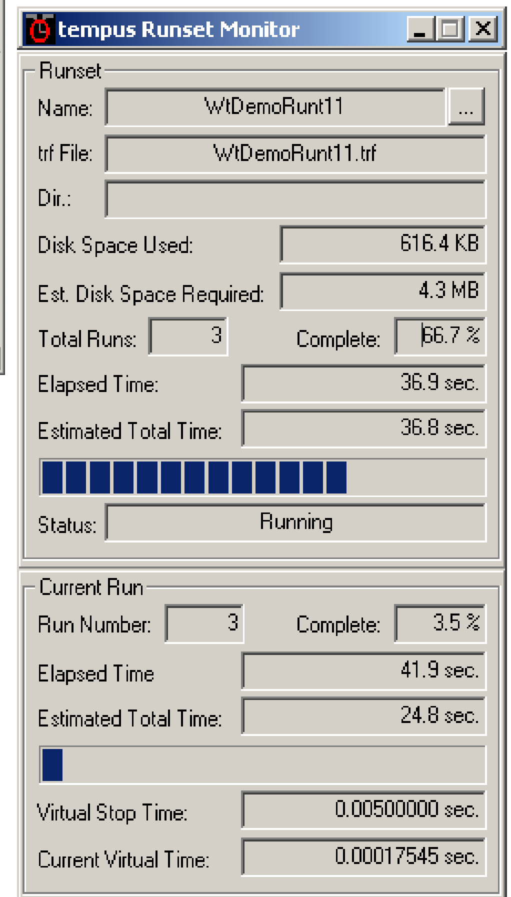
Running the simulation…

- Click on **Build->Execute**. This will automatically save the Runset Information to disk, generate the C++ main program, compile it, link it, and execute it.

- Shortly after execution begins, a "tempus Runset Monitor" will appear. This provides information such as elapsed time, disk space used, etc. When execution is complete, it will appear as shown.



- You could use the toolbar button to run instead.

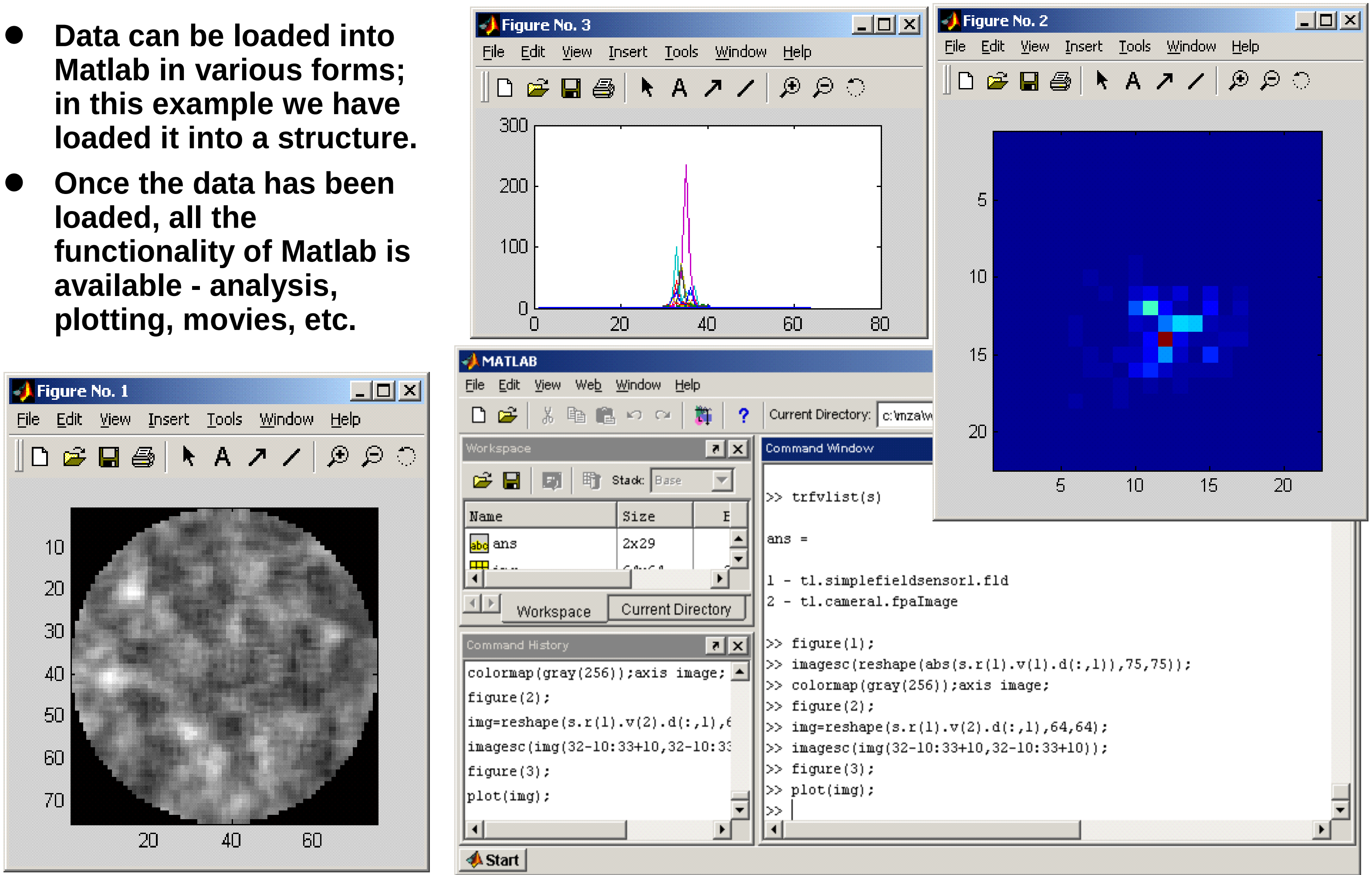


Run the simulation…

The time required to run a simulation can vary greatly. Some studies can be run in minutes. Others take CPU-years.

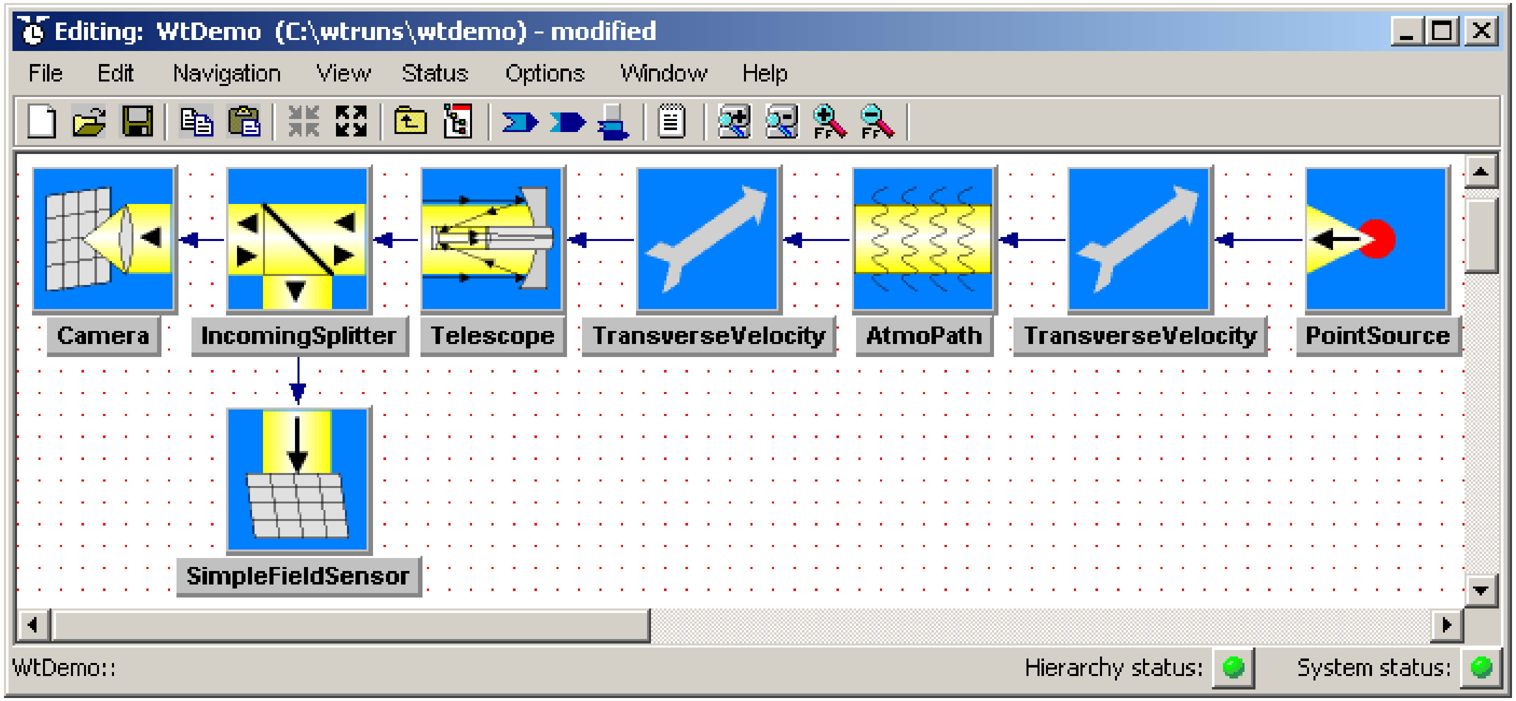
Analyzing the results in Matlab…

- **Data can be loaded into Matlab in various forms; in this example we have loaded it into a structure.**
- **Once the data has been loaded, all the functionality of Matlab is available - analysis, plotting, movies, etc.**



Finally, you can load the results into Matlab to visualize them.

WtDemo Model



- **This is a model of a telescope system imaging a point source through turbulence.**
- **Model features:**
  - **Records amplitude and phase at the pupil plane, and intensity at the focal plane.**
  - **Models platform motion, source motion, and/or wind.**
  - **Uses standard turbulence models, e.g. Clear 1 or Hufnagel-Valley, and/or user-defined models.**
  - **All major system variables are parameterized, so they can be changed without changing the model itself.**

Baseline Adaptive Optics and Track (BLAT) Model

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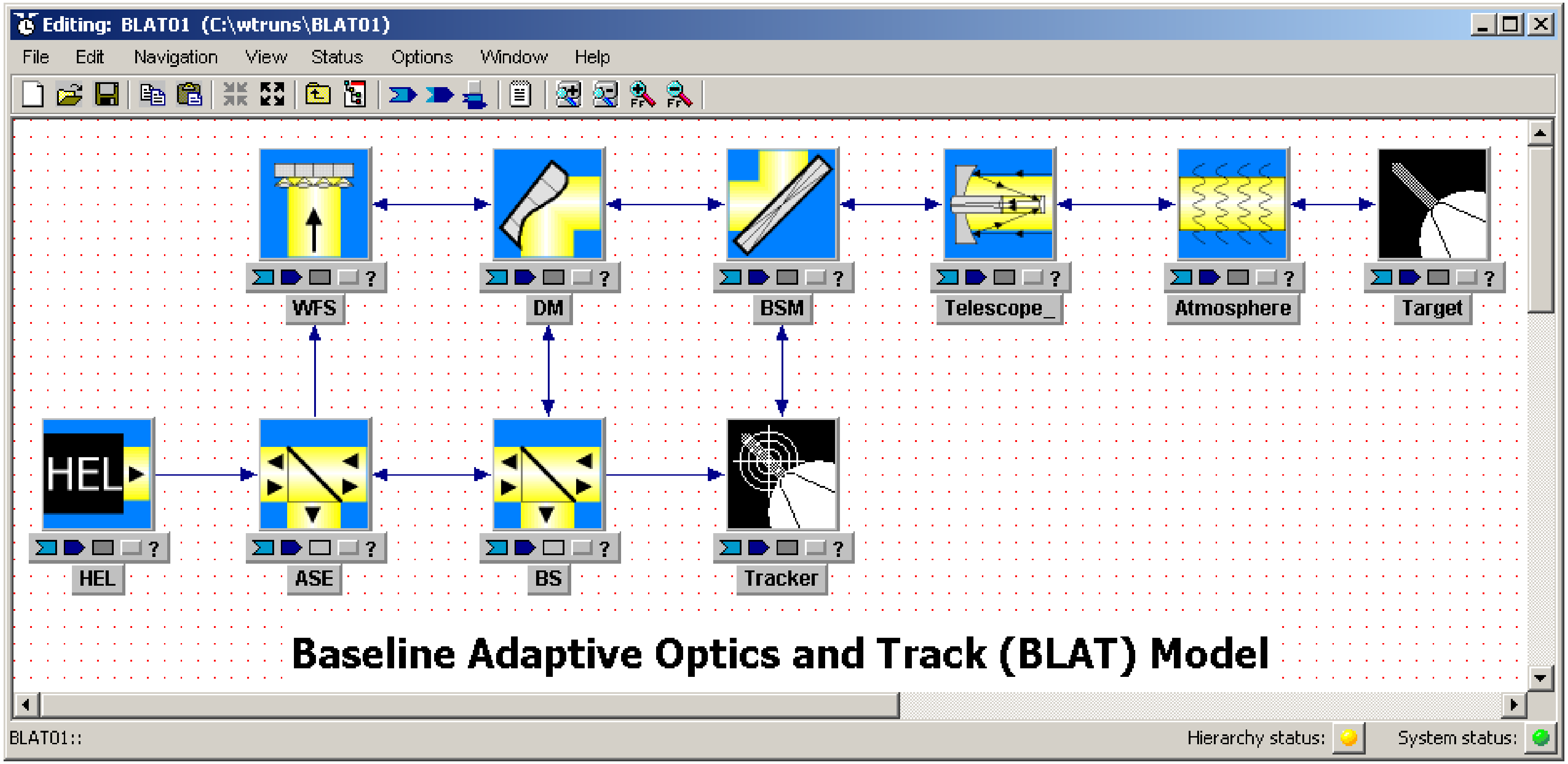
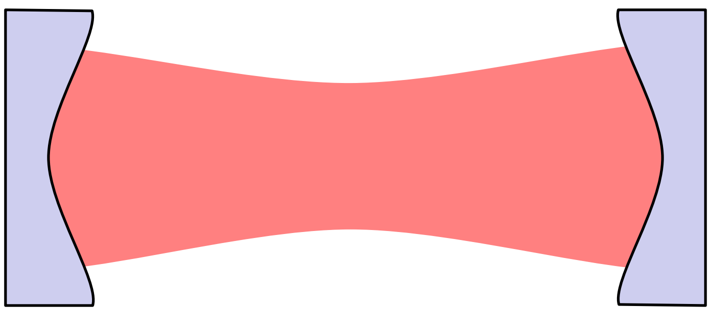


A closed-loop AO and track system using a standard tip-tilt centroid tracker and a tilt-removed least-squares reconstructor on a Shack-Hartmann wavefront sensor.

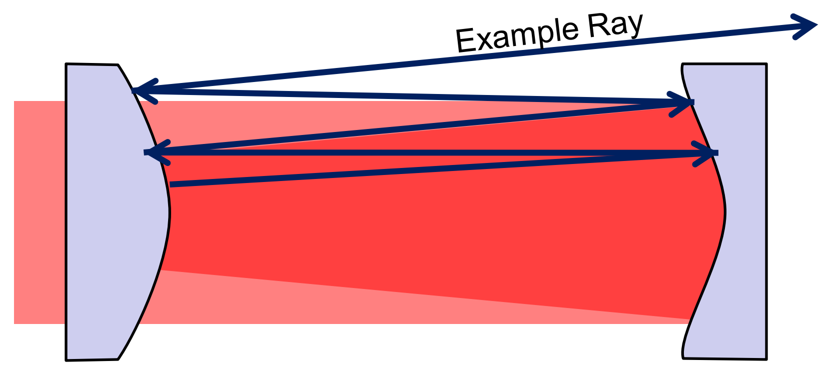
Laser Resonator Architectures: Stable vs. Unstable

Stable



Rays captured by a stable resonator will never escape geometrically.

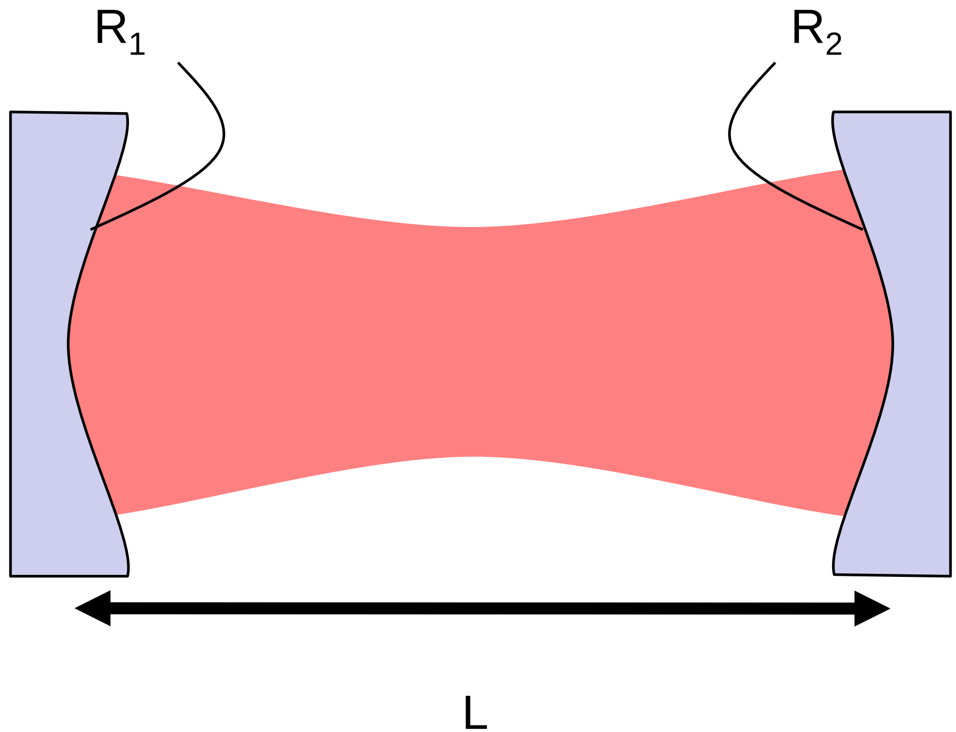
Unstable



All rays launched in an unstable resonator (except the on-axis ray) will eventually escape from the resonator.

Determining Resonator Stability

$$g_1 = 1 - \frac{L}{R_1}$$

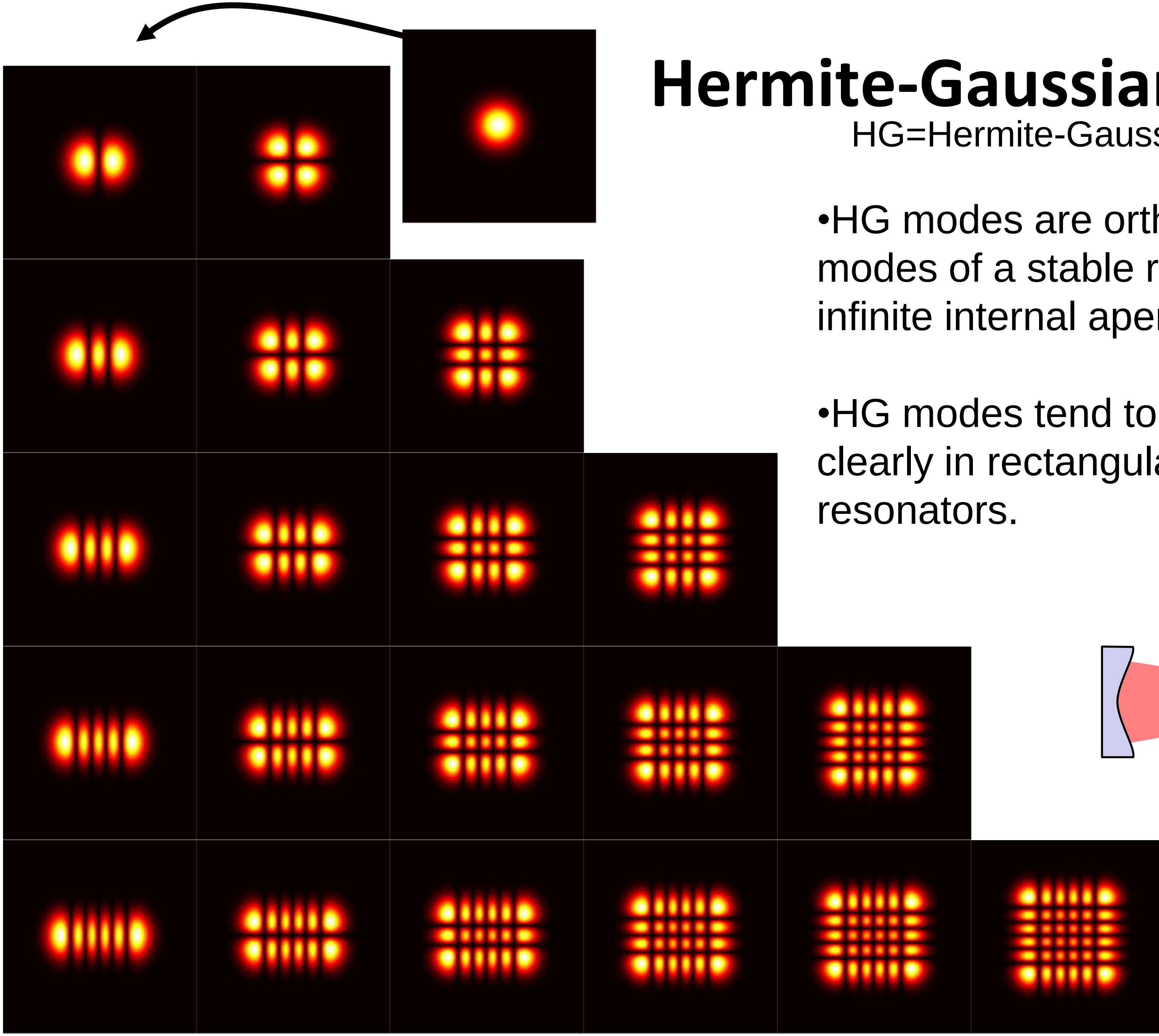


$$g_2 = 1 - \frac{L}{R_2}$$

Stability Criteria

$$0 \le g_1 g_2 \le 1$$

A. E. Siegman, Lasers, University Science Books (1986)

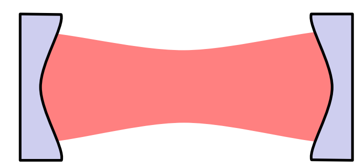


Hermite-Gaussian Modes

HG=Hermite-Gaussian

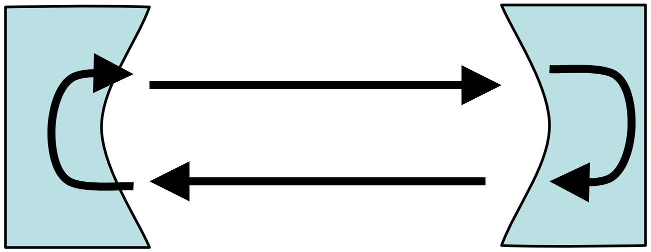
•HG modes are orthogonal modes of a stable resonator with infinite internal apertures.

•HG modes tend to appear clearly in rectangular-aperture resonators.



The Iterative Fourier Transform (aka Fox & Li) Technique

- A field is propagated through repeated round-trips until the field has converged to a stable field distribution.
- This is a commonly used technique for simplifying the 3D solution of Maxwell's Equations into a 2D problem (i.e. Gerchberg-Saxon technique)



A. G. Fox and T. Li. "Resonant modes in a maser interferometer", Bell Sys. Tech. J. 40, 453-58 (March 1961).

A. G. Fox and T. Li, "Computation of optical resonator modes by the method of resonance excitation", IEEE J. Quantum Electronics. QE-4, 460-65 (July 1968).

Comments on Fox & Li Solutions

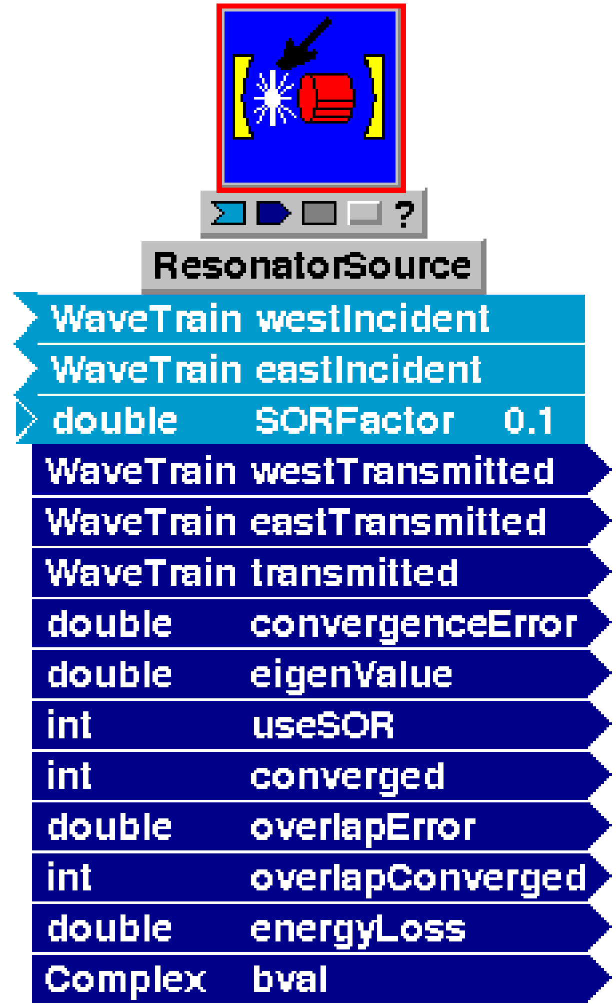
- Solution is for an instantaneous state, which is typically the steady-state of the laser.
- Stable resonators are much more computationally intensive to model than unstable resonators.
  - We attribute this to the geometric output coupling of an unstable resonator.
  - Larger eigenvalue difference between fundamental mode and the next higher-order mode.
- Not generally appropriate for pulsed or time-varying solutions unless the time-varying nature is much slower than a resonator round-trip time.
  - This is analogous to a split-time modeling techniques.

