LaserCanvas 5

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Contents

Contents 3
Introduction 5
Top-10 Tips 6
Tutorials 9
Simple Resonator 9
Bow-Tie Resonator 12
Collimating Telescope 17
Interface 23
Property Manager 23
Canvas 25
Draft Mode 28
Mode Plot 31
System Graph 32
Optic Graph 34
Inventory 36
Solver 36
Wireframe 39
Saved Files 41
Printing 42
Optics 43
Adding and Removing Optics 43
Common Properties 44
Mirror and Flat Mirror 46
Thin Lens and Thermal Lens 47
Plate 48

Brewster Plate 48
Crystal 48
Prism Pair 51
Screen 52
Output Coupler 52
Source 53
Equations and Variables 53
Data Files 56
File Structure 56
System Block 57
Optic Statements 59
Renderer Statements 64
Reference 70
Gaussian Beams 70
ABCD Matrices 72
Complex Beam Parameter *q* 74

Introduction

LaserCanvas is a rapid-development laser beam modelling and teaching application. It uses the *ABCD* matrix formalism to establish cavity stability and resonant mode sizes for oscillators, and beam propagation parameters for linear optical systems. This user guide is intended as a brief introduction to LaserCanvas features.

The core of LaserCanvas is the design "canvas," where an optical resonator or system can be designed real-time in 2D. Optics can be moved using the mouse. Alternatively optic parameters are specified using the Property Manager, which also lists properties relating to the optical system, such as wavelength, and gives access to advanced features including variables.

In addition to the 2D canvas, LaserCanvas offers the following design tools:

Tool	**Description**
Mode Plot	A linear representation of the optical system.
System Graph	A system parameter plotted against a variable value.
Optic Graph	An optic parameter plotted against a variable value.
Inventory	A table of values listing relevant properties for all of the optics in the system.
Solver	A tool for optimizing variable values by means of a fitness function.
3d Wireframe	Show the system and its mode in a perspective wireframe view.

Getting Started

To get started, we recommend you read the Top-10 Tips and work through the included Tutorials. Together, these sections introduce most of the features of LaserCanvas.

Bugs, Corrections, Suggestions

We hope that LaserCanvas is a reliable, useful, and robust application. However, it's a very difficult task to find all bugs and errors. If you find something that's wrong, or if there's something you'd like to see added to LaserCanvas, please send us your comments. We welcome your feedback!

Citation

If you wish to cite the use of this program, please use "LaserCanvas cavity modeling software, available from P. Schlup, Colorado State University, Fort Collins, CO 80523."

Top-10 Tips

1. Grab optics at the centreline.

Optics can only be selected and moved by their "vertex" at the centreline of the system. When the mouse is over an optic vertex, the mouse cursor changes to indicate that the optic can be selected and moved. The icons themselves cannot be selected.

Incorrect Correct

2. There are no space elements.

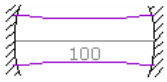
You do not need to insert space elements between optics. The positioning of the remaining optics (mirrors, lenses, etc.) automatically defines the spaces between them.

Distance to Next (mm)	100

To precisely define the separation between two optics, select the optic before the space you wish to define and enter the desired spacing in the Distance to Next item in the Property Manager.

Thickness (mm)	10

To precisely determine the thickness of a refractive element, select the input face and enter the desired thickness in the Thickness item in the Property Manager.



Displayed Separation

3. Set the system wavelength.

If you are looking for accurate mode sizes, the wavelength of the system (and the M^2 beam propagation factor) must be set correctly. By default, LaserCanvas assumes a wavelength of 1064 nm. The mode typically scales in proportion to the wavelength, so an incorrect wavelength leads to inaccurate mode sizes.

4. Flat mirrors have curvature = 0.

Mathematically, the radius of curvature of a flat mirror, or a flat wave front, is infinite. LaserCanvas uses ROC = 0 to denote flat mirrors and wave fronts.

Curvature (mm)	7.2e+18	7.2e+18

Due to floating-point round-off, flat or nearly-flat wave fronts may sometimes be displayed as large curvatures, such as 1×10^{18} mm.

5. Focusing mirrors have positive curvature.

Similarly, focusing lenses have positive focal lengths.

Radius Curvature (mm)	200

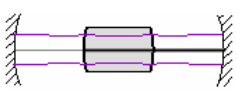
Radius Curvature (mm)	-200

Focal Length (mm)	200

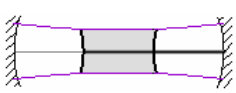
Focal Length (mm)	-200

6. Dielectric interface sign convention.

A concave dielectric interface, as seen from the refractive material, always has a positive radius of curvature, for both entrance and exit faces. Convex interfaces have negative ROC.



Radius Curvature (mm)	-100



Radius Curvature (mm)	100

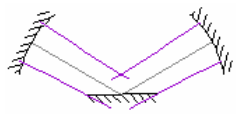
7. Units are metric, but not SI.

The *ABCD* formulae are not tied to any system of units and include no conversion factors. LaserCanvas uses a selection of metric convenience units to eliminate large pre-factors. All quantities are listed with their units. Lengths are in mm (10^{-3} m), except wavelength (nm = 10^{-9} m) and laser mode and waist sizes (μm = 10^{-6} m, displayed as "um").

If you wish, you can use any other length units (meters, inches, etc.) provided all lengths are expressed in the *same* units.

8. The mode is a guide only.

The displayed laser mode appears discontinuous at system corners and is not flush with curved interfaces.



Remember that the mode is displayed on a larger scale than the optical system (typically 20× larger). The small offset of curved optics and the actual intersection points with angled optics are not intended to be displayed accurately.

9. Sagittal and Tangential.

The tangential plane is the plane formed by the incidence ray and the normal to the optic. Since LaserCanvas only models two-dimensional systems, this is equivalent to the plane of the drawing. Thus, the *tangential* plane is parallel to the *table*. The *sagittal* plane *sticks out*.

10. Ring resonators are not supported.

This limitation is currently imposed by the interface engine of LaserCanvas, not the *ABCD* calculations. The calculations for ring resonators are no more complex than for standing-wave resonators.

Tutorials

In this chapter, we give three tutorials that illustrate some of the features of LaserCanvas. The first, *Simple Resonator*, is intended to get you started if you have never used LaserCanvas before. The remaining two, *Bow-Tie Resonator* and *Collimating Telescope*, introduce some more advanced features of LaserCanvas that help when designing cavities.

Simple Resonator

As a quick introduction to LaserCanvas, we create a simple resonator to illustrate the following points:

- Dragging optics on the Canvas
- Inserting Lenses and Mirrors
- Examining properties from the Property Manager

Part 1. Construct the Cavity

Initially, we will work with the default cavity. We will add some optics in the next section.

1. Select menu File | New Resonator, or click the New Resonator icon on the toolbar.
2. | Wavelength (nm) | 532 |
   Enter the laser wavelength, l = 532 nm. Here, we will be working with 532 nm light.

Part 2. Examine Some Properties

At this point, let's examine some relevant properties that are shown in the Property Manager.

Spot Size (um)	209	209
Curvature (mm)	-200	-200

In the Mirror group, LaserCanvas displays the spot size and radius of curvature of the resonant mode at the selected optic. In our case, the left-hand end mirror is selected. As a rule, the radius of curvature of the resonant mode must match the

radius of curvature at an end-mirror. (The opposite sign is due to the sign conventions.)

Stability	-0.875	-0.875
ABCD (Sagittal)	-1.5	-125
	0.005	-0.25
ABCD (Tangential)	-1.5	-125
	0.005	-0.25

In the System group, we find the round-trip *ABCD* matrices. Since there are no symmetry-breaking items in the cavity, all sagittal and tangential values are identical. The system stability parameter g is given for all resonators, including unstable ones. For a resonator to be stable, the stability parameter must satisfy $|g| < 1$.

3. Grab the right-hand mirror by clicking at the centreline.

4. Drag the optic around on the Canvas.

Observe how the parameters in the Property Manager change. In particular, if the mirrors are too close together, the cavity becomes unstable; similarly if they are too far apart.

A peculiarity of the *ABCD* treatment is that a cavity with $|g| = 1$ is not stable. If you drag the mirrors so they are *exactly* 200 mm apart, $g = -1$ and no stable mode exists.

To make it easier to achieve this condition:

5. Canvas

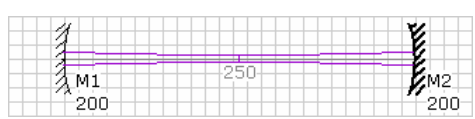
   Find the Canvas group in the Property Manager. You may need to use the scroll bar.

6. Snap to Grid ☒

   Check the Snap to Grid check box. A grid is drawn behind the cavity in the Canvas window.

7. Annotations ☒

   While we're here, we also check the Annotations check box. With this option selected, the most relevant properties of each optic are displayed on the canvas. For mirrors, the number represents the radius of curvature, in mm.

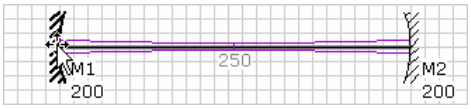


Now when you drag the mirror, its position is placed to the nearest grid point. You can change the grid spacing by editing the Grid Size field in the Property Manager.

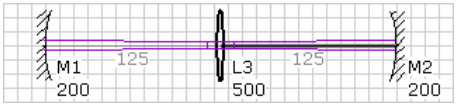
Part 3. Add a Lens

Next, we add a lens to the cavity. When adding new optics, we need to select the optic directly preceding the segment where the new optics should be added. In some special cases, not all types of optics can be added.

8. Select the left-hand mirror. Notice how the centreline of the cavity—the segment between the two mirrors—is highlighted.



9. Select menu Edit | Insert | Insert Lens, or click the Insert Lens button on the toolbar.

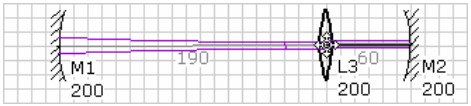


The new lens is created with a default focal length of f = 500 mm, centred between the mirrors. The lens and the following segment are automatically selected, so we could add more optics by repeating the Insert command.

10. Focal Length (mm) 200

    In the Property Manager, click the Focal Length field, and enter 200. The lens now has a focal length of f = 200 mm.

11. Grab the lens by clicking at the centreline, and drag it around.



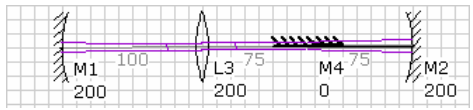
Unlike mirrors, lenses can only be moved along the section between two mirrors. This is also true for other type of optics, such as crystals.

Part 4. Add a Fold Mirror

One of the most important features of LaserCanvas is that it represents laser cavities in two dimensions, exactly how they

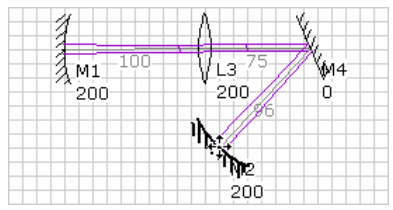
would be built on an optical breadboard. In this section, we add a mirror to fold the cavity.

12. With the lens selected, select menu Edit | Insert | Insert Mirror, or click the Insert Mirror button on the toolbar. Don't worry if your cavity looks a little different to that shown.



By default, a flat mirror is inserted. Its radius of curvature is displayed as 0.

13. Grab the end mirror M2 by clicking at the centreline, and drag it down and to the right to fold the cavity.



14.

To get a better view of the cavity mode, enter the value 100 in the Mode Scale field of the Canvas group in the Property Manager.

The Mode Scale is the magnification factor for the displayed mode size. For example, if the mode is 100 μm and the Mode Scale is 100, then the mode is displayed as 100 μm× 100 = 10 mm.

Bow-Tie Resonator

In this tutorial, we construct a typical bow-tie resonator with a Brewster-angled crystal. The incidence angle on the curved optics is adjusted to compensate for the astigmatism introduced by the laser crystal.

