LASCAD Tutorial No. 1:
Modeling a laser cavity with end pumped rod

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Note:
The project file `Tutorial_1.lcd` of the example generated with this tutorial can be found in the directory `Tutorials` on the CD-ROM or after installation of LASCAD in the subdirectory `Tutorials` of the LASCAD application directory. You can copy this file to a working directory and open it by double-click.

Note:
The numerical results shown in this tutorial are obtained, if for the computation the demo version of the LASCAD program is used. The wavelength in the demo version is fixed to 1134 nm which differs somewhat from the wavelength of a Nd:YAG laser. To obtain the correct results open `Tutorial_1.lcd` with the full version.

1 Starting LASCAD and Defining a Simple Laser Cavity

- Start LASCAD,
- Define a working directory,
- Click **OK** to open the LASCAD main window,
- Click the **New Project** button on the toolbar (leftmost button), or select **File→New**,
- Increase the **Number of Face Elements** to 4,
- Enter the appropriate wavelength (not possible with the demo version), and leave the other default settings unchanged,
- Click **OK**.

Now you can see the LASCAD main menu at the top and two other windows below. The upper one is titled **Standing Wave Resonator**, the lower one **Parameter Field,** as shown Fig. 1. The upper window shows the mode plot of a simple cavity with four elements; the lower window shows the parameters of the cavity. In the column below the element number, the parameters belonging to this element are shown, such as the radius of curvature of each mirror shown in the row labeled **Type-Param.** To change the element type use the drop-down boxes immedi-

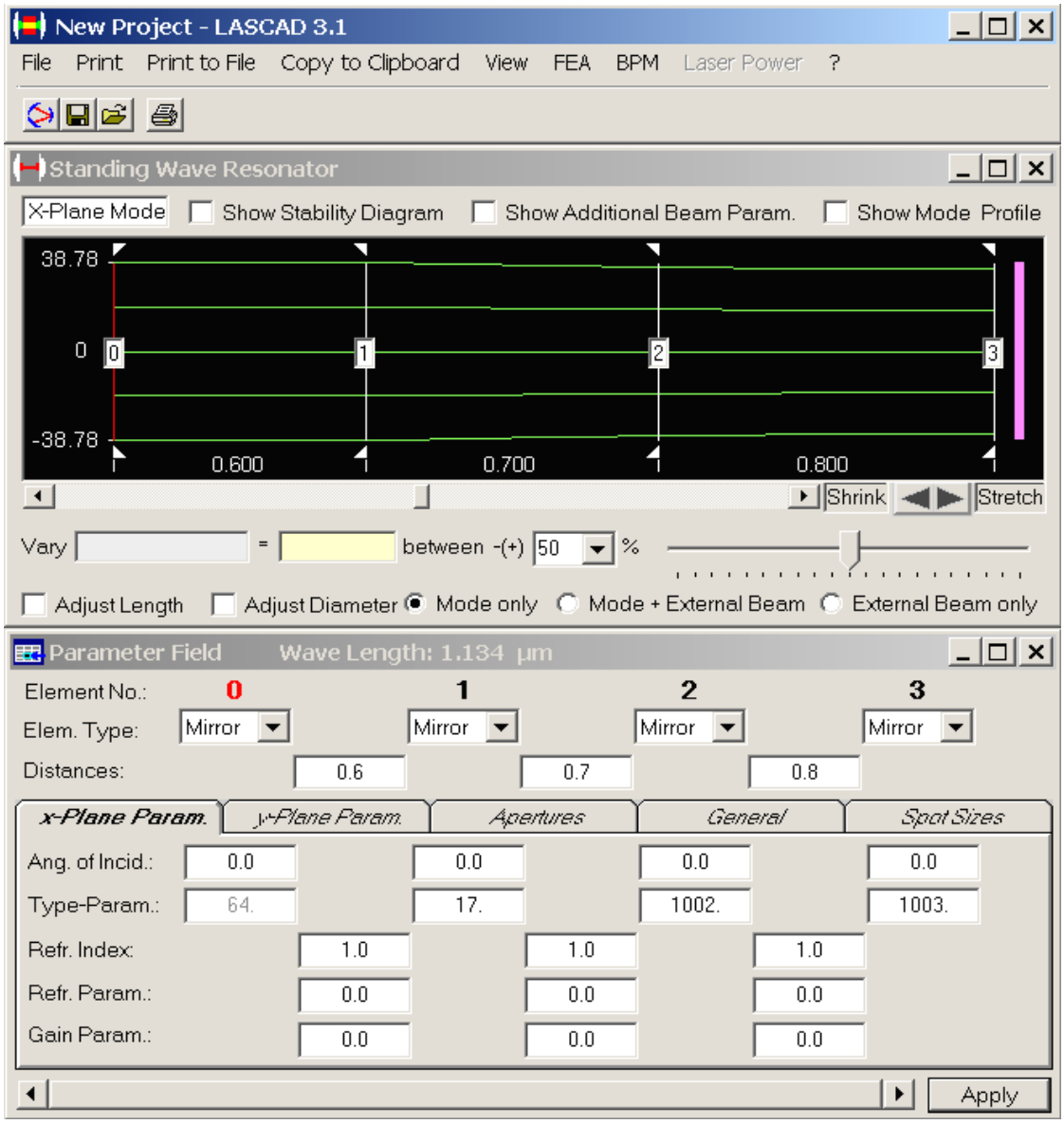

Fig. 1

ately below the element number. You can select from **Mirror, Dielectric Interface,** and **Lens**. The parameters of the columns between the element numbers define the properties of the space between the elements, such as the refractive index, or the **Refractive Parameter,** which corresponds to the second derivative of a parabolic transverse refractive index distribution. Information about additional functionalities of these windows for instance "How to insert or clear an element?" can be found in section 3, the Quick Tour or in the manual.

2 Defining and Analyzing an End Pumped Rod

2.1 Selecting crystal type and pump configuration

Select **FEA→Parameter Input & Start of FEA Code,** in the main LASCAD window, to open the window titled **Crystal, Pump Beam and Materials Parameters**, as shown in Fig. 2. Note the six tabs for defining various groups of parameters.

The tab labeled **Models** allows for selecting from a list of different crystal and pump configurations. Default setting is **(Dual) end pumped cylindrical rod**. At the bottom of this window the dimensions of the rod can be defined. For this example, we entered a rod length of 6 mm and a rod diameter of 2 mm, as shown in Fig. 2.

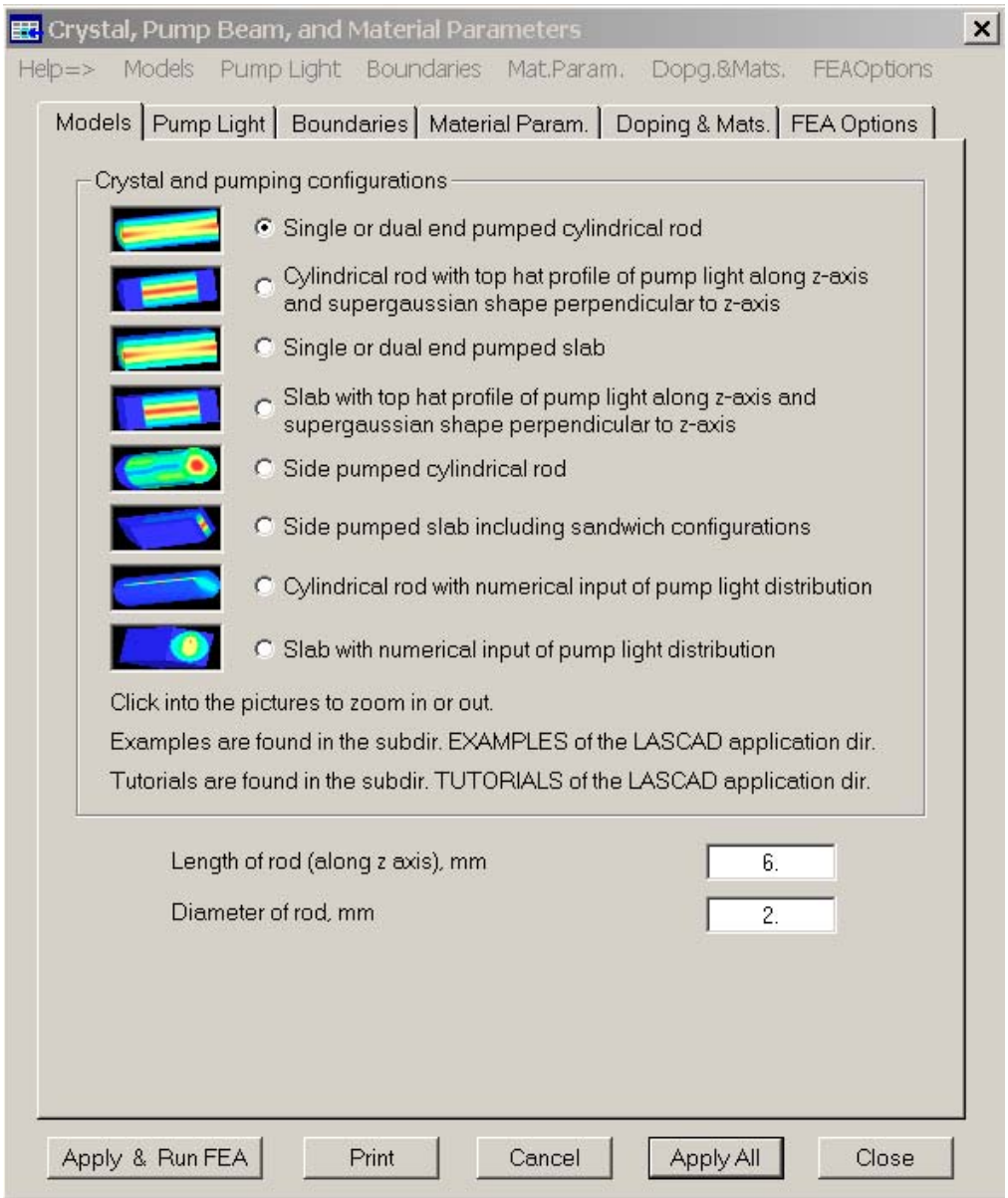

Fig. 2

2.2 Defining the pump light distribution

Select the tab labeled **Pump Light** to open the window shown in Fig. 3.

