Using

Beamline Simulator V1.3©

By Kurt Dehnel and Morgan Dehnel

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Beamline Simulator and Microsoft Windows
Beamline Simulator operates in a graphical environment called Microsoft Windows, created by Microsoft Corporation. Microsoft Windows gives a standard look and feel to Beamline Simulator and to other Windows applications.

To run Beamline Simulator under Microsoft Windows, you need to license and install Microsoft Windows 95, 98 or NT. With Microsoft Windows you can take advantage of the Windows environment, such as running multiple applications to create an integrated working environment, and exchanging data between applications.

From Our Users

Karl Erdman, Ph.D., Professor Emeritus, U.B.C., and Senior Scientific Advisor for Ebco Technologies writes on May 15, 1997.

> *I have seen the beamline simulation program that has been developed by Dr. Morgan Dehnel. This program provides a graphical user interface that will allow a beam line designer or a beam line operator to quickly assess the performance of a beamline. It permits an easy way to change the "tune" of a line in order to optimize the transmission or energy resolution of a beam of high energy particles. It will permit a user to set up a system without requiring complicated tracking programs such as TRANSPORT used by beam design experts. Such programs are both slow and require considerable mathematical skill and intuition in their application. In addition, the use of a PC with Windows 95 makes the program both user friendly and transparent.*

Dr. Nigel R. Stevenson, Head, Isotope Production Group, TRIUMF writes on May 9, 1997.

> *An accurate understanding of the properties of the cyclotron beams is essential for the success of our research/commercial objectives. By using the beamline simulation codes of DCL we have bean able to obtain information that advances our understanding of the technology we operate and, thereby, improve and increase the quality and quantity of production. Specifically, new beamlines and improved components to existing beamlines have been determined using this software. Incremental improvements to components and to the quality of the beam being transported are ongoing using this code along with other tools.*
>
> *Our facility is based around a federally supported research facility and as such focuses in on research aspects of cyclotrons and cyclotron-based products, which are subsequently commercialized with an industrial partner. The research aspects of our operation are many, one of which is the ongoing drive to higher and better quality beam currents. This type of research would be significantly hampered without the direct input available from such computer codes as the one being developed by DCL. We intend to continue using this program to help us develop the cyclotron systems as we anticipate increasingly complex problems that may not be addressable with existing conventional tools.*

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1.0 About This Software

To our knowledge, this is the first ever, real-time simulator for industrial beam transport systems *available on a PC/Windows platform*. Designed with accuracy and flexibility, Beamline Simulator will mimic a broad range of beam transport systems such as those used in radioisotope production, in micro-etching semi-conductors or in research.

Program features include:

- REAL TIME TUNING capabilities through the Vary Parameter Window. You may tune the magnet current or field strength and simultaneously observe changes in the beam spill data and beam plots. Beam spill data is given in percent.
- an easy and intuitive interface for building beamline systems. You may drag and drop icons representing common beamline elements such as dipole magnets, quadrupole magnets, solenoid magnets, drifts spaces, etc.
- the ability to define and model beam pipe, collimator and other physical device apertures.
- a Perturbation icon for beam mis-centering
- the simulation of multi-particle beams of up to 10,000 particles.
- the simulation of beam envelopes.
- two graphics windows for viewing plots. You may choose between longitudinal (beam profile), cross-sectional (transverse) and intensity (only for multi-particle runs).
- a Constraint icon for automatically determining system setting requirements for specific beam or transport conditions.

Beamline Simulator is ideal for quickly determining new beamline tunes, for allowing trainee operators to get the feel of beamline tuning, and for designing beamlines. It is a first-order modeling code that may be used by engineers or physicists to design completely new beamline systems.

2.0 What's In This Manual?

2.1 For Version 1.1 and 1.2 Users

We would like to advise you of the changes to the software through Versions 1.2 and 1.3. We have added:

- solenoid and thin lens ion-optical elements.
- icon naming in the Sequential Beam Icon window for easier element identification.
- a magnitude readout in the Vary Parameter Window for the parameter being adjusted.
- print, and copy to clipboard capability for the Apertures, System Metrics, Constraints, Collimator Text Readout and Beam Transport System Property Listings.
- particle charge capability for the Beam Source, and an easier method for entering "tilted" phase space beam ellipses. Multi-particle distributions can now be saved.
- the ability to enter bend angle or magnetic field data, and fringe field correction for Dipole magnets.
- the ability to enter field gradient, k, or magnetic field data for Quadrupole magnets.

Also, you don't need a hardware key to run the program now.

2.2 For New Users

As support for the program we have produced a manual that we believe will 'quick start' the learning process. The manual has ten chapters, five appendices, a glossary and an index. All are described here in brief.

Chapter 1.0 About This Software … describes the main features of the program and the realm of possibilities for using Beamline Simulator.

Chapter 2.0 What's In The Manual? … should raise your awareness of how the manual is organized and give you some strategies for best use.

Chapter 3.0 Starting Beamline Simulator … leads you step by step through loading and running the program, and uninstalling when you no longer need it.
Chapter 4.0 Using the Tutorials … contains two interactive tutorials and a question and answer forum. If you are new to Beamline Simulator, we suggest that you at least complete the first tutorial before diving into the program.

The first tutorial, called 'Running and Real-Time Tuning Procedures', walks you through the program basics. You'll look at a sample beamline, add an element and tune using the Vary Parameter Window — a key feature of the software. You'll also change the beam source from envelope type to multi-particle type, run the beamline and look in the Collimator Window for beam spill information. Throughout this process you will track your progress through the plots in the graphics windows.

The second tutorial called 'Automatic Tuning Using the Constraint Algorithm' is for those having attained a basic knowledge of Beamline Simulator. In this tutorial you will gain experience using the automatic tuning capabilities in the program. In a broad sense automatic tuning is a three-step process. Using a Form Fill-In dialog box, you will define the element parameter(s) you wish to vary. Next you will define a constraint on the beam half-sizes or on the cumulative transport matrix values using the Constraint Form Fill-In dialog box. Finally you will run the program and view the results. It's a bit more complicated than it sounds so we again walk you step by step through it.

Chapter 5.0 Defining the Beam Source … describes how to define a beam source of your choice. The options include: Beam Type — envelope or multi-particle; General Beam Information — name, energy, mass, charge, and number of particles; Maximum Beam Half Sizes — X, X', Y, Y', and Δ; and beam phase space tilt angles.

Chapter 6.0 The Ion-Optical Elements … introduces the ion-optical elements named Dipole, Drift Length, Non-Standard, Perturbation, Quadrupole, Solenoid Thin Lens and Rotation, plus the Constraint icon. It describes icon management such as how to insert, cut and paste, rearrange and delete icons. It also describes the use of the Form Fill-In Dialog boxes for the elements and constraints.

Chapter 7.0 Diagnostic Tools … describes how to use the Aperture Form Fill-In to enter data about the beam pipes, collimators and vacuum boxes. It also describes how to place the Cross-Section Plot and End Run icons to generate the data you require. Finally, it describes the use of the Get System Metrics icon to pull information about the beam parameters, the system matrices (both the cumulative beam sigma matrix and the cumulative transport matrix) and the particles, from anywhere along the beamline.

Chapter 8.0 Graphics Management … provides some examples of typical longitudinal, cross-sectional and intensity plots. It also provides a step by step procedure with screen prints and description to help you create quality graphics plots — plots that provide the information you need and that also look good when printed.

Chapter 9.0 Viewing Text Readouts … gives information about two very important text readout windows, the Collimator Window and the Beam Transport System Window. The Collimator Window shows the percent beam spill of readback and non-readback apertures, while the Beam Transport System Window shows a full listing of all beamline elements and their properties, plus all the beam matrices and cumulative transport matrices along the beamline.

Chapter 10.0 Command and Tool Reference … gives a brief description of the cursor actions and software terminology used in the manual. It also describes all the commands and tools from the General Window, the Base Application Window, the Vary Parameter Window and the Sequential Beam Icon Window. The final section repeats information from Chapter 6.0 about managing icons. This information applies to all icons, not just those described in Chapter 6.0.

Appendices

The five appendices at the end of the manual are:

Appendix A – Units of Measurement … gives the units used in the software for optical parameters, particles, beam half-sizes and the graphics plots.

Appendix B – The Resource Window … shows how memory is allocated to the software and also displays the time.

Appendix C – The Matrix Window … is a matrix multiplication calculator.

Appendix D – System Requirements … shows the minimum and suggested use of hardware and software for Beamline Simulator.

Appendix E – Ion-Optics Technical Notes … contains background ion-optics formulae and a short list of related reference papers.

Glossary … contains the definitions of key words used in the text.

Index … is a list of key words found in the manual with their associated page number(s).

Where to begin? If you haven't loaded the software yet, start at Chapter 3.0. Otherwise go to Chapter 4.0 and begin the first tutorial. Have fun!

3.0 Starting Beamline Simulator

3.1 Security

If you are not yet a registered user of Beamline Simulator, your program disk will allow only 10 runs. After that you must contact Dehnel Consulting Ltd. to arrange for registered user status and a password.

Note that demo usage is logged and displayed in a welcome window each time Beamline Simulator is restarted.

3.2 Installing the Software

Copy the program files to the new folder.

1. Click 

at the bottom left on your screen.
2. Find and open **Windows Explorer**.
3. Insert the Beamline Simulator disk into your 3½" 1.44 Mb floppy drive.
4. In the left frame of the Explore window, click, drag and drop **3½ Floppy {A:}** onto the hard drive of your choice.

3.3 Uninstalling the Software

1. Click 

at the bottom left of your screen.
2. Find and open **Windows Explorer**.
3. Select the appropriate hard drive.
4. Select the **Beamline Simulator Version 1.3** folder.
5. In the Explore base menu select **File/Delete**.

3.4 Running the Program

1. Click 

at the bottom left on your screen.
2. Find and open **Windows Explorer**.
3. In the left frame of the Explore window, select the appropriate hard drive to reveal the folders.
4. Double click **Beamline Simulator Version 1.3** to reveal the files.
5. Double click **BeamlineSimulator.exe** to run the program.

4.0 Using the Tutorials

4.1 Running and Real-Time Tuning Procedures

In this interactive tutorial we lead you step by step through some of the key features of a sample beamline. We then ask you to change the beamline and observe what happens.

Starting Beamline Simulator

1. Click  at the bottom left on your screen.
2. Find and open **Windows Explorer**.
3. In the left frame of the Explore window, select the appropriate hard drive to reveal the folders.
4. Double click **Beamline Simulator Version 1.3** to reveal the files.
5. Double click **BeamlineSimulator.exe** to run the program.
6. Click **OK** to close the Welcome Window.

If you are not yet a registered user of Beamline Simulator, your program disk will allow only 10 runs. After that you must contact Dehnel Consulting Ltd. to arrange for registered user status and a password.

Note that demo usage is logged and displayed in a welcome window each time Beamline Simulator is restarted.

Introducing the Windows

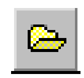
You will see four windows on the screen. The top window is called the Base Application Window. This window contains the **File**, **Edit**, **Window**, **Run Options** and **Help** menus. There is also a Toolbar below to simplify access to some of the menu items. For more information on the Base Application Window, see the Command & Tool Reference, page 93 to 111.

The middle windows are called Graphics Plot Windows. These windows give longitudinal, cross-sectional or intensity plots for each beamline run. To read about the various options available for plots see Chapter 8.0 Graphics Management.

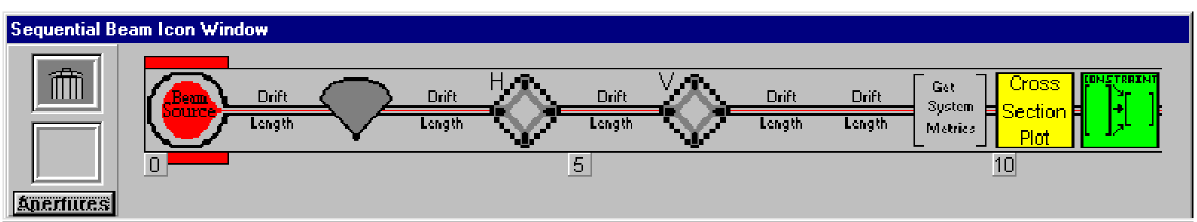
The bottom window is called the Sequential Beam Icon Window or SBI Window. You will spend most of your time working in this window. Here you will define the beam source, select and arrange ion-optical elements as they might appear in a real beam transport system and set up the diagnostic device apertures. For more information see Chapter 5.0 Defining the Beam Source, Chapter 6.0 The Ion-Optical Elements, and Chapter 7.0 Diagnostic Tools.

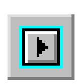
Note that the active window is identified by a navy blue title bar, and the inactive windows by dark gray title bars. These colors are typical of most computer default color settings.

Running the Sample Beam

7. To open the sample file click **File** and select **Open** or click  (Base Application Window - Toolbar).
8. Click **Sample1.bln**.
9. Click the **Open** button.

For the next procedures the Base Application Window should have the file name 'Sample1.bln' in its title bar and the SBI Window should look like the drawing below.

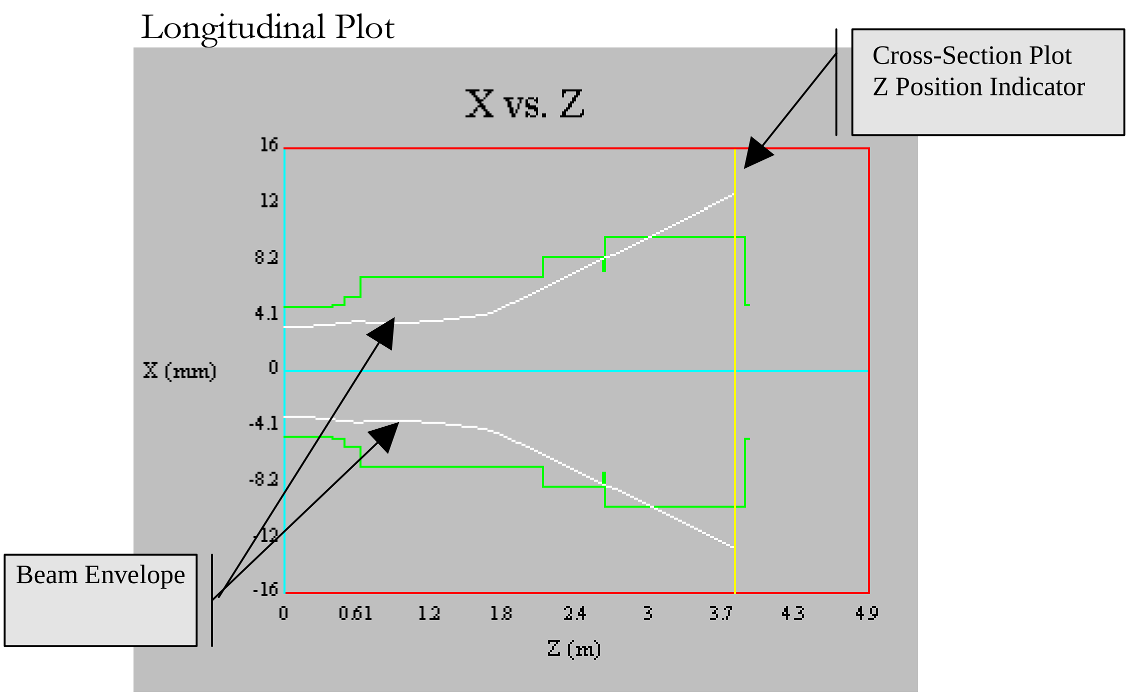


10. To initiate the run algorithm click  (Base Application Window - Toolbar run button).

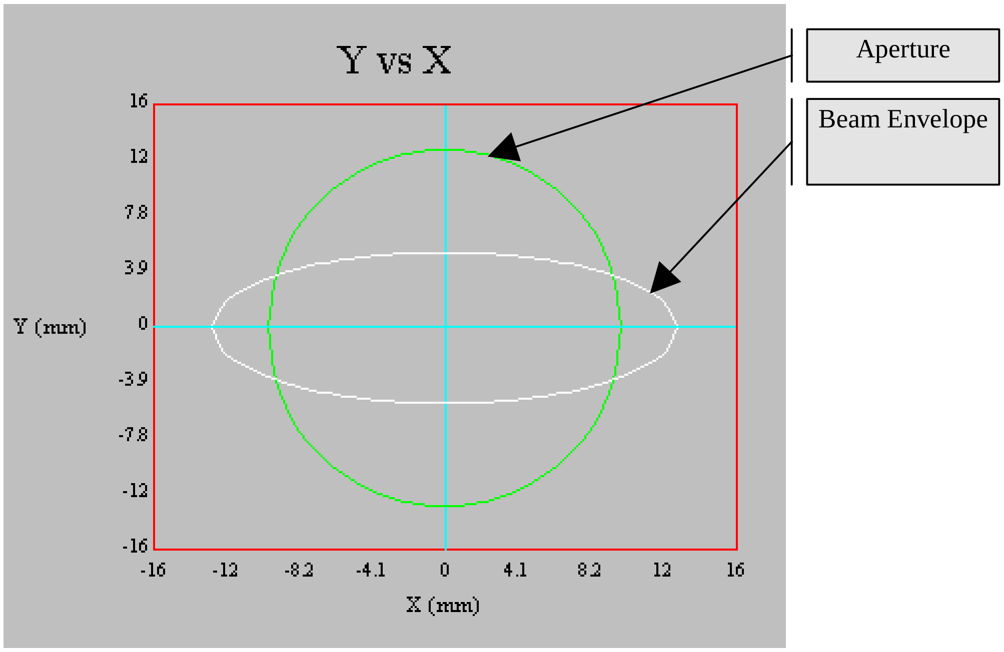
The run algorithm is the central numerical engine for the software. Basically it translates all information in the SBI Window into beam or transport matrices. The run algorithm then directs specific information to each window so that you can view the information in different ways.

It's important to remember that any change made in the SBI Window will not be reflected in the other windows until the beamline has been run. **So, after you make changes in the SBI Window you must rerun the beamline to see the changes in the other graphics windows.**

Viewing the Graphics



Cross-Sectional Plot



The Graphics Windows now show the longitudinal and cross-sectional plots for the current beamline. The white lines show the outer extents of the beam (also called the beam envelope) and the green lines show the inner diameters of the physical beamline apertures, (e.g., the beam pipe, collimators, vacuum boxes, et cetera).

Notice that in the longitudinal X vs Z plot the beam spreads out past the beamline aperture at the right end of the plot, and in the cross-sectional Y vs X plot the beam is outside the aperture along the X axis.

The cross-sectional plot is always produced at the Z co-ordinate of the Cross-Section Plot icon (found in the SBI Window). Its position is shown as a yellow vertical line in the longitudinal plot.

In the next three sections we lead you through a real-time tuning example. You will add one quadrupole magnet to the sample beamline so that you can tune the beamline to fit within the aperture on the extreme right.

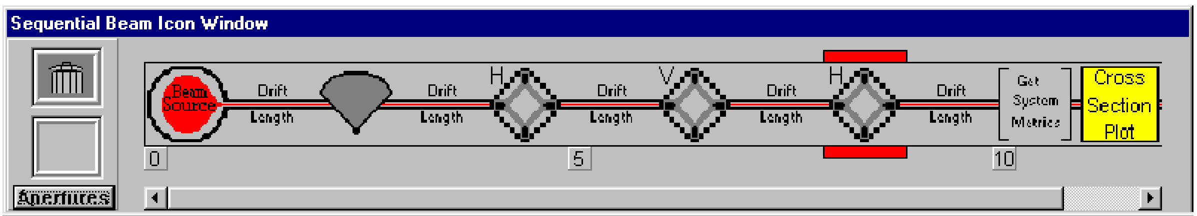
Adding a Quadrupole Magnet

11. Right-click on the SBI Window. This will bring up a pop-up menu with a choice of new elements.
12. Select **New Quadrupole.** Notice that the mouse pointer changes shape when pulled back into the SBI Window. This indicates that you are ready to insert the new element.

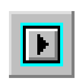
13. Position the cursor over the fourth drift length from the left.

14. Click the mouse to insert the quadrupole. Notice that the new quadrupole was placed *after* the fourth drift length. Also notice the *red bars above and below* the quadrupole. This means that the new quadrupole icon is also the current icon.

Note: any new element that is inserted or added to the SBI Window will be highlighted with red bars. It becomes the current icon. You can, at any time, make a different icon current simply by clicking on it.

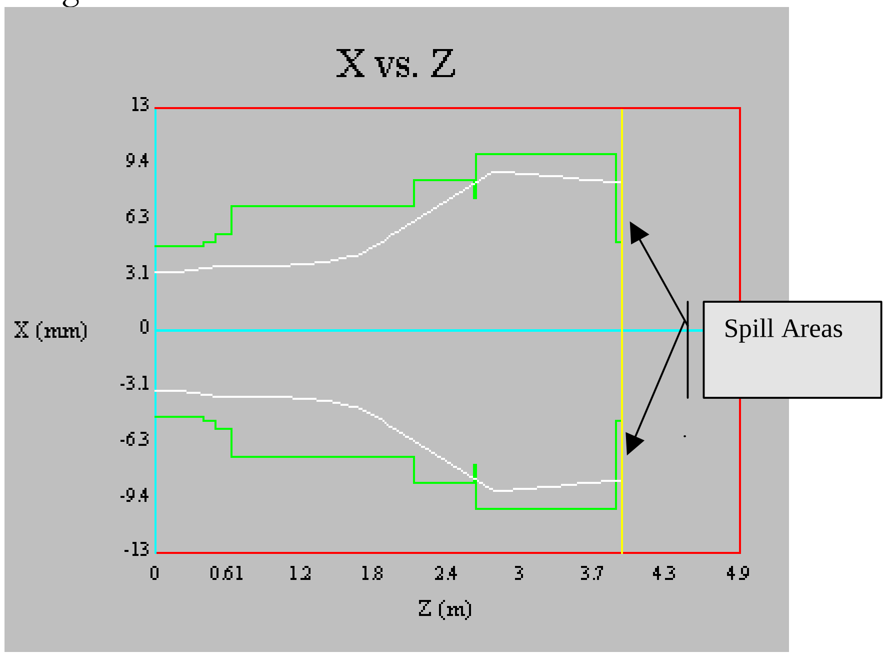


IMPORTANT NOTE: You must place the new quadrupole in the correct position in the SBI Window or you will NOT get the same demo results. If you did not place the quadrupole in the position indicated in the above figure, drag-and-drop it to the correct position now. Remember that you must drop the quadrupole on the fourth drift length from the left so that it appears to the immediate right of that drift length.

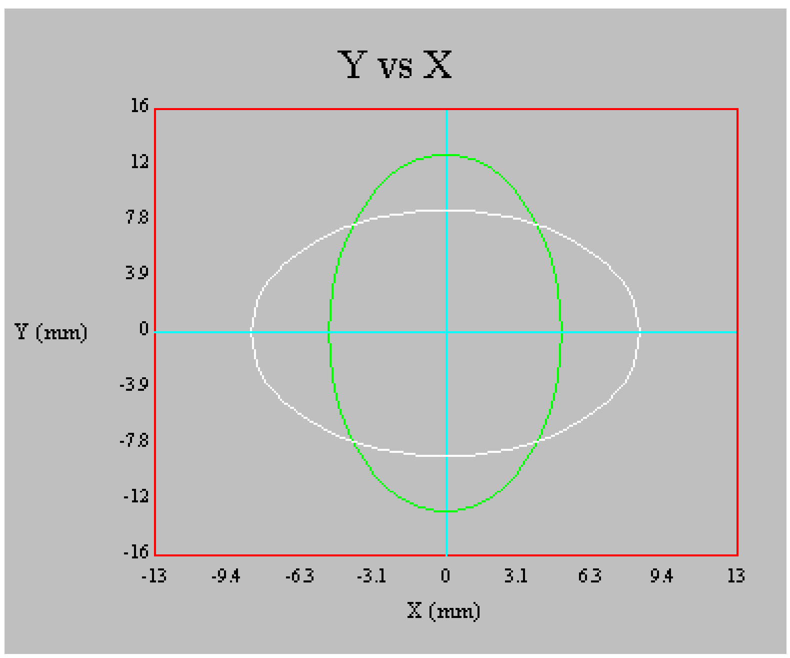
15. To rerun the beamline click  (Base Application Window - Toolbar run button). This will update the rest of the windows.

Viewing the Graphics Again

Longitudinal Plot



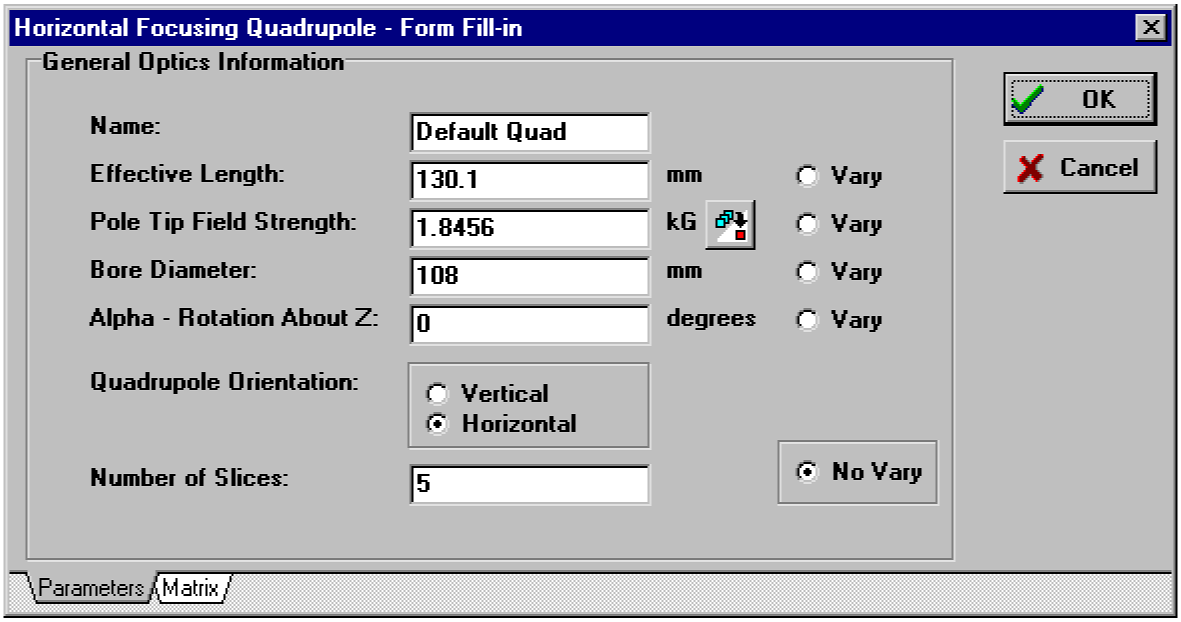
Cross-Sectional Plot



After adding the quadrupole magnet the beam has been focused horizontally and slightly de-focused vertically. The right end of the longitudinal plot shows that the last aperture is still irradiated with much of the beam. Also, the cross-sectional plot confirms that the beam is still outside the aperture along the X axis. In the next section you will find a better tune by varying the Quadrupole – Pole Tip Field Strength.

Real-Time Tuning With the Quadrupole Magnet

16. Double click the Quadrupole icon that you just inserted into the SBI Window. This brings up the Quadrupole Form Fill-In which allows you to re-define the quadrupole parameters.

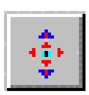


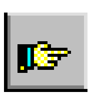
17. Click 

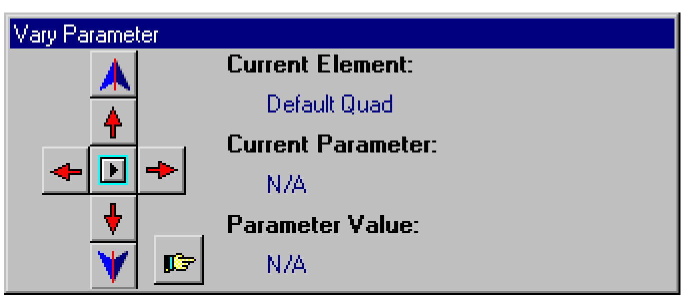
for the Pole Tip Field Strength parameter.

18. Click 

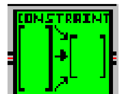
. Look in the SBI Window below the Quadrupole icon. There is a V tag which means that the icon has a parameter that you chose to vary.

19. Click  (Base Application Window - Toolbar). This will bring the Vary Parameter Window to the center of the screen.

20. Click  to view the full window.



21. Scroll full right in the SBI Window.

22. Double-click 

the Constraint icon to bring up the Constraint Form Fill-In – Variable Parameters page. Note that the first line shows the values for the Quadrupole – Pole Tip Field Strength. Here you can set the Maximum, Minimum, Small Step, and Big Step values. The Maximum and Minimum values set boundaries for how far the parameter will vary, and the Small and Big Step values determine how much of a jump applies to each step when tuning with the Vary Parameter Window.

Note: We asked you to open this window so you would see the direct relationship between the Vary Parameter Window and the Constraint icon. Both offer ways to tune. The Vary Parameter Window is used for hands on tuning of one element at a time while the Constraint icon offers automatic tuning for as many variable parameters and elements as you wish. In the latter case the constraint algorithm tries many different 'tunings' and selects the best solution for any imposed constraints.

23. Click 

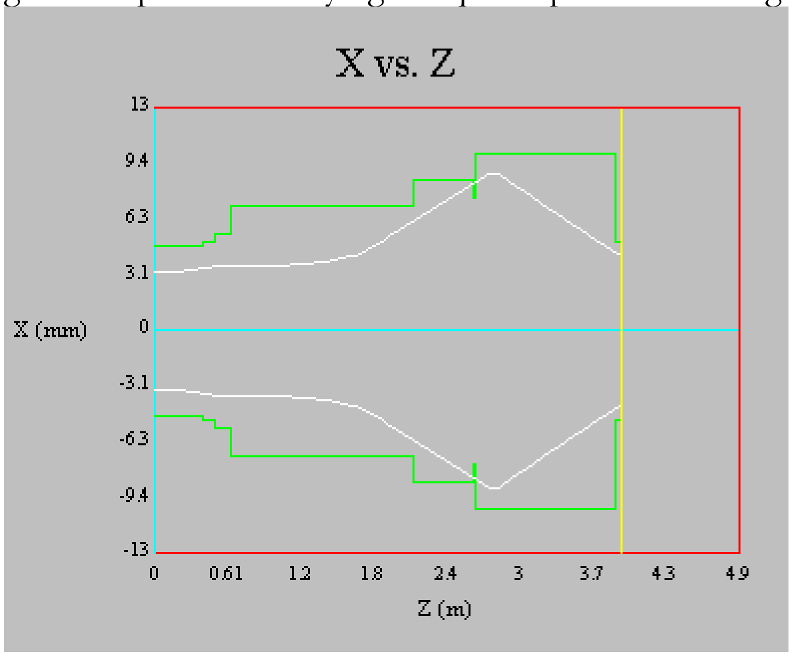
to close the Constraint Form Fill-In.

24. Ensure that the Quadrupole icon is the current icon. Remember that the current icon has red bars above and below it.

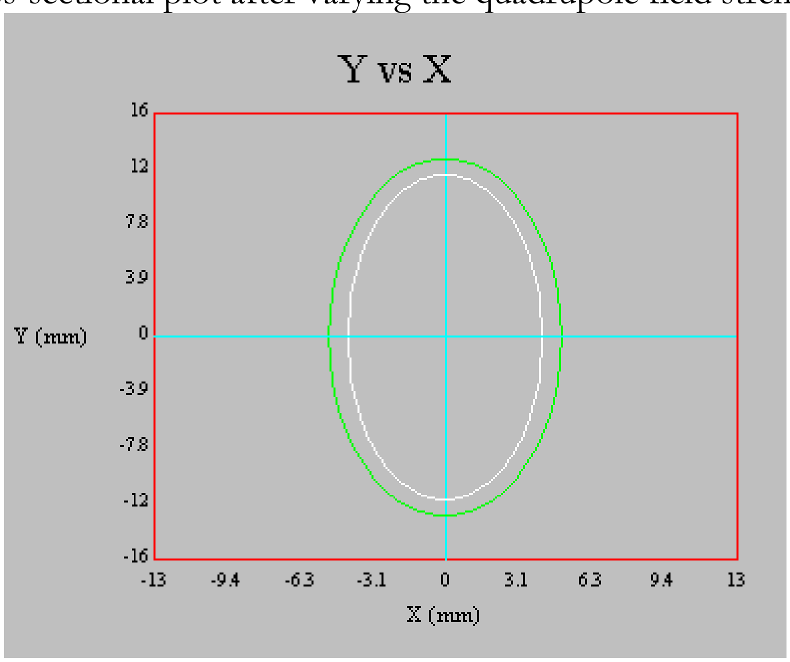
25. In the Vary Parameter Window, click one of the up/down arrow buttons to vary the Quadrupole – Pole Tip Field Strength parameter. For both the up/down arrow buttons, the blue arrow means a big step and the red arrow means a small step. Watch the graphics plots to see the changes that take place. It is your task now to vary the quadrupole field strength until the beam is within the aperture in the cross-sectional plot.

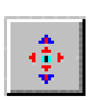
Tuning up will focus the X axis more while defocusing the Y axis. Tuning down will cause the quadrupole to have less powerful focusing along the X axis and less powerful defocusing along the Y axis.

Longitudinal plot after varying the quadrupole field strength.



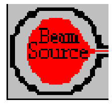
Cross-sectional plot after varying the quadrupole field strength.

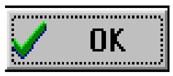


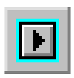
26. Click  (Base Application Window - Toolbar). This will hide the Vary Parameter Window.

Running a Multi-Particle Beam

A multi-particle beam will show beam spill clearly.

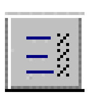
27. Scroll full left in the SBI Window.
28. Double-click 

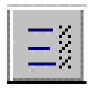
(SBI Window). This brings up the Beam Source Form Fill-In dialog box.
29. Under 'Beam Type' click **Multi-Particle**. Under 'Multi-Particle Generation' leave the setting as is.
30. Click 

.
31. Run  the beamline again (Base Application Window - Toolbar).

When you run the beam in particle mode you get different information about the beam. This time you will see particle trajectories all the way along the longitudinal plot and a scatter of particles in the cross-sectional plot. Notice the narrow aperture at Z= 2.6 m in the longitudinal plot. Some of the particles are stopped or spilled here. To see what percentage of the beam was spilled at that point and to detect any other beam spills along the beamline you can look in the Collimator Window.

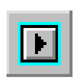
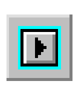
Viewing the Collimator Window

32. Click  (Base Application Window - Collimator Window Toggle) to bring up the Collimator Window. The first line in the window '**Total System Loss**' tells you how much of the beam has spilled.
33. Use the right side scroll to move to the aperture named '**Spill Here**'. The spill is measured by a TBLR readback type aperture. This readback type aperture keeps track of how many particles hit the Top, Bottom, Left, and Right.
34. Scroll further down and you will see '**Name: Default Aperture Percent Lost (**NoReadback**)**'. The percent spilled plus the percent lost through non-readback type apertures should add up to the total system loss.

35. Click  to close the Collimator Window.

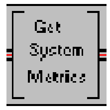
Selecting Graphics Properties

Each graphics window has the capability of displaying a variety of plots.

36. Right-click on the right graphics window to bring up its pop-up menu.
37. Select **Properties** to bring up the Properties Notebook first page called '**Graph Type**'.
38. Click the **Intensity** radio button to see an intensity plot.
39. Under **Graph Type – Intensity** you would normally choose the beam axis that you wish to view. Notice that the **X** axis is already selected. Leave it as is.
40. Before accepting the changes please familiarize yourself with the other pages of the Properties Notebook.
41. Click the **Accept** button to accept the changes you have made to the Graph Type.
42. Run  the beamline. You should now see the intensity plot of the distribution of particles along the X axis. Note that the intensity plot is produced at the Z position of the Cross-Section Plot icon within the SBI Window.
43. Repeat the above procedure but this time choose a longitudinal plot of type **Y-Z**.
44. Run  the beamline again and you should see a plot of Y vs Z in the graphics window.

Introducing the Diagnostics

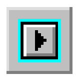
The System Metrics icon is used to display beam and transport system information *at a specific point (Z co-ordinate position) in the beamline*. You would normally add as many System Metrics icons as you want to the beamline in the SBI Window. For this example, leave the System Metrics icon where it is. We'll look at system metrics from the previous run.

45. Double-click 

to see the **System Properties** page. Look under **Beam Parameters** and you will see the beam half-sizes. These values are obtained at the Z position of the current System Metrics icon.

46. Click the **System Matrices** tab at the bottom to see the **Cumulative Beam Sigma Matrix.** Notice that the **Cumulative Transport Matrix** shows only the identity matrix. This is because the Cumulative Transport Matrices menu item is not toggled on.

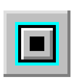
47. To toggle on the Cumulative Transport Matrices click **Run Options** (Base Application Window) and then toggle on ✔ **Cumulative Transport Matrices**.

48. Run  the beamline again.

49. Repeat steps 45 and 46 to view the **Cumulative Transport Matrix**.

50. You may also view all particle vectors by clicking the **Particles** tab.

In summary the System Metrics icon is very useful for viewing the beam and system matrices at any point along the beamline.

☺ You have now completed the tutorial on Running and Real-Time Tuning Procedures. To reinforce what you have already learned we suggest that you spend some time playing with the program. If at any time you wish to stop a multi-particle run or a run using the constraint algorithm, simply click the Stop  button. It is located to the right of the Run button on the Toolbar.

Play with the Run Options in the Base Application Window. Change the graphics window properties and the other elements in the SBI Window. As you try different things you will see what happens and why. If at anytime you get stuck on what a particular button or menu item does, check the Command and Tool Reference in the back of the manual or the chapters specific to the beam source, the ion-optical elements, the graphics windows and the diagnostics. So, dive into it...

4.2 Automatic Tuning Using the Constraint Algorithm

Automatic Tuning Using the Constraint Algorithm is an advanced tutorial for those having attained a basic knowledge of Beamline Simulator. If this is your first time using Beamline Simulator we recommend that you start at Chapter 3 and then work through Chapter 4.1 Running and Real-Time Tuning Procedures. Chapter 4.1 includes basic information about using the windows, viewing and interpreting the graphics, adding elements and varying a single element parameter. This tutorial reaches well beyond the basics.

The **Solve for Constraints** menu item is found under **Run Options** in the Base Application Window. The **Constraint** icon is found in the SBI Window.

The Beamline Simulator program is capable of *automatically adjusting* all beamline parameters that have been defined by the user as being *permissible to vary*, until values are found that cause the beamline *to meet user defined constraints* on the system. Two main examples of this are:

- when the user wishes the beam to be constrained to a certain size at some point along the beamline, or
- when the user wishes to constrain elements of the cumulative transfer matrix to have a certain value at a specific point in the system.

The algorithm used to solve for constraints is a brute force algorithm. For each variable parameter, it takes the difference between the maximum and minimum permissible values and divides this by the maximum number of iterations to yield a step size for searching through parameter space.

It then tries every combination of steps *using all variable parameters* and re-calculates the beam and cumulative transfer matrices to see if they are within the specified acceptance range. Even if all constraints are not met it still displays the best results obtained. You are then asked whether you wish to keep the values or discard them. If you choose to keep the values, the appropriate beamline icon information is updated in the SBI Window.

Central to the constraint algorithm is the parameter called Maximum Iterations. This parameter defines the size of the steps for all the variable parameters. If the Maximum Iterations parameter is high then the algorithm has a better chance of finding a solution for the beamline. Similarly, if the number of variable parameters is high you have an increased chance of finding a solution. The trade off is time.

The more variable parameters and iterations you use the longer the run takes. In the extreme, the run is so slow that it could occupy your computer for hours.

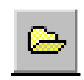
In this tutorial we guide you in the effective use of the constraint algorithm. The tutorial begins at the Start button because this will initialize the software. This is our only assurance that you will have the same settings as we do.

Initializing the Software

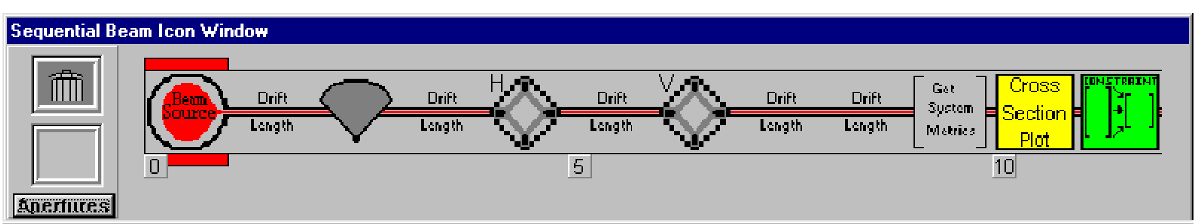
1. Click  at the bottom left on your screen.

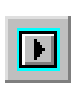
2. Find and open **Windows Explorer**.
3. In the left frame of the Explore window, select the appropriate hard drive to reveal the folders.
4. Double click **Beamline Simulator Version 1.3** to reveal the files.
5. Double click **BeamlineSimulator.exe** to run the program.

Opening and Running the Sample Beam

6. To open the sample file click **File** and select **Open** or click  (Base Application Window and Toolbar).
7. Click **Sample1.bln**.
8. Click the **Open** button.

For the next procedures the Base Application Window should have the file name 'Sample1.bln' in its title bar and the SBI Window should look like the drawing below.

