

# USING THE PARTICLE BEAM OPTICS LABORATORY (PBO LAB™) FOR BEAMLINE DESIGN AND ANALYSIS

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The Particle Beam Optics Interactive Computer Laboratory (PBO Lab) represents a new approach to providing software for particle beam optics modeling. The PBO Lab includes four key elements: (a) a graphic user interface shell, (b) a graphic beamline construction kit for users to interactively and visually construct optical beam lines, (c) a knowledge database on the physics and technology of optical elements, and (d) various charged particle optics computational engines. A first-order matrix code, including a space charge model, can be used to produce scaled images of beamlines together with overlays of single trajectories and beam envelopes. The qualitative results of graphically sliding beamline components, or adjusting bend angles, can be explored interactively. Quantitative computational engines currently include the third-order TRANSPORT code and the multi-particle ray tracing program TURTLE. The use of the PBO Lab for designing and analyzing a second order achromatic bend is illustrated with the Windows95/NT version of the software.

## 1 Introduction

Accelerators of many varieties are being used for an increasing spectrum of applications throughout the industrial, medical and research communities. New machines, as well as new uses for existing machines, often require improved simulation capabilities in order to reliably model and predict the performance needed for many emerging applications. Evolving system requirements also frequently demand the design of new beam delivery systems or improved secondary beamlines. Particle optics and beam simulation codes play an important role in meeting these challenges for both accelerator operators and designers. Enhanced software tools offer the promise of improved productivity and reliability. Improved software tools can also reduce the time required to train new personnel. This paper provides an overview of one such new tool, and illustrates the tool's use in the design and simulation of a common beamline example: a second-order achromatic bend and transport to a target (or diagnostic) station.

## 2 Overview

The Particle Beam Optics Laboratory (PBO Lab) is a modular application based upon the Multi-Platform Shell for Particle Accelerator Related Codes (S.P.A.R.C. MP) software technology. S.P.A.R.C. MP is written in the object oriented programming (OOP) language C++ and the software architecture was designed specifically to run on different operating systems including Windows95/NT, UNIX/X-Windows and the Mac OS. Figure 1 illustrates the main Document Window for the PBO Lab running on Windows95. An overview of the primary components of the PBO Lab has recently been published [1], and additional details are given elsewhere for (a) the graphic user interface

shell [2], (b) the graphical beamline construction kit [1,2] and (c) the tutorial help system [1,3]. This paper focuses on (d), the use of the computation engines that are integrated with the PBO Lab.

## 3 Designing and Simulating an Achromat

The basic layout for the beamline is a separated function achromatic bend system, described by Brown [4] and applied to several beamlines by Brown and Servranckx [5], followed by a drift to a target (or diagnostic) station. The bend system consists of four cells. Each cell contains one dipole magnet, two quadrupoles and two sextupoles, separated by drifts. A PBO Lab iconic representation for this type of beamline is shown on the Model Space Pane of the Document Window illustrated in Figure 1. Each cell has been defined as a subline. The iconic representation of the elements comprising the first cell is also shown in Figure 1.

### 3.1 Defining the Beamline

It is informative to outline the initial set up of this problem since it illustrates several of the useful features incorporated into the PBO Lab. The first cell is assembled by selecting (with the mouse) the drift, bend, quadrupole and sextupole icons from the palette bar and dragging them to the Model Space Pane. The Piece Windows [1,2] for the elements are used to edit a few initial parameter values, but most of the parameters are assigned either Symbolic Parameter Names or defined by Parameter Algebraic Expressions. Symbolic assignments is a very useful capability: a general beamline design can be set up and then applied to a variety of specific problems.