WaveTrain Components for Laser Resonators

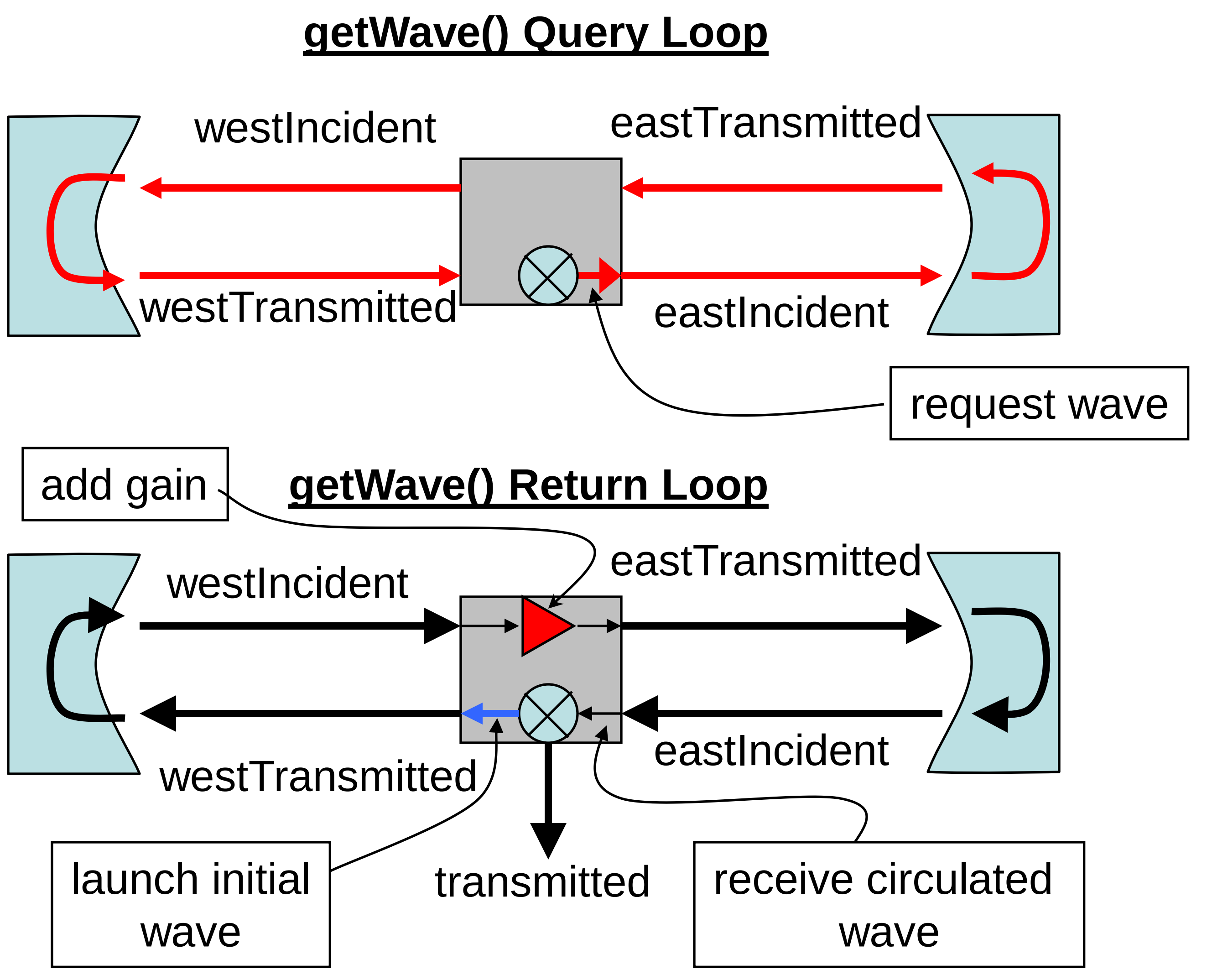
- ResonatorSource
  - Core of all resonator modeling
- SimpleSaturableGain
  - Implementation of the approximate gain equation derived from the rate equations

Introduction to the ResonatorSource in WaveTrain

- In WaveTrain, light is requested by a sensor and that query travels back through the path (or multiple paths) to the sources.
- ResonatorSource acts as both a sensor and a source because it both requests light and receives it.
- There is an output of the resonator source for evaluating the laser output during the Fox & Li iterations.



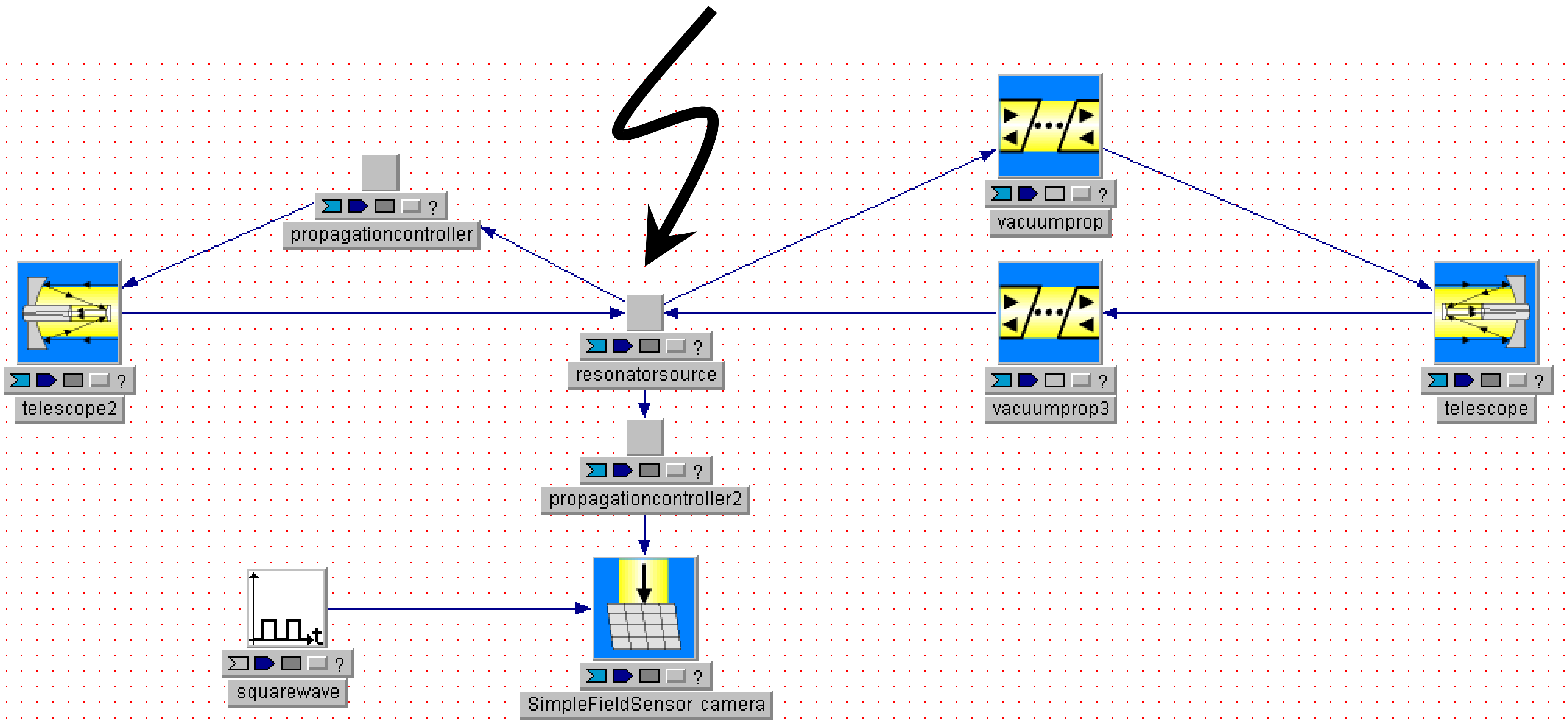
General RS Functionality



General ResonatorSource Functionality

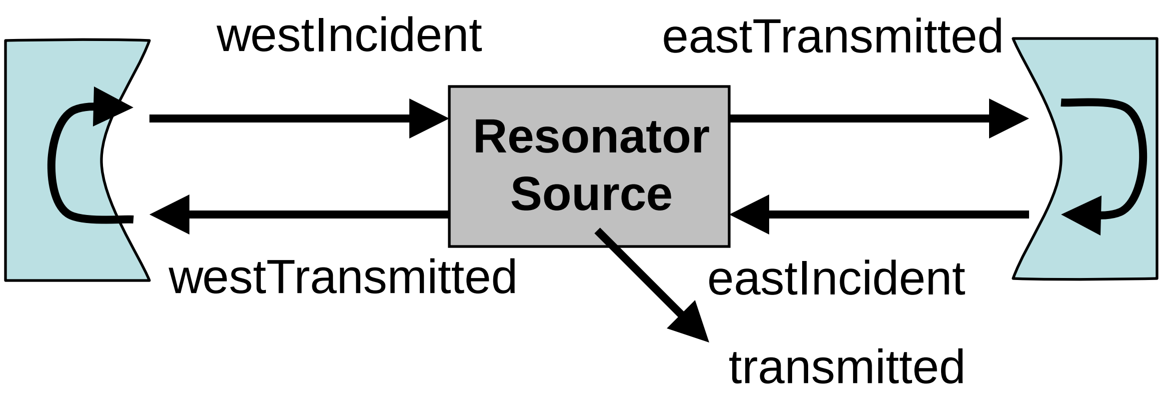
- Generally, the Resonator Source (RS):
  - passes waves going from west to east and adds gain to them,
  - returns the result of the last iteration for waves going east to west,
  - calculates the convergence error and eigenvalue, and
  - responds to outside requests for a wave by returning a wave from the wave buffer.

Development of a WaveTrain Resonator Source for Fox & Li



The WaveTrain Resonator Source

- Inputs
  - WaveTrains: westIncident, eastIncident
- Outputs
  - WaveTrains: westTransmitted, eastTransmitted, transmitted
  - Doubles: convergenceError & eigenValue



The WaveTrain™ Resonator I/O

- Inputs
  - westIncident - wave from the west
  - eastIncident - wave from the east
- Outputs
  - westTransmitted - wave out to the west
  - eastTransmitted - wave out to the east
  - transmitted - wave out of the resonator
  - convergenceError - error associated with the iterative convergence (rms difference between the field amplitudes)
  - eigenValue - ratio of two consecutive fields

Resonator Source Key Parameters

- Parameters
  - wavelength, initial field
  - roundTripLength - total propagation distance for one round-trip through the resonator
  - storageGrid - geometry of the buffer storage
  - gain - resonator gain factor
  - startTime - time to start the first light from the source
  - storageInterval - time interval upon which to sample the field
  - storageDuration- maximum storage look-back time duration

Gain Models

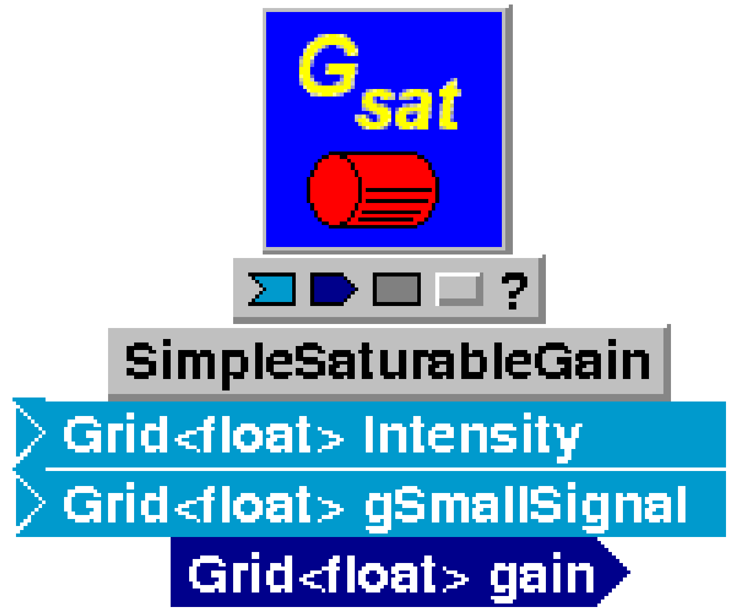
- WaveTrain currently has interfaces to several different gain models (some of which are proprietary to our commercial customers), but the most commonly used is SimpleSaturableGain.
- ComplexSaturableGain allows the user to specify a 2D gain and saturation intensity field.
- More complex effects like ASE have been successfully added the saturable gain models as an additional factor.
- Interfaces to high fidelity gain models have also been demonstrated for COIL modeling (GASP interface and OCELOT interface)

SimpleSaturableGain

- Gain in laser medium is represented by the WaveTrain component SimpleSaturableGain
- This component adds gain to the incoming beam according to the equation:

$$G = \exp\left(0.5 \cdot \alpha \cdot L \cdot \left({}^{1}\!/_{1 + I/I_{sat}} \right)\right)$$

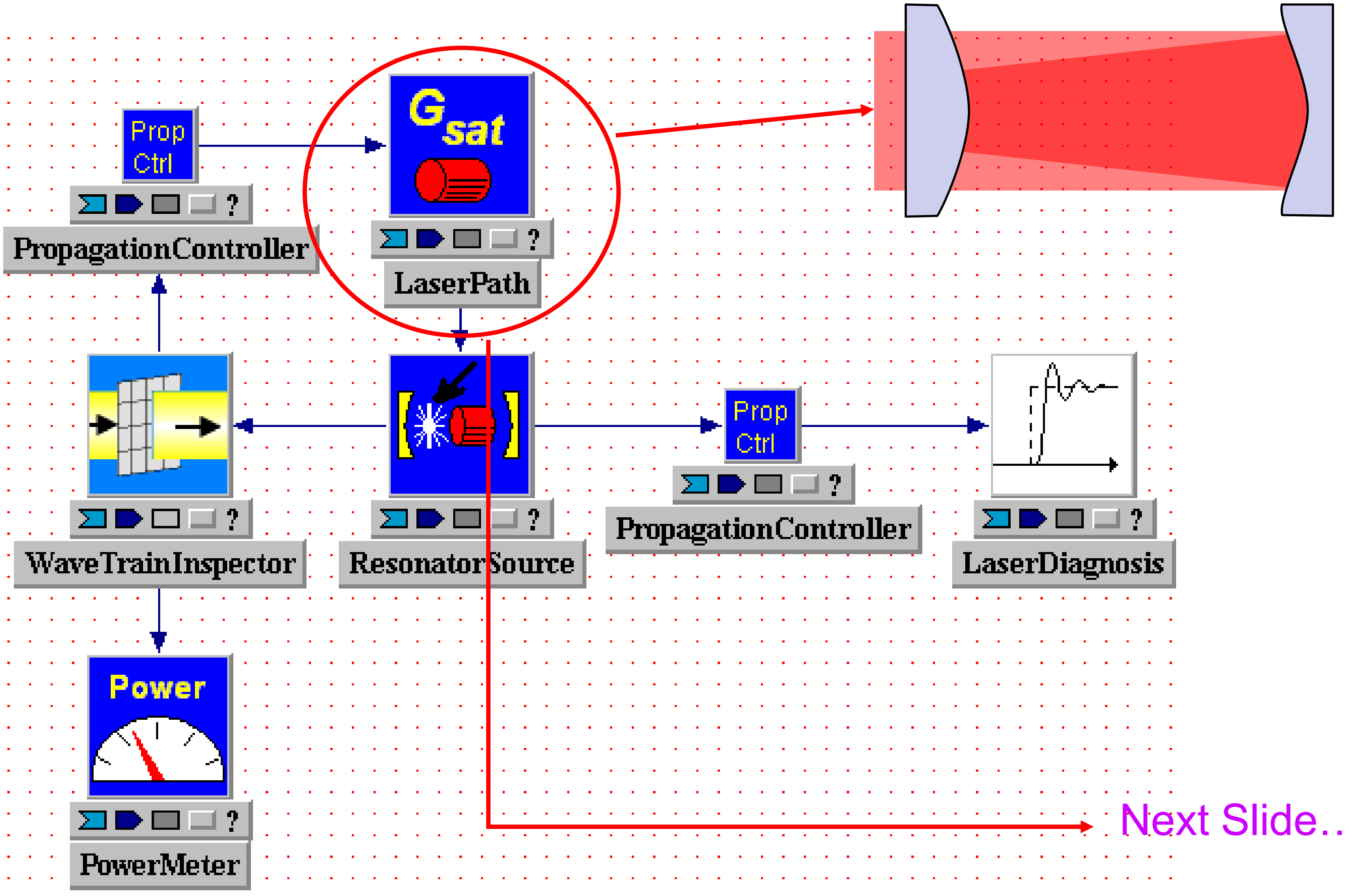
where α is gain per unit length,
L is cavity length, and
I_{sat} is the saturation intensity



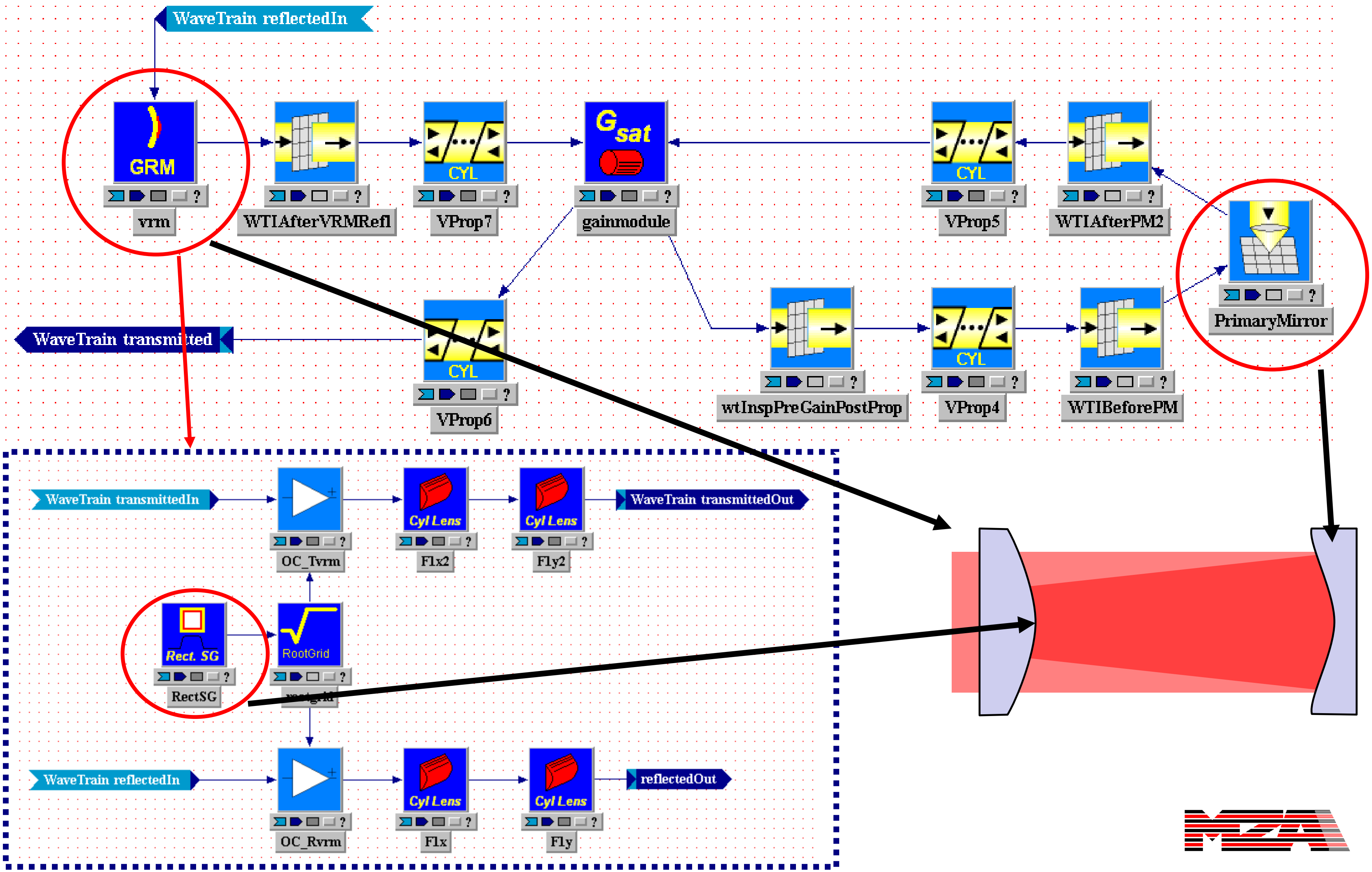
Unstable Laser Resonator

- Predictions from Theory
- WaveTrain Model Setup
- Example Parameters
- Results & Comparison with Theory
- Conclusions

WaveTrain Model



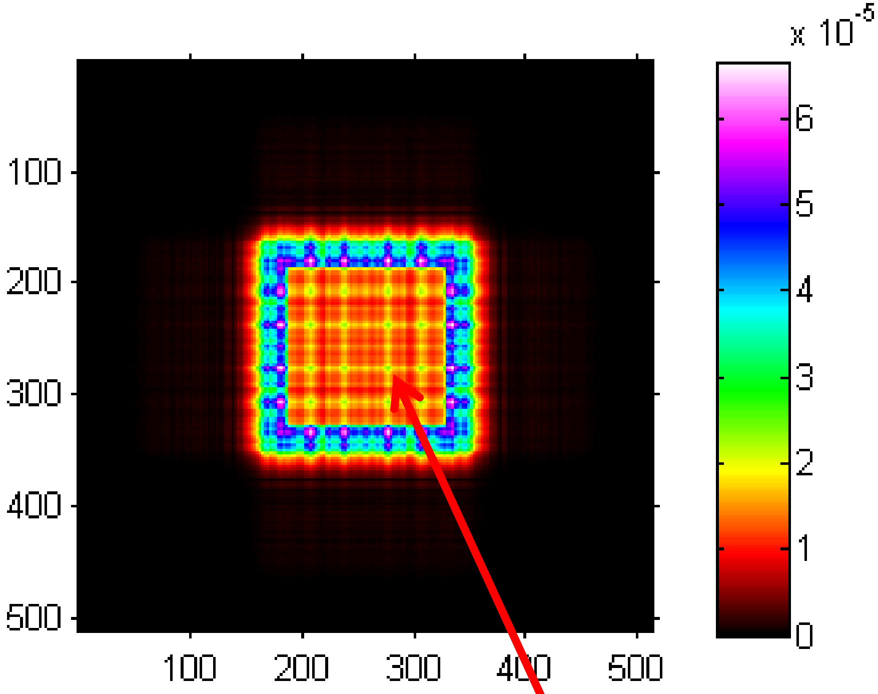
WT Model of Variable Reflectivity Mirror (VRM)

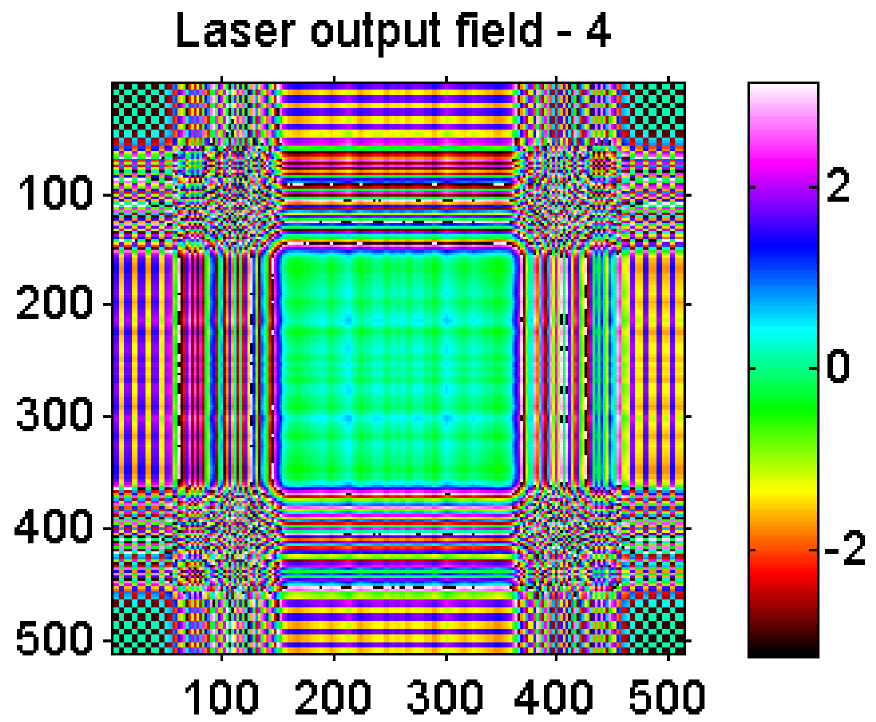


Parameters

- NumAvgs_vec = 1
- Reflectivity = 0.9
- Iterations = 4
- Rpm (Radius of curvature of primary mirror) = 7 m
- Rsm (Radius of curvature of secondary mirror) = -5 m
- cavityLength0 = 1.0 m
- Propagation Grid = 512 by 50e-6
- Ssgain = 1.0
- Amp0(Amplitude of initial field) = 15000
- Radius of initial field = 3.0e-2 m
- Wavelength = 1e-6
- Saturation intensity = 1e7 W/m^2
- Normalization = 0
- convergenceThreshold = 1e-9
- GainLength = 1.0
- Aperture Width (AW) = 1cm
- Magnification (M) = 1.4(Rpm/Rsm)
- Rectangular gaussian waist = AW /(2*M)