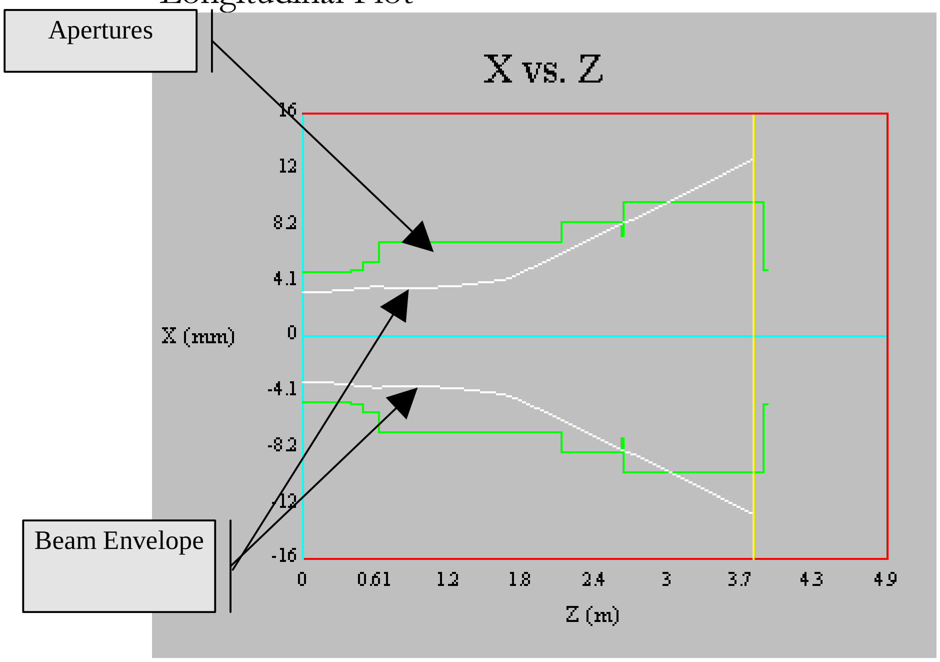


9. Ensure that the **Solve for Constraints** algorithm, **Run Options** menu is toggled off (not checked or ticked). This first run is just to update the windows with the 'Sample1.bln' file and not to solve for constraints.
10. Run  the beamline (Base Application Window - Toolbar).

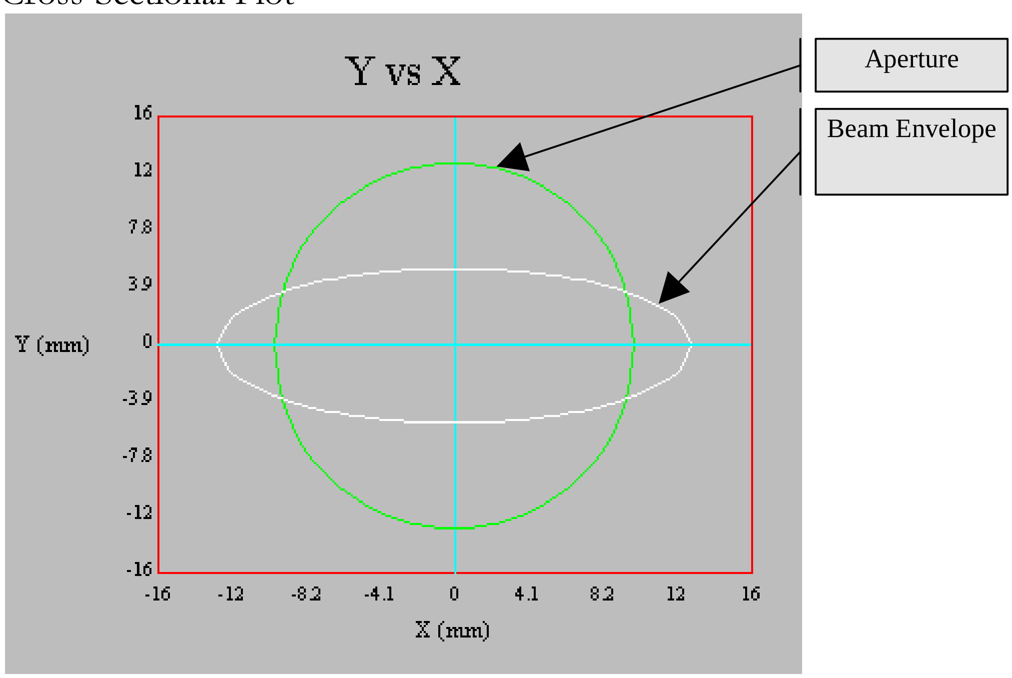
Viewing the Graphics

These are the same graphs you saw in Chapter 4.1 Running and Real-Time Tuning Procedures. The run shows the beam (white lines) extending outside the apertures (green lines) on the far right of the longitudinal plot and along the X axis of the cross-sectional plot.

Longitudinal Plot



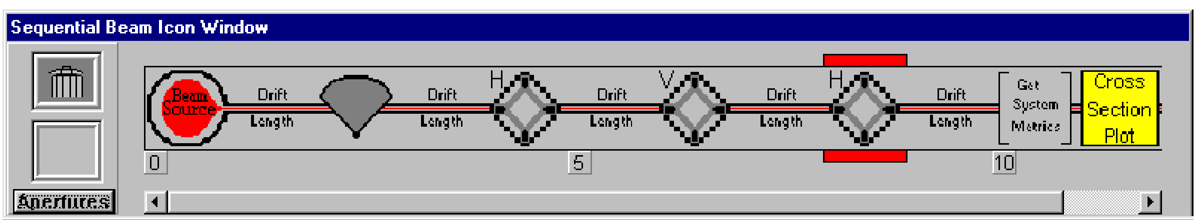
Cross-Sectional Plot



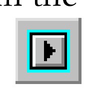
In the next section you will add a Quadrupole magnet icon. You'll then use the Constraint icon to apply constraints to the beam in both the X and Y dimensions near the end of the beamline. When you next run the beamline, variations in the quadrupole's pole tip field strength will automatically yield new profiles. One of these profiles will provide the solution to the constraints.

Adding a Quadrupole Magnet

11. Right-click on the SBI Window. This will bring up a pop-up menu with a choice of new elements.
12. Select **New Quadrupole.** Notice that the mouse pointer changes shape when pulled back into the SBI Window. This indicates that you are ready to insert the new element.
13. Position the cursor over the fourth drift length from the left.
14. Click the mouse to insert the quadrupole. Notice that the new quadrupole was placed *after the fourth drift length* and is *the current icon*.



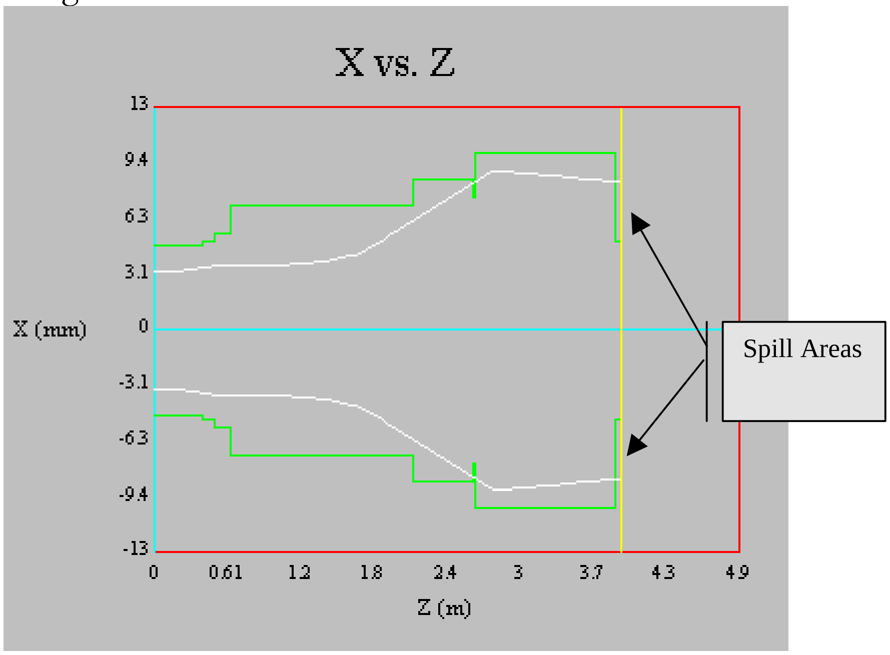
IMPORTANT NOTE: You must place the new quadrupole in the correct position in the SBI Window or you will NOT get the same demo results. If you did not place the quadrupole in the position indicated in the above figure, drag-and-drop it to the correct position now. Remember that you must drop the quadrupole on the fourth drift length from the left.

15. To rerun the beamline, click  (Base Application Window - Toolbar). This will update the windows.

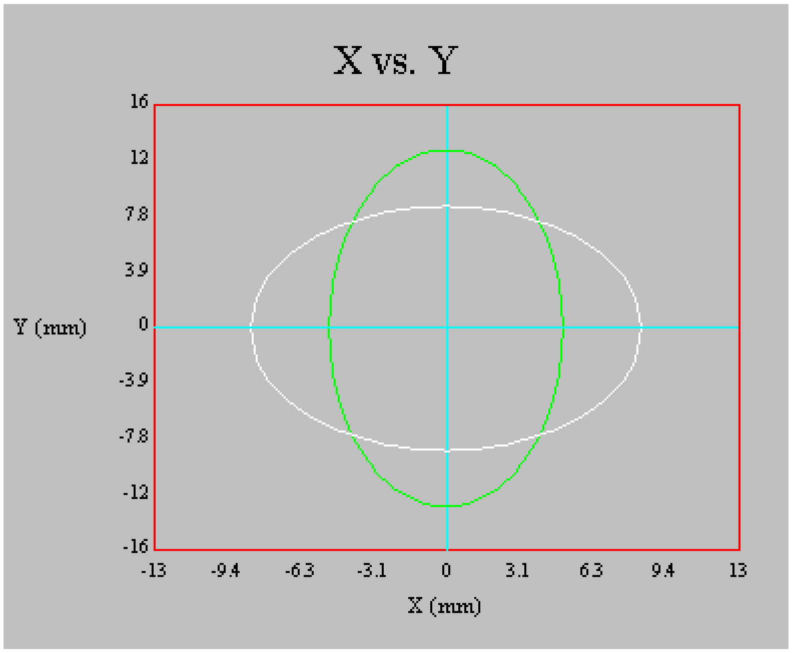
Viewing the Graphics Again

After adding the Quadrupole magnet the beam is focused horizontally and slightly de-focused vertically. The right end of the longitudinal plot shows that the last aperture is still irradiated with much of the beam. Also, the cross-sectional plot confirms that the beam is outside the aperture along the X axis.

Longitudinal Plot



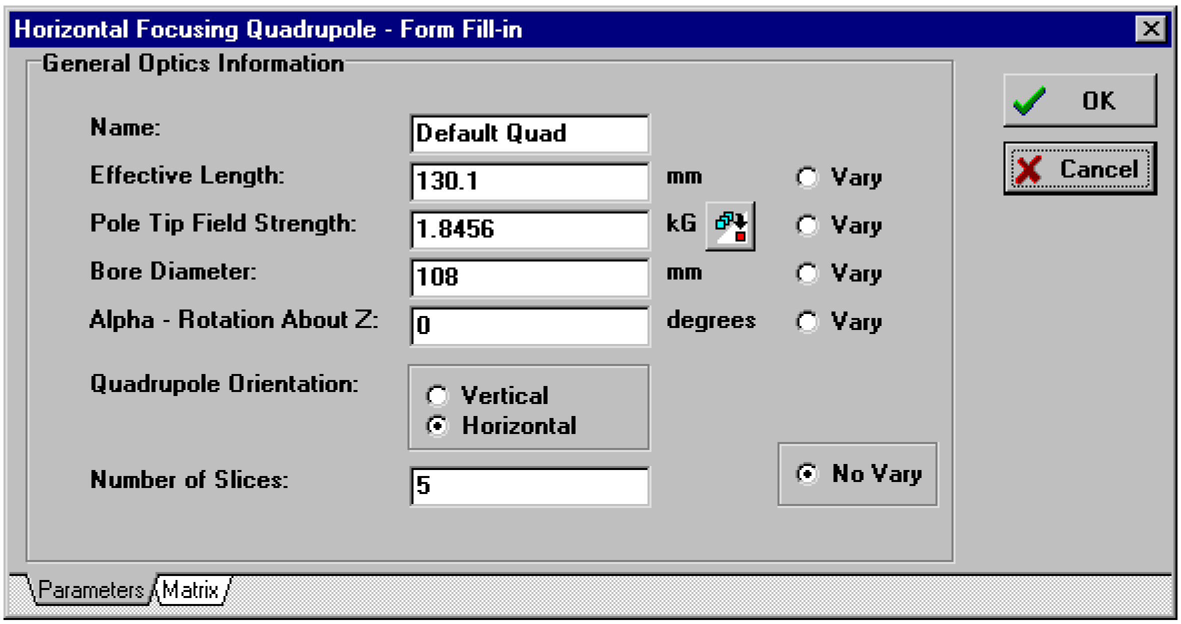
Cross-Sectional Plot



In the next section we ask you to find a better tune by automatically varying the Quadrupole – Pole Tip Field Strength using the Constraint icon.

Vary One or More Parameters

16. Double click the Quadrupole icon that you just inserted into the SBI Window. This brings up the Quadrupole Form Fill-In so you can re-define the quadrupole parameters.



17. Click 
 for the Pole Tip Field Strength parameter.

18. Click 
 . Look in the SBI Window below the Quadrupole icon. There is a V tag that means that the icon has a parameter that *you chose to vary.*

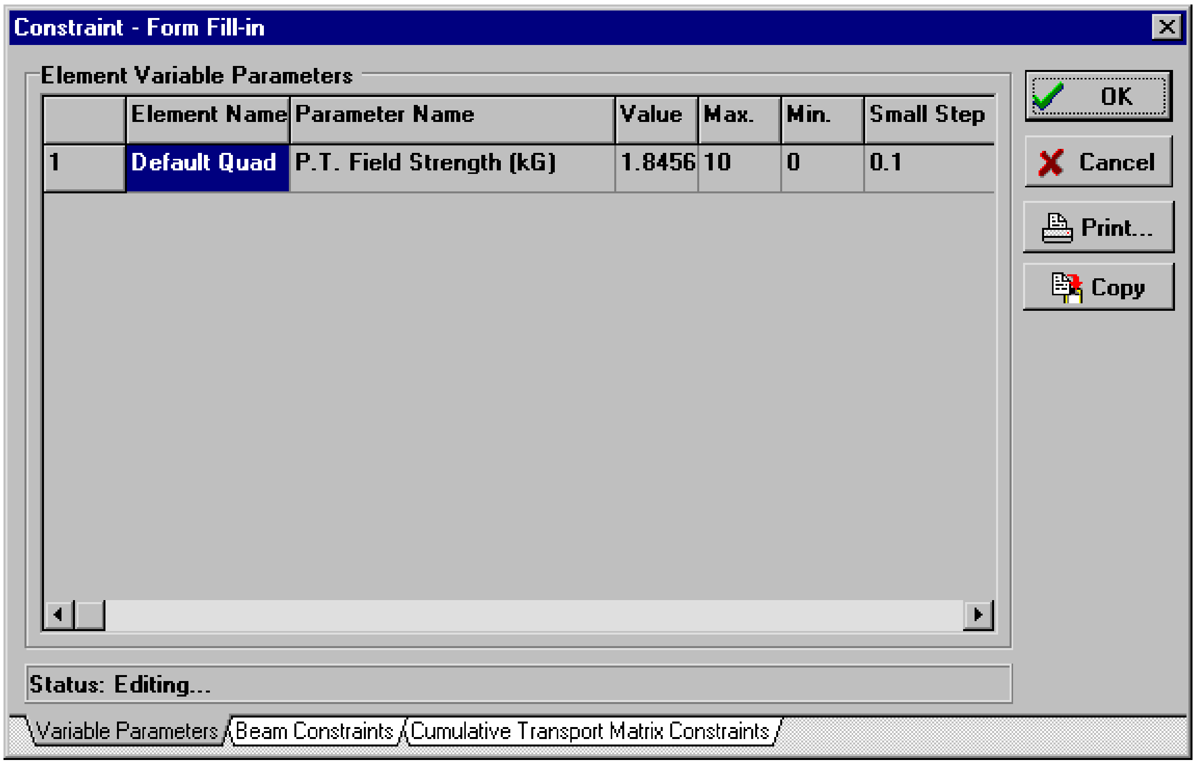
Although we could use other beamline elements and we could set other element parameters as variables, we are choosing to use one quadrupole with one variable parameter. Our only reason is simplicity for the tutorial.

Choosing What to Solve For

You could choose to constrain a beam half-size or a cumulative transport matrix element. Transport system designers may want to achieve certain optical characteristics by constraining the cumulative transport matrix elements.

Typically one wants a particular beam size at the target. So, for this tutorial we ask you to solve for particular beam half-sizes along both the X and Y axes at the end of the beamline.

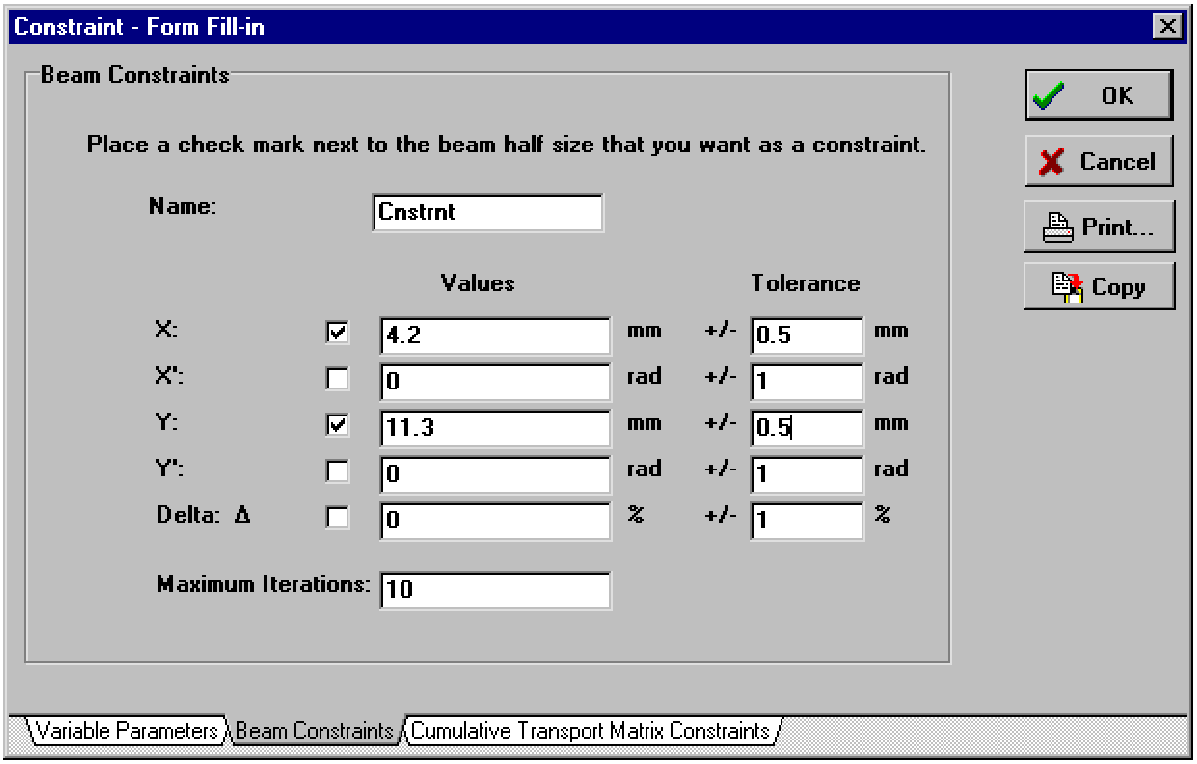
19. Double-click the **Constraint icon** to bring up the Constraint – Form Fill-In Variable Parameters page.



Note that the **Min**. and **Max.** values shown on this page are always used by the constraint algorithm. They put upper and lower limits on how far the constraint algorithm can vary each parameter. The **Small Step/Big Step** values are not used by the constraint algorithm. They are used by the real-time simulation during manual tuning in the Vary Parameter Window.

20. Leave all entries in the Variable Parameters page as is.

21. Click the **Beam Constraints** tab at the bottom of the dialog box.



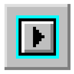
The **Beam Constraints** page allows you to constrain one (or more) beam half-size(s) to a specific value(s) within tolerances. A beam half-size with a check mark beside it will be solved for by the constraint algorithm.

22. Click the box beside **X** to activate it. Enter **4.2** as the half-size and **0.5** as the tolerance.
23. Click the box beside **Y** to activate it. Enter **11.3** as the half-size and **0.5** as the tolerance.
24. Set the Maximum Iterations to 10.
25. Ensure that your Constraint Icon pages match the ones above. Click **OK** to accept the changes.

Later on you'll use the **Transport Matrix Constraints** to see how they work.

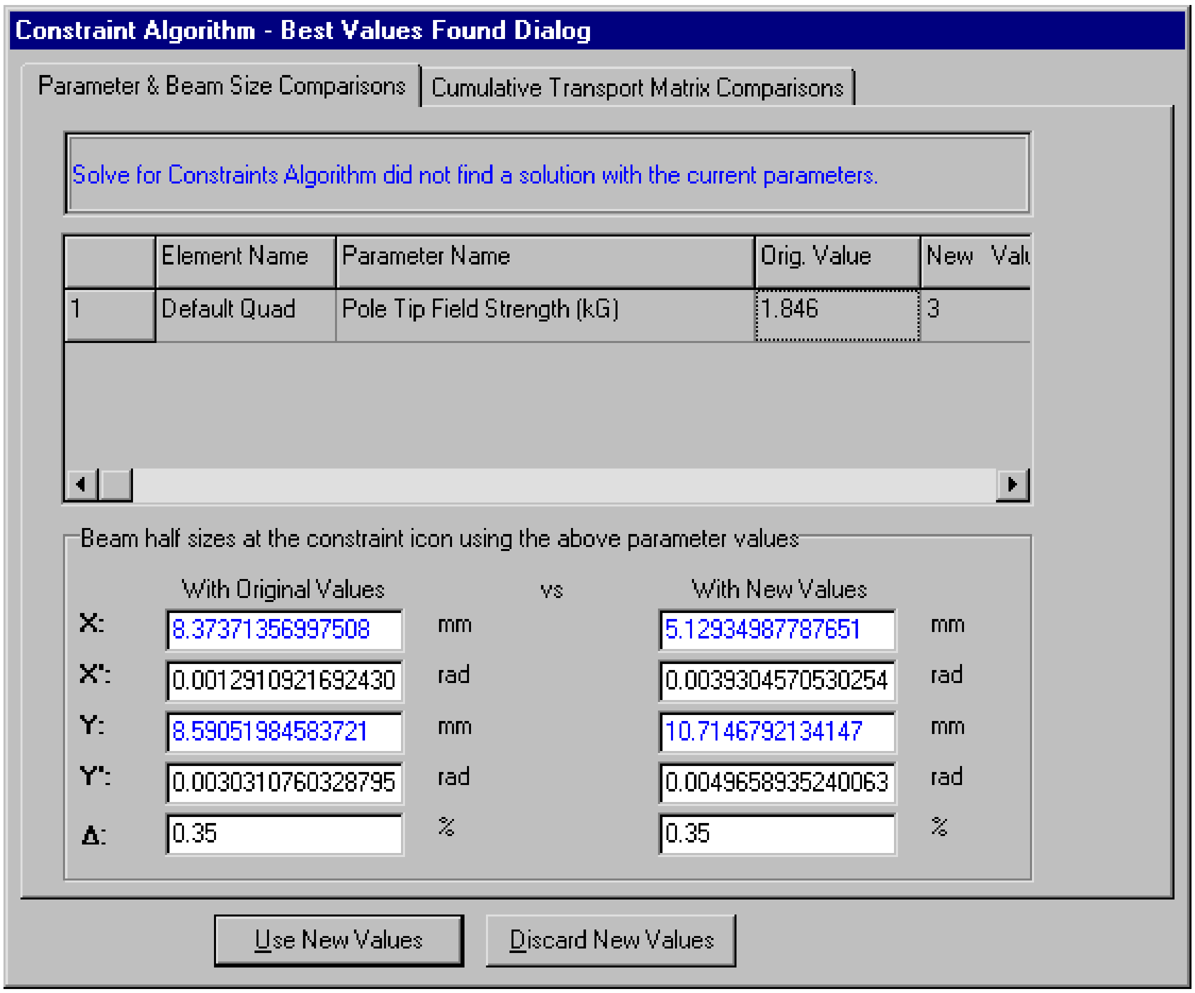
Running the Constraint Algorithm

26. Toggle on ✓ **Solve for Constraints**, **Run Options** menu. This puts the program in the constraint solving mode. The program will now *only recognise the instructions given to it within the Constraint icon.*

27. Run  the beamline and look at the top of the screen. There is a progress indicator that shows how close the algorithm is to completing all parameter step combinations.

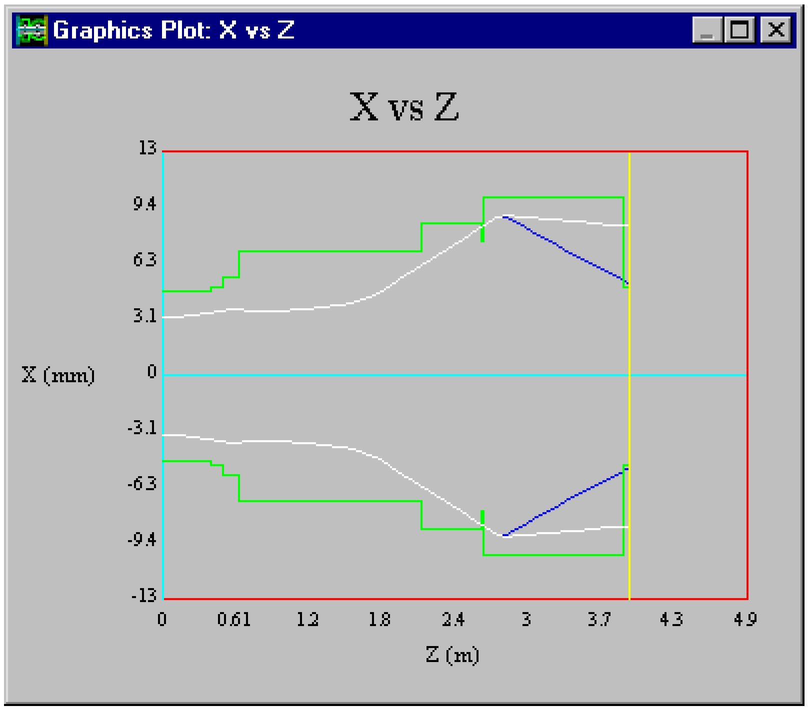
Interpreting the Results

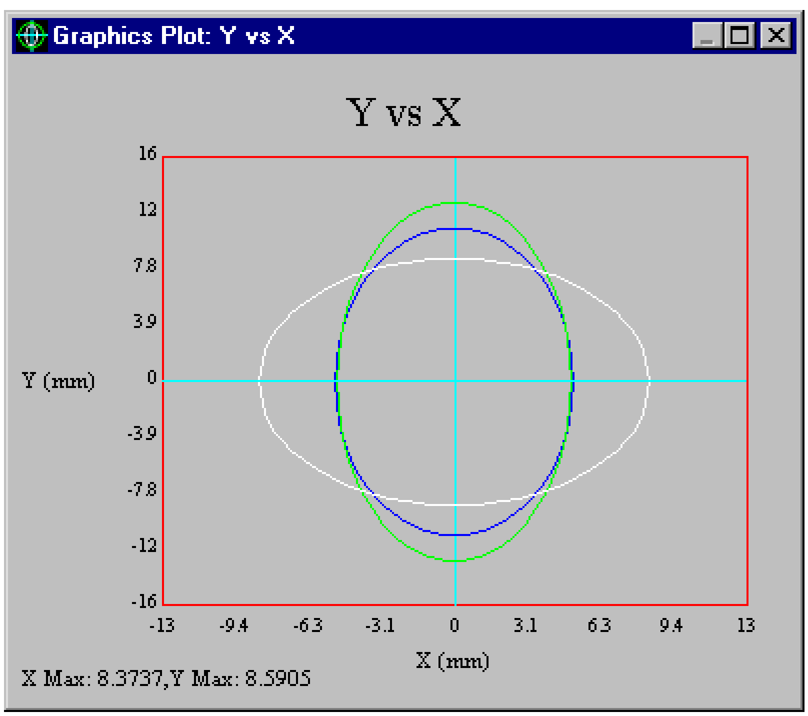
Soon after the plots are drawn, the Best Values Found Dialog box, Parameter & Beam Size Comparisons page appears on the screen.



The top panel explains how many of the total constraints are met. The middle grid shows a comparison of the before and after values for each variable parameter. The bottom data boxes give the before (pre-run original) and after (new) values for the beam half-sizes.

28. Click and hold on the title bar of the **Best Values Found Dialog** box. Drag the box to the bottom of the screen so that you can see the graphics plots.





Each graphic shows two beam plots, one on top of the other. The white curves show the beam plot from the pre-run parameter settings while the blue curves show the beam plot from the 'Solving for Constraints' run. The blue curves show the closest match possible given the one element (a quadrupole) with one variable parameter (the pole tip field strength) and the 10 iterations we chose.

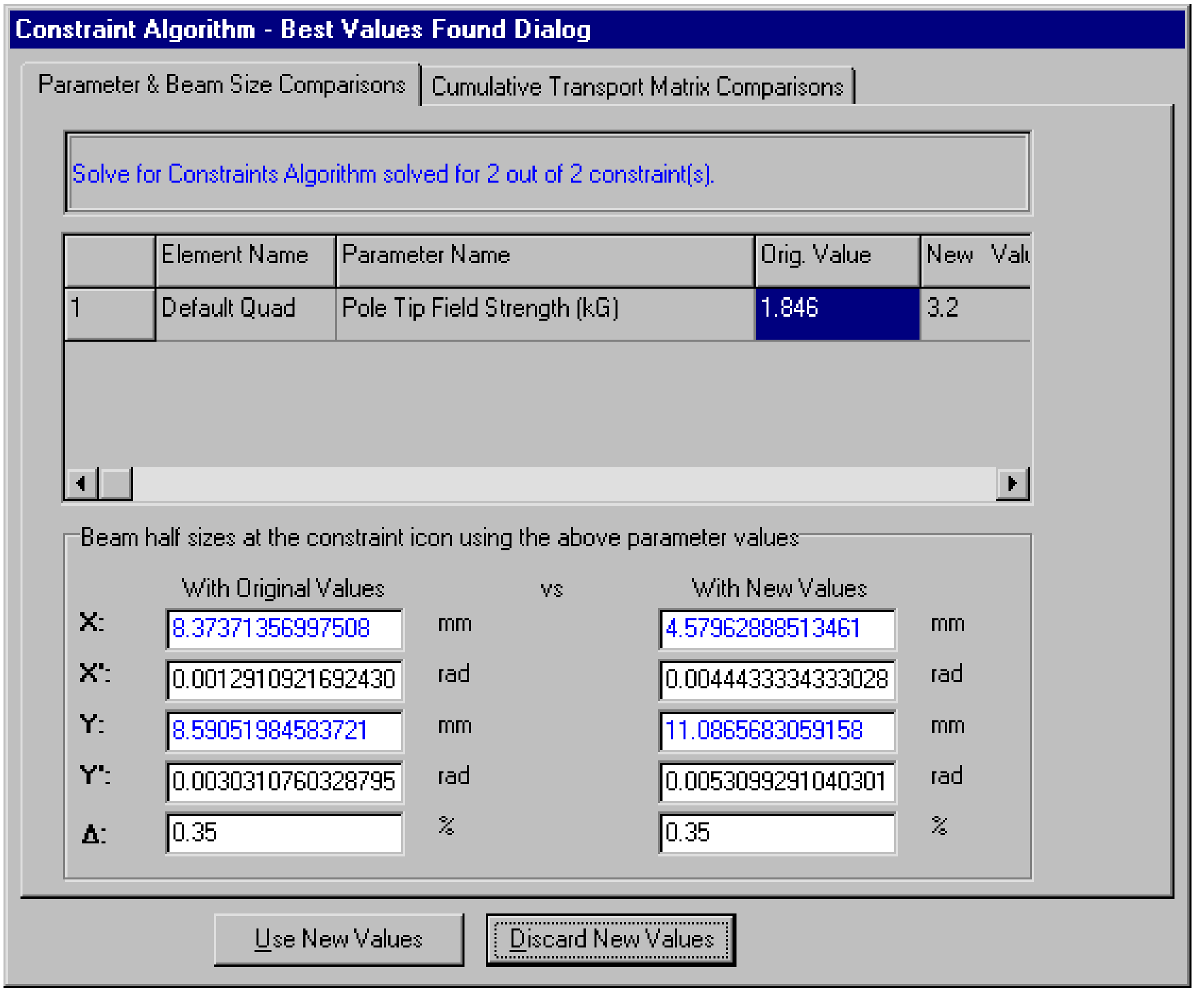
With a quick glance you can see whether the new values are worth keeping or whether they should be discarded. In this case you should discard them because only one of the two constraints that we chose were met.

29. Move the **Best Values Found Dialog** box back to the middle of the screen and click the **Discard New Values** button, bottom of the box.

Since the algorithm only solved for one of the two beam constraints we should see if increasing the maximum iterations parameter will help the algorithm.

30. Change the **Maximum Iterations** to **100** and run the beamline.

At about 25% through its total step combinations the algorithm stopped and displayed the Best Values Dialog box. This means that all the constraints have been solved. The program automatically found the quadrupole magnet setting that forced the beam half-sizes to be the values we chose. Note that the algorithm will always terminate as soon as all of the constraints have been accepted within their +/- tolerance range.



The graphics plots also show that the beam is within the aperture.

31. To save the values click the **Use New Values** button at the bottom of the box.

You can now fine tune the beamline by narrowing the tolerance allowed for the X and Y values.

32. Double-click the **Constraint icon** to bring up the Constraint – Form Fill-In Variable Parameters page.
33. Click the **Beam Constraints** tab at the bottom of the dialog box.
34. Set the **+/- ranges** for the **X** and **Y** constraint to **0.1** mm and keep the **Maximum Iterations** the same.
35. Run the beamline again.

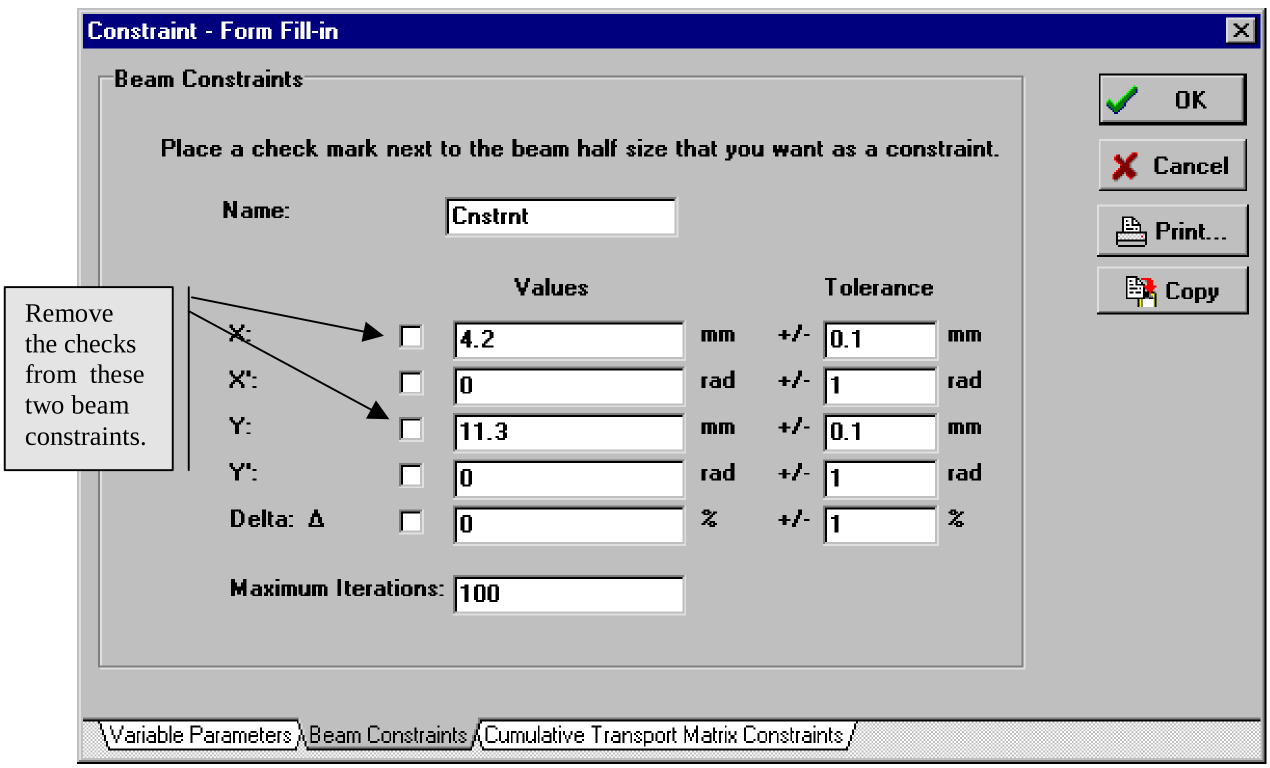
The Y-X blue plot should show that the beam is now perfectly inside the aperture. It is actually very close to the same shape and size as the beam obtained through manual tuning in the Chapter 4.1 tutorial, page 14.

36. Click the **Use New Values** button to accept the new values.

For the final run we ask you to constrain the [1,1] element entry of the Cumulative Transport Matrix.

37. Click the **Beam Constraints** tab, bottom of the dialog box.

38. Click the **X** and **Y** constraints to remove the check marks. We don't want you to solve for these anymore.

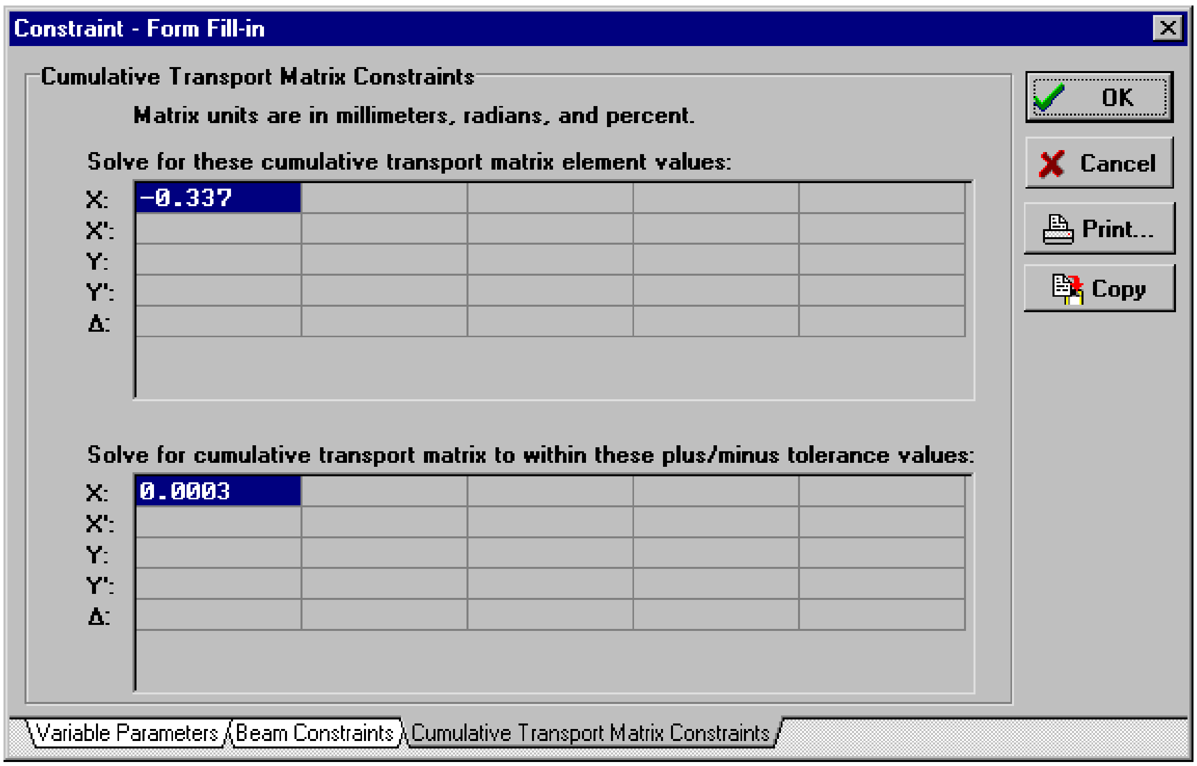


39. Click the **Cumulative Transport Matrix Constraints** tab at the bottom of the dialog box.

40. Under 'Solve for these cumulative transport matrix element values:' enter -0.337 in the [1,1] cell.

41. Under 'Solve for cumulative transport matrix to within these plus/minus tolerance values:' enter 0.0003 in the [1,1] cell.