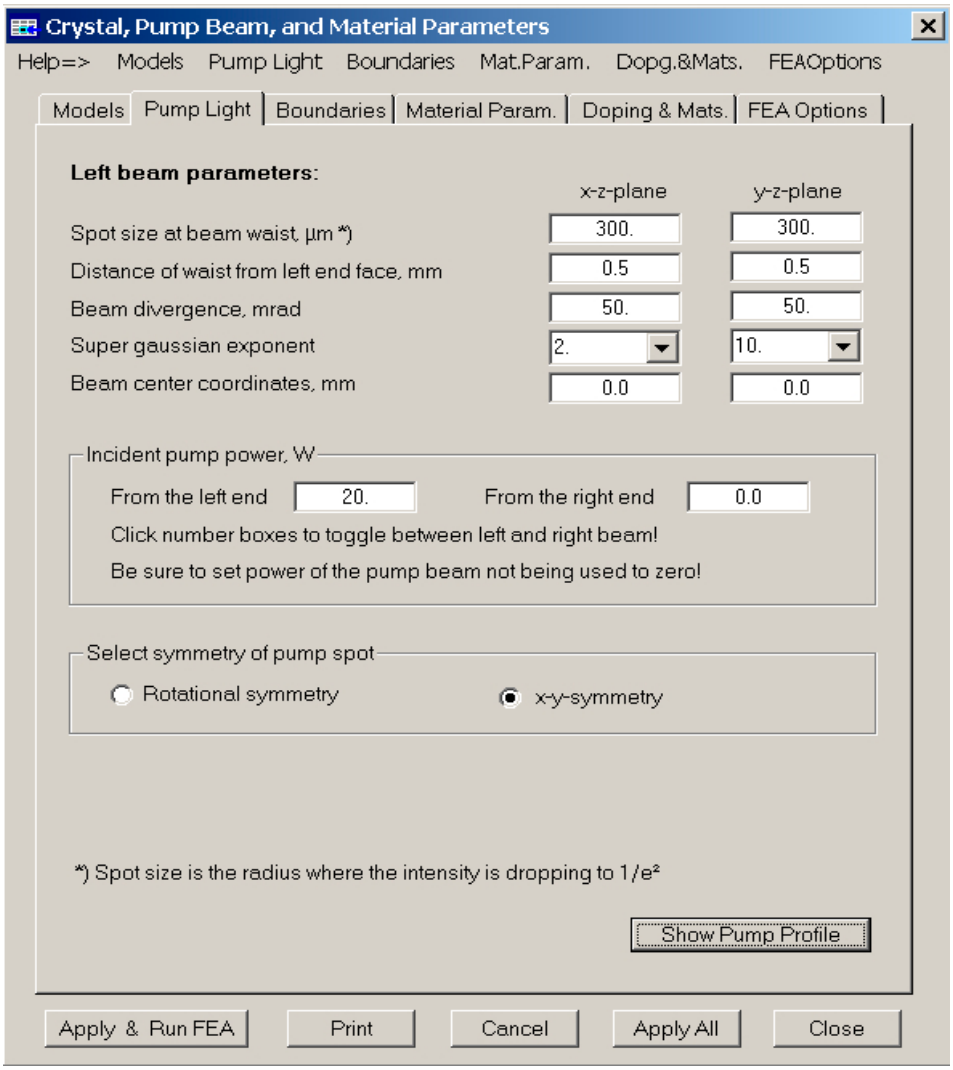

Fig. 3

The entries allow for approximating the pump light distribution by the use of supergaussian functions. Supergaussian function means that the expression used to describe the pump light distribution has the mathematical form of a gaussian distribution, but with an exponent that may be different from 2. A supergaussian function approaches a top hat distribution with increasing exponent. Section 6.10.2 of the LASCAD manual describes this in more detail.

The input boxes within the frame **Incident pump power, W** can be used to define the power of two pump beams impinging from the left, and/or from the right end, into the crystal, respectively.

Commonly, beams used for end pumping are focused into the rod as shown in Fig. 4. The entries, **Spot size at beam waist**, **Distance of waist from left end face,** and **Beam divergence** allow for specifying the related quantities.

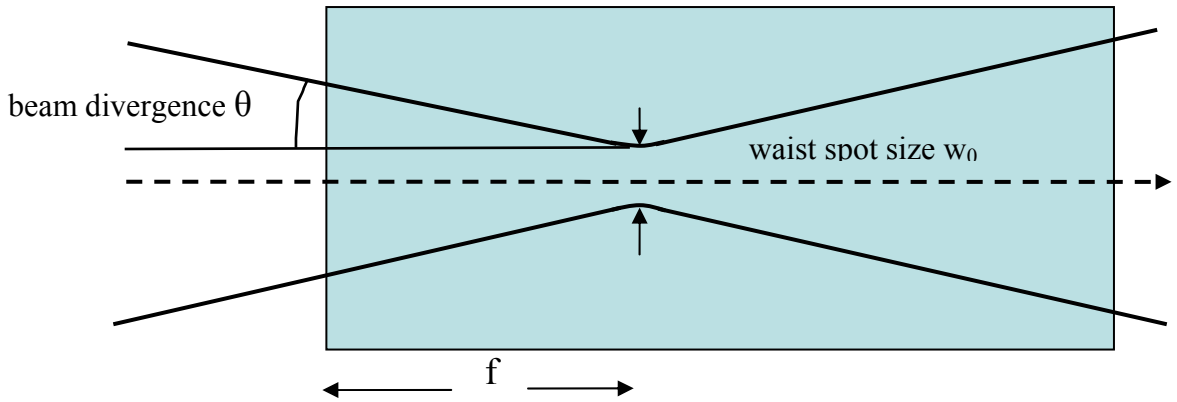

Fig. 4. Pump beam focused into the crystal, f is the distance of the waist from the left end face

If you click into the box labeled **From the left end,** you can enter the parameters of the beam coming from the left end.

To see the effect of the **Supergaussian exponent**:

- Check the option **x-y-symmetry**,
- Pull down the box **Supergaussian exponent** in the y-plane panel, and select 10, for example.
- Click the button, **Show Pump Light Distribution,** at the bottom right.

The window, **Pump Beam Profile,** is opened, as shown in Fig. 5. According to the entries for the supergaussian exponent, the beam profile along the x-axis has a common gaussian shape, whereas the profile along the y-axis approaches a top hat distribution. Moving the slider, located below the plot, from left to right, you can see how the absorbed pump power density decreases, due to absorption. Click within the plot to rescale the graph to full height.

Analogously, if you click into the box labeled **From the right end,** you can enter the parameters of the beam coming from the right end.

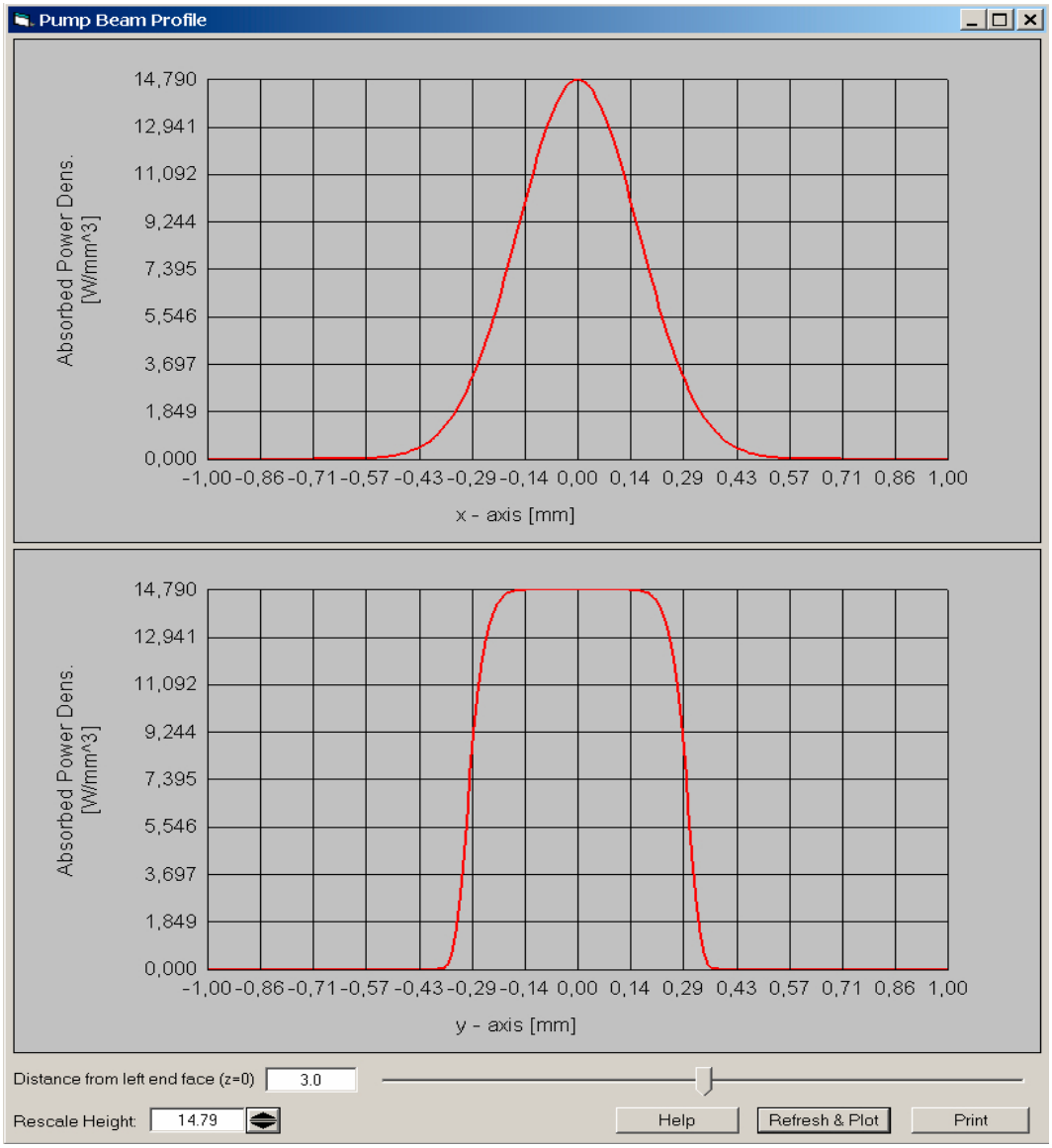

Fig. 5

2.3 Defining cooling of the rod

Select the tab labeled **Boundaries** to open the window shown in Fig. 6. The entries allow for defining cooling conditions individually for each surface of the rod.

You can define cooling as either by solid or fluid contact. For the fluid contact, additionally check the box **Fluid Cooling**.

In the case of solid cooling, the surface is kept at constant temperature, which is defined by the value in the box **Temperature, K**. For fluid cooling, the latter value defines the bulk temperature of the fluid. In the case of fluid cooling, a film coefficient, which describes the heat transfer through the interface solid-fluid, must also be defined (bottom row). Section 6.10.3 of the LASCAD manual describes this in more detail.

If you use temperature dependent material parameters or 3-level-materials, it is important to use the Kelvin scale here. Otherwise you can enter the value "0" for the cooled surfaces.

The entry **Reference temperature** is used with computation of thermal deformation and corresponds to the crystal temperature before heating. When boundary temperatures are defined using the Kelvin scale it is important to enter the correct value here.