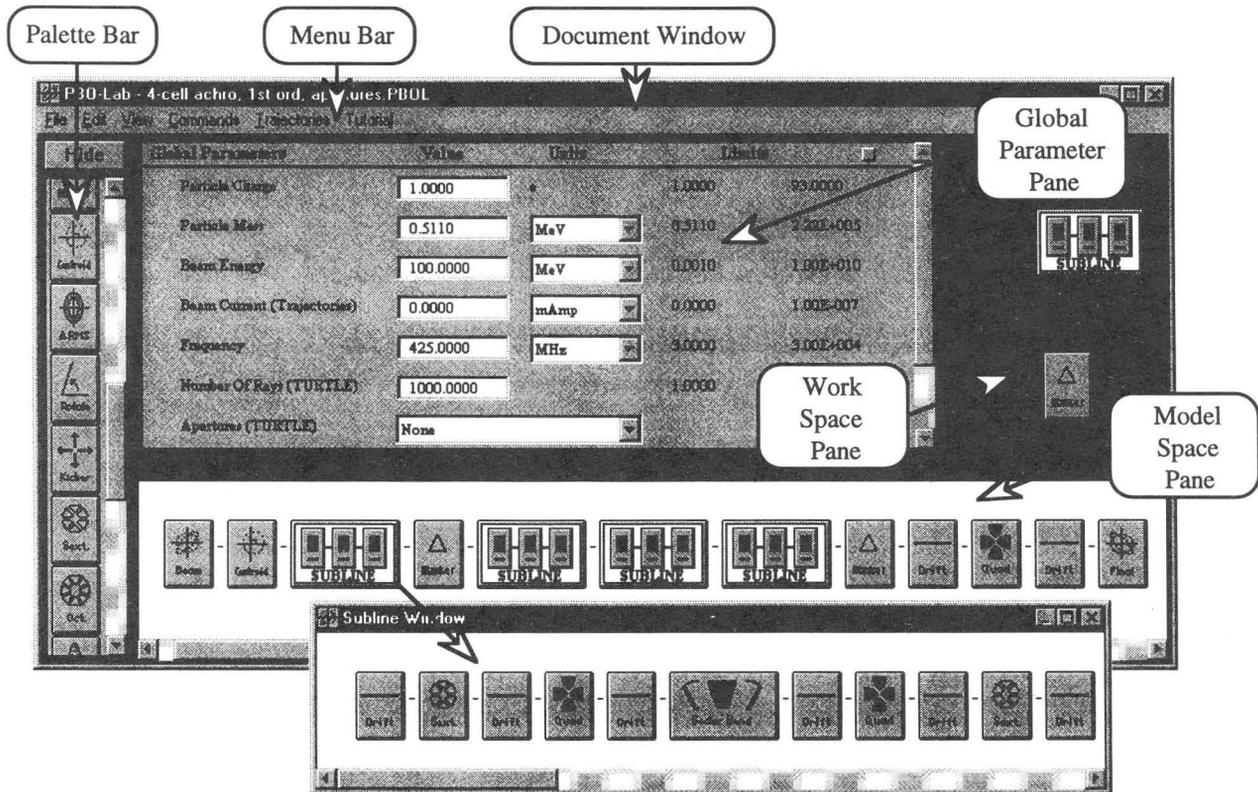


Figure 1. The PBO Lab graphic user interface, identifying key parts and illustrating the beamline icon representation (on Model Space Pane) for the achromatic bend system discussed in the text. The subline window (bottom) shows the components for the first of the four (identical) cells of the bend lattice.

Symbolic Parameter Names are assigned to the lengths and apertures for the first drift, sextupole, quadrupole and bend in the first cell of the lattice. These symbolic names are then used in Parameter Algebraic Expressions to define the corresponding parameters for all subsequent repetitions. The use of these two types of Special ("S") parameters assures that all quadrupoles, sextupoles and bends have the same dimensions (e.g. for ease of manufacturing), but allows for a simple, single-value editing, to change the length or aperture for each magnet type (e.g. for comparisons of different designs).