This tutorial will illustrate

- Standing-wave resonators
- Intra-cavity curved mirrors
- Brewster-angled plate
- Variables and graphs

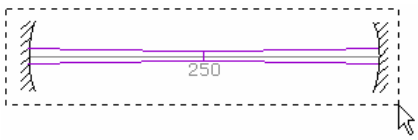
Part 1. Construct the Cavity

The cavity will consist of a Brewster-angled Nd:YAG crystal, which has a refractive index of 1.82; two 200-mm radius of curvature focusing mirrors, and flat cavity end mirrors.

1. Select menu File | New Resonator, or click the New Resonator icon on the toolbar.

2. Wavelength (nm) 1064

   Verify the laser wavelength. In our case, the default value of 1064 nm is what we will be using.

3. 

   Marquee-select both cavity mirrors. These will become the flat cavity end-mirrors.

4. Radius Curvature (mm) 0

   Enter 0 in the Radius Curvature field of the Property Manager. A radius of curvature of 0 represents a flat optic.

5. Insert the remaining optics using the Edit | Insert menu or the respective buttons on the toolbar:

   a. Insert Mirror

   b. Insert Brewster Plate

   c. Insert Mirror

6.

   Select the two intra-cavity mirrors by clicking at the centreline while holding the Shift key.

7. Enter 200 mm in the Radius Curvature field of the Property Manager.

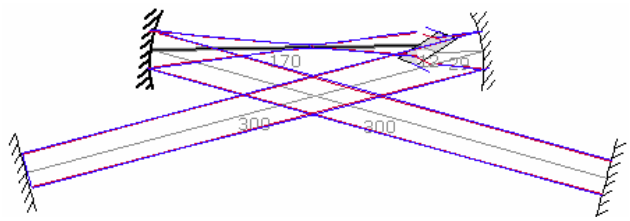
8.

Select the entrance face of the Brewster crystal. Notice that although the crystal thickness is 10 mm, the actual distance travelled within the crystal is 12 mm, due to refraction at the interfaces.

9.

Enter 1.82 in the Refractive Index field of the Property Manager.

10. Use the mouse to position the focusing and end mirrors in a bow-tie configuration. For the cavity to be stable, the total distance between the two focusing mirrors should be around 210 mm. Make the distance to the two end mirrors around 300 mm each side.



11. Save the file by selecting menu File | Save As… or clicking the Save button on the toolbar.

Part 2. Examine the Stability

Initially, we will examine what happens to the mode and cavity stability as we drag optics around. We are interested in three parameters: The positioning of the crystal, the position of the focusing mirrors, and the positioning of the cavity end mirrors.

12.
Grab either (or both) of the faces of the Brewster crystal, and drag the crystal along the entire length between the two focusing mirrors.

The cavity mode is *independent* of the precise crystal placement. This means we are free to place the crystal at exactly the waist.

13.
Grab one of the focusing mirrors, and drag it approximately horizontally.

The cavity has two stability modes. If the distance between the focusing mirrors is too short (< 200 mm) or too long (> 280 mm), the cavity is unstable. For some separations, the cavity is only stable in the sagittal plane, because of the off-axis curved mirrors.

14.
    Grab one of the end mirrors, and drag it around.

The end mirror can be moved over an extremely large range without greatly changing the cavity mode. When the cavity becomes unstable for long separations to the end mirror, moving the focusing mirrors closer together by a few mm makes the cavity stable again.

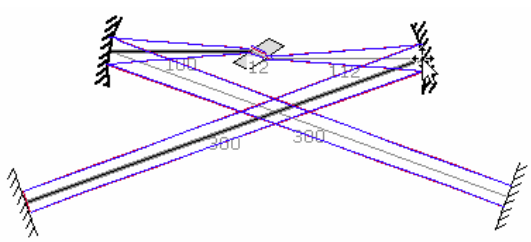
Part 3. Examine Astigmatism

In the previous step, you may have noticed that the mode symmetry changes as the angle on the focusing mirror is changed. For some angles, a circular beam can be attained at the end mirrors, when the astigmatism introduced by the Brewster-angled crystal is compensated by the off-axis curved optics.

Now, we introduce the variable x for the incidence angle on the curved optics and examine the mode symmetry as this variable is varied.

15. Drag the system into a configuration similar to that shown below. Be sure that the separation between the curved optics is such that the cavity mode is stable.

16. Select both of the focusing mirrors by clicking near the centreline while holding the Shift key.



17.

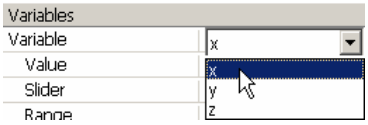
    In the Face Angle field of the Property Manager, enter “x”. (Don’t type the quotes.) The cavity layout will change drastically, don't worry about that for now.

18.

In the Rotation field (in the System group) of the Property Manager, enter the formula "180 + 2*x". (Spacing is not important.) The cavity layout will change again.

19.

If necessary, expand the Variables group of the Property Manager by clicking on the + Variables heading.

20. 

Select variable *x* from the Variable popup menu.

21.

In the Range field, enter "–20, 20" including the comma. In our case, the variable *x* represents the range of angles (in degrees) over which we wish to examine the cavity mode.

22.

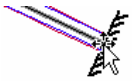
Now, drag the Slider back and forth. As the Slider is moved, the incidence angles on the mirrors change accordingly.

The formula "180 + 2*x" entered for the system rotation does not affect the cavity mode, only how the system is displayed in the window. We add it here so that the bow tie maintains its canonical layout.

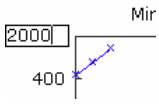
Dragging the focusing mirrors once these equations have been defined will erase the definitions. If you need to adjust the spacing between the optics, you'll have to re-enter the Face Angle formulas. Or, you could define another variable to specify the spacing.

Part 4. Optimize Astigmatism

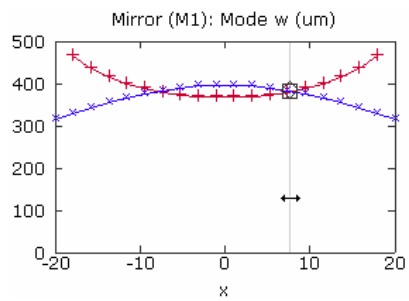
Now that the Face Angle of the focusing optics is a function of variable *x*, we create a graph of the cavity mode on one of the cavity end mirrors. This will allow us to find the angle needed to compensate for the astigmatism introduced by the Brewster-angled crystal.

23. 
Select one of the end mirrors.

24. Select menu Tools | Optic Graph, or click the Optic Graph button on the toolbar.

25. 

If you do not see any lines on the graph, click near the upper limit of the Y axis and type a larger number, such as 2000. Or, edit the Y-Axis Range field in the Property Manager.



26. The graph shows the sagittal (red) and tangential (blue) spot sizes on the selected mirror, as a function of the incidence angle (x) of the curved mirrors. The actual astigmatism compensation angle will depend on your cavity spacing.

27. Note that besides the Slider in the Property Manager, you can also drag the grey line on the graph to change the value of the x variable.

Collimating Telescope

We wish to construct a telescope that collimates an initially diverging HeNe laser source to a specific mode size, with the resulting waist at a large distance from the second lens. We wish to find the optimal spacing between two lenses of given focal lengths.

This tutorial will illustrate:

- Propagation System and its input parameters
- Lenses, positive and negative
- Variables
- Optic Graphs

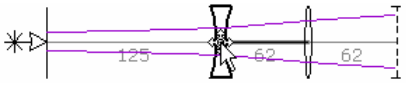
- Solver

Part 1. Construct the System

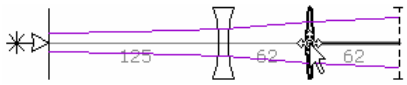
1. From the File menu, select New Propagation, or click the New Propagation button on the toolbar.
2. In the Propagation System properties, enter the HeNe laser wavelength, l = 632 nm.
3. Click on the radio button to set the Input Parameters as Mode and Curvature.
4. Enter the remaining parameters as shown.

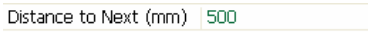
Propagation System	
Wavelength (nm)	632
Beam Quality M²	1
Rotation (deg)	0
Start X (mm)	0
Start Y (mm)	0
Physical Length (mm)	250
Optical Length (mm)	250
Input Parameters	○ Waist, Distance ● Mode, Curvature
Sag. Mode Size (um)	300
Tan. Mode Size (um)	300
Tan. Curvature (mm)	200
Sag. Curvature (mm)	200

5.
Select the system segment by clicking the Source optic at the centreline.
6. Insert two lenses by selecting menu Edit | Insert | Insert Lens or clicking the Insert Lens button on the toolbar.
7. Select the first lens by clicking at the centreline.
8. | Focal Length (mm) | -200 |
|---|---|
In the Property Manager, set the focal length to –200 mm. This is our diverging lens.



9. Select the second lens by clicking at the centreline.
10. | Focal Length (mm) | 400 |
|---|---|
In the Property Manager, set the focal length to +400 mm. This is our collimating lens.



11. 

Additionally, set the Distance to Next to 500 mm, to give some extra space to the terminating screen.

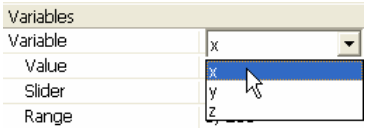
12. Save the system by selecting menu File | Save As… or clicking the Save button on the toolbar.

Part 2. Apply Variables

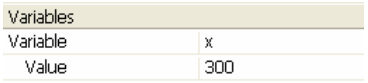
We introduce two variable lengths: The space x between the lenses, and the space y from the laser source to the first lens.

13.

If necessary, click the Variables group heading in the Property Manager to expand the Variables group.

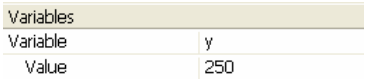
14. 

Select variable x from the Variable popup menu.

15. 

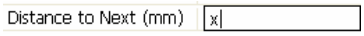
Enter value 300 into the variable Value field.

16. Select variable y from the Variable popup menu.

17. 

Enter value 250 into the variable Value field.

18. On the Canvas, select the first (diverging) lens.

19. 

In the Distance to Next field in the Property Manager, type "x". (Don't type the quotes.) When you press enter, the Distance to Next value will be displayed as 300, since this is the current value of x.

20. On the Canvas, select the Source element.

21. Set the Distance to Next item to "y".

22. Save the system by selecting menu File | Save or clicking the Save button on the toolbar.

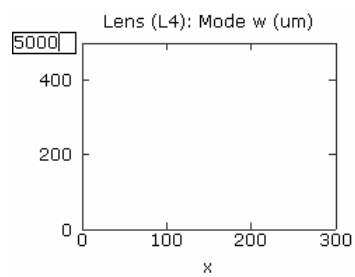
The system should now look similar to the illustration. If it is too long to fit into the window,

23. Select the Zoom tool from menu Canvas | Zoom or the Zoom Tool button on the toolbar.
24. Click the canvas while holding down the Shift key to zoom out.
25. Or, drag in the canvas while holding down the Control and Shift keys.

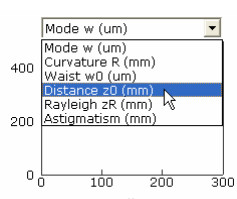
Part 3. Create graphs

Although we will attempt to optimize the system using the Solver in the next section, it is worth creating some graphs to observe the effects of changing the distances we just implemented. The parameters of relevance are the spot size at the collimating lens, and the distance z_0 to the waist.

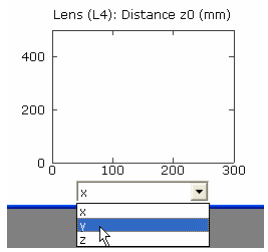
26. Select the second (collimating) lens.
27. Select menu Tools | Optic Graph or click the Optic Graph button on the toolbar.
28. In this graph, we wish to examine the mode size w as a function of variable x. These are the default values.