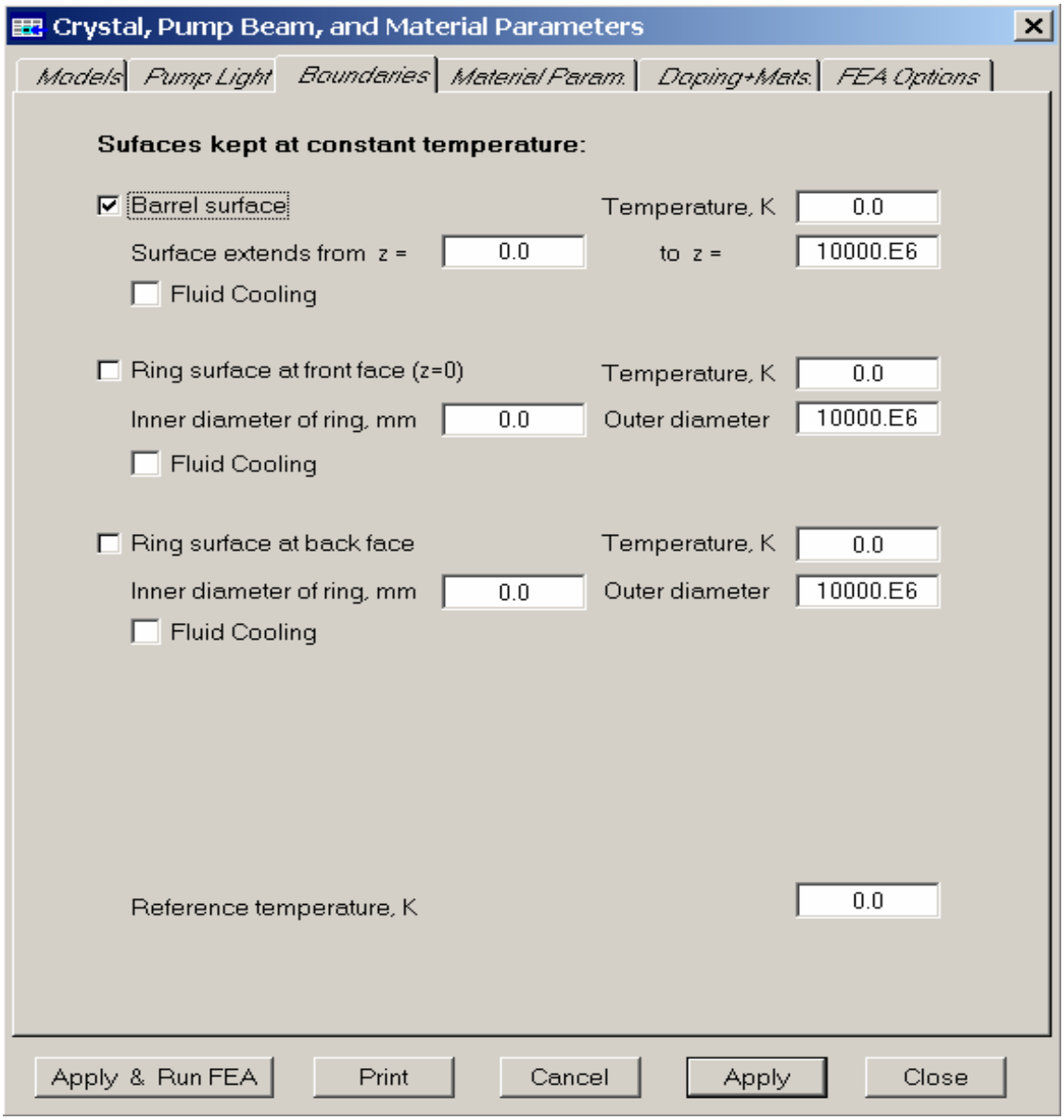

Fig. 6

2.4 Defining material parameters

Select the tab labeled **Material Param.** to open the window shown in Fig. 7. The entries are almost self-explaining.

The **absorption coefficient** describes the exponential attenuation of the pump beam according to $I(z) = I_0 \exp(-\alpha z)$, due to absorption of the pump photons; it depends on the doping level of the crystal. For non-isotropic crystals the absorption of the pump light can depend on the polarization of the pump light. In this case the absorption coefficients can be defined for two independent polarization directions. Details are described in the appendix of the manual. For Nd:YAG just enter identical values into the related boxes.

In addition, more sophisticated issues can be defined, like temperature dependent material parameters, or solids composed of two different materials, as described in the manual.

You can save the material parameters to a file and use them later with a new project.

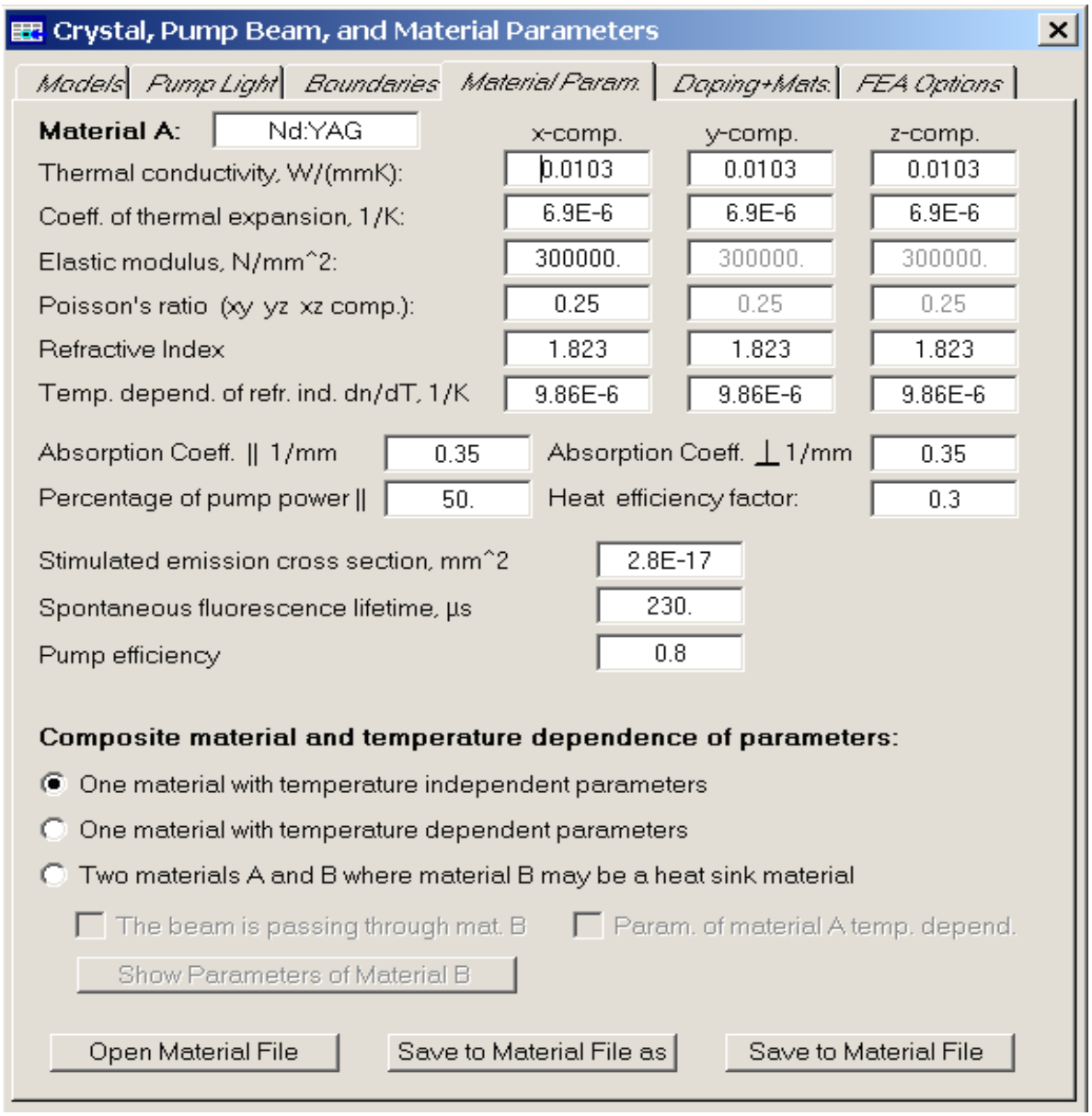

Fig. 7

2.5 Defining composite material

Select the tab labeled **Doping & Mats.** to open the window shown in Fig. 8. In the present example we use the entries to define a rod with undoped end-caps:

Pumped region extends [mm]

…
from z = 1.0 to z = 5.0

means, that pump light is absorbed only within a doped region $1 \le z \le 5$ mm. Since, in our example, the crystal is 6 mm long, we are defining two undoped end-caps of 1 mm length in this way.

The appearance of this tab depends on options selected in the tab **Material Param.**

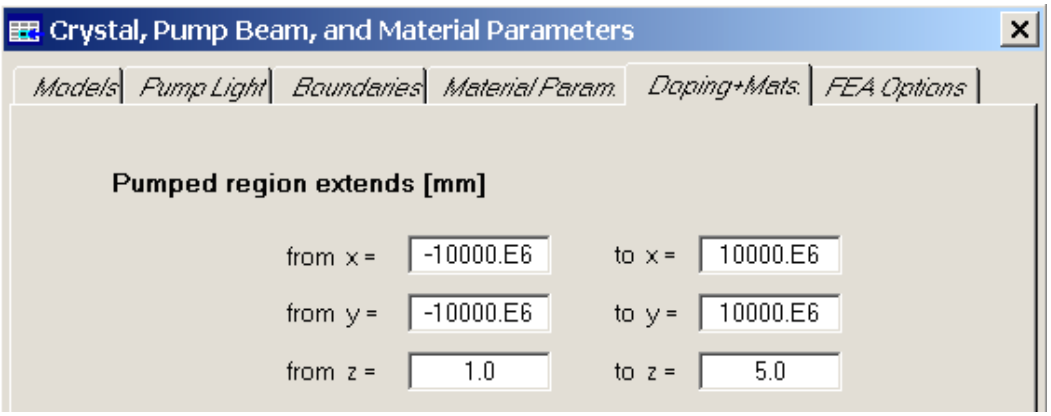

Fig. 8

2.6 Defining options to control the FEA computational procedure

Select the tab labeled **FEA Options** to open the window shown in Fig. 9.
The FEA code uses a regular rectangular mesh inside the crystal, which is connected to the boundaries of the crystal by small irregular elements.

Mesh size in x- and y-direction is the edge length of the voxels perpendicular to the crystal axis.

Mesh size in z-direction is the edge length of the voxels along the crystal axis.

Click **Estimated number of elements** to get information concerning the amount of memory needed to run the computation. The following rule of thumb can be used: If you have n elements, you should have roughly 2*n/1000 MB RAM available, otherwise the program becomes very slow as memory is paged to disk. (You can use the Windows Task-manager to determine the amount of free RAM currently available which can usually be opened by pressing Ctrl-Alt-Del. Open the Tab **System Performance**. The row **Available** in the box **Physical Memory** displays an estimate of currently available memory.)

The entries for **Convergence limits** control the convergence of the iterative computational procedure. The default value 1.0E-7 for the thermal analysis stops the code if the temperature maximum does not change within the first 7 digits. The limit for the structural analysis refers to the absolute value of maximum nodal displacement.