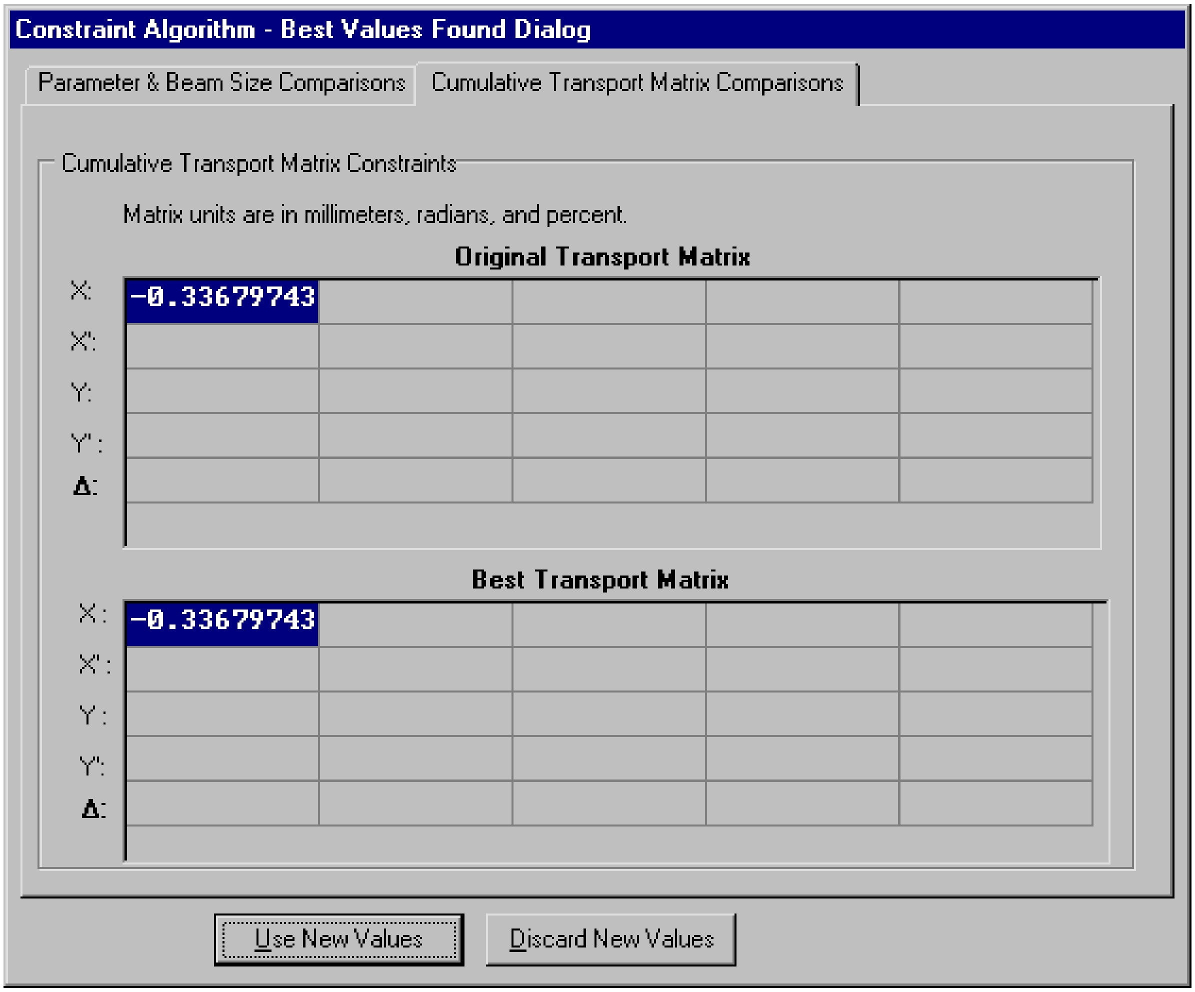
When you enter a value in the upper grid you MUST also enter a tolerance value into the corresponding cell in the lower grid.



42. Click the OK button to save the values.

43. Run the beamline again.

44. Click the Cumulative Transport Matrix Comparison tab at the top of the Best Values Found Dialog box.



You will see that the constraint algorithm solved for the same value in the transport matrix as was present before the run.

Now that you have some basic skills in using the constraint algorithm, we suggest that you play with some of the different features of the Constraint icon and see what the results are. You could add more variable parameters or try solving for different beam half-sizes. So, dive into it...

Remember: when you no longer want the program to automatically tune the beamline, toggle off **Solve for Constraints** in the **Run Options** menu.

4.3 Questions & Answers

When planning a run, you need to ask yourself, "What do I want from the run and what tasks do I want the run to perform?" There are many variables that may be turned on or off depending on your needs. Here we present a number of questions with answers to explain how and when to change the variables.

The run algorithm is the central engine for the software and so has multiple data generation responsibilities. Given its central role, you MUST do a new run every time that a change is made in the SBI or other windows. A new run will refresh the information in every window.

Question 1: How do I change the beam type for a run?
Answer: Double-click the Beam Source icon (SBI Window) to bring up the form fill-in dialog box. Choose envelope or multi-particle. When you choose *envelope* the graphics plots will show the outer extents of the beam. T*he run will not produce beam spills or show any interaction with the apertures*. When you choose a *multi-particle* beam type the program *will be able to generate beam spills and aperture interactions*. Also, when you choose a multi-particle beam type you can enter the Number of Particles that you wish to have transported along the beamline. Once you have chosen your beam type click the Run button to see the new plots and data.

Question 2: How do I do an envelope plot?
Answer: Double-click the Beam Source icon to bring up the form fill-in dialog box. Click the Envelope radio button under Beam Type and click OK to accept the new beam type. Run the beamline. If one of the graphics windows is an *intensity plot you will not see the plot because there are no particles to make up the distribution.*

Question 3: How do I do a multi-particle plot?
Answer: Double-click the Beam Source icon to bring up the form fill-in dialog box. Click the Multi-Particle radio button under Beam Type. Notice that the Number of Particles Edit Box Label comes alive. Click the edit box and enter the number of particles that you want in the run (maximum 10,000), then click OK to accept the new beam type. Run the beamline. If one of the graphics windows is an *intensity plot then you will see the plot because there are particles to make up a distribution*

Question 4: How do I do a multi-particle plot with color variation?
Answer: Click Run Options and select Particle Color... (Base Application Window). This brings up the Particle Color dialog box. Choose the axis where you want color representation. Click the OK button and then run the beamline with a multi-particle beam type. Adding color gives you a third dimension. If the plot is X vs Z and the particles are colored depending on where they are along the Y axis, you get a third dimension in the X – Z plot.

Question 5: Why does the constraint algorithm come on when I haven't selected parameters for varying? There aren't any constraints to be matched. How do I turn it off?
Answer: The constraint algorithm can only be turned off from the Run Options menu, Base Application window. Click Run Options then look to see if there is a check mark beside the Solve for Constraints menu item. If there is one, then the constraint algorithm is active and will try to solve for constraints in the next run. To toggle the constraint algorithm off, click the Solve for Constraints menu item to remove the check mark.

Question 6: I have been doing a number of envelope runs with the constraint algorithm off. When I went to solve for some constraints I forgot that I had set the maximum iterations too high. Can I stop the run or do I have to let it run its course?
Answer: Use the Stop button located to the right of the Run button. You can stop both particle beam type runs and runs that use the constraint algorithm. The Stop button does not work with basic envelope runs as these take very little time to complete.

Question 7: How do I see what the beam looks like if there were no apertures to interact with?
Answer: Click Run Options, then toggle off Show Apertures and Clip Particles.

Question 8: How do I view a particle plot with the apertures shown but not have the particles interact with them?
Answer: Click Run Options, then toggle on Show Apertures and toggle off Clip Particles.

Question 9: When I do a run and then look at the System Metrics dialog box, it always shows the identity matrix for the Cumulative Transport Matrix. How do I get it to show the correct Cumulative Transport Matrix?
Answer: Click Run Options and toggle on Cumulative Transport Matrices.

Question 10: When I do a run and then click the Show/Hide BTS Text Window button to show the BTS Text Window, I find that the window was not updated. How do I update the window after a run?
Answer: The window must be showing for it to be updated. By showing the window you toggle a variable in the run algorithm that tells it that you want to update the window. The default setting is hide or toggle off. This was done to make the run algorithm as streamlined and quick as possible.

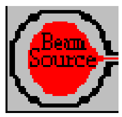
Question 11: How do I manually tune my system or do a real-time run?
Answer: See Chapter 4.0 section 4.1 Running and Real-Time Tuning Procedures.

Question 12: How do I see quantitatively how much beam spill there may be?
Answer: There are a number of variables that you must set for the run to work. In the Run Options menu toggle on Clip Particles.... *This is the important variable to have on.* Next choose a *multi-particle beam type*. And finally, in the Windows menu toggle on Collimator Text Window. Run the beamline and see if any spill shows in the Collimator Window.

5.0 Defining the Beam Source

To test a beamline you need a beam. Using the Beam Source Form Fill-In pages, you may set the beam parameters to model a beam with any emittance that you wish.

5.1 Beam Source Form Fill-In

The Beam Source icon 

is always the first icon on the left in the SBI Window, bottom of the screen. Click the Beam Source icon to bring up the Beam Source Form Fill-In — Parameters page.

Beam Source – Form Fill-In — General Beam Information

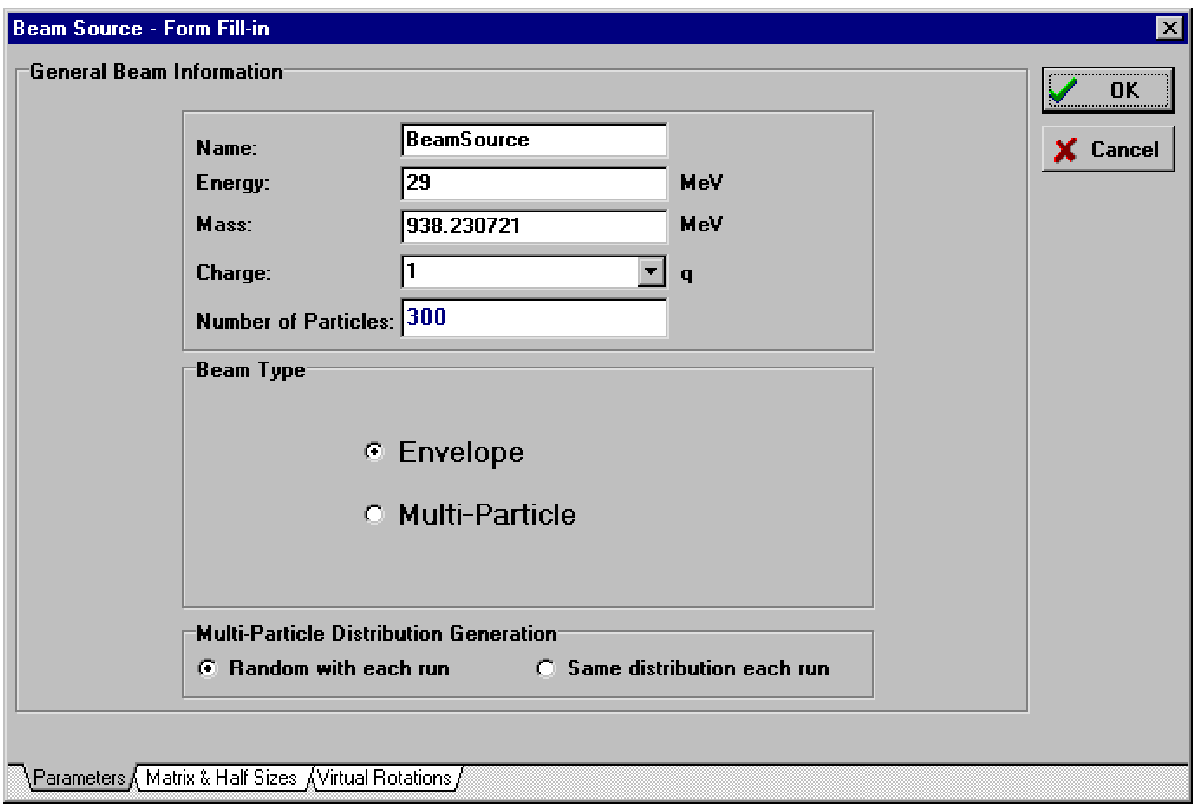


Figure 5-1, General Beam Information — Parameters

The Parameters page groups information in three ways. Here you enter 'General Beam Information', 'Beam Type' and 'Multi-Particle Distribution Generation'.

Under 'General Beam Information' you enter your choice of beam name, the beam kinetic energy value, particle mass, charge and number of particles. For a multi-particle run you may enter from 1 to 10,000 particles.

Under 'Beam Type', select either 'Envelope' or 'Multi-particle' mode. An envelope run shows the extents of the beam only, whereas a multi-particle run will show the beam as a particle distribution.

Under 'Multi-Particle Distribution Generation' select either random particle generation with each run, or the same distribution for each run. Choosing the same distribution will give you consistency from one run to the next and will speed up the run time a bit.

Beam Source Form Fill-In — Matrix & Half Sizes

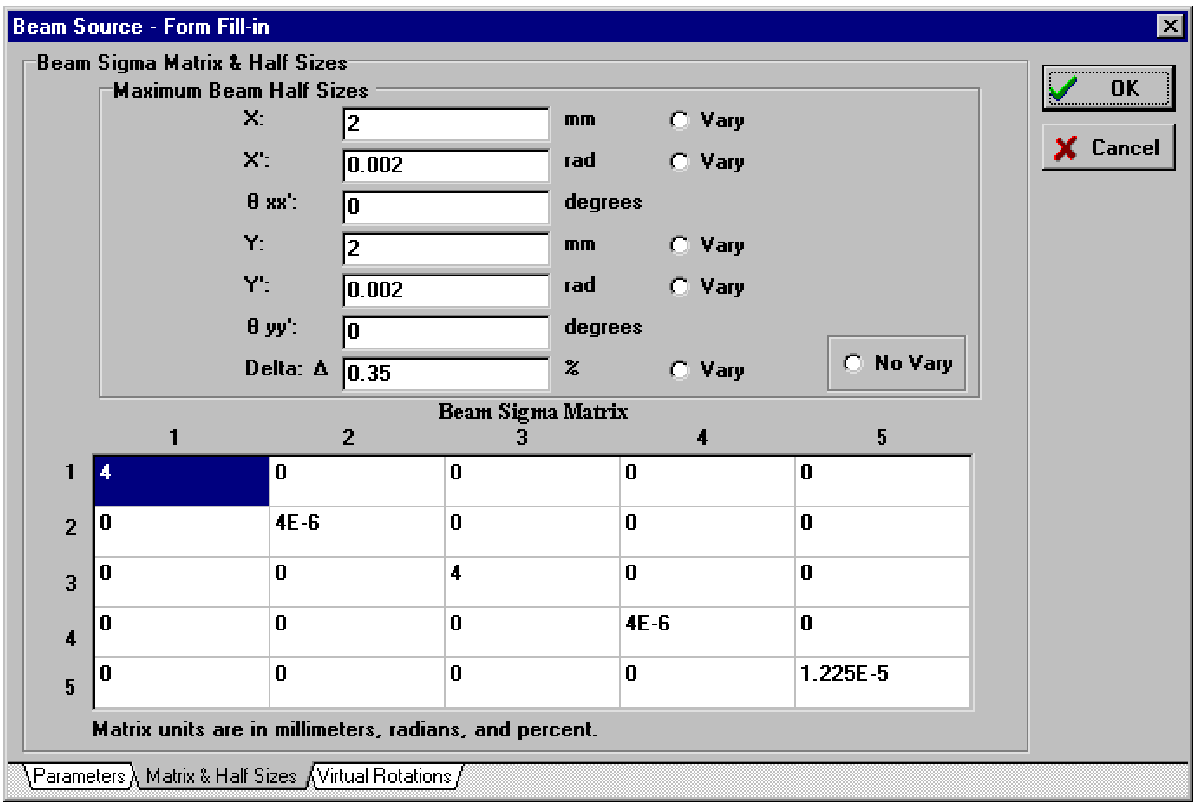


Figure 5-2, Beam Source Form Fill-In — Matrix & Half Sizes

X is the horizontal half-width of the beam in millimeters.
X' is the horizontal half-divergence of the beam in radians
θ xx' is the tilt angle of the horizontal phase space ellipse in degrees.
Y is the vertical half-width of the beam in millimeters.
Y' is the vertical half-divergence of the beam in radians.
θ yy' is the tilt angle of the vertical phase space ellipse in degrees.
Δ is the momentum spread of the beam in percent.

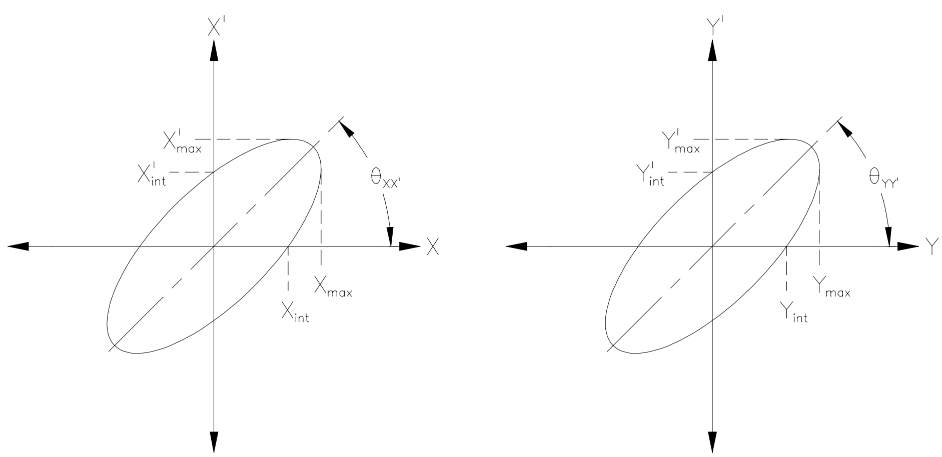
Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied at a time. *No vary* is the default.

The bottom of the form fill-in contains the *Beam Sigma Matrix* entries. These entries contain the co-efficients of the beam ellipse equations.

Usually the manufacturer of the actual beam source (whether an ion source, a cyclotron, a linear accelerator, a synchrotron or any other type of beam source) will have beam source data that can be used to specify the initial beam half-size values.

Note: to make improvements to your system you may wish to experiment with the beam half-sizes or the beam sigma matrix entries. Enter different values and compare the simulated beam plots and beam spill information with measured data from the actual system.

There are several approaches to entering data into the Matrix & Half-Sizes Dialog box. Refer to Figure 5-3.



For an **untilted** beam phase ellipse (i.e., $\theta_{xx'} = 0$ and $\theta_{yy'} = 0$) the beam emittances are: $\varepsilon_{xx'} = X_{max} \cdot X'_{max}$ $\varepsilon_{yy'} = Y_{max} \cdot Y'_{max}$.

In a more general case, if the beam phase ellipses are **tilted** such that $\theta_{xx'} \neq 0$ and $\theta_{yy'} \neq 0$, then the beam emittances are $\varepsilon_{xx'} = X_{max} \cdot X'_{int} = X_{int} \cdot X'_{max}$ and $\varepsilon_{yy'} = Y_{max} \cdot Y'_{int} = Y_{int} \cdot Y'_{max}$. The equations of the phase ellipses are:

$$\varepsilon^2_{xx'} = \sigma_{22}\, x^2 - 2\sigma_{21}\, xx' + \sigma_{11}\, x'^2 \qquad \varepsilon^2_{yy'} = \sigma_{44}\, y^2 - 2\sigma_{34}\, yy' + \sigma_{33}\, y'^2 .$$

To **completely specify the ellipses** in the form fill-in, you will need to describe: X_{max} , X'_{max} , $\theta_{xx'}$, Y_{max} , Y'_{max} , $\theta_{yy'}$, and $\Delta = \frac{dp}{p} \times 100\ \% =$ momentum spread ,

where: $p = T\sqrt{1 + \frac{2M}{T}}$, T = particle kinetic energy in MeV, and

M = particle Mass in MeV.

Note that if **xx' and yy' phase planes are uncoupled** then:

$$\theta_{xx'} = \frac{1}{2}\tan^{-1}\frac{2\,\sigma_{12}}{\sigma_{22} - \sigma_{11}} \qquad \theta_{yy'} = \frac{1}{2}\tan^{-1}\frac{2\,\sigma_{34}}{\sigma_{44} - \sigma_{33}}$$

These tilt angles cannot be entered directly into the Beam Source Form Fill-In, Maximum Beam Half-Sizes section. The σ_{12} and σ_{34} entries must be filled in and then $\theta_{xx'}$ and $\theta_{yy'}$ are automatically computed and displayed as slave outputs.

Another approach is to **edit the beam sigma matrix** directly by placing values into the matrix. In this case:

$$\sigma_{11} = (X\ max)^2$$

$$\sigma_{22} = (X'\ max)^2$$

$$\sigma_{12} = \sigma_{21} = [\sigma_{22}\ (\sigma_{11} - (X_{int})^2)]^{1/2} = [\sigma_{11}\ (\sigma_{22} - (X'_{int})^2)]^{1/2}$$

$$\sigma_{33} = (Y\ max)^2$$

$$\sigma_{44} = (Y'\ max)^2$$

$$\sigma_{34} = \sigma_{43} = [\sigma_{44}\ (\sigma_{33} - (Y_{int})^2)]^{1/2} = [\sigma_{33}\ (\sigma_{44} - (Y'_{int})^2)]^{1/2}$$

$$\sigma_{55} = (\Delta)^2$$

All other beam sigma matrix elements are zero if the beam phase ellipses are uncoupled or independent of each other which is usually the case.

Beam Source Form Fill-In — Virtual Rotations

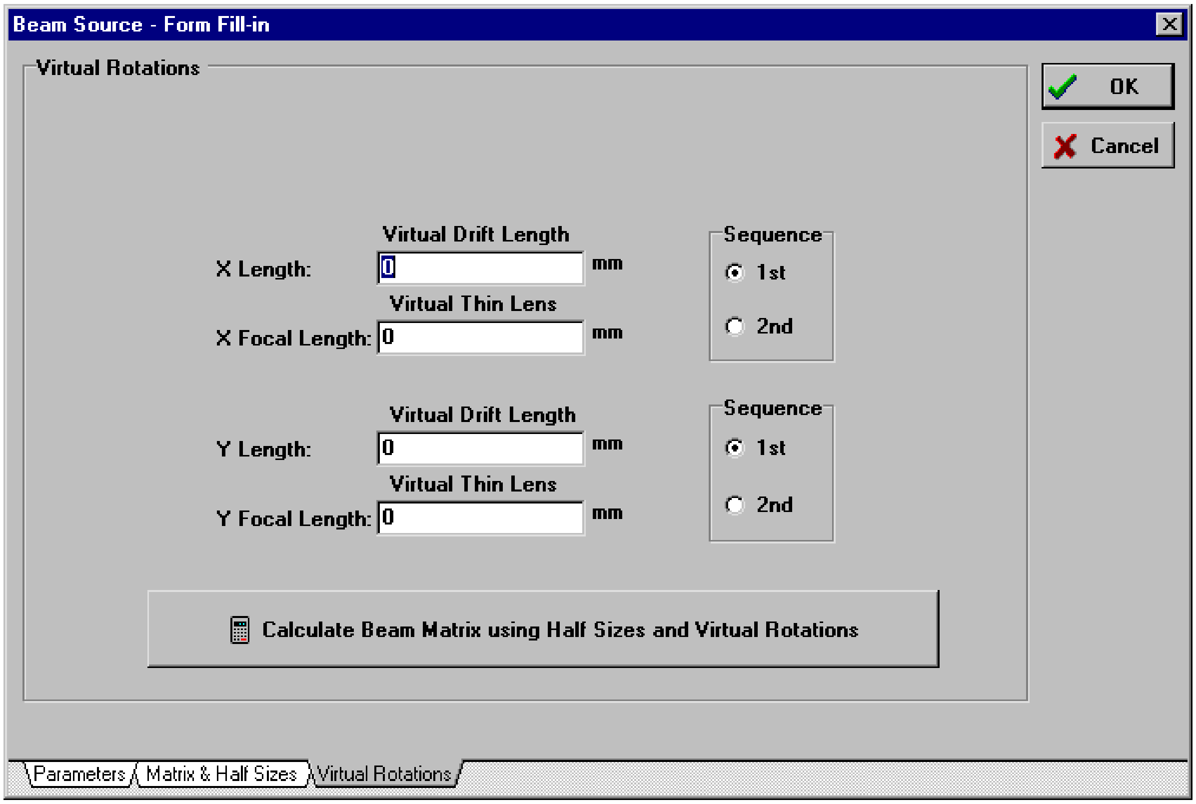


Figure 5-3, Beam Source Form Fill-In — Virtual Rotations

Under 'Virtual Rotations' you may specify values that adjust (X, X') or (Y,Y') phase space orientation of the input beam ellipses. These adjustments may improve the input model. The adjustments are defined below.

X Length (Virtual Drift Length): a virtual drift of X Length mm is applied to only the (X, X') phase space of the beam prior to entry to the beamline.

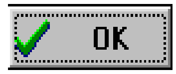
X Focal Length (Virtual Thin Lens): a virtual focus of X Focal Length mm is applied to only the (X, X') phase space of the beam prior to entry to the beamline.

Y Length (Virtual Drift Length): a virtual drift of Y Length mm is applied to only the (Y, Y') phase space of the beam prior to entry to the beamline.

Y Focal Length (Virtual Thin Lens): a virtual focus of Y Focal Length mm is applied to only the (Y, Y') phase space of the beam prior to entry to the beamline.

Note: if you want an input beam that is an upright ellipse in both (X, X') and (Y, Y') phase spaces, enter zeros in all four Input Beam Adjustment edit boxes.

In the 'Sequence' boxes you are allowed to choose which virtual calculation is done first and which is done second. This allows you to experiment a bit. Click the radio buttons in the order that you want. The button will show a tag with the ranking.

When you have completed the form click 

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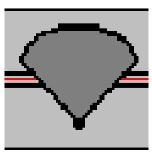
6.0 The Ion-Optical Elements

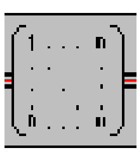
Within the SBI Window (Command and Tool Reference pages 106 to 111 you may choose any number of the following elements and arrange them in any order you wish. In this chapter you'll find instructions to help you add, rearrange and delete elements. You'll also find instructions for specifying element parameters and for applying constraints to variable parameters.

6.1 Ion-Optical Elements

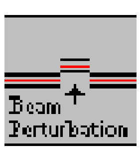


The DIPOLE element represents a dipole magnet.

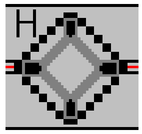
The DRIFT LENGTH element represents regions in the beam line where the beam drifts through regions of zero applied fields.



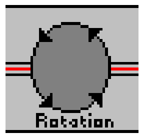
The NON-STANDARD element can be used to represent non-standard steering or focusing components in a beamline.



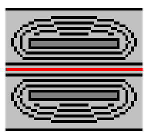
The PERTURBATION element can be used to represent translational or angular displacements of the beam. These displacements may be inherent in the source beam or introduced by a steering magnet for example.



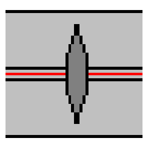
The QUADRUPOLE element represents a quadrupole magnet.



The ROTATION element represents systems where the elements are rotated about the Z axis.



The SOLENOID element represents a solenoid magnet.



The THIN LENS element represents an ideal focusing element.

6.2 Managing Icons (Element or Other)

Making an Icon Current

The current or selected icon in the SBI Window has the *red bars above and below* it. When cutting and pasting icons and when using the Vary Parameter Window, it is important to be aware of which icon is current. The Vary Parameter Window adjusts parameters for the current icon only.

To make an icon current:

1. Place the cursor over the icon and click.

Inserting Icons

To insert a new icon:

1. Place the cursor in the gray area of the SBI Window.

2. <u>Right</u> click the mouse to view the pop-up menu.
3. Click the ELEMENT NAME of your choice.
4. Move the cursor to the desired location in the SBI Window and click to insert.

Cutting and Pasting Icons

To cut and paste an existing icon:

1. In the SBI Window, click the icon you wish to move.
2. Place the cursor in the gray area of the SBI Window.
3. <u>Right</u> click the mouse to view the pop-up menu.
4. Click **CUT**.
5. Again, <u>right</u> click the mouse to view the pop-up menu.
6. Click **PASTE**. The element is always inserted after the current icon.

Note: any icon that you handle (e.g., insert, cut and paste, drag and drop or left click) becomes the current icon.

Rearranging Icons by Drag and Drop

To drag and drop an icon:

1. Click the icon and continue to hold the mouse button down.
2. Drag the cursor across the SBI Window and watch the purple bars move with you. When you reach the new location release the mouse button. The icon will drop into place.

3 Ways to Delete an Icon

To delete an icon:

1. Click the icon to make it the current icon.
2. Press the <u>**Del**</u> key. The garbage can (upper left corner of the SBI Window) will become animated to show that the icon has been deleted.

OR

1. Click the icon and continue to hold the mouse button down.
2. Drag the cursor to the garbage can and release the mouse button. The garbage can will become animated to show that the icon has been delete.

OR

3. Click the icon to make it the current icon.
4. Right click the mouse to view the pop-up menu.
5. Click DELETE ELEMENT.

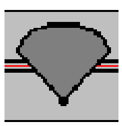
6.3 Specifying Parameters for Elements

To define or change a parameter for any element in the SBI Window:

1. Double click the element icon to view the Form Fill-In pages.
2. Click inside the parameter box or on a radio button.
3. Type in the new parameter.
4. Click OK.

Using the Form Fill-In pages you can easily define each element in a different way — no matter how many elements there are.

Dipole Form Fill-In



A dipole magnet is normally used to cause a charged particle beam to be transported along a curved trajectory. Five common uses for a dipole magnet are to:

- enable the transport system to avoid physical obstacles
- maintain particles on a closed or spiral orbit
- permit momentum selection and
- select different beamlines for transport
- correct misaligned beams by steering them

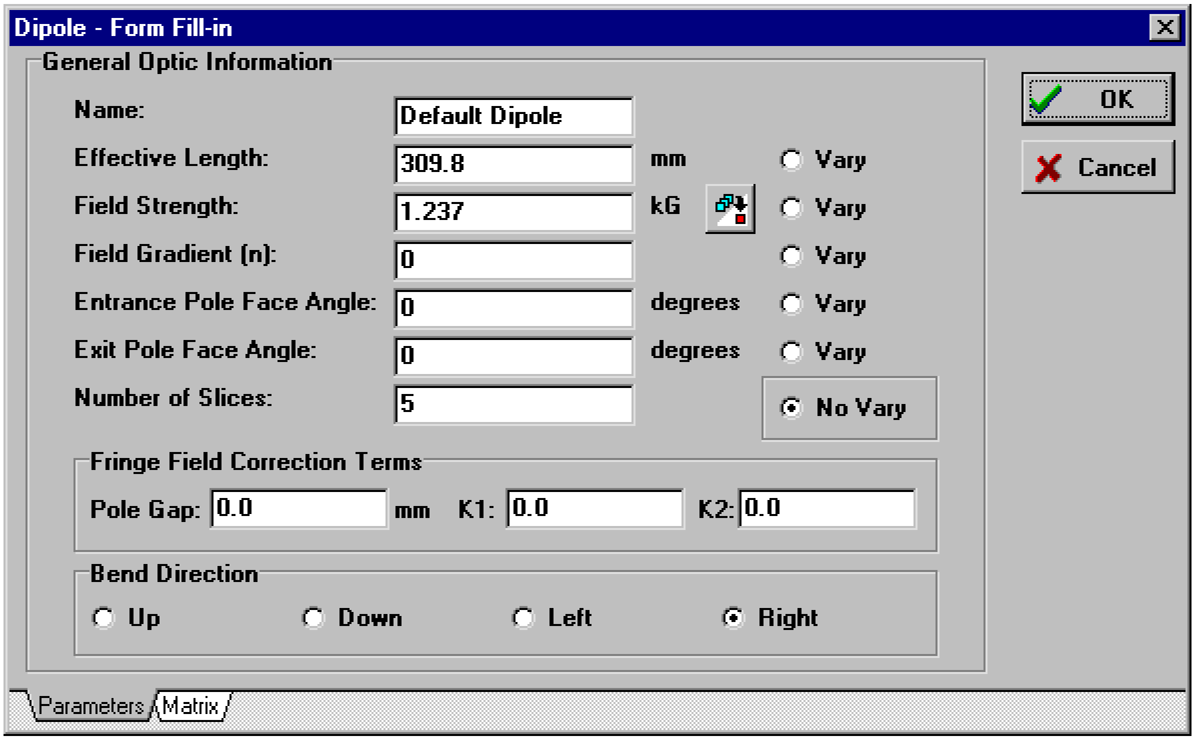


Figure 6-1, Dipole Form Fill-In — Parameters Page

Name is the default name but you may rename it as you wish. You may want to number the dipole magnets sequentially, e.g., Dipole 1, Dipole 2, Dipole 3, etc.

Effective Length is the effective optical length of the dipole magnet in millimeters. The effective length of a dipole magnet is typically longer than the physical length of the magnet because the magnetic field bulges outward at the entrance and exit of the magnet. *A useful rule of thumb is that the effective length equals the length of the iron poles plus the gap width between the poles.* For more information see Appendix E, Ion-Optics Technical Notes.

Field Strength is the magnetic field strength in kilo Gauss.

 Clicking the speed button brings up the Dipole Primary Input Parameter Dialog box. Refer to Figure 6–2, page 48.

Field Gradient (n) is dimensionless and is defined by the equation:

$$n = \frac{-dB/B}{d\varrho/\varrho}$$

where B is the magnetic flux density and ϱ is the radius of curvature.

Entrance Pole Face Angle is the angle in degrees that the beam central trajectory makes with a line drawn perpendicular to the pole face at the point where the beam enters the magnet.

Exit Pole Face Angle is the angle in degrees that the beam central trajectory makes with a line drawn perpendicular to the pole face at the point where the beam exits the magnet. A positive sign of the angle on either entrance or exit pole faces corresponds to a non-bend plane focusing action and a bend plane defocusing action.

Number of Slices is an input used by the graphics routines. The number entered into the edit box is the number of points along the beam's trajectory (through the element) at which calculations will be made and data plotted.

Choosing a larger number will cause more data points to be calculated and plotted. The resulting plot will be more detailed. Choosing a smaller number will speed up calculations but reduce the resolution of the plots.

Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied per element. *No Vary* is the default.

Fringe Field Correction Terms correct for the fact that the field fall-off outside of the magnet is gradual rather than a step function. The default values for the terms are zeros.

The first order transport matrix for a pole face rotation θ is:

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \frac{\tan\theta}{\varrho} & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{-\tan(\theta-\alpha)}{\varrho} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where the correction term $\alpha = \left(K1 \cdot \frac{g}{\varrho} \cdot \frac{(1+\sin^2\theta)}{\cos\theta}\right) \cdot \left(1 - K1 \cdot K2 \cdot \frac{g}{\varrho} \cdot \tan\theta\right)$.

If no data exists for your magnet then values of K1 = ½ and K2 = 0 should be reasonable.

Other **common values** are:

Dipole Type	*K1*	*K2*
Linear	.16667	3.8
Clamped Rogowski	.4	4.4
Unclamped Rogowski	.7	4.4
Square Edged	.45	2.8

IMPORTANT NOTE: if you are using K2 then your results should be checked by a rigorous ray-trace program.

Bend Direction is the direction in which the beam is bent by the dipole magnet — as viewed when looking in the direction of beam travel.

The Matrix page (not shown) displays the element transport matrix for a single slice. If the number 1 is entered into the "*Number of Slices*" edit box, the matrix will represent a single element. (i.e., one slice represents the whole element). If 'n' is entered, n being any number of slices, then the matrix will represent $^1/n$ of the element.

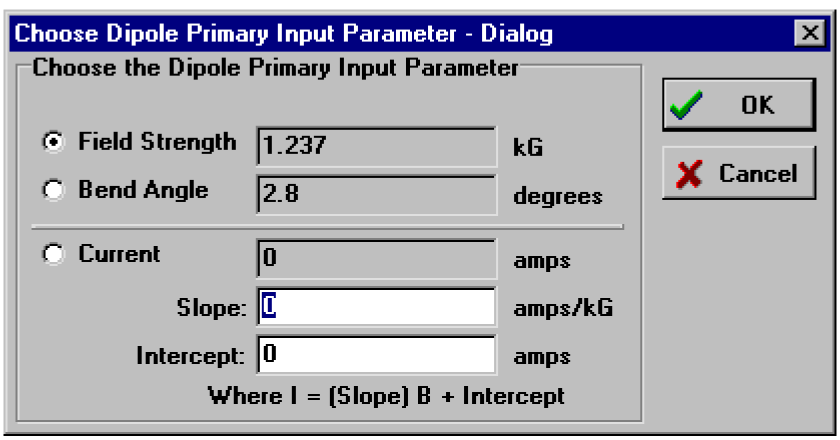


Figure 6-2, Dipole Primary Input

Field Strength is the default and shows in this screen for convenience.

Bend Angle may be known when field strength is not known. For this reason you have the option of entering the bend angle.

The relationship between the *Field Strength* and *Current* is given by the equation in the dialog box, where 'B' is the magnetic field strength and 'I' is the power supply output current.

If you know the linear relationship between the power supply output current and the field strength, and you enter the *Slope* and *Intercept* values, you may choose *current* as the primary data input for the dipole magnet.

Drift Length Form Fill-In

A drift length or drift space is any region in a beam transport system where no magnetic or electric fields are present. For example, the spaces between magnets are usually drift spaces.

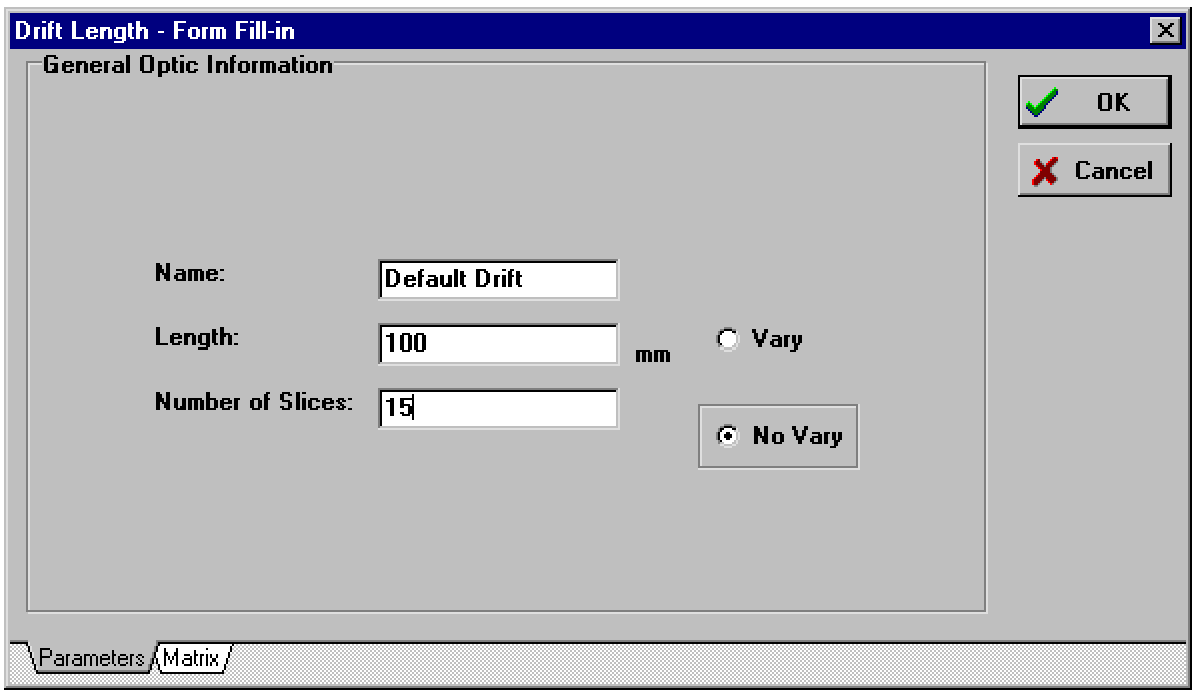


Figure 6-3, Drift Length Form Fill-In

Name is the default name but you may rename it as you wish.

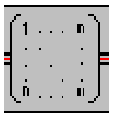
Length defines the total field free distance in millimeters.

Number of Slices is an input used by the graphics routines. The number entered into the edit box is the number of points along the beam's trajectory (through the element) at which calculations will be made and data plotted.

Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied per element. *No Vary* is the default.

The Matrix page (not shown) displays the element transport matrix for a single slice. If the number 1 is entered into the "*Number of Slices*" edit box, the matrix will represent a single element. (i.e., one slice represents the whole element). If 'n' is entered, n being any number of slices, then the matrix will represent $^1/n$ of the element.

Non-Standard Form Fill-In



A non-standard element is typically an optical component whose transport matrix must be numerically determined by specialized programs. For example, the fringe field of a cyclotron may be included as a non-standard element. This element will only be used by experts.

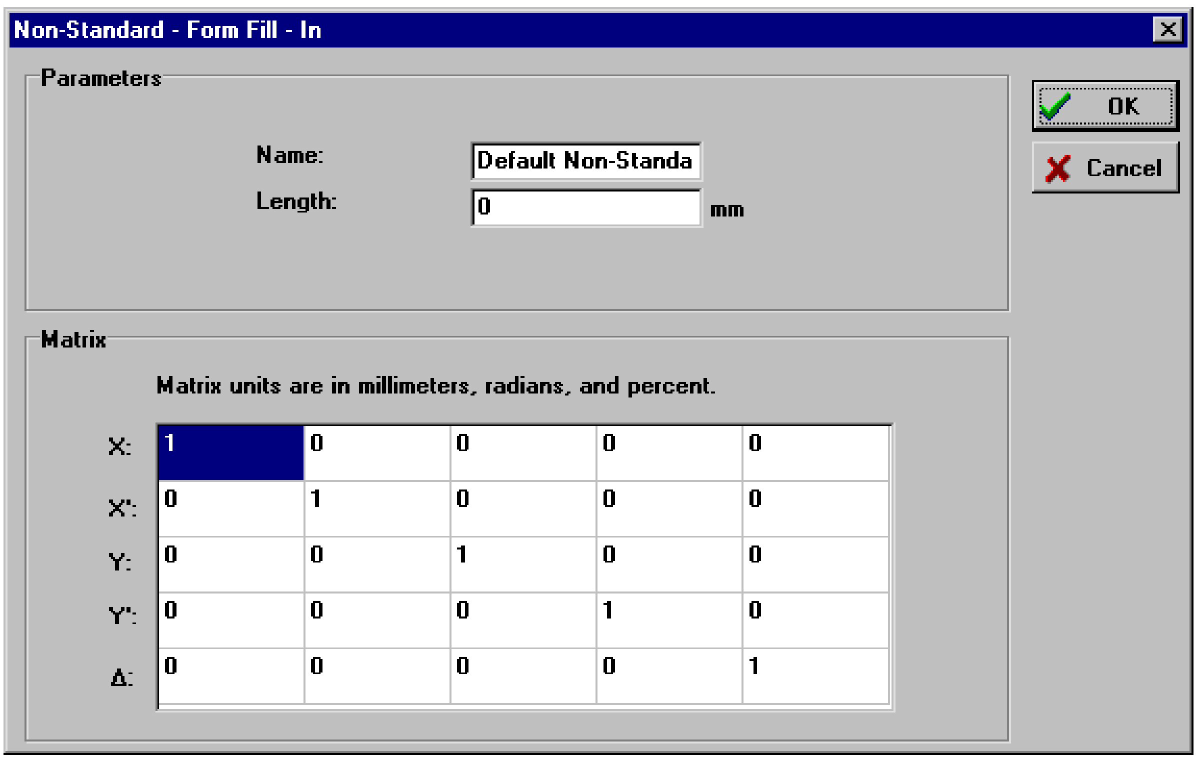


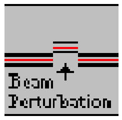
Figure 6-4, Non-Standard Form Fill-In — Parameter & Matrix Information

Name is the default name but you may rename it as you wish.