Since the field strengths of the magnets must be adjusted (as discussed later), the field strengths for the first two quadrupoles and first two sextupoles are each defined as parameters that can be varied. Vary parameters have Symbolic Parameter Names assigned and can thus be used in Parameter Algebraic Expressions. Figure 2 illustrates the assignment of the Symbolic Parameter Names for the length, field and aperture of the first quadrupole of the achromat, and the specification of the pole tip field of the first quadrupole as a Vary parameter.

The setup of the second quadrupole builds upon the symbolic names defined for the first quadrupole. The length and aperture of the second are set, by using Parameter Algebraic Expressions, to be equal to the

corresponding Symbolic Parameter Names for the first quadrupole. The pole tip field for the second quadrupole is assigned a different Symbolic Parameter Name from that of the first quadrupole, so that it can be varied independently during the fitting process. The S parameter assignments for the second quadrupole are also illustrated in Figure 2.

A similar procedure is used to set up the sextupoles for the first cell, using additional S parameters. The length and bend angle for the bend in the center of the first cell are also defined with symbolic names. Likewise, a Symbolic Parameter Name is used for the length of the first drift, and then the second, fifth and sixth drifts are assigned related values using Parameter Algebraic Expressions. The third and fourth drifts are handled somewhat differently in this example, in order to illustrate another capability of the S parameters. The length for each of these drifts is defined by a formula that assures that the overall length of each half of the first cell will be equal to eight (8) times the length of the first drift element. Figure 3 illustrates the Parameter Algebraic Expression for the third drift. In this example, magnets of different lengths may be easily substituted, but the achromat length will be unchanged.

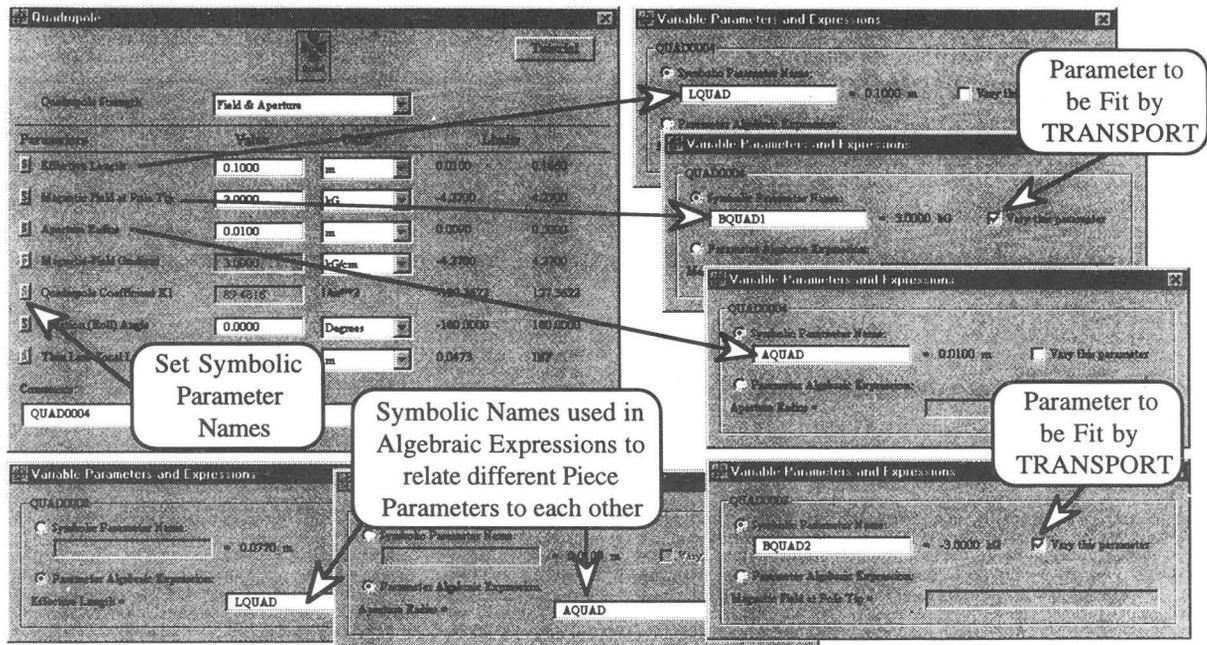


Figure 2. Piece Window (top left) for the first quadrupole of the achromat, illustrating the use of the Special ("S") button to define Symbolic Parameter Names for the length, field and aperture (upper right windows). Also shown are the S parameters for the second quadrupole (lower windows) that use Parameter Algebraic Expressions for the length and aperture.