Regardless of the convergence limits, the iteration process is stopped, if the number of iterations exceeds the numbers entered in **Maximum number of iterations**.

The input box **Directory for output of FEA results** can be used to define a directory where the files created by the FEA code are stored. Default setting is the subdirectory FEA of the Working Directory.

The input box, **Position of cutting plane perpendicular to z-axis,** allows for placing a cutting plane perpendicular to the z-axis, to show the distribution of physical quantities inside the crystal with the **3D Visualizer,** as described in the next section. If the **entry** into this control is **zero**, a cutting plane along the rod axis and perpendicular to the y-axis is used. If the entry is **greater than zero and smaller than the rod length**, a cutting plane perpendicular to the rod axis is used. If the entry is **greater than the rod length**, the full crystal is shown.

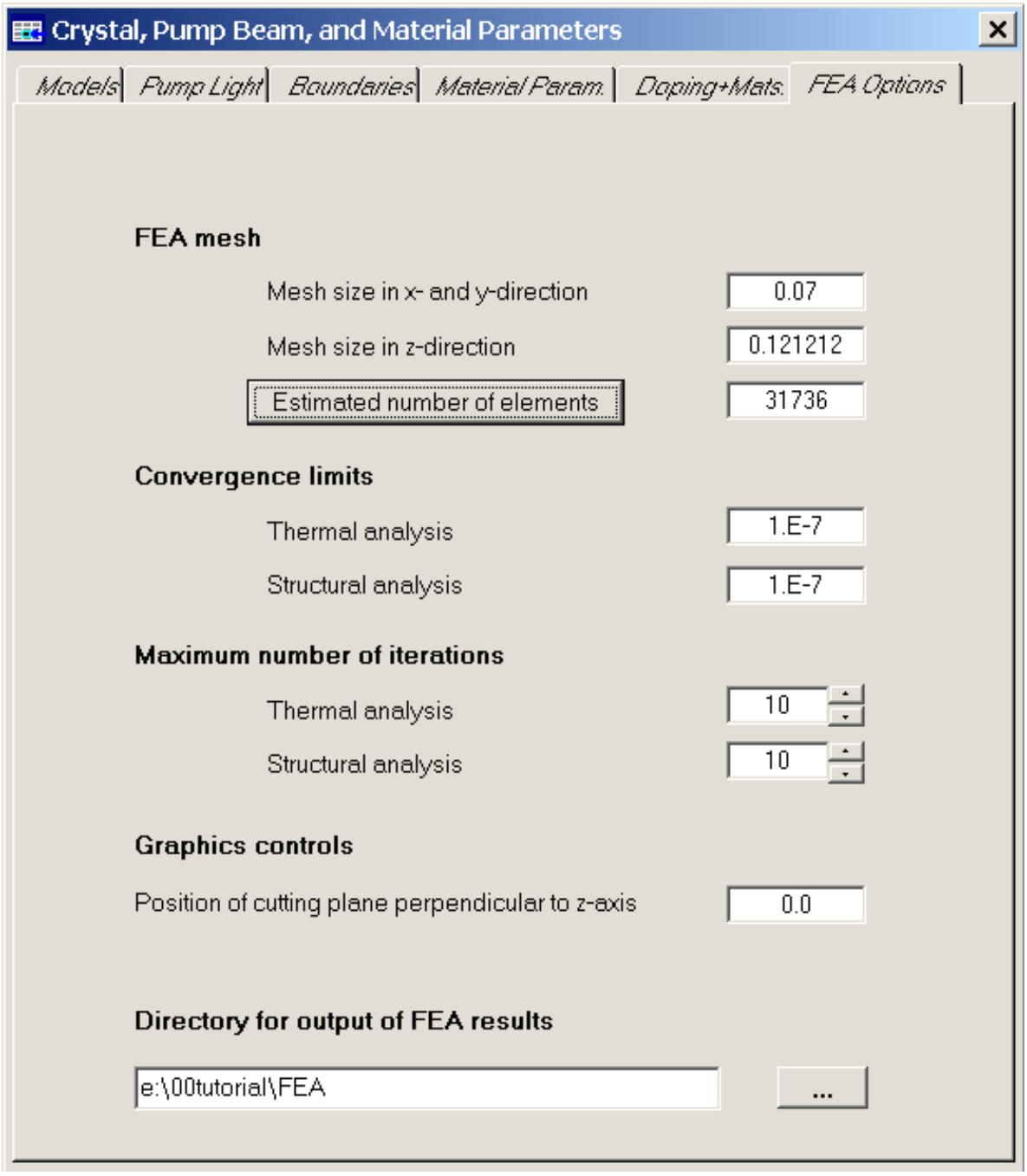

Fig. 9

Use the button, **Apply and run FEA** to transfer the input data to internal variables and to start the FEA code. The window **Finite Element Analysis** is pops up, showing the number of the currently running iteration. In addition, it shows the maximum temperature during thermal analysis, and the absolute value of maximum nodal displacement during structural analysis. At the end of the computation the message **FEA finished successfully** appears. Click **OK** to close the dialog.

Please be aware that initialization of the FEA and generation of the mesh may take some time for large element numbers.

2.7 Visualizing results of the FEA

LASCAD provides 3D and 2D tools to visualize the FEA results data.

2.7.1 3D Visualizer

To show 3D plots of the FEA results, select **FEA→3D Visualizer** in the main LASCAD menu. It opens an easy to handle 3D Visualizer based on OpenGL. As an example, a 3D temperature

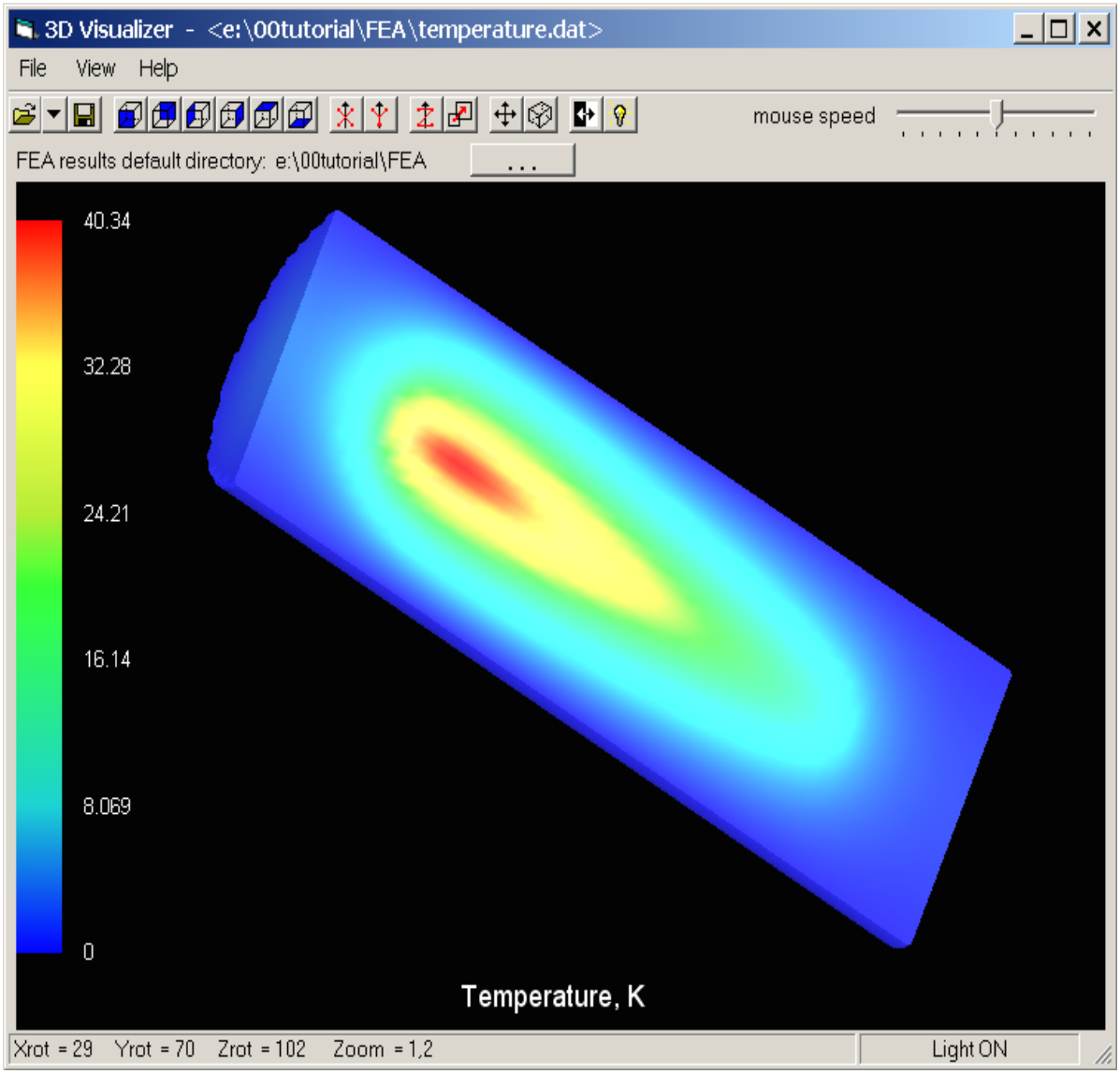

Fig. 10

plot is shown in Fig. 10. Since undoped end-caps have been defined in section 2.5, the rise of the temperature is confined to the inner region of the rod.

2.7.2 2D Data Profiles and Parabolic Fit

Alternatively it is possible to show 2D data profiles at different positions along the z-axis. Click the item **FEA→2D Data Profiles and Parabolic Fit,** in the main LASCAD menu, to use this second tool.

A dialog pops up, where you can select the directory containing the FEA results data. Keep the default setting, and click **Open Fit Window**.