Length is the length of the element in millimeters. The length value is used to adjust the graphics plots to the correct scale.

Matrix values are known values that come from programs that track charged particle trajectories through three-dimensional electromagnetic field maps.

Perturbation Form Fill-In



The perturbation capability allows the user to represent a beam whose central trajectory is off-centered by X mm horizontally and/or Y mm vertically. In addition, a beam whose central trajectory is diverging (mis-steered) by an angle in the horizontal plane of X' radians, and/or in the vertical plane of Y' radians can be represented.

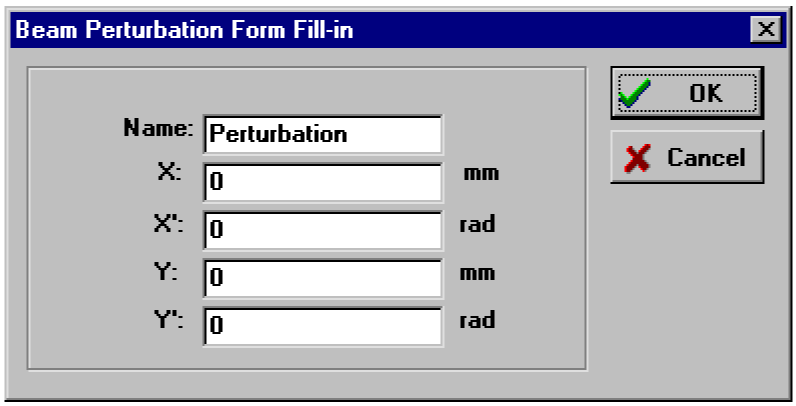
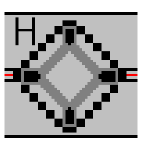


Figure 6-5, Beam Perturbation Form Fill-In

Name is the default name but you may rename it as you wish.

X, X', Y, Y' parameter values will offset the beam central trajectory by the amounts specified in the Beam Perturbation Form Fill-In. The offset occurs at the Z co-ordinate where the Perturbation icon is located in the SBI Window.

Quadrupole Form Fill-In



A quadrupole magnet is used for focusing a charged particle beam. However, unlike a lens used in the optics of light, a quadrupole magnet focuses in one plane while defocusing in the perpendicular plane. For example, a 'horizontal' quadrupole magnet focuses in the horizontal plane but defocuses in the vertical plane.

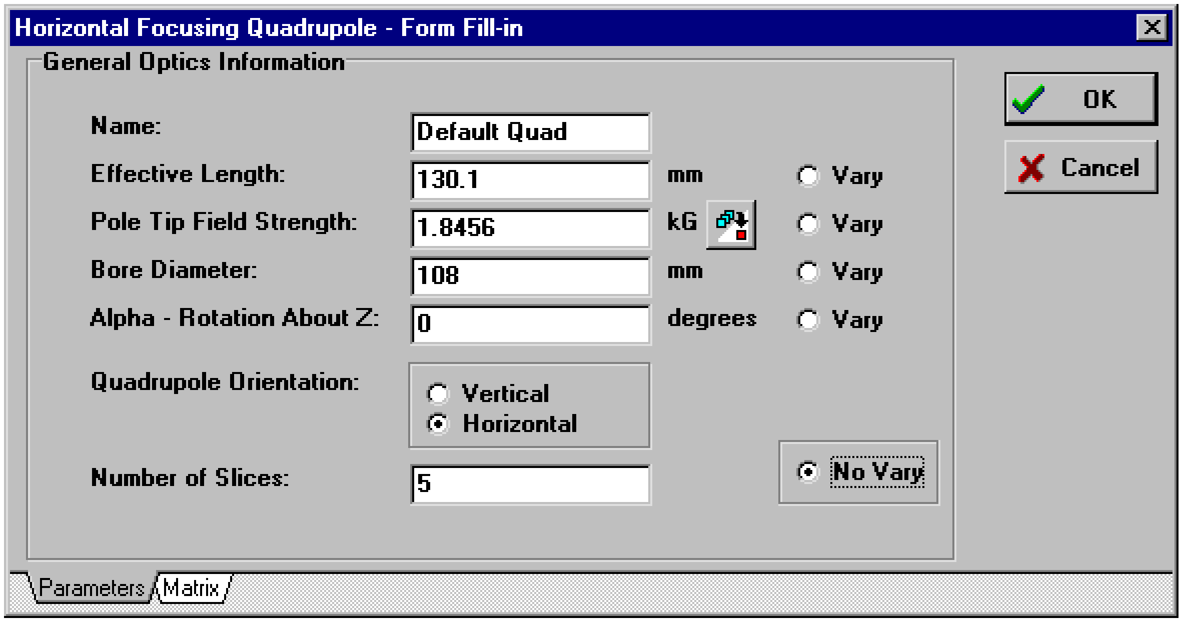
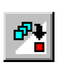


Figure 6-6, Quadrupole Form Fill-In — Parameters Page

Name is the default name but you may rename it as you wish.

Effective Length is the effective optical length of the quadrupole magnet in millimeters. The effective length of a quadrupole magnet is usually estimated as the length of the pole plus the bore diameter between the poles. Consequently, the effective length is usually a bit longer than the physical length of the magnet, since it accounts for the field that bulges outside the magnet on either end.

Pole Tip Field Strength is the magnetic field strength in kilo Gauss.

 Clicking the speed button brings up the Quadrupole Primary Input Parameter Dialog box. Refer to Figure 6–7, page 53.

Bore Diameter is the aperture size of the quadrupole magnet in millimeters.

Note: the term aperture has two different uses in this document. Usually it refers to the aperture size of the physical beam pipe or diagnostic collimators, but when talking about bore diameters it refers to the aperture size of the quadrupole magnet.

Alpha – Rotation About Z is the rotation angle of the quadrupole about the Z axis.

Quadrupole Orientation may be either vertical or horizontal. Vertical quadrupoles will focus in Y and defocus in X. Horizontal quadrupoles will focus in X, and defocus in Y.

Number of Slices is an input used by the graphics routines. The number entered into the edit box is the number of points along the beam's trajectory (through the element) at which calculations will be made and data plotted.

Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied per element. *No vary* is the default.

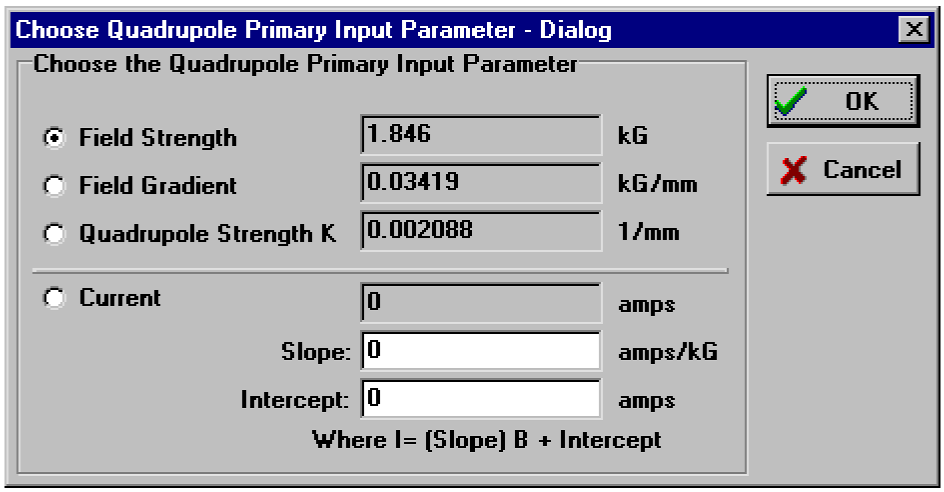


Figure 6-7, Quadrupole Form Fill-In — Primary Input

Field Strength radio button is the default.

Field Gradient is defined as $\left(\frac{\text{field}}{\text{bore radius}}\right)$

Quadrupole Strength K is defined as $\sqrt{\frac{\text{field gradient}}{\frac{\text{momentum}}{\text{charge}}}}$

The relationship between the *Field Strength* and *Current* is given by the equation in the dialog box, where 'B' is the magnetic field strength and 'I' is the power supply output current.

If you know the linear relationship between the power supply current and the field strength, and you enter the *Slope* and *Intercept* values, you may choose *current* as the primary data input for the quadrupole magnet.

Quadrupole Form Fill-In — Matrix Page

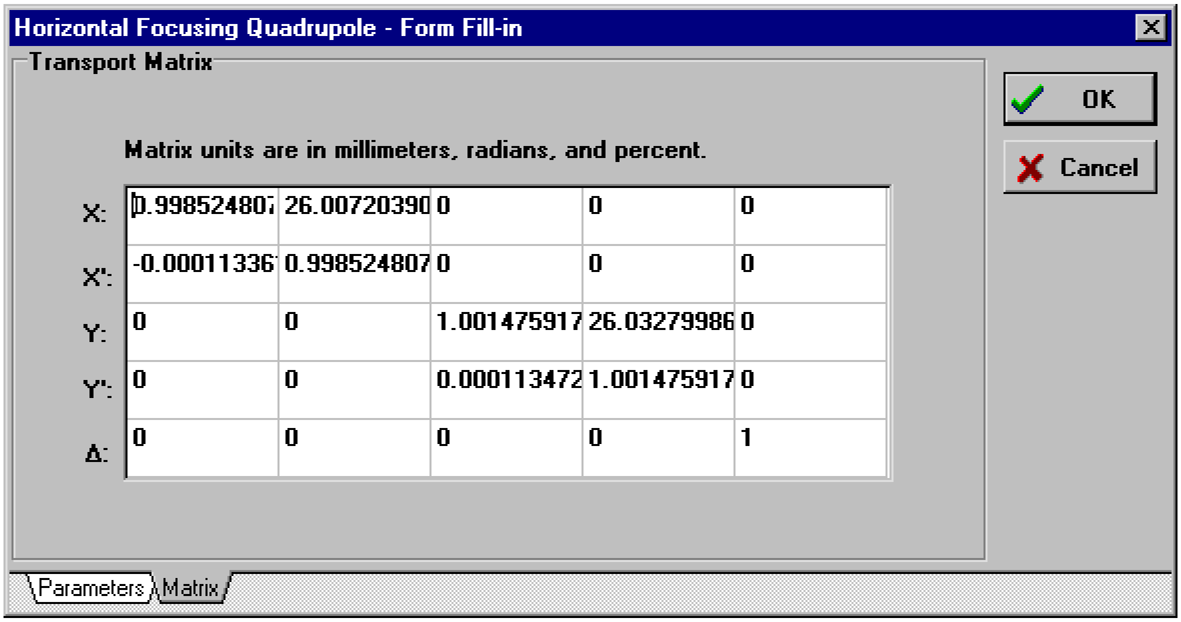
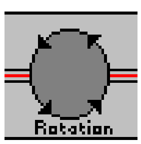


Figure 6-8, Quadrupole Form Fill-In — Matrix Page

Matrix displays the element transport matrix for a single slice. If the number 1 is entered 1 into the "*Number of Slices*" edit box (Quadrupole Parameters page), the matrix will represent a single element (i.e., one slice represents the whole element). If 'n' is entered, n being any number of slices, then the matrix will represent $^1/n$ of the element.

Rotation Form Fill-In



Standard optical elements such as quadrupole and dipole magnets are sometimes installed at angles rotated about the Z axis. One way to simulate transport through such a rotated element is to rotate the beam co-ordinates by the appropriate angle before entry into the element and then to rotate the beam co-ordinates by the negative angle after exiting the element. The sequence in the SBI Window would be: Rotation icon positive (+) angle; Standard Element icon; and Rotation icon negative (-) angle.

Note that the quadrupole magnet element can be rotated directly using Alpha – Rotation about Z.

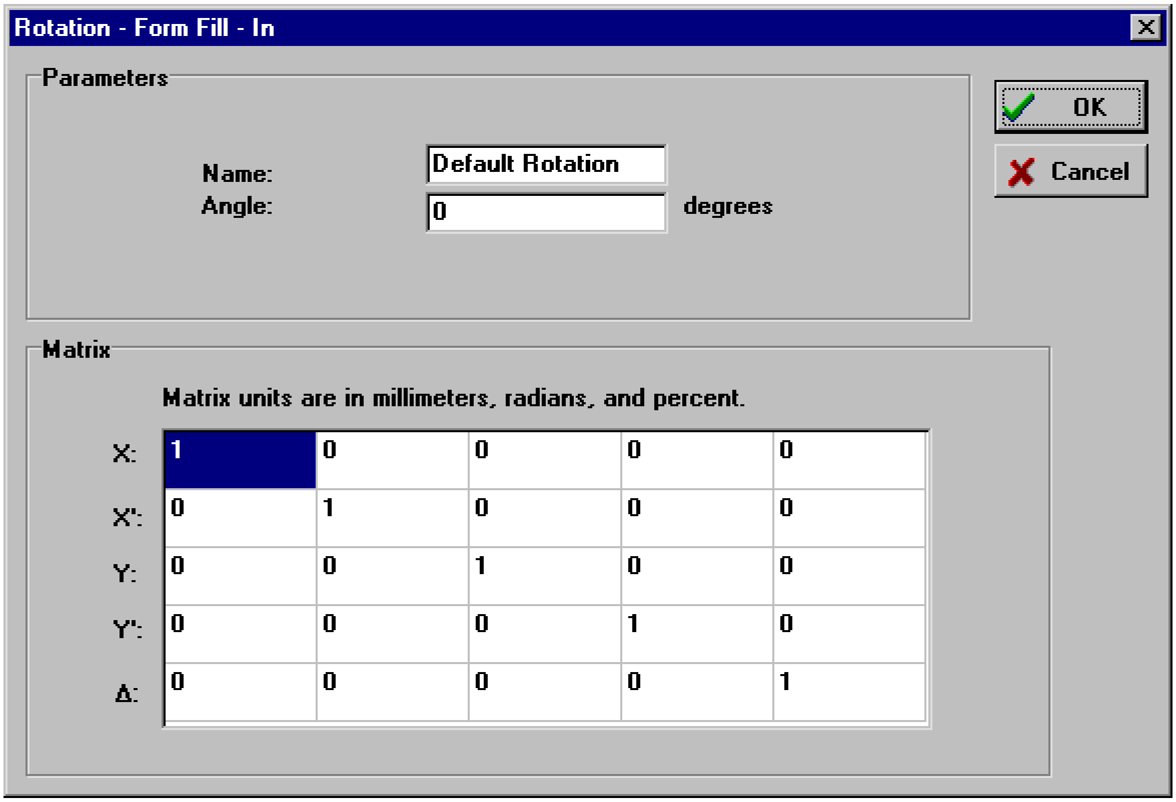


Figure 6-9, Rotation Element — Form Fill-In

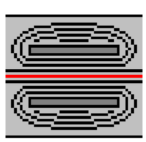
Name is the default name but you may rename it as you wish.

Angle is the amount of beam rotation about the Z axis in degrees.

Matrix displays the transfer matrix for the rotation icon.

Note that you are not able to edit the matrix table because it is defined by the Parameters box above.

Solenoid Form Fill-In



A SOLENOID magnet focuses in both planes at the same time and also causes the beam to rotate about the Z axis.

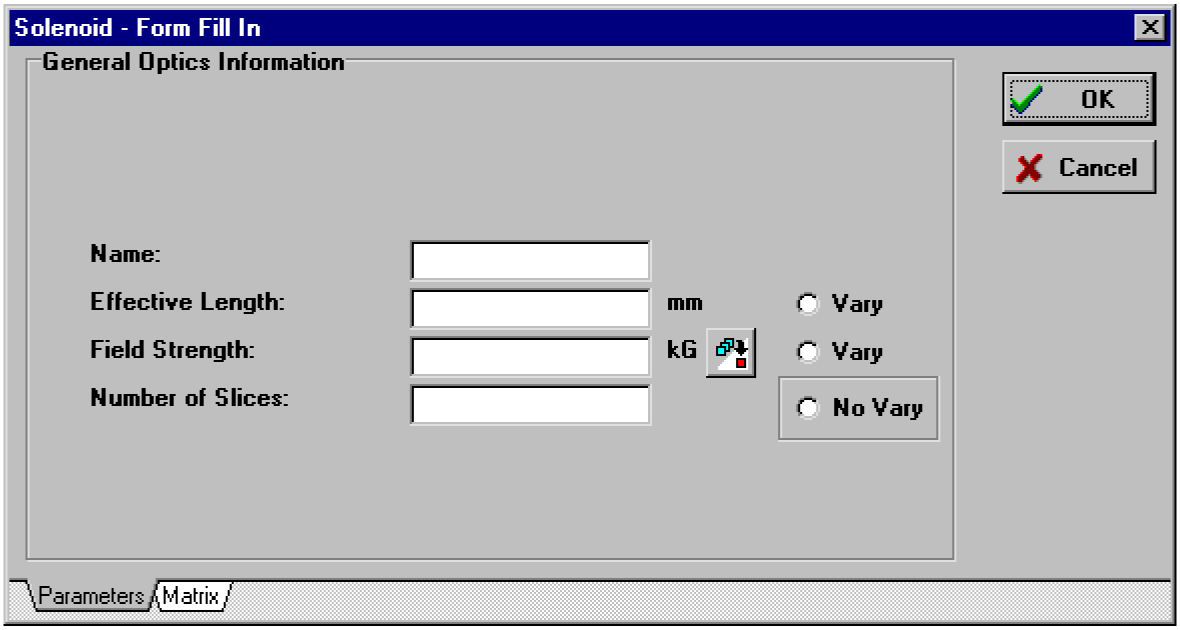
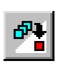


Figure 6-10, Solenoid Form Fill-In

Name is the default name but you may rename it as you wish.

Effective Length is the effective optical length of the solenoid element in millimeters. The effective length is usually estimated as the axial length of the coils plus the solenoid bore diameter to account for the field that bulges out at either end of the magnet.

Field Strength is the magnetic field strength in kilo Gauss.

 Clicking the speed button brings up the Solenoid Primary Input Parameter - Dialog box. Refer to Figure 6–11.

Number of Slices is an input used by the graphics routines. The number entered into the edit box is the number of points along the beam's trajectory (through the element) at which calculations will be made and data plotted.

Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied per element. *No Vary* is the default.

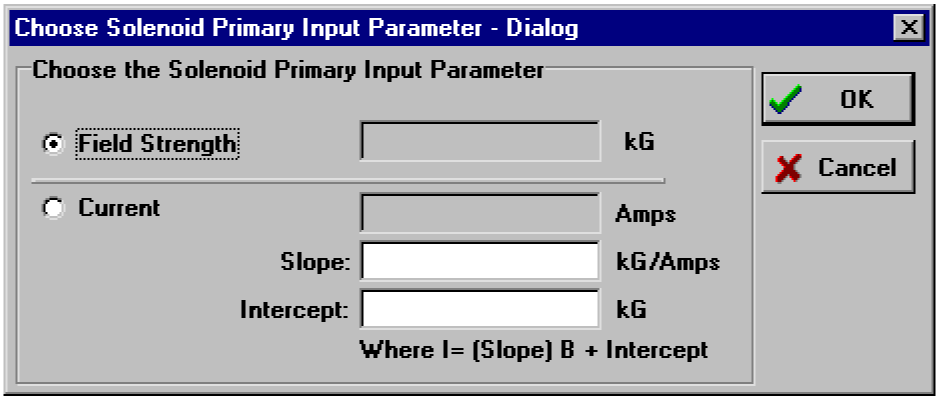
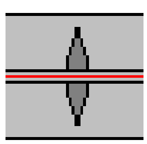


Figure 6-11, Solenoid Primary Input

The relationship between the *Field Strength* and *Current* is given by the equation in the dialog box, where 'B' is the magnetic field strength and 'I' is the power supply output current.

If you know the linear relationship between the power supply current and the field strength, and you enter the *Slope* and *Intercept* values, you may choose *current* as the primary data input for the solenoid magnet.

Thin Lens Form Fill-In



The THIN LENS element represents an ideal lens. This element adjusts the beam focus instantly and can be used as a correction within the system, or to mimic lenses that are not part of this software, e.g., electrostatic lenses.

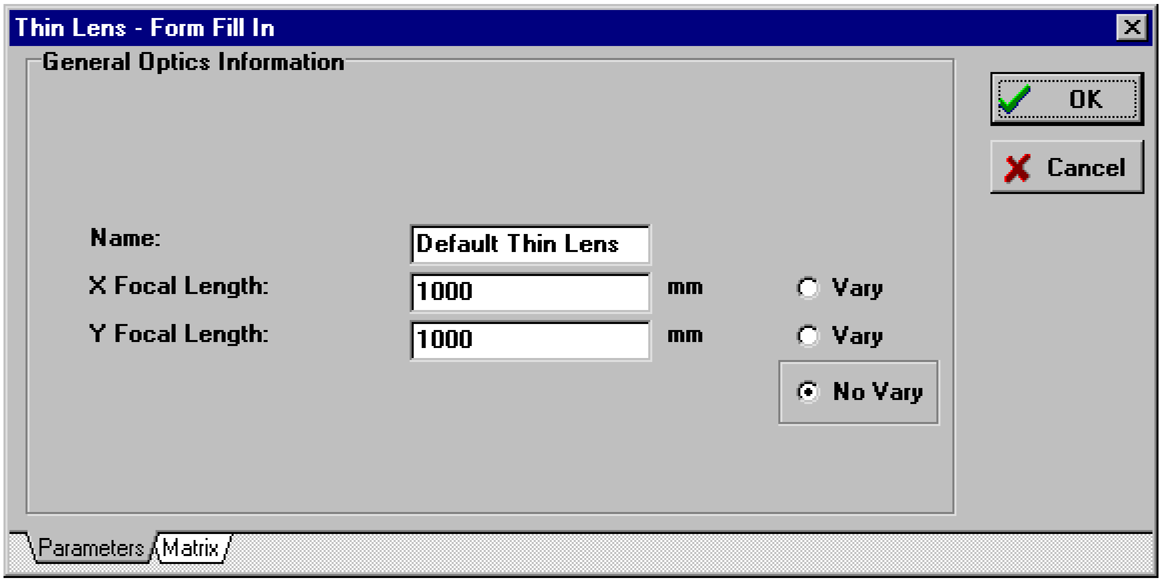


Figure 6-12, Thin Lens Form Fill-In

Name is the default name but you may rename it as you wish.

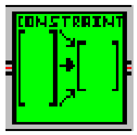
X Focal Length is the focal length in millimeters of the thin lens along the X axis. This value may be positive or negative.

Y Focal Length is the focal length in millimeters of the thin lens along the Y axis. This value may be positive or negative.

Vary is a radio button that indicates which parameter may be varied during the run. Only one parameter may be varied per element. *No Vary* is the default.

Note: the thin lens cannot be sliced.

6.4 Applying Constraints



The Constraint icon can be manipulated in the same way as the other icons in the SBI Window. See Section 6.2 Managing Icons.

To use the Constraint icon, place it at any point in the beamline (SBI Window) where you must meet a beam or transport matrix constraint. Typically the Constraint icon is left at the end of the beamline to enable the user to constrain the beam size to fit the target.

Constraints can be placed on the beam size or divergence, or on the cumulative transport matrix. The constraints are activated at the location of the Constraint icon along the Z axis in the SBI Window.

For example, the beam transport system specified in the SBI Window may not yield a beam of appropriate size at the target. By placing the Constraint icon at the target position and specifying the required beam size, the program will automatically adjust the 'vary' parameters from the various beamline elements to try to achieve conditions that will cause the beam to meet its constraints. Alternatively, the user may choose to try to manually tune a single element through the Vary Parameter Window.

To access the Constraint Form Fill-In dialog box, double click the Constraint icon to bring up the pages.

Constraint Form Fill-In — Variable Parameters

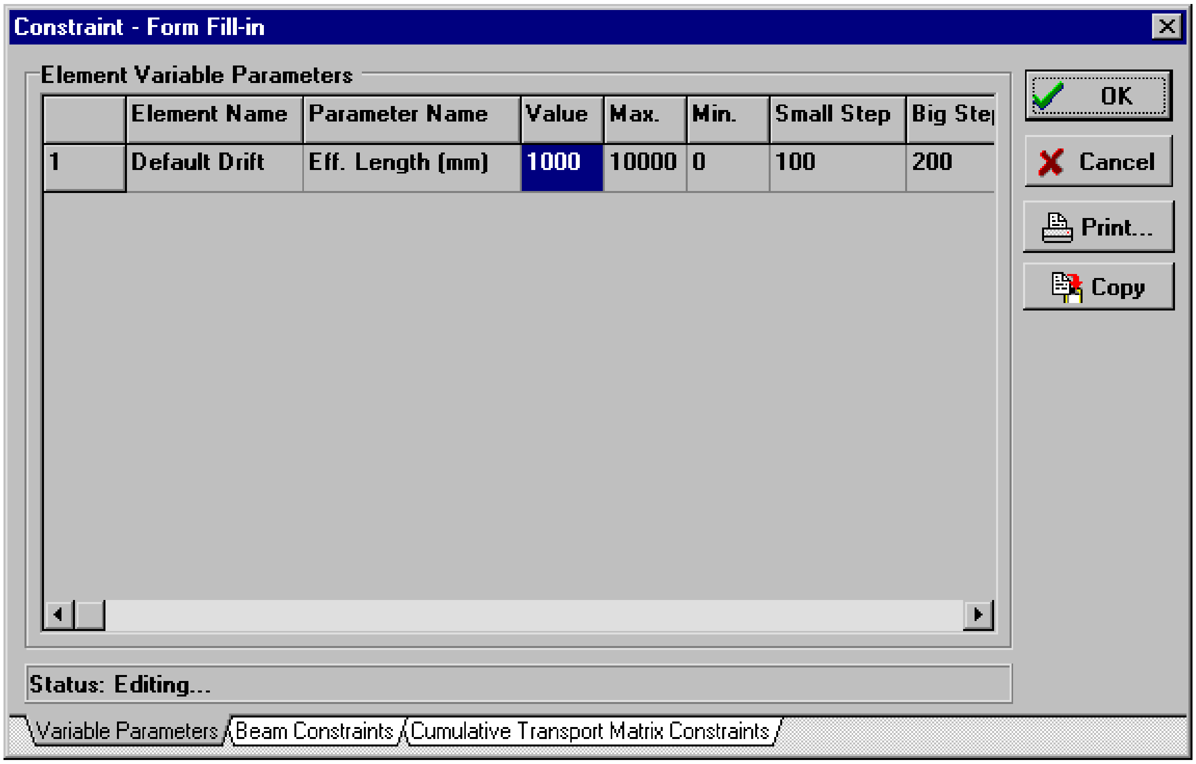


Figure 6-13, Constraint Form Fill-In — Variable Parameters

The Variable Parameter page gives a summary of beamline element parameters throughout the system that have been selected as 'vary' parameters. This page shows that only one 'vary' parameter called Effective Length has been selected for a Drift Length element. The Effective Length value is 1000 mm. The Maximum and Minimum values, 10000 mm and 0 mm respectively, are the range that the program uses when it automatically solves for user specified beam or transport matrix constraints.

The Small Step and Big Step Values are used when you manually tune the system through the Vary Parameter Window. They define how large a jump the program makes with each new try. You may choose to take big steps or small steps.

Note: To add or delete elements in this form you must exit the form and go back to the SBI Window. Double click the element icon you wish to change. This opens the element Form Fill-In dialog box where you may toggle the appropriate

Vary radio button on or off. To accept your changes click OK. To get back to the Contraint Form Fill-In page, double click the Constraint icon. The changes you made to the 'vary' parameters should be reflected in the Variable Parameters page.

To change the element Value and/or the Maximum, Minimum, Small Step, or Big Step values click on the appropriate grid box and enter the new number(s).

Remember that you must select ✔ **Solve for Constraints** under the **Run Options** menu, Base Application Window to use the automatic constraint solving algorithm. The program then searches the range between the maximum and minimum values in equidistant steps as defined by the number of iterations. At each iteration the program checks to see if the constraints have been met.

Constraint Form Fill-In — Beam Constraints

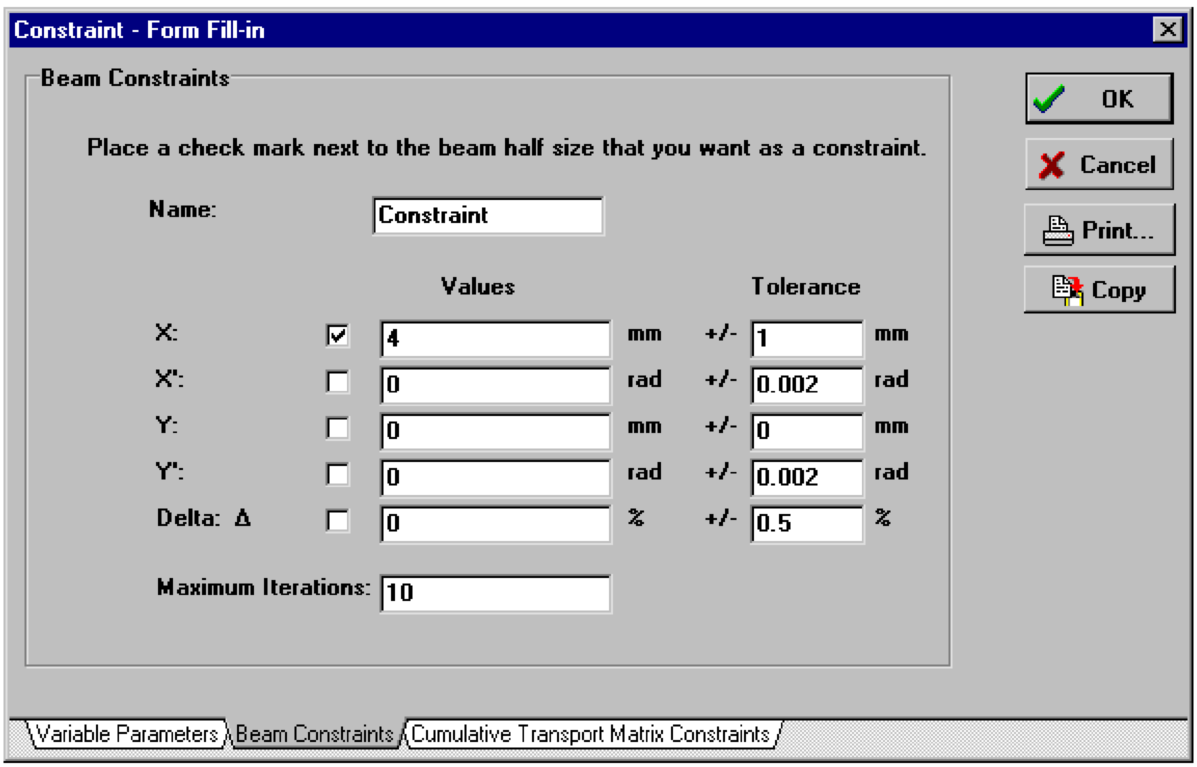


Figure 6-14, Constraint Form Fill-In — Beam Constraints.

Constraint Form Fill-In — Beam Constraints

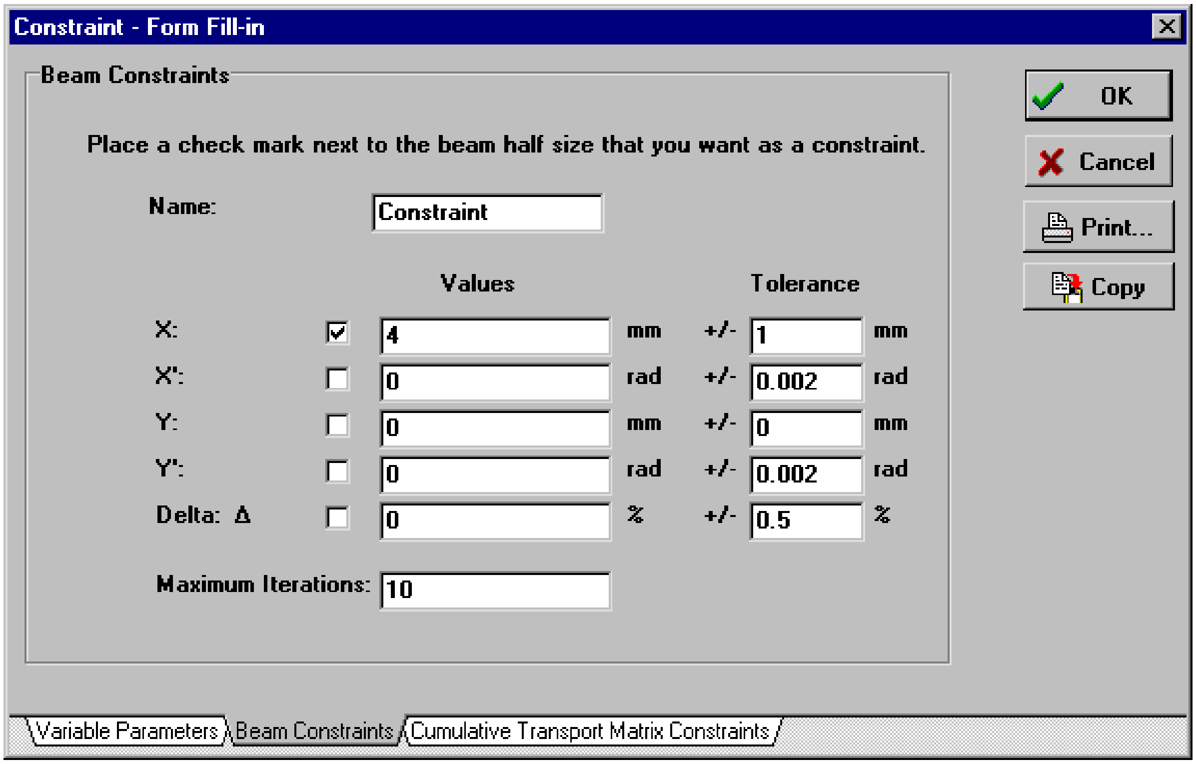


Figure 6-14, Constraint Form Fill-In — Beam Constraints.

If one of the beam half-size parameters contains a ☑ in the small box beside its edit box, then the run algorithm will attempt to meet that constraint, but only if

✓ **Solve for Constraints** under the **Run Options** menu has been selected. Otherwise the program will model the system based on the nominal data that resides in the SBI Window.

The **Tolerance +/-** edit box provides an acceptance or 'close enough' range for the beam half-size constraint. If the simulated half-size is within the +/- amounts, then the program declares that it has found a tune that solves the constraint.

Constraint Form Fill-In — Transport Matrix Constraints

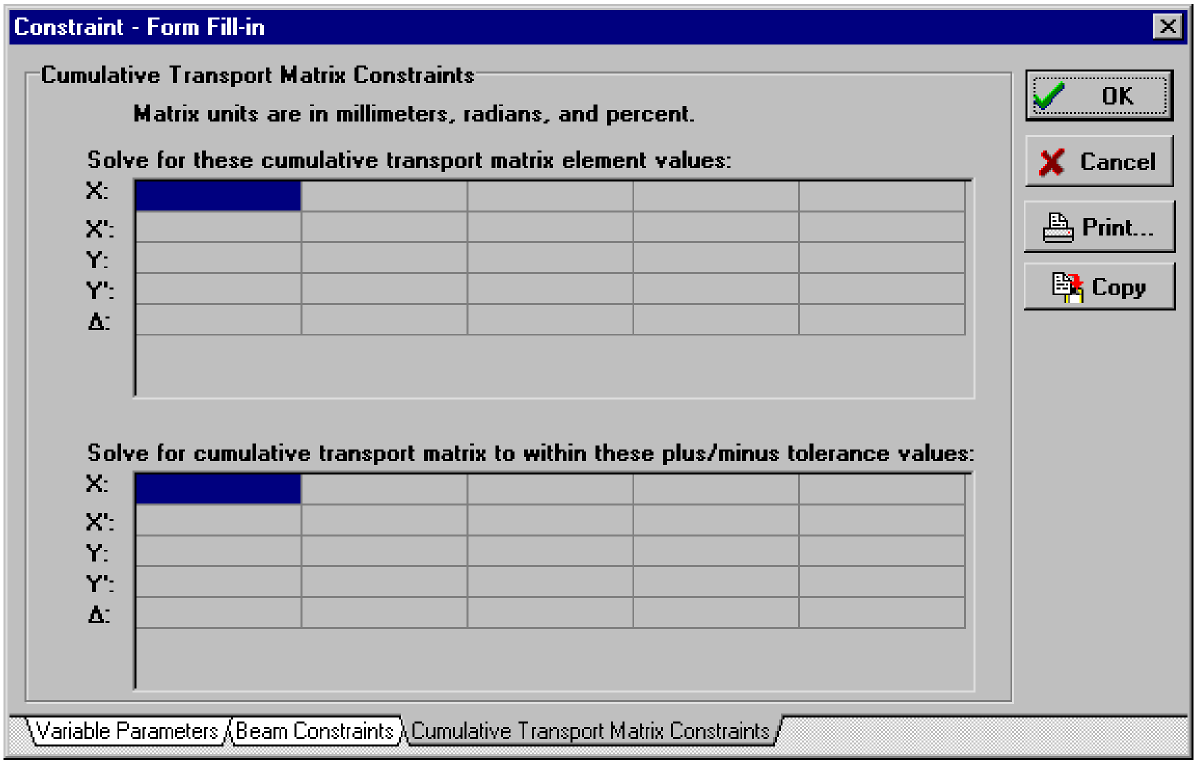


Figure 6-15, Constraint Form Fill-In — Transport Matrix Constraints.

Should you require a particular ion-optical condition in the system, you can specify constraints on the system transport matrix. This is primarily used by experts or system designers. The Transport Matrix Constraints will constrain the cumulative transport matrix at the location of the Constraint icon in the SBI Window.

If a value is entered into a cell in the top matrix, that cell will be one of the constraints to be solved for in the next run. If there is nothing in a cell, then that cell is ignored.

If you enter a value in a cell in the top matrix you must also enter a value in the corresponding cell in the bottom matrix. The bottom matrix defines the range of acceptance on the constraint so the program knows when it is 'close enough' to a solution.

7.0 Diagnostic Tools

Diagnostic information about your beamline will largely come from the graphics windows, the Collimator Text Window and the Beam Transport System (BTS) Window.

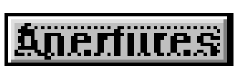
In addition to these windows, there are several diagnostic tools available within the SBI Window. They are:

- the Apertures button,
- a Cross-Section Plot icon,
- an End Run icon, and
- the System Metrics icon.

The Apertures button, the Cross-Section Plot icon, and the End Run icon define how the diagnostic output looks and/or where along the beamline the data comes from. The System Metrics icon is used to extract useful information from the system.

The icons are managed in the same way as those discussed in Chapter 6.2 Managing Icons. The Apertures button functions in its own unique way.

7.1 Apertures Button



The Apertures button is located in the bottom left corner of the SBI Window. When you click the Apertures button you bring up the Transport System – Aperture Form Fill-In.

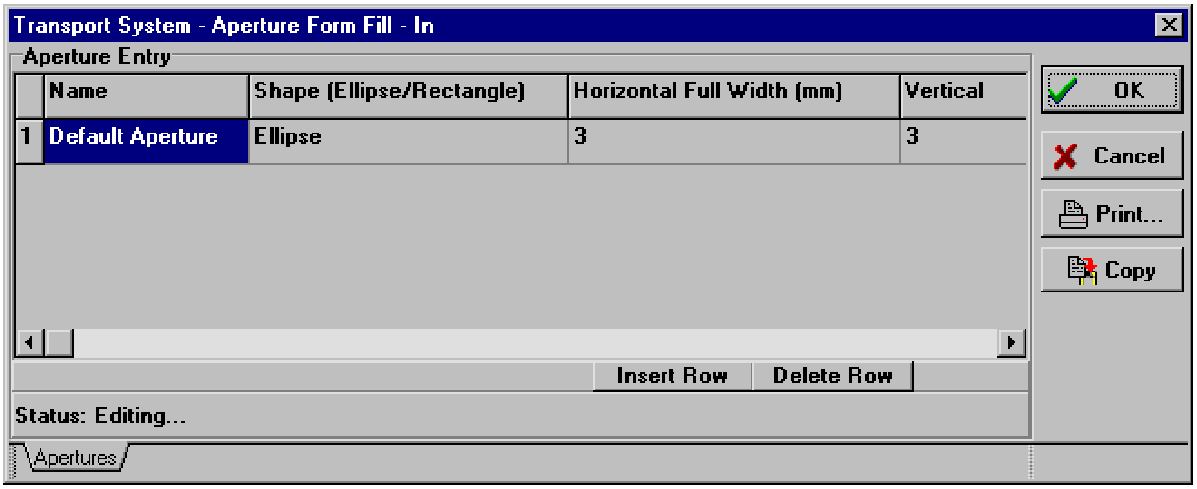


Figure 7-1, Transport System — Aperture Form Fill-In

This very important dialog box is used to describe the physical dimensions of the beam transport system beam pipe, collimators and vacuum boxes. All the apertures described here will be displayed in the graphics plots.