29. Click near the top of the Y axis and enter an upper limit of 5000. Or, edit the Y-Axis Range in the Property Manager.
30. Create a second optic graph for the collimating lens, again using menu Tools | Optic Graph or the Optic Graph button on the toolbar.



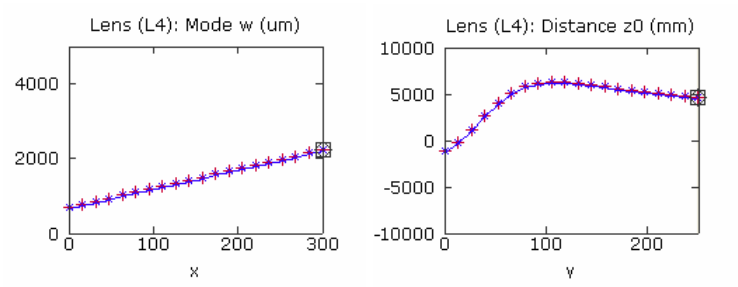
31. Click the graph title, and select Distance z_0 (mm) from the popup menu. Or, select the Distance z_0 radio button from the Optic Property list in the Property Manager.



32. Click the graph X-Axis label, and select *y* from the popup menu. Or, use the Ordinate Variable radio list in the Property Manager.

33. Set the upper and lower limits of the graph to be ±10000.

You should now have two graphs as shown. (The tick spacing will vary depending on the window size.)



Step 4. Optimize with the Solver

We wish to find an optic spacing that creates a beam size of 2 mm at the collimating lens. As an approximately collimated condition, we specify that we wish the waist position to be 100 m after the lens. In addition, we add Solver penalties for variables *x* and *y* should they become negative or larger than 500 mm. See also the Solver section.

34. Create a system Solver by selecting menu Tools | Solver or clicking the Solver button on the toolbar.

35. In the edit field, enter the expression below to be minimized. The text can wrap over several lines, but must form a valid expression.

```
(L4.w_sag-2000)^2 + 1e-6*(L4.z0_sag-100000)^2
+ (y<0)*y^2 + (y>500)*(y-500)^2
+ (x<0)*x^2 + (x>500)*(x-500)^2
```

36. Click the Solve button. For best results, you may wish to click the Solve button several times.

Conclusions

The Solver finds the following values:

- Distance between lenses x = 274.5 mm.
- Distance from laser to first lens y = 225.4 mm.

Inspection of the graphs indicates that, as desired, the mode size is 2 mm and the distance to the waist is large, although not precisely 100 m.

The solution found is not the only condition in which the two lenses can satisfy the given criteria. This is mainly because the concept of a "collimated" beam is somewhat vague for Gaussian propagation.

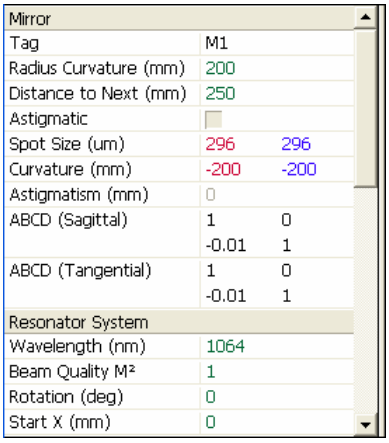
Interface

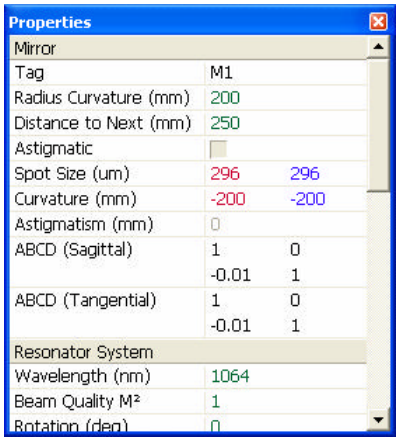
In this chapter, we introduce the elements of the LaserCanvas user interface. The most important parts are the *Property Manager* and the *Canvas* where the systems are edited.

In addition, a number of other tools, such as graphs and an inventory list, are useful for designing laser systems. These design tools can be accessed under the Tools menu. Each system has at most one Canvas, Inventory, Solver, and Wireframe windows, but any number of Mode Plot, System Graph, and Optic Graph windows.

Property Manager

The Property Manager gives access to all of the relevant optic, system, and display window properties. The properties are split up into different groups including those relevant to the selected optic, the system, and the active window.





Docking the Property Manager

The Property Manager can be shown either within the LaserCanvas window (the default), or as a separate floating window.

To show or hide the Property Manager, select menu Tools | Properties or select the Properties button on the toolbar.

To toggle the Property Manager between docked and in a floating window, select menu Tools | Dock Properties.

When the Property Manager is docked, you can

- Change the width by dragging the size bar.
- Display the Property Manager at the left or right of the LaserCanvas window by holding the Ctrl key while clicking the size bar.
- Display the Property Manager in a floating window by holding the Ctrl + Shift keys while clicking the size bar.
- For both docked and floating windows, you can change the column widths by dragging the centreline.

Property Groups

The properties displayed within the Property Manager are divided into the following groups:

- Optic Group
- System Group
- Variables Group
- Canvas Group
- Graph Group
- Common Tasks Group

Which of the groups, and which of the properties within each group, are accessible at any time depend on the visible window and the optics selected within the canvas. The Common Tasks are always visible.

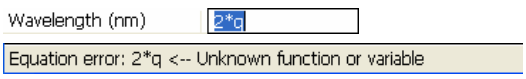
Each group can be expanded or collapsed by clicking the group heading. If a group of properties is collapsed, a "+" symbol is displayed in the group heading.

Property Fields

Each property has a title, shown in the left-hand column, and a value, shown in the right. The exceptions are the Common Task commands, which span the entire width of the window.

For editable properties, clicking in the right-hand column allows you to edit the property value. Press the Enter key, or click outside the edit field, to accept the new value. Press the Escape key to cancel the input.

If the entered value of an edit field contains an error, the edit field remains visible, with the contents selected. If there is an error in an equation, the status bar will indicate the error.

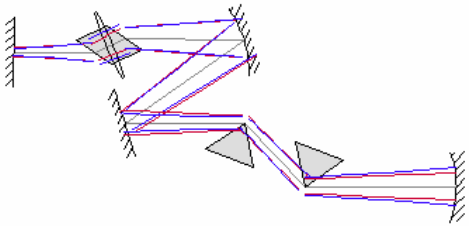


Optic and system properties that can be entered as equations usually show the current value of the equation. To display the source equation for these items, select menu Tools | Property Equations or select the Equations button on the toolbar.

Some properties are read-only and cannot be edited.

Canvas

The Canvas is the main window in which a system layout is edited. Each opened system is shown in a Canvas window; closing the Canvas window also closes the file. For out-coupled systems, closing the Canvas window deletes the out-coupled system from the file.



The Canvas shows the optical system, with to-scale optic positions, angles, and sizes subject to the scaling properties listed below. The display includes an icon for each optic and the beam mode along the system.

Canvas Properties

Property	Description
Zoom (%)	The overall magnification factor. The default value is 100%, which corresponds to 1 mm per pixel.
Mode Scale	The magnification factor for the displayed mode. For example, if the mode is 250 μm and the Mode Scale is 20, then the mode is displayed as 250 μm × 20 = 5 mm large.
Optics Size (mm)	The displayed diameter of the optics.
Grid Size (mm)	The spacing between adjacent grid lines. The grid lines are only displayed and movement is only constrained when the Snap to Grid box is checked.
Snap to Grid	When checked, displays the grid and constrains mouse dragging of optics to fall on the intersections of grid lines.
Separations	When checked, the separation between optics is displayed near the centreline.
Annotations	When checked, information about each optic is displayed adjacent to the optic icon.
Waists	When checked, waists in the beam are highlighted by a vertical line.

Canvas Tools

The Canvas windows includes a number of editing tools, listed in the Canvas menu and as buttons on the toolbar.

In general, the Control key acts as a tool modifier.

- Holding Ctrl while dragging pans the Canvas view.
- Holding Ctrl + Shift while dragging changes the Zoom level.

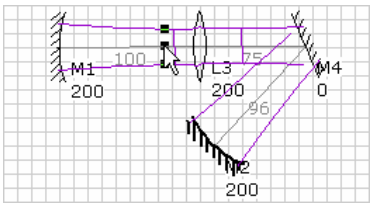
Selection Tool

For editing, the Selection tool is normally used. The Selection tool allows for single and multiple selections using the Shift key, as well as marquee selection by dragging across the

Canvas. Selected optics can then be manipulated by dragging them at the centreline.

Measure Tool

The Measure tool supports all of the functionality of the Selection tool. In addition, the Measure tool allows you to quickly examine the mode size at arbitrary points within the cavity.

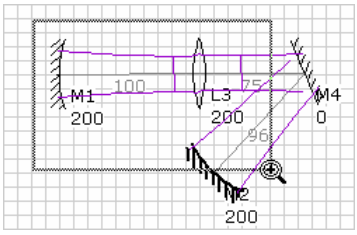


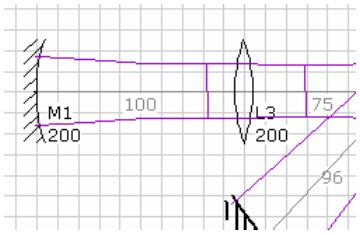
129.739, 129.739 um

The cavity mode size at the position marked is shown in the status bar at the bottom of the LaserCanvas window. The two numbers refer to the sagittal and tangential mode size, respectively.

Zoom Tool

The Zoom tool gives a convenient way to zoom in on a particular section of the cavity. The selection dragged in the Canvas is enlarged to fill the window.



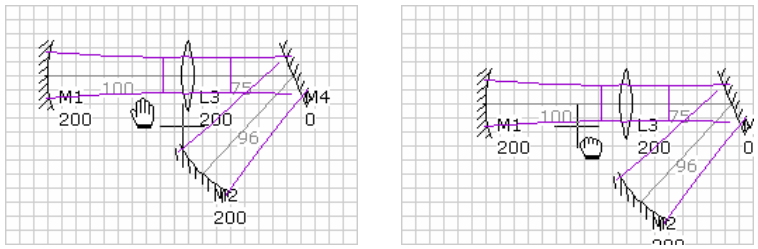


Zoom (%) 1

To zoom out, hold down Shift and click in the Canvas. Alternatively, enter the desired magnification level in the Zoom field in the Property Manager.

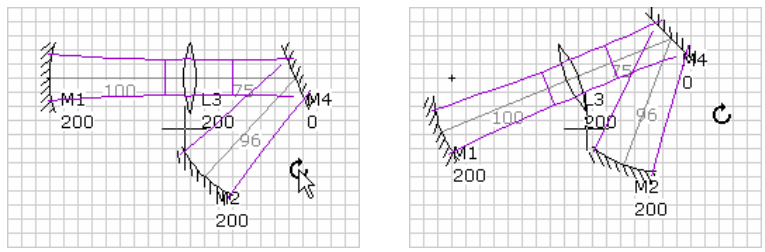
Pan Tool

With the Pan tool selected, clicking and dragging the Canvas scrolls the visible portions of the system in the window. The coordinates of the optics in the system remain unchanged.



Rotate Tool

The Rotate tool allows you to rotate the entire system. Unlike the Pan tool, the Rotate tool changes the system directly by modifying the Rotation, Start X, and Start Y properties.



Rotation (deg)	0
Start X (mm)	0
Start Y (mm)	0

Rotation (deg)	338.151
Start X (mm)	-6.53786
Start Y (mm)	38.1273

The system is rotated about the centre of the window, indicated by the cross-hairs. If you wish to move the rotation axis, use the Pan tool to position the system under the cross-hairs as desired, then Rotate the system.