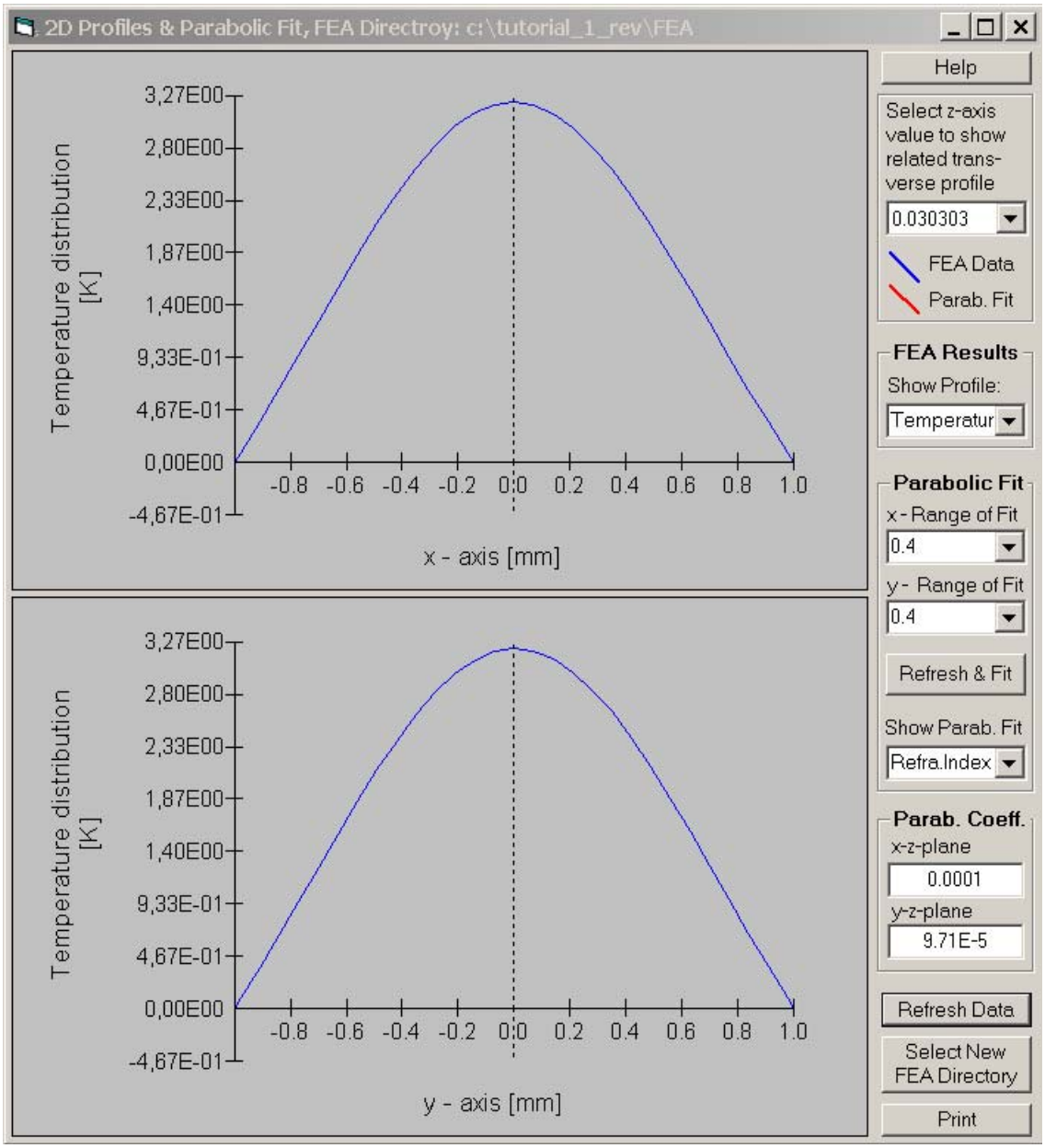

Fig. 11

The window **2D Data Profiles and Parabolic Fit** opens as shown in Fig. 11.

The window displays transverse profiles of FEA results data. Use the drop-down box at the right upper corner of the window, and select a position along the crystal axis, to show the transverse temperature profile at this position. The wheel of the mouse can be used to scroll to different positions. The available positions correspond to the mesh subdivisions created by the FEA. The drop-down box **Show Profile** in the frame **FEA Results** can be used to show profiles of other quantities, for instance the pump light distribution.

2.8 Computing gaussian modes

To use the FEA results with the gaussian mode-algorithm, the profiles of the temperature induced refractive index and of the deformation of the crystal end faces of the crystal must be fitted parabolically, transverse to the optical axis.

In advance, a **Range of Fit** has to be defined, that depending on the expected spot size of the mode, usually can be much smaller than the diameter of the crystal. We are using the default settings for the present example.

Click **Refresh & Fit** in the window **2D Data Profiles & Parabolic Fit** to carry through the parabolic fit which is shown in Fig. 12.

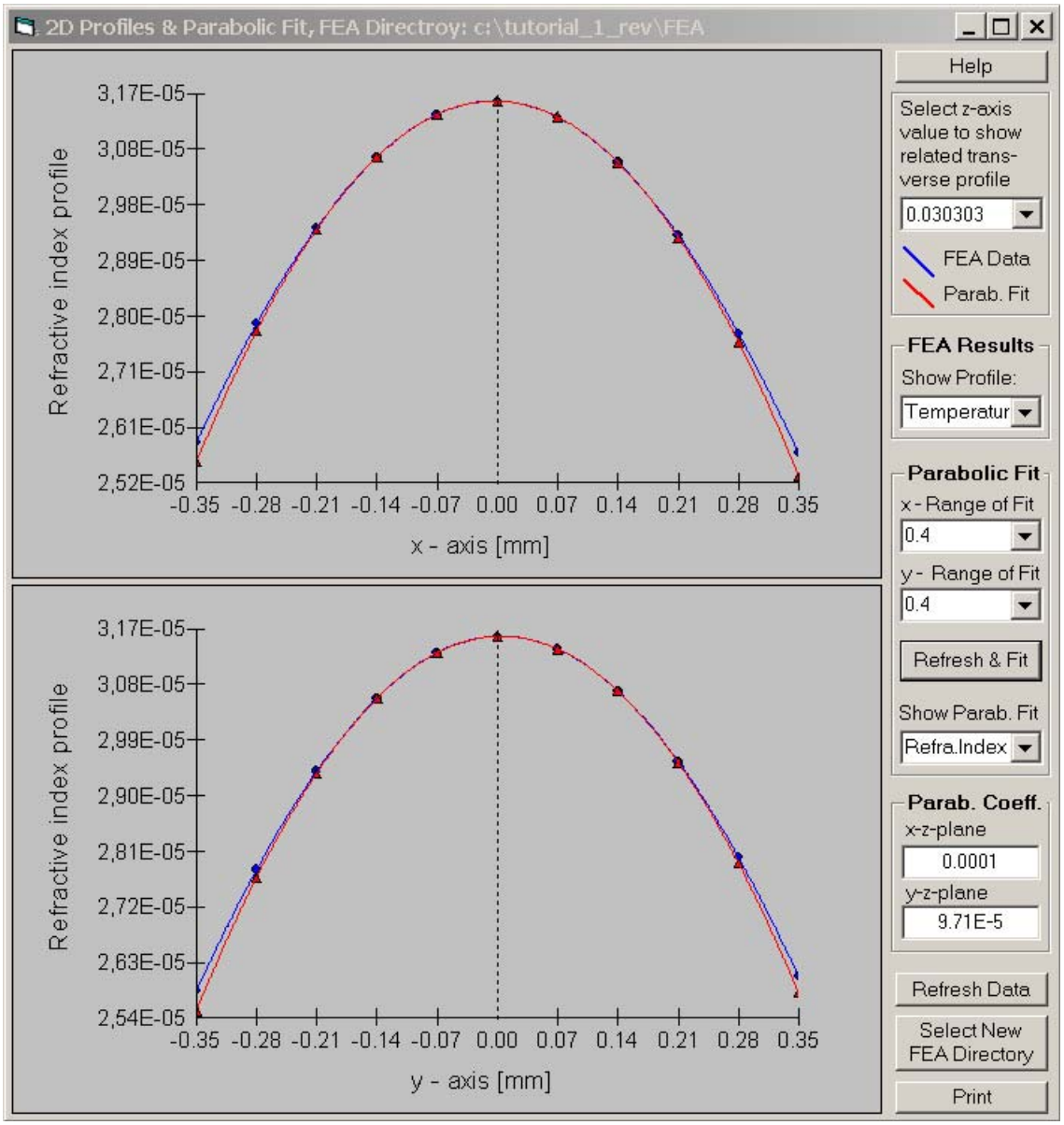

Fig. 12

The red lines represent the parabolic curves, and the blue lines the FEA results, respectively. The fit is being accomplished for all subsections along the crystal axis generated by the FEA meshing procedure. That means that the crystal is subdivided into a series of GRIN lenses, each of them having its individual parabolic refractive index distribution. The left end face of the leftmost subsection coincides with the left end face of the crystal, in the same way the right face of the rightmost subsection coincides with the right end face of the crystal. The deformation of these end faces is taken into account by fitting radii of curvature to these astigmatic end faces.

Again, you can use the drop-down box in the right upper corner of the window to show the fit at different positions along the z-axis. The parabolic coefficients obtained for each individual fit are shown in the frame **Parab. Coeff.**. Additionally, they are written into the file `FIT.dat`, in the FEA subdirectory.

2.9 Inserting the crystal into the mode plot

Press the ALT key, and click into the mode plot, such as between element 1 and 2, to insert the crystal between these two face elements. A yellow element appears in the mode plot symbolizing the thermally lensing crystal. The face elements 1 and 2 have been converted into the left and right end face of the crystal, respectively; and their distance has been adjusted to the length of the crystal. To compute the mode shape, ABCD matrices for all FEA subsections and the deformed end faces of the crystal have been built by the use of the computed parabolic coefficients, and have been combined with the matrices of the end mirrors of the cavity. Then all matrices have been multiplied with each other to compute the full round-trip ABCD matrix that finally delivers the gaussian fundamental mode shape, as shown in Fig. 13.