Note: To view hidden parts of the window, use the scroll bars to move the text to the right or left.

Rules for Entering Data

- Each row in the grid represents a single aperture.
- The sequence of apertures is read from top to bottom. This means that the beam passes through the top aperture first, then through the second aperture, and so on down the list.
- The current row is the row with the highlighted cell.
- New rows are always inserted before the current row.
- If there is only one row in the grid, you cannot delete it.

Insert, Delete and Edit Actions

- To insert a new row click 

.
- To delete a row click any cell in that row and then click 

.
- To edit a cell double-click it. When you see the blinking cursor or highlighted text you may start editing.
- To accept your entries and close the form click 

.

Troubleshooting

Watch for messages in the status bar. If a message reads, 'This cell should not be empty,' then you must enter a cell value before the row will be accepted.

Column Descriptions

Name is the name of the aperture.

Shape is the shape of the aperture — either `Ellipse` or `Rectangle`. The entry must be in the exact format shown, written in full, including the capital letters at the beginning of the words. If you enter it incorrectly, the status bar will display a message saying that an error has occurred.

Horizontal Full Width is the full size of the aperture along the horizontal axis in millimeters.

Vertical Full Width is the full size of the aperture along the vertical axis in millimeters.

Center Co-ordinates are the center X - Y co-ordinates for the aperture in millimeters. X=0, Y=0 means that the aperture is centered with respect to the beamline axis. X=1, Y=1 means that the center of the aperture is 1 millimeter to the right and 1 millimeter above the beamline axis.

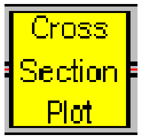
Length is the length of the aperture along the Z axis in millimeters.

Type is one of five different apertures. You may choose NR (No Readback), R (Readback), TB (Top and Bottom Readback), LR (Left and Right Readback), or TBLR (Top, Bottom, Left, Right Readback). The type you choose will define how beam spill data is presented in the Collimator Window.

Description is a description of the aperture. You may enter any description you wish.

shows the status messages for the dialog box. Also, when data are entered incorrectly, it displays error messages and gives suggestions.

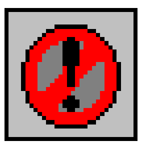
7.2 Cross-Section Plot Icon



The Cross-Section Plot icon can be placed at any location along the beamline's Z axis (SBI Window). It is typically placed at locations of interest to the user, such as at the target at the end of the beamline.

The placement of the Cross-Section Plot icon determines where all cross-sectional and/or intensity plot data will be generated. The position of the Cross-Section Plot icon shows as a vertical yellow line in all the longitudinal plots. There is no dialog box associated with the Cross-Section Plot icon.

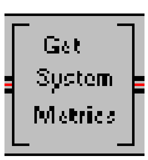
7.3 End Run Icon



The End Run icon is used to stop the run algorithm at a desired Z co-ordinate. It is used only for multi-particle beams and can be placed at any location in the beamline along the Z axis.

If you are only interested in obtaining data at a particular Z location along the beamline with the Get System Metrics icon, there is no need to do further calculations along the beamline. In this case the End Run icon should be placed immediately after (to the right) of the Get System Metrics icon, so no further calculations are performed. There is no dialog box associated with the End Run icon.

7.4 Get System Metrics Icon



Any number of Get System Metrics icons can be inserted in the beamline at positions of your choice along the Z axis. The only condition is that they be placed after the Beam Source icon.

When you place a Get System Metrics icon you are asking for measurement information about the beam half-sizes, the cumulative beam sigma matrix, the cumulative transport matrix and the particle vector co-ordinates. This data is generated at the Z co-ordinate of the Get System Metrics icon.

Measurement Readouts

To access the three System Metrics readout pages, double click the Get System Metrics icon. This brings up the System Properties page.

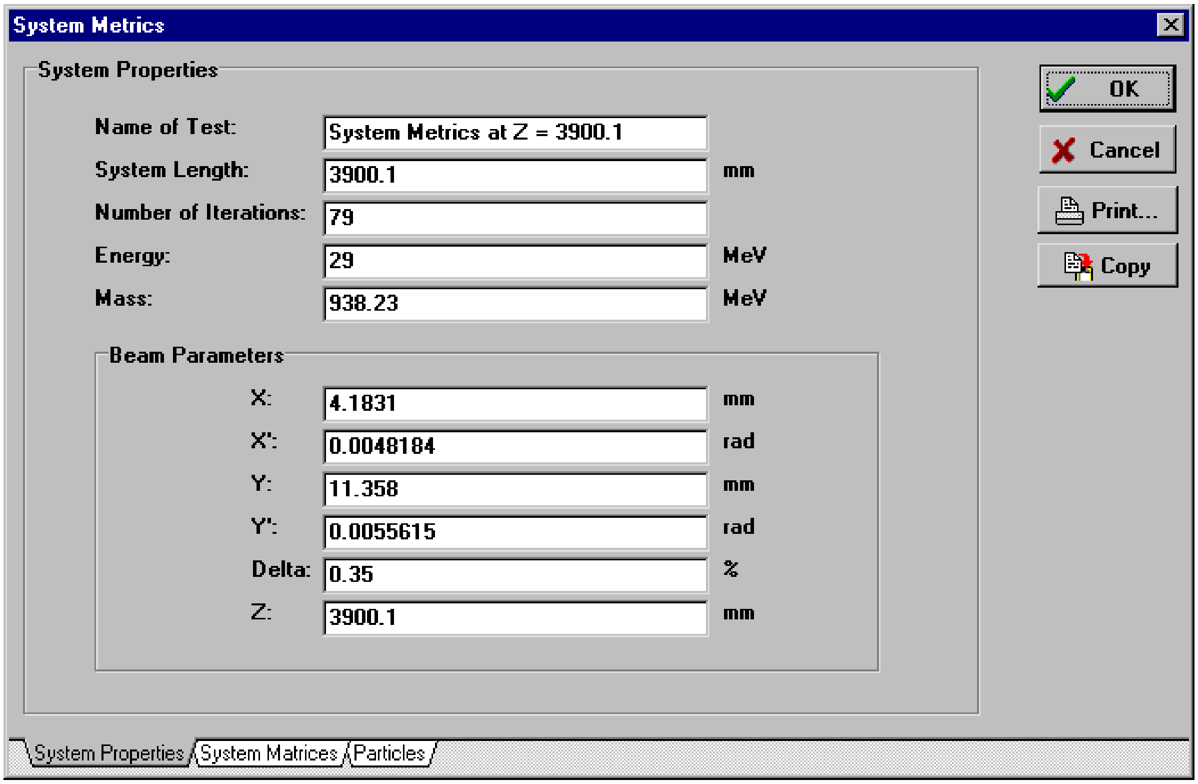


Figure 7-2, System Properties Page

The System Properties page shows the main Beam Parameters such as the beam half-sizes at the Z co-ordinate noted in the edit box titled 'Z:'.

This icon was originally used for testing the software but has been kept as a utility icon. Note that you cannot edit the parameters in this screen. They are readouts only.

The system information values can be printed or copied from this screen, or, can be printed from the Beam Transport System (BTS) Text Window, found in the Window menu, Base Application. Refer to Chapter 9.2.

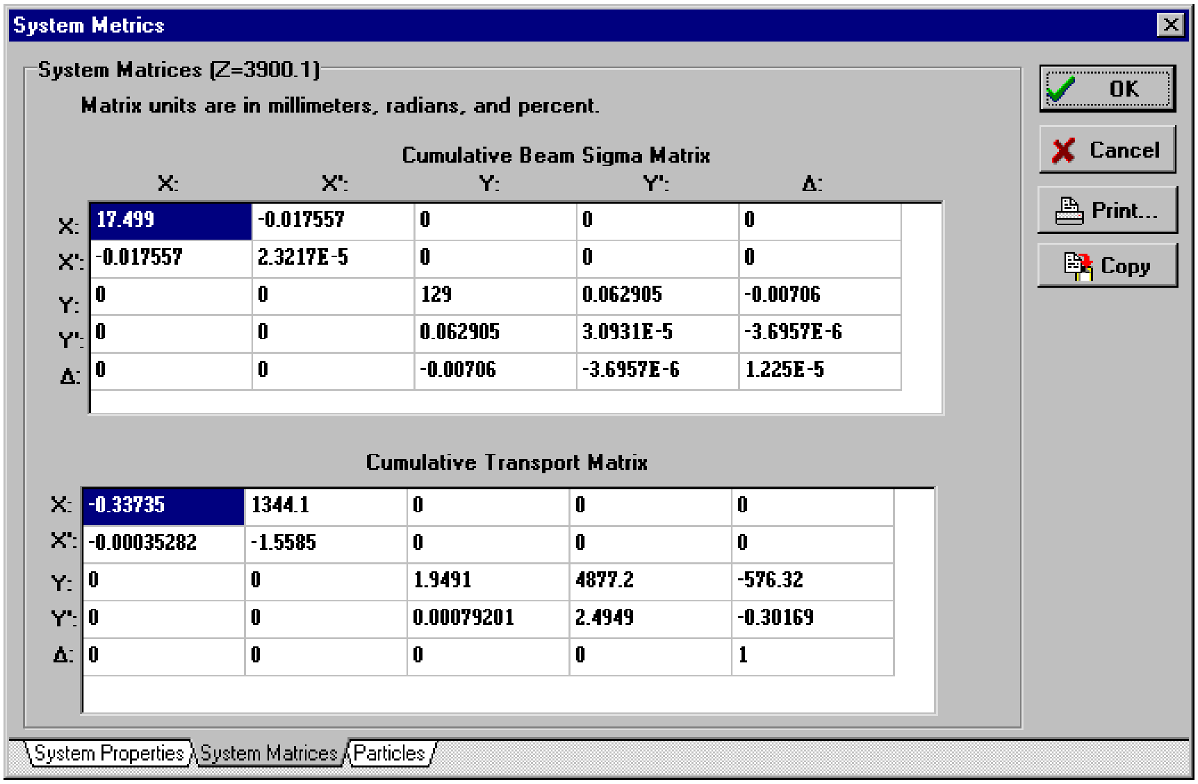


Figure 7-3, System Matrices Page

The System Matrices page shows the Cumulative Beam Sigma Matrix and Cumulative Transport Matrix at the Z co-ordinate of the Get System Metrics icon. In this example, the Z co-ordinate written at the top of the page is Z=3900.1 .

The system matrices values can be printed or copied from this screen, or, can be printed from the Beam Transport System (BTS) Text Window, found in the Window menu, Base Application. Refer to Chapter 9.2.

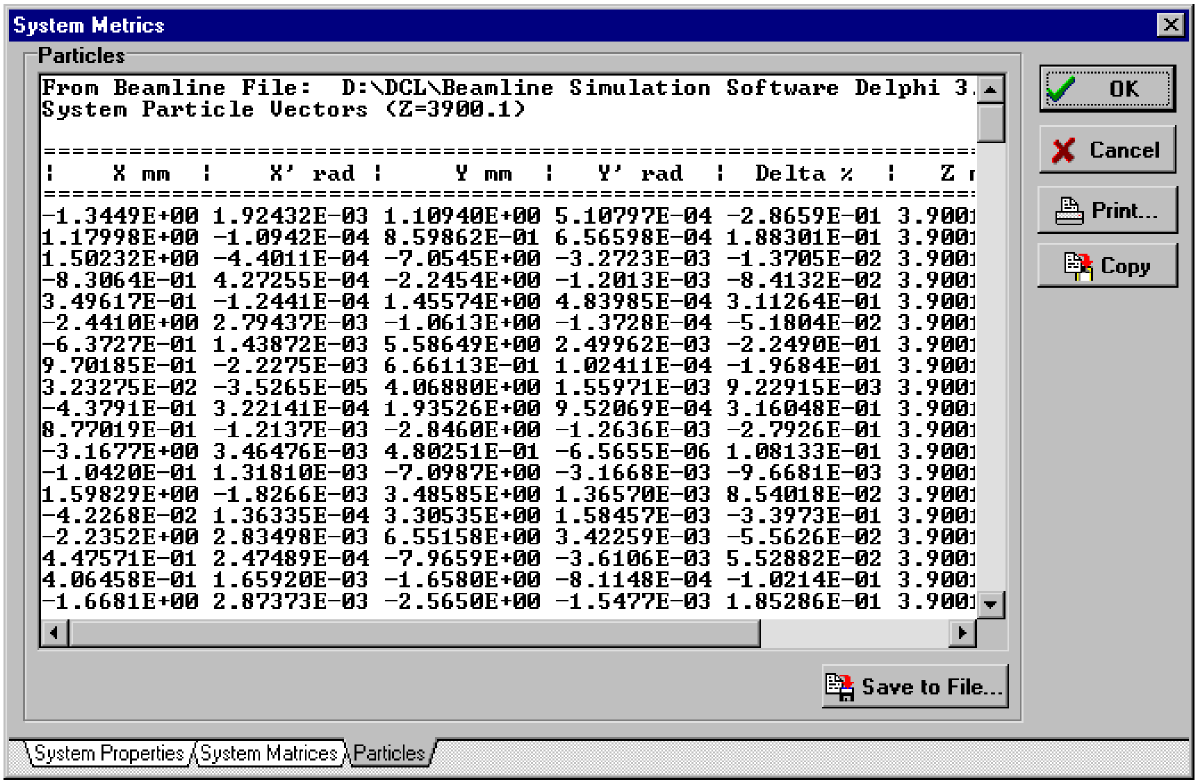


Figure 7-4, Particles Page

Provided that you ran a multi-particle beam (not an envelope beam), the Particles page shows the co-ordinates for all particles at the Get System Metrics icon Z location.

The particle co-ordinates can be saved to file, printed or copied.

8.0 Graphics Management

This chapter looks at the choices you must make to get the most out of the graphics windows.

8.1 Looking at Plot Types

Here we show examples of the three main plot types — longitudinal, cross-sectional and intensity.

Longitudinal Plot

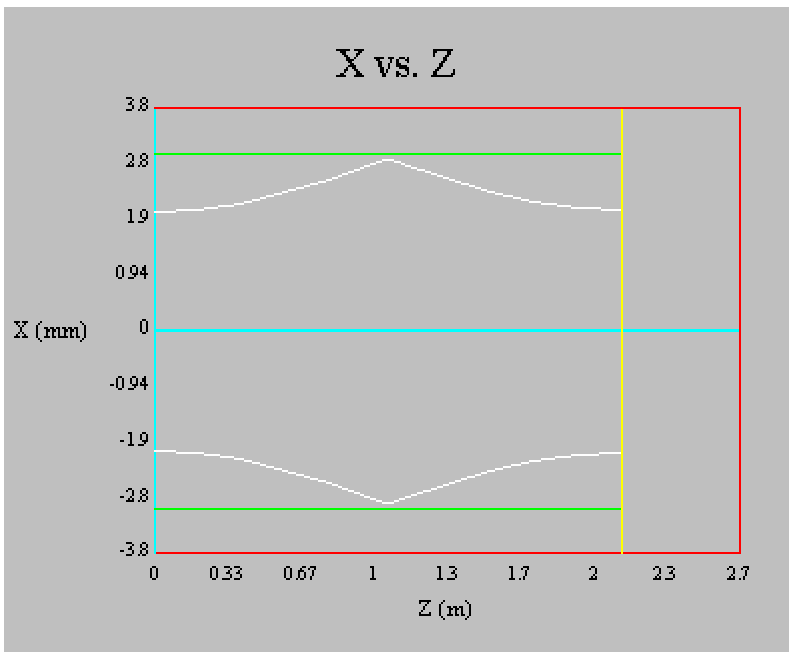


Figure 8-1, Longitudinal Plot of an Envelope Beam Run

Longitudinal Plot

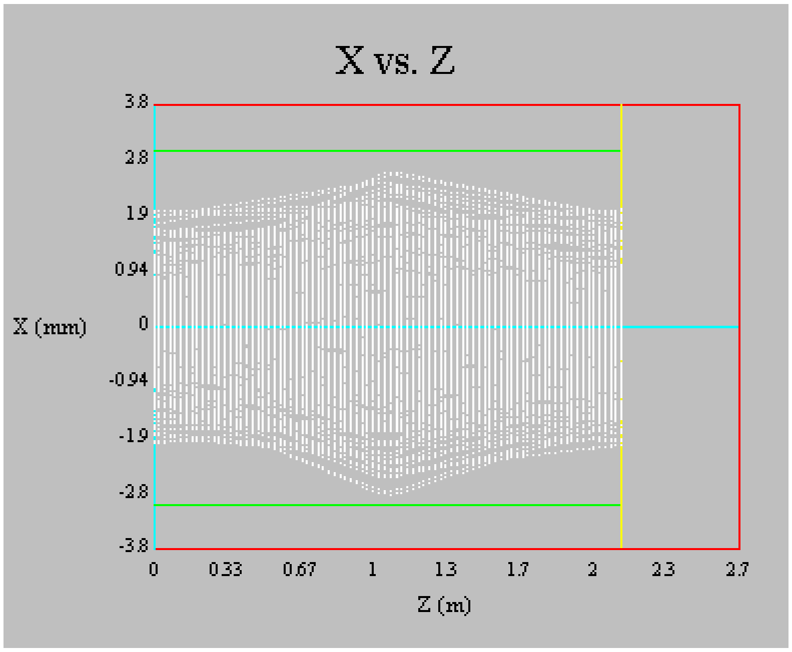


Figure 8-2, Longitudinal Plot of a Particle Beam Run

Cross-Sectional Plots

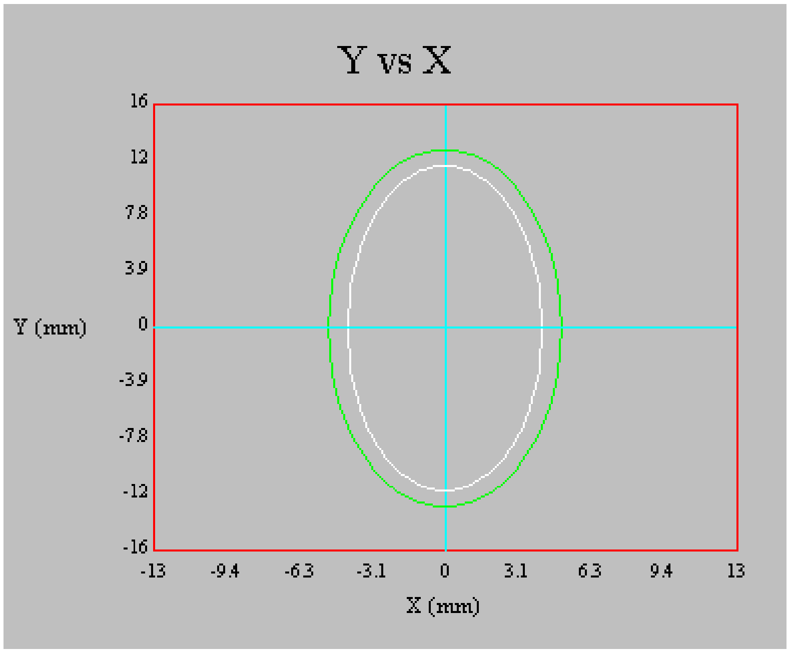


Figure 8-3, Cross-Sectional Plot of an Envelope Beam Run

Cross-Sectional Plot

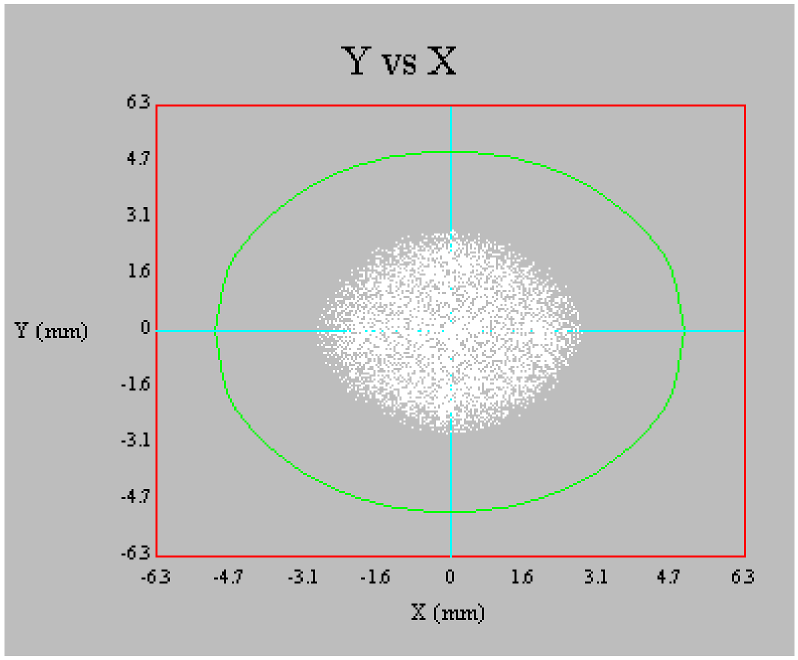


Figure 8-4, Cross-Sectional Plot of a Particle Beam Run

Intensity Plot

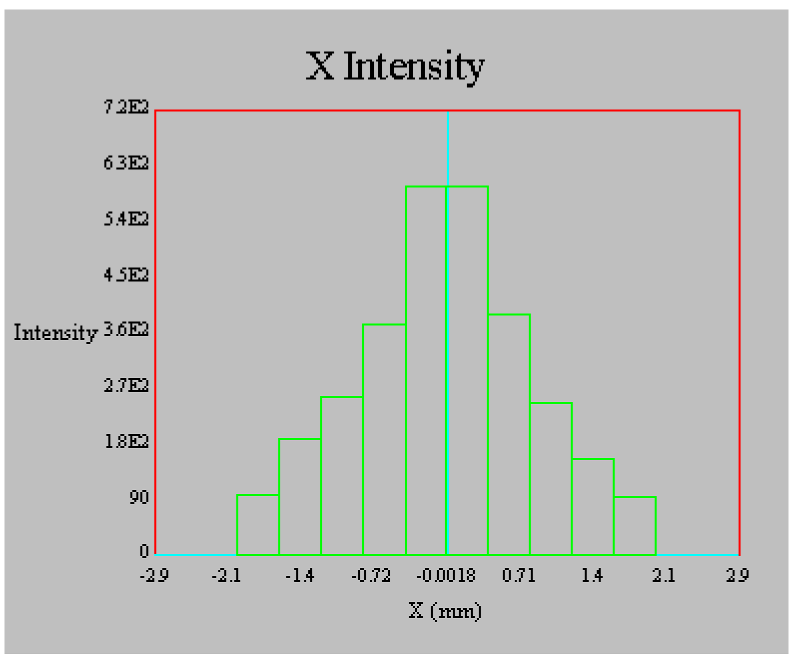


Figure 8-5, Intensity Plot of a Particle Beam Run

In the next section we cover the graphics properties associated with each plot type.

8.2 Choosing Graphics Properties

1. Place the cursor in either of the graphics windows and right click. This brings up the pop-up menu.
2. Select **Properties** to view the Properties Notebook, **Graph Type** page.

There are six pages in the Properties Notebook. All graphics window properties are set or changed within these pages. The options are described below.

Graph Type Page

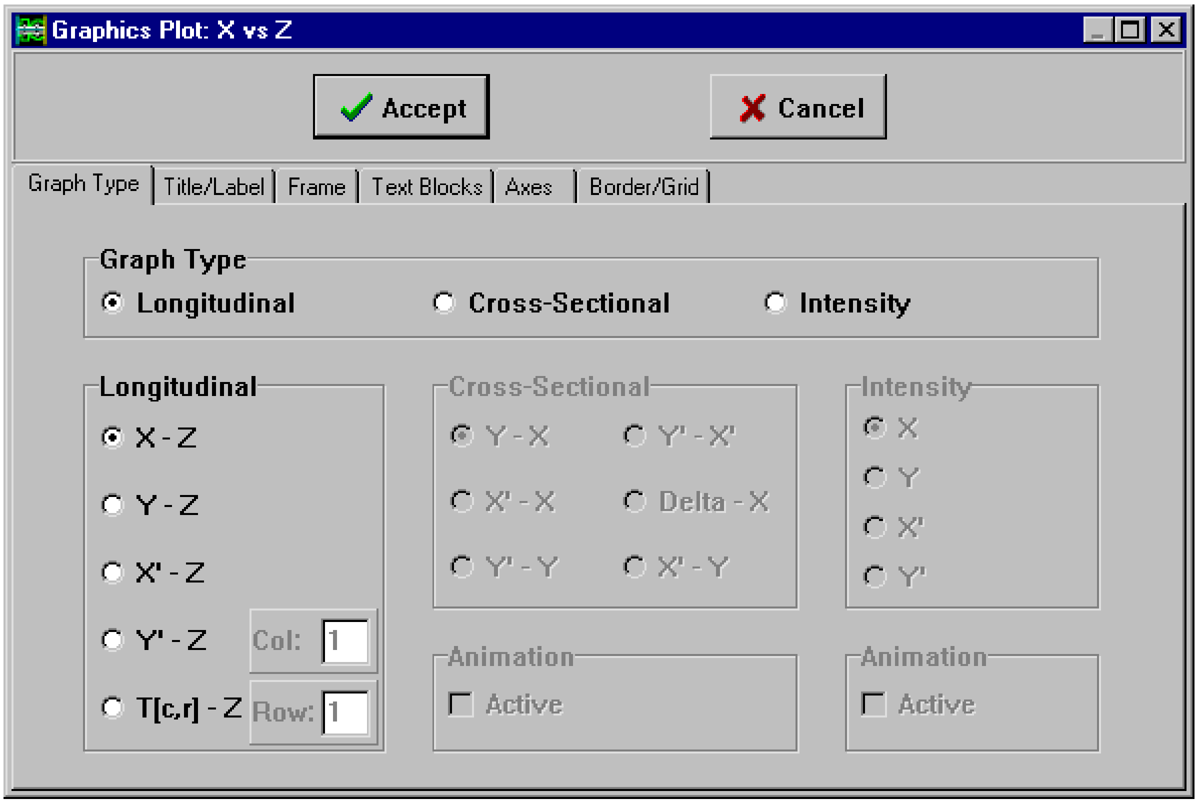


Figure 8-6, Graph Type Page

3. Under Graph Type click **Longitudinal, Cross-Sectional or Intensity.** This will activate the box(es) directly below.
4. Select the axes of your choice. The 6 main co-ordinate axes of interest are **X**, **X'**, **Y**, **Y'**, Δ and **Z**. The co-ordinate axis **T[c,r]** refers to the Cumulative Transport Matrix element located in the user-defined **Column** (c) and **Row** (r).
5. Select **Active** in the Animation box (for Cross-Sectional and Intensity Plots only) if you wish to see these transverse plots appear

as an animated movie using each slice in the beamline. Without animation, you will see only one plot at the Z co-ordinate of the Cross-Section Plot icon.

6. To keep your changes click the **Accept** button. To ignore them click the **Cancel** button.
7. To go to a different page click the top page tab of your choice.

Title/Labels Page

Enter the graph titles and labels on this page.

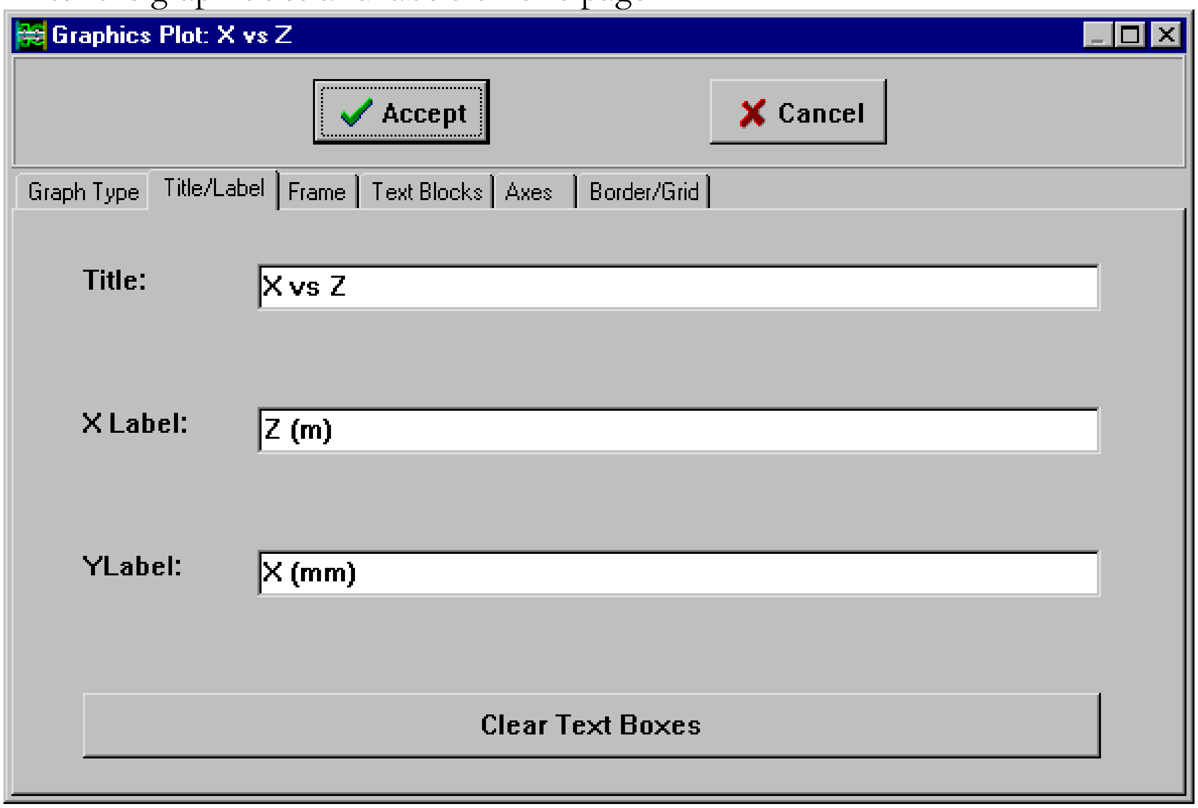


Figure 8-7, Title/Labels Page

8. To enter new text into all the text boxes, click the **Clear Text Boxes** button.
9. Enter the graph title in the '**Title:**' text box. The title will be displayed centered at the top of the graphics window.
10. Enter the axes names in the '**X Label:**' and/or '**Y Label:**' text boxes. These become labels to the appropriate axes in the graphics window.
11. To keep your changes click the **Accept** button. To ignore them click the **Cancel** button.

Frame

Choose the position of the frame and the screen background color in this page.

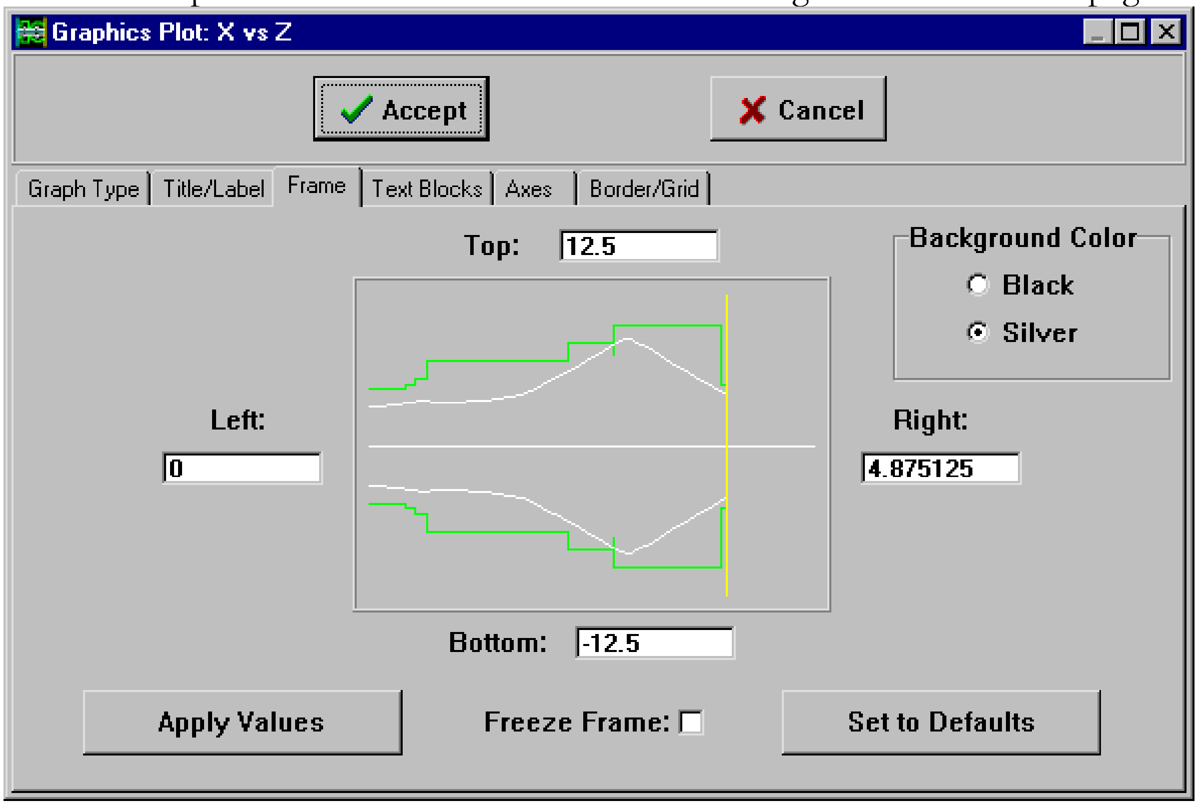


Figure 8-8, Frame Page

12. To set the frame display range enter your numbers or co-ordinate choices into the '**Bottom:, Left:, Top: and Right:**' text boxes. The numbers correspond to the full extents of the plot being displayed. For the example shown, the beamline went from Z=0 mm to Z=2.662625 mm, and the envelope extents were + or – 3.75 mm. You may choose any co-ordinates you wish. And yes, you can zoom using this feature.
13. To preview the frame display, click the **Apply Values** button. The values are NOT applied to the real graphics display until you click the Accept button.
14. To use the default values for the frame display click **the Set to Defaults** button. It resets the four frame values to Bottom: -1, Left: -1, Top: 1 and Right: 1.
15. To lock the frame display values and prevent accidental or intentional changes to the text boxes click the **Freeze Frame** on.

16. **IMPORTANT!** To set the window background color for screen use, click **Black**. If you plan to print the graphics, click **Silver**. You can then copy the graphics to the clipboard and paste into another document knowing you will have a good print out with a silver background.

17. To keep your changes click the **Accept** button. To ignore them click the **Cancel** button.

Text Blocks

Text blocks or comments can be added to a graphics window in Longitudinal or Cross-Sectional mode through the following notebook page.

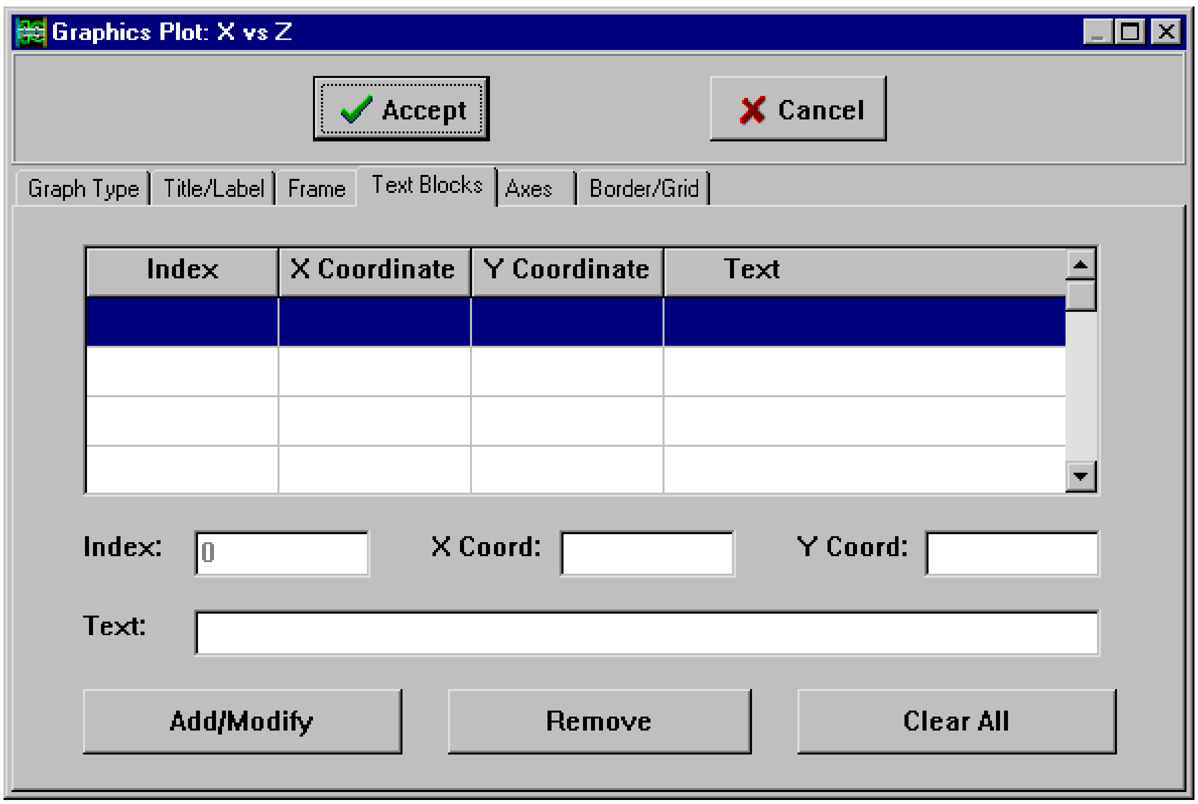


Figure 8-9, Text Blocks Page

The Text Blocks page is divided into two main sections. The upper section grid is a display of all currently entered text blocks. The lower section edit boxes and commands are used to enter any text you wish and to place it at the co-ordinates of your choice.

18. Click an existing item in the string grid to load its parameters into the edit boxes.

19. Click **Add/Modify** to edit the currently selected text block.
20. Click **Remove** to delete the current selected text block.
21. To add a new text block, click an empty row at the bottom of the string grid. This will load an empty text block with a new index value into the edit boxes. Then, enter all the required parameters and click **Add/Modify**.
22. To clear all existing text blocks, click **Clear All**.
23. To save your changes, click **Accept**. To ignore your changes, click **Cancel**.

Axes

Choose the axes color and location through this page.

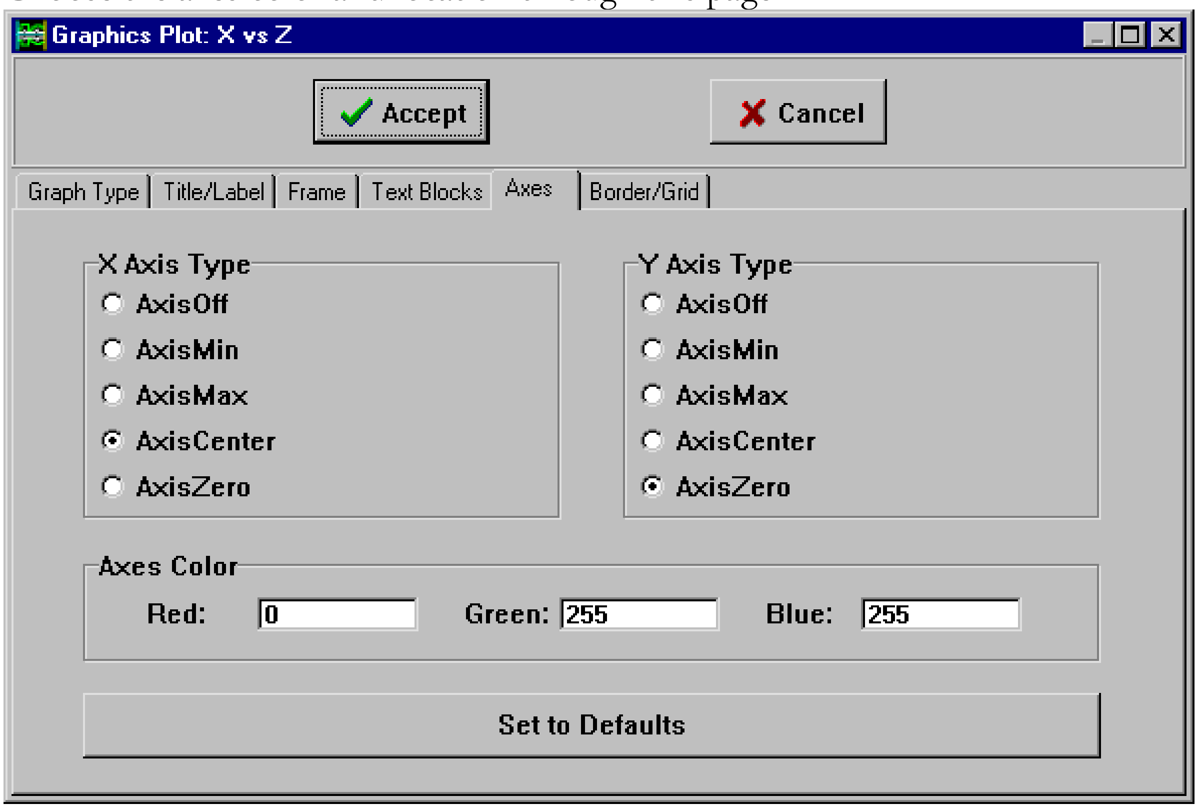


Figure 8-10, Axes Page

24. Click one radio button under 'X Axis Type' and one under 'Y Axis Type'. Your choices are:
    - **AxisOff** - no axis appears.
    - **AxisMin** - the axis appears in the minimum position — at the bottom for an X axis and at the left for a Y axis.