Draft Mode

Draft Mode is a special editing mode for building cavities. Optics can be placed arbitrarily on the Canvas, and then linked together to form a cavity. When a cavity is in Draft Mode, the *ABCD* calculations are not performed, and several other features, such as the Inventory table and saving the file, have limited functionality.

Draft Mode is only available for resonator systems. A resonator cannot be edited in Draft Mode if it contains

- Prisms, and/or
- Out-coupled systems.

Entering Draft Mode

To edit a cavity in Draft Mode, select menu Canvas | Draft Mode, or click the Draft Mode button on the toolbar.

Editing in Draft Mode

In Draft Mode, all optic icons are drawn upright. Optics not yet linked into the cavity are drawn in blue.

To insert additional optics, select the desired optic from the Edit | Insert menu, or click the respective button on the toolbar.

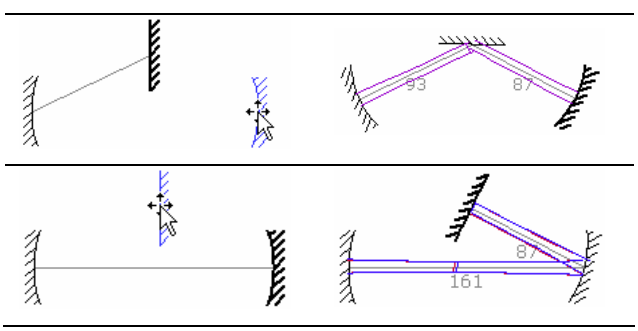
To delete an optic, select menu Edit | Delete Optics or click the Delete Optics button on the toolbar. The first and last optics cannot be deleted, but the ordering can be changed, as described below.

Linking the Cavity

Once the optics have been placed in their desired locations, the cavity is linked together by clicking the optics in order. Linked optics are drawn black.

To unlink an optic, simply click it again. This will also unlink the remainder of the system after the selected optic.

The order in which the optics are linked determines the layout of the cavity.



When the final optic is linked, the system is checked for validity (there must be a mirror at both ends). If the system satisfies the criteria, the cavity is linked together and editing resumes in the normal Canvas mode.

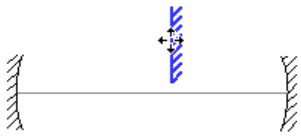
Example

In the following, we add a mirror to a simple resonator to illustrate adding optics and linking in Draft Mode.

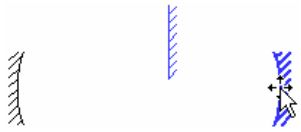
1. We start with a simple two-mirror resonator.

2. Select menu Canvas | Draft Mode or click the Draft Mode button on the toolbar. In Draft Mode, all cavity optics are shown upright, and no mode is calculated.

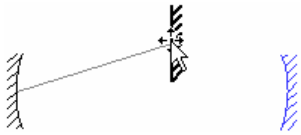
3. Insert a new mirror by selecting menu Edit | Insert | Insert Mirror, or clicking the Insert Mirror button on the toolbar. Since the mirror is not linked into the cavity, it is shown in blue. Drag the mirror away from the centreline.



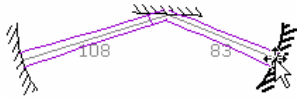
4. Now, we unlink the right-hand cavity mirror by clicking on it. Since it is not linked into the cavity, it is shown in blue.



5. Click on the newly inserted mirror to link it next.

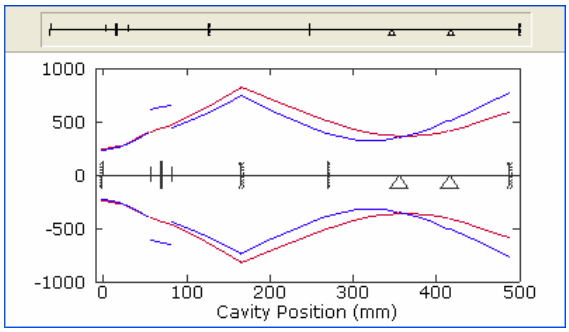


6. Finish linking the system together by clicking on the remaining mirror. Once all of the optics have been linked together, we automatically exit out of Draft Mode and resume normal Canvas editing.



Mode Plot

The Mode Plot displays the cavity mode on a graph. It is useful for visualising the mode without the complication of the two-dimensional layout of the canvas.



Cavity Bar

In the upper part of the Mode Plot window, the entire cavity is displayed, with the cavity optics distributed according to their spacings. The highlighted rectangle indicates the range over which the mode is displayed in the graph. You can drag the highlight rectangle and change its width using the mouse.

Mode Graph

In the lower part, a standard graph displays the cavity mode. You can change the axes limits by clicking near the ends of the axes to open an edit box. Or, you can edit the axis range properties in the Property Manager.

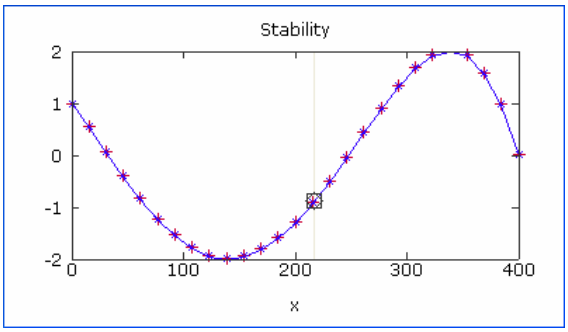
Mode Plot Properties

The mode plot properties are divided into the Graph and Canvas groups.

Property	Description
X-Axis Range	Specifies the minimum and maximum of the horizontal (Cavity Position) axis.
Y-Axis Range	Specifies the minimum and maximum of the vertical (mode size) axis.
Icons	When checked, displays optic icons on the zero-line of the mode graph. The icons scale with the graph size.
Waists	When checked, highlights the mode waists by a vertical line.

System Graph

A System Graph displays the evolution of a system parameter as a function of a variable. For a System Graph to be useful, one or more system or optic property should be defined as an equation including the selected ordinate variable.



To change the system property being graphed, click on the graph title and select the desired property from the popup menu. Or, select it from the System Property list in the Property Manager.

To change the variable against which the property should be plotted, click on the X-axis label and select the desired variable from the popup menu. Or, select it from the Ordinate Variable list in the Property Manager.

The X-axis range does not automatically change when the variable range is changed in the Property Manager. To update the graph to show the entire span of the variable range, click on the ordinate variable radio button.

System Graph Properties

Property	Description
System Property	Specifies which system property value should be plotted on the Y-axis. See table below.
Ordinate Variable	Specifies the variable against which the system property should be plotted. Any of the LaserCanvas variables can be used.
X-Axis Range	Specifies the minimum and maximum of the horizontal (ordinate variable) axis.
Y-Axis Range	Specifies the minimum and maximum of

Property	Description
	the vertical (system property) axis.
Points	Gives the number of points that should be plotted. The number of points is the same for all graphs that plot the same LaserCanvas variable. Note that specifying a large point number can lead to increased calculation times and an unresponsive interface.

The System Property can be one of the following.

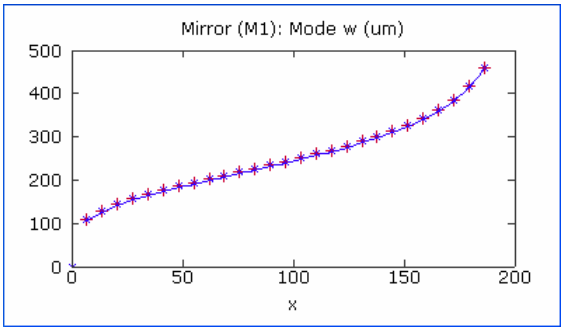
System Property	Description
Physical Length (mm)	The physical length of the system. This is the sum of all of the geometrical separations between the optics.
Optical Length (mm)	The optical length of the system. This is the sum of all of the optical lengths, defined as nL for refractive optics, where n is the refractive index and L the geometrical length. In free space, the optical and physical lengths are identical.
Mode Spacing (MHz)	For resonators, adjacent longitudinal cavity modes are separated by $c/2nL$ where c is the speed of light and nL the optical length of the resonator.
Stability	The stability parameter of the optical system. For more information, see the Reference section.

For the Physical Length, Optical Length, and Mode Spacing properties, the System Graph displays a single line. For the Stability property, two lines are shown for the sagittal (red) and tangential (blue) planes.

Optic Graph

An Optic Graph displays the evolution of a parameter from the selected optic as a function of a variable. For the graph to be useful, one or more system or optic property should be defined as an equation including the selected ordinate variable.

To create an optic graph, the optic whose property is to be graphed must be selected in the Canvas window. If you wish to examine the properties at a specific location within the cavity, you can insert a Screen at that location, and create an Optic Plot of its properties.



To change the optic property being graphed, click on the graph title and select the desired property from the popup menu. Or, select it from the Optic Property list in the Property Manager.

To change the variable against which the property should be plotted, click on the X-axis label and select the desired variable from the popup menu. Or, select it from the Ordinate Variable list in the Property Manager.

The X-axis range does not automatically change when the variable range is changed in the Property Manager. To update the graph to show the entire span of the variable range, click on the ordinate variable radio button.

Optic Graph Properties

Property	Description
Optic Property	Specifies which system property value should be plotted on the Y-axis. See table below.
Ordinate Variable	Specifies the variable against which the optic property should be plotted. Any of

Property	Description
	the LaserCanvas variables can be used.
X-Axis Range	Specifies the minimum and maximum of the horizontal (ordinate variable) axis.
Y-Axis Range	Specifies the minimum and maximum of the vertical (optic property) axis.
Points	Gives the number of points that should be plotted. The number of points is the same for all graphs that plot the same LaserCanvas variable. Note that specifying a large point number can lead to increased calculation times and an unresponsive interface.

The Optic Property can be one of the following. The mode properties refer to the mode just after the optic.

Optic Property	Description
Mode w (um)	The size of the laser mode at the selected optic, in μm.
Curvature R (mm)	The radius of curvature of the wave front at the optic, in mm.
Waist w0 (um)	The size of the waist nearest the optic, in μm. Note that the waist is not necessarily be physically present, because it could be "behind" the optic, or the mode could be modified by another optic before the waist is reached.
Distance z0 (mm)	The distance from the optic to the nearest waist, in mm. See notes to the Waist property, above.
Rayleigh zR (mm)	The Rayleigh length of the mode, in mm.
Astigmatism (mm)	The distance between the waists in the sagittal and tangential planes. See notes to the Waist property, above.

For the Astigmatism property, the Optic Graph displays a single line. For the remaining properties, two lines are shown for the sagittal (red) and tangential (blue) planes.

Inventory

The Inventory lists all of the optics within the current system, as well as the relevant mode properties at those locations in the system.

Wavelength (nm) / M		1064		4	
Length (mm) (Phys./		488.214		500.232	
Mode Spacing (MHz)		299.653			
Stability (sag/tan)		0.917068		0.540738	
Optic Tag	X Y	ROC/FL Angle	Dist n	Mode (mm)	Curv (mm)
Mirror M1	0 0	0 0	57.5	246.696 233.542	-1.6134e+ -3.05044e
Brewster BI4	57.4999 0.085904	0 56.3099	12.0185 1.5	400.704 610.767	92.5975 192.802
Thermal L TL6	68.6008 -4.52002	500	12.0185	436.218 636.397	119.298 325.396
Brewster BO5	79.7017 -9.12594	0 0	84.2984	466.18 434.86	122.13 144.178

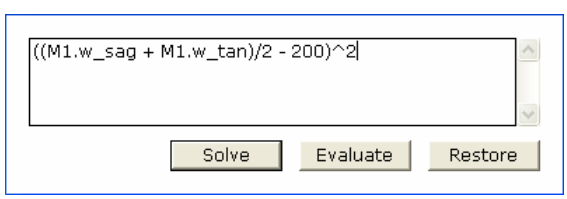
An Inventory list can only be created for the top-level system in each file. Out-coupled systems are not included in the Inventory.