Output Field After 4 Iterations with a 200^{th} Order Super-Gaussian



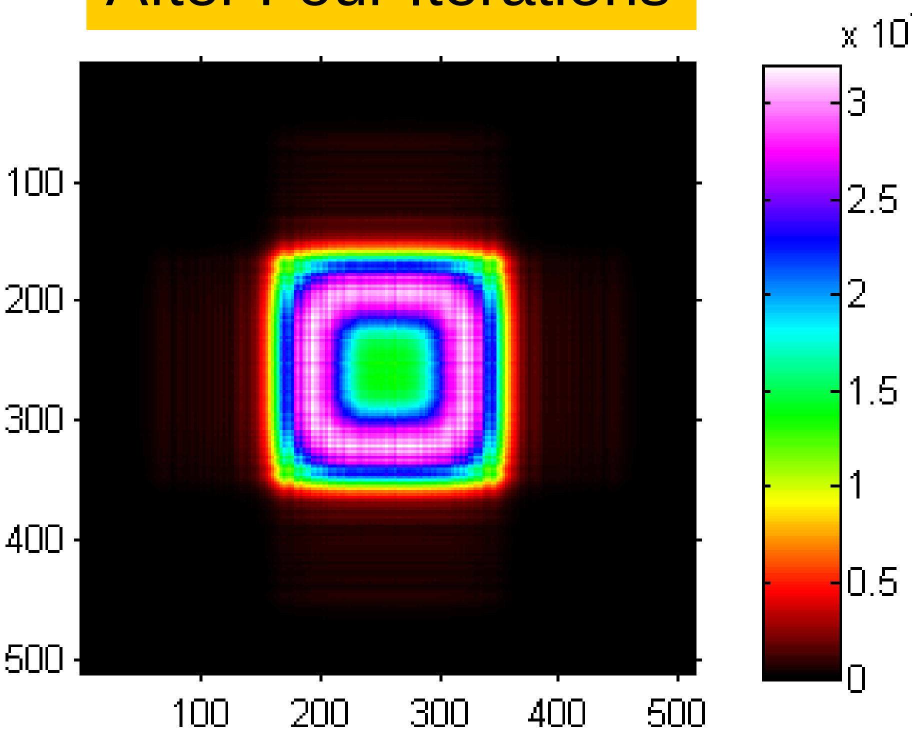


Significant structure from Fresnel ringing

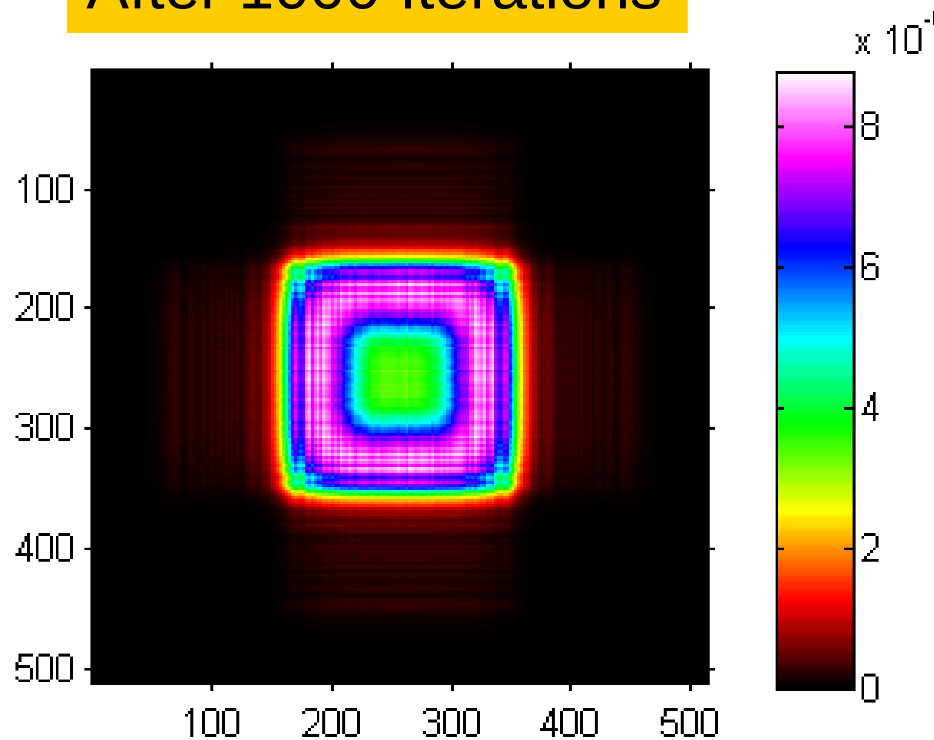
The Unstable Resonator Mode is Established Very Early.

4th Order Super-Gaussian

After Four Iterations



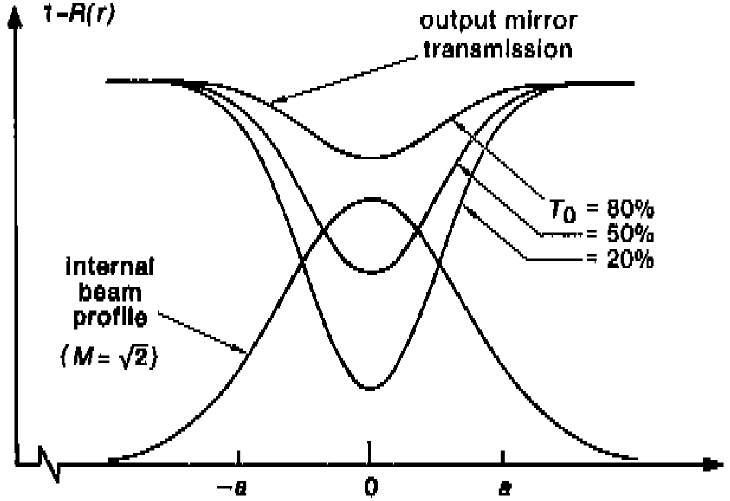
After 1000 Iterations

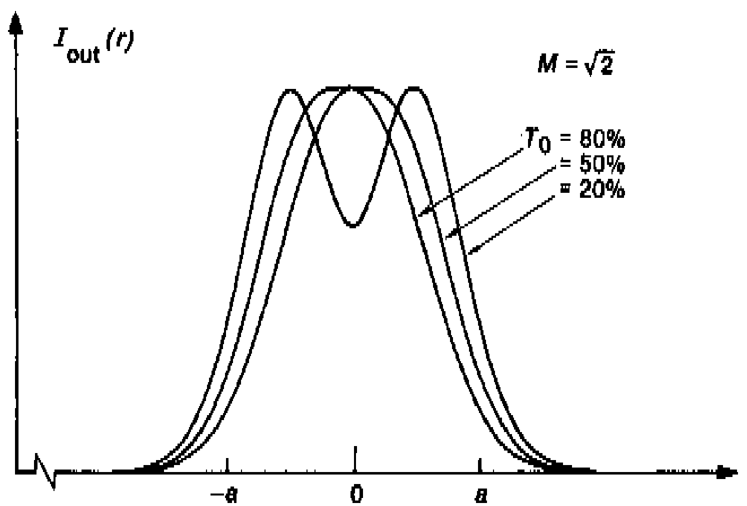


Fresnel ringing still present from the internal aperture.

GRM Unstable Resonator Theory

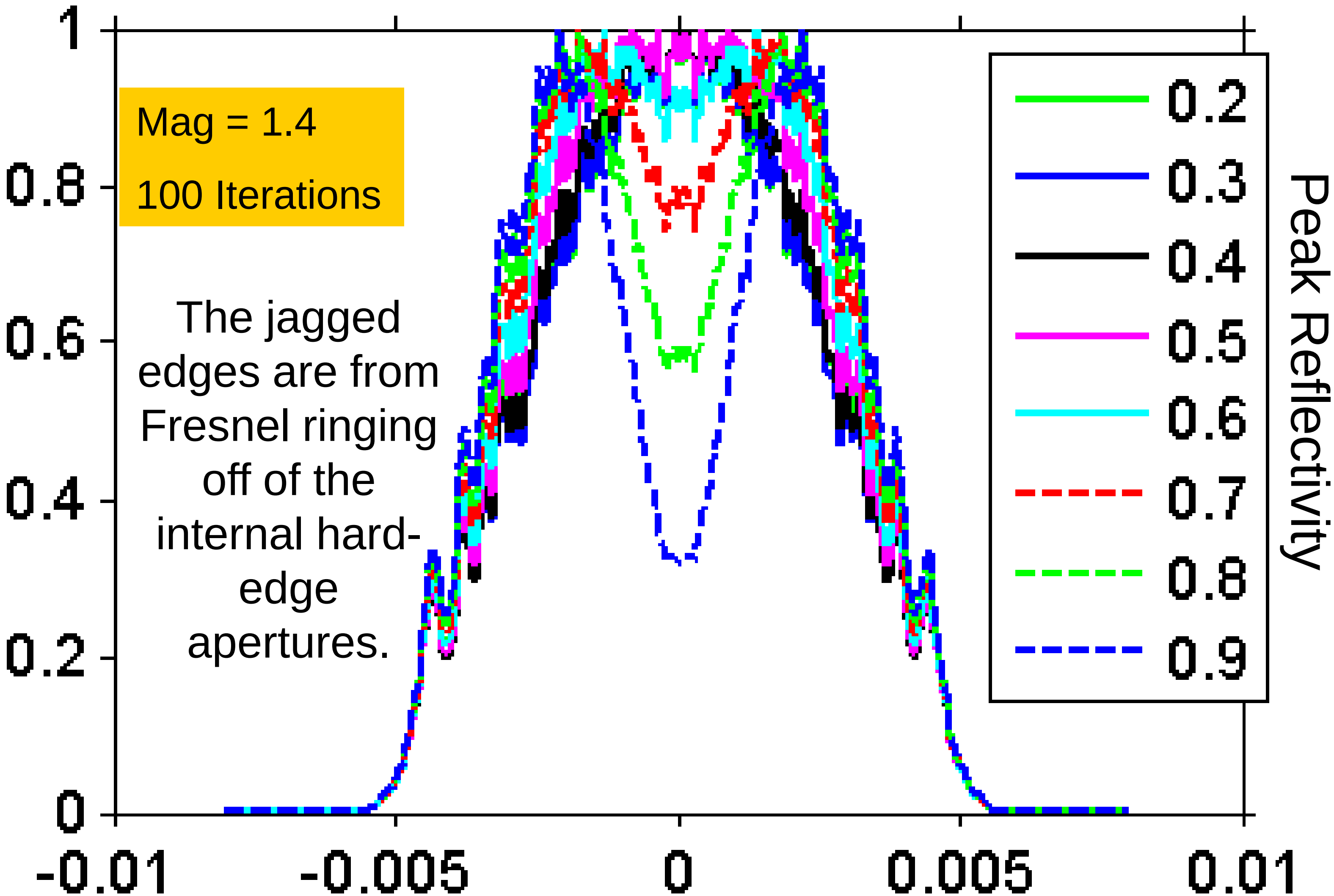
- To avoid Fresnel ringing at the edges of the beam, give the laser designer more control over the output beam profile, and reduce the effect of the spot of Arago, many laser designers use variable or graded reflectivity mirrors (VRMs or GRMs) in their resonators.
- Siegman presents some of the theory behind a gaussian GRM in <u>Lasers</u>.
- In the next few slides, we use WT to duplicate the results described by Siegman for a gaussian GRM.



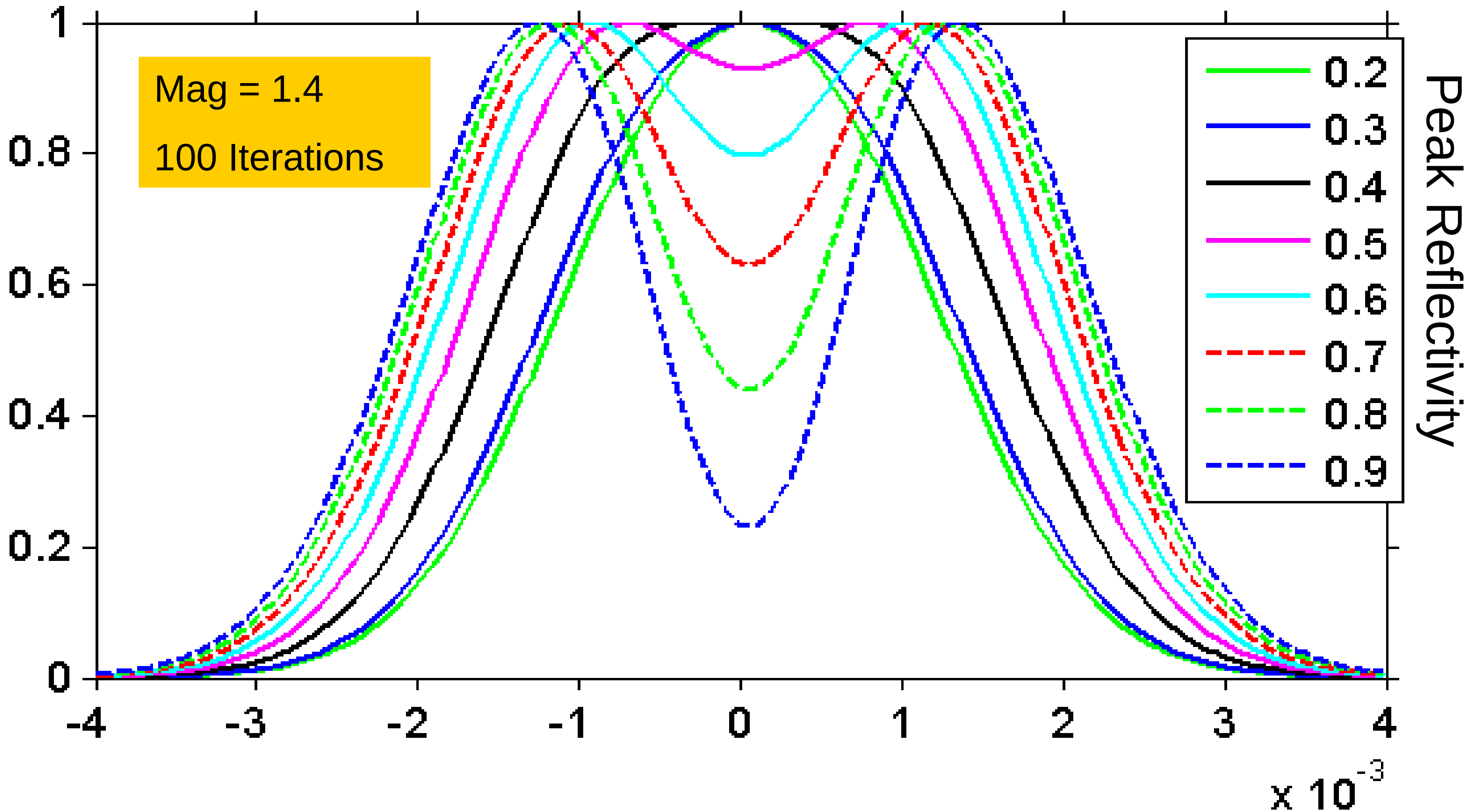


A. E. Siegman, Lasers, University Science Books (1986)

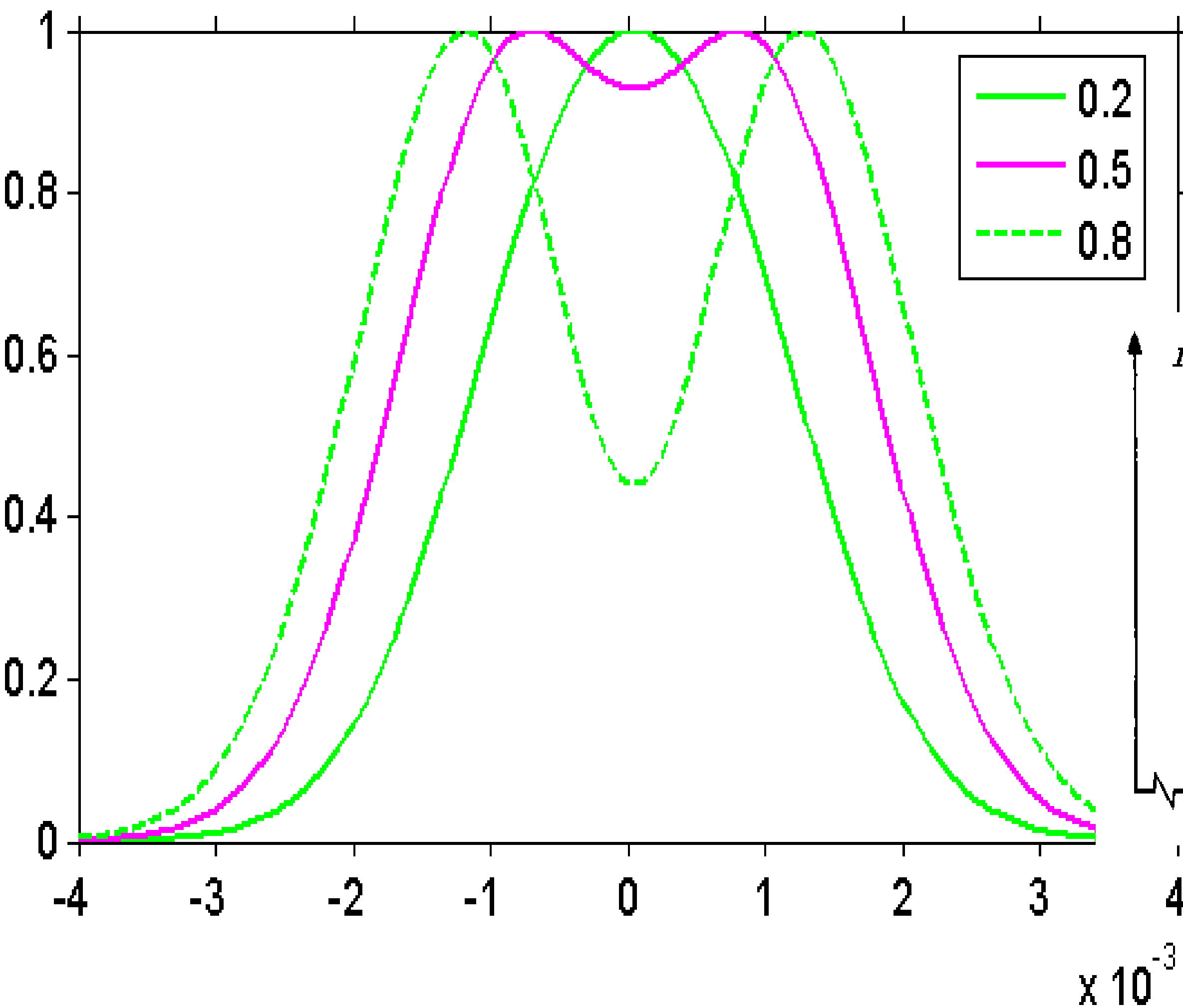
Gaussian GRM Intensity Profiles



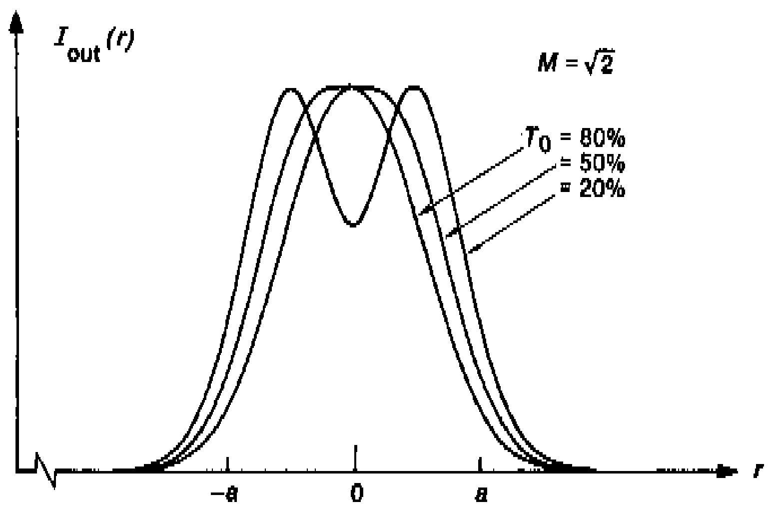
Gaussian GRM with Larger Apertures



Comparison to Siegman's Results



We see here a slight discrepancy, but the shapes are quite similar.



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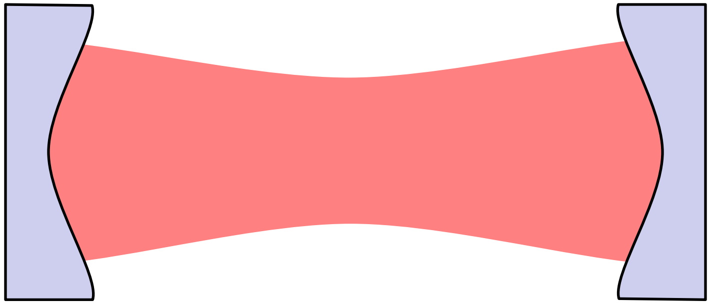
Conclusions

- We have presented how we have adapted WaveTrain to model laser resonators.
- We presented examples of modeling results from stable resonators with and without gain and unstable laser resonators with gain.
- We also presented a new modeling technique for increasing the speed and stability of models of multi-mode stable laser resonators.

Stable Resonator Without Gain

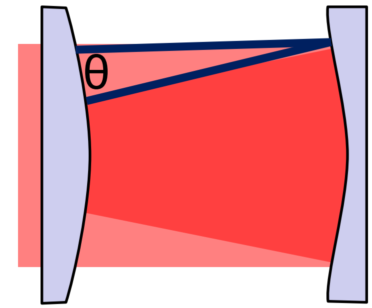


Stable Resonator without Gain

- Predictions from Theory
- WaveTrain Model Setup
- Example Parameters
- Results & Comparison with Theory
- Conclusions

Mesh Parameters for Laser Modeling

- Most Rigorously Correct Method:
  - Determine the mesh required for a round-trip and use that mesh.
  - For systems of simple optics, use the technique outlined by Mansell, Praus, and Coy
- Simple Approximation: Determine the mesh required for the propagation between the two end-optics using the simple Coy and Mansell formulas embodied in the MZA worksheet.
- Unstable Resonator Approximation: Determine the maximum ray angle needed to map the scraper hole or GRM edge to the edge of the primary/collimating mirror.
- Stable Resonator Corollary: Reduce the required mesh angle by the number of round-trips for ray-reproduction/imaging (more discussion on how to calculate this factor later).