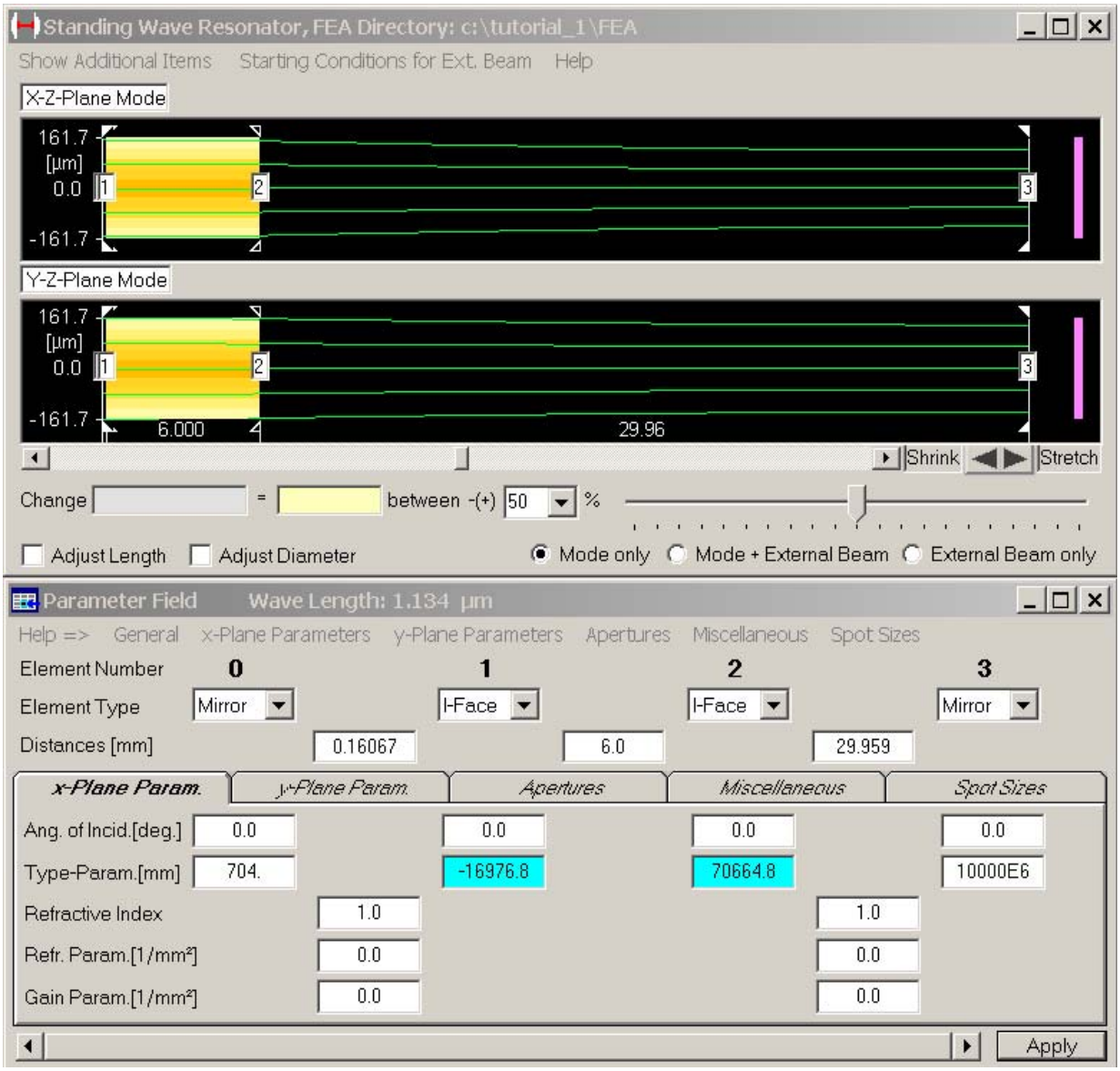

Fig. 13

Notice, that several parameters in the window **Parameter Field** have been changed in comparison with Fig. 1.

3 Modifying cavity parameters

To modify parameters of a resonator configuration for instance the cavity shown in Fig. 13 many tools are provided in LASCAD.

You can shrink and stretch the plot by the use of the two arrows immediately below the mode plot.

You can click on the end mirrors and move them with the mouse.

Also the yellow symbol for the crystal can be moved with the mouse.

To insert an additional element, press the SHIFT key, and click into the mode plot at a position where you would like to insert the new element. The **Insert Element** window is pops up, as shown in Fig. 14. The setup of this window corresponds to the **Parameter Field** window. For the sake of simplicity, new face elements are inserted, together with a new definition of the properties of the medium, at the left-hand side of the new element. Use the entries to define the type of the element, focal distance, radius of curvature etc.

To clear an element, position the mouse pointer over the element, press the CTRL key, and then the left mouse button. The thermal lens can also be cleared in this way.

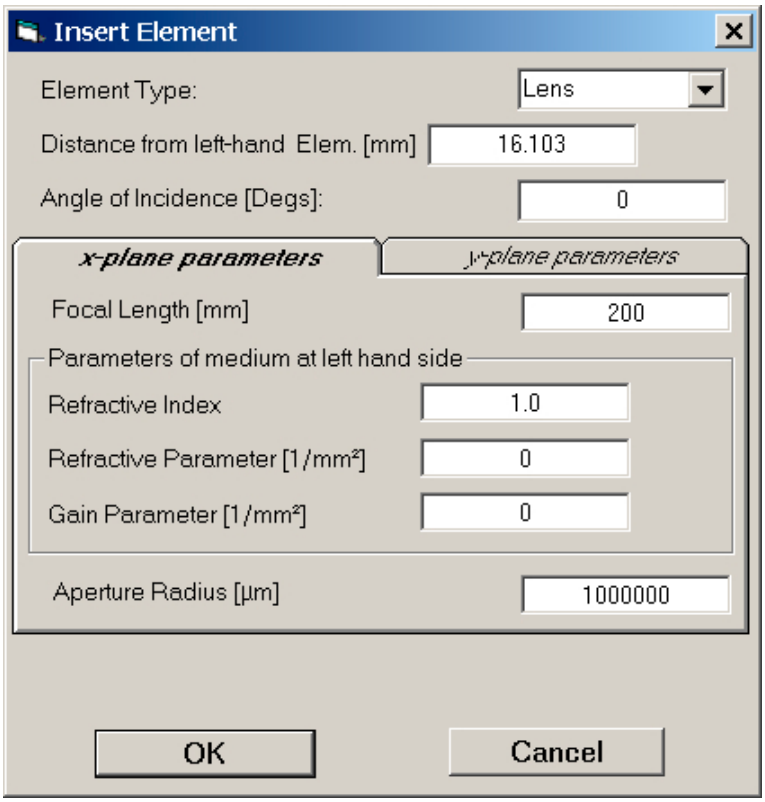

Fig. 14

The curvature of the end mirrors can be modified by changing the entries into the related boxes in the row **Type-Param.,** in the window **Parameter Field**.

Another way to change parameters works as follows: click into one of the boxes in the window **Parameter Field,** and then move the slider below the mode plot to change the related quantity, as described in the manual and in the Quick Tour.

To investigate dependence of the thermal lensing effect on the pump power, proceed as follows: click the tab **Miscellaneous** in the window **Parameter Field,** and enter a new value into the box **Pump power for rescaling** (not available with the demo version). All thermal effects will be linearly rescaled corresponding to the ratio between original pump power and the value entered for rescaling.

Additional tools are described in the LASCAD manual.

4 Tools to analyze the properties of a laser cavity

LASCAD provides several tools to analyze the properties of the cavity. Some of them are explained below in context with the present example.

4.1 Analyzing stability of a laser cavity

Select the menu item, **Show Additional Items→Stability Diagram,** in the mode plot window, to open the window **Stability Diagram,** as shown in Fig. 15.

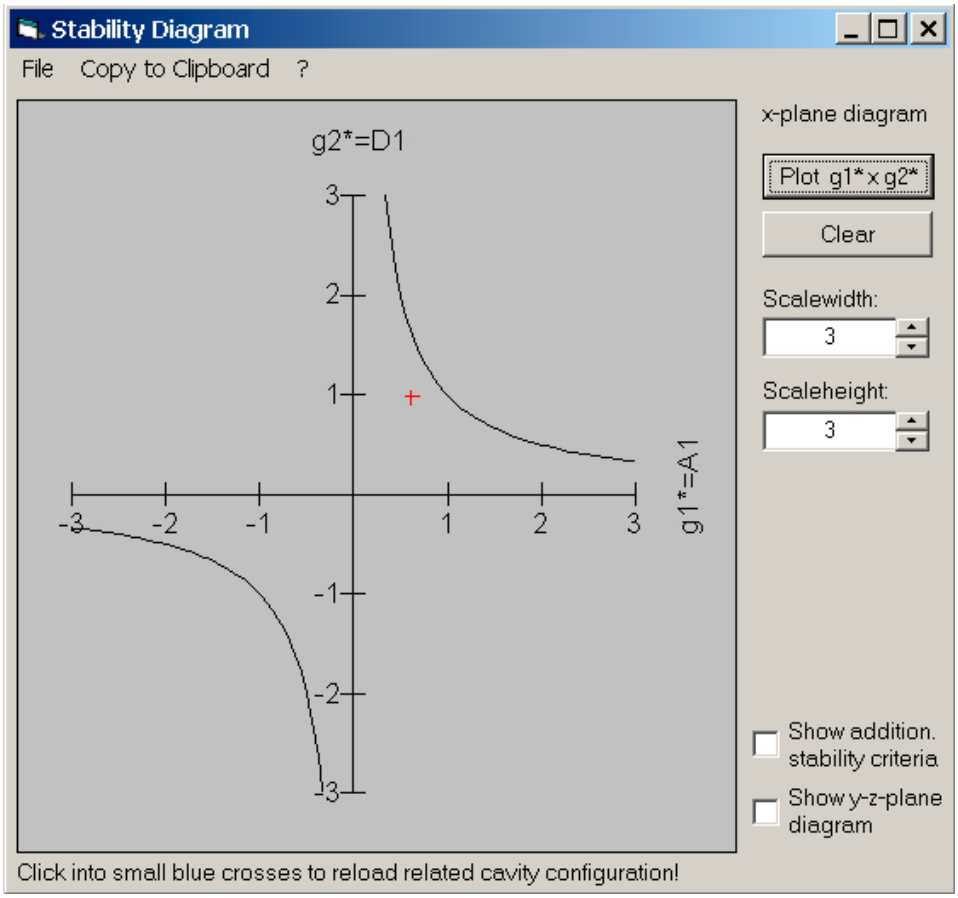

Fig. 15

Click **Plot g1*x g2*** to show the stability of the actual resonator configuration. A red cross symbol is plotted, whose position within the diagram represents the stability of the cavity. After changing a cavity parameter, for instance the curvature of a mirror, click the button again to plot a second cross, whose position shows the influence of the parameter modification on the stability of the cavity. You can continue in this way and plot a series of crosses. The color of the latest one always is red, and the previously plotted crosses change to blue.

An important issue is the dependence of the cavity stability on the pump power. To analyze this, rescale the pump power, as described in section 3 (not available with the demo version).

Check the box **Show y-plane diagram** to also show the stability diagram for the y-plane mode.

Theoretical explanations, such as the definition of the generalized g-parameters, can be found in the manual Sect. 6.5.

4.2 Showing transverse gaussian mode profiles and their overlap with the pump profile

Select the menu item, **Show Additional Items→Transverse Gaussian Mode Profile,** in the mode plot window, to open the window **Gaussian Mode Profile,** as shown in Fig. 16.