Setting up the next three cells for the achromat is particularly easy. The first cell is made into a subline (this uses an option from the Edit menu of the Menu Bar illustrated in Figure 1). The subline is then selected (with the mouse) and dragged to the Work Space Pane. This creates a duplicate of the subline on the Work Space, as shown in Figure 1. This copy is then dropped onto the end of the beamline on the Model Space Pane. To define this cell in terms of the first cell, the lengths, fields and apertures set as Symbolic Parameter Names in the first cell are replaced with Parameter Algebraic Expressions in the second cell. Then the second cell can be duplicated twice, with no additional parameter modifications, with each new cell placed on the end of the beamline to form the achromat. It is worth noting that this second cell could be duplicated as many times as necessary to extend the total bend angle to 360°, which would then lead to an achromatic model of a storage ring. With the topology of the achromatic bend complete, the next step is to use TRANSPORT [5] to determine the quadrupole and sextupole fields needed.

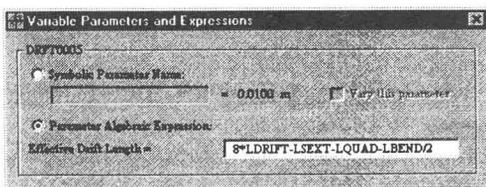


Figure 3. Using a Parameter Algebraic Expression to impose an overall length constraint on a half-cell of the achromat.

### 3.2 Determining the Magnet Strengths

The dipole field strength for each bend magnet can be determined directly within the Piece Window for the sector bend, since the expert rule system of the PBO Lab automatically calculates and displays the field required for a specified magnet (path) length and bend angle. To determine the quadrupole and sextupole fields, the fitting capabilities of TRANSPORT are used. The first-order transfer matrix (R-matrix) for the four-cell achromat should be the identity matrix, I. At the midpoint of the achromat, the R-matrix should be -I. For the two transverse (horizontal and vertical) directions, the equivalent requirements on the R-matrix at the end of the first cell, corresponding to phase shifts of 90° in both x and y (also known as a quarter-wave transformer), are:

$$R_{11} + R_{22} = 0 \quad (1)$$

and  $R_{33} + R_{44} = 0 \quad (2)$

Fit conditions are imposed using a Marker element. The two conditions (1) and (2) are set using the Marker Piece that has been inserted between the first and second cell sublines shown in Figure 1. A first order TRANSPORT run is then executed, using a selection from the Commands menu. For the parameters used in the problem illustrated here, the two quadrupole pole tip fields are 0.09684 T and -0.1018 T. Each pair of quadrupoles is not exactly an anti-symmetric doublet due to the first order focusing effects of the sector bends. PBO Lab plots of four R-matrix elements for the full 4-cell achromat are shown in Fig. 4.

The sextupole magnets strengths are determined by executing a second-order TRANSPORT fitting calculation. Two T-matrix conditions are imposed using the Marker Piece shown at the end of the 4-cell achromat in Figure 1:

$$T_{126} = 0 \quad (3)$$

and 
$$T_{346} = 0 \quad (4)$$

A characteristic of this type of achromat is that all second order aberrations, chromatic and geometric, will vanish [4] if the four conditions (1)-(4) are satisfied. For the example described here, the resulting pole tip fields for the two sextupole magnets are 0.01070 T and -0.01457 T.