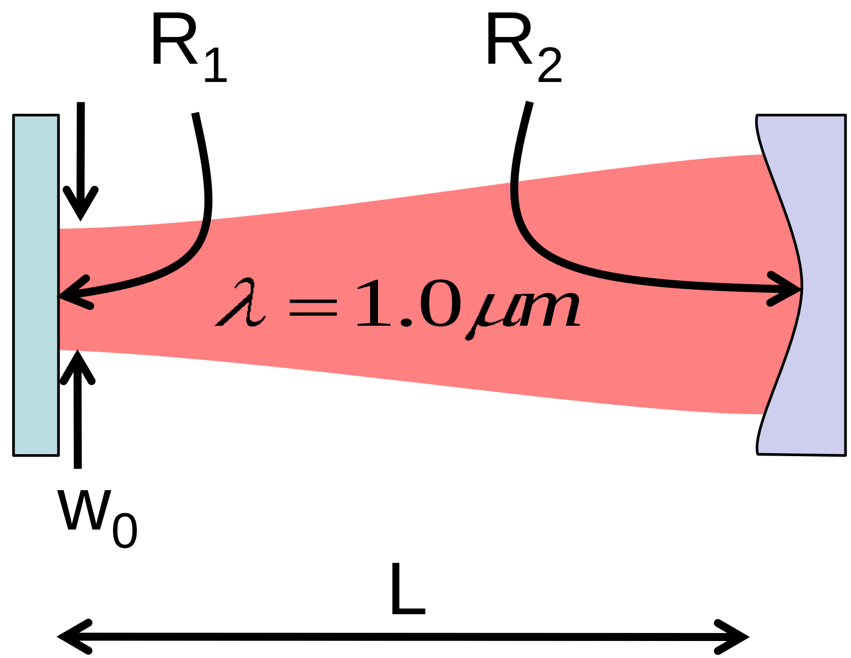
$$\theta \approx \frac{\left(D_{\max} - \frac{D_{\max}}{M}\right)}{L} = \frac{D_{\max}}{L}\left(1 - \frac{1}{M}\right)$$

$$\theta \le \frac{\lambda}{2\delta} \Rightarrow \delta \le \frac{\lambda}{2\theta}$$

$$N \ge \frac{D_{\max} + \theta \cdot L}{\delta}$$

Plano-Concave Resonator
Lowest-Order Mode

$$w_0^{\,2} = \left(\frac{\lambda}{\pi}\right)\left[L\left(R_2 - L\right)\right]^{1/2}$$



Example: λ = 1µm, L = 0.8 m, R_2 = 10 m → w_0=0.93 mm

W. Koechner, *Solid-State Laser Engineering,* Springer.

Notes on Lowest Order Mode Theory

- Derivation:
  - The lowest order mode (Gaussian) size is can be derived for any resonator using Gaussian beam propagation equations.
  - Example: For the plano-concave resonator, when is the wavefront curvature equal the end mirror radius of curvature or R(z=L) = $ROC_{\text{primary mirror.}}$
- This theory assumes no internal apertures or gain media.

$$w(z) = w_0 \left(1 + \left(\frac{z}{z_R} \right)^2 \right)^{1/2}$$

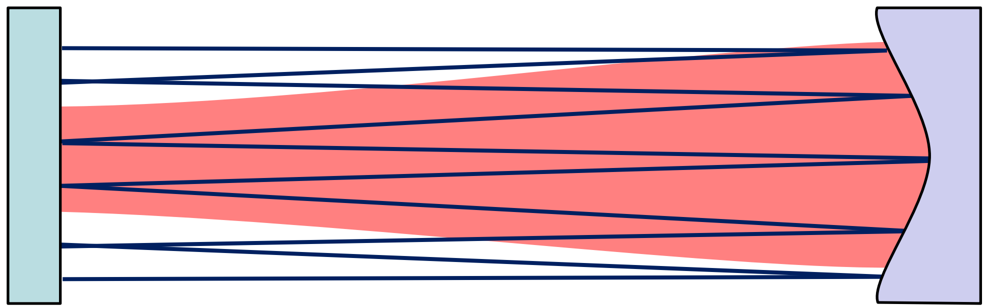
$$R(z) = z + \frac{{z_R}^2}{z}$$

$$z_R = \frac{\pi \cdot {w_0}^2}{\lambda}$$

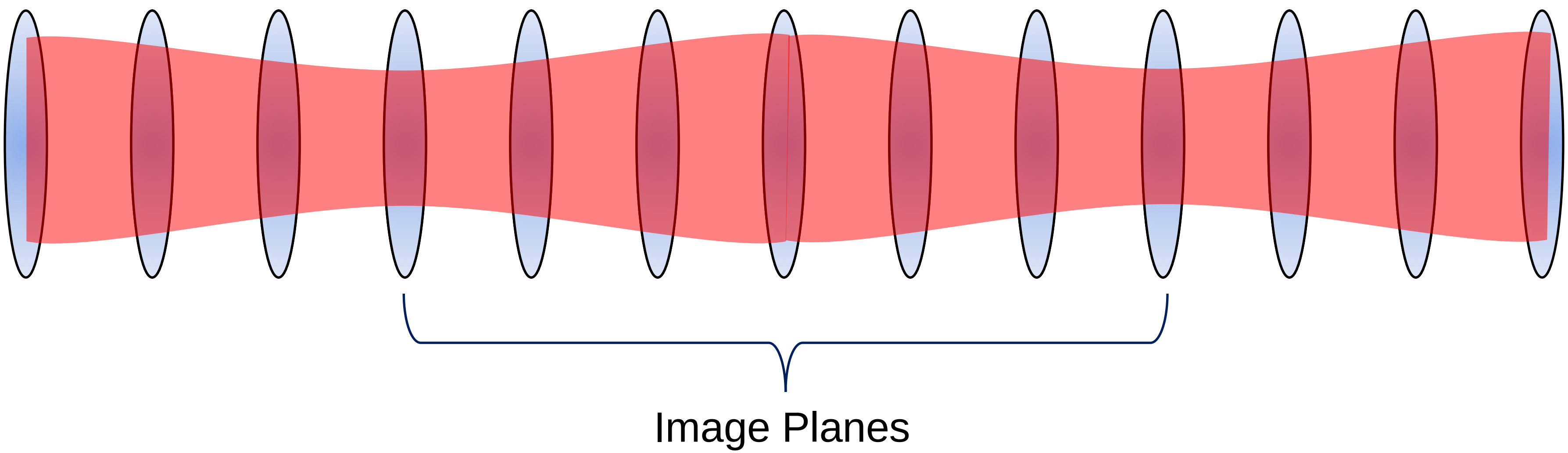
A. E. Siegman, Lasers, University Science Books (1986)

Number of Round-Trips to Image/Repeat

Plano-Concave Stable Resonator



Linearized Plano-Concave Stable Resonator



Number of Round-Trips to Image/Repeat

This problem can be addressed using ray matrices. Consider a resonator with a round-trip ray-matrix given by M. In N round-trips, the ray-matrix will be given by M^N. To reproduce any input ray, we need to determine the number of round trips to make the identity matrix, or $M^N=I$.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^N = M^N = I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

This can be determined numerically, but can also be addressed using eigenvalue analysis. The approach on the right derives an equation for N assuming a plano-concave resonator with length L and the end mirror radius of curvature equal to 2f.

$$M^N v_i = \lambda^N v_i$$

$$M^N = \lambda^N$$

$$M = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$$

$$M = \begin{bmatrix} 1 - L/f & 2L - L^2/f \\ -1/f & 1 - L/f \end{bmatrix}$$

$$X = 1 - L/f$$

$$\lambda = X \pm \sqrt{1 - X^2}\, j$$

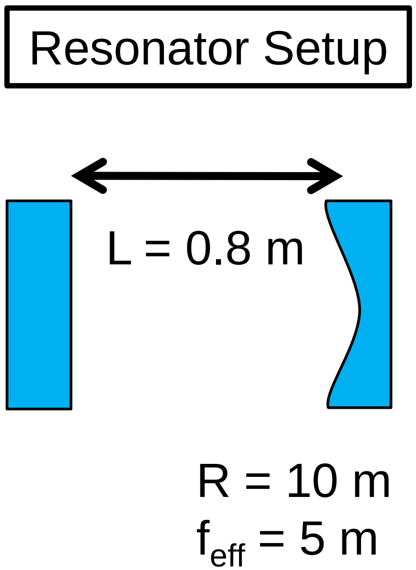
$$\lambda = e^{j\phi}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{1 - X^2}}{X} \right)$$

$$\lambda^N = e^{jN\phi}$$

$$N = \frac{2k\pi}{\phi} = \frac{2k\pi}{\tan^{-1}\left(\frac{\sqrt{1 - X^2}}{X} \right)}$$

Example Plano-Concave Resonator



$$M = \begin{bmatrix} 1 - L/f & 2L - L^2/f \\ -1/f & 1 - L/f \end{bmatrix} = \begin{bmatrix} 0.84 & 1.472 \\ -0.2 & 0.84 \end{bmatrix}$$

$$X = 1 - L/f = 0.84$$

$$\phi = \tan^{-1}\left(\frac{0.5426}{0.84}\right) = 0.5735$$

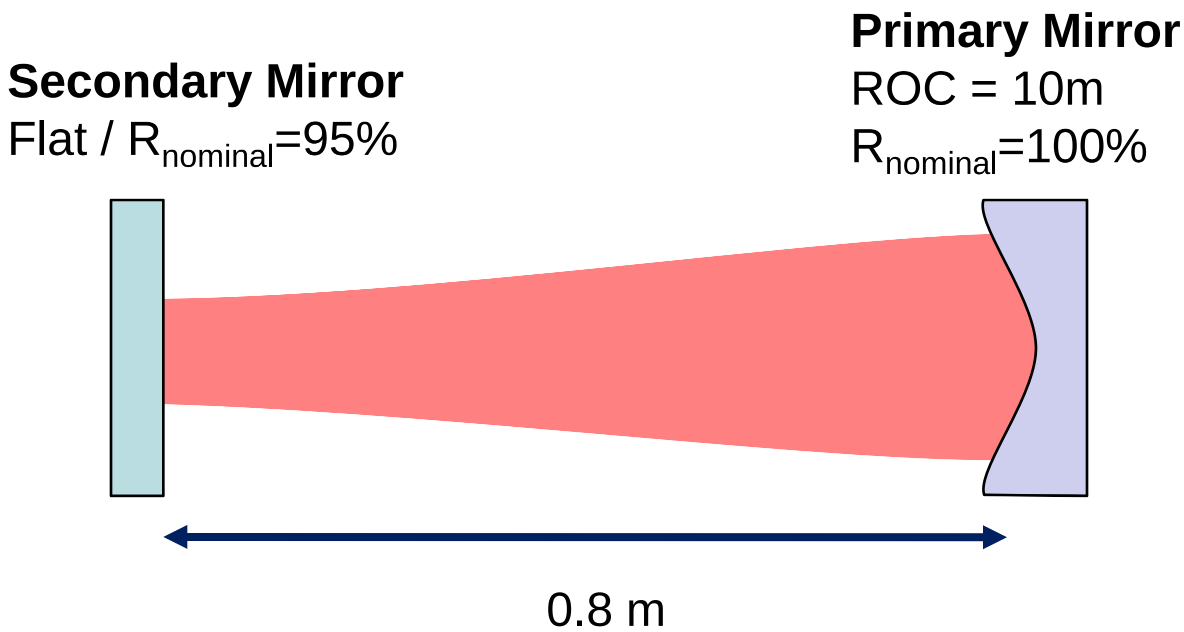
$$N = \frac{2\pi}{\phi} = \frac{2\pi}{.5735} \approx 11$$

$$M^{11} \approx \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I$$

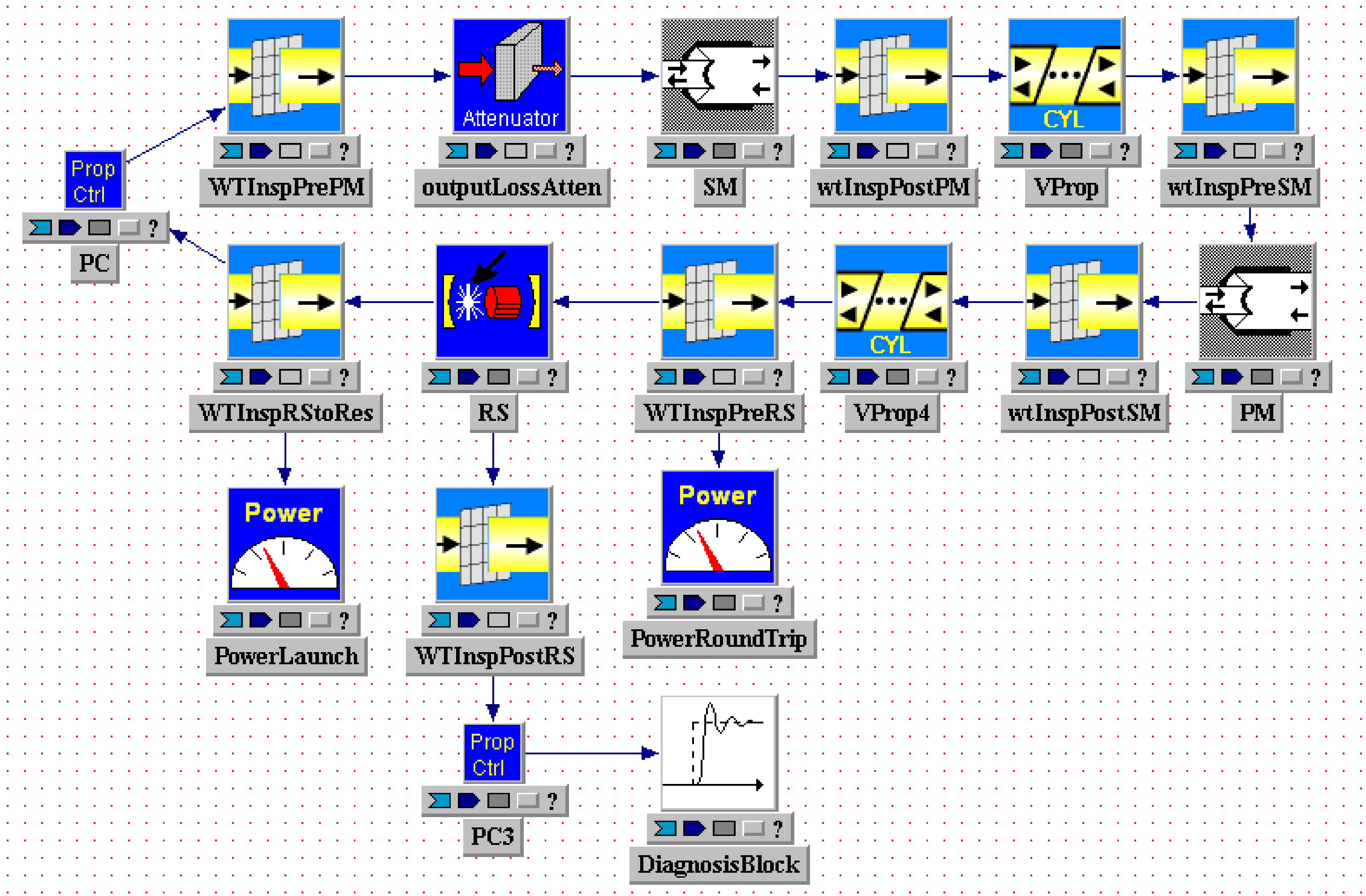
Impact of the Number of Round-Trips to Image

- This number is approximately the reduction factor of the required angular bandwidth predicted by the Coy/Praus/Mansell theory referenced earlier.
- This number is also the number of intensity profiles that need to be averaged to achieve a stable intensity for saturable gain calculations in a stable resonator (more on this later).

Example Laser Resonator Setup



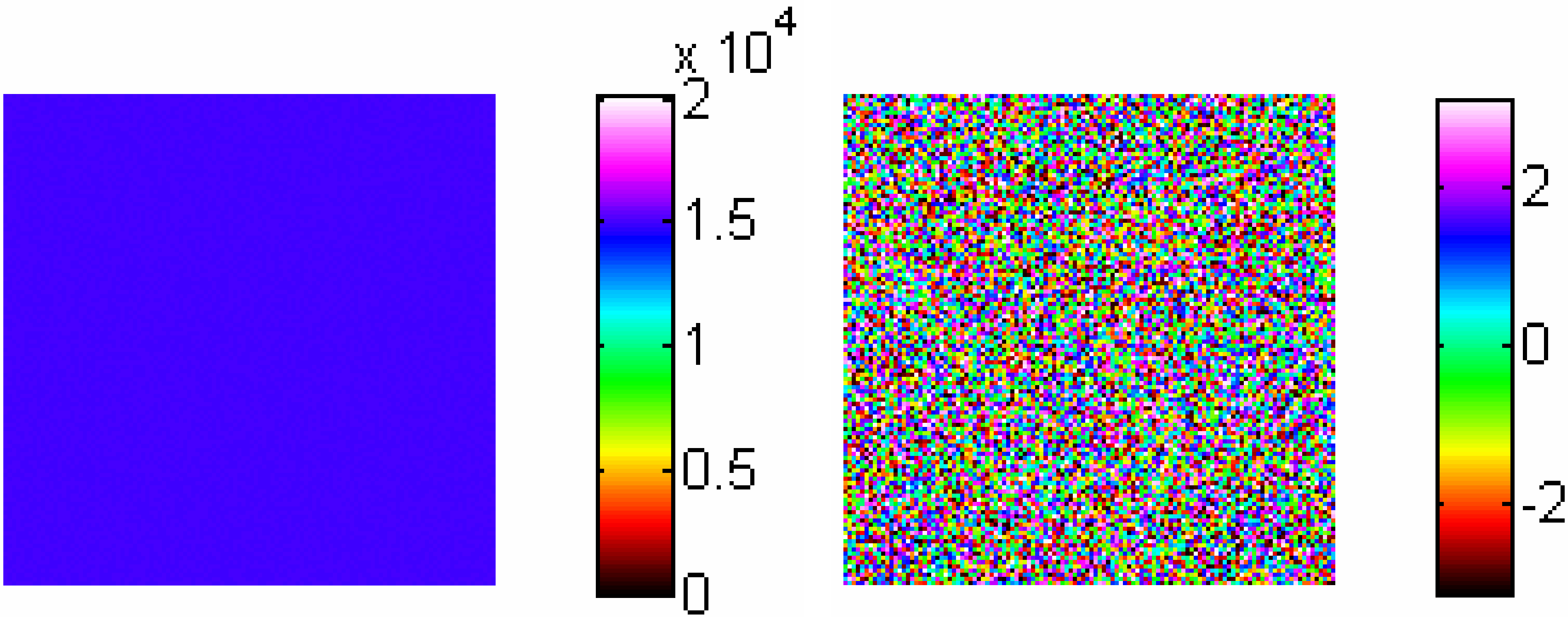
Wave Train Model



Parameters

- R_c (Radius of curvature of secondary mirror) = 10 m
- Cavity Length = 0.8 m
- Propagation grid = 256 by 56 µm (earlier 128 by 75 µm)
- Wavelength = 1 µm
- Reflectivity of output mirror = 95 %
- Initial Field = BwomikTopHat field of 6 cm initial Radius and 15000 amplitude
- Normalization = 1
- Iterations = 10000
- Varying Aperture diameter

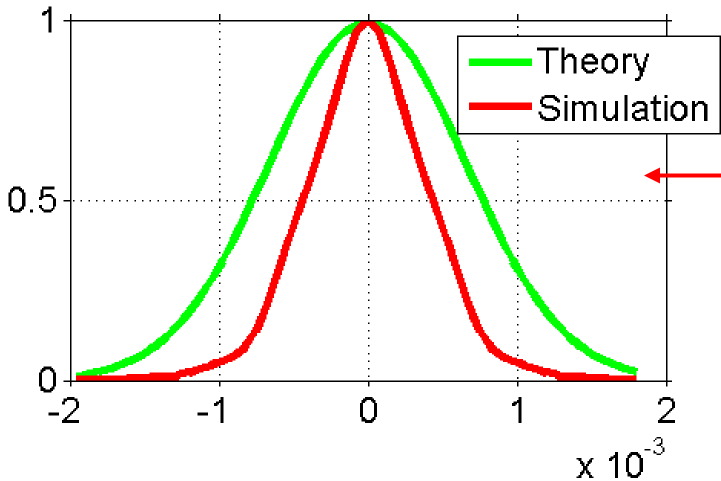
Seed all laser modes with a Bwomik field.

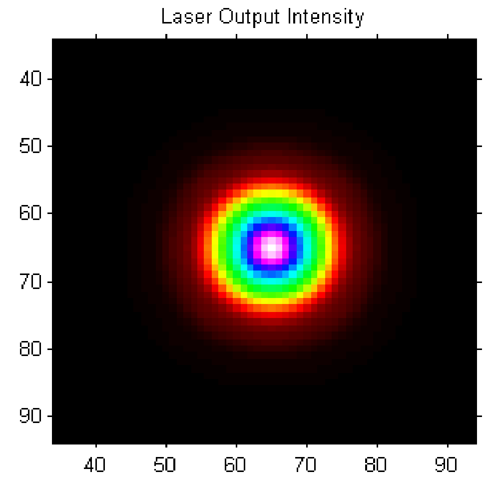


Bwomik Field is a plane wave with random phase that tends to seed all the modes of a resonator. This is implemented in “LaserGridInitializers.h”.

Converged Resonator Field Dependence on Internal Aperture Diameter

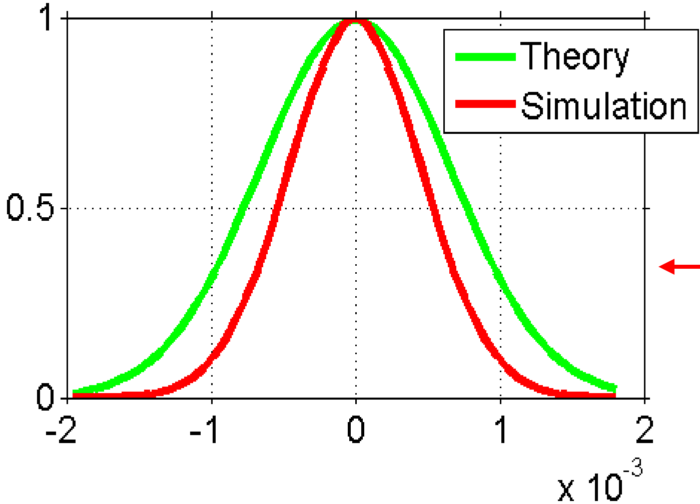
Larger aperture results approximate the theory more accurately.

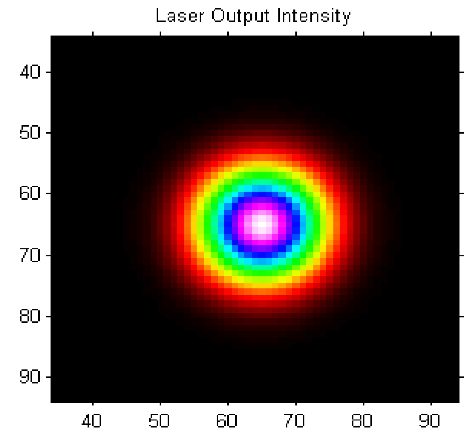




Iterations = 10000

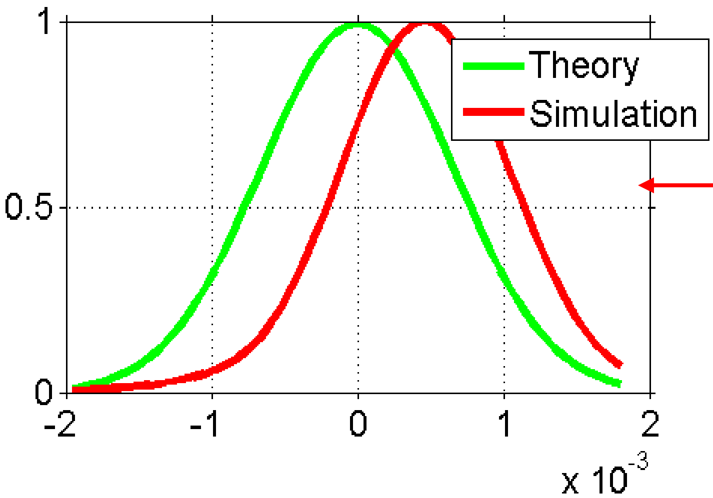
Aperture diameter = 2.0 mm

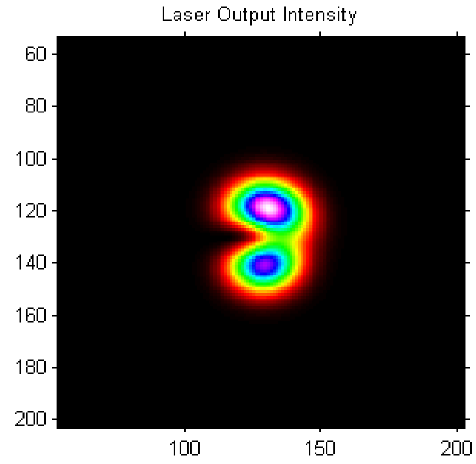




Aperture diameter = 4.0 mm

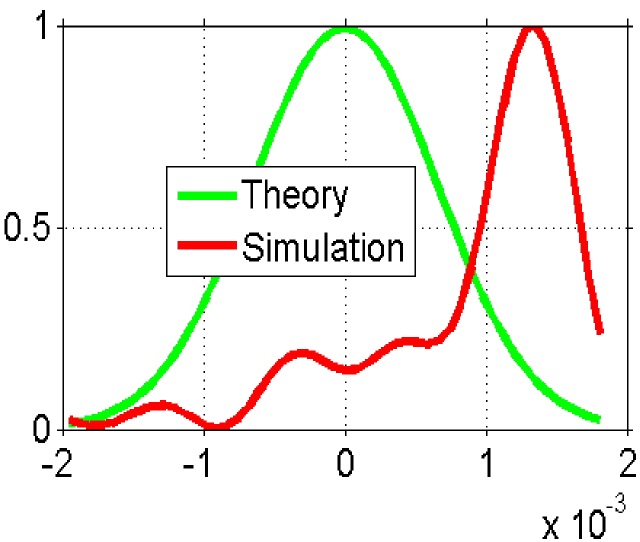
Bigger apertures require more iterations to converge.