To change the width of any of the optic property columns, drag the line divider in the optic property header. Note that because the table is scaled to fit the width of the window, the adjacent column widths are also scaled.

The Inventory has no further user-settable properties in the Property Manager.

Solver

The Solver attempts to find optimal values for the LaserCanvas variables my minimizing or maximizing its fitness function.



The expression to be optimized is entered into the edit field. The equation can span multiple lines.

Clicking the Solve button commences the search.

Clicking the Evaluate button displays a window indicating the current value that the expression evaluates to, without initiating the search.

Clicking the Restore button returns the LaserCanvas variable values to those before the Solver was opened.

Fitness Function

The fitness function is expressed as an equation that evaluates to a single value. The solver attempts to either minimize or maximize its value.

If you wish to optimize to a value other than zero, we recommend minimizing terms such as

```
(x - 500)^2
```

that diverge as x deviates either above or below 500.

For solving, it may also be useful to use comparative operators such as

```
(x <= 20)
```

which evaluate to 1 if the condition is true, and 0 otherwise.

Optic Parameters

The parameters of the optics in the system can be accessed using the notation

```
M1.w_sag
```

where `M1` is the optic's tag and `w_sag` is one of the parameters in the following table.

Property		Description
`w_sag`	`w_tan`	Sagittal or tangential mode size at the optic.
`R_sag`	`R_tan`	Sagittal or tangential wave front radius of curvature at the optic.
`w0_sag`	`w0_tan`	Sagittal or tangential mode nearest the optic. See the notes on Optic Graph.s
`z0_sag`	`z0_tan`	Distance from the optic to the nearest sagittal or tangential waist. See notes on

Property	Description
	Optic Graphs.
`zR_sag` `zR_tan`	The mode Rayleigh length in the sagittal or tangential plane.
`dz0`	The beam astigmatism at the optic.

System Parameters

Properties of the system can be accessed directly by typing in one of the following.

Property	Description
`G_sag` `G_tan`	Cavity stability in the sagittal or tangential plane.
`Lopt`	Optical cavity length, in mm.
`frep`	Cavity mode spacing, in MHz.

Variable Values

Finally, the LaserCanvas variables can be included in the fitness function, by typing `x`, `y`, or `z`.

Algorithm

The Solver performs a *very simple* Nelder–Mead type simplex minimize search. For optimal results, it may be necessary to try different variable starting values and different weightings to the desired parameters in the optimization equation. Cases where the Solver cannot find a satisfactory solution do not necessarily imply that a solution cannot be found, although there are many instances when solutions do not exist.

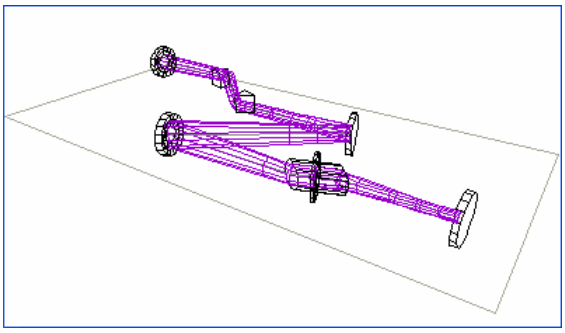
Solver Properties

Property	Description
Max. Iterations	The maximum number of solver steps to perform. Setting a high value may cause the program to become unresponsive.
Function Tolerance	The tolerance on the fitness function to terminate the search.
Solve For	Specifies whether the fitness function

Property	Description
	should be minimized or maximized. Finding the maximum is equivalent to finding the minimum of the negative fitness function.

Wireframe

The wireframe displays the system and the laser mode in a perspective 3D view. Similarly to the Canvas window, you can control the displayed optic and mode sizes.



The coordinate system used by the wireframe renderer maps to that used by the Canvas as follows:

Wireframe	Canvas
X	*Y*
Y	Out of plane
Z	*X*

The display routines use the concept of a "camera" to display the system as it would appear if an image were captured at the specified location. The central plane of the system is formed by the plane in which the centres of all the optics and centrelines lie. When viewing the system from above the optical bench, a grey frame is drawn around the whole system.

Wireframe Properties

Property	Description
Mode Scale	The magnification factor for the displayed mode. For example, if the

Property	Description
	mode is 250 μm and the Mode Scale is 20, then the mode is displayed as 250 μm × 20 = 5 mm large.
Optics Size (mm)	The displayed diameter of the optics.
Look At (mm)	The coordinates in the plane of the system where the camera is pointed.
Camera (mm)	The coordinates in the plane of the system where the camera is located.
Elevation (mm)	The distance above or below the system plane at which the camera is positioned.
View Angle (deg)	The viewing angle of the camera lens. Small values correspond to telescope objectives, where objects appear with little perspective distortion. Large values, around 60°, give large perspective distortion similar to a wide-angle lens.

Wireframe Tools

The view in the Wireframe window can be manipulated using the tools listed in the Canvas menu and as buttons on the toolbar. The tools behave similarly as for the Canvas window.

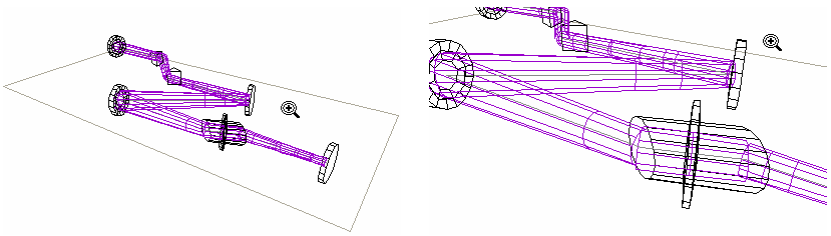
The Wireframe Tools do not modify any system properties, only how the system is displayed in the window.

In general, the Control key acts as a tool modifier.

- Holding Ctrl while dragging pans the view.
- Holding Ctrl + Shift while dragging changes the zoom by moving the camera closer or further away from the Look At point.

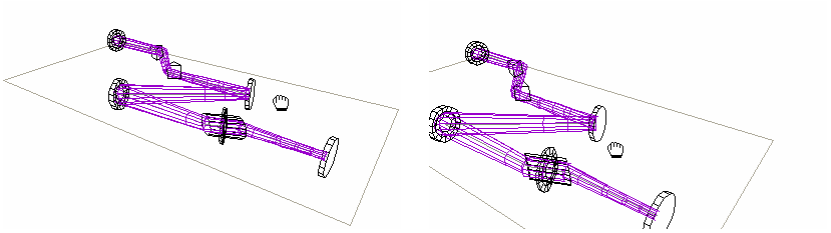
Zoom Tool

The Zoom tool moves the camera closer or further away from the Look At point. Dragging upwards in the window takes the camera closer. Downwards moves it further away.



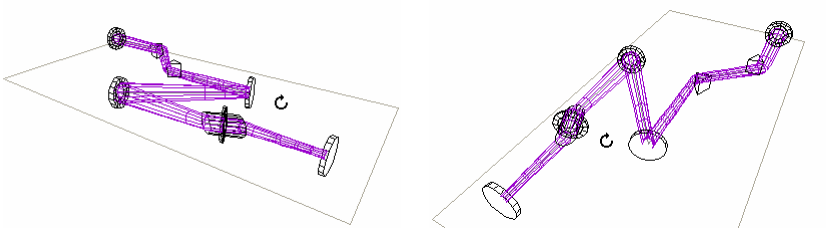
Pan Tool

With the Pan tool selected, clicking and dragging the wireframe moves camera over the system. This equivalent to a "fly-over" of the camera.



Rotate Tool

The Rotate tool allows you to rotates the view of the system.



Saved Files

When saving a file, LaserCanvas effectively saves the "workspace," including the top level system, any out-coupled systems, as well as all graphs and other design tool windows that are open. All of the properties for each window, including the position within the LaserCanvas window, are also saved.

Saving a File

To save a file, select menu File | Save or click the Save File button on the toolbar. If the file has not been previously saved, you will be prompted to type in a file name. Otherwise, any

changes you have made since opening the file are saved to the same file name.

To save the file under a different name, select menu File | Save As….

Since LaserCanvas uses a text-based file format, the default file extension is `txt`.

Loading a File

To open a file, select menu File | Open… or click the Open File button on the toolbar.

If there is an error within the file, LaserCanvas attempts to keep as much of the system as possible. For example, if one optic is poorly defined, the remaining optics are still loaded, if possible.

When loading a file that contains variables while another file is already open, the system being opened may be different to its configuration when it was saved. This is because the existing LaserCanvas variable values are used. To use the variable values in the stored file, close all other systems before opening the file.

Printing

Any of the LaserCanvas design tool windows, excluding the Solver, can be printed.

To print the current window, select menu File | Print… or select the Print button on the toolbar.

To print all of the windows for the current system, select menu File | Print All….

In most cases, the window is printed to the printer without changes. For example, if the Canvas window shows only a section of the system, only this portion is printed.

When printing a Mode Plot window, the Cavity Bar is not printed.

Optics

LaserCanvas systems are modelled as a series of "vertices," or optics. Each optic has a number of user-settable properties, many of which can be defined using Equations and Variables.

There may not be a one-to-one correspondence between a LaserCanvas vertex and a real-world optic; for example, a laser crystal with a thermal lens is modelled as three vertices: An entrance face, a "thin" thermal lens, and an exit face.

Unlike many other *ABCD* laser modelling programs, LaserCanvas does not include a "space" element. This is because the space between optics is automatically determined by their positioning on the Canvas.

Adding and Removing Optics

Inserting Optics

To insert an optic into the system:

- Select the optic before the segment where the new optic should be placed. The optic and the segment will be highlighted.
- Choose the desired optic from the Edit | Insert menu, or click the appropriate button on the toolbar.
- If multiple segments are selected, then a new optic is inserted into each selected segment.

In some cases, only certain optics may be inserted. For example, only a screen or a thermal lens can be placed within a refractive plate, and only a flat mirror can be placed between a prism pair.

Deleting Optics

To delete one or more optics:

- Select them optics to be deleted using the mouse.

- Choose menu Edit | Delete Optics, or click the ☒ Delete Optic(s) button on the toolbar.

When deleting optics, LaserCanvas attempts to maintain the remaining system. For example, if the distance between an optic to be deleted was defined as an equation, LaserCanvas adds the adjacent distances to the equation definition.

Common Properties

The following properties are displayed irrespective of the type of optic that is selected.

Tag

Tags are used to uniquely identify each optic in the system. By default, each optic is assigned a tag that consists of one, two, or three letters designating the type of optic, as listed in the table below, followed by a number.

Letter	Optic Type
BI	Brewster Plate entrance face
BO	Brewster Plate exit face
CI	Crystal entrance face
CO	Crystal exit face
FM	Flat Mirror
I	Screen
L	Lens
M	Mirror
OC	Output Coupler
Pa	Prism A
Pb	Prism B
PI	Plate entrance face
PO	Plate exit face
Src	Source
TL	Thermal Lens

You may assign a different tag to any optic, up to 31 characters. If you will be using the Solver to access the optic's properties, the Tag must conform to the style rules of variable names, thus contain no spaces and commence with a letter.

Optic Tags are used as follows:

- Canvas: when the Annotations check box is selected.
- Inventory: In the Optics column.
- Solver: When properties of the optic are used in the optimization equation.
- Saved files: If a file being loaded does not specify a Tag for one or more optics, the default Tags are created for those optics.

Distance to Next (mm)

Limit: > 0.

The Distance to Next value or equation determines the length of the segment immediately following the optic. This is the segment that is highlighted when the optic is selected.

The spacing of optics in the system is governed by the Distance to Next properties, since LaserCanvas does not include specific space elements.