- **AxisMax** - the axis appears in the maximum position — at the top for an X axis and at the right for a Y axis.
- **AxisCenter** - the axis always appears centred within the frame.
- **AxisZero** - the axis appears at zero if the value zero is within the frame. Otherwise it appears as AxisMin or AxisMax whichever side of the frame is closest to the zero value.

25. To set the axes color, enter a value from 0 to 255 in each of the 'Axes Color' text boxes. Both axes show the same color. This color is a combination of the Red, Green and Blue values.
26. To use the default settings, click **Set to Defaults**. The default settings are: X Axis Type – AxisCenter; Y Axis Type – Axis Zero; Axes Colors – Red 0, Green 255, and Blue 255.
27. To keep your changes click the **Accept** button. To ignore the changes click the **Cancel** button.

Border/Grid

Add a border or grid to the graphics window through this page.

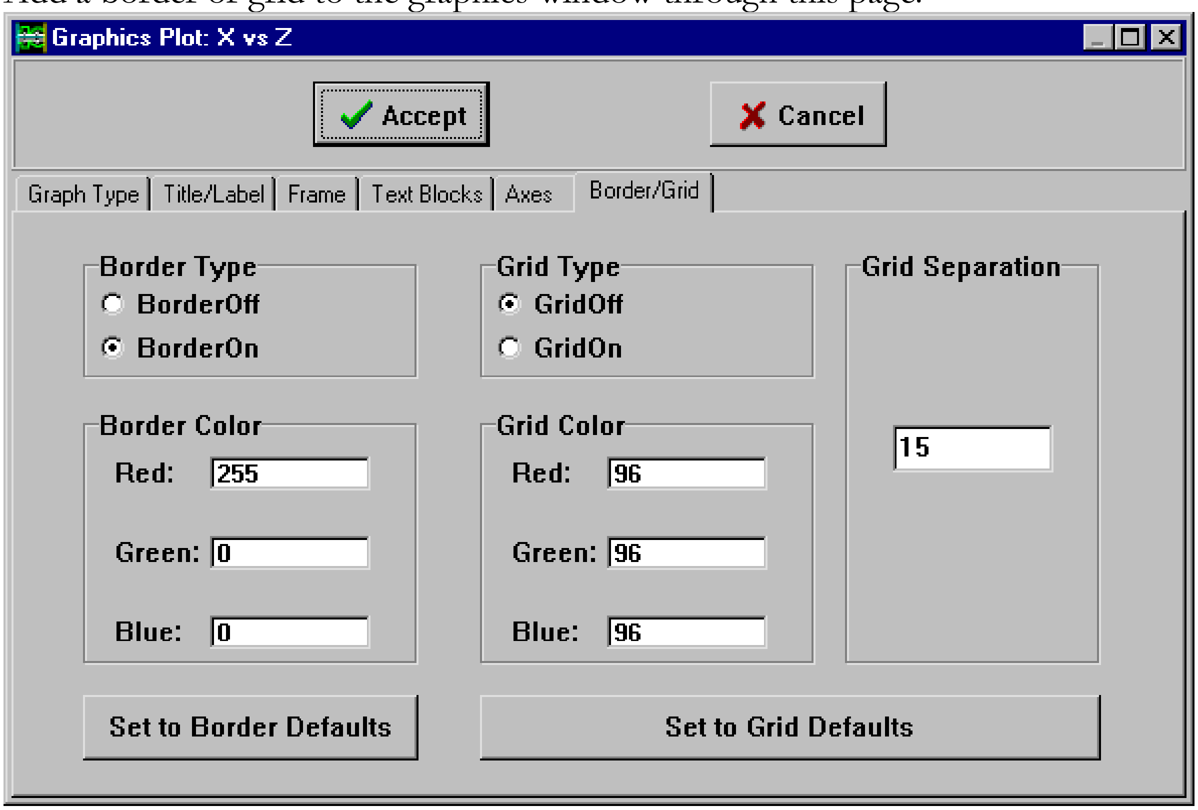


Figure 8-11, Border/Grid Page

28. Click **BorderOn** to add a border. Click **BorderOff** to remove the border.

The border is a rectangle around the area of the canvas that displays the longitudinal, cross-sectional or intensity plots.

29. Click **Grid On** to add a grid. Click **GridOff** to remove the grid.

The grid is a series of vertical and horizontal lines separated by the number of pixels specified in the 'Grid Separation' text box.

30. Under 'Border Color' enter values from 0 to 255 for the **Red:, Green: and Blue:** text boxes.
31. Under 'Grid Color' enter values from 0 to 255 for the **Red:, Green: and Blue:** text boxes.

The final color for the border or grid is a combination of the Red, Green and Blue values.

32. To load the default values click either the **Set to Border Defaults** button and/or the **Set to Grid Defaults** button.
33. To keep your changes click the **Accept** button. To ignore the changes click the **Cancel** button.

8.3 Graphics Pop-up Menu

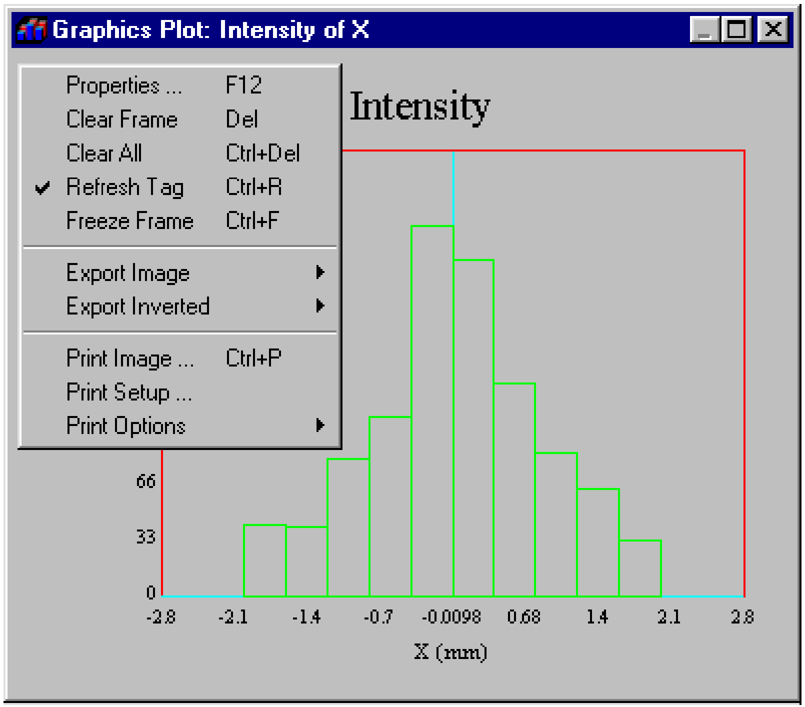


Figure 8-12, Border/Grid Page

Place the cursor in either of the graphics windows and right click. This brings up the pop-up menu. The pop-up menu contains all the global commands that apply to the graphics windows.

Select:	**To:**
Properties	See section 8.2, this chapter.
Clear Frame	Remove all points, lines and ellipses currently stored within the window.
Clear All	Remove the data that specifies how the graphics windows look and reset to the window defaults. There is a confirmation dialog box to verify this action.

Refresh Tag	Choose whether the next beamline run will be drawn over top of the existing plot (Refresh Tag is off) or whether the screen is refreshed prior to each beamline run (Refresh Tag is on).
Freeze Frame	Freeze the frame display settings, Properties Notebook.
Export Image	Export the actual window image…
To File	Save the image as a newly named bitmap. A save dialog box opens with a text box to enter the new filename.
To Clipboard	Copy the image as a bitmap to the clipboard.
Export Inverted	Export an inversion of the actual window image
To File	save an inverted image as a newly named bitmap. A save dialog box opens with a text box to enter the new filename.
To Clipboard	Copy the inverted image as a bitmap to the clipboard
Invert To Color/ B&W	Toggle between the two options. If the caption is 'Invert to Color' then a color approximation of the inverted image is created. If the caption is 'Invert to B&W' then the image is strictly black and white.
Print Image	Print the current window image according to the specifications in the Print Setup and Print Options. A print dialog box opens for you to click the OK button.
Print Setup	Open the standard Windows Print Setup dialog box.

Print Options

Stretch to Page	Stretch the window image to cover the entire page print area. This does not maintain the aspect ratio of the graphics window.
Expand to Page	Expand the window image to fit into the print area of the page while maintaining the aspect ratio of the graphics window.
Select Color	
Color	Select to make full color printouts on a printer.
Simulate Color	Select to make black and white printouts. The various colors are represented by different line types.
B&W	Select to make black and white printouts. All non-black components in the source graphics window will be solid black in the final printed image. The black background will be white in the printed image.
Landscape/ Portrait	Switch between orientation landscape and orientation portrait. This is identical to, and a shortcut to, the standard Orientation item in the Print Setup dialog box.
Center Vertical	Specify whether the final image will be top-justified or centered on the printed page. This has no effect when Stretch to Page is selected.
Center Horizontal	Specify whether the final image will be left justified or centered on the printed page. This has no effect when Stretch to Page is selected.

8.4 Getting the Most from the Graphics Windows

- **ReFresh/Freeze Frame**: Using these two properties allows you to overlap plots and to compare them. Toggle 'ReFresh' off and toggle 'Freeze Frame' on. This will tell the graphics window that you do not want it to refresh its plot after the next runs, and that you do not want it to change the range for the X and Y axes. The next plots will be on top of any plots that were there from previous runs. For example, you could plot a particle plot on top of an envelope plot.

- **Animation**: Both intensity and cross-sectional plots have the ability to animate the dynamics of a multi-particle type beam from beginning to end. Click the Animation check box at the bottom of the Graph Type page in the properties dialog box. The next multi-particle plots of cross-sectional or intensity type will no longer be at just one Z co-ordinate. They will now show a plot at each Z co-ordinate along the entire beamline. This gives the effect of looking at the beam as it comes towards you.

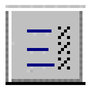
- **Graph Types**: Try many different types. You might see something that you would have otherwise missed.

- **Zoom**: Another way to zoom in on a plot is to click on the plot inside the border where you want the top left corner of the new plot to go. Then click while holding down the SHIFT key for the lower right corner of the new plot. A message box will appear asking whether you want to resize the plot to the new ranges. If you answer YES, then the plot will be re-sized for the smaller plot.

9.0 Viewing Text Readouts

9.1 Collimator Window

When you run a multi-particle beam, use the Collimator Window to show the beam spills in the system. The Collimator window shows total particle hits to the apertures as a percent of all particles initially streaming through the beamline.

To access the Collimator Window click Window and select Collimator Window or, click  Collimator Window Show/Hide toggle (Base Application Window).

Collimator Text Readout — In Real Time

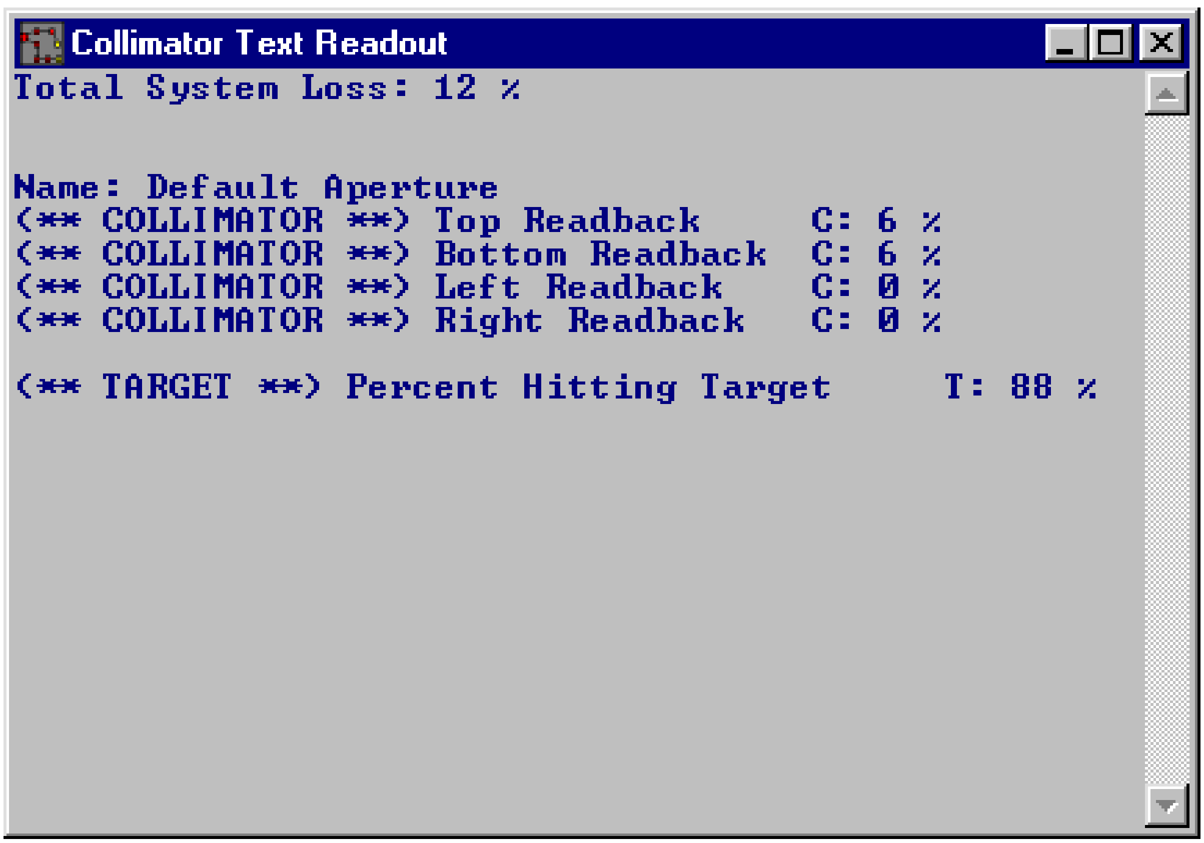


Figure 9-1, Collimator Text Readout — In Real Time

Within this program, all system apertures record beam spill. In practice, beam pipes and vacuum boxes do not provide beam spill readbacks, whereas collimators do.

So that you can choose to set up a simulation exactly like your system, we differentiate two types — those that record hits (readback) and those that don't (non-readback).

Note: you can still look at spills on apertures like beam pipes that in reality do not provide spill readbacks. This is a handy feature.

Collimator Text Readout — Pop-Up Options

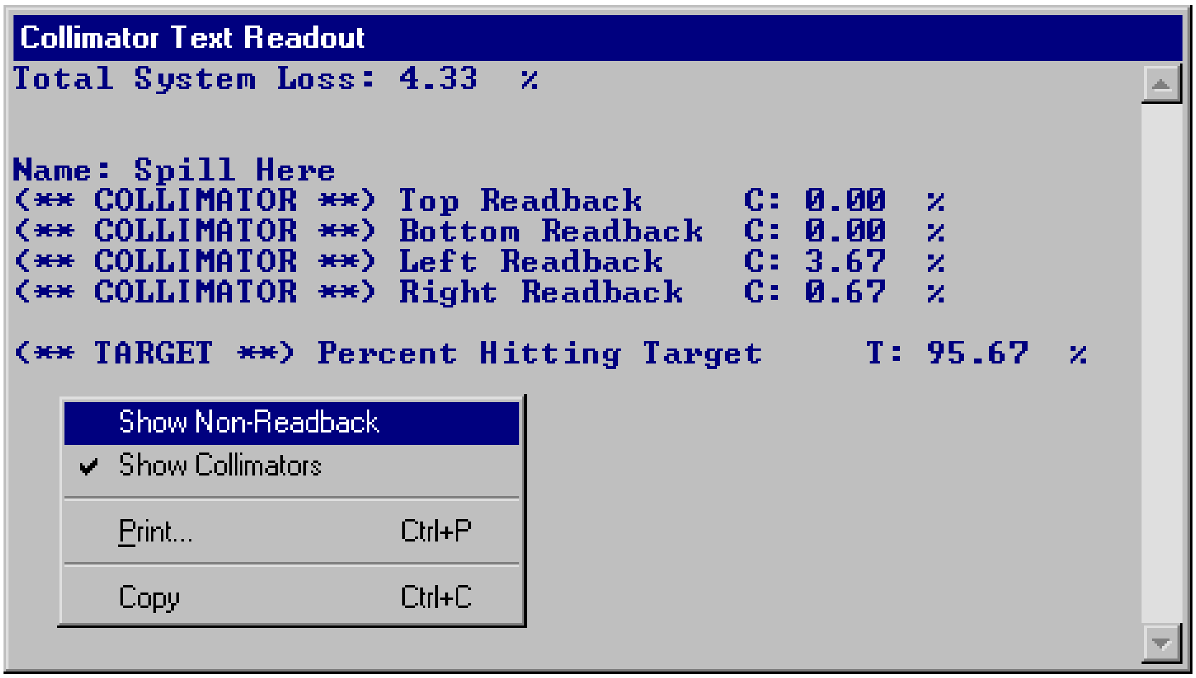
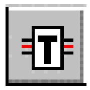


Figure 9-2, Collimator Text Readout — Pop-Up Options

Select:	**To:**
Show Non-Readback	show/not show the beam spill for the non-readback type apertures.
Show Collimators	show/not show the beam spill for all readback type apertures.
Print… or Ctrl+P	print the Collimator Text Readout Window.
Copy or Ctrl+C	copy the Collimator Text Readout Window to the clipboard.

9.2 Beam Transport System (BTS) Text Window

To access the BTS Text Window click Window and select BTS Text Window or, click  BTS Text Window Show/Hide toggle (Base Application Window). By selecting one of the four tabs at the bottom of the 'Beam Transport System' window, you can access the Beamline Elements page, the Beam Matrices page, the Cumulative Transport Matrices page, or the System Waists page.

Each page has its own pop-up menu. To activate the pop-up menu place the cursor over the text area on the page and right click the mouse. **Common printing features for all pages are the 'Print…' and 'Printer Setup…' menu items**.

Note: To view hidden parts of the window, use the scroll bars to move the text to the right or left, up or down.

Beamline Element Properties

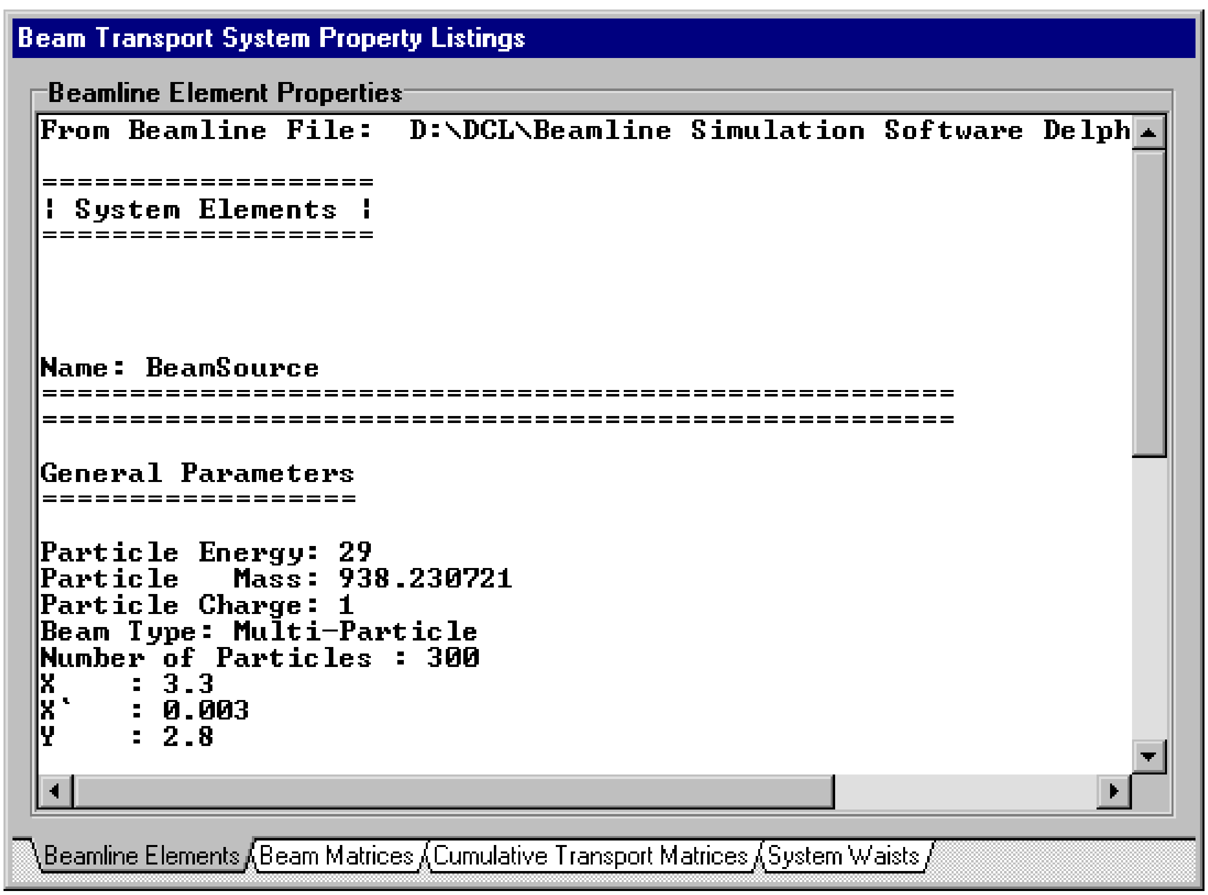


Figure 9-3, Beam Transport System — Beamline Element Properties

The Beamline Elements page shows a sequential listing of all beamline elements with their properties. The beamline elements are listed in the same order as their icons appear in the SBI Window.

A number of other options are available through the pop-up menu. To access these options, right click the mouse while on the Beamline Elements page.

Beam Transport System — Pop-Up Options

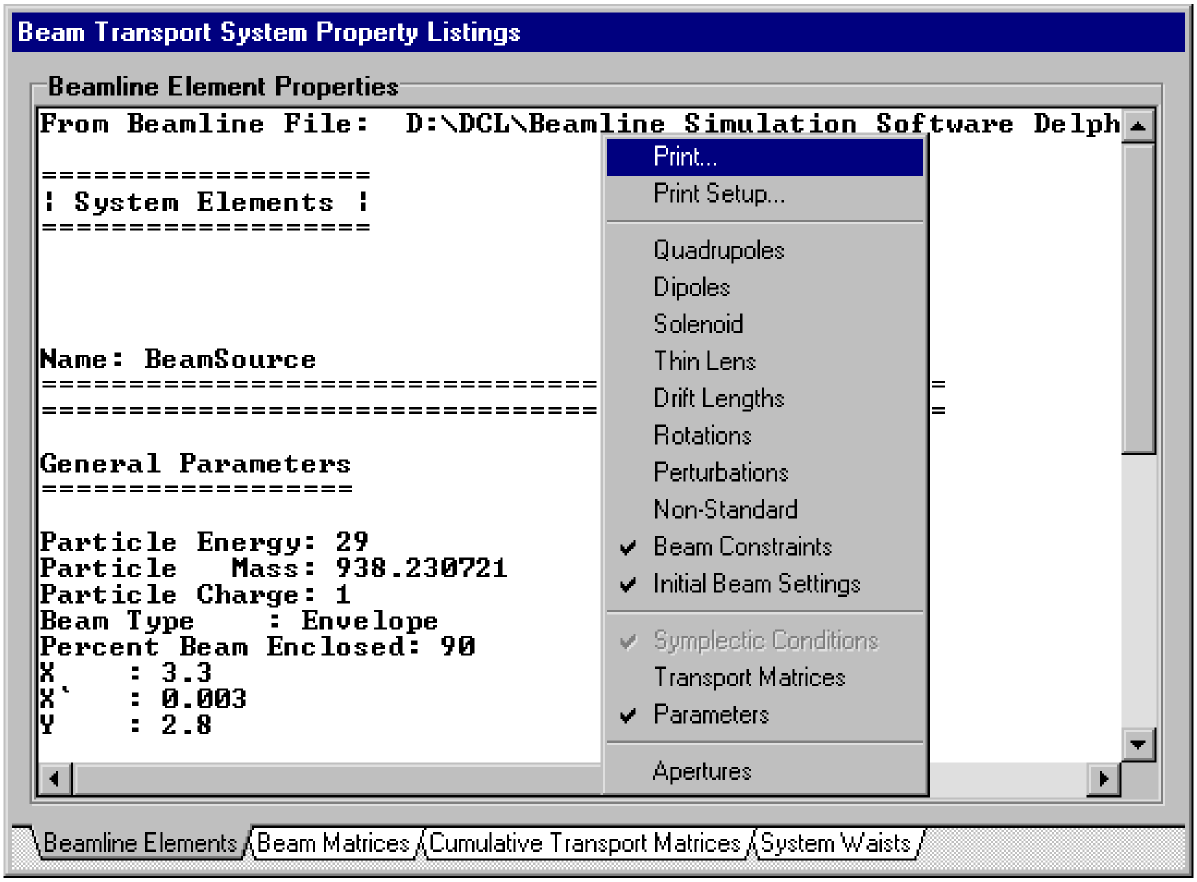


Figure 9-4, Beam Transport System — Pop-Up Options

Select:	**To:**
Print...	view the print options.
Print Setup	choose the printer.
Quadrupoles	show/not show the quadrupoles.
Dipoles	show/not show the dipoles.
Solenoids	show/not show the solenoids.
Thin Lenses	show/not show the thin lenses.
Drift Lengths	show/not show the drift lengths.
Rotation	show/not show the rotation elements.
Perturbations	show/not show the perturbation elements.
Non-Standard	show/not show the non-standard elements.
Beam Constraints	show/not show the constraint element.
Initial Beam Settings	show/not show the beam source element.
Symplectic Conditions	test the validity of the system *(to be implemented)*.
Transport Matrices	show/not show the matrix associated with each element.
Parameters	show/not show the parameters associated with each element.
Apertures	show/not show the apertures.

Beam Matrices

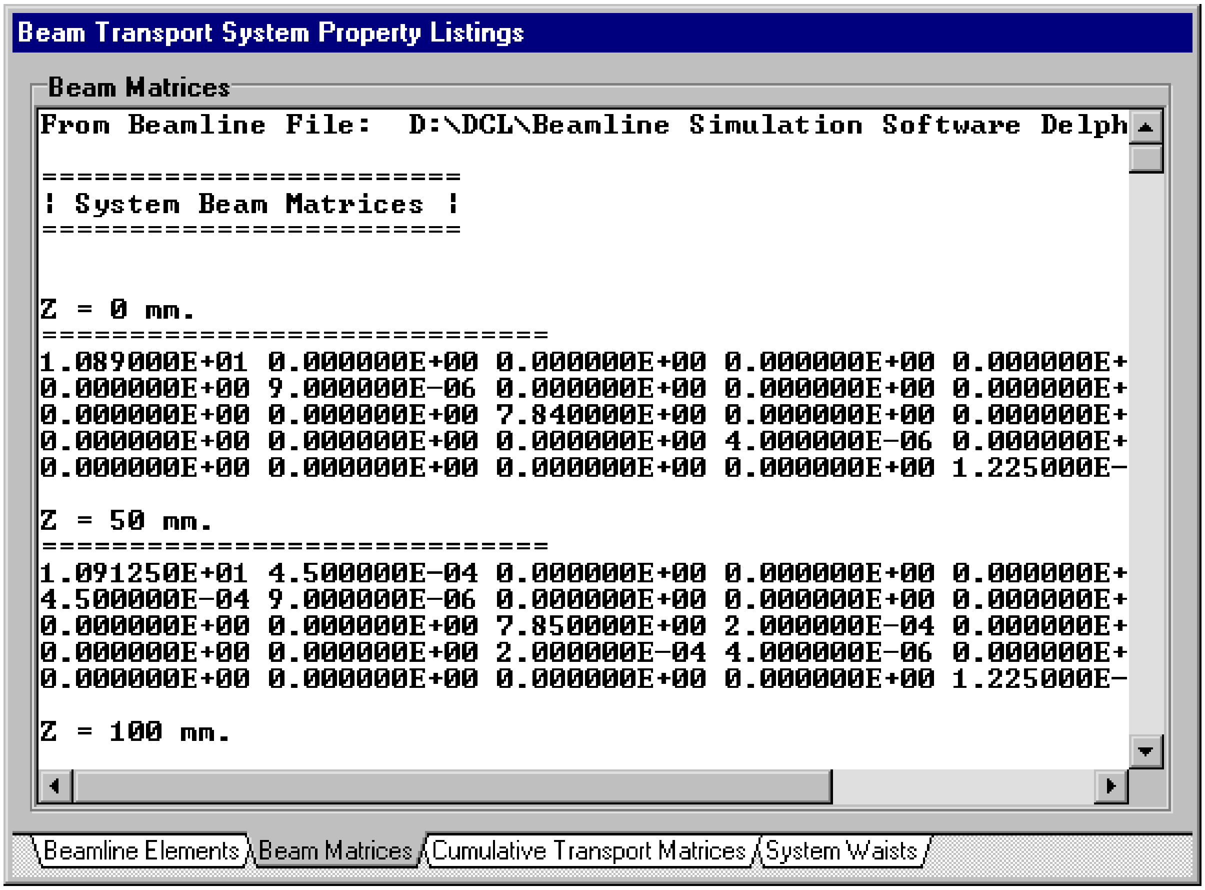


Figure 9-5, Beam Transport System — Beam Matrices

The Beam Matrices page shows the beam matrix at each slice along the beamline. Notice that the Z co-ordinate for each matrix is shown just above it.

WARNING: To ensure that all matrices are printed, you must limit the number of slices through the beamline. If there are too many slices in the system, then a huge file of matrices will be created and they may tie up your hard drive. It is often best to double click on each icon in the SBI Window and to change the number of slices to 1 per icon. In this way only one matrix is generated per icon when the beamline is re-run. This often yields sufficient detail for analysis.

Cumulative Transport Matrices

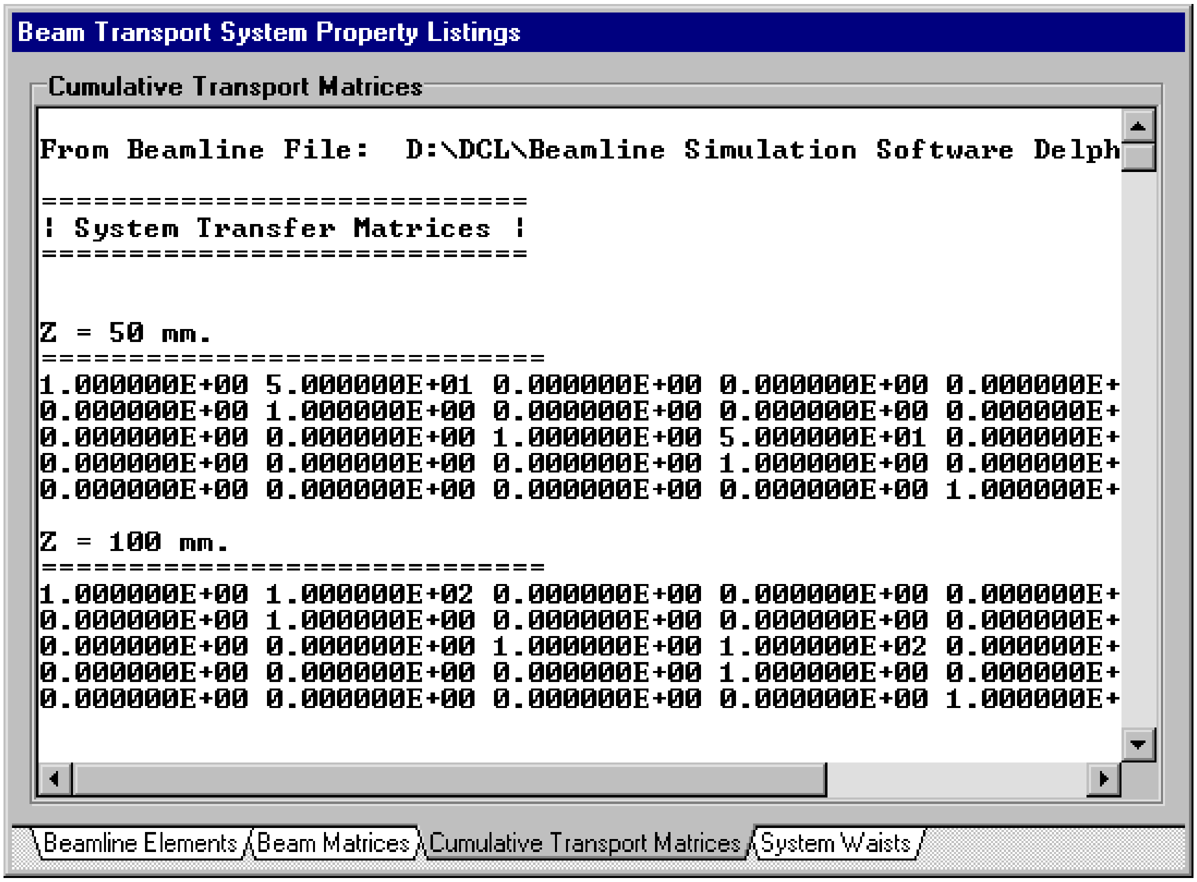


Figure 9-6, Beam Transport System — Cumulative Transport Matrices

The Cumulative Transport Matrices page shows the cumulative transport matrix at each slice along the beamline. Notice that the Z co-ordinate for each matrix is shown just above it.

Again, this window cannot hold an unlimited amount of information. To ensure that all matrices are printed you must limit the number of slices in each element along the beamline.

System Waists

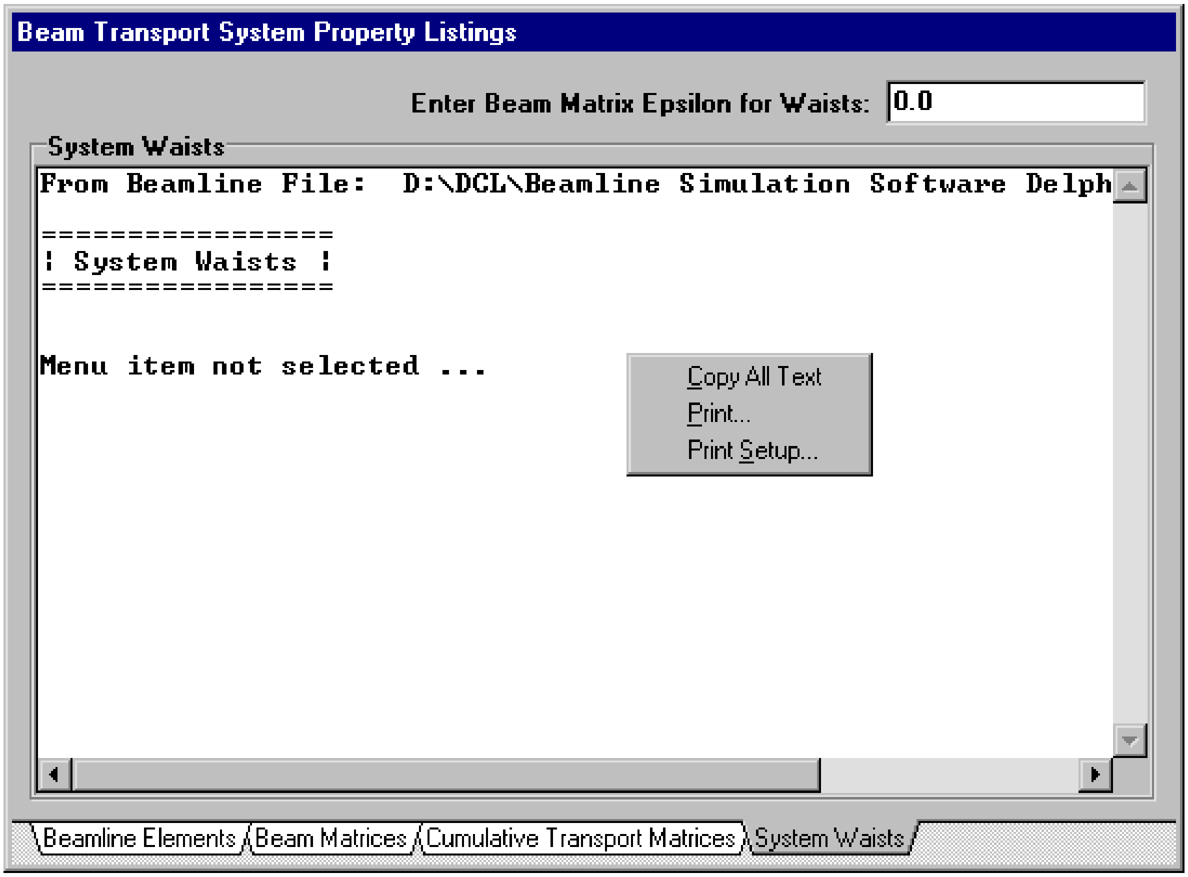


Figure 9-7, Beam Transport System — System Waists

The system waists page lists all beam waists found along the beamline. A beam waist occurs whenever the xx' or yy' beam ellipse is upright (not tilted). The narrowest portion of an x vs z or y vs z longitudinal beam envelope is always at a beam waist. From a computational point of view a horizontal axis beam waist occurs when the beam sigma matrix elements $\sigma_{21} = \sigma_{12} = 0$. A vertical axis beam waist occurs when $\sigma_{34} = \sigma_{43} = 0$. Since it is unlikely that these off-diagonal elements will be exactly zero, you are asked to enter a value for epsilon. If the absolute value of $\sigma_{21} = \sigma_{12}$ or $\sigma_{34} = \sigma_{43}$ is less than epsilon then a waist has been found.

10.0 Command & Tool Reference

10.1 Document Definitions

This section includes some of the generally accepted terminology for a graphical user interface (GUI). The first part covers some of the action terminology like what to do with the mouse to drag-and-drop an object, and the second part deals primarily with descriptions of actual GUI objects.

Cursor Actions

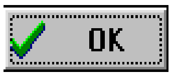
Click	Means to press and release the **left** mouse button. You should hear 1 click.
Double Click	Means to press and release the **left** mouse button two times in quick succession. The second action must happen within one half a second of the first. You should hear 2 clicks.
Right Click	Means to press and release the **right** mouse button. You should hear 1 click.
Select	Means to press and release the **left** mouse (just like click) but in this case you will be choosing one item from a menu list.
Drag and Drop	Is used to move an object from one location to another**. Click** the object and **hold the mouse button down**. Then move the object by moving the mouse. To drop the object, release the mouse button. You should see an action when you drop the object. If no action is visible then try again. All of our objects show that they are ready to receive another object by highlighting themselves. For example, the garbage can will light up with a violet frame when it is ready to delete a beamline icon. If done correctly, the garbage can will go through an animation sequence to show that it did receive the element, and deleted it correctly.

Software Terminology

Application

An Application is an abstract object that manages all the files, documents, windows, and user commands.

Button

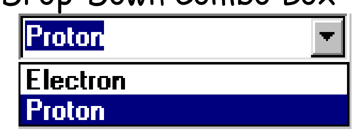


A Button executes an action in one step. As in the real world, when you press the Coke button on a pop machine you get a Coke.

Dialog Box

A Dialog Box maintains a dialog between the user and the object the user is modifying. The dialog box enables the two to exchange data. An example is the dialog you might have with a Quadrupole element, through its form fill-in dialog box.

Drop-Down Combo Box



The Drop-Down Combo Box only allows certain items to be entered into its edit box. These specific items are contained in a drop-down menu that is displayed when the user clicks the down arrow with the mouse pointer. Select one of the items for the edit box.

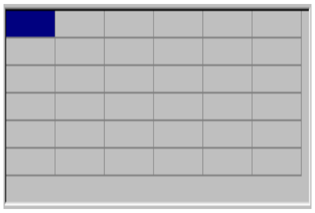
Fields

Fields are edit boxes that can be modified by both the user and the application. Usually there are default values entered in these boxes to help the user.

Fly-Over Help

Fly-Over Help hints appear when the mouse pointer is over a button, an icon or other feature. The hint will usually explain an action or show a name. Check the garbage can in the SBI Window. The fly-over help reads, ‘Garbage Beamline Elements’.

Grid



A grid contains different kinds of information in each cell depending on the meaning of the row and column. Title bars, if used, are the static bars at the top and left of the grid. In our grid example, the very top left cell is the current cell and the top row is selected. To select a row, click any cell in the row to make it the current cell. Important! Within our grids, columns can never be selected.

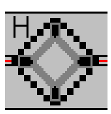
Hotkeys - Menu Item

These keys allow quick access to pop-up or main menu functionality such as ALT-F to get to the file menu in the Base Application Window.

Hotkeys – Real Time

These keyboard keys are constantly scanned by the SBI Window application. When one of the hotkeys is pressed then the value of one beamline element parameter is varied. The run algorithm simulates the changes made to the beam as the parameter value is changed.

Icon



An icon is a picture that looks like the object it represents. An icon is used to graphically show where an object is located on the screen.

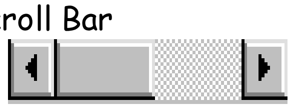
Menu Bar

A menu bar holds a series of menus. To view one of the menus (for example the file menu), click on the word File, and down drops a list of menu items to choose from.

Radio Button

A radio button is either marked or unmarked. Some groups of radio buttons are programmed so that only one radio button in the group can be marked at a time.

Scroll Bar



A scroll bar is used to scroll the picture in a window so that the part of the picture you wish to see comes into view. There are three ways to use a scroll bar: one way is to click on the arrow buttons to scroll in the direction of the arrow, a second way is to drag the middle bar in the direction that you want to scroll, and a third way is to click on the part of the scroll bar container that does not contain the scroll bar. It will scroll the window in that direction with a big step size.

Window

A window is an object that encompasses a view of the underlying picture such as the Resource Window.

10.2 General Window Functionality

Figure 10-1, Control Menu

Control Menu

To access the control menu, click the icon in the top left hand corner, Base Application Window. This brings up the pop-up menu.