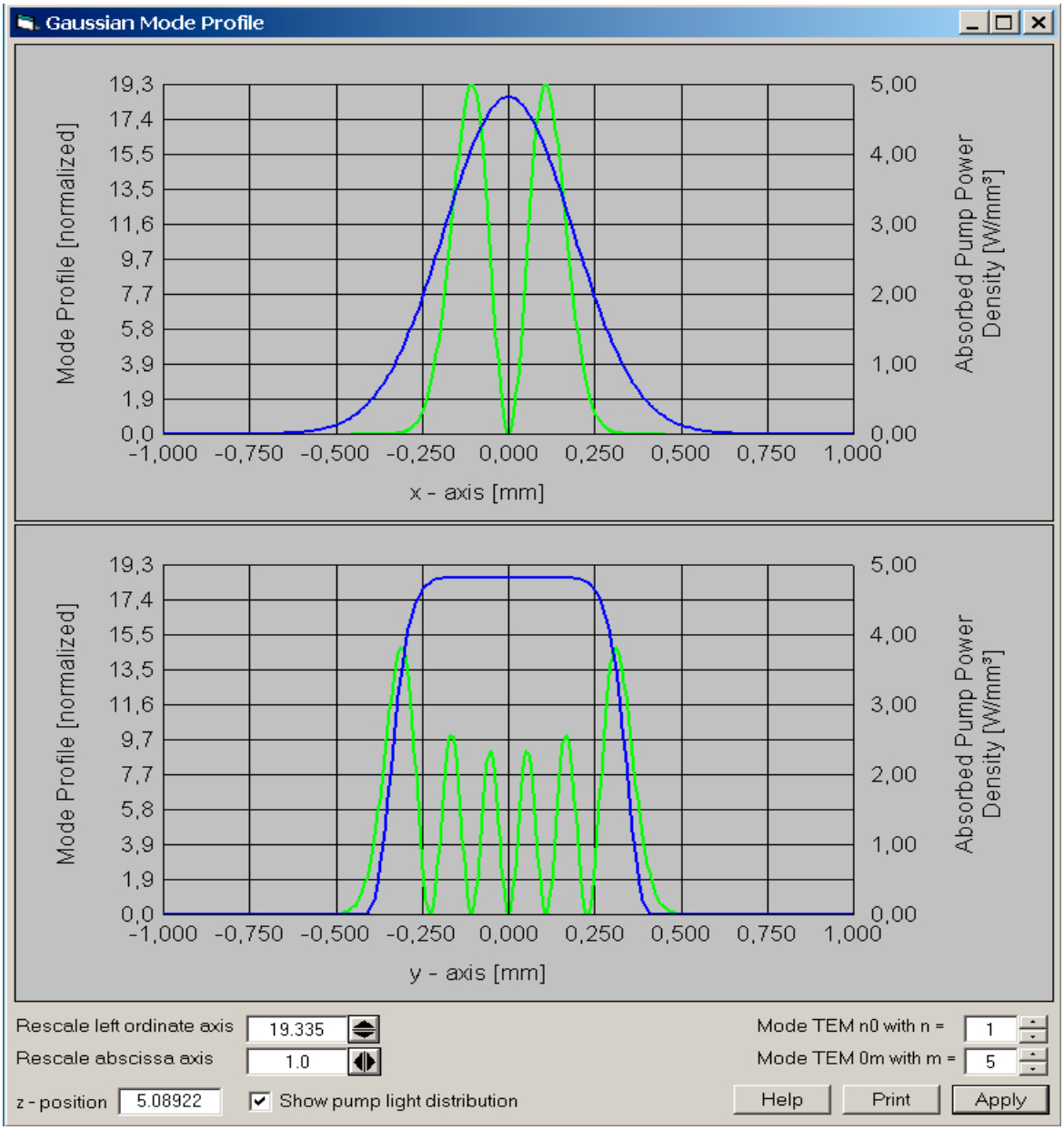

Fig. 16

Click on the vertical magenta colored bar, at the right end of the mode plot window (see Fig. 1), and move it into the mode plot, to see the transverse gaussian profile at the position of the bar.

If you move the bar over the crystal, in addition to the mode profile, the transverse pump light profile (blue line) is shown to visualize the overlap between both profiles. By the use of the up-down arrow controls, at the right lower corner of the window, higher order transverse modes can be displayed, that allow for estimating the probability of higher order modes being excited.

The different shape of the pump profile along x- and y-axis is caused by the different entries for the super-gaussian exponent in Fig. 3.

4.3 Computing the laser power output

Select the menu item, **Laser Power CW,** in the main LASCAD window, to open the window **Laser Power Output,** as shown in Fig. 17.

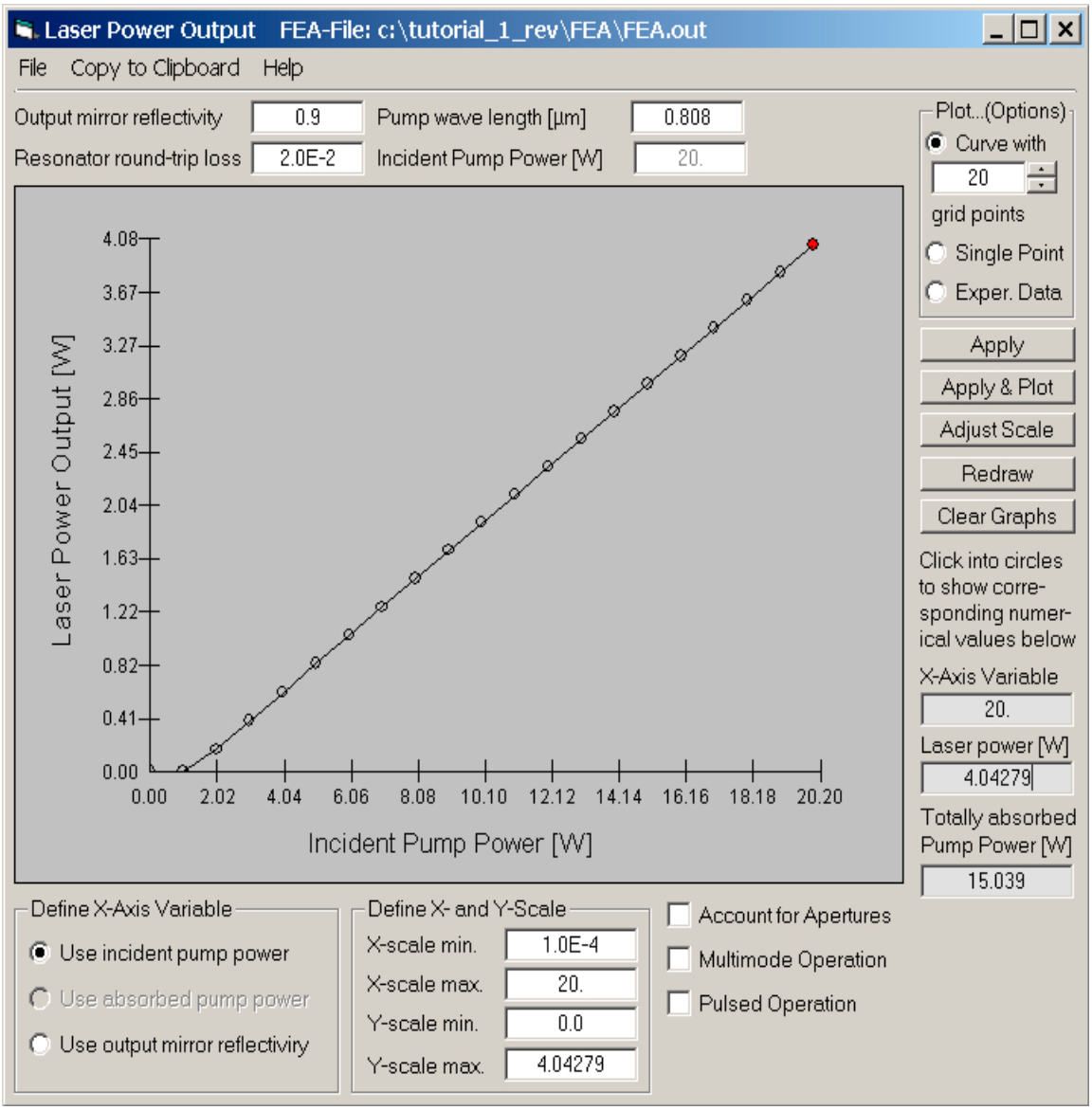

Fig. 17

Click **Apply & Plot,** to compute the laser power output as a function of the incident pump power. At the end of this computation you will get a warning concerning the mesh size, but discard it for the moment. To adjust the plot to the limits of the coordinate axes, click the button, **Adjust Scale**. To compute this graph the thermal lensing effects are linearly rescaled, as described in section 3, "Modifying cavity parameters". The number of points being computed can be adjusted, by using the up-down arrow control in the right upper corner of the window.

Select the option, **Single Point,** in the frame, **Plot … (Options),** to plot a single point.

Select the option, **Use output mirror reflectivity,** in the frame, **Define X-Axis Variable,** to plot the laser power output as a function of the output mirror reflectivity.

Check the box, **Multimode Operation,** to plot the laser power output for multimode operation. In this case the mode shape corresponding to the superposition of several transverse modes is approximated by a top-hat shape, whose width is adjusted to the width of the highest order

transverse mode being excited. In doing so, the variation of the width of this mode along the cavity axis is taken into account. For additional information see "Tutorial No. 2".

Pulsed operation is approximated by the use of rectangular pulses. Check the box, **Pulsed Operation,** to enter pulse duration and frequency.

Multimode and pulsed operation can be computed much more accurately with the new code DMA, for dynamic analysis of multimode and Q-switch operation, which is described in Tutorial No. 4.

5 The Beam Propagation Code (BPM)

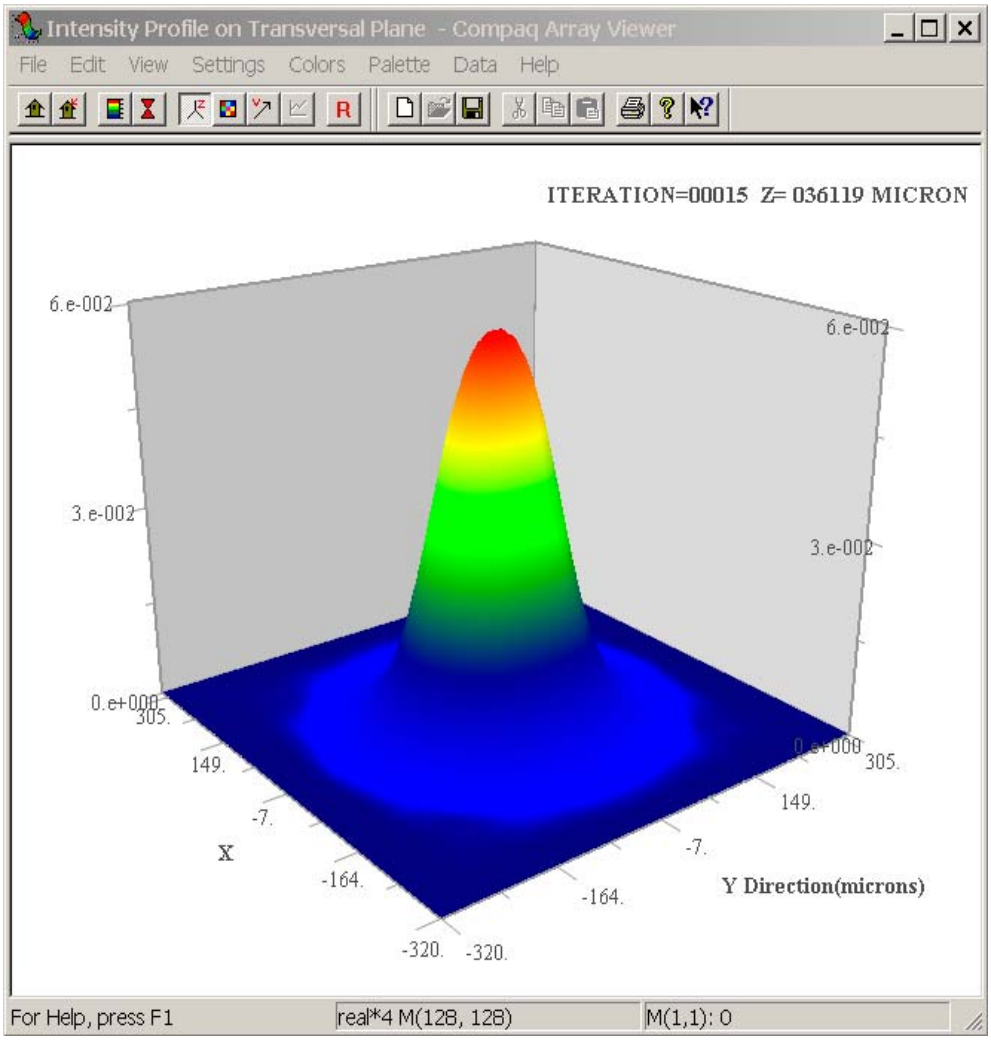

Fig. 18

Parabolic approximation and ABCD matrix code are not always sufficient.