The Distance to Next property is not available for the following optics:

- Entrance faces for the refractive elements Plate, Brewster Plate, and Crystal.
- Thermal Lenses and Screens internal to refractive elements.
- The last optic in the system.

Spot Size (um)

Limit: > 0.

For stable Resonators and Propagation systems, specifies the mode radius, in units of μm (10^{-6} m), for respectively sagittal (red) and tangential (blue) planes of the system. This value is read-only.

The mode size is given just after the optic. For entrance faces of refractive elements, the spot size is internal to the material. For exit faces, the spot size refers to that outside the material.

Curvature (mm)

For stable Resonators and Propagation systems, specifies the wave front radius of curvature, in units of mm (10^{-3} m), for respectively sagittal (red) and tangential (blue) planes of the system. This value is read-only.

The wave front radius of curvature is given just after the optic. For entrance faces of refractive elements, the value is internal to the material. For exit faces, the value refers to that outside the material.

Due to computational round-off errors, flat wave fronts are often approximated by large radii of curvature, such as 10^{14}.

Astigmatism (mm)

For stable Resonators and Propagation systems, specifies the relative distance between the real or virtual waists in the sagittal and tangential planes. This value is read-only. The focal astigmatism is given in units of mm (10^{-3} m). The value applies to the segment following the optic that is highlighted when the optic is selected.

ABCD (Sagittal) and ABCD (Tangential)

These two items display the 2×2 matrices used for the *ABCD* calculations. A list of the matrices can be found in the Reference section.

Mirror and Flat Mirror

Mirrors are optics that reflect the beam at arbitrary angles, and can, in general, be dragged anywhere on the Canvas. In addition, mirrors can act as partially-reflective output coupler to give out-coupled systems.

Between the prisms of a prism pair, only flat mirrors can be inserted. Flat Mirrors have the same properties as standard mirrors, except the radius of curvature, which is flat.

To insert a mirror or flat mirror, select menu Edit | Insert | Mirror or clicking the Insert Mirror button on the toolbar.

Radius Curvature (mm)

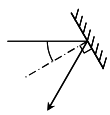
Specifies the radius of curvature of the mirror, in units of mm (10^{-3} m). In practice, mirrors are sometimes described by their focal lengths f, which is related to the radius of curvature R by $f = R / 2$. (A curved mirror is equivalent to a lens.)

If the Astigmatic option is checked, separate values can be entered for the mirror's radius of curvature in the sagittal and tangential planes.

This property is not available for Flat Mirror optics.

Face Angle (deg)

Limits: –90° < Face Angle (deg) < 90°.



Specifies the angle of incidence that the ray makes to the mirror normal, in units of degrees. A positive angle means that the normal to the mirror surface is rotated anti-clockwise from the input ray. The Face Angle is, by definition, a rotation in the tangential plane.

Astigmatic

Checking the Astigmatic box allows separate sagittal and tangential values to be entered for the Mirror optic's Radius Curvature property.

This property is not available for Flat Mirror optics.

Locked Angle

When the Locked Angle box is checked, dragged optics in the Canvas are moved so as to maintain the specified Face Angle. If the check box is clear, Mirror or Flat Mirror optics are free to rotate when optics are dragged.

Under some circumstances, dragging optics with the Locked Angle box checked can lead to unpredictable optic placements.

Thin Lens and Thermal Lens

Thin lenses are model lenses that focus or defocus the beam, but have zero thickness. In most cases practical, physical

lenses can be modelled as thin lenses with a good results. The apparent thickness of thin lens icons drawn on the Canvas is for display only.

Within a refractive element, only thermal lenses can be inserted. The thermal lens is centred within the element.

To insert a lens or thermal lens, select menu Edit | Insert | Insert Lens or click the Insert Lens button on the toolbar.

Focal Length (mm)

Specifies the focal length of the lens, in units of mm (10^{-3} m). If the focal length is 0, the laser mode passes through the lens unaffected. A positive focal length focuses the beam, negative causes the beam to diverge.

If the Astigmatic option is checked, then separate values can be entered for the lens optic's focal length in the sagittal and tangential planes.

Astigmatic

Checking the Astigmatic box allows separate sagittal and tangential values to be entered for the Lens or Thermal Lens optic's Focal Length property.

Plate
Brewster Plate
Crystal

LaserCanvas provides three different forms of refractive elements. These are equivalent except for the respective definitions of incidence angle.

- A Plate can be inserted at arbitrary angles. The incidence angle q is the external angle between the face normal and the incident beam.
- A Brewster Plate is inserted at Brewster's angle q = atan(n), where n is the refractive index of the material.
- The angle q of a Refractive Crystal is defined as the angle between the face normal and the crystal

centreline, within the crystal. The crystal is inserted such that the external angle q_e agrees with Snell's law, $\sin q_e = n \sin q$, where n is the refractive index of the crystal, and the refractive index of the surrounding space is assumed to be unity. If the crystal cut angle is such that total internal reflection (TIR) would occur, the insertion angle is set to 90°. Note that the calculated mode may be inaccurate in this case.

Each refractive element comprises at least two "optics:" An entrance face, and an exit face. The faces are linked to each other, so that deleting one also deletes the other.

Within a refractive element, there can be at most one Thermal Lens or one Screen optic. These optics are automatically centred within the refractive element thickness.

To insert a plate, select menu Edit | Insert | Insert Plate or click the Plate button on the toolbar.

To insert a Brewster-angled plate, select menu Edit | Insert | Insert Brewster or click the Brewster Plate button on the toolbar.

To insert a crystal, select menu Edit | Insert | Insert Crystal or click the Crystal button on the toolbar.

Radius Curvature (mm)

Specifies the radius of curvature of the entrance or exit faces of the refractive elements, in units of mm (10^{-3} m).

If the Astigmatic option is checked, then separate values can be entered for the radius of curvature in the sagittal and tangential planes.

Face Angle (deg)

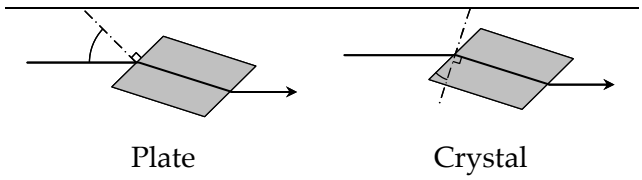
Limits: –90° < external angle < 90°.

For refractive Plate optics, specifies the external angle of incidence that the ray makes to the entrance face normal, in units of degrees. A positive angle means that the normal to the entrance face surface is rotated clockwise from the input ray.

For Crystal optics, specifies the angle within the material between the entrance face normal and the refracted beam, in units of degrees. A positive angle means that the normal to the entrance face surface is rotated clockwise to the internally refracted ray.

The insertion angle of a Brewster Plate is calculated from its refractive index.

Face Angle Definition



The Face Angle is, by definition, a rotation in the tangential plane. The angle of the exit face is equal and opposite to that of the entrance face.

This property is not available for exit faces.

This property is not available for Brewster Plate optics.

Refractive Index

Limit: > 1.

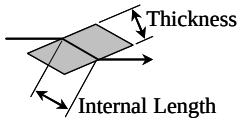
Specifies the refractive index of the material. For Brewster Plate optics, this determines the incidence and refraction angles at the interfaces.

This property is not available for exit faces.

Thickness (mm)

Limit: > 0.

Specifies the thickness, or crystal length, of the refractive element. If the element contains an internal Thermal Lens or Screen, they are automatically centred within the element.



The actual distance traversed within the element may be larger than the optic thickness. The thickness is to be interpreted as the distance between the parallel faces of the element. The internal distance travelled will be larger for non-normal incidence due to refraction.

This property is not available for exit faces.

Direction: Flip

For Brewster plates, the Flip toggle command inverts the sense of the Brewster angle. It is equivalent to a negative Brewster angle.

This property is not available for exit faces.

Astigmatic

Checking the Astigmatic box allows separate sagittal and tangential values to be entered for the refractive element face's Radius Curvature property.

Prism Pair

Brewster-angled Prisms can be inserted into the cavity in pairs. Solitary prisms, as well as prism-like objects such as non-parallel dispersive blocks, are currently not handled by LaserCanvas, since they introduce spatial dispersion and the laser mode becomes more difficult to define.

To insert a prism pair, select menu Edit | Insert | Prism Pair or click the Prism Pair button on the toolbar.

Only flat mirrors and screens are allowed to be placed between the prisms of a Prism Pair.

Besides deflecting the beam, a prism pair has no effect on the resonator mode. This is because it is assumed that the beam travels through no material (the beam is at the apex of both prisms).

Refractive Index

Limit: > 1.

Specifies the refractive index of the prism material. This determines the incidence and refraction angles for the prisms, since the prisms are inserted be at Brewster's angle. Note that the space *between* the prisms is in air (vacuum).

This property is not available for Prism B.

Direction: Flip

Inverts the sense of the Prism angle. This is equivalent to a negative face angle.

This property is not available for Prism B.

Screen

A Screen is a virtual element that allows the beam parameters in a specific location to be displayed in a Graph. It does not modify the resonant mode. When placed in an empty segment, the distance between the Screen and the next optic can be set using the Distance to Next property. Screens within refractive elements are automatically centred within the element thickness.

To insert a screen, select menu Edit | Insert | Insert Screen or click the Insert Screen button on the toolbar.

A screen is also used as the terminal optic in a propagation system. This screen cannot be deleted.

Screens have no further user-settable properties.

Output Coupler

An output coupler is a special type of optic that is intimately related to out-coupled systems.

Within a resonator, any mirror (except the top mirror) can be made partially reflective by selecting menu Edit | Output Coupler or clicking the Output Coupler button on the toolbar.

Out-coupled System

This creates a new system. The initial mode for the out-coupled system is taken from the resonant mode just before the output coupling mirror, and is then propagated through the Output Coupler optic.

The Output Coupler is linked to the mirror in the parent system. Properties such as face angle and radius of curvature are taken from the original mirror. The properties of the Output Coupler include only those that are necessary for transmission through the optic but not for reflection.

Refractive Index

Limit: > 1.

Specifies the refractive index of the output coupler material. This determines the refraction and focusing characteristics of the output coupling mirror.

Thickness

Limit: > 0.

Specifies the thickness of the output coupler. The actual distance traversed within the element may be larger than the optic thickness due to refraction.

Source

The source optic is a special type of optic used at the start of Propagation systems. It cannot be inserted or deleted.

Sources have no further user-settable properties.

The initial mode for Propagation systems can be set in the System group of the Property Manager. The mode can be characterised in two ways:

- The mode size w_0 and wave front radius of curvature R at the Source optic.
- The waist w_0 and its distance z_0 relative to the Source optic.

The parameters can be set independently for the sagittal and tangential planes.

Equations and Variables

Using equations and variables provides a very flexible way to design a cavity in a specific way. Many optic and system properties can be defined using equations that depend on any of the LaserCanvas variables.

Variables

LaserCanvas provides three variables, called “x”, “y”, and “z”. Each of these variables has a specific value at any given time. The value is the same for all systems that are open at the same time. The system that results for the given variable values is the one that is displayed in the Canvas.

Each variable also has an associated range. You can create graphs of system or optic properties as a function of the variables. When the system is changed, for example when you drag optics with the mouse, each variable is scanned through its range, and the graphs update to show the effect of the variable sweep in the new system.

Equations

Properties that can be entered as equations are displayed with a green font in the Property Manager. The value displayed in the Property Manager is the equation value for the given variable values. You can choose to have the source equations displayed by clicking the Σ Show Equations button on the toolbar.

An equation can consist of operators, functions, values, variable names, constants, and brackets. The recognized symbols are listed in the table below.

Type	**Recognized Symbols**
Binary Operators	+, –, *, /, ^
Functions	abs, acos, asin, atan, ceil, cos, cosh, exp, floor, log, log10, sin, sinh, sqrt, tan, tanh
Constants	pi
Comparators	<, <=, ==, >=, >, !=
Logical Operators	&, &&, |, ||, !()
Variables	Any allowed variable name

An example of a valid equation is

```
x^2 + (cos(3*pi*y) - (z > 0)*floor(z))/2
```

Any spaces in the equation are ignored.