Restore	Restores the window to the size it was before you minimized it.
Move	Allows you to move the window with the mouse.
Size	Allows you to re-size the window with the mouse.

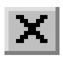
Minimize	Minimizes the window to an icon.
Maximize	Maximizes the window to use the full screen.
Close Alt + F4	Closes the window.

Common Window and Dialog Box Attributes

Cancel Button

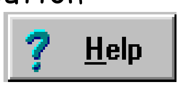
This button is used to cancel any changes made to the window — without saving them.

Close Window Button



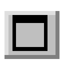
This button is used to close the window. If you click this button in the Base Application Window, the entire application will terminate.

Help Button



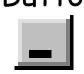
This button displays the help information associated with the window.

Maximize Button



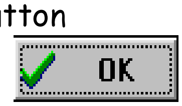
This button is located at the top right corner of the window and is used to maximize the window.

Minimize Button



This button is located at the top right corner of the window and is used to minimize the window.

OK Button



This button is used to accept and save the changes to the window.

Window Title Bar

This is the top bar in the window and displays the title of the window. It is also used to move the window with the mouse.

10.3 Base Application Window

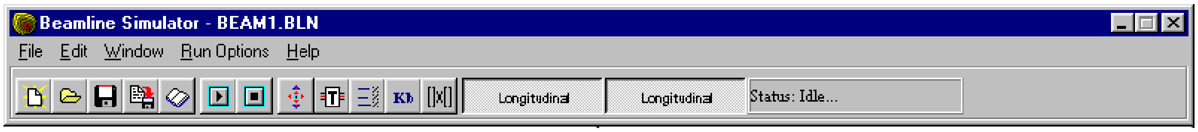


Figure 10-2, Base Application Window

The menu bar contains most of the general functionality for the application. Specific pop-up menus and menu items are discussed below.

File Menu

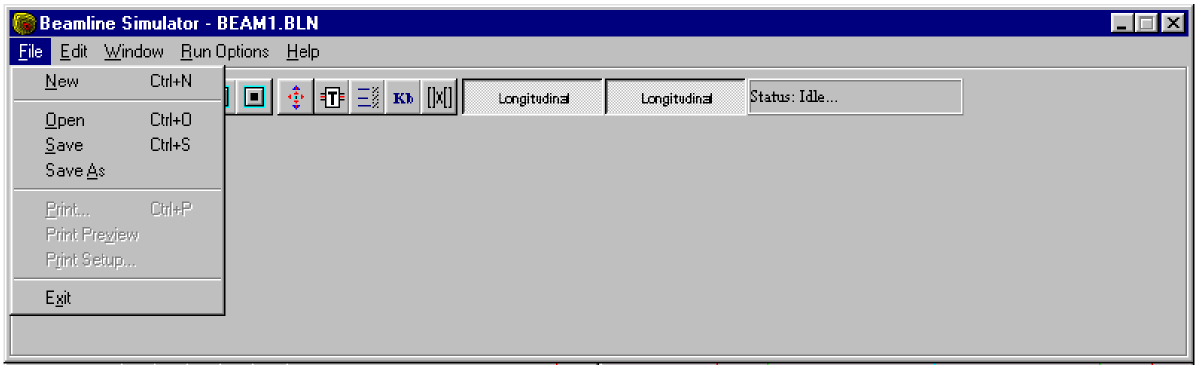


Figure 10-3, File Menu

New Ctrl + N	Creates a new beam transport system document. If the current beamline file has not been saved since a modification, then a Save Confirmation dialog box will appear to ask whether the current file should be saved or not.
Open Ctrl + O	Opens an existing document from any drive. This is done through a dialog box. If the current beamline file has not been saved since a modification, then a Save Confirmation dialog box will appear to ask whether the current file should be saved or not.
Save Ctrl + S	Saves the current active window data.
Save As ...	Saves the current document with a user specified filename. This is done through a dialog box.
Exit	Exits the application. If the current beamline file has not been saved since a modification, then a Save Confirmation dialog box will appear to ask whether the current file should be saved or not.

Print ... Ctrl + P, Print Preview and Print Setup have yet to be implemented under the File menu. Don't worry. You can print from many of our screens. See Chapter 8.3 Graphics Pop-Up Menu for printing the graphics window plots, and Chapter 9.1 and Chapter 9.2 for printing the Collimator Text Readout and the Beam Transport System Text Windows respectively.

Edit Menu

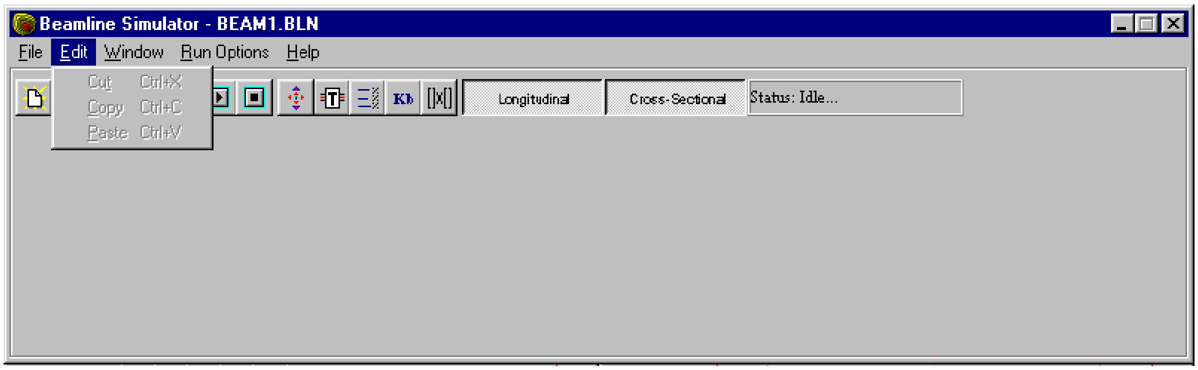


Figure 10-4, Edit Menu

Cut Ctrl + X	Cuts a beamline element from the SBI Window to the Clipboard. To be implemented.
Copy Ctrl + C	Copies a beamline element from the SBI Window to the Clipboard. To be implemented.
Paste Ctrl + V	Pastes a beamline element from the Clipboard to the SBI Window. To be implemented.

While not functional in the base window, these edit actions can be accomplished from within specific windows.

Window Menu

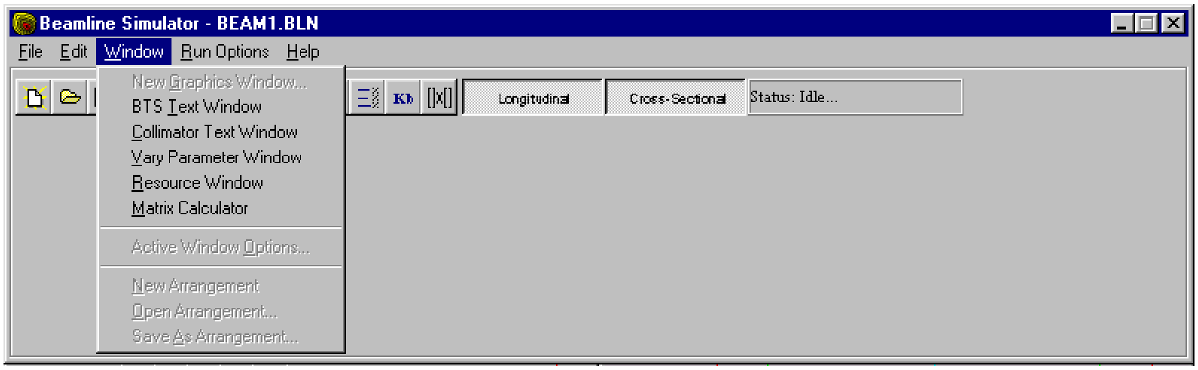


Figure 10-5, Window Menu

New Graphics Window ... — Creates a new type of graphics window. *To be implemented.*

BTS Text Window — Will show/hide the Beam Transport System Text Window. For more information see Chapter 9.

Collimator Text Window — Will show/hide the Collimator Window. For more information see Chapter 9.

Vary Parameter Window — Will show/hide the Vary Parameter Window. For more information see Chapter 10.5 Vary Parameter Window.

Resource Window — Will show/hide the Resource Window. For more information see Appendix B.

Matrix Window — Will show/hide the Matrix Window. See Appendix B.

The Active Window Options — New Arrangement, Open Arrangement, and Save As Arrangement may be implemented in the future.

Run Options Menu

The Run Options Menu changes the behavior of the run algorithm depending on what is selected.

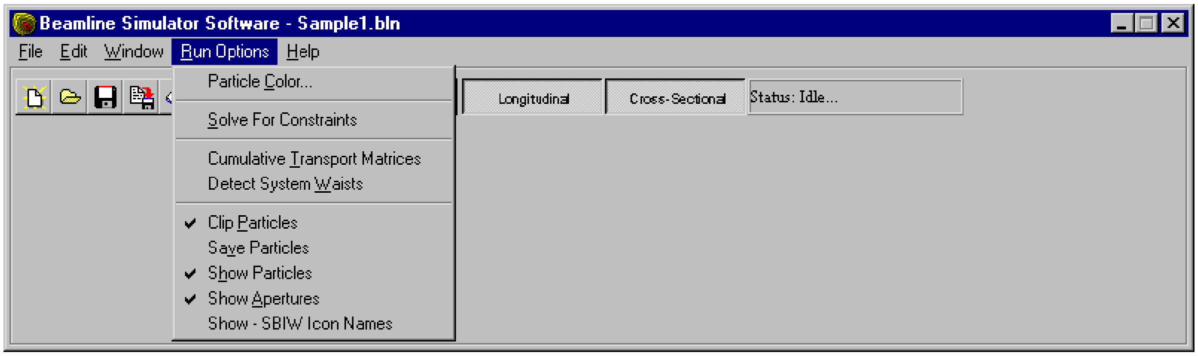
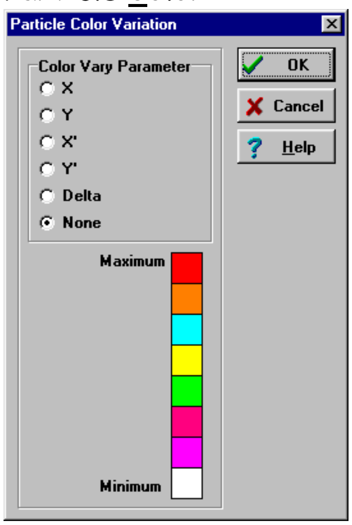


Figure 10-6, Run Options Menu

Particle Color



Provides a third dimension in the graphics plots by using particle color. This option is for multi-particle runs only. Click Particle Color to bring up the Particle Color Variation dialog box. Choose any of the five axes as the varying parameter. The parameter is then divided into eight ranges with a color assigned to each range. The color square next to the Maximum label will be assigned to a particle that has a value within the top eighth range of the color vary parameter. To change one of the colors in the squares, click on the square. A color selection dialog box appears and you may click on the color you prefer to use. Then click the OK button.

Detect System Waists

Toggles the System Waists function on and off. If this function is not needed then leave it off. The program will run slightly faster.

Solve for Constraints

Toggles the constraint algorithm on or off. When on, the algorithm will try to solve for user specified contraints in the next run.

Cumulative Transport Matrices	Toggles the Cumulative Transport Matrices on or off. When off, the System Metrics element displays only the identity matrix for the Cumulative Transport Matrix and the BTS Text window displays no matrices on the Cumulative Transport Matrix page. This option was implemented because some of the older computers showed a noticeable improvement in calculation speed if the cumulative transport matrices were not calculated.
Clip Particles	Toggles particle clipping on or off. When on, the particles will be clipped by the boundaries set up by the apertures. Even when Show Apertures is off, the particles will not be allowed past the aperture boundaries. **Important! This option must be on to get accurate readings in the Collimator window.**
Save Particles	Toggles the Save Particles feature on or off for both graphics windows. When on, the particles are saved so that the windows can be resized (to show bigger or smaller plots) without having to redo the run. When toggled off, the particles are lost if a graphics window is re-sized. You then need to do a new run. The advantage to leaving this feature off is that the run is faster.
Show Particles	Toggles the 'Show Particles' for the graphics window on or off. When on, the particles will be shown during a multi-particle run.
Show Apertures	Toggles the apertures in the graphics window on or off. When on, the apertures will appear in the next run as green lines in the graphics plots.
Show – SBIW Icon Names	Toggles the names for the elements in the Sequential Beam Icon Window on or off.

Help Menu

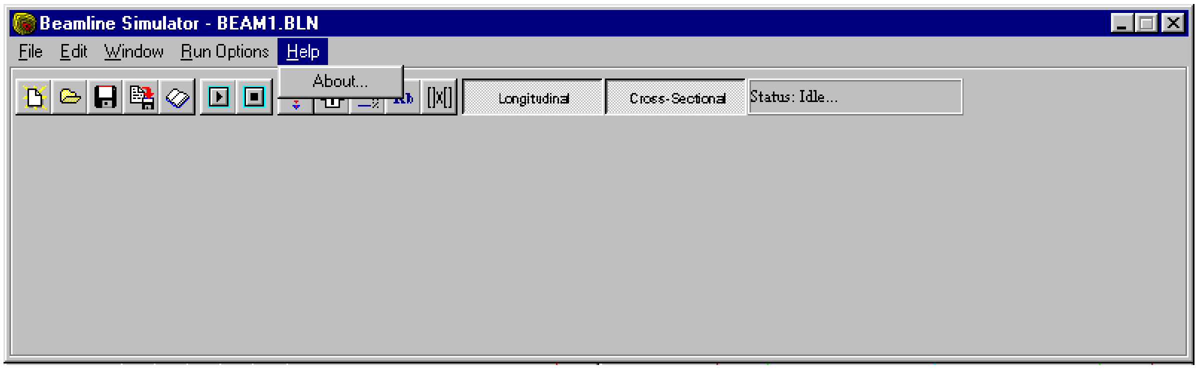


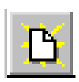
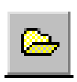
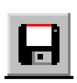
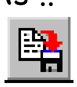
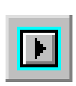
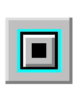
Figure 10-7, Help Menu

About ...	Displays information about the Beamline Simulator application such as date of creation and copyright.

10.4 Toolbar

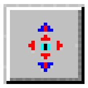
The Toolbar buttons are one-step action initiators for some of the menu items found on the Main menu bar.

Speed Buttons

New 	Creates a new beam transport system.
Open 	Opens an existing beamline system on disk.
Save 	Saves the current beamline with the current file name and drive.
Save As .. 	Saves the current beamline with a new filename.
Test 	Opens a file in the current file directory called TEST.BLN .
Run 	Initiates the run algorithm.
Stop 	Stops the run algorithm at any iteration during a multi-particle run or constraint algorithm run.

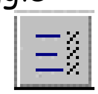
Window Show/Hide Buttons

Vary Parameter Window Toggle



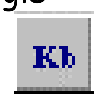
Opens the Vary Parameter Window and brings it to the forefront ahead of all other windows, or closes and hides it.

Collimator Window Toggle



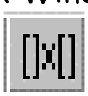
Opens the Collimator Window and brings it to the forefront ahead of all other windows, or closes and hides it.

Resource Window Toggle



Opens the Resource Window and brings it to the forefront ahead of all other windows, or closes and hides it.

Matrix Window Toggle



Opens the Matrix Window and brings it to the forefront ahead of all other windows, or closes and hides it.

Graphics Window#1 Toggle

Opens Graphics Window #1 and brings it to the forefront ahead of all other windows, or closes and hides it.

Graphics Window #2 Toggle

Opens Graphics Window #2 and brings it to the forefront ahead of all other windows, or closes and hides it.

Status Bar

Displays the status of the software.

10.5 Vary Parameter Window

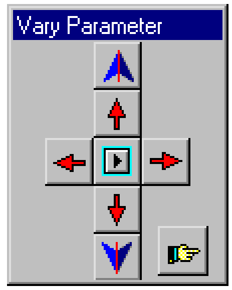
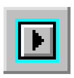
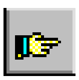


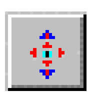
Figure 10-8, Vary Parameter Window

The Vary Parameter Window is used for hands on tuning of one beamline element at a time.

 is a conveniently located run button. It works exactly like the one on the Toolbar.

Use  to expand the window to include information on the current element, vary parameter and parameter value.

To use the Vary Parameter Window:

1. Decide which beamline element parameter you wish to vary and then double click that element icon in the SBI window.
2. Click the vary radio button beside the appropriate parameter.
3. Click OK to accept the changes and close the dialog box.
4. Click your chosen element to ensure that it is the current element in the SBI Window. There should be red bars above and below it.
5. Click  (Base Application Window - Toolbar) or select Vary Parameter Window under the Window menu (also in the Base Application Window). This brings the Vary Parameter Window to the center of the screen.
6. Click one of the up or down arrow buttons to vary the chosen parameter. The blue arrow takes a big step and the red arrow takes a smaller step. The step sizes are set in the Constraint Form Fill-In Variable Parameters dialog box. See Chapter 6.4, Applying Constraints.
7. Watch the graphics plots to see the changes that take place.

8. To move to the next element with a variable parameter, use the left or right red arrows.

10.6 Sequential Beam Icon Window

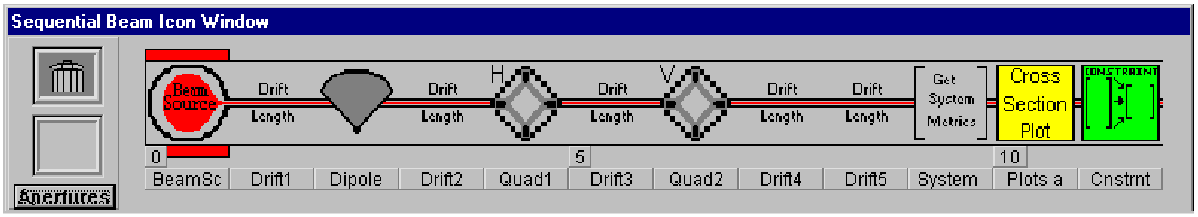


Figure 10-9, Sequential Beam Icon Window

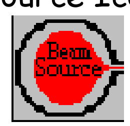
The Sequential Beam Icon Window (SBI Window) is always found at the bottom of the screen. This is where you will spend much of your time. The SBI Window is used to arrange the beam transport system elements in a sequence (or a string of icons from left to right) as they would appear in a real system. All the icons placed in this window come from the SBI Window's pop-up menu.

SBI Window Features

Apertures Button

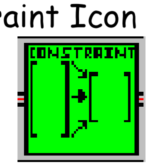
The Apertures button brings up a dialog box containing information related to the apertures (physical beam pipe, collimators and vacuum boxes). See Chapter 7.1, Apertures Button.

Beam Source Icon



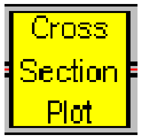
The Beam Source icon is always the first icon in the beamline sequence. Click this icon to bring up the Beam Source Form Fill-In dialog box. It contains all that you need to simulate a real beam source. See Chapter 5.1, Beam Source Form Fill-In.

Constraint Icon



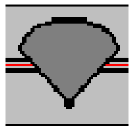
Place the Constraint icon at any point in the beamline where you must meet a beam or transport matrix constraint. Typically the Constraint icon is left at the end of the beamline to enable the user to constrain the beam size to fit the target. See Chapter 6.4 , Applying Constraints.

Cross-Section Plot Icon



The placement of the Cross-Section Plot icon determines where all cross-sectional and/or intensity plot data will be generated. The Cross-Section Plot icon can be placed at any location along the beamline's Z axis. See Chapter 7.2, Cross-Section Plot Icon.

Dipole Element

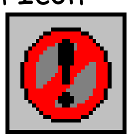


The dipole element represents a dipole magnet. A dipole magnet is normally used to cause a charged particle beam to be transported along a curved trajectory. See Chapter 6.3, Specifying Parameters for Elements.

Drift Length Element

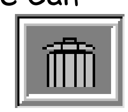
The Drift Length element represents a region of the beamline where the beam drifts through zero applied fields. For example, the spaces between magnets are usually drift spaces. See Chapter 6.3, Specifying Parameters for Elements.

End Run Icon



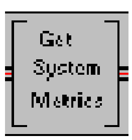
The End Run icon is used to stop the run algorithm at a desired Z co-ordinate. It is used only for multi-particle beams and may be placed at any location in the beamline along the Z axis. See Chapter 7.3, End Run Icon.

Garbage Can



Drag and drop beamline icons (or elements) into the Garbage Can. You've successfully deleted an icon when the garbage can becomes animated.

Get System Metrics Icon



When you place a Get System Metrics icon you are asking for measurement information about the beam half-sizes, the cumulative beam sigma matrix, the cumulative transport matrix and the particle vector co-ordinates. This data is generated at the Z co-ordinate where the icon is located in the SBI Window. Any number of Get System Metrics icons can be used. See Chapter 7.4, Get System Metrics Icon.

Hot Keys

8, **I**, **K**, **M**, **L**, **J**

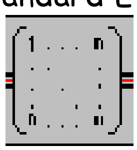
.

The hot keys are used to manually tune the variable parameter for the current element. They work in much the same way as the arrows in the Vary Parameter Window.
8 is a big step up.
M is a big step down.
I is a small step up.
K is a small step down.
L activates the next icon to the right with a varied parameter.
J activates the next icon to the left with a varied parameter.
The step sizes are set in the Constraint Form Fill-In Variable Parameters dialog box. See Chapter 6.4 Applying Constraints.

Icon Activation

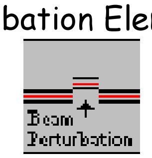
Red colored bars at the top and bottom of an icon indicates that it is the current icon. This also indicates a connection to the hotkeys.

Non-Standard Element



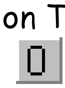
The Non-Standard element represents a non-standard steering or focusing component in the beamline. The transport matrix for the non-standard optical component must be numerically determined by specialised programs. See Chapter 6.3, Specifying Parameters for Elements.

Perturbation Element



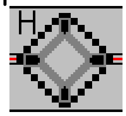
The Perturbation element is used to represent translational or angular displacements of the beam. These displacements may be inherent in the source beam or introduced by a steering magnet. See Chapter 6.3, Specifying Parameters for Elements.

Position Tags



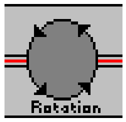
A position tag is placed at intervals along the beamline to indicate the positions of icons or elements. The position tags are placed after every 5 icons so they read 0, 5, 10, etc.

Quadrupole Element



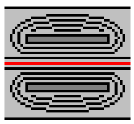
The Quadrupole element represents a quadrupole magnet. A quadrupole magnet is used for focusing a charged particle beam. See Chapter 6.3, Specifying Parameters for Elements.

Rotation Element



The Rotation element is used to represent systems where the elements are rotated with respect to the horizontal and vertical axes. See Chapter 6.3, Specifying Parameters for Elements.

Solenoid Element

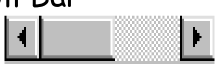


The SOLENOID element represents a solenoid magnet.

SBI Window Clipboard Viewer

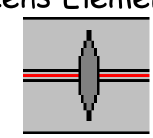
Move the mouse pointer over top of the clipboard viewer to see the name of the element that is on the clipboard.

Scroll Bar



By default, the scroll bar is inactive and invisible. When there are too many icons to be contained in one window the scroll bar is used to bring the desired icons into view.

Thin Lens Element



The THIN LENS element represents an ideal focusing element.

Vary Tags

A vary tag is placed at the bottom of an icon to indicate an icon with a varying parameter.

Making an Icon Current

The current or selected icon in the SBI Window has the *red bars above and below* it. When cutting and pasting icons and when using the Vary Parameter Window, it is important to be aware of which icon is current. The Vary Parameter Window adjusts parameters for the current icon only.

To make an icon current:

1. Place the cursor over the icon and click.

Inserting Icons

To insert a new icon:

1. Place the cursor in the gray area of the SBI Window.
2. Right click the mouse to view the pop-up menu.
3. Click the ELEMENT NAME of your choice.
4. Move the cursor to the desired location in the SBI Window and click to insert.

Cutting and Pasting Icons

To cut and paste an existing icon:

1. In the SBI Window, click the icon you wish to move.
2. Place the cursor in the gray area of the SBI Window.
3. Right click the mouse to view the pop-up menu.
4. Click **CUT**.
5. Again, right click the mouse to view the pop-up menu.
6. Click **PASTE**. The element is always inserted after the current icon.

Note: any icon that you handle, e.g., insert, cut and paste, drag and drop or left click becomes the current icon.

Rearranging Icons by Drag and Drop

To drag and drop an icon:

1. Click the icon and continue to hold the mouse button down.
2. Drag the cursor across the SBI Window and watch the purple bars move with you. When you reach the new location release the mouse button. The icon will drop into place.

3 Ways to Delete an Icon

To delete an icon:

1. Click the icon to make it the current icon.
2. Press the **<u>Del</u>** key. The garbage can (upper left corner of the SBI Window) will become animated to show that the icon has been deleted.

OR

1. Click the icon and continue to hold the mouse button down.
2. Drag the cursor to the garbage can and release the mouse button. The garbage can will become animated to show that the icon has been deleted.

OR

1. Click the icon to make it the current icon.
2. Right click the mouse to view the pop-up menu.
3. Click DELETE ELEMENT.

Specifying Parameters for Elements

To define or change a parameter for any element in the SBI Window:

1. Double click the element icon to view the Form Fill-In page.
2. Click inside the parameter box or on a radio button.
3. Type in the new parameter.
4. Click OK.

Using the Form Fill-In pages you can easily define each element in a different way — no matter how many elements there are.

Appendices

Appendix A … Units of Measurement

These are the units used throughout the software.

Optical Parameters

Field Strength: kilo Gauss (kG)
Current: Amps (A)
Length: millimeters (mm)
Angle: degrees

Beam Half-Sizes

X: (mm)
X': radians (rad)
0 xx': tilt angle of the horizontal phase ellipse in degrees
Y: (mm)
Y': radians (rad)
0 yy': tilt angle of the vertical phase ellipse in degrees
Δ, delta: percent (%)

Particles

Particle Energy: (MeV)
Particle Mass: (MeV)

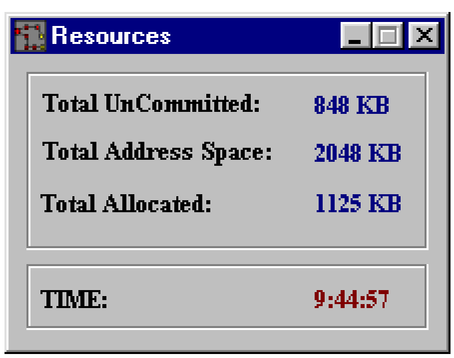
Graphics Plots

Z: meters (m)

Appendix B … Utilities

Resource Window

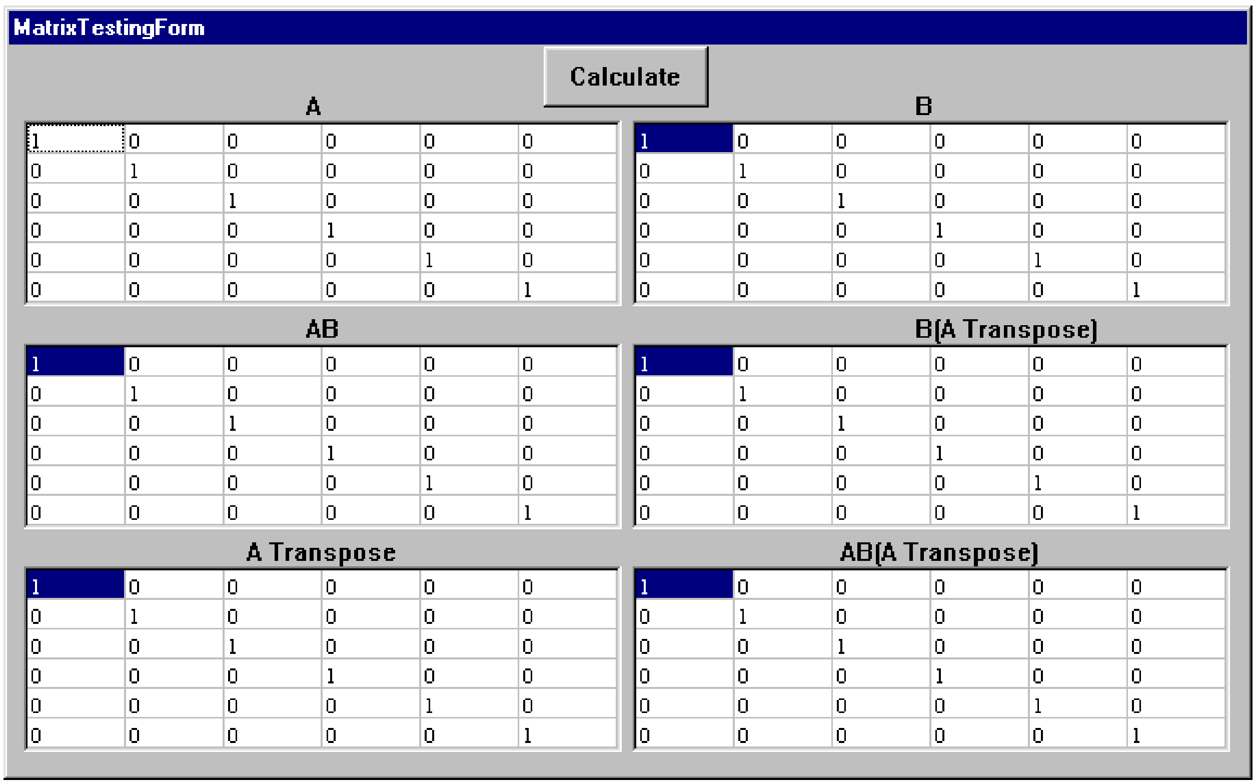
The resource window shows how memory is allocated to the software. 'Total Address Space' shows how much memory the entire application is using. 'Total Uncommitted' shows how much of the total address space can still be used. 'Total Allocated' shows how much physical memory the software is using. 'Time' is also displayed. Features in this window are updated every second.



Appendix B, Resource Window

Matrix Testing Window

This matrix window was used to test the software and has been left in as a matrix multiplication utility. You can multiply A and B matrix together in a number of ways. The first step is to edit the A and B matrices with matrix element data. After the numbers are entered and the desired matrices are ready to be multiplied, click the Calculate button and the results are put into the respective resultant matrices. The resultant matrices are: AB, BA, A^T, and ABA^T.



Appendix B, Matrix Testing Window

Appendix C … System Requirements

	Minimum	**Suggested**
CPU	i486 – 66 MHz	Pentium – 166 MHz
Hard Drive	20 Mb free	60 Mb free
Memory	8 Mb	32 Mb
Mouse	Required	Required
Keyboard	Required	Required
Video Board	1 Mb	2 Mb
Operating System(s)	Windows 95	Windows 95 or Windows NT

Appendix D … Customer Support

If you are a registered Beamline Simulator user you are entitled to certain customer support services which are explained in this appendix.

Registration

To register Beamline Simulator, fax or mail your completed registration form to the contact number or address listed below.

Customer Service & Technical Support

If you need more information about *Dehnel Consulting Ltd.* products and services or if you require technical support, contact Dr. Morgan Dehnel at:

Telephone: 1 (250) 352-5162
Fax: 1 (250) 352-3864
e-mail: mdehnel@wkpowerlink.com

You may also write to us at:

Dehnel Consulting Ltd.
PO Box 201
Nelson, BC Canada V1L 5P9

Appendix E … Ion-Optics Technical Notes

The appendix gives an overview of charged particle optics and also describes a number of common ion-optical elements.

E.1 CHARGED PARTICLE OPTICS AND TRANSPORT

A large number of charged particle beam transport systems have been built over the past fifty years, and so it is not surprising that there are a number of good books and papers describing such systems [1 – 13]. Charged particle transport systems are typically designed to guide an input charged particle beam to the exit of the transport system with minimal particle loss and without degradation in beam quality. In addition, specific optical properties may be forced upon the beam during transport to enhance the usefulness of the beam upon exiting the system.

E.1.1 PHASE SPACE

A good description of phase space is given by Banford [2]:

"Consider a particle moving in a three dimensional Cartesian coordinate system 0x, 0y, 0z. For present purposes a particle is completely specified if we know where it is and where it is going, that is to say we require to know the three coordinates x, y, z and the three momentum components p_x, p_y, p_z. All this information can be represented by the position of a point in a six-dimensional space with coordinates x, y, z, p_x, p_y, p_z. This six-dimensional space is known as phase space."

A representative ion which has just been extracted from an accelerator is located in phase space, and as it proceeds through the transport system (beamline) it describes a curve in phase space. Similarly, each of the beam's ions can be represented by a point in phase space, and beam transport can be considered to be the manipulation of the finite region occupied by these points in phase space.

Having introduced the concept of phase space, it is now prudent to introduce Liouville's theorem. The ramifications of this theorem affect nearly all aspects of charged particle transport. As presented in [2], the theorem states that:

"Under the action of forces which can be derived from a Hamiltonian, the motion of a group of particles is such that the local density of the representative points in the appropriate phase space remains everywhere constant."

The consequence of this theorem is that if satisfied, the hypervolume of the region occupied by the beam in phase space is conserved. The orientation and shape of the beam region may change throughout the transport process. However, if a particular phase space dimension of the beam shrinks, one or more of the other dimensions grows to maintain the hypervolume occupied by the beam. Often the hypervolume of the beam in a lower dimensional sub-space is also conserved during transport. This occurs when the motions of the particles in the sub-space are independent or uncoupled from their other phase space dimensions. In fact, a large number of transport systems are designed such that the (x, p_x), (y, p_y) and (z, p_z) sub-spaces act independently of each other.

Transport systems are usually designed to ensure that Liouville's theorem is applicable. A Hamiltonian can be written for any charged particle beam acted upon by forces arising from external macroscopic electric and/or magnetic fields. For such beams, the theorem applies. However, if particles are lost from the beam due to collimation, if interactions with targets occur, or if synchrotron radiation is emitted by the beam, the theorem does not apply [14]. Although a Hamiltonian in a higher dimensional space can be found, in principle, for electrostatic interactions between individual charged particles within the beam (space charge) [2], we limit ourselves to six dimensions. Within this six dimensional space, the beam does not adhere to Liouville's theorem for space charge interactions.

E.1.2 LINEAR CHARGED PARTICLE TRANSPORT

E.1.2.1 Coordinate System

A fixed (x, y, z) coordinate system is of limited utility for most transport systems. The mathematical expression for the trajectory of an individual particle becomes extremely complicated in all but the simplest transport systems when a fixed coordinate system is used. The coordinate system which is best suited to describing charged particle trajectories is the curvilinear system illustrated in Figure E.1. This is an orthogonal right-handed coordinate system which moves with an ideal mono-energetic charged particle along the central trajectory of the transport system. The unit vector **z** is the coordinate tangential to the central trajectory and in the direction of motion. The transverse coordinates **x** and **y** measure the displacement of a particle from the central trajectory. It is usual for **x** to be the coordinate in the lab horizontal plane and **y** to be the coordinate in the lab vertical plane.

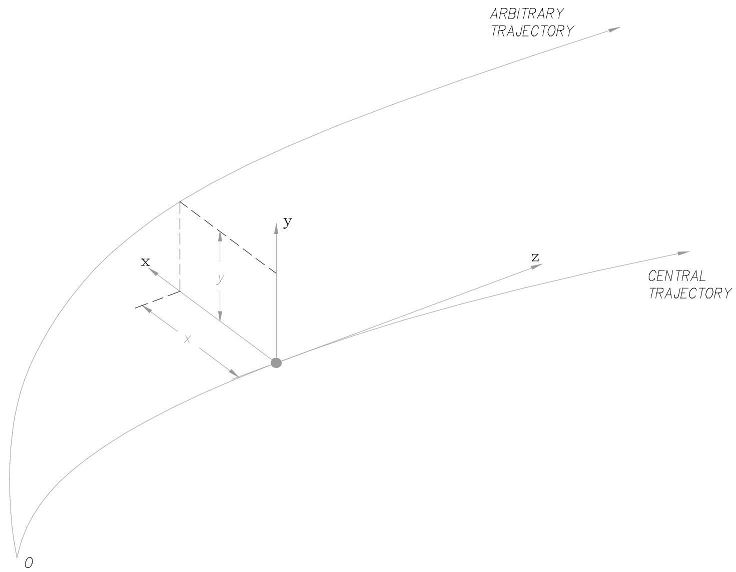


Figure E.1: *The curvilinear coordinate system.*

The commonly used TRANSPORT [8] formalism for describing charged particle transport utilizes the curvilinear coordinate system described above. The full description of the six coordinates in TRANSPORT's version of phase space are as follows:

- **x** = the horizontal displacement of the arbitrary trajectory or ray with respect to the central trajectory.
- **x'** = the angle the arbitrary ray makes in the horizontal plane with respect to the central trajectory.
- **y** = the vertical displacement of the arbitrary ray with respect to the central trajectory.
- **y'** = the angle the arbitrary ray makes in the vertical plane with respect to the central trajectory.
- **l** = the path length difference between the arbitrary ray and the central trajectory.
- δ = the fractional momentum deviation of the ray from the central trajectory ($\Delta p/p_{Tot}$).

The momenta in Banford's description of phase space are not explicitly used here. However, they are included in the sense that the angular divergence of a particle relative to the beam axis ($x' = dx/dz$, and $y' = dy/dz$) is equal to the ratio of transverse and axial momenta.

The path length difference associated with arbitrary trajectories is usually of no consequence in industrial beamlines. Thus, phase space from this point hence will be limited to the five dimensions (x, x', y, y',δ). As is shown in [2], Liouville's theorem still applies in this lower dimensional phase space.

E.1.2.2 Linear Transport Matrices

Charged particle transport can be simplified to a process of matrix multiplication as developed by Brown [10]. The particle's coordinates are contained in a column vector $\mathbf{X}_1 = (x_1,\ x'_1,\ y_1,\ y'_1,\ \delta_1)$. The subscript 1 indicates that the transverse coordinates are with respect to the curvilinear coordinate system at some position 1 along the central trajectory within the transport system. Similarly, the particle's coordinates at some position 2 along the central trajectory are then $\mathbf{X}_2 = (x_2, x'_2, y_2, y'_2, \delta_2)$. The goal in charged particle transport is to be able to calculate a particle's coordinates at 2 knowing $\mathbf{X}_1$ and the linear transport matrix $\mathbf{R}_{12}$. The matrix $\mathbf{R}_{12}$ provides a very good approximation to the optical transformation that occurs between positions 1 and 2. The multiplication that is performed is as follows:

$$\mathbf{X}_2 = \mathbf{R}_{12} \cdot \mathbf{X}_1. \tag{E.1}$$

The standard linear transport matrices used in the Beamline Simulator can all be derived using theory based on mirror symmetric magnetic systems. The derivation of these matrices starts, for a particle of mass m and charge q, with the Lorentz equation

$$\frac{d\mathbf{p}}{dt} = \frac{d(m\mathbf{v})}{dt} = q(\mathbf{v} \times \mathbf{B}), \tag{E.2}$$

where **p** is the momentum, **v** is the velocity, **B** is the magnetic flux density, and t is time.

By breaking this equation into its constituent (x, y, z) components, changing the variable of differentiation from time to distance along the trajectory, and performing some algebraic manipulation as done in [10, 14], one arrives at the following two equations

$$x'' = \frac{q}{p}\sqrt{1 + x'^2 + y'^2}\,[x'y'B_x - (1 + x'^2)B_y + y'B_z] \tag{E.3}$$

$$y'' = \frac{q}{p}\sqrt{1 + x'^2 + y'^2}\,[(1 + y'^2)B_x - x'y'B_y - x'B_z], \tag{E.4}$$

where primes (') indicate differentiation with respect to distance along the trajectory. As yet, no simplifying assumptions have been made. Therefore, equations E.3 and E.4 are valid to any order.

In solving equations E.3 and E.4 for the linear case, one makes the paraxial ray approximation which removes terms of order higher than x' and y'. To tailor the equations to describe transport through a particular device, one uses the appropriate magnetic field expansion for the device to substitute for the variables (B_x, B_y, B_z). The simplest example is the case of a field free region, which is known as a drift space in the jargon of charged particle optics. Equations E.3 and E.4 become

$$x'' = 0 \quad \text{and} \quad y'' = 0, \tag{E.5}$$

for a drift space.

Solving (E.5) for a drift of length L between positions 1 and 2 along the central trajectory results in the solution

$$x_2 = x_1 + Lx_1' \quad \text{and} \quad x_2' = x_1' \tag{E.6}$$

$$y_2 = y_1 + Ly_1' \quad \text{and} \quad y_2' = y_1', \tag{E.7}$$

which can be written as

$$\begin{pmatrix} x_2 \\ x_2' \\ y_2 \\ y_2' \\ \delta_2 \end{pmatrix} = \begin{pmatrix} 1 & L & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_1' \\ y_1 \\ y_1' \\ \delta_1 \end{pmatrix}. \tag{E.8}$$

The linear transport matrix $\mathbf{R}_{12}$ for any magnetic optical element can be derived following this same procedure. An analogous procedure can, of course, be developed for electric field based optical elements. The standard optical elements used in the study undertaken for Beamline Simulator include: the drift space, the dipole magnet, the quadrupole magnet, the solenoid magnet, an electrostatic lens (modeled as an ideal thin lens) and the coordinate rotation.