In these cases the FEA results can be alternatively used as input for a physical optics beam propagation code. This code provides full 3D simulation of the interaction of a propagating wave front with the hot, thermally deformed crystal, without using parabolic approximation. Here only a short instruction is given for starting the BPM code, using default parameter settings. For details the reader is referred to the manual.

Click **BPM→Run BPM** in the menu bar of the main LASCAD window to open a window with entries to control the execution of the BPM code, as shown in Fig. 19.

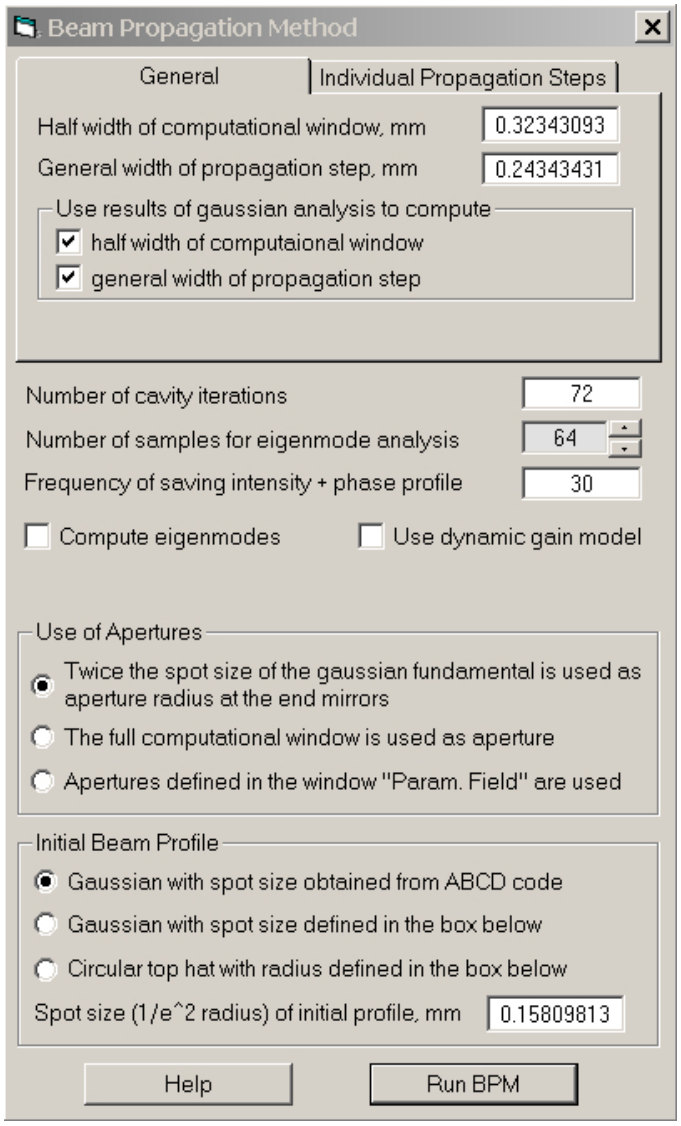

Fig. 19

Leave the default settings of this window unchanged, and click **Run BPM,** to start the BPM code. Together, with the BPM main window, two graphics windows are opened. One of them displays the mode profile at the right end mirror, as shown in Fig. 18. The other one shows the convergence of the beam radius with increasing cavity iteration, as shown in Fig. 20. The scale, **Cavity Iteration,** shows the number of full round trips of the wave front propagating back and forth between the mirrors. The large scale fluctuations are caused by interference of the fundamental mode with higher order transverse modes. Use the box, **Enter Yrange,** to adjust the vertical scaling of the plot.

The convergence limit shown in Fig. 20 is in good agreement with the mode spot sizes shown in Fig. 21, obtained by the use of the gaussian algorithm, in combination with parabolic approximation, as described above. Notice that the spot sizes are different in x- and y-plane. This is a consequence of the strongly asymmetric pump light distribution, as shown in Fig. 5 which is generating an astigmatic thermal lens. Fig. 20 shows the spot size averaged with respect to the azimuth angle around the cavity axis.

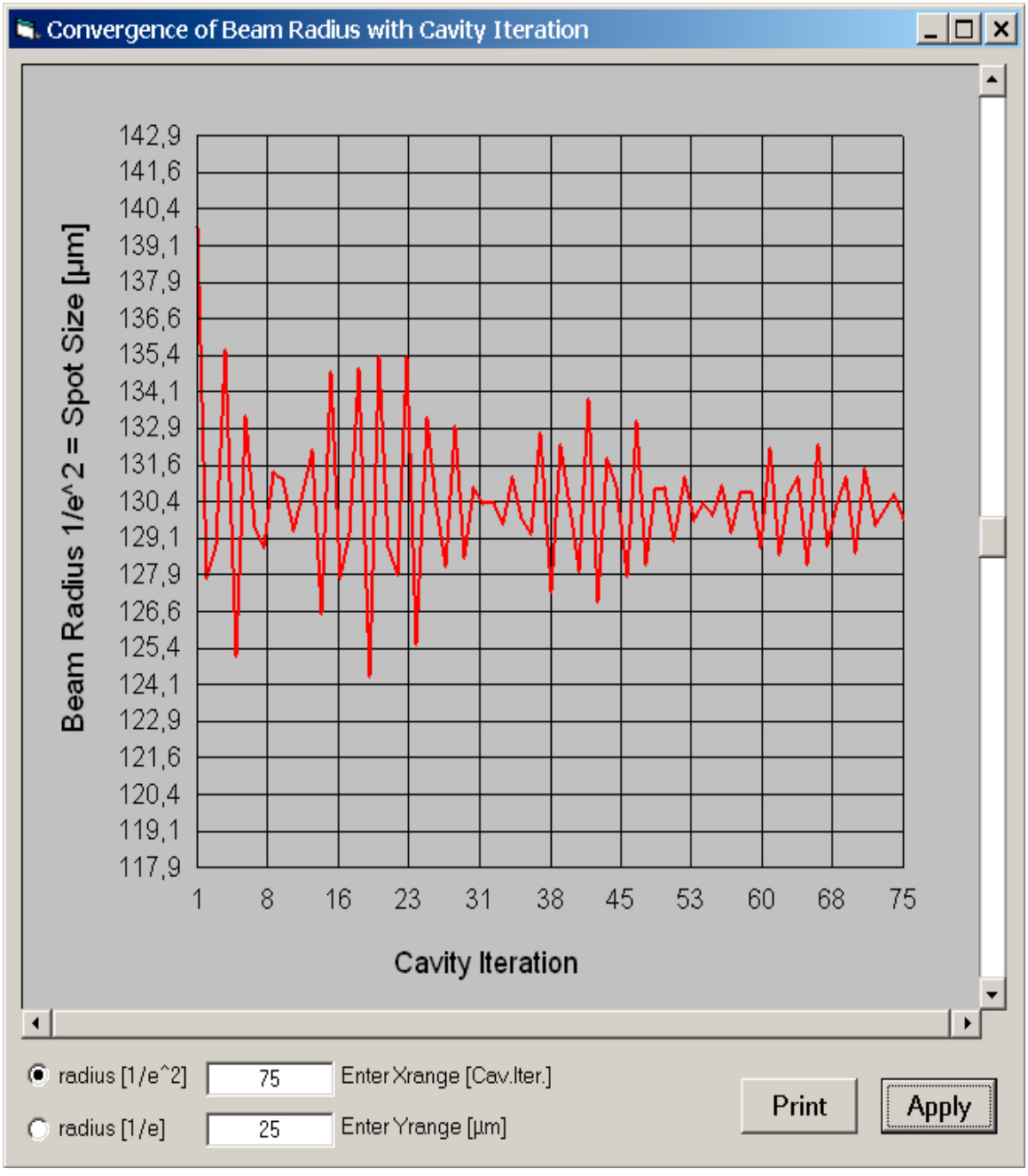

Fig. 20

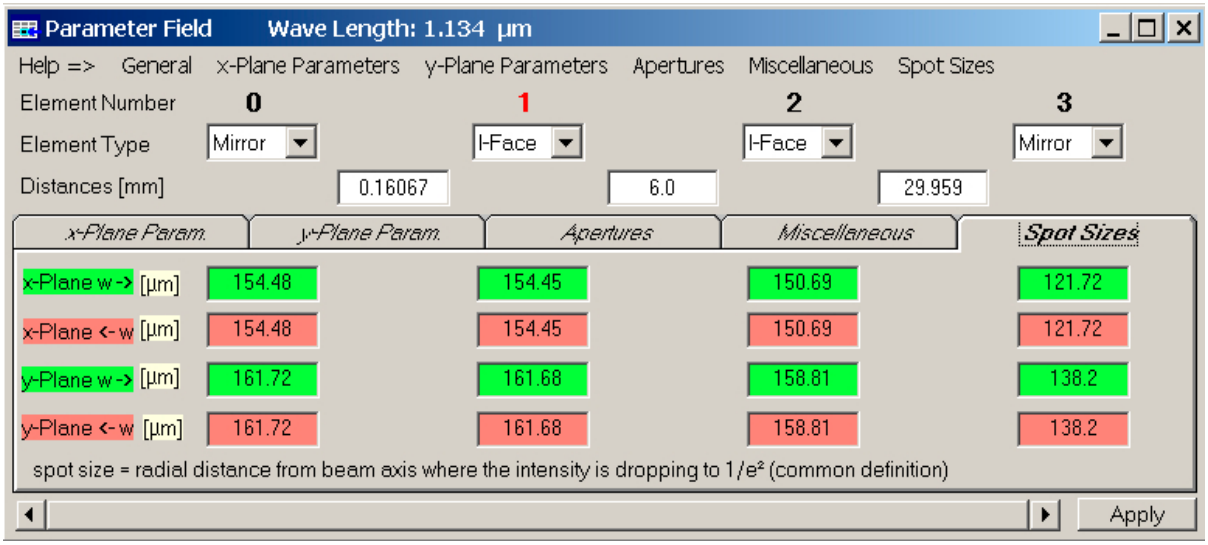

Fig. 21

Please refer to Tutorial No. 2 for instructions, how to run the BPM code for multimode operation.

A detailed listing of numerical results created by the BPM code such as laser power output, beam quality etc. can be found in the file `lyra.txt` in the subdirectory `BPM` of the LASCAD working directory. A user guide for the BPM code can be found in the file `BPM user_guide.chm` in the subdirectory `Documentation` of the LASCAD application directory.