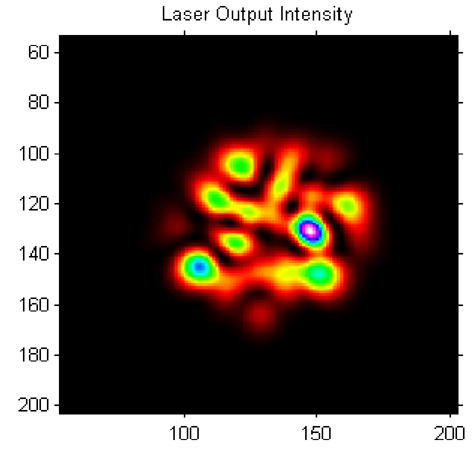




Iterations = 10000

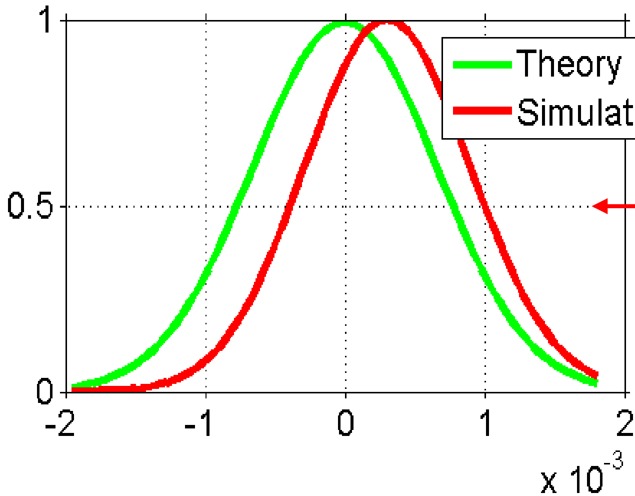
Aperture diameter = 5.0 mm

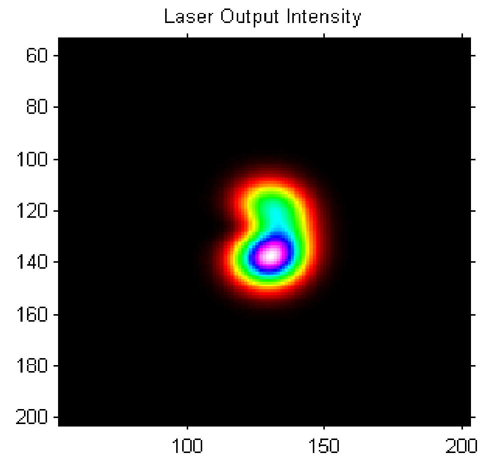




Aperture diameter = 7.0 mm

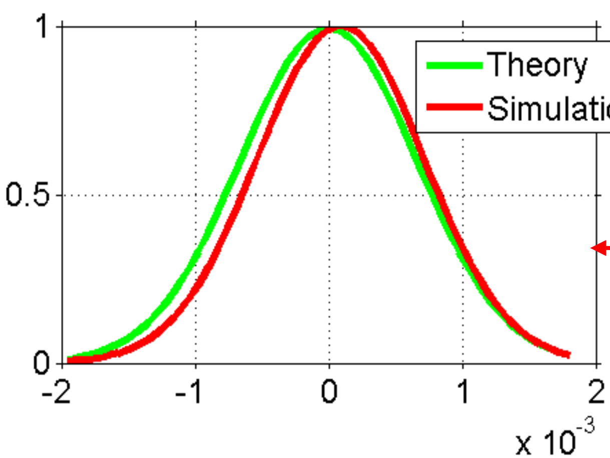
The 5-mm case begins to approach convergence after 50,000 iterations.

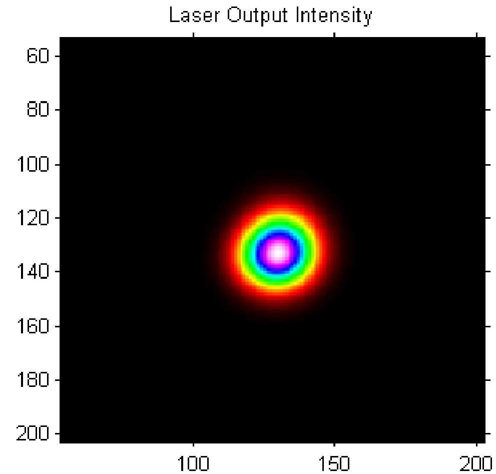




Iterations = 25000

Aperture diameter = 5.0 mm

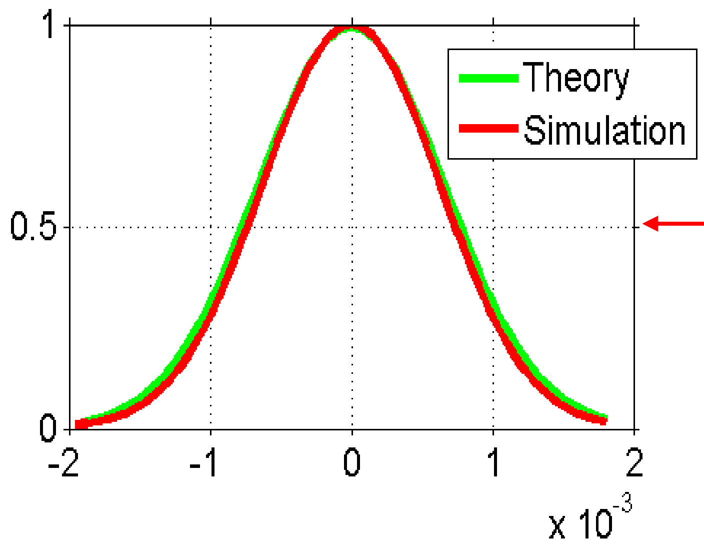


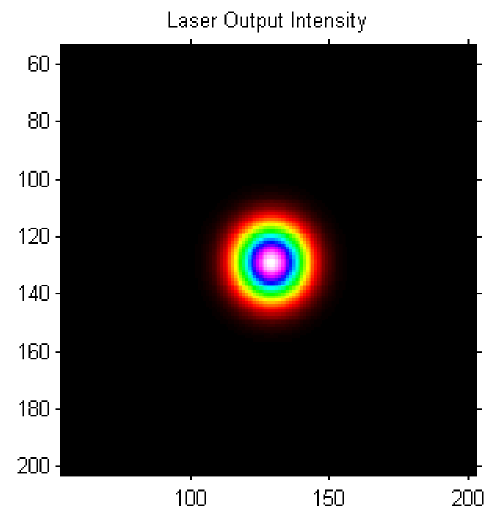


Iterations = 50000

Aperture diameter = 5.0 mm

The 5mm diameter aperture was reasonably well converged after 75,000 iterations.

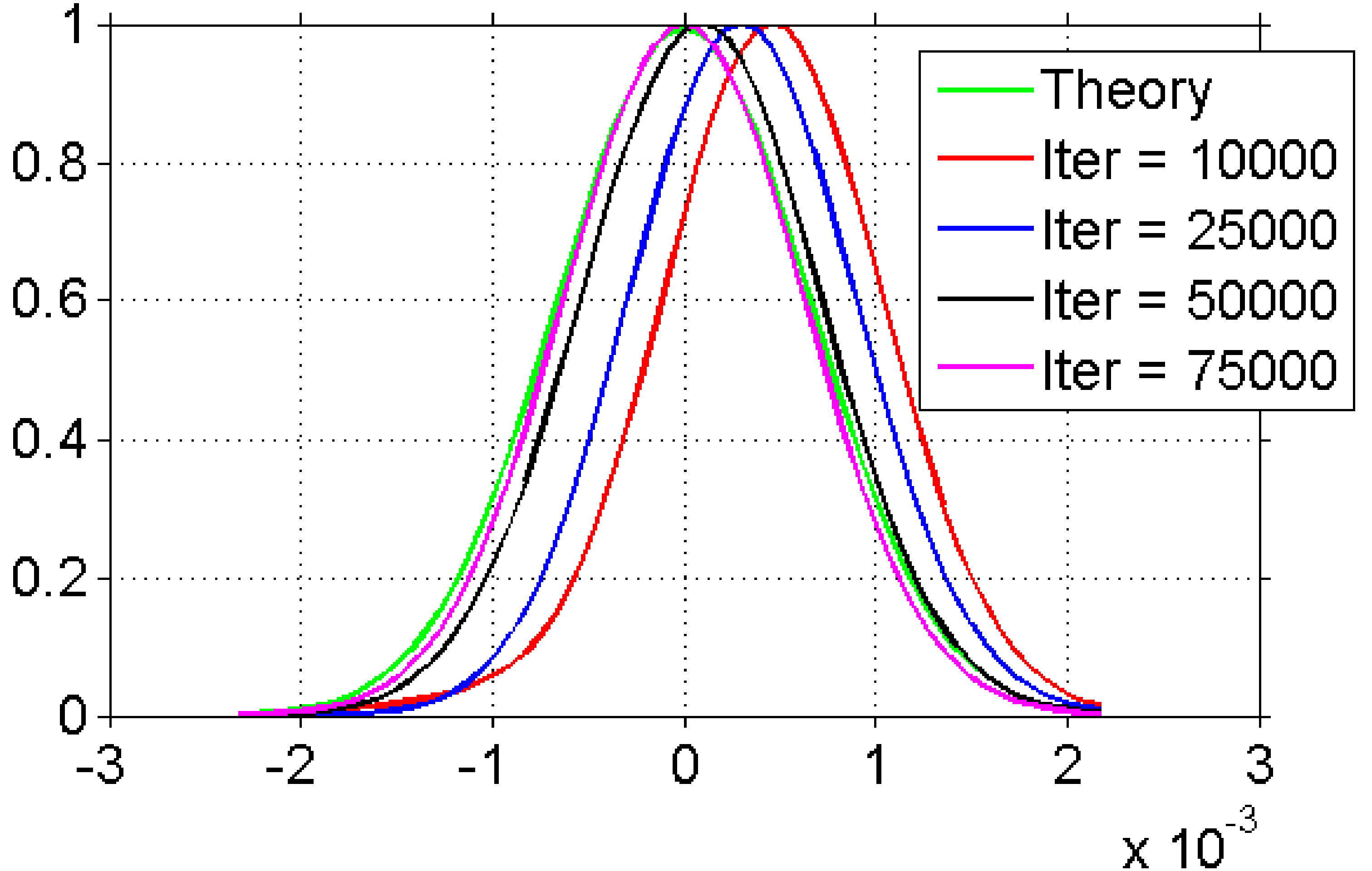




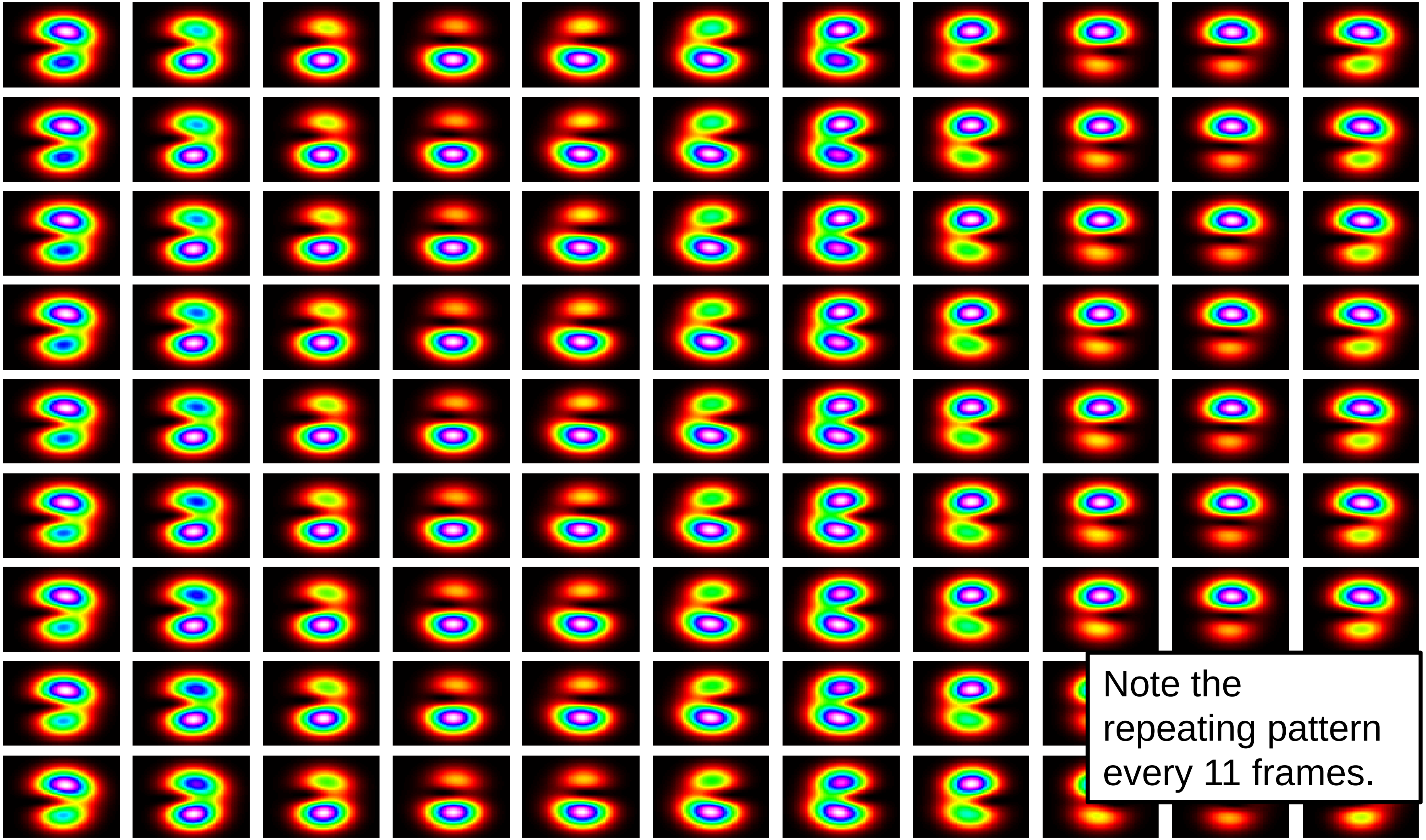
Iterations = 75000

Aperture diameter = 5.0 mm

Intensity Cross-Section Comparison for 5-mm Aperture Cases with Different Iteration Numbers

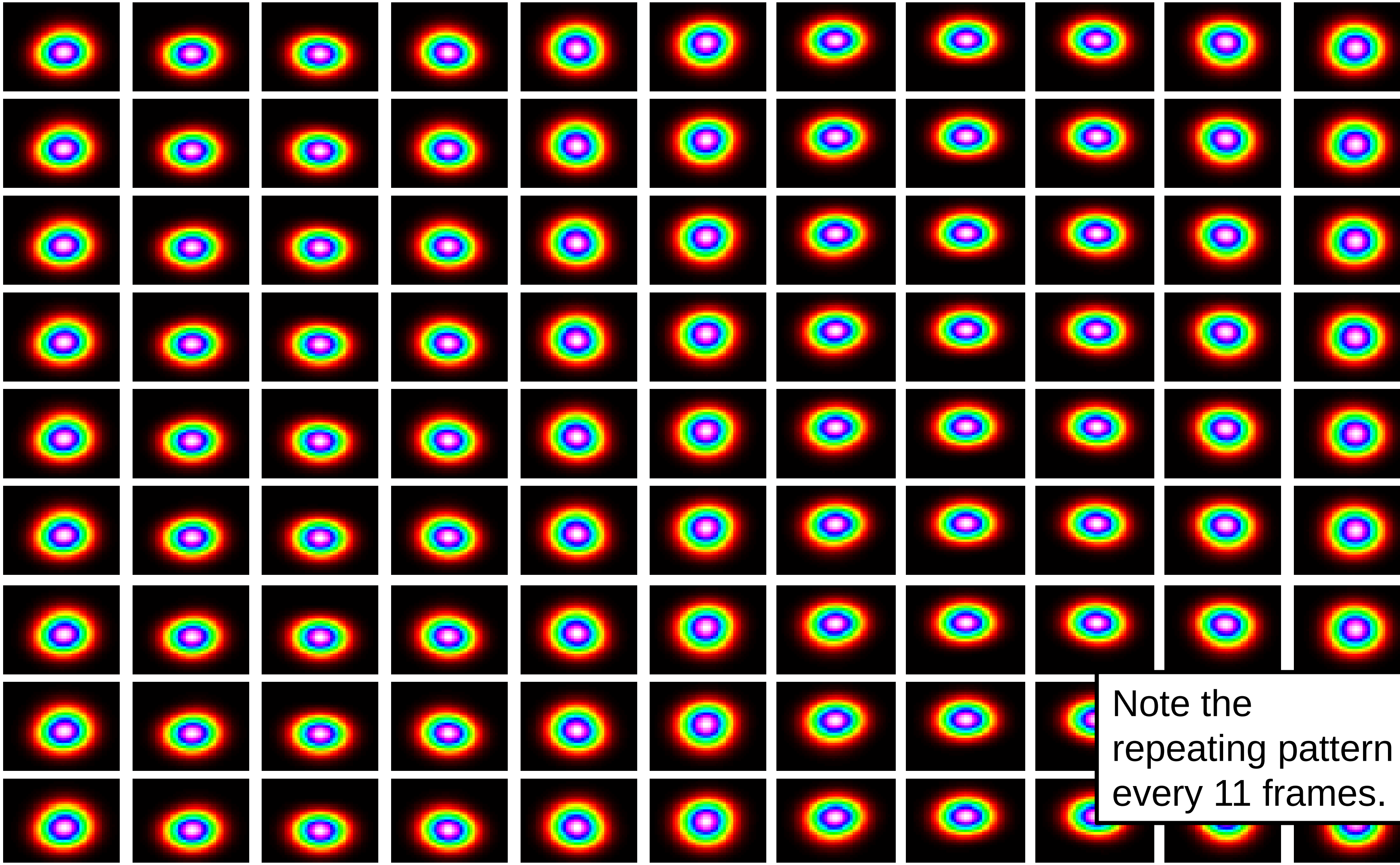


Variation of Output Intensity with Last 99 Frames of 10,000 with 5-mm Diameter Aperture



Note the repeating pattern every 11 frames.

Variation of Output Intensity with Last 99 Frames of 50,000 with 5-mm Diameter Aperture



Note the repeating pattern every 11 frames.

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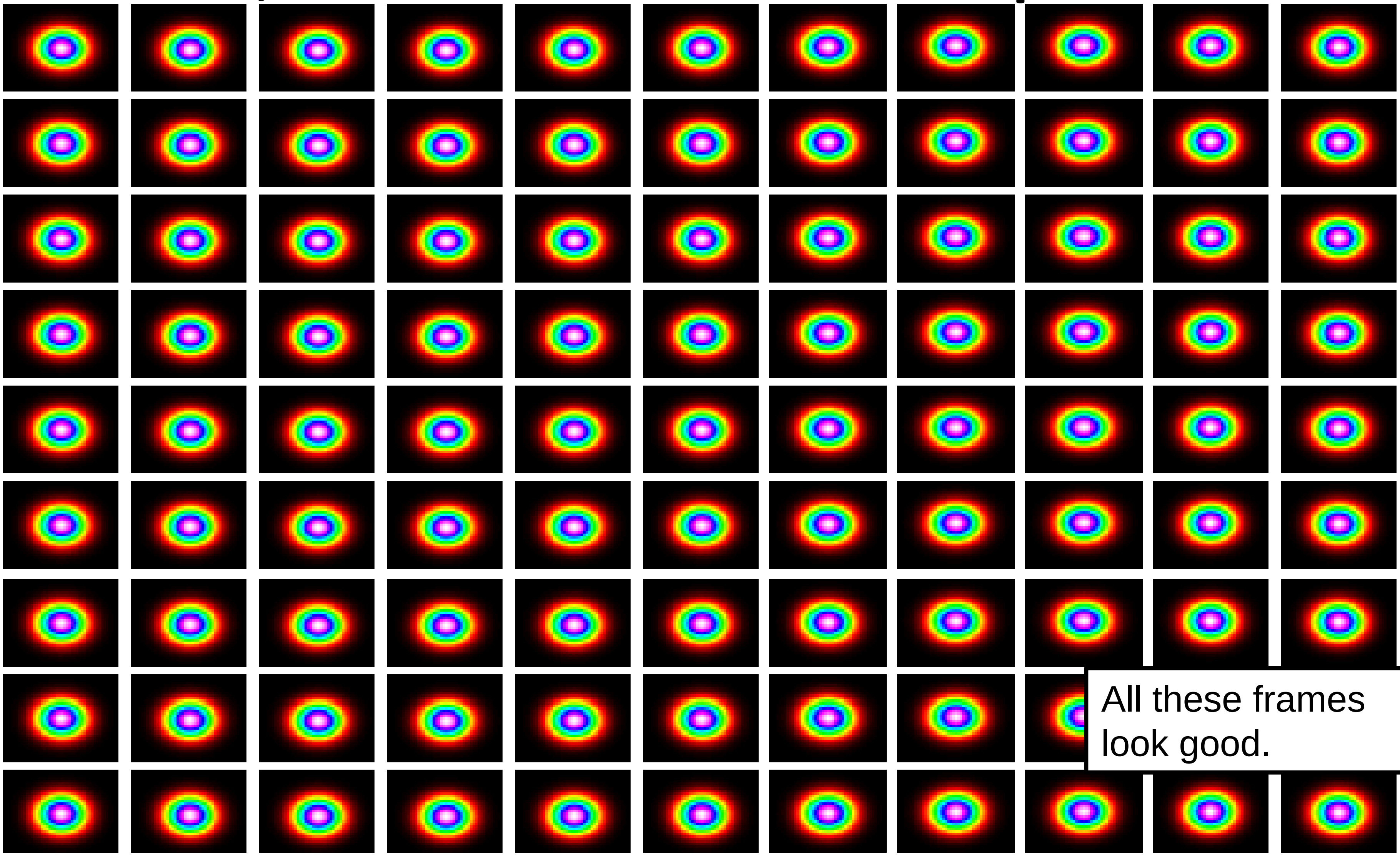
Variation of Output Intensity with Last 99 Frames of 75,000 with 5-mm Diameter Aperture



All these frames look good.

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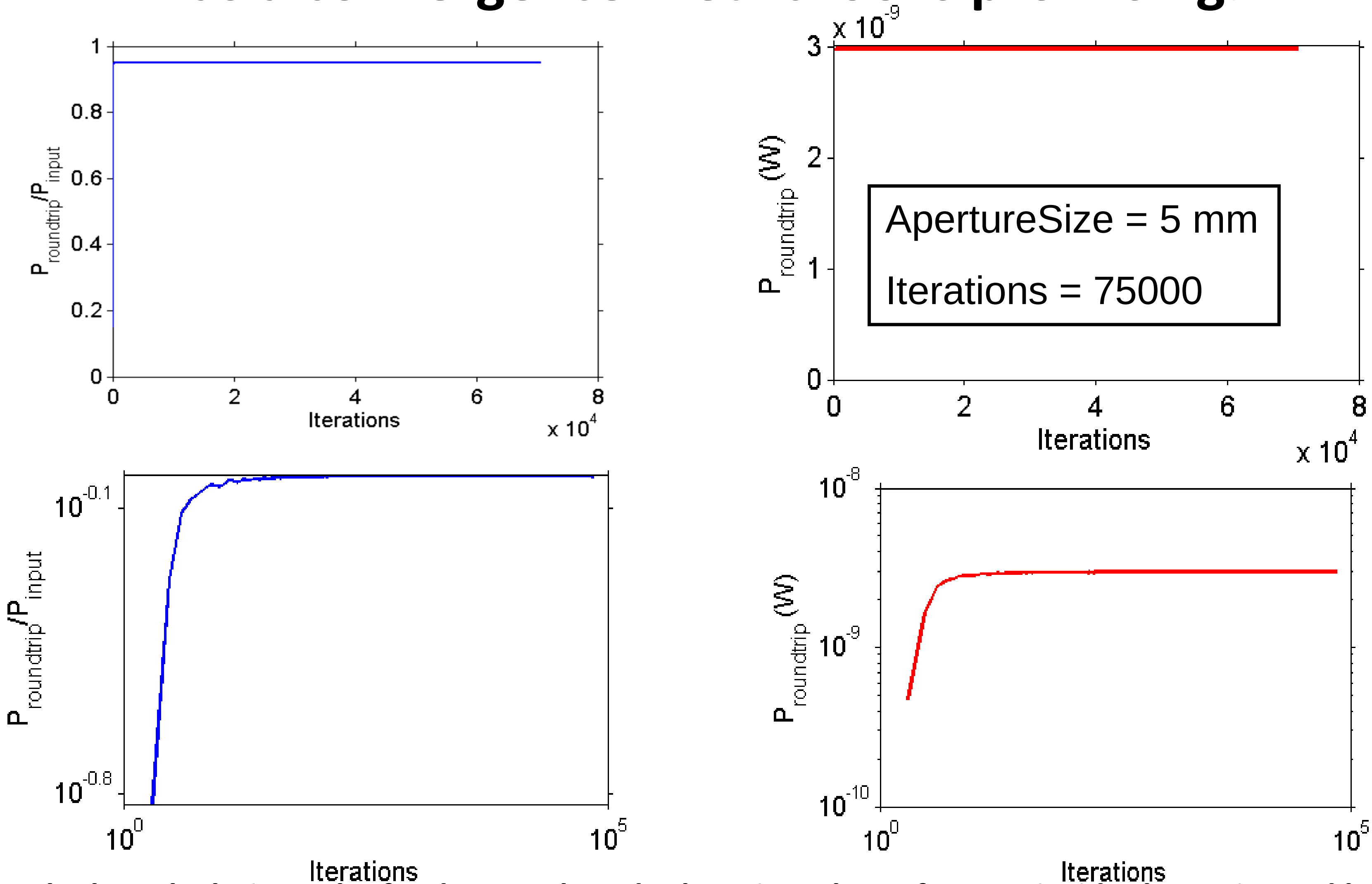
Evaluation of power stability or power reproducibility as a convergence metric looks promising.