Constant Equations

If an expression evaluates to a constant value, i.e., if the equation does not contain any references to LaserCanvas

variables, you can enter it into any field that expects a constant. For example, entering

`0.707` and `sqrt(2)/2`

are interchangeable.

The exception is in fields that expect two values separated by a comma, for example the Variable Range field in the Property Manager.

Data Files

LaserCanvas saves data files in a text format. Although not directly intended to be edited by the user, the file format is described in this chapter for reference.

WARNING

Creating your own data files and loading them into LaserCanvas can lead to unpredictable results. You must ensure that your systems are physically meaningful.

File Structure

The file contains at least one system block, each containing at least two optic statements. At the end of the file is a list of renderer statements. Each optic or renderer statement includes one or more definition lines and flags. The file is case-sensitive.

- A system block takes the form: `[Sys_00966444]`
- A statement takes the form: `Mirror @ M1 { … }`
- A definition takes the form: `Wavelength = 1064`
- A flag takes the form: `Flipped`

In general, most definitions can be omitted. Any property that isn't defined in the data file is given a default value as described in the following sections.

Many lines define properties that can be described by equations. In these cases, the equation string follows the '=' sign of the line, without further formatting.

The preferred formatting is to have each definition on a separate line. However, the file format is designed to be largely independent of white space such as empty lines and carriage returns. The end-of-line is marked by the return and new-line characters `0x0D`, `0x0A`.

System Block

The data file must start with a system block declaring the top-level system in the file.

System Tag

Each system block commences with a heading containing the system Tag in square brackets, such as

```
[Sys_00966444]
```

The Tag must uniquely identify the system within the file, but is not visible, and cannot be edited, by the user through the LaserCanvas interface.

System Type

For the top-level system, the second line must declare one of the following system type keywords:

```
Resonator
Propagation
```

All subsequent systems in the file are assumed to be output coupled systems.

System Variables

For the top-level system, the requested variable values and ranges are listed next. For example, the x variable could be described by the lines

```
Variable(x) = 50.000
Range(x) = 0, 100
```

If another system is already open, the variable values and ranges are ignored from any subsequently opened files. See the section on Equations and Variables.

The variable names must match those pre-defined by LaserCanvas, viz. ‘x’, ‘y’, and ‘z’.

Top System Properties

The system header concludes with a list of system properties. All of these properties can be defined as constants or equations.

Property	Default	Description
`Wavelength`	1064	The laser wavelength, in nm.

Property	Default	Description
`MSquared`	1	The beam propagation factor in the sagittal plane. If the `MSqAsymmetric` keyword is not specified, this value applies to both the sagittal and tangential planes.
`MSquareTan`	1	If the `MSqAsymmetric` keyword is specified, the beam propagation factor in the tangential plane.
`MSqAsymmetric`	—	If this keyword is specified, the beam propagation factors in the sagittal (`MSquared`) and tangential (`MSquareTan`) plane are defined individually.
`InputType`	—	For propagation systems, specifies how `Input-` parameters are to be interpreted. If `InputType` is 0, `wSag` and `wTan` specify the waist (in μm) and `RzSag` and `RzTan` the distance (in mm) to the waist. If `InputType` is 1, `wSag` and `wTan` specify the mode size (in μm) at the Source optic, and `RzSag` and `RzTan` the wave front radius of curvature (in mm).
`InputwSag`	200	The input beam waist or mode size in the sagittal plane, in μm.
`InputwTan`	300	The input beam waist or mode size in the tangential plane, in μm.
`InputRzSag`	0	The distance to the input beam waist, or the wave front radius of curvature, in the sagittal plane, in mm.
`InputRzTan`	0	The distance to the input beam waist, or the wave front radius of curvature, in the tangential plane,

Property	Default	Description
		in mm.

System Properties

The remaining system properties are available for all system types, including output coupled systems.

Property	Default	Description
`Rotation`	0	The Canvas rotation of the first optic in the system, in degrees.
`StartX`	0	The Canvas X location of the first optic, in mm.
`StartY`	0	The Canvas Y location of the first optic, in mm.

Optic Statements

In each system block, there should be at least two optics depending on the type of system:

- Resonator: Two cavity end mirrors.
- Propagation: A Source and a Screen.
- Out-coupled system: An Output Coupler and a Screen.

Format

Each optic statement starts with an optic type keyword, followed by an the optic tag delimited by an `@` character. If a tag is not specified, a default tag is given to the optic. The remaining lines defining the optic parameters are bracketed by `{ … }` braces. For example,

```
Mirror @ M1 {
   DistanceToNext = 100
   ROC = 200
}
```

Optic Type Keywords

The optic type must be one of the following keywords.

Keyword	Description
`BrewsterInput`	Entrance face of a Brewster-angled plate. Must be linked to a `BrewsterOutput` optic.
`BrewsterOutput`	Exit face of a Brewster-angled plate. Must be linked to a `BrewsterInput` optic.
`CrystalInput`	Entrance face of a crystal. Must be linked to a `CrystalOutput` optic.
`CrystalOutput`	Exit face of a crystal. Must be linked to a `CrystalInput` optic.
`FlatMirr`	Flat mirror. Only `FlatMirr` and `Screen` optics may appear between `PrismA` and `PrismB`. If it is between prisms, must be linked to a `PrismA` optic. `FlatMirr` can also be used in place of a `Mirror` optic.
`Mirror`	A general mirror.
`OutputCoupler`	A special type of optic that is used at the start of out-coupled systems.
`Screen`	An information screen. A `Screen` object is used to terminate propagation systems. If the `Screen` is within a Brewster-angled plate, a crystal, a plate, or between prisms, it must be linked to a `BrewsterInput`, `CrystalInput`, `PlateInput`, or `PrismA` optic.
`Source`	Optic used to start propagation systems.
`ThermalLens`	A thin lens. Only a `ThermalLens` or a `Screen` object may appear between the `Input` and `Output` optics. If the `ThermalLens` is within a Brewster-angled plate, a crystal, a plate, or between prisms, it must be linked to a `BrewsterInput`, `CrystalInput`, `PlateInput`, or `PrismA` optic, respectively.
`ThinLens`	A general thin lens.

Keyword	Description
`PlateInput`	Entrance face of a refractive plate. Must be linked to a `PlateOutput` optic.
`PlateOutput`	Exit face of a refractive plate. Must be linked to a `PlateInput` optic.
`PrismA`	First prism in a prism pair. Must be linked to a `PrismB` optic.
`PrismB`	Second prism in a prism pair. Must be linked to a `PrismA` optic.

Optic Properties

Property	Description
`DistanceToNext`	Specifies the free-space distance to the subsequent optic. This property is ignored for the last optic in the system. It cannot be used for `BrewsterInput`, `CrystalInput`, `PlateInput`, and `ThermalLens` optics, or `Screen` when linked to an `Input` optic, since the spacing of these optics is governed by the Thickness property of the entrance face optic.
`FaceAngle`	The face angle of `Mirror`, `FlatMirr`, `PlateInput` and `CrystalInput` optics. See the Optics section for information about how this value is interpreted.
`FL`	The focal length of a `ThinLens` or `ThermalLens` optic. If the lens definition is astigmatic, the `FL` property refers to the focal length in the sagittal plane.
`FL_tan`	For astigmatic `ThinLens` or `ThermalLens` optics, the focal length in the tangential plane.
`RefractiveIndex`	Specifies the refractive index. This property is only valid for `BrewsterInput`, `CrystalInput`, `PlateInput`, and `PrismA` optics.

Property	Description
ROC	The radius of curvature of Mirror or any of the interface optics BrewsterInput, BrewsterOutput, CrystalInput, CrystalOutput, PlateInput, and PlateOutput. If the mirror or interface curvature is astigmatic, the ROC property refers to the radius of curvature in the sagittal plane. See the Optics section for information about the sign conventions in each of these.
ROC_tan	For astigmatic mirror or interface optics (see ROC), the radius of curvature in the tangential plane.
Thickness	Defines the thickness for BrewsterInput, CrystalInput, and PlateInput optics.

Optic Linking

Two keywords are used for linking systems and optics together. If the target of a link is missing, such as when an optic of with the tag specified by LinkedTo is not specified within the file, the linking optic is removed from the system.

Keyword	Value	Description
LinkedTo	Optic tag	Links to together optics including • BrewsterInput • BrewsterOutput • CrystalInput • CrystalOutput • PlateInput • PlateOutput • ThermalLens • PrismA • PrismB • Screen when within a refractive element or

Keyword	Value	Description
		between prisms.
`Spawn`	System tag	Defines a new out-coupled system. The `Spawn` keyword can only be used for `Mirror` optics. The system block for the out-coupled system should follow after the last optic in the top-level system.

Optic Flag Keywords

The following flag keywords can appear anywhere within an optic statement.

Property	Description
`Selected`	Specifies that the optic is selected.
`LockedAngle`	Specifies that the `Mirror` or `FlatMirr` optic face angle is locked, and should not be changed when optics are dragged in the Canvas.
`Flipped`	For `BrewsterInput` and `PrismA` optics, specifies that the refraction should turn the centreline anti-clockwise. If the `Flipped` keyword is not specified, the centreline is turned clockwise at the Brewster-angled interface.
`Astigmatic`	Specifies that the optic focal length or radius of curvature is defined separately in the sagittal and tangential planes. applies to the following optics: • `Mirror` • `ThinLens` • `ThermalLens` • `BrewsterInput` • `BrewsterOutput` • `CrystalInput` • `CrystalOutput`

Property	Description
	• `PlateInput` • `PlateOutput`

Renderer Statements

Renderer statements are typically placed at the end of a file. A Renderer is any interface component that occupies a separate window such as the Canvas editor or a System Graph.

LaserCanvas creates Renderer windows in the order in which the statements appear in the file. Thus, the last-created window is active when the file finishes loading.

If no renderers are defined within a file, LaserCanvas automatically creates a Canvas window.

Format and Type

Each renderer statement starts with the `Renderer` keyword, followed by the renderer type. The remaining lines defining the renderer are bracketed by `{ … }` braces. For example,

```
Renderer 2d {
   System = Sys_00966444
   Window = 75, 70, 690, 200
}
```

The renderer type keyword must be one of the following: `1d`, `2d`, `3d`, `Inventory`, `Solver`, `SystemGraph`, `VertexGraph`. See the following sections for information about each renderer type. The renderer statement must include at least the `System` definition.

Unlike optic properties, renderer properties must be constant expressions or equations that evaluate to constants.

Common Properties

The following properties apply to all renderers.

Property	Description
`System`	Defines the system that the renderer applies to. The `System` line must specify the tag of a system

Property	Description
	defined within the file. If the specified system tag cannot be found, the renderer statement is ignored.
`Window`	Defines the position of the renderer window, in pixels. The first two numbers specify the horizontal and vertical offset from the upper left-hand corner of the LaserCanvas window. The last two numbers are the width and height of the renderer window, respectively.

Renderer 1d Properties

The `Renderer 1d` statement creates a window of a Cavity Mode plot.

Property	Description
`Flags`	The sum of any or none of the following: 1: Display optic icons on the graph 2: Highlight beam waists with a vertical line.
`XMax`	Maximum X-axis (Cavity Position) value.
`XMin`	Minimum X-axis (Cavity Position) value.
`YMax`	Maximum Y-Axis (Mode Size) value.
`YMin`	Minimum Y-axis (Mode Size) value.

Renderer 2d Properties

The `Renderer 2d` statement creates a Canvas editor window. If the a `Renderer 2d` statement is not supplied for each system defined in the file, LaserCanvas creates a Canvas window with default values.