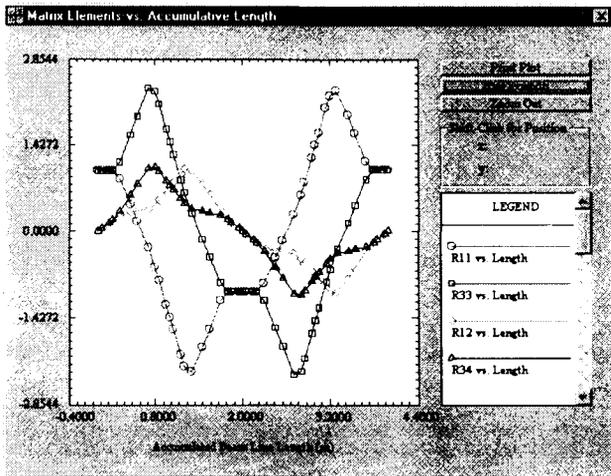


Figure 4. Transverse R-matrices for the four cell achromat.

### 3.3 Simulating the Beamline Performance

The design performance of the achromat can be simulated using TRANSPORT [56] for certain properties and TURTLE [6] for others. Root-mean-square (RMS) beam properties, beam centroids and similar characteristics can be calculated using TRANSPORT. Figure 5(a) shows the beam positions (XC, YC) and RMS beam sizes for a -3% off-momentum beam, each as a function of distance along the 4-cell bend, both with and without the sextupole correctors. Detailed performance using thousands of particles can be simulated using TURTLE. Figure 5(b) shows beam cross section plots near the center of the achromat for two different choice of magnet apertures.

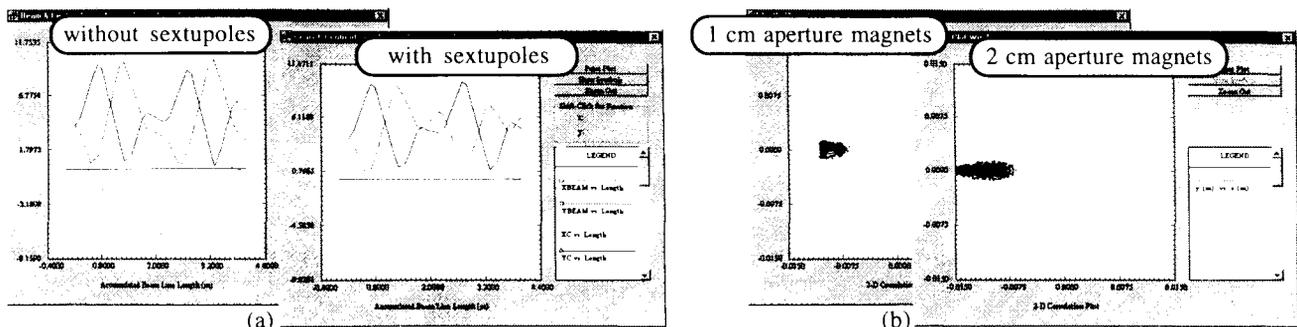


Figure 5. Using the PBO Lab TRANSPORT module (a) and TURTLE module (b) to simulate the achromat performance.

## 4 Conclusions

The Particle Beam Optics Laboratory is a useful new tool for designing and analyzing the performance of beamlines. The seamless integration of the PBO Lab with the third-order TRANSPORT code and the TURTLE ray tracing program facilitates the use of the programs without requiring the user to have any knowledge of the input format, syntax, or other details. Graphical output from these programs is displayed automatically without the use of post processors. The PBO Lab has been applied to the design of a general second-order achromatic bend, and the performance of the design has been verified. Aperture studies have been undertaken that illustrate the overall usefulness of the tool to easily and quickly iterate and improve designs. The PBO Lab provides improved productivity for scientists and engineers involved in the analysis or design of accelerators, and can also yield a significant reduction in the time required for new researchers to learn how to use particle optics programs.

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