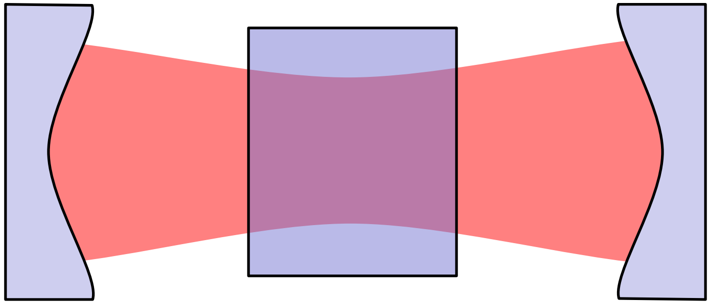


When the laser locks in to the fundamental mode there is no loss of power inside the cavity and hence the ratio of Laser output power to input power slowly increases with time and approaches 1

Stable Resonator Model Conclusions

- The WaveTrain stable resonator model showed that the models with larger aperture (~5 times w_0) converged very close to the theoretical shape in many (75,000) iterations.
- Even fairly early in the iterations, the beam intensity shape repeats itself every 11 iterations, as is predicted by theory.
- Power convergence appears to be a promising metric for the WT model convergence.

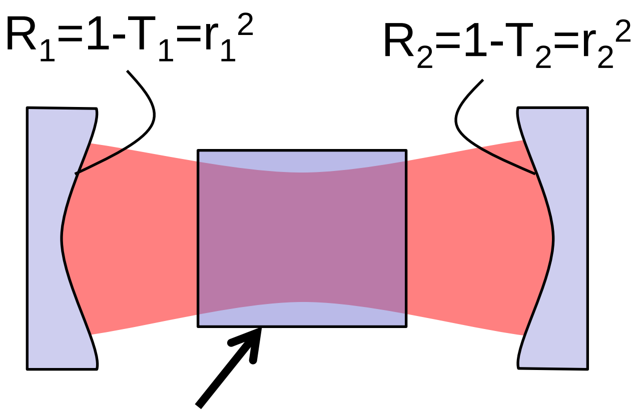
Stable Resonator With Gain



Stable Resonator with Gain

- Predictions from Theory
- WaveTrain Model Setup
- New Technique & Component
- Example Parameters
- Results & Comparison with Theory
- Conclusions

Rigrod Theory



$$I_{out} = T_2 I_2 = \frac{T_2 I_{sat}}{\left(1 + r_2/r_1\right)\left(1 - r_1 r_2\right)}\left[\ln\left(G_0\right) - \ln\left(\frac{1}{r_1 r_2}\right)\right]$$

$$I_{available} = \ln\left(G_0\right) I_{sat}$$

$$\eta \equiv \frac{I_{out}}{I_{available}} = \frac{T_2}{\left(1 + r_2/r_1\right)\left(1 - r_1 r_2\right)}\left[1 + \frac{\ln\left(r_1 r_2\right)}{\ln\left(G_0\right)}\right]$$

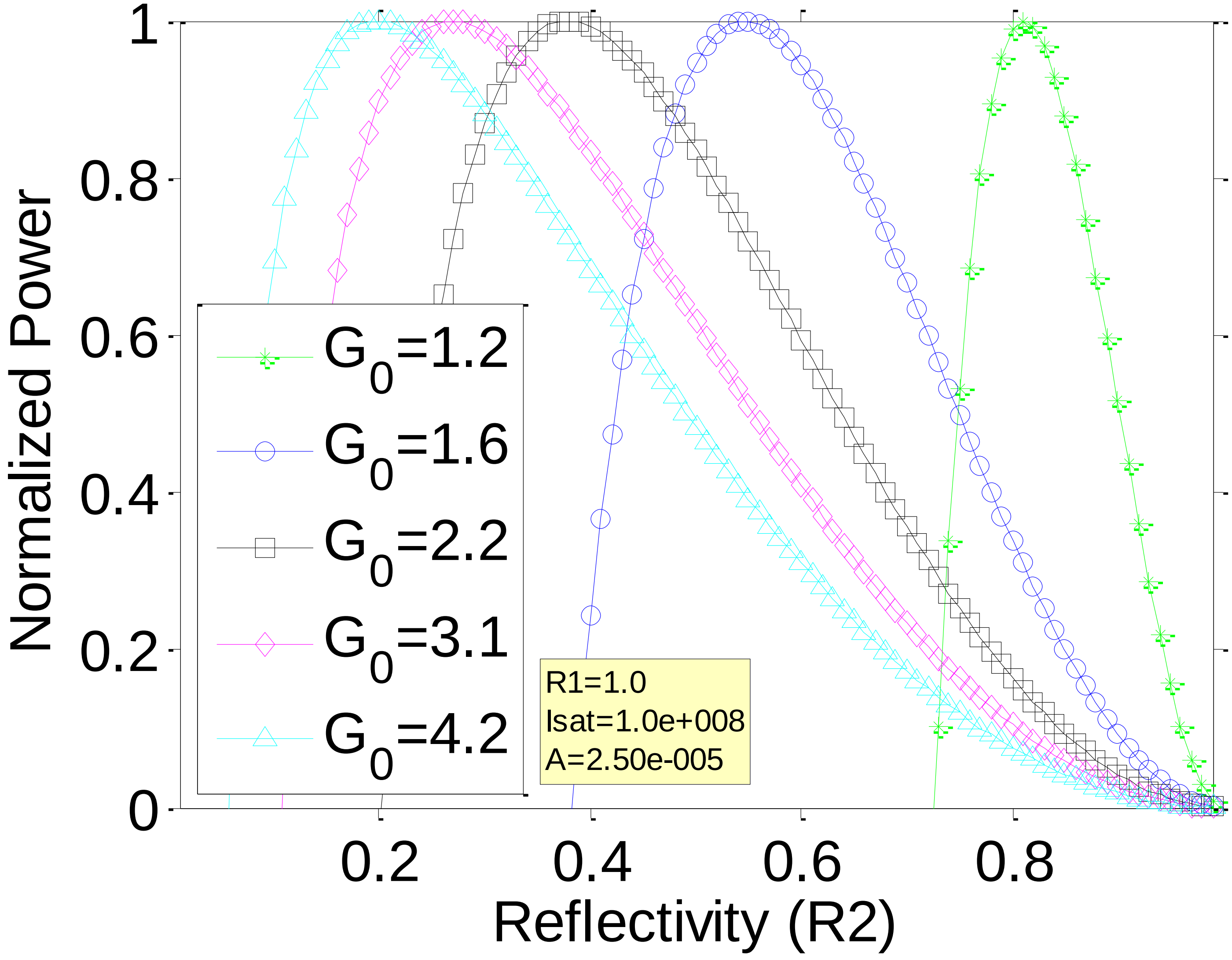
$$G_0 = \exp\left(2\alpha_{m0} L\right)$$

$$\alpha_{m0} = \text{small signal gain per length}$$

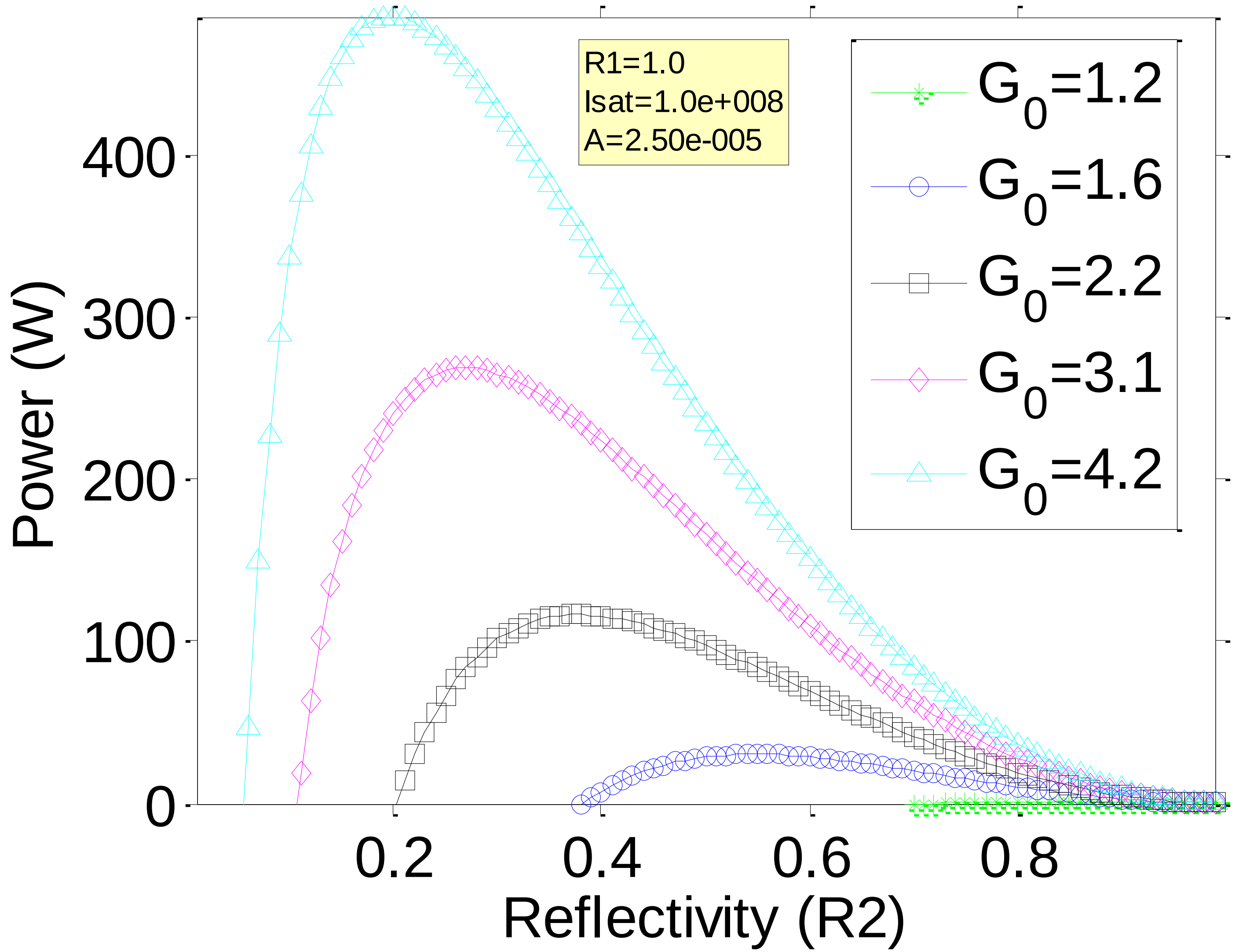
R is power reflectivity, r is field reflectivity

A. E. Siegman, Lasers, University Science Books (1986)

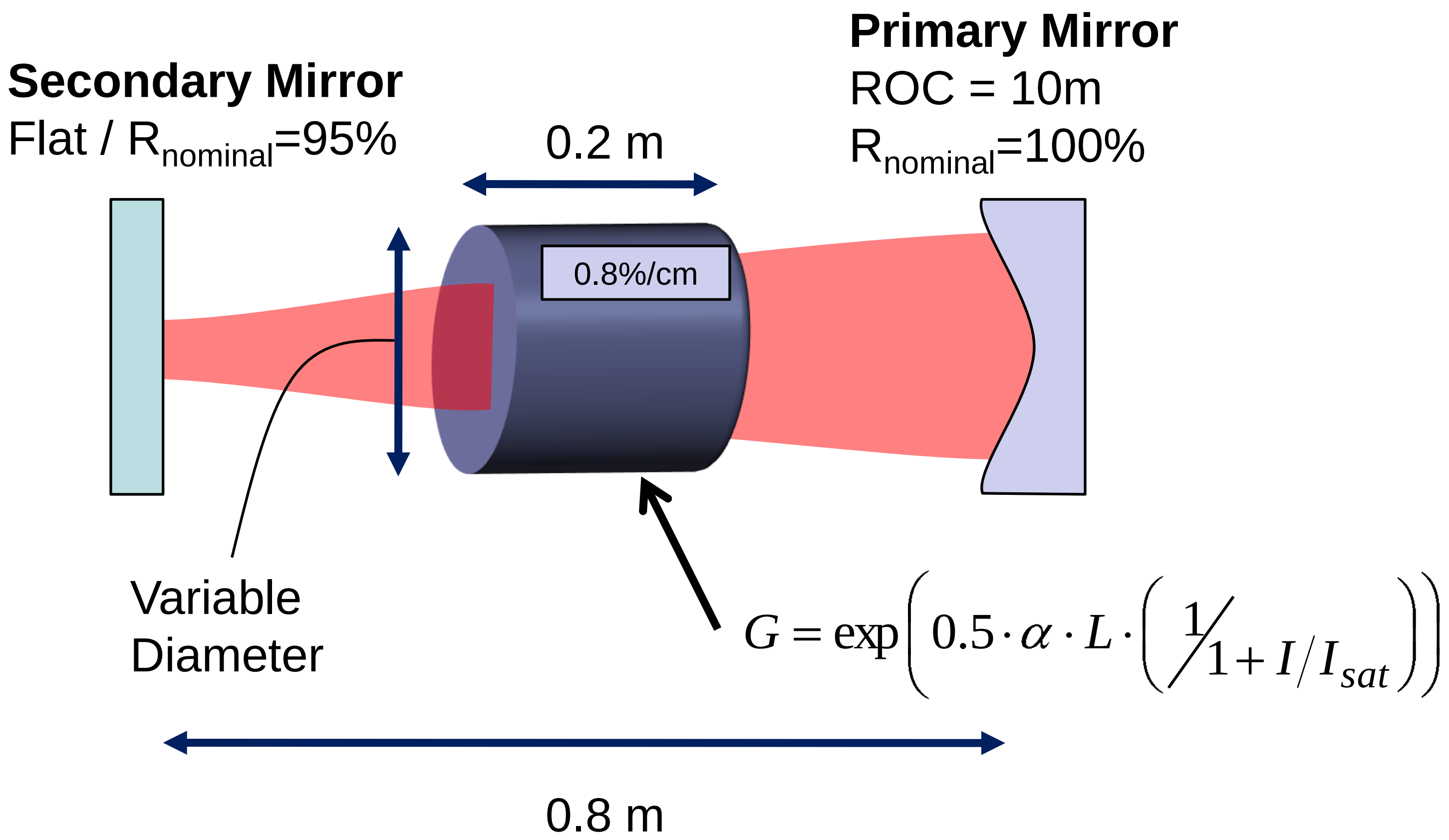
Typical Rigrod Results



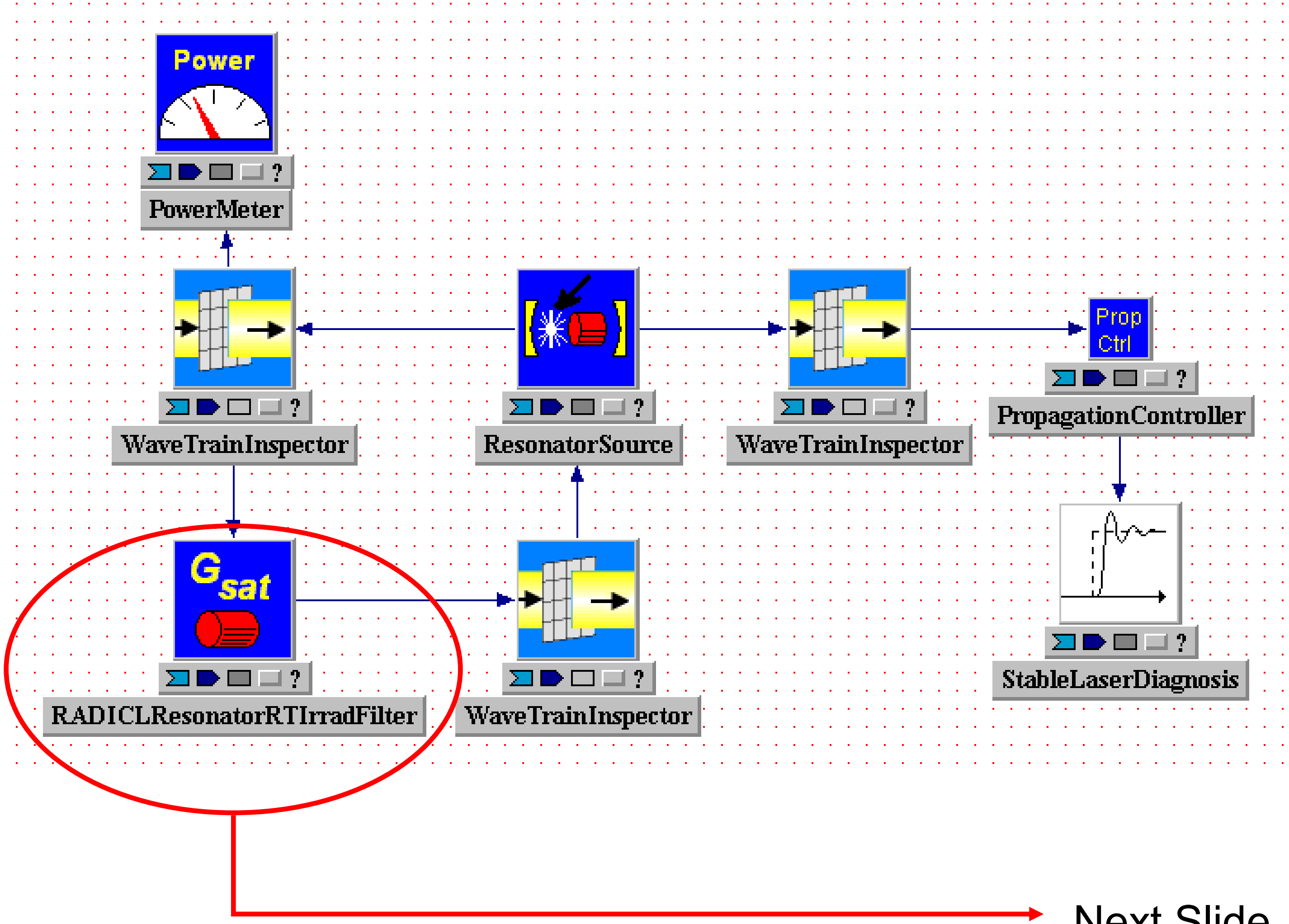
Typical Rigrod Results



Example Laser Resonator Setup

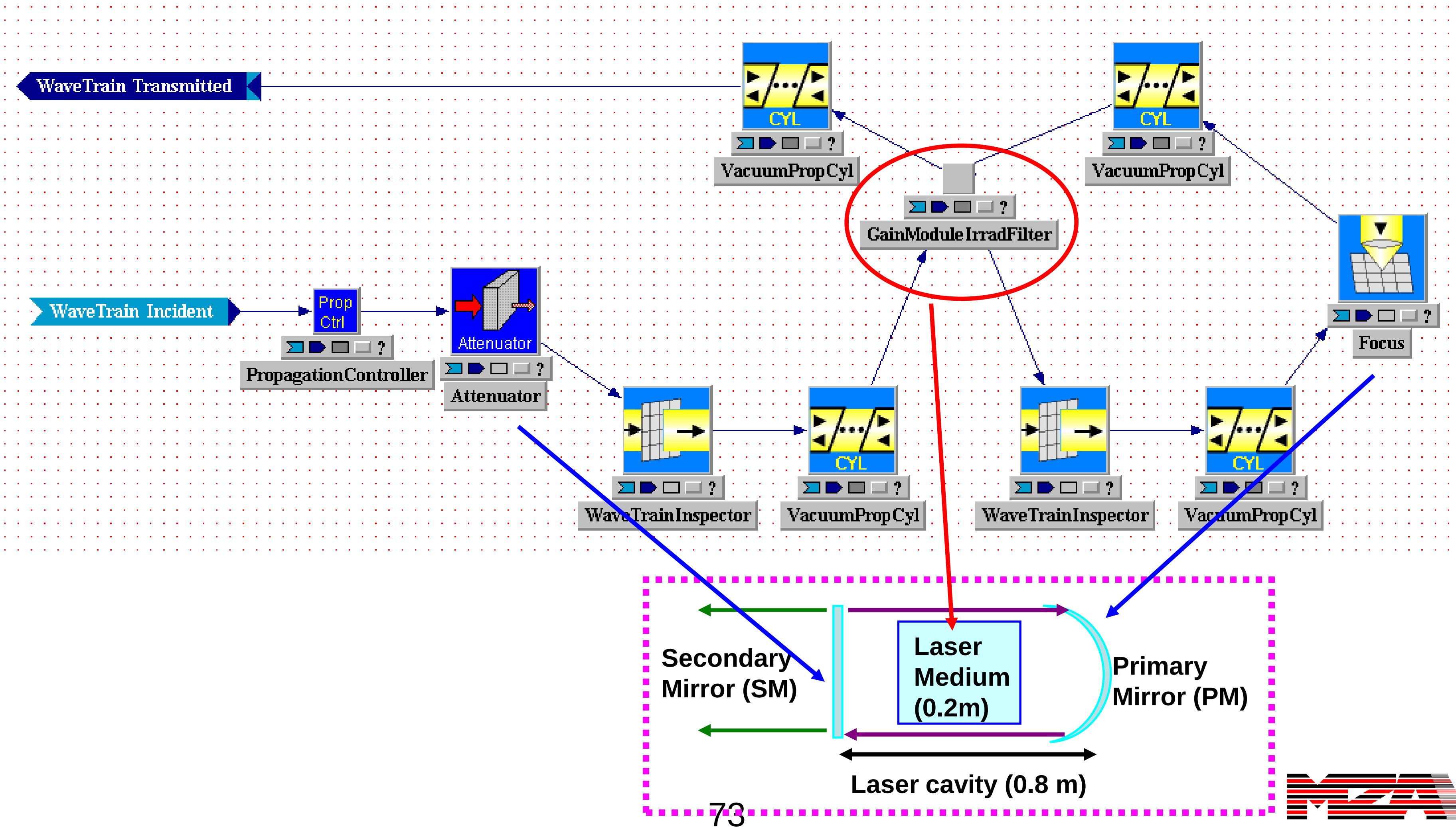


Wave Train Model

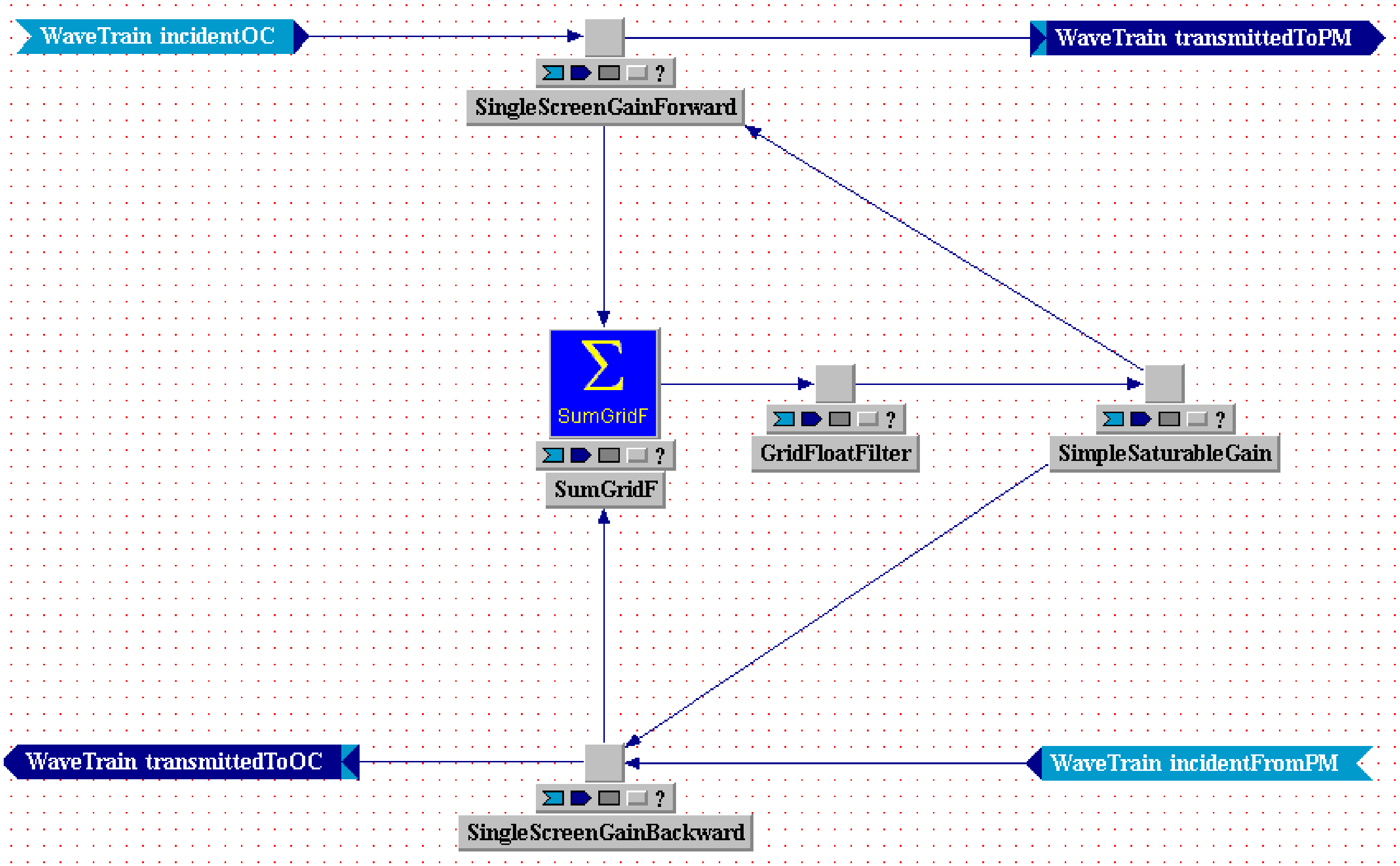


Next Slide…

Wave Train Model Of Laser Cavity



WT Model of Gain Medium



Description of the GridFloatFilter

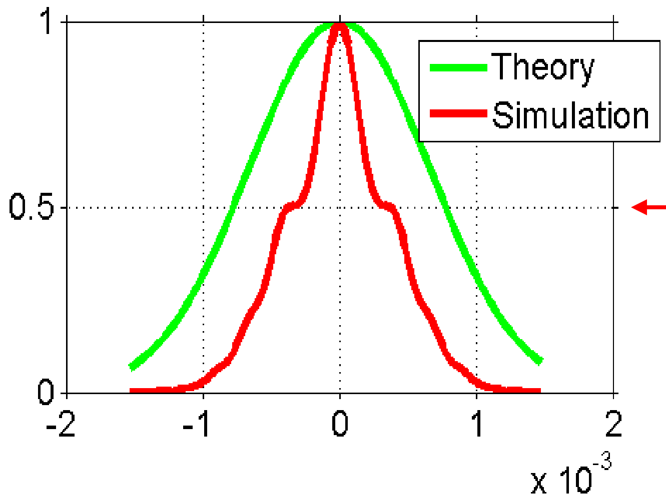
- We developed the GridFloatFilter to average a user-specified number of intensity frames together to get a more stable intensity profile.
- We found that the best results are achieved when the number of iterations over which to average is equal to the number of round-trips to image (see earlier derivation).
  - The original logic here was that the Fox & Li technique is modeling a single slice of a continuum of fields and by averaging we can take this into account.