Property	Description
`Flags`	The sum of any or none of the following: 1: Show the grid and snap to it when dragging optics. 2: Display distances between optics. 4: Display annotations for optics. 8: Highlight beam waists with a vertical line.

Property	Description
`GridSize`	The size of the grid, in mm. The grid is only used if flag 1 is specified.
`ModeScale`	The display scale factor for the laser mode.
`OpticScale`	The display size of optics, in mm.
`XMiddle`	The cavity *X* position that is to be centred within the Canvas window, in mm.
`YMiddle`	The cavity *Y* position that is to be centred within the canvas window, in mm.
`Zoom`	The display zoom factor. A zoom factor of 1 corresponds to 100% zoom.

Renderer 3d Properties

The `Renderer 3d` statement creates a 3d wireframe window.

Property	Description
`CameraAngle`	Tthe camera viewing angle, in degrees.
`CameraX`	The camera *X* position, in mm.
`CameraY`	The camera *Y* (elevation) position, in mm.
`CameraZ`	The camera *Z* position, in mm.
`ModeScale`	The display scale factor for the laser mode.
`OpticScale`	The display size of optics, in mm.
`OriginX`	The cavity *Y* position of the view centred in the window.
`OriginZ`	The cavity *X* position of the view centred in the window.
`Flags`	This property is currently not used.

Renderer Inventory Properties

The `Renderer Inventory` statement creates an Inventory window.

Property	Description

`Width0`
`Width1`
`Width2`
`Width3`
`Width4`
	Specifies the column width for each column. The width is nominally in pixels, but the displayed column widths are adjusted so that the entire

Property	Description
`Width5` `Width6`	Inventory fits within the window.
`XScroll`	This property is currently not used.
`YScroll`	The vertical offset, in pixels, for the Inventory rows.

Renderer Solver Properties

The `Renderer Solver` statement creates a Solver window.

Property	Description
`Equation`	The function equation to be optimized. Unlike other equations, the Equation is enclosed in double quotation marks (") and can span multiple lines.
`FunctionTolerance`	The accuracy to which the function is to be optimized.
`MaxIterations`	The maximum number of iterations.
`SolveMode`	Solve strategy. Can be one of the following: `0`: Solve for function minimum. `1`: Solve for function maximum.

Renderer SystemGraph Properties

The `Renderer SystemGraph` statement creates a new system graph window.

Property	Description
`Function`	The system property to be plotted, see table below.
`Variable`	The variable against which the `Function` is to be plotted. Must be one of the LaserCanvas variable names.
`XMax`	Maximum X-Axis (variable) value.
`XMin`	Minimum X-Axis (variable) value.
`YMax`	Maximum Y-Axis (function) value.

Property	Description
`YMin`	Minimum Y-Axis (function) value.

The `Function` property must specify one of the following system properties to plot.

System Property	Description
`PhysicalLength`	The physical cavity length of the system, in mm.
`OpticalLength`	The optical cavity length of the system, in mm.
`ModeSpacing`	The frequency spacing of adjacent cavity modes, in MHz.
`Stability`	The system stability parameter g.

Renderer VertexGraph Properties

The `Renderer VertexGraph` statement creates a new optic graph window. The `VertexGraph` statement must specify a valid `Vertex` property.

Property	Description
`Function`	The optic property to be plotted, see table below.
`Variable`	The variable against which the `Function` is to be plotted. Must be one of the LaserCanvas variable names.
`Vertex`	A tag specifying the optic whose property is to be graphed.
`XMax`	Maximum X-Axis (variable) value.
`XMin`	Minimum X-Axis (variable) value.
`YMax`	Maximum Y-Axis (function) value.
`YMin`	Minimum Y-Axis (function) value.

The `Function` property must specify one of the following optic properties to plot.

Optic Property	Description
`Astigmatism`	The distance between waists in the sagittal and tangential planes, in mm.

Optic Property	Description
`Curvature`	The wave front radius of curvature R, in mm, at the optic.
`Distance`	The distance z_0 to the waist, in mm.
`Mode`	The mode size w, in μm, at the optic.
`Waist`	The waist size w_0, in μm.

Reference

This section provides some more background to the definitions and internal workings of LaserCanvas. More exhaustive treatments can be found in numerous optics textbooks.

Gaussian Beams

Fundamental Mode

The beam propagation, i.e., the evolution of the laser mode $w(z)$ as a function of distance z from the waist, is given for the fundamental TEM_{00} Gaussian beam by

$$w(z) = w_0 \sqrt{1 + \left(\frac{z\,l}{\pi w_0^2} \right)^2} \ ,$$

where w_0 is the mode size at the waist, and l is the laser wavelength. This equation is sometimes expressed in terms of the Rayleigh length

$$z_R = \frac{\pi w_0^2}{l} \ .$$

For large distances $z >> 1$, this leads to a far-field divergence of

$$q \approx \frac{w(z)}{z} = \frac{l}{\pi w_0} \ .$$

Similarly, the wave front radius of curvature evolves according to

$$R(z) = z \left[1 + \left(\frac{\pi w_0^2}{l\,z} \right)^2 \right].$$

Embedded Gaussian and M^2

The propagation of a non-perfect fundamental Gaussian beam can be described using the beam propagation factor M^2. This parameter is sometimes colloquially referred to as the beam

quality. For physical beams, $M^2 > 1$, with the limit $M^2 = 1$ for perfect TEM_{00} beams.

The propagation of a beam with beam propagation factor M^2 is established as follows:

- From the beam waist W_0, we construct a virtual embedded Gaussian beam with waist $w_0 = W_0 / M$.
- The embedded Gaussian mode $w(z)$ is propagated according to the formula above.
- The full beam mode at any position is given by $W(z) = w(z)\, M$.

For laser resonators, deriving the resonant mode using the *ABCD* self-consistency argument yields the embedded Gaussian mode.

From the definition of the Rayleigh length, that the mode $W(z)$ is $\sqrt{2}\, W_0$, it can easily be shown that the Rayleigh length is the same for the full beam as for the embedded Gaussian.

Internal Representation

LaserCanvas includes the M^2 beam propagation factor in its calculations. Since the embedded Gaussian is rarely of interest, the formula

$$W(z) = W_0 \sqrt{1 + \left(\frac{zM^2 l}{\pi W_0^2} \right)^2}$$

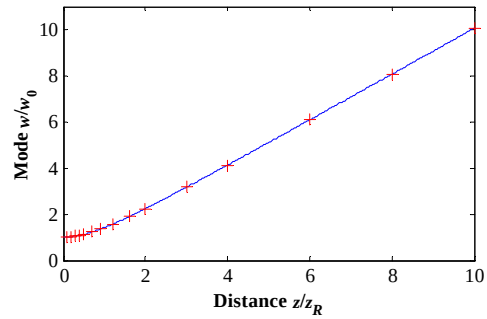
is used directly when calculating mode sizes.

The beam evolution from one optic to the next is performed by calculating the q parameter using the optic and space *ABCD* matrices.

The spot sizes reported by the Measurement tool use the formula above directly.

For painting, the mode evolution can be divided into near-field and far-field. In the near field, the mode exhibits a characteristic curving, approaching the far-field asymptote.

To minimise the number of drawing cycles required, LaserCanvas scales a tabulated near-field mode evolution up to a distance of $10z_R$. In the far field, a single data point is plotted at the end of each segment.



ABCD Matrices

The *ABCD* or ray-matrix formalism is used in the paraxial approximation of geometrical optics. A ray is characterised by its lateral position r relative to the central axis of the system, and the slope r'.

We can then define a 2×2 matrix for an optic or a set of optics that maps the incident r, r' to new values according to

$$\begin{bmatrix} r \\ r' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} r \\ r' \end{bmatrix}_0 .$$

LaserCanvas uses the reduced-angle convention described in A.E. Siegman, *Lasers*, University Science Books (1986). In this convention, the second element of the [r, r'] vector is not the geometric divergence angle, but the effective divergence reduced by refraction. The resulting *ABCD* matrices have unit determinant.

The *ABCD* matrices as used by LaserCanvas are listed in the following table.

Element	Parameters	Sagittal	Tangential
Space	Distance L Refractive index n	$\begin{bmatrix} 1 & \frac{L}{n} \\ 0 & 1 \end{bmatrix}$	
Lens	Focal length f	$\begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix}$	

Element	Parameters	Sagittal	Tangential
Mirror	Radius Curvature R (Concave: $R > 0$) Incidence angle q	$\begin{bmatrix} 1 & 0 \\ \frac{-2}{R\cos q} & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ \frac{-2\cos q}{R} & 1 \end{bmatrix}$
Curved dielectric	$n_1 \sin q_1 = n_2 \sin q_2$ $\Delta n_{SAG} = n_2 \cos q_2 - n_1 \cos q_1$ $\Delta n_{TAN} = \frac{n_2 \cos q_2 - n_1 \cos q_1}{\cos q_1 \cos q_2}$	$\begin{bmatrix} 1 & 0 \\ \frac{\Delta n_{SAG}}{R} & 1 \end{bmatrix}$	$\begin{bmatrix} \frac{\cos q_2}{\cos q_1} & 0 \\ \frac{\Delta n_{TAN}}{R} & \frac{\cos q_1}{\cos q_2} \end{bmatrix}$
Duct (not used)	$n(x) = n_0 - \frac{1}{2} n_2 x^2$ $g = \sqrt{\frac{n_2}{n_0}}$	$\begin{bmatrix} \cos gz & \frac{\sin gz}{n_0 g} \\ -n_0 g \sin gz & \cos gz \end{bmatrix}$	

Stability Parameter

For a resonator, the system stability can be calculated from the trace of the round-trip matrix **M** by

$$g = \frac{\mathrm{Tr}(\mathbf{M})}{2}.$$

For stable resonators, $|g| < 1$. The stability parameter gives some indication of the robustness of the resonant mode against slight changes in the cavity configuration.

Internal Representation

The *ABCD* matrices are not explicitly stored. They are calculated whenever necessary from the optic properties. Since many of the optics' properties can be defined using Equations, the *ABCD* matrices are, in general, not constant.

For the resonant and propagating mode calculations, the *ABCD* matrices are represented in a custom 4-element class using IEEE double precision. The matrix pre-multiplication used in resonator calculations is explicitly expanded by element.

Complex Beam Parameter *q*

For Gaussian beams, the complex beam parameter q is defined to as

$$\frac{1}{q} = \frac{1}{R} - i\frac{l}{\pi w^2}$$

where R is the wave-front radius of curvature, w the mode size, and l the wavelength. At a waist, $R = \infty$ and q is purely imaginary.

After passing through an optical element whose transfer matrix elements are A, B, C and D, the complex beam parameter becomes

$$\frac{1}{q'} = \frac{C + \frac{1}{q}D}{A + \frac{1}{q}B} .$$

If the matrix represents the round-trip matrix of a resonator, then a self-consistency argument requires that $q' = q$, from which we can derive q as

$$\frac{1}{q} = \frac{D - A}{2B} - \frac{i}{2|B|}\sqrt{4 - (A + D)^2} .$$

Internal Representation

Information about the reciprocal complex beam parameter $1/q$ is stored in a custom class using the four elements listed in the following table. The elements and their definitions are chosen to minimise calculation cycles, especially division, while at the same time providing some protection from division-by-zero errors.

Symbol	Definition
`R` $= \frac{1}{R}$	The reciprocal of the wave front radius of curvature.
`V` $= \frac{\pi w^2}{l}$	A scaled waist, equal to the Rayleigh length at the waist.
`L` $= l$	The wavelength, in nm.
`M2` $= M^2$.	The beam propagation factor.

As with optic curvatures, a wave front curvature of 0 is used to represent a plane wave front. However, since the calculations are performed using IEEE double-precision

floating point arithmetic, round-off errors can lead to curvatures on the order of 10^{18}, which should be interpreted as flat wave fronts.