Linear transport matrices are also used to represent non-standard magnetic and/or electric field based optical elements. The appropriate matrix for a non-standard element is produced by first integrating five linearly independent paraxial particle coordinate vectors from the input of the element (position 1) through to the output of the element (position 2) using an orbit tracking code such as CASINO or CYCLONE [15], and appropriate field maps. The five input particle coordinate vectors ($\mathbf{X^1}_1$, $\mathbf{X^2}_1$, $\mathbf{X^3}_1$, $\mathbf{X^4}_1$, $\mathbf{X^5}_1$) are assembled into the columns of a matrix as are the five output beam column vectors ($\mathbf{X^1}_2$, $\mathbf{X^2}_2$, $\mathbf{X^3}_2$, $\mathbf{X^4}_2$, $\mathbf{X^5}_2$). One can then solve for the linear transport matrix representing the device by performing the following matrix operation

$$[\mathbf{X^1}_2, \mathbf{X^2}_2, \mathbf{X^3}_2, \mathbf{X^4}_2, \mathbf{X^5}_2]\cdot[\mathbf{X^1}_1, \mathbf{X^2}_1, \mathbf{X^3}_1, \mathbf{X^4}_1, \mathbf{X^5}_1]^{-1} = \mathbf{R}_{12}. \tag{E.9}$$

A linear transport system is usually composed of a number of optical elements. If the input coordinates of a charged particle are known, then the particle coordinates at the output of an N element system can be calculated as follows

$$\mathbf{X}_N = \mathbf{R}_{(N-1)N} \cdot \ \cdots \ \cdot \mathbf{R}_{12} \cdot \mathbf{X}_1. \tag{E.10}$$

Space charge forces can be included as an impulse (thin lens) after each application of an **R** matrix. The strength of each impulse is calculated with the linear space charge approximation [16], which is a function of the beam current and cross-section. In the code TRANSPORT, the distance traveled between each impulse must be optimized for best results. In the code TRANSOPTR [17], linear space charge forces, and all other first order optical elements can be computed using an infinitesimal transport matrix formalism which elegantly incorporates the fact that **R** becomes a function of the beam size when space charge forces are included [18].

E.1.3 HIGHER ORDER CHARGED PARTICLE TRANSPORT

In single pass transport systems the effect of non-linearity's are often quite small. However, in accelerators and storage rings where particles may be transported through many tens of thousands of identical focusing elements, the compounding of even relatively small higher order effects can have a dramatic effect on beam size and stability.

If higher order terms from equations (E.3) and (E.4) are retained in the procedure of section E.1.2.2., one can construct matrices which represent transport to a higher order. For example, to second order, as described by [10] and used in TRANSPORT and TRANSOPTR, one can compute the coordinates of an output beam vector (position 2) in terms of the original (position 1) using

$$\mathbf{X}(i)_2 = \mathbf{R}(i,j)_{12} \cdot \mathbf{X}(j)_1 + \mathbf{T}(i,j,k)_{12} \cdot \mathbf{X}(j)_1 \cdot \mathbf{X}(k)_1 \tag{E.11}$$

where **T** is the second order transport matrix. Beamline Simulator, however, does not offer a second order option.

In recent years, the need for dealing with higher order charged particle optics for repetitive systems has lead to sophisticated differential algebraic techniques which provide maps from initial beam coordinates and system parameters to final beam coordinates. These maps can be created to arbitrary order and can describe standard optical elements, fringe fields and even radiation effects. These techniques are not necessary for the purpose for which Beamline Simulator is intended, and have only been mentioned for completeness. The reader can refer to [19] and [20] for an introduction to these techniques.

As alluded to in section E.1.2.2, another common technique for studying nonlinear effects is to determine a particle's trajectory by numerically solving the equation of motion for the particle as it passes through the appropriate electric and magnetic field maps. The accuracy of such techniques depends on the integration algorithm, the step size and any approximations that are inherent in the field maps. The codes CASINO, CYCLONE and ZGOUBI [21] are three such codes.

E.1.4 CHARGED PARTICLE BEAM TRANSPORT

Thus far single-particle transport has been discussed. It is, however, usually much more informative to consider the transport of a multi-particle beam. In particular, one is often interested in the transverse envelope of the beam as a function of position along the central ray. One way to simulate charged particle beam transport is to choose a number of representative particles within the region occupied by the beam in phase space, and to calculate the trajectories of each of these particles with the matrix formalism introduced previously. In this manner the size of the beam can be ascertained by considering the particles with the outermost transverse coordinates at various positions along the central trajectory. This method is particularly useful when particles removed from the beam by collimation are to be considered, since this can be easily done by comparing the collimator's (x, y) boundaries with the coordinates of the particles, and then removing those particles with excessive (x, y) coordinates from further transport computations.

Liouville's theorem permits a different approach to simulating charged particle beam optics. One can bound the beam with an appropriately sized and shaped surface in phase space, and then transport this surface using the fact that the hypervolume of this closed surface in phase space must remain constant. The standard surface to use for this purpose is an ellipsoid. An ellipsoid is chosen for two main reasons. The first is that the transport of an ellipsoid is relatively easy to describe with the transport matrix approach, and the second is that, although actual beams can have almost any shape in phase space, the ellipsoidal shape corresponds well with measured beams.

The equation for an n dimensional ellipsoid defined by a positive definite symmetric matrix σ is given by [12]

$$\mathbf{X}^{\mathbf{T}}\sigma^{-1}\mathbf{X} = 1. \tag{E.12}$$

The hypervolume enclosed by such an ellipsoid is

$$\mathbf{V} = \frac{\pi^{n/2}}{\Gamma(n/2+1)}\sqrt{\det(\sigma)} \quad . \tag{E.13}$$

Often, the two and four dimensional sub-spaces of phase space are of interest. The hypervolume of a four dimensional (4D) ellipsoid is $(\pi^2/2)\{\det(\sigma_{4D})\}^{1/2}$, and the area of a two dimensional (2D) ellipse is given by $\pi \{\det(\sigma_{2D})\}^{1/2}$.

Recall that $\mathbf{X}_i$ corresponds to a beam vector at position (i) along the central ray. The matrix $\sigma_{\mathbf{i}}$ corresponds to the beam ellipsoid at this position (i), and for the two dimensional case we have

$$\mathbf{X_i} = \begin{pmatrix} x(i) \\ x'(i) \end{pmatrix} \quad \text{and} \quad \sigma_{\mathbf{i}} = \begin{pmatrix} \sigma_{11}(i) & \sigma_{12}(i) \\ \sigma_{21}(i) & \sigma_{22}(i) \end{pmatrix} \tag{E.14}$$

which yields

$$\mathbf{X_i^T}\sigma_{\mathbf{i}}^{-1}\mathbf{X_i} = 1 \quad \text{or} \quad \sigma_{22}x^2(i) - 2\sigma_{21}x(i)x'(i) + \sigma_{11}x'^2(i) = \det(\sigma_{\mathbf{i}}). \tag{E.15}$$

Note that $\sigma_{12}(i)$ is equal to $\sigma_{21}(i)$. Beam transport from position 1 to position 2 along the central ray is accomplished within the linear matrix formalism by performing the following matrix operation

$$\sigma_{\mathbf{2}} = \mathbf{R}_{12}\sigma_{\mathbf{1}}\mathbf{R}_{12}^{\mathbf{T}}. \tag{E.16}$$

For beam envelope computations in either 2 or 4 dimensional spaces one could invert the $\sigma_{\mathbf{i}}$ matrix at each position (i) and use the analytical formulation of the ellipsoid as indicated in (E.15). However, it can be shown that the square root of the diagonal components of $\sigma_{\mathbf{i}}$ are the projections of the extreme points of the ellipsoid on the coordinate axes. For example, $\{\sigma_{11}(i)\}^{1/2}$ is equal to $x_{max}(i)$, and $\{\sigma_{33}(i)\}^{1/2}$ is equal to $y_{max}(i)$. Thus, a plot of the x and y envelope of the beam as a function of positions (i) along the central ray can easily be produced by using the matrix elements of $\sigma_{\mathbf{i}}$ at each position (i). As an example, Figure E.2 illustrates a projection of the four dimensional beam ellipsoid onto the (x, x') plane.

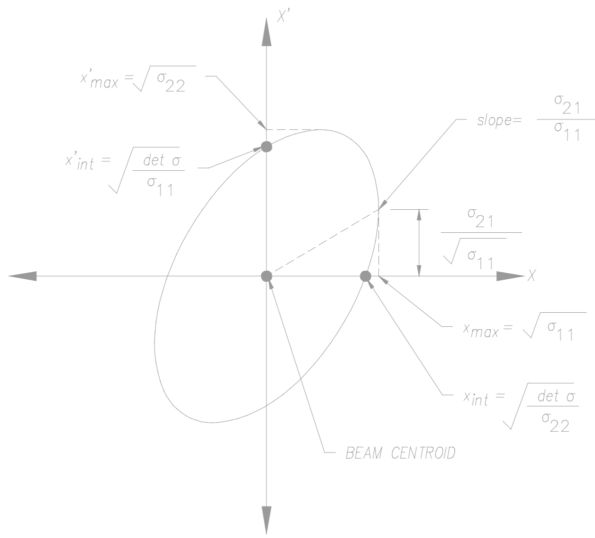


Figure E.2: *A projection of the beam ellipsoid onto the (x, x') plane. Note the dependence of the (x, x') ellipse's size and orientation on the σ matrix elements.*

Recall that Liouville's theorem requires that the hypervolume of a beam ellipsoid at position 1 must equal that at position 2. This corresponds to requiring that

$$\det(\sigma_1) = \det(\sigma_2), \tag{E.17}$$

and this implies that

$$\det(\mathbf{R}_{12}) = 1. \tag{E.18}$$

That the determinant of the transport matrices is equal to one is just a manifestation of Liouville's theorem. This result is built into the **R** matrix as well as the higher order transport matrices as a result of their derivation from Hamiltonian based systems.

E.1.5 BEAM EMITTANCE

So far we have not addressed how best to specify the size of the ellipsoid representing the beam. The emittance is a term used to describe the size of the beam in either the (x, x') or (y, y') phase space. It is defined by the equation [14]

$$\varepsilon = \sqrt{\det(\sigma)}, \tag{E.19}$$

where σ, when used to compute emittances, corresponds to the two dimensional sub-space associated with either (x, x') or (y, y'). The emittance of the beam is usually specified for the (x, x') and (y, y') phase space projections with units of (mm·rad). Using equation (E.13) it is apparent that the area of the beam in the (x, x') sub-space is equal to $\pi\varepsilon_{xx'}$, and in the (y, y') sub-space it is equal to $\pi\varepsilon_{yy'}$.

The emittance is a good measure of the size of the beam in the (x, x') and (y, y') phase spaces, as it is proportional to the area of the beam in these spaces. The emittance is often thought of as being related to the quality of the beam. A beam of small emittance corresponds to a high quality beam. This is because the (x, y) projection of a small emittance beam is easier to maintain with small dimensions than a beam with a large emittance. This in turn means that a high quality beam usually loses fewer particles during transport than a low quality beam.

As indicated in [22], the emittance of a finite beam with a uniform charge distribution in phase space is well defined. However, as the charge density of most actual beams is usually not uniform, the emittance of an actual beam must then be related to the fraction of particles included within an idealized beam ellipse. A common way to compute the emittance of the idealized beam ellipse, in a manner which is a fair representation of the real physical beam it corresponds to, is to ensure that the idealized beam and the actual beam have the same integrated intensity and the same second moments [23]. The second moments of a beam in the (x, x') sub-space are

$$\overline{x^2}, \quad \overline{x'^2} \quad \text{and} \quad \overline{xx'} \tag{E.20}$$

and a representative calculation for the first term is as follows

$$\overline{x^2} = \frac{\iint x^2 \rho(x, x')dxdx'}{\iint \rho(x, x')dxdx'}, \tag{E.21}$$

where ρ is the current density. If one computes these quantities for a real beam, and represents this real beam using the idealized ellipse of uniform charge density defined by the 4rms emittance [23]

$$\varepsilon_{4rms\ xx'} = 4\left[\overline{x^2}\,\overline{x'^2} - (\overline{xx'})^2\right]^{1/2}, \tag{E.23}$$

then both beams will have the same integrated intensity and the same second moments. Note that ε_{4rms}, as calculated in (E.23), is accurate regardless of the real beam phase space orientation at the time of measurement.

Many real beams are quite closely approximated with a gaussian distribution. In the case of a real beam having a gaussian distribution, ε_{4rms} defines an idealized ellipse whose boundary contains 86% of the real beam.

An important point to note concerning emittances is that they vary as a function of the total momentum (p_{Tot}) of the beam. That this is so can be illustrated by noting that in two dimensions

$$\varepsilon_{xx'} = x_{max} \cdot x'_{int}, \tag{E.24}$$

for the x_{max} and x'_{int} defined in Figure E.2, and since $x'_{int} = p_{x\,int}/p_{Tot}$, it is apparent that the emittance of this beam will decrease as p_{Tot} increases. So, if beams of different total momentum are being compared, as is done at different points during acceleration, one normally uses the normalized emittance of the beam. The normalized emittance of the beam is calculated with the formula

$$\varepsilon_{nxx'} = \varepsilon_{xx'}\beta\gamma = x_{max} \cdot \frac{p_{x\,int}}{mc}, \tag{E.25}$$

where m is the mass of the particle, c is the speed of light and β and γ are the usual relativistic parameters. The normalized emittance describes the beam size with respect to transverse momentum and transverse dimensions regardless of the total momentum.

E.1.6 EMITTANCE GROWTH

Recall that a beam with a small emittance is considered to be a high quality beam. This is because a beam with a small emittance is usually easier to transport than a beam with a large emittance. Therefore, it is important that every effort is made to create and maintain a beam of small emittance. Unfortunately, there are a number of ways in which the emittance can grow.

In linear transport systems with midplane symmetry, the (x, x') and (y, y') sub-spaces are uncoupled, and the emittances corresponding to these sub-spaces remain constant. A linear transport system in which cross-plane coupling exists maintains a constant beam volume in the five dimensional phase space, however, the projection of the beam phase space ellipsoid onto the (x, x') and (y, y') sub-spaces results in two dimensional ellipses with equal or larger emittances than the projected (x, x') and (y, y') beam ellipses at the beginning of the system.

Non-linear beam transport systems which satisfy Liouville's theorem can introduce an effective emittance growth, although the actual volume of the beam in phase space remains constant. This sort of emittance growth is illustrated for a two dimensional sub-space in Figure E.3. As can be seen, the ellipse which effectively represents the beam, as far as the transport system is concerned, occupies a larger portion of the two dimensional sub-space than the region actually occupied by the beam particles.

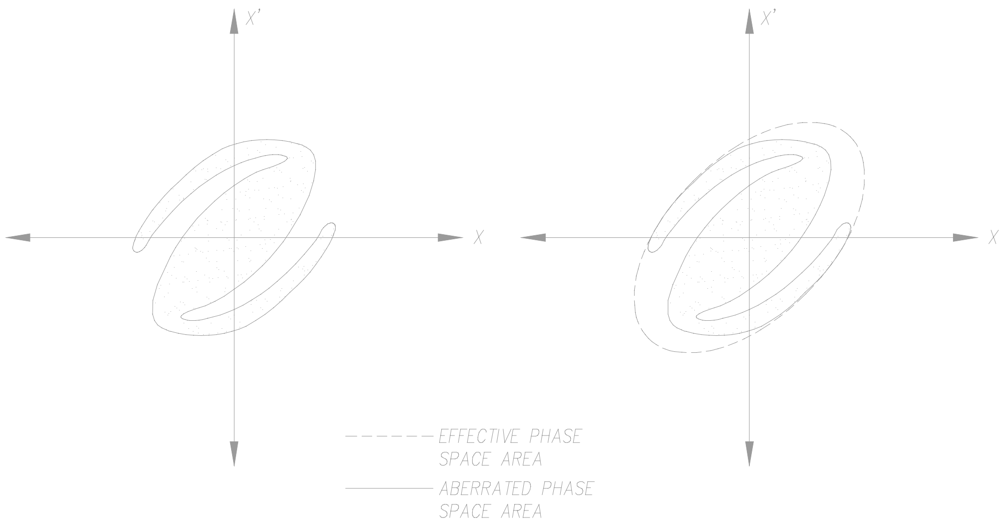


Figure E.3: *The effective emittance region of an aberrated beam in phase space.*

When a beam is injected into an accelerator or a storage ring there are (x, x') and (y, y') machine ellipses of particular orientations and aspect ratios to which these machines force the beam ellipses to conform to. If the injected beam ellipses do not have the required (x, x') and (y, y') shapes and orientations at injection, then new beam ellipses similar to the machine ellipses become filled (refer to Figure E.4), or effectively filled, if the beam ellipses simply rotate within the machine ellipses. If new ellipses are filled or effectively filled, emittance growth will have occurred. The process of manipulating the characteristics of a beam so that the beam ellipses are already similar to the machine ellipses at the injection point is called beam matching.

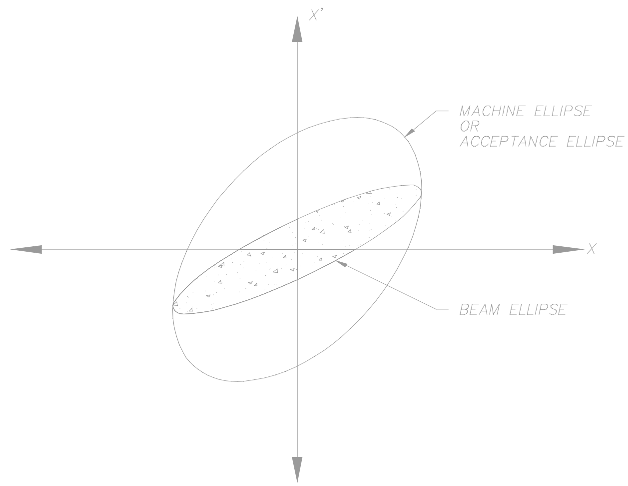


Figure E.4: *An arbitrary machine ellipse bounding the input beam ellipse. The machine ellipse becomes filled or effectively filled yielding a new beam ellipse which has experienced emittance growth.*

In section E.1.1, it was pointed out that Liouville's theorem does not apply for space charge forces, interactions with targets, or, in the case of a H^- cyclotron, interactions with extraction foils. Consequently, emittance growth is associated with these phenomena.

E.1.7 ACCEPTANCE

At the point where the central trajectory of a charged particle beam crosses the entrance of a device in a transport system, one can define an acceptance region in five dimensional phase space. This region corresponds to the coordinates of all particles which, if injected at the entrance of the device, would be transmitted. It is apparent that if the five dimensional hyper-volume of the beam is larger than the acceptance of a device, particles will be lost. In this case the region of phase space occupied by the beam will shrink. Typically this is not an acceptable way to create a beam with a small emittance. It is also common to define two dimensional acceptances in the (x, x') and (y, y') phase spaces with units compatible with the beam emittances.

If devices with narrow apertures in (x, y) space are present in the transport system, and if the beam emittance is relatively large, the focusing elements of the system can often be used to cause the beam ellipse to be oriented so that most of the emittance is distributed along the x' and y' axes at the location of each device with a narrow aperture. Consequently, the projection of the beam in (x, y) space will be small enough to allow a high rate of transmission through each narrow device. Tailoring the beam in this manner is one of the main goals of beam transport.

E.1.8 Dipole Magnet

The primary use of a dipole or bending magnet is to cause a charged particle beam to be transported along a curved trajectory. There are many reasons why such a feature is desirable. Five common reasons for using a dipole magnet are to enable the transport system to avoid physical obstacles, to maintain particles on a circular or racetrack orbit, to permit momentum selection, to select different beamlines for transport, and for steering. Dipole magnets can have first order focusing effects and higher order effects, as well. Dipole magnets are somewhat restrictive in their focusing capabilities because the magnitude of the magnetic field is usually fixed for achieving a particular bending requirement, and therefore the focusing effects can not be easily adjusted.

The field of a dipole magnet is as illustrated in Figure E.5 (a). Note that the typical dipole field bows outward as shown, and that for the purposes of bending calculations an effective length is established over which the peak pole tip field effectively acts. This is best described by the following integral

$$\int B dl = B_0 L\,, \tag{E.26}$$

where B is the magnitude of the magnetic field that the central ray experiences along its trajectory, dl is the differential path length, B_0 is the peak pole tip magnetic field and L is the effective length of the magnet. The field B_0 needed for a particular beam steering requirement can be calculated by using

$$B\rho(\mathrm{kG\cdot mm}) = 33.356 p/q \ (\mathrm{MeV/c}), \tag{E.27}$$

and $\rho \approx L/\theta$. Note that ρ is the radius of curvature of the charged particle in the dipole field, p is the momentum, θ is the azimuthal angle traversed by the particle's trajectory in the dipole field, and q is the charge (refer to Figure E.5 (b)). The momentum of the charged particle is calculated with the following formula

$$p = T\sqrt{1 + 2\frac{M}{T}}\,. \tag{E.28}$$

The units of p are in (MeV/c), if the rest mass M and the kinetic energy T of the particle are both given in (MeV).

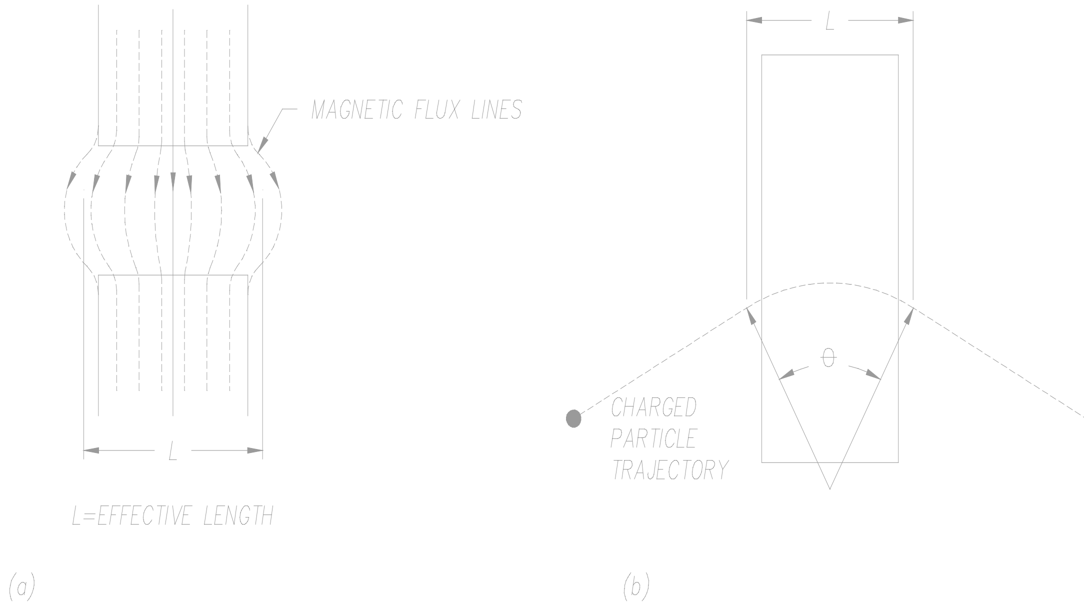


Figure E.5: (a) *Side view of a dipole magnet* (b) *Plan view of a dipole magnet.*

The first order focusing effects of a dipole magnet can be described in terms of the field index which is defined as the negative of the fractional change in field associated with a fractional change in radius [1], and is given by

$$n = -\frac{\mathrm{dB}/\mathrm{B}}{\mathrm{d}\rho/\rho}. \tag{E.29}$$

This quantity is used to describe the magnetic field at a given radius within the dipole magnet. The focusing induced beam oscillations related to the field index are known as betatron oscillations. Vertical or axial oscillations are described in terms of the axial tune ν_y which is the number of axial oscillations per revolution of the central ray around the dipole ($\theta = 2\pi$). The axial tune is calculated using

$$\nu_y = \sqrt{n}. \tag{E.30}$$

Similarly, the radial tune ν_x describes the number of radial oscillations per revolution around the dipole, and is given by

$$\nu_x = \sqrt{1-n}. \tag{E.31}$$

In terms of these tunes then, the first order transport matrix for a dipole magnet in which the central ray enters and exits normal to the pole faces is given by

$$\begin{pmatrix} \cos(\nu_x\theta) & (\rho/\nu_x)\sin(\nu_x\theta) & 0.0 & 0.0 & (\rho/\nu_x^2)(1-\cos(\nu_x\theta)) \\ -(\nu_x/\rho)\sin(\nu_x\theta) & \cos(\nu_x\theta) & 0.0 & 0.0 & \sin(\nu_x\theta)/\nu_x \\ 0.0 & 0.0 & \cos(\nu_y\theta) & (\rho/\nu_y)\sin(\nu_y\theta) & 0.0 \\ 0.0 & 0.0 & -(\nu_y/\rho)\sin(\nu_y\theta) & \cos(\nu_y\theta) & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix}. \tag{E.32}$$

Note that further first order focusing and defocusing effects can be introduced if the central ray does not enter or exit the dipole magnet normal to the pole faces. Refer to [2, 6, 14] for further reading on dipole optics.

E.1.9 Quadrupole Magnet

A quadrupole magnet is used for focusing a charged particle beam. However, unlike a lens used in the optics of light, a quadrupole magnet focuses in one plane while defocusing in the other plane. Fortunately, quadrupole magnets can be used in combination to produce an overall focusing effect in both planes. One such combination is the quadrupole doublet. A quadrupole doublet is a grouping of two quadrupoles in which, for example, one focuses in the horizontal plane and the other focuses in the vertical plane. Figure E.6 illustrates the quadrupole magnet structure and the field lines used in vertically focusing a positively charged particle. In addition, the forces exerted on a positively charged particle moving into the magnet are shown.

The magnetic field for a quadrupole magnet is given by [5, 14]

$$\mathrm{B_x} = g\mathrm{y}, \tag{E.33}$$

$$\mathrm{B_y} = g\mathrm{x}, \tag{E.34}$$

$$\mathrm{B_z} = 0. \tag{E.35}$$

The field gradient g is equal to (B_0/a) where B_0 is the pole tip magnetic field strength and a is the aperture radius of the magnet. The first order transport matrix for a vertically focusing quadrupole magnet is given by

$$\begin{pmatrix} \cosh(kL) & k^{-1}\sinh(kL) & 0 & 0 & 0 \\ k\sinh(kL) & \cosh(kL) & 0 & 0 & 0 \\ 0 & 0 & \cos(kL) & k^{-1}\sin(kL) & 0 \\ 0 & 0 & -k\sin(kL) & \cos(kL) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \tag{E.36}$$

where k^2 is equal to g/(p/q) and L is the effective length of the quadrupole magnet.

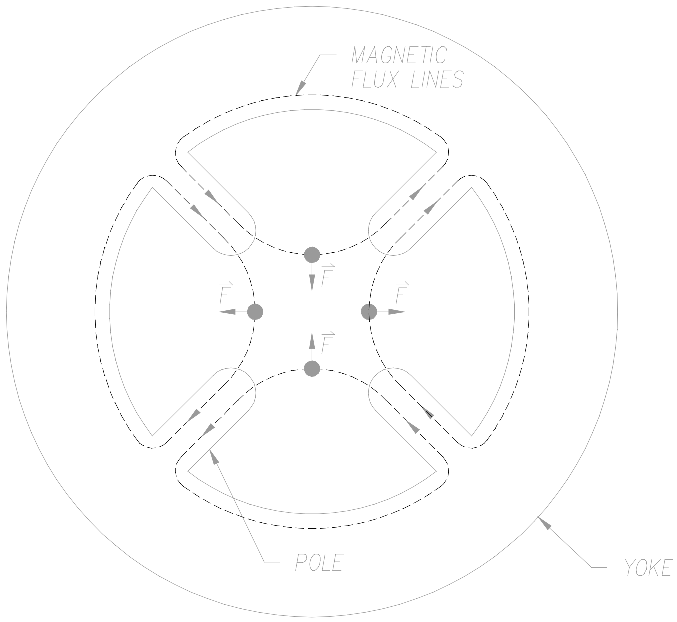


Figure E.6: *The field lines for a quadrupole magnet which vertically focuses positively charged particles. The forces experienced by positively charged particles along each axis are also shown.*

E.1.10 Solenoid Magnet

The magnetic field lines for a solenoid magnet are shown in Figure E.7. There are three optically important regions in a solenoid magnet. At the entrance and exit regions the magnetic field has a radial and an axial component, except on the magnet axis, whereas in the central region of the solenoid the field is strictly axial. The overall effect of the solenoid is to provide focusing, however, it also causes charged particles to rotate about the axial axis as they are transported through the magnet. This is useful if one wants to couple the (x, x') phase space of the beam to the (y, y') phase space.

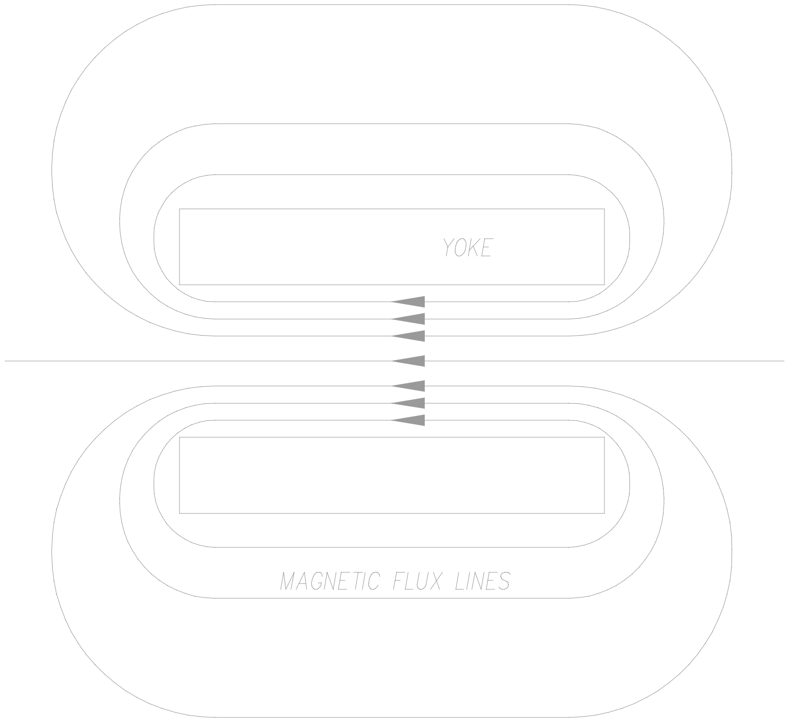


Figure E.7: *The magnetic field lines of a solenoid magnet.*

The overall first order transport matrix for a solenoid magnet is [2, 14]

$$\begin{pmatrix} \cos^2(\theta/2) & K^{-1}\sin(\theta/2)\cos(\theta/2) & \sin(\theta/2)\cos(\theta/2) & K^{-1}\sin^2(\theta/2) & 0 \\ -K\sin(\theta/2)\cos(\theta/2) & \cos^2(\theta/2) & -K\sin^2(\theta/2) & \sin(\theta/2)\cos(\theta/2) & 0 \\ -\sin(\theta/2)\cos(\theta/2) & -K^{-1}\sin^2(\theta/2) & \cos^2(\theta/2) & K^{-1}\sin(\theta/2)\cos(\theta/2) & 0 \\ K\sin^2(\theta/2) & -\sin(\theta/2)\cos(\theta/2) & -K\sin(\theta/2)\cos(\theta/2) & \cos^2(\theta/2) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \quad \text{(E.37)}$$

The angle θ is equal to $B_0L/(p/q)$ with B_0 being the peak axial field, and the factor *K* is equal to θ/2L.

E.1.11 Circular Aperture Electrostatic Lens

The ion source extraction electrodes accelerate and focus the beam. These electrodes are circular aperture electrostatic lenses. Figure E.8 shows a sketch of such a lens. The focal length for this lens is given by [24]

$$f = \frac{4V}{E_2 - E_1}. \quad \text{(E.38)}$$

The electrostatic potential of the lens plate is V, the magnitude of the upstream electric field is E_1 and the downstream electric field magnitude is E_2.

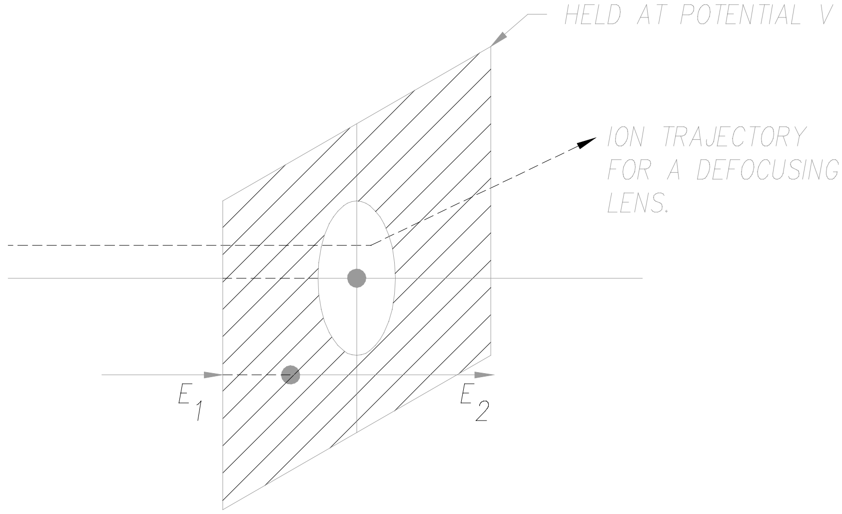


Figure E.8: *An electrostatic lens with a circular aperture [24].*

The first order transport matrix for an electrostatic lens with a circular aperture is

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ -1/f & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1/f & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{E.39}$$

E.12 Rotation Matrix

Standard optical components are sometimes rotated with respect to the lab horizontal and vertical axes. In order to avoid introducing complicated transport matrices for rotated components, optics codes usually rotate the particle coordinate vector or the beam sigma matrix while leaving the component's transport matrix in the usual unrotated form. Thus, the action of the rotated optical component is properly represented by the multiplication of three transport matrices. The first matrix represents a rotation of the curvilinear coordinate system by an angle θ, the second matrix is just the usual unrotated transport matrix of the optical component, and the third matrix represents a rotation of the curvilinear coordinate system by an angle −θ to bring the system back to the lab coordinates.

The rotation matrix used in this multiplication process is given by

$$\begin{pmatrix} \cos\theta & 0 & -\sin\theta & 0 & 0 \\ 0 & \cos\theta & 0 & -\sin\theta & 0 \\ \sin\theta & 0 & \cos\theta & 0 & 0 \\ 0 & \sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{E.40}$$

REFERENCES

[1] J.J. Livingood, PRINCIPLES OF CYCLIC PARTICLE ACCELERATORS, New Jersey: D. van Nostrand Company, Inc., 1961

[2] A.P. Banford, TRANSPORT OF CHARGED PARTICLE BEAMS, London: E. & F. N. Spon Ltd., 1966.

[3] M. Month (Ed.), PHYSICS OF HIGH ENERGY PARTICLE ACCELERATORS, *AIP Conf. Proc.*, No. 105, 1983.

[4] M. Month and M. Dienes (Eds.), PHYSICS OF PARTICLE ACCELERATORS, *AIP Conf. Proc.*, No. 184, Vol. 1 & 2, 1989.

[5] M. Month and M. Dienes (Eds.), THE PHYSICS OF PARTICLE ACCELERATORS, *AIP Conf. Proc.*, No. 249, Vol. 1 & 2, 1992.

[6] H. Wiedemann, PARTICLE ACCELERATOR PHYSICS, Berlin: Springer-Verlag, 1993.

[7] D.A. Edwards and M.J. Syphers, AN INTRODUCTION TO THE PHYSICS OF HIGH ENERGY ACCELERATORS, New York: John Wiley & Sons, 1993.

[8] K.L. Brown, D.C. Carey, Ch. Iselin and F. Rothacker, "TRANSPORT, A Computer Program for Designing Charged Particle Beam Transport Systems", SLAC 91 (1973), NAL 91 and CERN 80–04.

[9] E.D. Courant and H.S. Snyder, "Theory of the Alternating Gradient Synchrotron", *Ann. Phys.*, No. 3, pp. 1–48, 1958.

[10] K.L. Brown, "A First- and Second-Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers", *Adv. Particle Phys.*, No. 1, pp. 71–134, 1968.

[11] K.L. Brown, "Beam Envelope Matching for Beam Guidance Systems", *Nucl. Instr. and Meth.*, Vol. 187, pp. 51–65, 1981.

[12] K.L. Brown and R.V. Servranckx, "First- and Second-Order Charged Particle Optics", SLAC–PUB–3381, 1984.

[13] K.L. Brown and R.V. Servranckx, "Optics Modules for Circular Accelerator Design", SLAC–PUB–3957, 1986.

[14] G.M. Stinson, "A Brief Course in Beam Optics", Physics 675 Course Notes, University of Alberta, 1990.

[15] B.F. Milton, "CYCLONE Version 6.4", TRIUMF internal report, 1991.

[16] I.M. Kapchinsky and V.V. Vladimirsky, *Proc. Int. Conf. on High-Energy Accelerators and Instrumentation*, CERN, pp. 274–288, 1959.

[17] E.A. Heighway and R.M. Hutcheon, "TRANSOPTR – A Second Order Transport Design Code with Optimization and Constraints", *Nucl. Instr. and Meth.*, Vol. 187, pp. 89–95, 1981.

[18] M.S. de Jong and E.A. Heighway, "A First Order Space Charge Option for TRANSOPTR", *IEEE Trans. Nucl. Sci.*, Vol. 30, pp. 2666–2668, 1983.

[19] Y.T. Yan, "Application of Differential Algebra to Single-Particle Dynamics in Storage Rings", *AIP Conf. Proc.*, No. 249, pp. 380–455, 1992.

[20] M. Berz, "High-Order Computation and Normal Form Analysis of Repetitive Systems", *AIP Conf. Proc.*, No. 249, pp. 456–489, 1992.

[21] F. Méot and S. Valéro, "ZGOUBI USERS' GUIDE", SATURNE Note LNS/GT/93–12, 1993.

[22] W.T. Weng and S.R. Mane, "Fundamentals of Particle Beam Dynamics and Phase Space", *AIP Conf. Proc.*, No. 249, pp. 3–45, 1992.

[23] Lejeune and J. Aubert, "Emittance and Brightness: Definitions and Measurements", *Adv. Electronics and Electron Phys.*, Supplement 13A, pp. 159–259, 1978.

Glossary

Aperture: has two different uses in this document. Usually it refers to the aperture size of the physical beam pipe or diagnostic collimators, but when talking about bore diameters it refers to the aperture size of the quadrupole magnet.

Beam adjustments: phase space adjustments made to the simulated source or input beam through drifting and focusing in the (X, X') and/or (Y, Y') phase planes. The beam adjustments cause the beam ellipses to tilt which may or may not improve the accuracy of the beam model depending on whether your actual ellipses are upright or not.

Beam half-size: values determine the outer extents or maximum dimension of the beam and are used to calculate the beam matrices. The beam half-sizes are one half the width of the full width of the beam. The phase space ellipses of the beam are assumed to be upright unless beam adjustments are made.

X: is the horizontal half-width of the beam in millimeters.
X': is the horizontal half-divergence of the beam in radians
0 xx': is the tilt angle of the horizontal phase ellipse in degrees
Y: is the vertical half-width of the beam in millimeters.
Y': is the vertical half-divergence of the beam in radians.
0 yy': is the tilt angle of the vertical phase ellipse in degrees
Δ, delta: is the momentum spread of the beam in percent.

Beam transport system (actual): includes all the ion-optical elements, the beam pipe, the collimators and vacuum boxes.

Beam transport system (simulated): includes the Ion-Optical Elements, the Constraint icon, and the diagnostic tools such as the Apertures (or beam pipe, collimators and vacuum boxes), the Cross-Section Plot icon, the Get System Metrics icon, and the End Run icon.

Bore diameter: is the aperture size of the quadrupole magnet in millimeters.

Constraint icon: is used to define beam size or cumulative transport matrix requirements anywhere along the beamline.

Dipole magnet: is normally used to cause a charged particle beam to be transported along a curved trajectory. Four common uses for a dipole magnet are:

- to enable the transport system to avoid physical obstacles
- to maintain particles on a closed or spiral orbit
- to permit momentum selection and
- to select different beamlines for transport
- to correct misaligned beams by steering them

Drift length: or drift space represents any region in a beam transport system where no magnetic or electric fields are present. For example, the spaces between magnets are usually drift spaces.

Envelope beam type: a simulated beam that is represented in the graphics plots by lines that define the outer extents of the beam.

Get System Metrics icon: a diagnostic icon that can be inserted in the beamline at positions of your choice along the Z axis. The only condition is that they be placed after the Beam Source icon. When you place a Get System Metrics icon you are asking for measurement information about the beam half-sizes, the cumulative beam sigma matrix, the cumulative transport matrix and the particle vector co-ordinates. This data is generated at the Z co-ordinate of the Get System Metrics icon.

Multi-particle beam type: a simulated beam that contains from 1 to 10,000 particles.

Non-Standard element icon: is typically an optical component whose transport matrix must be numerically determined by specialized programs. For example, the fringe field of a cyclotron may be included as a non-standard element. This element will only be used by experts.

Perturbation icon: allows you to represent a beam with a central trajectory that is off-centered by X mm horizontally and/or Y mm vertically, and/or to represent a beam whose central trajectory is diverging (mis-steered) by an angle in the horizontal plane of X' radians and/or in the vertical plane of Y' radians.

Pole tip field strength: for quadrupole and dipole magnets, measured in kilo Gauss or amps, is the magnetic field strength measured at the magnet's pole tip. Magnetic field strengths are usually measured in kilo Gauss, however, many users may be more comfortable adjusting the power supply current setting (in amps) which is directly related to the pole tip field strength.

Quadrupole magnet: is used for focusing a charged particle beam. Unlike a lens used in the optics of light, a quadrupole magnet focuses in one plane while defocusing in the perpendicular plane. For example, a 'horizontal' quadrupole magnet focuses in the horizontal plane but defocuses in the vertical plane.

Solenoid: a magnet that focuses in both planes at the same time and also causes the beam to rotate about the Z axis.

Thin Lens: represents an ideal lens. This element adjusts the beam focus instantly and can be used as a correction within the system, or to mimic lenses that are not part of this software, e.g., electrostatic lenses.

Uniform distribution: within the bounds of the beam (or within the maximum half-sizes) the density of the particles that make up the beam is constant.

Z coordinate: a location along the Z axis or the central transport axis of the beamline.

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