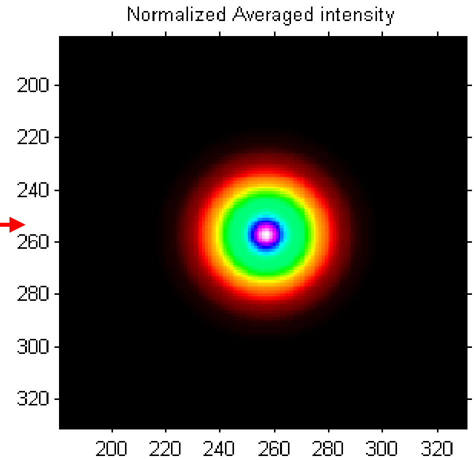
Parameters

- NumAvgs_vec = 11
- Reflectivity = 0.7 – 0.9
- Iterations = 1000
- Rc (Radius of curvature of convex mirror) = 10 m
- cavityLength0 = 0.8 m
- Propagation Grid = 512 by 30e-6
- Ssgain = 0.8
- Amp0(Amplitude of initial field) = 15000
- Radius of initial field = 6.0e-2 m
- Seed = 12345
- Wavelength = 1e-6
- Saturation intensity = 1e7 W/m^2
- Focus = Rc/2
- Normalization = 0
- convergenceThreshold = 1e-9
- GainLength = 0.2
- Aperture diameter= 3mm

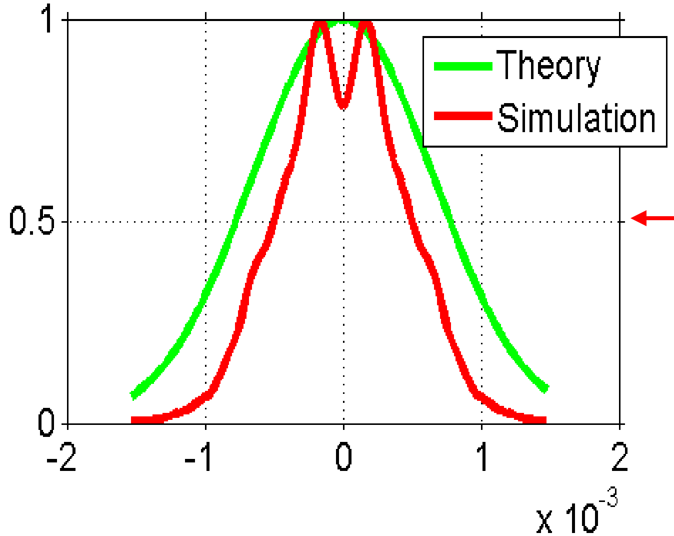
Model Results for No Intensity Averaging

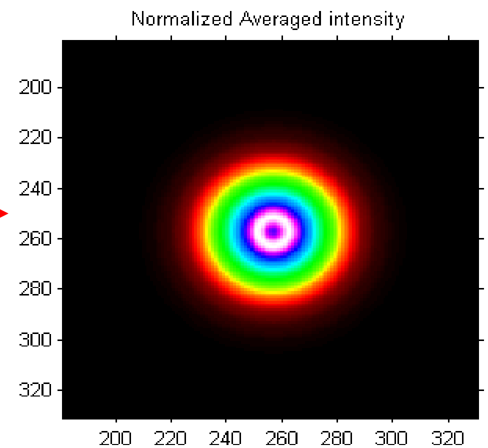
Intensity patterns for last frame and intensity plot along the central axis of Averaged intensity show the evolution of various modes with increase of aperture diameter





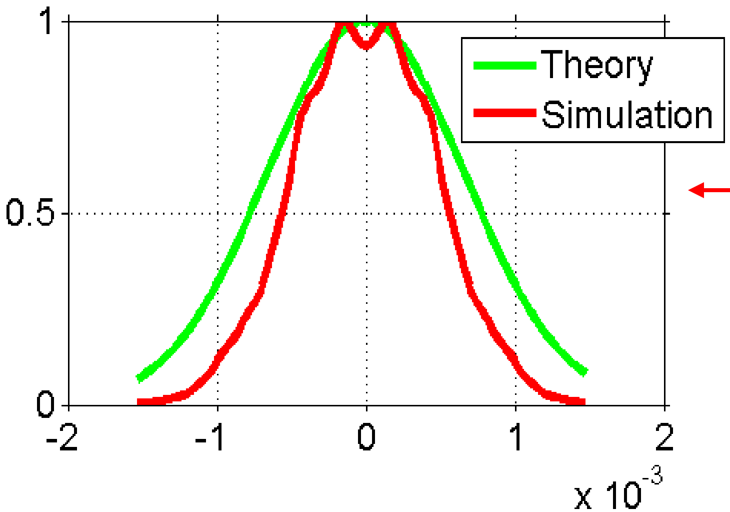
Aperture diameter = 2.0 mm

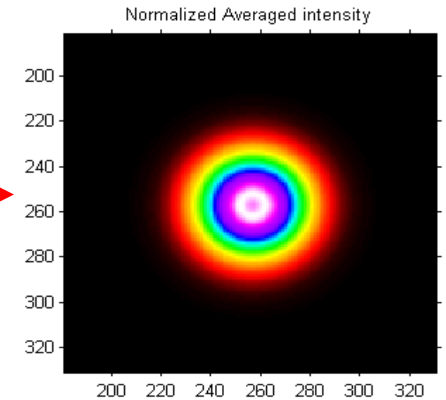




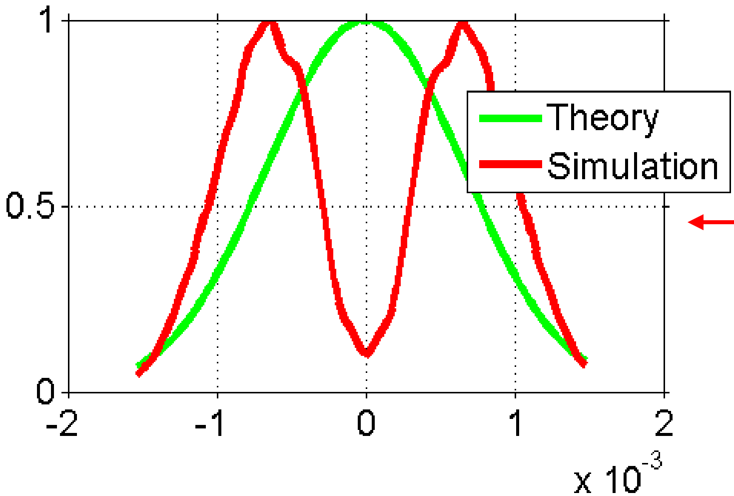
Aperture diameter = 2.5 mm

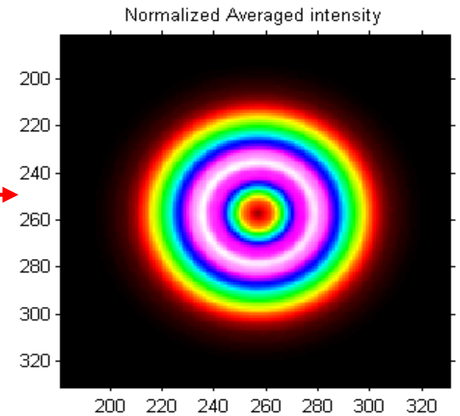
Intensity patterns for last frame and intensity plot along the central axis of Averaged intensity show the evolution of various modes with increase of aperture diameter





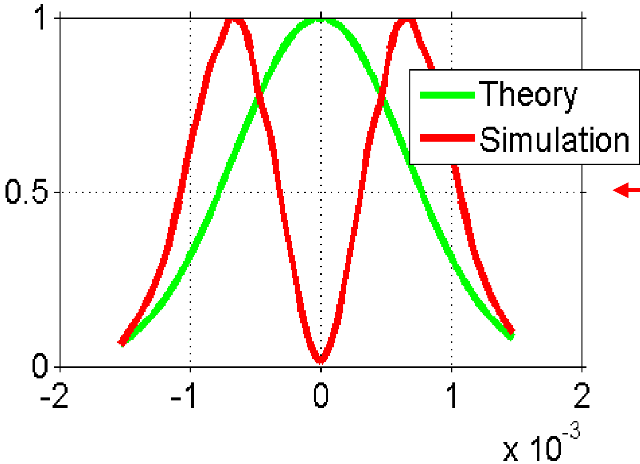
Aperture diameter = 3.0 mm

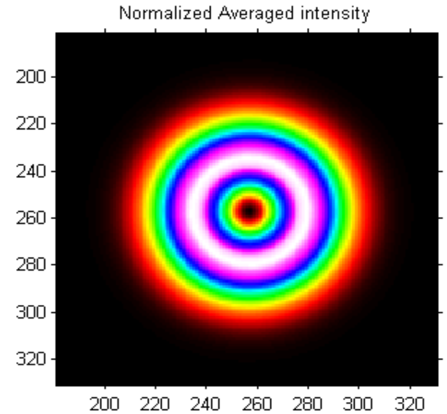




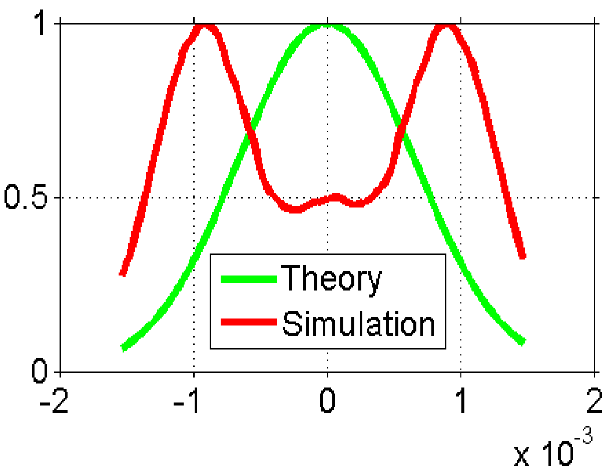
Aperture diameter = 3.5 mm

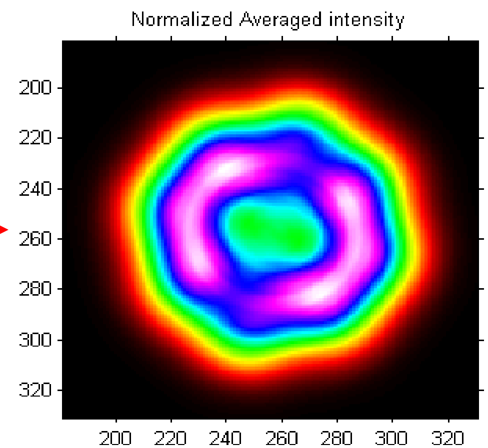
Intensity patterns for last frame and intensity plot along the central axis of Averaged intensity show the evolution of various modes with increase of aperture diameter





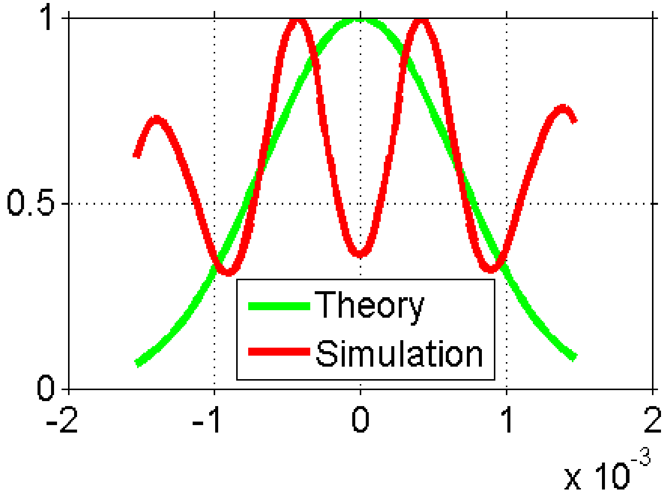
Aperture diameter = 4.0 mm

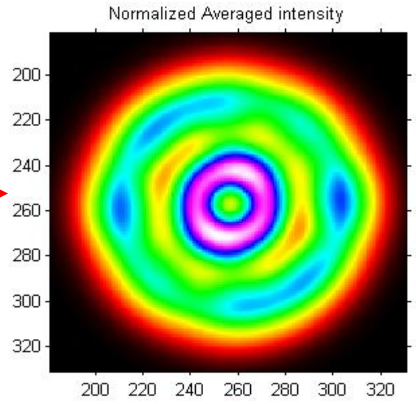




Aperture diameter = 4.5 mm

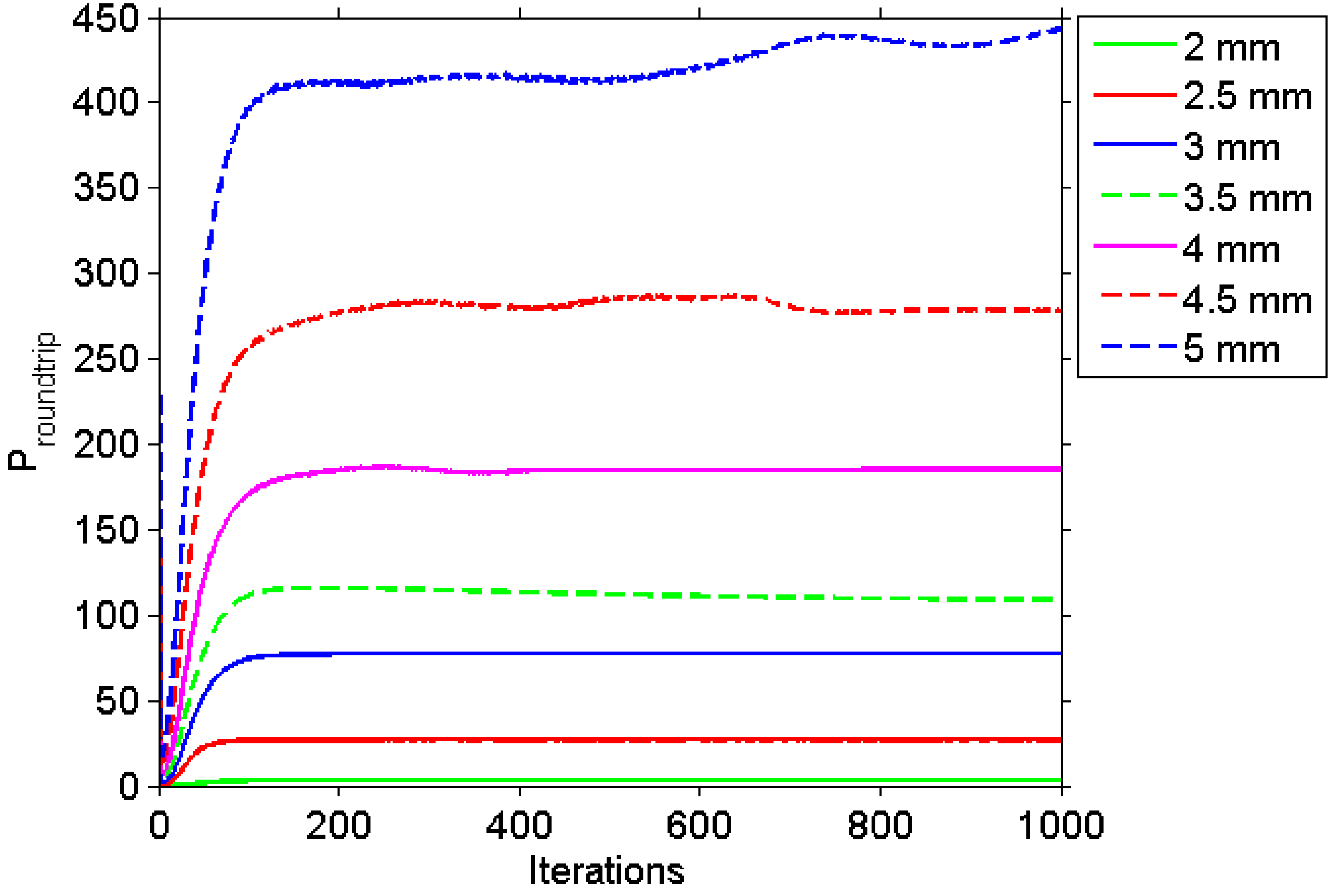
Intensity patterns for last frame and intensity plot along the central axis of Averaged intensity show the evolution of various modes with increase of aperture diameter





Aperture diameter = 5.0 mm

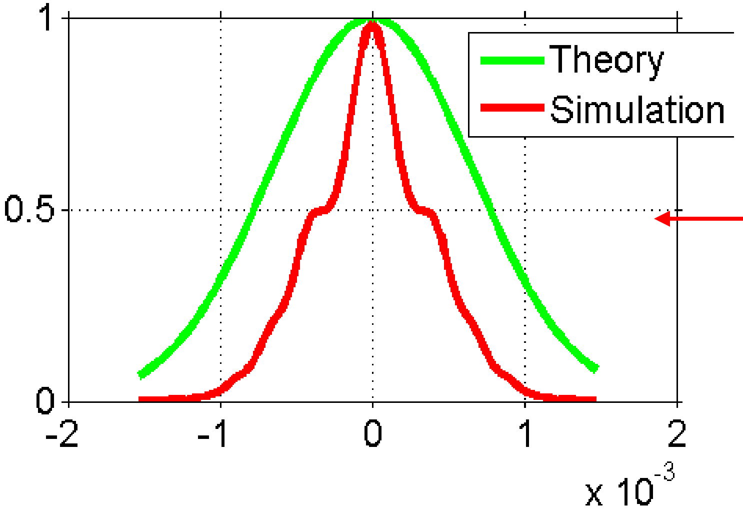
Output Power

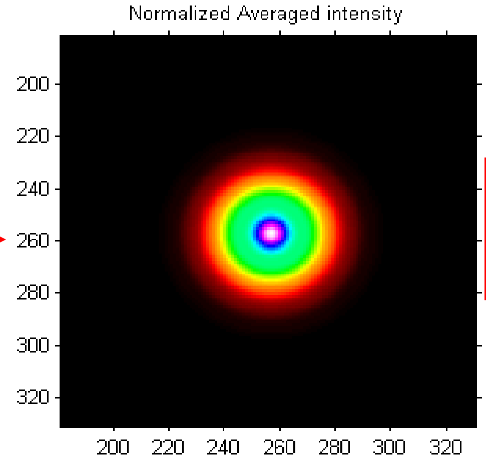


Model Results for 11-Frame Intensity Averaging

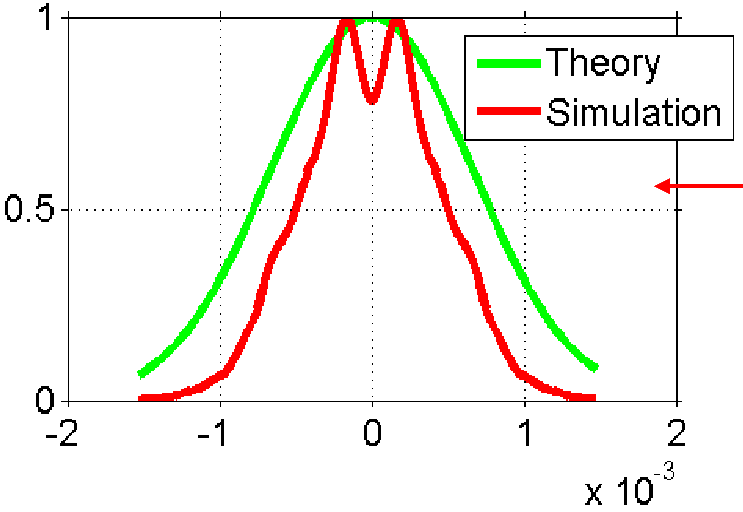
1000 Iterations

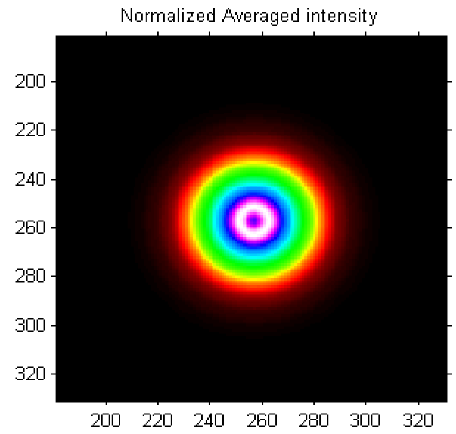
Small Aperture Results





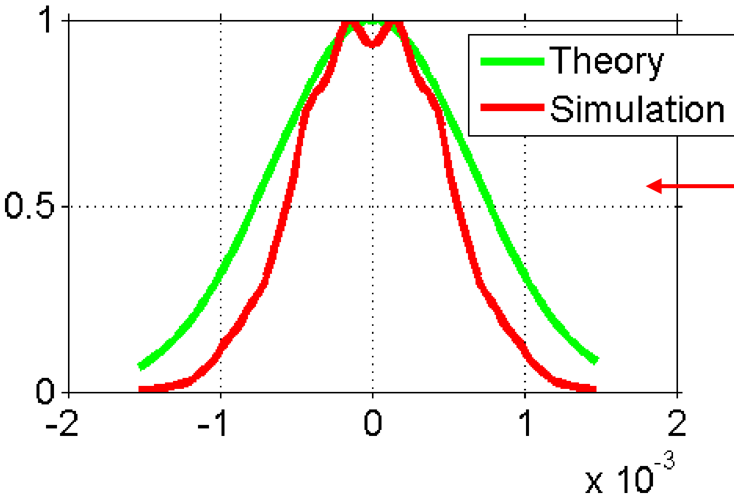
Aperture diameter = 2.0 mm

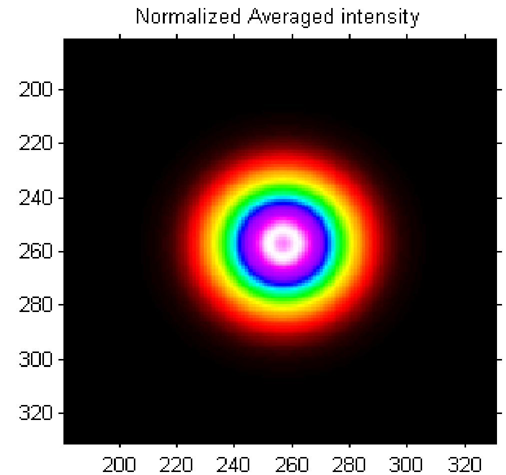




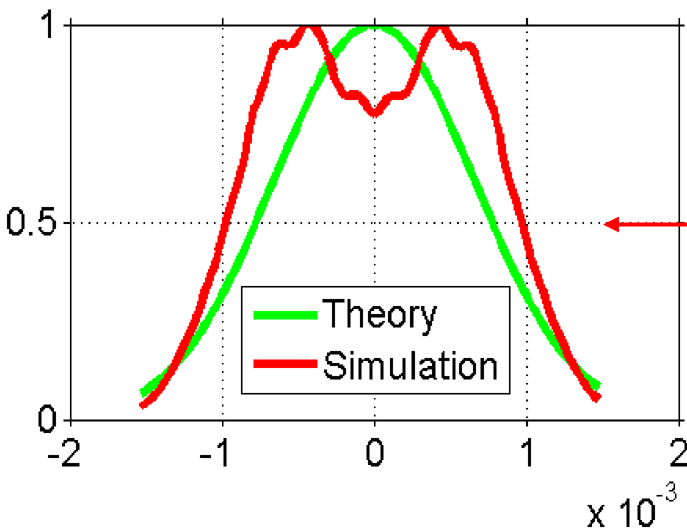
Aperture diameter = 2.5 mm

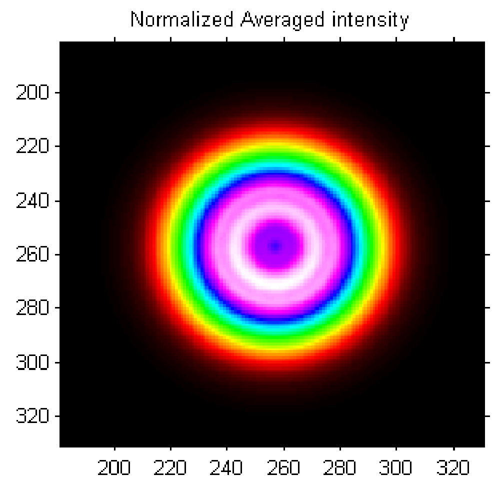
Medium Aperture Results





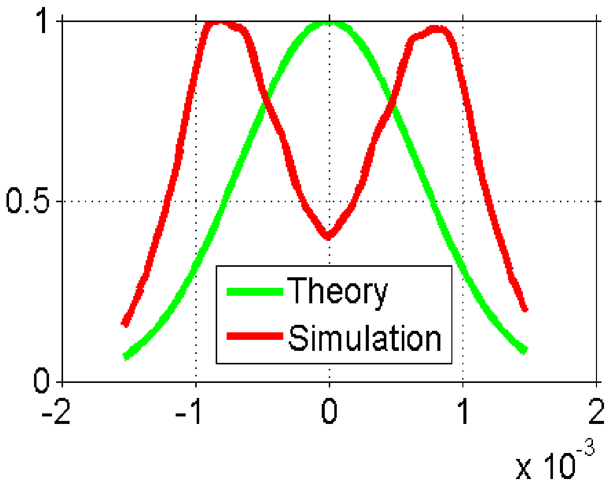
Aperture diameter = 3.0 mm

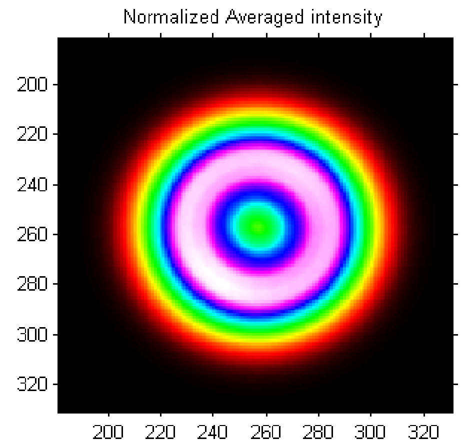




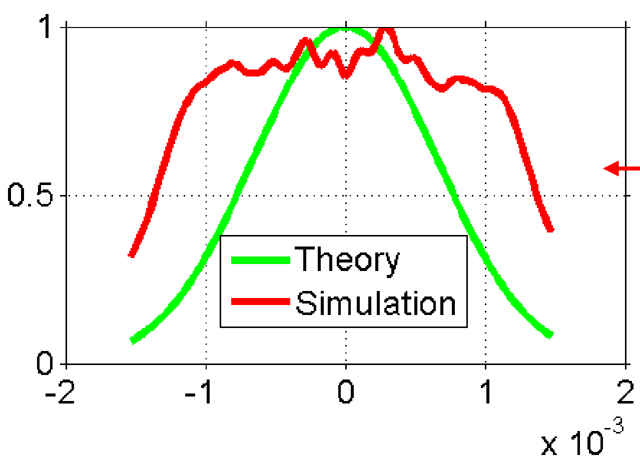
Aperture diameter = 3.5 mm

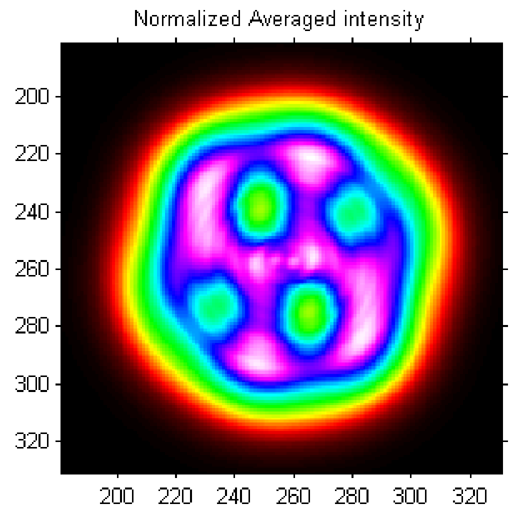
Larger Aperture Results





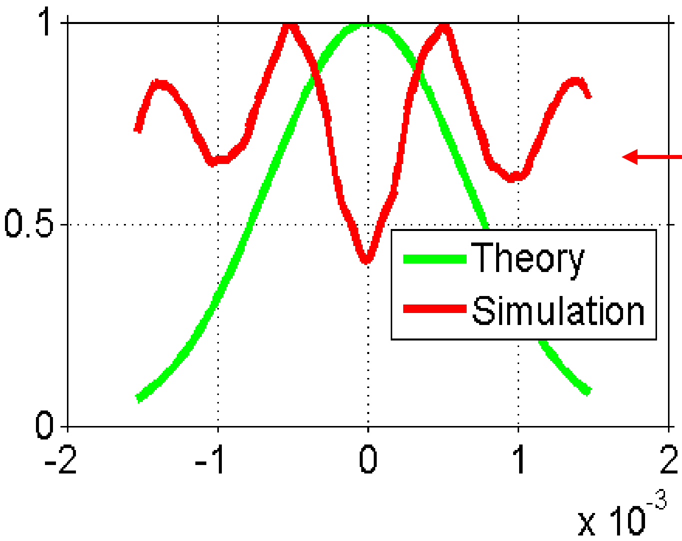
Aperture diameter = 4.0 mm

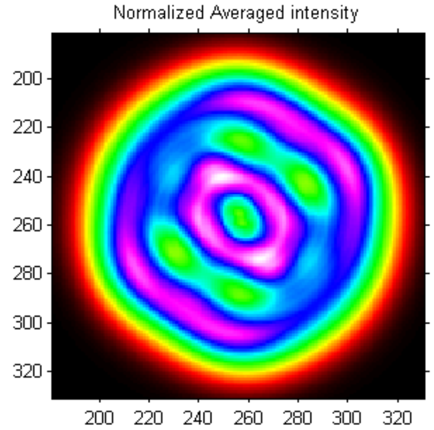




Aperture diameter = 4.5 mm

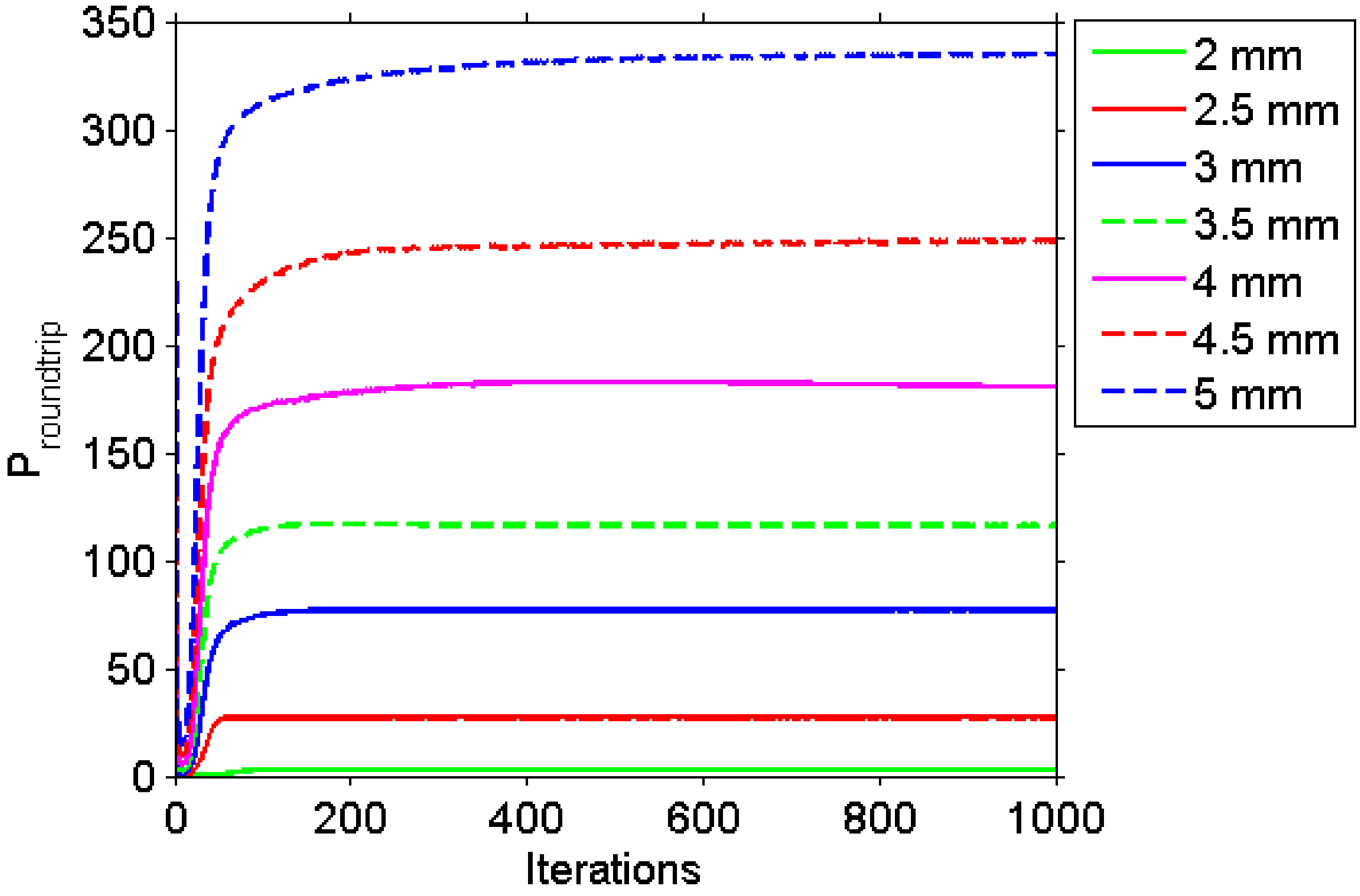
Largest Aperture Results





Aperture diameter = 5.0 mm

Output Power Analysis vs. Iteration



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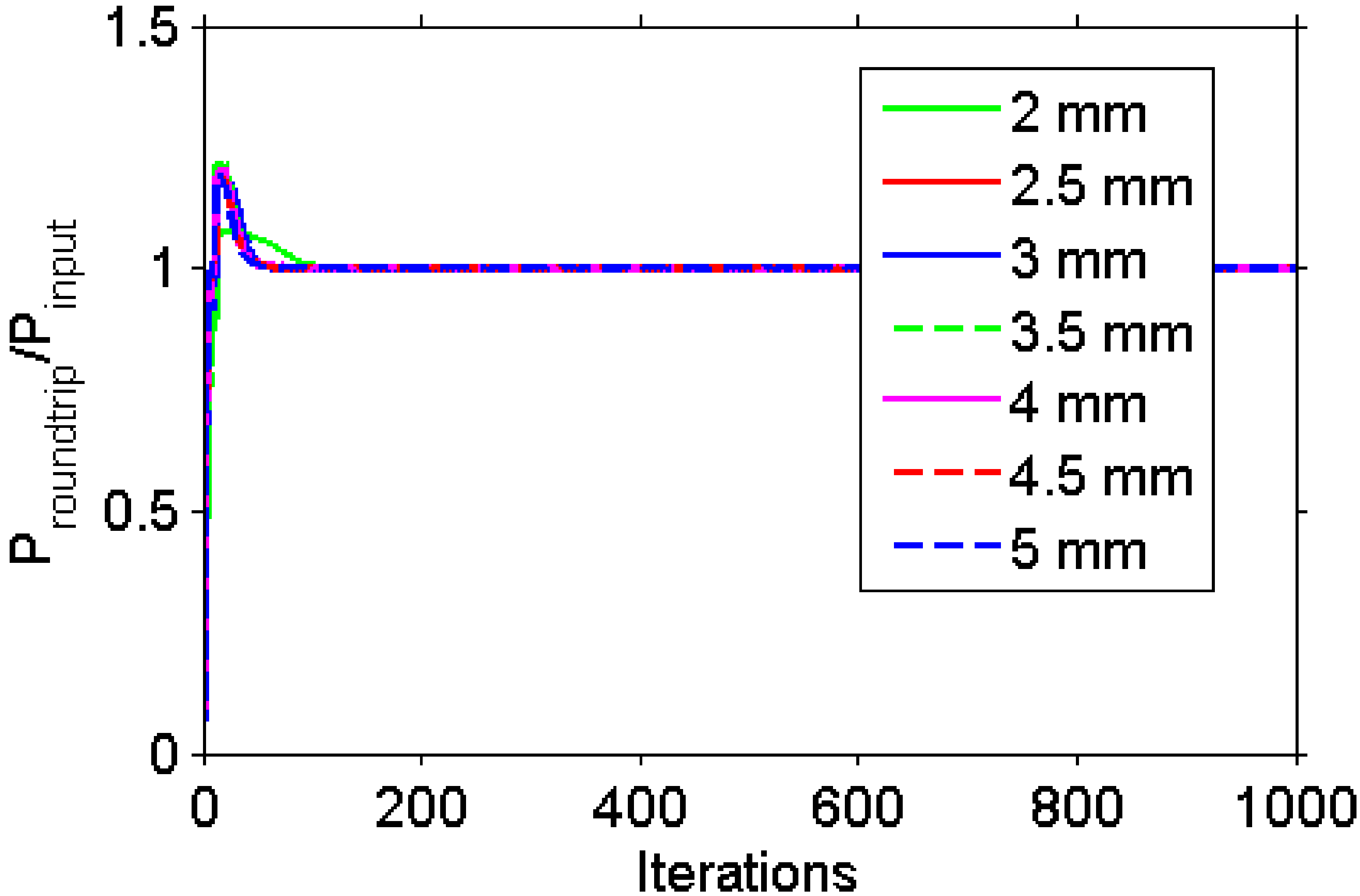
Output Power Ratio vs. Iteration



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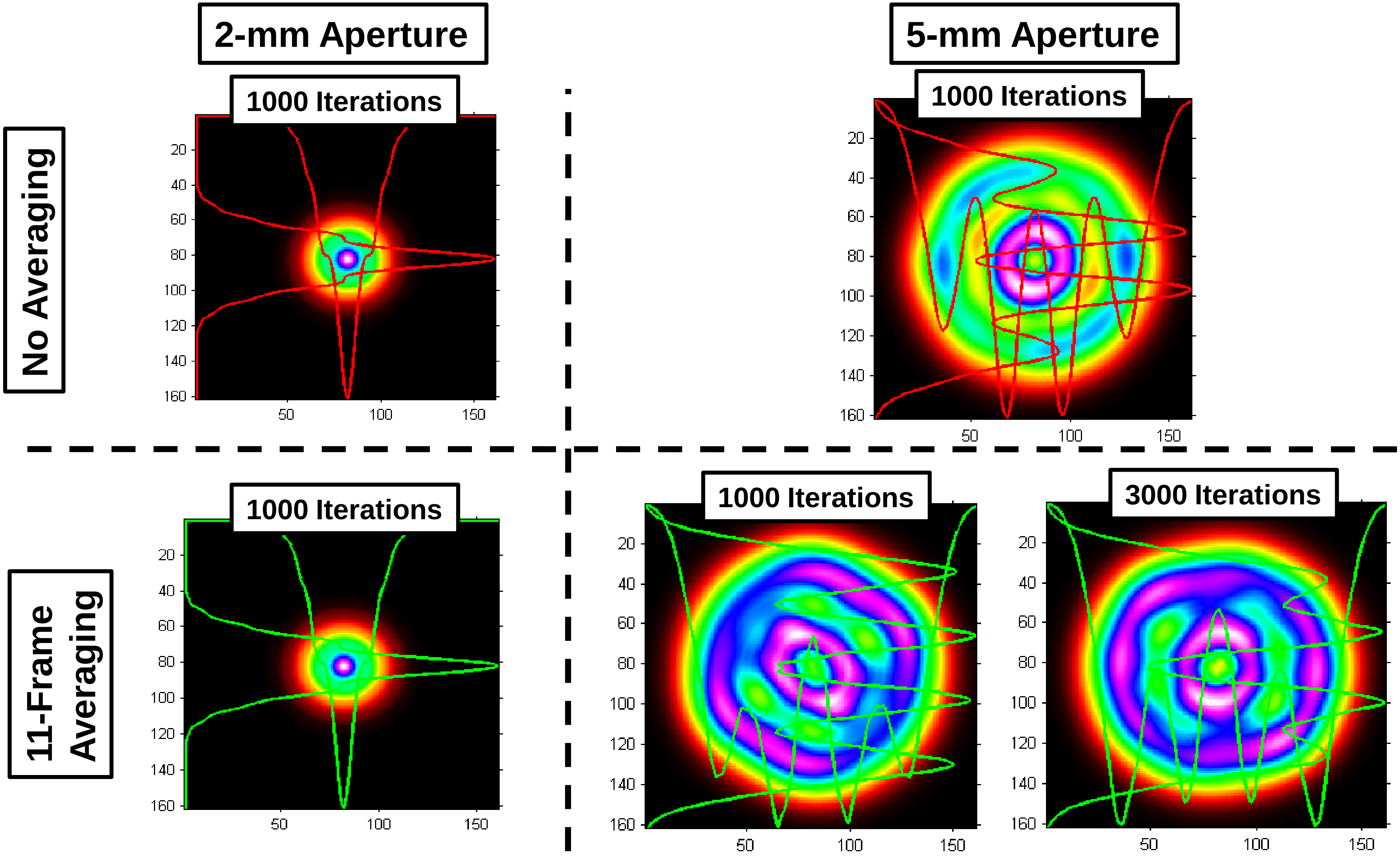
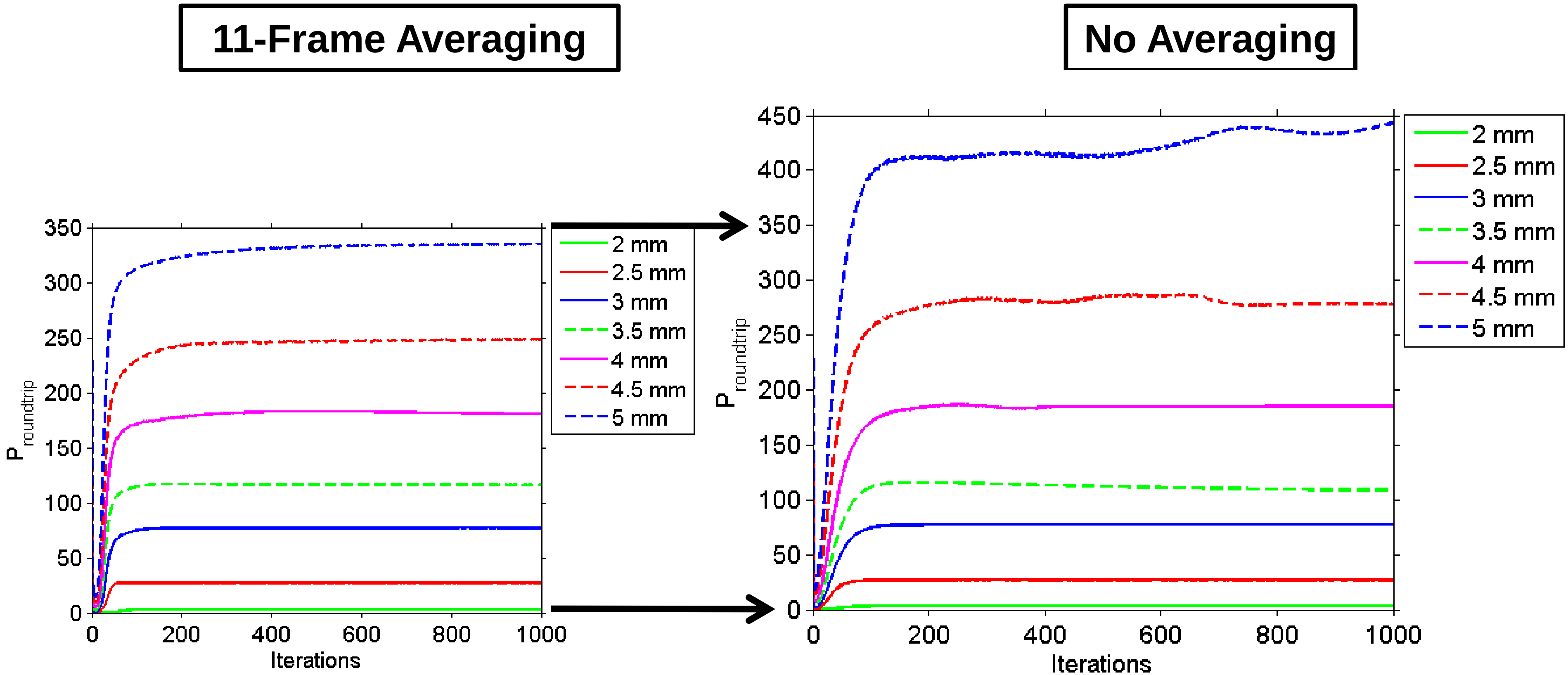
Comparison of Intensity Profiles

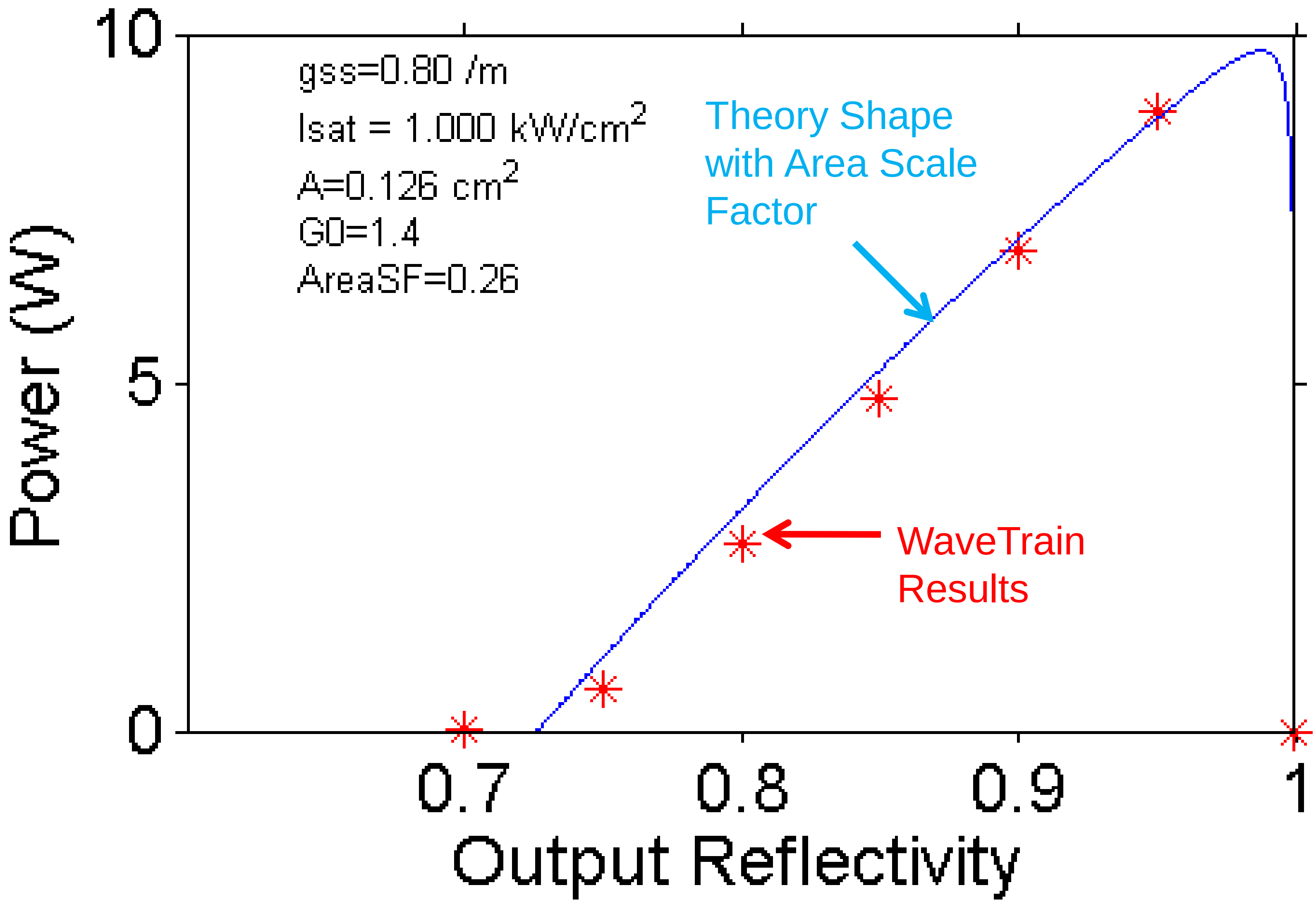


The averaging case converges more rapidly and to a steadier state in the presence of multiple transverse modes running.



Shape and power Level is comparable for small apertures, but significantly different for larger apertures. We are now trying to anchor to Rigrod power predictions.

Preliminary Rigrod Comparison



Conclusions

- The model of the stable resonator with gain using the internal intensity averaging appears to converge much faster and operate much more stably than the model without the averaging.
- We need to perform more anchoring experiments to complete the verification of this new technique, but the results so far are promising.